An evaluation of hitchhiker seedlings with native boreal species as a revegetation tool of industrially disturbed sites in Alberta, Canada

By

Jessica Jacquelene Hudson

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in
Land Reclamation & Remediation

Department of Renewable Resources
University of Alberta

ABSTRACT

Herbaceous forbs hitchhiked, or co-grown, with a woody species, is a solution to establish both native woody and herbaceous species at recently disturbed sites. The broad study objectives were to (1) assess the growth of fireweed hitchhiked with three deciduous woody species and one conifer over two growing seasons as a reclamation tool, and (2) evaluate the growth responses of singly grown native species to a range of existing soil conditions.

To test the hitchhiker seedling concept, fireweed was sown with woody species at different time intervals to produce seedling stock with two species in each container with a range of root and shoot characteristics. Fireweed (*Chamerion angustifolium*) was sown with green alder (*Alnus viridis*), paper birch (*Betula papyrifera*), and Bebb's willow (*Salix bebbiana*) at the same time, 2 weeks later and 4 weeks later as well as grown alone. Fireweed was sown with white spruce (*Picea glauca*) 8 weeks and 10 weeks later.

Hitchhiker seedlings were planted at a soil stockpile and recently reclaimed borrow pit near Fort McMurray, Alberta, Canada. The growth and survival of woody and fireweed plants differed among sow dates with later sow dates consisting of a larger woody plant and a smaller fireweed plant as the woody plants had a longer period of growth prior to adding fireweed into the container. Initial seedling characteristics were especially evident after one growing season and faded after the second growing season. Fireweed spread was not determined by sow date, but rather site conditions. Sow dates recommended for revegetation of industrially disturbed sites were based on balanced growth of woody and fireweed plants relative to singly grown plants: 2-week alder, 0-week willow, and 10-week white spruce. The sow dates used in this study did not lead to a birch and fireweed hitchhiker seedlings with balanced growth and survivorship.

Although species responded differently to soil conditions due to their life history characteristics and autecology, most species growth was better in soil with lower bulk density and moderate total nitrogen and labile organic matter, while greater survival occurred in soils with greater bulk density.

The production of hitchhiker seedlings is encouraged as a revegetation tool at reclamation sites where the natural ingress of native herbaceous and woody species may be limited, and non-native species are controlled. Other herbaceous species should be tested with the hitchhiker concept with the consideration that deciduous woody species grow more quickly than conifers, each species may differ in autecology traits, and species selected should be site specific.

PREFACE

This project was in collaboration with Amanda Schoonmaker at NAIT Center for Boreal Research, and M. Derek MacKenzie and Bradley Pinno at University of Alberta. Financial and in-kind support was provided by ConocoPhillips Canada and financial support from NSERC. Amanda Schoonmaker, Derek MacKenzie and Bradley Pinno provided guidance on this research project scope, content, statistical analysis and interpretation.

ACKNOWLEDGMENTS

I am grateful for this opportunity and experience granted to me by Amanda Schoonmaker, Derek MacKenzie and Brad Pinno. Thank you for the collaboration of ecological knowledge, soils expertise and insight brought into this project. I am also forever thankful to Amanda Schoonmaker for the mentorship, guidance, support, generosity and encouragement throughout my journey from a summer research assistant to a young professional.

I am appreciative for NSERC and ConocoPhillips Canada industry funding that made this unique project happen. I was also lucky to receive the Queen Elizabeth II Graduate Scholarship and the Graduate Student Scholarship.

A special thank-you goes out to the past and present family at NAIT Center for Boreal Research Institute as well as the summer students that were with me through thick and thin vegetation, giant spiders, puffball mushrooms, flies, mosquitoes, hot sun, and also pouring rain. I couldn't have done it without the support from my parents and friends along the way with their patience and understanding.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TN: Total Nitrogen

LOM: Labile Organic Matter

EC: Electrical Conductivity

pH: Soil acidity

BD: Bulk density

AIC: Akaike Information criterion

varIdent: constant variance function structure

Cum.: cumulative

Inc.: increment

Wk: week

Ga: *Alnus viridis*

Bw: *Betula papyrifera*

Sx: *Salix bebbiana*

Sw: *Picea glauca*

Fw: *Chamerion angustifolium*

C: control

1.0 CHAPTER 1 – Introduction of the hitchhiker seedling concept and reclamation

1.1 Natural and anthropogenic disturbances in the boreal forest

1.1.1 Overview

The Canadian boreal forest spans the entire width of Canada which includes many heterogenous landscapes (Johnson et al., 1995). This region is defined by short growing seasons, low temperatures, and low productivity (Tamm, 1991). Forests are often composed of white spruce (*Picea glauca*), black spruce (*Picea mariana*), paper birch (*Betula papyrifera*), and trembling aspen (*Populus tremuloides*) (Rowe, 1972). In northern Alberta, mixedwood forests, which are characteristically well-drained uplands with heterogeneous coniferous and deciduous tree species, are common in the boreal region (Rowe, 1972). Strong seasonality occurs in this region causing a short growing season and plant dormancy during the winter months (Tamm, 1991). The boreal forest supplies many critical services, such as carbon sequestration, water filtration, resource extraction, and recreational use (Leatherdale, 2008).

1.1.2 Natural disturbances

Disturbances occurring in natural ecosystems can cause ecosystem fragmentation (Sahney et al., 2010), patchwork mosaics (Stocks et al., 2001), or gaps (Attiwill, 1994). Ecosystem fragmentation is described as discontinuity of wildlife habitats and patches of ecosystem function (Sahney et al., 2010). Impacts from disturbance differ in scale, type, and intensity (Capin et al., 2011). Naturally occurring disturbances, such as wildfires and insect outbreaks, are known to be critical to ecosystem structure and function (Attiwill, 1994; Ilisson & Chen, 2009). The effects of disturbances are generally considered harmful to forest goods and services, but there are also simultaneous positive effects on forest ecosystems (Stocks et al., 2001; Capin et al., 2011; Thom

& Seidl, 2016). Recently, Thom and Seidl (2016) assessed the effect of natural disturbances on ecosystem services and found there were negative effects on all ecosystem services, but disturbance also positively influenced biodiversity, such as species richness and diversity.

1.1.2.1 Wildfires

Wildfire is the dominant natural disturbance regime in the boreal forest where the size, severity and return-interval have substantial impacts on the composition of vegetation and soil chemical properties (Rowe & Scotter, 1973; Stocks et al., 2001; Yarmuch, 2003). Wildfires contribute organic matter (pyrogenic carbon), which can make up to 40% of the soil organic matter in boreal forests (Schmidt et al, 2011). The severity, frequency, and size of wildfires create a patchwork mosaic and encourage mixed species forests, through the evolution and adaptations of plant species (Stocks et al, 2001; Ilisson & Chen, 2009; Gutschick & BassiriRad, 2003). For instance, paper birch and trembling aspen naturally regenerate respectively with stump suckers and root suckering, which are physiologically triggered following canopy removal (Ilisson & Chen, 2009). Lodgepole pine (*Pinus contorta*) is also a fire adapted species by having serotinous cones where seeds are released by heat, allowing pine stands to quickly regenerate after a wildfire (Landhausser, 2009).

1.1.2.2 Insects

There is an interaction between fire and insect regimes among different ecological systems, such as grasslands and forests (McCullough, 1998). Insect outbreaks can affect the severity and likelihood of forest fires by increasing accumulated deadfall, and in return increase the risk of wildfire occurrence (Goheen & Hansen, 1993; McCullough, 1998). Forest fires can also control pests by altering the quality and availability of insect habitat (McCullough, 1998). Burning has been used to successfully reduce populations of bark beetles, such as spruce beetle (*Dendroctonus rufipennis*) in western Canada (Safranyik, 1978). Spruce beetle outbreaks are a significant natural disturbance and can cause widespread mortality of spruce (*Picea* spp.) species (Werner and Holsten, 1982). Deadfall due to insect outbreaks can also be beneficial for new forest growth by creating space for new growth to occur (Attiwill, 1994).

1.1.3 Anthropogenic disturbances

There are several anthropogenic disturbances that affect natural ecosystems, such as forest harvesting, conventional and in-situ oil and gas development, surface mining, as well as all the infrastructure required to support these activities. As a result, roads, seismic lines and pipelines are scattered among the landscape. Several seismic lines are cut through the forest 5-10m wide and 300-500m in length to perform geological surveys to evaluate the oil and gas potential (EMR, 2006; Dabros et al., 2018). Similarly, pipelines facilitate the transportation of liquids and gases between facilities, such as bitumen and produced salt water, which requires clearing lines through forest leaving an impressionable open linear corridor. Lastly, anthropogenic disturbances may attract the colonization of weedy or undesirable species, which may prohibit the establishment of native vegetation (Radosevich et al., 2007).

1.1.3.1 Forest harvesting

Forestry operations have been improved over time to mitigate environmental impacts, such as conducting harvesting during winter months to minimize soil disturbance (Kreutweiser et al., 2008). Logging can affect biogeochemistry of the boreal forest, but responses can be highly variable and site specific due to several factors including soil type, method of harvest, and hydrological connectivity (Kreutweiser et al., 2008). Although forest harvesting affects plant and wildlife habitat and watersheds, it is arguable that the concept of forestry has become more inclusive to ecological considerations over time, such as ecological integrity and considering landscape scale effects (Wiersbum, 1995; Schlaepfer & Elliot, 2000). Partial-harvest logging has reduced impacts relative to whole tree clear-cutting (Kreutweiser et al., 2008). For example, extended research of retention patches is ongoing in part of the Ecosystem Management Emulating Natural Disturbance (EMEND) project with a range of retention patch sizes or living patches of trees remaining as a strategy to maintain ecosystems similar to naturally disturbed mixedwood landscapes (Lieffers & Sidders, 2009). This was applied in 4 stands with different dominant trees. One key finding, among many in this large interdisciplinary project, was that white spruce seedlings grew best in aspen stands with 50% retention combined with mixing or mounding site preparations (Lieffers & Sidders, 2009).

1.1.3.2 Conventional and in-situ oil and gas development

The conventional oil and gas extraction processes involve extracting light oil and conventional gas by drilling into the reservoirs, which are permeable geologic formations, and then utilizing pumpjacks or well compression techniques (Petroleum Services Association of Canada (PSAC), 2019). These methods require less infrastructure and do not require the same specialized technologies compared to unconventional oil and gas extraction (PSAC, 2019). Unconventional methods are required when the formations are impermeable (ie. tight gas and shale gas) or the resource does not mobilize well (ie. bitumen, a heavy oil nearly solid at room temperature) (PSAC, 2019; Oil Sands Magazine, 2019). In Alberta, oil sands lie beneath 142 400 km^2 and consists of heavy oil intermingled within the sand deposit; these deposits must be extracted through physically separating the sand and other minerals from the oil using in-situ or surface mining techniques (Alberta Energy, 2019a; Kennedy, 1990). In-situ techniques are used when deposits are deeper than 75m and require specialized technologies, such as steam-assisted gravity drainage (SAG-D) (Natural Resources Canada, 2016; Pembina, 2019).

Roads, facilities, and seismic lines are created to support conventional and in-situ oil and gas operations. Prior to the creation of industrial facilities, the topsoil and subsoils are separately stockpiled. Long-term stockpiled soils are stored for about 30 years and used as reclamation material when the facility is no longer needed. Long-term topsoil storage has been shown to lead to greater chemical effects deeper than 1m, such as ammonium and anaerobic conditions (Harris & Birch, 1989). In addition, the viability of the seedbank decreases with soil depth (Harris & Birch, 1989; Rivera et al., 2012). Wick et al (2009) found that moving soil into a pile was shown to decrease soil aggregates, and expose organic carbon leading to organic carbon loss. In addition, a decrease in soil organic matter was due to consumption of organic matter by soil microbes with a lack of soil organic matter returned from plants (Wick et al., 2009). Soil erosion can also occur given a lack of vegetation on stockpiled soil (Zhang et al., 2004). Generally, the effects of long-term topsoil storage are from mechanized handling of the soil during stockpile construction as well as the depth of the stockpiled soil. Stockpiled soil used for reclamation topsoil capping led to slower vegetation recovery compared to direct placement of fresh salvaged topsoil (Dhar et al., 2018).

Borrow pits are also associated with well-sites, which are created when materials, such as clay, are excavated to build roads and well pads. This first requires rolling back topsoil to the edges, removing the subsurface material, and then spreading the stored topsoil over the disturbed area. Similar to soil stockpiling, handing the topsoil and the use of heavy equipment can decrease soil structure, increase bulk density, and disturb existing plant establishment (Wick et al., 2009). These properties can decrease the rate of natural vegetation recovery.

1.1.3.3 Mining (mineral resources & oil sands)

In Canada, many minerals and metals are mined, such as nickel, iron, coal, zinc, as well as oil in certain cases (Kennedy, 1990; Natural Resources Canada, 2019). Environmental impacts from mining acid drainage from tailings solids and ecological disturbances through the development of associated facilities. Changes in soil texture and water content can occur in disturbed soils and leads to changes in plant communities, as plants tend to have a low tolerance for metals in the soil (Mummey et al., 2002). Bioaccumulation of contaminants will occur for plants that are exposed to contamination within the vicinity of mining and adversely affect wildlife that eat them (Mummey et al., 2002). Soil acidification can also negatively affect plant habitat (Steignhauser et al., 2009). In addition, microorganisms are sensitive to changes in pH, temperature, and chemical concentrations (Steignhauser et al., 2009). A loss of microorganisms can lead to decreased plant nutrient availability (Steignhauser et al., 2009). However, Visser et al. (1983) found in another study that bacteria counts were higher and fungal community differed in mined soil compared to undisturbed soil at a coal mining site in Alberta.

Oil sands mining is surface mining that involves removing overburden to reach the oil sands deposits located within the upper 75 meters, and then separating bitumen from minerals and water (Poveda & Lipsett, 2013). Environmental impacts are at the landscape scale due to the complete removal of the ecosystem during the mining process, which involves removing surface soils and minable materials below it, as well as the construction of roads, facilities, and seismic lines (Grant et al., 2013; Rooney et al., 2012). In addition, tailings ponds are manmade ponds built to hold the by-products of extracting bitumen, where tailings consist of water, sand, clay, and residual bitumen (Canada's Oil & Natural Gas producers). Reclaiming tailings ponds can be a complex and timely due to fine clays, residual bitumen, and toxicity, which can be unfavorable for plant establishment (Nix & Martin, 1982; MacKinnon & Sethi, 1993).

1.2 Restoration Ecology

Restoration ecology is the study of repairing the ecological function and structure of degraded, damaged, or destroyed ecosystems (Society for Ecological Restoration International Science & Policy Working group, 2004). Ecological restoration is the process of recovering ecosystem function and structure of a disturbed ecosystem based on a target ecosystem (Society for Ecological Restoration International Science & Policy Working group, 2004).

Restoration ecology is a relatively young science and in Alberta, Canada, restoration of disturbed ecosystems uses a combination of reclamation certification requirements and restoration standards using a multidisciplinary approach (Hobbs & Cramer, 2008; Environment and Sustainable Resource Development, 2013; Society for Ecological Restoration International Science & Policy Working group, 2004). Reclaiming boreal forest landscapes involves returning land to a similar state prior to disturbance and supports a specified land use, which requires an evaluation of characteristics including topography, hydrology, soils and vegetation (Environment and Sustainable Resource Development [ESRD] 2013, Province of Alberta, 2016). The establishment of native species is a key objective of reclamation and reforestation of industrial sites, and certification criteria for well sites and associated facilities aim to reach a specified woody density and 25% ground cover of native vegetation, among other criteria for forested lands (Environment and Sustainable Resource Development, 2013). Regulatory criteria and legislation clearly define the need to control and eradicate noxious weed species as well as undesirable species (Environment and Sustainable Resource Development, 2013, 2013; Government of Alberta, 2010). Classic agricultural weed management tools include tillage, hand pulling and herbicides

(Radosevich, 1997), while intense mechanical site preparation is an alternative weed management approach (Lof et al., 2012).

Effort towards maintaining ecosystem connectivity can positively affect biodiversity of native species, ecosystem production, and stability (Moilanen et al., 2005; Cardinale et al., 2006; Wardle & Bardgett, 2004). Maintaining ecosystem connectivity naturally occurs when disturbance regimes enhance new growth of disturbance adapted plants. It is recommended that maintaining ecosystem connectivity should involve mimicking the natural disturbance regimes (Kern et al., 2014). For example, where wildfire is a dominant natural disturbance regime, the natural disturbance agent in the form of prescribed burning can be used (Bergeron et al., 2002). To restore bark beetle disturbance regimes, it is recommended to mimic various patches as a result of insect disturbance to stimulate biodiversity (Kern et al., 2014).

Rooney et al. (2012) argued that reclamation criteria in Alberta, Canada can be improved as there are situations where the 'equivalent land capability' may not be a reasonable target. It may not be practical or feasible to restore land similar to previous conditions, such as topography, if significant large-scale disturbances occur that deconstructs existing vegetation structure and diversity as well as soil landforms. Topography will especially dictate the moisture availability and hydrology, which will affect the plant species that are restored. The restored landscape can have different characteristics from the ecosystems of the past and may be a combination of known ecosystem types, known as novel ecosystems (Audet et al., 2015). Novel ecosystems do not have a strict definition, but may be described as constructed ecosystems with anthropogenic soils (Norris, 2013). Accepting that these novel ecosystems are allowable and functional would result in a reasonable endpoint.

1.3 Passive restoration & Active Restoration

Passive and active restoration are two approaches that differ relative to the disturbance type, available resources, and public perception (Hobbs & Cramer, 2008). Passive restoration is also known as the 'do nothing' approach (Jones et al., 2018). This approach is suitable where natural regeneration will be successful, such as a local rich seed source of forest soil seed bank of stockpiled soils. This is also an approach with minimal costs associated with restoration. No intervention may occur in a wildland setting where minimal human impacts are desirable or if minimal disturbance occurred and there is indication of natural regeneration potential (Hobbs & Cramer, 2008). However, active restoration may be required when there is a low likelihood of natural regeneration (Hobbs & Cramer, 2008). Intervention may also be required if weedy species are introduced during disturbance and prevent the establishment of native species (Radosevich et al., 2007). Intervention using restoration strategies can enhance the success and rate of recovery (Jones et al., 2018; Hobbs, 2007; Hobbs & Cramer, 2008; Bradshaw, 2000). For instance, the application of woody debris at a reclamation site facilitated greater species richness, lower soil temperature range, and greater volumetric water content (Brown, 2010). Furthermore, planting seedlings (Burger et al., 2017) and the addition of organic amendments (Larney & Angers, 2011) are techniques that can enhance restoration of disturbed sites.

1.4 Reclamation with an agricultural perspective

Land reclamation initially drew from agricultural perspectives and techniques to reclaim cropland and rangelands. The agricultural approach for revegetation involved direct seeding of agronomic grasses and forbs, which was cost-effective and could quickly establish ground cover and nitrogen fixing species, and in turn protect the soil from erosion and degradation of soil quality (Tordoff et al., 2000; Elliot et al., 1987; Richards et al., 1998).

It was clear that the agricultural reclamation approach lacked focus on the ecological function of forested lands, which consists of understory, shrub, and tree establishment that are crucial to boreal forest structure and function. Native tree, shrub and forb species can be negatively affected by agronomic species that establish in recently disturbed sites, which can prolong forest succession (Eis, 1981; Lieffers et al., 1993).

Reclamation of the aforementioned industrial disturbances within the boreal forest has been challenging and stimulated research and development of new guidelines to support the restoration of forested lands with a forest ecology perspective, rather than an agricultural one. Revegetation at a recently disturbed site should promote "the redevelopment of the target forest plant community" (Environment and Sustainable Resource Development, 2013). The "2010 Reclamation Criteria for Wellsites and Associated Facilities for Forested Lands (Updated July 2013)" was a significant improvement, which distinguishes reclamation of disturbed forested land by oil and gas operations from cultivated, native grasslands, and peatlands (Environment and Sustainable Resource Development, 2013). This reclamation criteria report supplies guidance and directives for reclaiming land to a similar productive forest ecosystem prior to disturbance.

1.5 Reclamation Certification challenges

Reclamation certification of forested lands is granted when the site meets reclamation criteria. Certification criteria involve drainage, erosion, soil quality, and desired species (Environment and Sustainable Resource Development, 2013). Although site occupancy with native plant species is a key objective of reclamation and reforestation of industrial sites, noxious weeds and other undesirable vegetation, such as invasive agronomic species (e.g. sweet clover [*Melilotus* spp.], alsike clover [*Trifolium hybridum*], smooth brome [*Bromus inermis*], etc.) present challenges to the development of forest plant communities (Environment and Sustainable

Resource Development, 2013; Bosco et al, 1991). Weedy species may be native to the region, but are competitive for light, nutrients, and space, which may not be desirable for reaching the site-specific revegetation goals (Bell et al., 2011).

1.6 Establishing native herbaceous species in disturbed landscapes

Choosing to actively revegetate recently disturbed sites may stem from lack of seed sources, limited topsoil, or compacted soils giving reason that slow natural revegetation would occur (Hobbs & Cramer, 2008). Establishing native species as disturbed sites can support the development of the targeted forest community as well as soil quality through nutrient cycling and protection against erosion (Environment and Sustainable Resource Development, 2013; Macdonald et al., 2012; Zhang et al., 2004). Native species may allow opportunity for other native species to establish and decrease the management of weedy and undesirable species. In addition, native herbaceous species can establish ground cover and increase diversity, which is important to ecosystem production and stability (Native Plant Working Group, 2001; Cardinale et al., 2006; Wardle & Bardgett, 2004).

There are a variety of ways that native species can become established after disturbance. As mentioned, passive restoration includes the natural recovery of plant species from the soil seedbank, vegetative propagules, and natural ingress. It may be arguable that native herbaceous forbs may establish on their own through natural ingress of local seed sources. For instance, if sufficiently uniform natural revegetation occurs, the established shrubs and trees may facilitate the ingress of native herbaceous forbs and create vegetation layers.

However, a faster revegetation rate may be desirable to meet reclamation certification criteria or beat the establishment of undesirable species. Actively establishing native woody, shrub, and native herbaceous forb species would take up space otherwise occupied by undesirable species. Direct seeding, planting seedlings, cuttings, or spreading root propagules can directly establish native species.

1.7 The hitchhiker seedling concept

Woody species are often planted during afforestation while most native shrubs and native herbaceous plants are left to regenerate through natural ingress. Greater restoration success could occur with the inclusion of native shrub and herbaceous seedlings that are evolved to tolerate the climate and soil conditions within the disturbed area. The production of seedlings consisting of herbaceous plants alone is more costly than direct seeding (Campos-Filho et al., 2013). However, the quantity of seed required for direct seeding is generally not commercially available and emergence of native forbs from direct sowing is low (less than 5%) (Native Plants Working Group, 2001; Smreciu & Gould, 2015).

Growing woody species in containers to produce seedlings is already a common approach (Burger et al., 2017). Thus, growing both a woody and herbaceous plant in the same container would ultimately reduce costs and ideally establish the ground cover with a native herbaceous forb as well as establish desirable woody species at reclamation sites.

Recent research involving planting container grown seedlings consisting of white spruce (*Picea glauca*) co-grown with showy aster (*Eurybia conspicua*) or fireweed (*Chamerion angustifolium*) has indicated that seeding herbaceous species later in hitchhiker stock production had enhanced aboveground growth (Mathison, 2018). However, seeding two different species into a single container does present some challenges, particularly as it relates to consideration of timing.

1.8 Autecology of green alder, paper birch, Bebb's willow, and white spruce

The responses and adaptations of plants to their environment is known as autecology (Barbour et al., 1987). Plant species respond differently to disturbances based on the disturbance type and plant life history characteristics (Wienscyk et al., 2011).

All species in this study are native to the site ecosystem and have been recommended for reclamation of industrially disturbed areas in Alberta, Canada (Hardy BBT Limited, 1989; Native Plant Working Group, 2001; Smreciu et al., 2014; Cumulative Environmental Management Association [CEMA], 2006). However, reclamation practice using deciduous woody species and native forbs is lacking. Our reclamation study utilizes four deciduous shrubs and trees, one coniferous species, as well as one forb: green alder (*Alnus viridis* [Chaix] DC. Subsp. *Crispa* [Aiton] Turill), paper birch (*Betula papyrifera* Marsh.), Bebb's willow (*Salix bebbiana* Sarg.), white spruce (*Picea glauca* [Moench] Voss), and fireweed (*Chamerion angustifolium* [L.] Holub) (Moss, 1959).

1.8.1 Green alder

Green alder is a shrub-like tree, can grow up to 3m tall, and is often found in open forest and slopes subject to well-drained soils and course textured soils (Johnson et al., 1995). Reproduction of green alder (Betulaceae family) is limited to seed and stump sprouts (Bell et al., 2011). Green alder tends to establish in a wide variety of landscapes from wetlands and streams to sandy hills (Moss, 1959). Alder range in shade tolerance as they can establish in fairly shaded forest canopy as well as in forest openings (Farrar, 1995; Bell et al., 2011). Green alder is particularly known for resource enhancement by nitrogen fixation (Bell et al., 2011).

1.8.2 Paper birch

Paper birch (Betulaceae family) is a mid-sized tree that is widespread in the boreal forest, grows up to 15m tall, and is characterized by the peeling white to brown bark and diamond shaped leaves (Johnson et al., 1995). This early successional tree is often found in open to dense forests with well-drained and moist soils and can reproduce by seed and stump sprouts (Johnson et al., 1995; Bell et al., 2011). Paper birch prefer full sun conditions, but are moderately shade tolerant (Bell et al., 2011; Farrar, 1995). In Alberta, paper birch mainly occurs in wetter areas as they are relatively short-lived. They are sparse in upland sites as they are quickly outcompeted by other species, such as trembling aspen (*Populus tremuloides*) by suckering, and therefore relegated to wetter sites.

1.8.3 Bebb's willow

Beaked or Bebb's willow (Salicaceae family) is a tall shrub and is a common and widespread species to the western boreal forest as it is found in a range of habitats from inner forests to wetlands (Johnson et al., 1995). However, this species may often be found in areas with good soil moisture and light availability as it is moderately shade tolerant (Farrar, 1995). Similar to other *Salix* species, Bebb's willow can reproduce by seed, stump sprouts and suckers (Bell et al., 2011).

1.8.4 White spruce

White spruce (Pinaceae family) is a common tree in the boreal forest and, depending on site conditions, approximately ranges from 7 to 20m in height and can exceed 20m in good conditions (Johnson et al., 1995). It is the only conifer species in this study and is limited to reproduction by seed (Johnson et al., 1995; Bell et al., 2011). This tree grows best in well-drained moist soils and is very shade tolerant (Johnson et al., 1995; Farrar, 1995). This tree has been widely studied and it is well known that the combined effect of transplanting stress and competition with other species, such as Canadian reed grass (*Calamagrostis canadensis*), during the early phase of seedling establishment can negatively affect the success of planted spruce seedlings (Rietveld, 1989; Grossnickle, 2000; Lieffers et al., 1993; Matsushima & Chang, 2006; Sloan & Jacobs, 2013).

1.8.5 Fireweed

Fireweed (Onagraceae family) is native to the boreal forest, can grow up to 2m tall with several purple flowers, and is found from open forests to roadsides (Johnson et al., 1995; Moss, 1959). This early successional herbaceous forb often establishes after recent soil disturbances, especially fires, and tends to be found in open areas as it is shade intolerant (Maundrell & Hawkins, 2004; Landhäusser et al., 1996; Lieffers & Stadt, 1994; Moss, 1994). Fireweed can reproduce by seed and rhizomes as well as thick creeping roots, which allows the plant to spread vigorously (Moss, 1959; Johnson et al., 1995). This native forb is a good competitor for light and space as it can occupy aboveground space quickly and spreads by rhizomes (Landhausser & Lieffers, 1994; Landhausser et al., 1996).

Fireweed has been suggested to use for revegetation at reclamation sites due to its early establishment and vigorous growth (Moss, 1959; Pinno et al., 2013). Thus, it may contribute native ground cover while decreasing the ability for undesirable plants to spread.

1.9 Plant responses to soil conditions

In natural systems it is well known that sunlight, moisture, and nutrients are among the most important requirements for plant growth and establishment (Taiz & Zeiger, 2002; Bell et al., 2011). Soil parameters, including bulk density, soil water infiltration, electrical conductivity, and pH can also hinder plant development when these values are beyond their level of tolerance (Barbour, 1999; Bell et al., 2011; Millward et al., 2011; Baligar et al., 1998). For example, higher bulk density can lead to lower infiltration, and in turn negatively affect soil moisture (Millward et al., 2011). In addition, many native boreal species are intolerant of extremely saline soils (Howat, 2000), yet they tend to have tolerance to mild saline soils. Soil pH is important for soil bacteria, nutrient availability, and toxic elements and most nutrients are available to plants between pH 5.5-6.5 (Perry, 2003; Tucker et al., 1987). Organic matter is a component of soil nutrient cycling and supplies nutrients for uptake by plants, which is critical for plant function, growth, and survival (Taiz & Zeiger, 2002; Bot, 2005).

It is difficult to determine which soil parameters are most important for plant growth and survivorship as soil-plant relationships are complex and involve the interaction of physical and chemical environmental components. Fu et al (2004) found that soil total nitrogen affected shrub growth more than soil organic matter, pH, and volumetric water content. More shoot and root growth of giant reed (*Arundo donax*) plants was also associated with greater nitrogen availability (Van der Weele et al., 2000; Quinn et al, 2007). Nitrogen fixing plants can positively affect nutrient cycling (Bell et al., 2011), and have been shown to rapidly revegetate gravel pits without the addition of topsoil (Bosco et al, 1991). Plant growth and establishment may also show preferences towards loosened soils, since compacted soils negatively impact water infiltration, as well as the ability of plants to spread roots and absorb nutrients and water (Susnjar et al., 2006, Rohand et al., 2004; Millward et al., 2011).

Soil disturbances from machinery can lead to compacted soils and changes in drainage, hydrology, microbial communities, and chemical properties. Soil moisture and infiltration can be negatively affected by soil compaction, which are important to plant establishment and growth

(Toivio et al., 2017). Native species may be more sensitive to compaction, but disturbed soils are often inviting for weedy and undesirable species to establish and spread quickly (Bell et al., 2011). Compacted soils post mining is suggested to be loosen up to 1.5 meters depth prior to planting seedlings for better plant development (Ashby, 1996; Kew et al., 2007; Kost et al., 1998; Lof et al, 2012; Zipper et al, 2011).

Soil disturbance, such as tilling or deep ripping, can expose organic matter, increase nutrient availability and thus fertility (Wick et al., 2009). Weedy species can quickly take advantage of the exposed soil surface and quickly establish by seed dispersal. However, reconstructed ecosystems can lack native seed bank and vegetative propagules. The quick establishment of weedy species can also deter the natural ingress of native species or planted seedlings. Therefore, it can be important to aid revegetation with planted seedlings of desirable species to enhance the development of canopy and understory species that are tolerant of some community competition. In addition, optimizing the growth and survival of planted seedlings can be a achieved with a greater understanding of the responses to reclaimed soil conditions.

1.10 Motivations and objectives of this study

A novel propagation method, mixed species or hitchhiker seedling, is a potential technique to ensure establishment of native herbaceous plants concurrent with woody species. Some immediate benefits of this approach could include: reduced planting costs (planting 1 plug vs. 2) and ensuring the herbaceous species is adjacent to the desirable woody species. This adjacency may be beneficial in competitive reclamation sites as competition from the native herbaceous species may be more desirable than from other ruderal species. However, this concept has seen limited field testing and to-date there has been no evaluation of this approach with fast-growing deciduous woody species.

Although plant growth is well observed in natural conditions, there is a lack of literature suggesting how plants respond to anthropogenic or novel systems. In particular, there is little information regarding green alder, paper birch, and Bebb's willow responses to recently reclaimed soil conditions. Further exploration of plant responses to reconstructed soil conditions are warranted.

The purpose of this study was to determine suitable hitchhiker stock types of four different woody species, each grown with fireweed (*Chamerion angustifolium*), and to evaluate early growth and survival in recently re-vegetated industrial sites. The principle of hitchhiker seedlings was assessed using four native woody species (*Picea glauca, Betula papyrifera, Salix bebbiana, and Alnus viridis*) grown with fireweed (*Chamerion angustifolium*) and outplanted in the field at two reclamation sites near Fort McMurray, Alberta, Canada. This thesis will address the following key questions:

(1) Is there a difference in growth or survival for hitchhiker stock types compared with individually grown stock of fireweed or woody plant?

(2) Of the hitchhiker stock types evaluated for each species mixture, which one led to the greatest balance in growth of both species?

(3) Does hitchhiker-planting alter the development and species composition of vegetation in the vicinity of the recommended hitchhiker plants?

(4) What soil conditions led to better growth and survival of green alder, paper birch, Bebb's willow, white spruce, and fireweed among a range of reclamation soil conditions and plant community?

2.0 CHAPTER 2 – Nursery seedling production and growth of hitchhiker seedlings in field conditions

2.1 Introduction

The establishment of native species is a key objective of reclamation and reforestation of industrial sites (ESRD, 2013). However, noxious species and undesirable vegetation present challenges to the development of forest plant communities (ESRD, 2013; Government of Alberta, 2010). Non-native forbs often have tolerances that allow them to quickly establish on disturbed sites and outcompete native vegetation for space and shared resources (Bell et al., 2011; Bosco et al., 1991; Radosevich, 1997).

Seeding native plants is one approach to ensure that desirable plants are present on disturbed sites, however this technique is typically only utilized with grasses and these species (though native) may surpass the natural establishment of native forbs (non-grass) (Gonzalez-Rodrigues et al., 2011; Campos-Filho et al., 2013). However, seeding native shrubs and forbs has historically been unpopular since emergence rates are often low. For example, Canada goldenrod seed application of 1000 seeds m^{-2} resulted in 0.27% emergence at best (Smreciu & Gould, 2015). In addition, the commercial availability of native boreal seed species is limiting (Lanoue & Qualizza, 2000; Native Plant Working Group, 2001).

Nursery stock seedlings are considered a reliable method of revegetation given they have sufficient height, cover, and plant reserves for successful growth, survival, and reproduction under field conditions (B.C. Ministry of Forests, 1998; Bell et al., 2001; Burger et al., 2017). Although nursery seedlings are often grown as one plant per container, growing both a woody and herbaceous plant in the same container would ultimately reduce costs, relative to growing a single forb, and ideally establish ground cover with a native herbaceous forb as well as establish desirable woody species. However, the time which the forb is added to the container with the woody plant is important to consider as the herbaceous forb can grow quickly and overtake the slower growing woody species. Faster growing species have a higher rate of nutrient uptake from higher respiration rates (Lambers & Poorter, 1992). Recent research of hitchhiker planting for reclamation purposes involving *Picea glauca* and *Eurybia conspicua* or *Chamerion angustifolium,* had shown that sowing a forb 10- and 12-weeks following sowing of *Picea glauca* had greater aboveground growth of the forb (Mathison, 2018). The timing of seeding herbaceous forbs into the container with woody species can be better understood by exploring the physiological and life history characteristics. By evaluating the traits of the species desired to use for hitchhiker seedling stock, the growth rate, reproductive strategies, and environmental tolerances can suggest the compatibility between species used in hitchhiker seedlings stock and what environmental conditions they may prefer.

The responses and adaptations of plant species vary based on the physiological and life history characteristics, also known as autecology (Barbour et al., 1987; Wienscyk et al., 2011). It is well known in ecology that an important aspect of plant growth is available resources (Bloom et al, 1985). For example, the growth and survivorship of individuals are affected as they compete for shared resources (Begon et al., 1996; Brooker et al., 2008). In turn, this can cause changes in plant tissue nitrogen and signal that plants were unable to obtain nutrients (Taiz & Zeiger, 2002). Additionally, plants with larger root surface areas have greater potential for soil water and nutrient absorption (Taiz & Zeiger, 2002). *Salix caprea* had the ability to alter the understory community mainly through belowground competition, which resulted in lower vegetative cover and biomass of herbaceous plants in the understory (Mudrak et al., 2016). Paper birch (*Betula papyrifera*) were found to be strongly affected by both resource and non-resource competition where high competition resulted in limited fine root growth and root specific length of paper birch plants (Messier et al., 2009). Roots have the ability to determine which plant roots are of itself and which are of other species and this ability varies among species (Callaway & Mahall, 2007; Dudley & File, 2007; Semchenko et al., 2007).

Species chosen for this study are native to the boreal forest and include three deciduous shrubs and trees, one coniferous species, as well as one forb: green alder (*Alnus viridis* [Chaix] DC. Subsp. *Crispa* [Aiton] Turill), paper birch (*Betula papyrifera* [Marsh.]), Bebb's willow (*Salix bebbiana* Sarg.), white spruce (*Picea glauca* [Moench] Voss), and fireweed (*Chamerion angustifolium* L. [Holub.]) (Moss, 1959). Willow and green alder tend to compete for moisture, light, and nutrients, but paper birch mainly competes for light and nutrients (Bell et al., 2011). Alder is more shade-tolerant than paper birch and willow, but white spruce is very shade-tolerant relative to the deciduous species (Farrar, 1995). It is well known that the combined effect of transplanting stress (Rietveld, 1989; Grossnickle, 2000) and competition with other species, such as *Calamagrostis canadensis* (Lieffers et al., 1993), during the early phase of seedling establishment can negatively affect the success of planted white spruce seedlings. Green alder is especially known for resource enhancement by nitrogen fixation and paper birch utilizes mycorrhizae to obtain nutrients (Bell et al., 2011; Moss, 1959).

Fireweed is an adaptable flowering herbaceous plant that can grow up to 2m tall and has potential benefits for forest reclamation (Pinno et al., 2013). It has been suggested that fireweed is a strong competitor for light, moisture, and nutrients in part due to an expansive belowground rhizome network (Landhausser & Lieffers, 1994; Landhausser et al., 1996; Bell et al., 2001; Moss, 1959). The role of fireweed is most prominent during early establishment and as trees become larger, fireweed decreases in abundance over time due to its lack of shade tolerance and preference to disturbed soils (Maundrell & Hawkins, 2004; Landhäusser et al., 1996; Landhausser & Lieffers, 1994). The presence of fireweed ground cover may discourage the spread of undesirable plants and increase the ability for other native species to establish.

In this chapter, the production of hitchhiker stock types and the response to site conditions was explored. Hitchhiker seedlings consisted of a woody species (three deciduous species and one conifer) and a native forb (fireweed) grown together in the same nursery container. The intent of this study was to evaluate the effect of varying the date which fireweed was introduced into the container (manipulated sow date), thereby providing recommendations on an appropriate methodology to grow multiple species together. Individually grown woody and fireweed plants were also produced as a reference point to infer on how much the hitchhiker stock varied from a typical, singly-grown nursery seedling. The specific questions that were addressed included:

(1) Is there a difference in growth or survival for hitchhiker stock types compared with individually grown stock of fireweed or woody plant?
(2) Is the hitchhiker seedling concept appropriate for each woody species and fireweed and of the hitchhiker stock types evaluated for each species mixture and which one led to the greatest balance in growth of both species?
(3) Does hitchhiker-planting alter the development and species composition of vegetation in the vicinity of the hitchhiker plants?

2.2 Methods

2.2.1 Seedling production

Seeds for this study were collected near Fort McMurray, AB, Canada in seed zone CM3.1 (Table 2-1) (Alberta Agriculture and Forestry, 2005). Seedlings were grown at the NAIT Center for Boreal Research greenhouse in Peace River, Alberta, Canada. Styroblocks (Beaver Plastics Ltd. Acheson, Alberta) facilitated the growth of seedlings starting April 7, 2016 using a completely randomized block design where each block consisted of one hitchhiker species and treatment (Table 2-2). The deciduous woody species (*Betula papyrifera, Salix bebbiana,* and *Alnus viridis*) were sown with fireweed (*Chamerion angustifolium*) at three different time intervals; fireweed was sown into the containers with each deciduous woody species 0-, 2-, and 4-weeks following sowing of the woody species. Fireweed was later introduced to white spruce (*Picea glauca*) (8 and 10 weeks) due to considerably slower growth of white spruce compared to the deciduous species (Mathison, 2018). Sowing at different time intervals produced a hitchhiker seedling with a range of root and shoot characteristics. Individually grown plants represented a reference treatment to compare the effect of mixed container stock.

Throughout the results and discussion, hitchhiker seedling sow dates and plants will be referred to as the sow interval which fireweed was added to the container to produce the seedling as well as the woody species. Using green alder for example: 4-week alder, 2-week alder, and 0-week alder refers to the alder plant in that particular sow date.

For fireweed, the following will identify fireweed plants of each sow interval with the addition of referencing the woody species fireweed was grown with: 0-week fireweed, 2-week fireweed, and 4-week fireweed. For instance, vegetative cover of 4-week fireweed grown with paper birch was greatest.

Considerations during the production of the seedlings included shading during germination to reduce high sun exposure, bi-weekly block rotation allowing for even temperature and lighting conditions, as well as covered with grit to reduce moss growth and soil drying. At two and three weeks after sowing, young germinants were fertilized with a low-N fertilizer (4-12-4) to encourage root development. Four weeks after sowing, seedlings began routine fertigation 3 times per week. Custom fertilizer concentrations were as follows: 66 ppm N, 84 ppm P, 92 ppm K, 94 ppm Ca, 39 ppm Mg, 57 ppm S, 3 ppm Fe, 0.01 ppm Mn, 0.17 ppm Zn, 0.58 ppm Cu, 0.25 ppm B, 106 ppm HCO_3, 87 ppm $CaCO_3$, and 26.4 ppm Na. Additionally, green alder seedlings were inoculated with field soil collected from a green alder plant two weeks after germination to ensure that root nodules (with the symbiotic N-fixing bacteria, *Frankia*) would form. Without this treatment, reliance on spontaneous nodule formation can be delayed and result in non-uniformity of growth between plants. Plant heights were recorded August 15, 2016, prior to moving seedlings outdoors to promote shoot dormancy ahead of field out planting.

Seedlings were subsampled in mid-September to characterize the stock types (n=8, fireweed control n=9). At this time, fireweed plants had begun to enter dormancy with aboveground leaves dying back. However, deciduous plants remained intact and therefore aboveground biomass of woody plants (stems and leaves) were cut from the base of the plant and oven dried for 24 hours at 70˚C prior to weighing the dry biomass. Only belowground plant material of fireweed was characterized due to the dieback from fall temperatures.

Woody and fireweed roots were washed using sieves and carefully separated. After root washing, each woody plant and fireweed root sample was cut into 1" segments and mixed prior to randomly selecting a representative subsample for analyzing root length and surface area using Regent Instruments WinRhizo™ 2013 (Quebec, Canada). After scanning, bulk sample and subsample roots were dried separately at 70˚C for 24 hours and weighed. The total root length and surface area of the sample was later calculated based on the total root biomass per plant sample.

Plant tissue from the dried fireweed root, deciduous woody shoot biomass, and white spruce needles were mixed and subsampled for plant tissue nitrogen analysis among sow dates. Subsamples were ground to a homogeneous fine powder using a combination of the Thomas Scientific™ Wiley© Mini Mill (New Jersey, USA) and the Thomas Scientific™ MM200 Mixer Mill (Retsch) (Haan, Germany), and then analyzed for total nitrogen using Dumas Combustion Method with the Thermo Scientific™ Flash 2000 Elemental Analyzer (Bremen, Germany) (Sparks et al., 1996) (Appendix 5.1, Table 2-1). Nitrogen content per plant was calculated (EQ.1) using each plant's total biomass and relative subsample of N concentration:

$$Total\ nitrogen\ content\ per\ plant\ (mg) = biomass\ (g) * N\ concentration\ \left(\frac{mg\%}{g}\right) \quad \text{EQ.1}$$

The remaining hitchhiker seedlings that were subjected to dormancy were extracted from styroblocks on September 23, 2016, transported to the study site, and planted over a three-day period during September 26-28th 2016. The study site was located approximately 70 kilometers south of Fort McMurray, Alberta, Canada, located among the boreal forest.

2.2.2 Site description

The study site was located approximately 70 kilometers south of Fort McMurray, Alberta, Canada, located within the mixed wood boreal forest (NAD83, Zone 12, 56.20303°E, 110.93312°N). The average annual temperature and precipitation at these sites was 1.4ºC and 494.4mm, from 1998 to 2017 (Alberta Agriculture and Forestry, 2018) (Appendix 6). The growing season length in northern Alberta is approximately 5 months from May through September (Rowland, 2008). Data was available up to the end of August 2018; thus weather data was averaged between May 1 and September 31 for 2016 and 2017, but between May1 and August 31 for 2018. The average daily temperature high of the summer months at the time of planting (2016) and two consecutive years later (2017 & 2018) was 21.2ºC, 21.4ºC, and 18.5ºC (Alberta Agriculture and Forestry, 2018). The accumulated precipitation during summer of 2016, 2017, and 2018 was 381mm, 348mm, and 324mm (Alberta Agriculture and Forestry, 2018).

Two reclamation sites, Surmont Regional Residence (SRR) soil stockpile and a large borrow pit (SMC #110009), were situated 5 km apart within the ConocoPhillips Surmont in-situ facility. The soil stockpile was a storage location for the surrounding industrial disturbances (primarily the SRR, which was immediately adjacent to the soil stockpile). The majority of the stockpile had been corner bladed with a dozer to create deep furrows or mounded with an excavator in October 2015, with the exception of one sandy side that was left conventionally track-packed (stockpile plot 2). The second site was a recently reclaimed upland borrow pit. The borrow pit formed a secondary comparison of stock development on soils which had not benefited from surface site preparation. Soil preparation at the borrow pit included placement of subsoil and topsoil with dozers through the summer period in 2016; this created a relatively smooth soil surface compared with the surface heterogeneity created by the furrowing and mounding at the stockpile.

Planted seedlings were subject to substantial variation in soil conditions among conventionally track-packed and furrowed plots (Table 2-3). The greatest soil moisture occurred during July and ranged from 31 to 14% VWC whereas May had relatively low soil moisture and ranged from 24 to 14% VWC (Table 2-3). The highest soil temperature occurred in July and ranged from 7 to 19°C whereas the lowest soil temperature occurred during September and ranged from 3 to 8°C (Table 2-3). Soil total nitrogen (TN) widely varied between plots, ranging from approximately 0.5 to 2.6 $mg{\cdot}g^{-1}$ (Table 2-3). The labile organic matter (LOM) approximately ranged from 1.3 to 9.6%, which is more easily decomposed than recalcitrant organic matter and therefore nutrients are more readily available for plant uptake (Baffi et al., 2007; Bot, 2005). At the soil surface (0-5cm), bulk density ranged from approximately 0.5 to 1.4 $g \cdot cm^{-3}$, electrical conductivity (EC) ranged approximately from 0.3 to 1.0 $dS \cdot m^{-1}$, and pH approximately ranged from 5 to 8 (Table 2-3). Lastly, infiltration widely ranged among plots from $0.9 x 10^{-4}$ to $16 x 10^{-4}$ $cm \cdot s^{-1}$ (Table 2-3). Soil sampling and analysis protocols are explained in detail in chapter 3.

The vegetation also differed slightly at furrowed and conventionally track-packed plots. Alsike clover (*Trifolium hybridum* L.) and sweet clover (*Melilotus sp.* Mill.) had the greatest average vegetation cover for furrowed and conventional plots, respectively (Table 2-4). Conventionally-track-packed plots ranged from 6-12 grass species, 4-14 native forb species, 3-10 woody species, and 6-8 non-native forb species (Table 2-5). Furrowed plots ranged from 9-11 grass species, 6-10 native forb species, 7-8 woody species, and 9-10 non-native forb species (Table 2-5).

2.2.3 Field study

The study included seven replicated plots at the SSR stockpile and four replicated plots at the borrow pit (Figure 2-1) to evaluate growth of mixed species container stock across a range of soil characteristics (Table 2-3). Within each plot, sixteen lines were spaced 2 meters apart. Each line was associated with one hitchhiker woody species grown with fireweed (4 lines per species). Within each line, every treatment combination (sow date and controls for woody species and fireweed) was randomly assigned to a planting location along the line and three individuals of each treatment were planted 1.5 m apart. Due to shortages in green alder, green alder was only planted at the stockpile and only 2 plants per line were established on plots 2-4 for the 2-week mixed-species stock type. Therefore, plots at the borrow pit consisted of 12 lines. As the fireweed control group was represented in every line at each block, only two fireweed plants per line were established at the SRR and the borrow pit.

Planted seedlings were assessed late August 2017 and 2018, one and two growing seasons after being planted. Survivorship, total plant height, and height increment were recorded for woody species. Presence/absence and vegetation cover (%) were recorded for fireweed based on a $0.5m^2$. Additionally, after two growing seasons (2018), aboveground biomass was collected, and fireweed spread was assessed. Only the third individual from each sow date was harvested on each line. Fireweed spread was assessed by measuring the fireweed vegetative cover and collecting aboveground fireweed biomass within $1.5m^2$ (3x3 $0.5m^2$ quadrats) centered on the hitchhiker seedling (Figure 3). The large collection of biomass was first air dried in an empty greenhouse on metal grates to improve air flow and once the plant material was visibly dry, the remaining moisture was removed by oven drying for approximately 12 hours at 70ºC. Leaves, stems and total woody dry biomass and fireweed shoots were weighed. Dried aboveground biomass was subsampled, and TN was analyzed with the same method as used for tissue analysis of the nursery seedlings (Appendix 5.2, Table 2-2).

In addition to the second-year hitchhiker measurements (2018), the plant community surrounding each recommended hitchhiker sow date and singly grown plants was also assessed within a $0.5m^2$ quadrat centered on the woody seedlings. The percentage cover of each species was recorded and grouped into grass, woody, native forb, and non-native forb species (Appendix 10).

2.2.4 Statistics

R statistical software was used for all analysis and graphing (R Core Team, 2018). Nursery seedling characteristics were modeled with linear (function 'lme'4) and generalized least squares (gls) models (Appendix 4.1). Differences between sow dates among the measured seedling characteristics were analyzed with one-way ANOVA. Assumptions of normality and variance were assessed graphically in combination with model comparisons of gls and lm using Akaike Information criterion (AIC) values where the lower AIC value represented a better model fit (Konishi and Kitagawa, 2008) (Appendix 4.1). The gls model allowed for unequal variance and was reflected in a better model fit. Significant differences ($\alpha < 0.05$) between treatment means were separated with a post-hoc multiple comparison test using emmeans function (Lenth, 2018).

Seedling responses to growing conditions were assessed by considering the plot design and site preparation effects as cofactors. Thus, seedling growth measurements, such as height and fireweed vegetative cover, were modeled and graphically presented to illustrate general trends and patterns using a single-factor mixed effects model (function 'lme'4) with two nested random factors: site preparation and plot. Normality and equal variance assumptions of ANOVA were assessed graphically. When variances were unequal, the lme model included weights with the function 'varIdent', which is a constant variance function structure (Appendix 4.2).

The effect of community vegetation surrounding recommended hitchhiker seedlings was compared to singly grown plants with the same method as seedling growth measurements above. However, a lack of community vegetation establishment occurred at stockpile plot 2 due to exposed subsoil with higher EC (~1.6 dS m^{-1}) and lower pH (~4.5). Higher EC and pH are generally unfavorable for plants (Taiz & Zeiger, 2002). Thus, stockpile plot 2 was excluded from assessing the effect of recommended hitchhiker seedlings on community development. Note that the planted seedlings did not appear to be impacted by these soil conditions because they already had developed aboveground and belowground tissue.

Cumulative woody survivorship and fireweed presence were analyzed as a generalized linear model with binomial distribution using glmer (GLM with random effects). In addition, the spread of fireweed was assessed using a simple glm model without including the random effects of site preparation and plot due to several zeros. GLM model assumptions of two possible outcomes and no over-dispersion were met (EQ.2). Over-dispersion was considered to occur over 1.5 (Crawley, 2013):

$$Dispersion = \frac{Deviance}{Number\ of\ observations - df} \qquad \text{EQ. 2}$$

For the purposes of graphing and interpretation, cumulative survivorship and presence mean and standard error were back transformed (Crawley, 2013). For all seedling parameters, significant differences ($\alpha < 0.05$) between treatment means were separated with a post-hoc multiple comparison test using emmeans function (Lenth, 2018).

$$Back\ transformed\ mean\ (m_2) = \left(\frac{1}{1+\frac{1}{e^{m_1}}}\right) * 100 \qquad \text{EQ. 3}$$

**m_1 is the original computed mean*

Supplementary photo documentation was supplied as reference material to describe the nursery seedlings and growth under field conditions: nursery seedling photos (Appendix 1), growth of seedlings in field conditions after one (Appendix 8) and two growing seasons (Appendix 9).

2.2.5 Selecting recommended hitchhiker seedling sow dates

Recommended hitchhiker seedling sow dates were selected on the bases that the woody height and fireweed vegetation cover and survival of mixed stock seedlings was similar to singly grown seedlings, which in turn supports both tree and forb establishment in disturbed soils. A sow date that resulted in an acceptable level of growth and cumulative woody survivorship or fireweed presence was considered to be a more successful and resilient hitchhiker seedling, where the woody plant was the primary focus.

Based on the selection of recommended sow dates, the effect of hitchhiker plants on the development of community vegetation was compared to woody and fireweed plants grown alone. Community vegetation cover of the plant species identified in vegetation surveys were grouped into native forb, non-native forb, grass, and woody species. Desirable species were defined as native forbs and woody species. Undesirable species included species that could have negative implications to the growth of seedlings, especially in larger quantities, and this included weedy and grass species.

2.3 Results

2.3.1 Green alder

Later sow dates led to green alder nursery stock with morphological characteristics that superseded green alder grown alone in some instances. The 4-week green alder nursery stock had higher stem nitrogen content and total root biomass than green alder grown alone, while stem nitrogen content and total root biomass of green alder grown alone was similar to all sow dates (Table 2-6, 2-7). Although green alder nursery stock R:S ratio did not differ among treatments, shoot biomass was approximately 3 times greater than root biomass (Table 2-6, 2-7). Fireweed co-grown with green alder nursery stock did not differ in aboveground and belowground plant development among sow date relative to fireweed grown alone.

After two growing seasons, 2-week green alder, 4-week green alder, and green alder grown alone were taller than the 0-week green alder, which followed the same trend as green alder nursery stock (Table 2-8, Figure 2-2). Despite this, growth increment, total, stem, leaf biomass and leaf nitrogen content did not differ among sow dates relative to green alder grown alone after two growing seasons (Table 2-8, 2-9, Figure 2-2). The cumulative survivorship of 2-week and 4-week green alder plants was also similar to green alder grown alone (~90%) while the 0-week green alder had the lowest survivorship at ~50% (Figure 2-2).

The vegetative cover and extent of spread of fireweed co-grown with green alder did not differ among sow dates after two growing seasons (Table 2-8, 2-10, Figure 2-3). However, cumulative fireweed presence of 0- and 2-week fireweed plants co-grown with green alder was similar to fireweed grown alone (~60%) while the 4-week fireweed plants had significantly lower presence (~30%) relative to fireweed grown alone (Table 2-8, Figure 2-3). The presence of fireweed consistently declined between the first and second growing season (Figure 2-3).

2.3.2 Paper birch

Root biomass, length, and surface area as well as total shoot, stem, and leaf biomass of 4-week paper birch nursery stock was much greater than 0-week paper birch (Table 2-6). The root biomass, length, surface area and leaf biomass of 0-week and 2-week paper birch was similar to paper birch grown alone (Table 2-6). However, the total shoot biomass and stem biomass of paper birch grown alone was similar to all sow dates (Table 2-6). The 0-week paper birch nursery stock resulted in a greater R:S ratio (more aboveground development) compared to paper birch grown alone (more root development) (Table 2-6). The R:S ratio of paper birch grown alone was similar to the 2-week and 4-week paper birch (Table 2-6). The 0-week paper birch was shortest and the height of 2- and 4-week paper birch was similar to paper birch grown alone, but 0-week, 2-week and paper birch grown alone had about 50% less stem nitrogen content than 4-week paper birch (Table 2-6, 2-7).

Fireweed nursery stock characteristics of 0-week and 2-week sow dates co-grown with paper birch were most similar to fireweed grown alone, which opposed the trend of larger paper birch at later sow dates (Table 2-6, 2-7). The 0-week, 2-week and fireweed grown alone were taller than 4-week fireweed (Table 2-6). Total nitrogen content of fireweed root grown alone was similar to 0-week and 2-week fireweed, but 4-week fireweed root had much less nitrogen content (Table 2-6, 2-7). Fireweed root length and surface area of 4-week nursery stock was significantly less than that of fireweed grown alone (Table 2-6, 2-7). Fireweed grown alone had similar root length and surface area to that of 0-week and 2-week plants (Table 2-8). Root biomass of fireweed grown alone was much greater than 2-week and 4-week nursery stock, but was similar to 0-week fireweed (Table 2-6).

After two growing seasons, the 2-week paper birch height was similar to paper birch grown alone, yet the 4-week paper birch outgrew 0-week, 2-week and paper birch grown alone (Table 2-8, Figure 2-4). Paper birch grown alone had a similar growth increment compared to all sow dates after the first and second growing season, but the first growing season also resulted in 4-week paper birch with a larger growth increment than 0-week and 2-week paper birch (Table 2-8, Figure 2-4). Total shoot biomass of 4-week paper birch and paper birch grown alone was greater than 0-week paper birch, which was driven by stem biomass, and 2-week total shoot biomass was similar to 0-week and 4-week plants as well as paper birch grown alone (Table 2-8, Figure 2-4). However, fireweed co-grown with paper birch did not affect the leaf nitrogen content (Table 2-9) or cumulative survivorship (~90%) of paper birch after two growing seasons (Figure 2-4). Survivorship did not decline between the first and second growing season (Figure 2-4).

In contrast, the cumulative presence of 0-week fireweed and fireweed grown alone (~65%) was greater than the cumulative presence of the 2-week (~30%) and 4-week (~20%) fireweed

(Figure 2-5). The presence of fireweed declined between the first and second growing season (Figure 2-5). After one growing season, 0-week, 2-week, and fireweed grown alone had similar vegetative cover, but 4-week fireweed had much less vegetative cover than 0-week and fireweed grown alone (Table 2-8, Figure 2-5). However, after two growing seasons the fireweed vegetative cover and extent of spread of all sow dates was similar to fireweed grown alone (Table 2-8, Figure 2-5, Table 2-10).

2.3.3 Bebb's willow

The 4-week Bebb's willow nursery stock was tallest, 0-week was taller than Bebb's willow grown alone, and 2-week willow was similar in height to that of 0-week and Bebb's willow grown alone (Table 2-6, 2-7). Bebb's willow nursery stock grown alone had similar stem nitrogen content to that of 2-week and 4-week Bebb's willow, but 0-week willow had much less stem nitrogen content (Table 2-6, 2-7). Total shoot biomass and stem biomass of Bebb's willow grown alone was similar to all sow dates, but 2-week and 4-week had greater total and stem biomass then 0-week Bebb's willow nursery stock (Table 2-6, 2-7). Bebb's willow grown alone had similar leaf biomass to all sow dates, but 2-week leaf biomass was greater than 0-week biomass (Table 2-6, 2-7). The total root biomass of Bebb's willow nursery stock was similar to 0-week and 4-week Bebb's willow (Table 2-6, 2-7). The 2-week willow root biomass was similar to 4-week Bebb's willow nursery stock, but 2-week Bebb's willow had greater root biomass than 0-week and Bebb's willow grown alone. Bebb's willow root surface area did not differ among treatments (Table 2-6, 2-7). The R:S ratio of Bebb's willow nursery stock also did not differ between treatments, but there was a lot of variation ranging from 1.5- 0.5 (Table 2-6, 2-7). Overall, there was a lack of upward or downward trend of nursery willow characteristics relative to sow date.

In contrast, fireweed nursery stock showed a decline in growth characteristics with later sow dates. The 0-week, 2-week, and fireweed plants grown alone were taller than 4-week fireweed (Table 2-6, 2-7). Additionally, total root biomass, length, and surface area of nursery fireweed were significantly greater for fireweed plants grown alone compared to 2- and 4-week sow dates (Table 2-6, 2-7). The total root biomass, length, and surface area of 0-week fireweed was similar to 2-week, 4-week and fireweed grown alone (Table 2-8, 2-9). Fireweed root nitrogen content did not differ among treatments (Table 2-6, 2-7).

After two growing seasons, the height of 0-week, 2-week, and Bebb's willow grown alone was similar, but 4-week Bebb's willow height exceeded all other treatments (Table 2-8, Figure 2-6). The growth increment and cumulative survivorship (~90%) of Bebb's willow grown alone was similar across all sow dates, and survivorship was similar between the first and second growing season (Figure 2-6). Although the total aboveground biomass and leaf nitrogen content of all sow dates did not differ from Bebb's willow grown alone, the 4-week Bebb's willow stem biomass was greater than Bebb's willow grown alone (Table 2-8, 2-9, Figure 2-6).

Vegetative cover of 0-week fireweed co-grown with Bebb's willow was similar to fireweed grown alone after one growing season, which was greater than 2-week and 4-week fireweed vegetative cover (Table 2-8, Figure 2-7). However, fireweed cover of all sow dates did not differ from fireweed grown alone after two growing seasons (Table 2-8, Figure 2-7). The 0-week fireweed cumulative presence was also similar to fireweed grown alone (~70%), while presence of fireweed in the 2-week and 4-week sow dates was significantly less at approximately 20% (Figure 2-7). The presence of fireweed declined between the first and second growing season (Figure 2-7). Lastly, the extent of fireweed spread co-grown with Bebb's willow did not differ from fireweed grown alone (Table 2-10).

2.3.4 White spruce

Overall, white spruce nursery stock grown alone had greater belowground and aboveground development and, in some cases, showed similarities to the later sow date (10-weeks). The 10-week white spruce and white spruce grown alone were taller than 8-week white spruce (Table 2-6, 2-7). White spruce nursery stock grown alone had the greatest shoot total biomass, stem biomass, and total root biomass relative to white spruce co-grown with fireweed (Table 2-6, 2-7). Leaf biomass of white spruce grown alone was similar to 10-week white spruce, but greater than 8-week white spruce, and 8-week and 10-week spruce had similar leaf biomass (Table 2-6, 2-7). The root length, root surface area, stem nitrogen content, and R:S ratio were similar among treatments (Table 2-6, 2-7). Although the R:S ratio of white spruce nursery stock was similar among treatments, there were about 3 times more aboveground biomass than belowground biomass (Table 2-6, 2-7).

The 8-week fireweed nursery stock co-grown with white spruce were most similar to fireweed grown alone, which opposed the growth trends of white spruce nursery stock. The height and root nitrogen content of fireweed nursery stock grown alone was greater than fireweed co-grown with white spruce, and 8-week nursery fireweed height was greater than the 10-week sow date (Table 2-6, 2-7). The 10-week fireweed had greater total root biomass than 8-week and fireweed grown alone (Table 2-6, 2-7). Fireweed root length and surface area of fireweed grown alone was similar to 8-week and 10-week fireweed, but 10-week fireweed had greater root length and surface area than 8-week fireweed (Table 2-6, 2-7).

White spruce co-grown with fireweed (both sow dates) in field conditions grew less in height and biomass than white spruce grown alone after two growing seasons (Table 2-8, Figure

2-8). White spruce grown alone also had the greatest growth increment after the first growing season whereas growth increment in second growing season was similar across co-grown and singly grown white spruce (Table 2-8, Figure 2-8). After two growing seasons, the total biomass of white spruce grown alone was significantly greater than white spruce co-grown with fireweed, and the total biomass of 10-week white spruce was much greater than 8-week white spruce (Table 2-8, Figure 2-8). Stem biomass of white spruce grown alone was greater than 8-week and 10-week white spruce (Table 2-8, Figure 2-8). The leaf biomass of white spruce grown alone was greater spruce co-grown with fireweed, and the 10-week white spruce leaf biomass was greater than 8-week white spruce leaf biomass (Table 2-8, Figure 2-8). Leaf nitrogen content of white spruce grown alone was significantly greater than spruce grown with fireweed (Table 2-9). Cumulative survivorship of white spruce was high, did not vary among treatments (~97%), and was similar between the first and second growing season (Figure 2-8).

After the first and second growing season, fireweed vegetative cover of plants grown alone was similar to 8-week fireweed, and the 8-week and 10-week fireweed vegetative cover was similar (Table 2-8, Figure 2-9). The 8- and 10-week fireweed cumulative presence (~75%) and the extent of fireweed spread did not differ from fireweed grown alone, but the presence of fireweed declined after the first growing season (Figure 2-9, Table 2-10).

2.3.5 Recommended hitchhiker seedling sow dates & community vegetation cover

Selecting the recommended hitchhiker sow dates was defined previously (Section 2.2.5). Recommended sow dates were 2-week green alder, 2-week paper birch, 0-week Bebb's willow, and 10-week white spruce; the reasoning for each selection is discussed below (Section 2.4.3).

However, there were no clear indications that hitchhiker seedlings led to a difference in plant community composition (Figure 2-10).

2.4 Discussion

A later sow date produced hitchhiker seedlings with a larger woody plant simply due to the woody plant growing longer prior to adding fireweed into the container. Established larger woody plants (4-week) were able to withstand the competitive effects of fast-growing fireweed while fireweed development was impeded by shading from older woody plants. Other studies had similar findings; Noland et al. (2001) found that larger conifer seedlings were able to withstand competitive effects of herbaceous plants in field conditions. Limited fireweed development in the understory has also been observed as it is shade intolerant (Maundrell & Hawkins, 2004; Landhäusser et al., 1996; Lieffers & Stadt. 1994).

Initial nursery stock characteristics were indicative of growth after the first growing season, yet by the second growing season, environmental conditions became more influential to seedling growth and survival and this was a similar finding by Pinto et al. (2011) where establishment of seedlings is initially affected by seedling morphological characteristics. Where hitchhiker stock consisted of a large woody plant and small fireweed, such as 4-week willow co-grown with fireweed, the larger woody plant had more growth whereas the smaller fireweed had less growth in field conditions; greater growth and survival was likely due to greater nutrient and carbohydrate reserves buffering planting and competition stress (B.C. Ministry of Forests, 1998; Bell et al, 2001; Noland et al., 2001). Fireweed cover (~5%) and spread was limited overall relative to fireweed cover observed in the previous hitchhiker study by Mathison (2018), which ranged from 10-20%.

It was strongly suggested by Pinno et al. (2013) that site conditions, such as soil type or existing herbaceous competition, could have limited the development of fireweed.

2.4.1 *Hitchhiker nursery stock evaluation*

Stachowicz (2001) found that the presence of other species can alter the growing environment, such as fireweed growing in close proximity to each woody species in the containers leading to fireweed using rooting space that could have potentially otherwise been used by the woody species. Lambers & Poorter (1992) found that faster growing species, such as fireweed, are able to uptake nutrients faster and gain biomass faster. In turn, competitive effects from fireweed were stronger on the woody plants in earlier sow dates (Table 2-6). At later sow dates, a young fireweed competed with an established woody plant strongly inhibiting the development of fireweed root relative to fireweed grown alone (Appendix 2).

It was anticipated that the earliest sow date may have favored fireweed dominance, while later sow dates would favor woody plant dominance. The pattern observed for Bebb's willow did not follow with other species. From the earliest sow date, Bebb's willow dominated the cavity space with 0-week fireweed root mass being 50% less than 0-week fireweed with paper birch, as well as substantially lower than any sow date between fireweed and green alder (Appendix A3.3). Bebb's willow growth may have been stimulated by competition with fireweed as it was unexpected that height and root development of 4-week Bebb's willow would supersede that of Bebb's willow grown alone (Appendix 2, 3). Mudrak et al. (2016) found that *Salix caprea* had the ability to alter the understory community mainly through belowground competition, which resulted in lower vegetative cover and biomass of herbaceous plants. In contrast, Mosseler et al. (2014) had shown that Bebb's willow cuttings had poor rooting ability and indicated some genotypes had good growth and survival. Despite this contradiction of willow growth, Volk and Kuzovkina (2009) studied the characteristics of 36 willow species and found that they tend to have a wide range of environmental tolerances, such as drought and nutrient availability.

Bell et al. (2000) and Brand (1991) found greater growth of white spruce when vegetative competition was lower. Although Eis (1981) suggested that fireweed does not inhibit the growth of white spruce to the same extent that grasses do, it appeared that fireweed competing with 8-week and 10-week white spruce for space and nutrients limited the growth of white spruce stem biomass (Table 2-6), which is an indirect indicator of storage reserves critical for future growth in field conditions (BC Ministry of Forests, 1990; Stachowicz, 2001). However, several other parameters, such as height and total shoot biomass, suggested that 10-week white spruce was able to withstand the competitive effects of fireweed, just as Noland et al (2001) found that larger conifer seedlings were able to withstand competitive effects of herbaceous plants in field conditions.

In addition, fireweed was affected by interspecific competition with white spruce resulting in lower height and root nitrogen content relative to fireweed grown alone, which contrasts the finding by Hangs et al (2002) where fireweed co-grown with white spruce had greater N^{15} uptake. These species may have similar nutrient and moisture preferences thereby competing for the same resources.

It was also unexpected that stem total nitrogen concentration of 4-week paper birch was greater than paper birch grown alone (Figure 2-6). Faget et al. (2013) determined that interspecific competition may lead plants to adjust their foraging strategy by enhancing root length (Appendix 3) and thereby capturing more nutrients.

2.4.2 Hitchhiker growth response in the field

2.4.2.1 Woody plants

There were differences in growth among fireweed and woody species of hitchhiker stock types relative to fireweed and woody plants grown alone. Similar to this study where initially larger plants were able to withstand site competitive effects and planting stress, Le (2017) found that taller trembling aspen (*Populus tremuloides*) were more likely to overcome competition. However, once seedlings were established, growth was influenced more by site conditions rather than morphology, just as Pinto et al. (2011) suggested.

Green alder and paper birch had similar growth and survival trends between sow dates, which consisted of taller green alder plants as well as taller paper birch plants with greater biomass occurring at later sow dates after two growing seasons, though growth increments did not differ among sow dates after the second growing season (Figure 2-2, 2-3). This was likely due to initially taller nursery plants which most likely indicates capability to resist competition from existing vegetation and planting stress (BC Ministry, 1987). In the case of green alder, less root development of smaller green alder (0-week) may have been associated with lower survivorship after two growing seasons (Appendix A.31), which was similar to the findings of Rose et al (1997) where ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) with less root volume were less likely to survive.

The Bebb's willow plants co-grown with fireweed at a later sow date had demonstrated comparable rates of survival and growth as woody plants grown alone; the later sow date and control woody plants were a similar size and often larger (both above and belowground) than earlier sow date plants as Bebb's willow was a faster growing species than fireweed (Appendix 2). This indicates that these woody plants surpassed a minimum height, which varies on species, required for high survival, although it is noted that height may not be the best growth indicator for shrub species, such as Bebb's willow.

In this study, white spruce co-grown with fireweed were smaller than white spruce grown alone (Figure 8-2). However, Mathison (2018) found 10-week and 12-week white spruce to be generally similar to white spruce grown alone, which were grown in a different region (NW Alberta) relative to this study (NE Alberta). In addition, even though hitchhiker trees were smaller than trees grown alone, white spruce had good overall survival (~97%). Again, this may be due to white spruce surpassing the minimum height required for good growth as well as to resist planting stress and competition.

2.4.2.2 Fireweed

Fireweed vegetative cover and presence tended to decrease with later sow dates after one growing season, which was likely due to the characteristics of nursery stock. At later sow dates, fireweed competed with a larger woody plant that would have occupied proportionally more for space (aboveground and belowground) leading to nursery fireweed plants with poor root and shoot development (Appendix 3). Smaller fireweed plants would therefore have a smaller absolute pool of carbohydrates reserves with which to resprout from in the spring, potentially creating greater planting stress and less ability to compete with community vegetation (BC Ministry, 1989; Rose et al., 1997).

It was unexpected that the extent of fireweed spread was limited throughout both sites as well as among treatments (Figure 2-10). Fireweed spread may have been limited by environmental conditions, such as soil type (Pinno et al., 2013). It is also possible that fireweed, especially plants with smaller root systems, could have been limited by stronger competitors (BC Ministry, 1989).

Soil compaction at conventionally track-packed areas may have prevented the ability for fireweed plants to spread roots and develop rhizomes away from the planted seedlings as Millward et al (2011) saw this similar trend with limited tree root development in compacted soils.

Given that Bebb's willow was relatively unaffected by being co-grown with fireweed, fireweed could benefit from an earlier sow date such that fireweed is sown prior to willow by 1 or 2 weeks. This would ensure greater rooting development of fireweed given that Bebb's willow developed its root system much faster than fireweed did.

2.4.3 Hitchhiker stock type recommendations

Hitchhiker seedling sow dates were recommended based on a balance between woody and fireweed plant growth after two going seasons, which was described in detail earlier (Section 2.2.5). Nursery produced hitchhiker seedlings were expected to have similar growth and survival to that of woody and fireweed plants grown alone.

The 2-week green alder and fireweed hitchhiker seedlings produced the best balance of woody and forb development. Although 4-week green alder had the largest plant growth after two growing seasons (Figure 2-2), this was associated with poor fireweed presence (~25%) (Figure 2-3). The 0-week and 2-week treatments consisted of fireweed presence similar to fireweed grown alone, but the 0-week green alder growth was less than green alder grown alone (Figure 4, 2-3).

Of the tested sow dates for paper birch and fireweed hitchhiker seedlings, not one sow date could be confidently recommended. Although the 0-week fireweed growth was similar to fireweed grown alone, the 0-week paper birch tree was short and biomass was lower relative to paper birch grown alone (Figure 2-4, 2-5). The 2-week and 4-week paper birch had similar tree growth relative to paper birch grown alone, but fireweed cumulative presence was significantly lower than fireweed grown alone (approximately 50% lower) (Figure 2-4, 2-5). In this situation, sowing fireweed 1-week later than paper birch may be an appropriate strategy but would require further testing.

Given the sow dates assessed, sowing fireweed with Bebb's willow at the same time (0-weeks) was the recommended stock type. Bebb's willow growth was unimpeded by fireweed across all sow dates while 2 and 4-week sow dates resulted in smaller fireweed plants with lower cumulative presence. The 0-week fireweed had similar survival and cover after two growing seasons relative to fireweed grown alone but further testing of this species mixture by sowing fireweed prior to Bebb's willow by 1 or 2 weeks may have resulted in improved fireweed in the field as the root stock of fireweed was still 50% smaller than control seedlings initially (Table 2-6).

Of the sow dates tested with white spruce and fireweed, the 10-week white spruce and fireweed hitchhiker seedling is recommended and based on a previous study, the 12-week hitchhiker white spruce stock type in Mathison's (2018) study should be considered. It is noted that the cumulative presence of fireweed mixed with white spruce was better than deciduous species. Although total height and biomass of white spruce co-grown with fireweed was less than white spruce grown alone, the growth increment and cumulative survivorship of white spruce co-grown with fireweed was similar to white spruce grown alone (Figure 2-9). It is possible that sowing fireweed later (12-weeks) would have resulted in more similar initial characteristics to white spruce grown. Fireweed cover of 12-week white spruce may be further limited under sub-optimal environmental conditions for fireweed, but the cumulative presence would likely not be inhibited. Both the 10-week and 12-week sow dates were acceptable in Mathison's study (2018).

2.4.4 The effect of recommended hitchhiker seedlings on community development

Planting recommended hitchhiker seedling sow dates did not alter the development and species composition of vegetation within the local vicinity. Fireweed was expected to be the main driving factor affecting the development of community vegetation, but fireweed did not flourish well overall as the coverage of control plants was about 5% on average. It is also plausible that dry fall planting conditions with the addition of competition with existing competitive vegetation could have negatively impacted or stalled the establishment of fireweed in particular. There is also a possibility that if these hitchhiker plants were planted at a site more favorable to fireweed growth and establishment, then there is still potential for fireweed to impact the community vegetation. Fireweed may not grow consistently at reclamation sites if the range of tolerated environmental conditions is limited. Soil conditions that fireweed grew best in was discussed in chapter 3.

2.5 Future studies and conclusions

Several paper birch nursery stock characteristics (ie. stem nitrogen content, total shoot and root biomass) were much higher for the 4-week paper birch compared to paper birch grown alone (Table 2-6). It is unclear why 4-week paper birch benefited from the interaction with fireweed, but this could be explored with another study focusing on mechanisms, such as mycorrhizal fungi, to explain this result.

Further exploration is required for Bebb's willow co-grown with forbs, such as fireweed, as Bebb's willow was more aggressive than anticipated. For instance, fireweed could be sown in the container 1 week prior to Bebb's willow. Similarly, additional trial work with fireweed and paper birch with a 1-week sow date may demonstrate a better balance of growth between these species. Alternatively, further examination of other forbs that demonstrate greater belowground competition and tolerance to shading [such as showy aster (*Eurybia conspicua* (Lindl.) G.L. Nesom) or goldenrod (*Solidago canadensis* L.)], may prove to be more useful mixtures with fast growing deciduous woody species.

In summary, the production of hitchhiker seedlings requires careful consideration of the species autecology. Nursery seedling conditions were a result of sow date and were an indication of growth in field conditions, where later sow dates led to a larger woody plant and a smaller fireweed plant relative to the individually grown plants. The variation of growth in field conditions may be explained by further exploring the soil conditions. The hitchhiker seedlings studied can be used for boreal forest reclamation, but woody and forb species selection and sow date should be carefully considered and tested as further investigation of different native boreal woody and forb species is required.

2.6 Tables

Table 2-1. Species used to produce hitchhiker container seedlings.

Species	Scientific name and (author)	Family	Seedlot
Green alder	*Alnus viridis* ([Chaix] DC.) Subsp. *Crispa* ([Aiton] Turill)	Betulaceae	SAOS 17-82-7-4-2015
Paper birch	*Betula papyrifera* (Marsh)	Betulaceae	CPCRC 18-83-06-4-2015
Bebb's Willow	*Salix bebbiana* (Sarg.)	Salicaceae	BHS 36-64-4-4-2015
White spruce	*Picea glauca* ([Moench] Voss)	Pinaceae	OSLI 23-78-9-4-2007
Fireweed	*Chamerion angustifoloum* ([L.] Holub)	Onagraceae	LFCRC 19-83-06-6-2015

Table 2-2. Production of hitchhiker seedlings occurred in 615 containers while single fireweed and woody plants were grown in 512 containers (no sow date required indicated by 'NA') in order to ensure that seedlings would be extractable by September 2016.

Species	Forb sow date (Treatment)	Stock size	# of cavities	# of blocks	Cavity volume (mL)
Green alder	0 wk	615A	45	4	336
Green alder	2 wk	615A	45	4	336
Green alder	4 wk	615A	45	4	336
Green alder	NA	512A	60	3	220
Paper birch	0 wk	615A	45	4	336
Paper birch	2 wk	615A	45	4	336
Paper birch	4 wk	615A	45	4	336
Paper birch	NA	512A	60	3	220
Bebb's Willow	0 wk	615A	45	4	336
Bebb's Willow	2 wk	615A	45	4	336
Bebb's Willow	4 wk	615A	45	4	336
Bebb's Willow	NA	512A	60	3	220
White spruce	8 wk	615A	45	4	336
White spruce	10 wk	615A	45	4	336
White spruce	NA	512A	60	3	220
Fireweed	NA	512A	60	9	220

Table 2-3. Soil properties of block replicates at the stockpile (SP) and borrow pit (BP): soil moisture, temperature, TN, LOM, and infiltration as well as bulk density (BD), pH, and EC measured at 3 depths, 0-5cm, 10-15cm, and 25-30cm. Mean ± one standard error (n=4, except infiltration n=3 and temperature n=2). Temperature values without SE had limited data.

Site Plot	Moisture high (July) (%VWC)	Moisture low (May) (%VWC)	Temp. HIGH (July) (°C)	Temp. LOW (Sept.) (°C)	TN ($mg \cdot g^{-1}$)	LOM (%)	Infiltration ($x10^{-4}$ $cm \cdot s^{-1}$)
BP1	31.0±4.5	19.3±1.3	16.6	7.5	2.5±0.6	6.8±1.0	5.8±1.3
BP2	25.1±1.7	24.4±1.6	17.8	5.5	0.5±0.03	1.6±0.2	1.1±0.2
BP3	20.9±2.3	18.4±1.3	NA	NA	0.5±0.01	1.4±0.03	1.5±0.2
BP5	24.0±4.0	14.4±1.8	NA	NA	1.9±0.1	5.6±0.5	1.5±0.3
SP1	30.4±3.3	19.6±2.7	7.6±5.8	2.6±2.9	0.5±0.1	1.3±0.2	1.0±0.3
SP2	14.5±4.3	14.0±4.1	19.6	7.8	0.4±0.07	1.5±0.1	7.5±3.5
SP3	27.3±7.1	16.9±4.9	16.0	7.2	0.8±0.05	2.6±0.3	4.1±0.3
SP4	27.9±4.1	18.8±2.2	16.0±0.3	7.6±0.2	0.7±0.06	2.3±0.3	4.5±1.1
SP5	25.7±2.4	21.8±1.9	16.6±0.4	7.0±0.2	0.5±0.02	1.7±0.1	0.9±0.4
SP6	23.5±1.9	20.3±2.0	15.3±0.01	6.9±0.3	2.6±0.03	9.6±1.4	8.8±4.3
SP7	24.4±3.5	22.3±2.3	17.05	8.3	0.8±0.1	2.9±0.6	16.0±9.3

Site Plot	BD 0-5cm ($g \cdot cm^{-3}$)	EC 0-5cm ($dS \cdot m^{-1}$)	pH 0-5cm	BD 10-15 cm ($g \cdot cm^{-3}$)	EC 10-15cm ($dS \cdot m^{-1}$)	pH 10-15cm
BP1	0.9±0.05	0.5±0.02	7.2±0.2	01.0±0.03	0.6±0.1	7.5±0.3
BP2	1.4±0.05	0.3±0.08	8.06±0.2	1.4±0.06	0.4±0.02	7.5±0.4
BP3	1.3±0.08	0.4±0.05	7.7±0.1	1.0±0.1	0.7±0.3	7.9±0.1
BP5	1.0±0.2	0.6±0.08	7.5±0.09	1.2±0.2	0.6±0.07	7.7±0.06
SP1	1.2±0.04	0.5±0.1	7.4±0.2	1.2±0.06	0.6±0.07	7.3±0.1
SP2	1.07±0.2	1.0±0.3	4.8±0.6	1.08±0.1	1.6±0.7	4.4±0.4
SP3	1.03±0.02	0.4±0.05	7.4±0.1	1.0±0.07	0.4±0.01	7.8±0.1
SP4	1.06±0.03	0.4±0.04	7.5±0.1	1.0±0.06	0.4±0.04	7.6±0.2
SP5	1.02±0.02	0.4±0.1	7.3±0.2	1.03±0.07	0.5±0.08	7.9±0.2
SP6	0.5±0.07	0.5±0.02	7.09±0.06	0.5±0.03	0.5±0.1	7.01±0.2
SP7	1.0±0.02	0.3±0.05	7.5±0.3	0.9±0.1	0.2±0.05	7.3±0.2

Site Plot	BD 25-30 cm ($g \cdot cm^{-3}$)	EC 25-30cm ($dS \cdot m^{-1}$)	pH 25-30cm
BP1	1.3±0.03	0.5±0.05	8.08±0.05
BP2	1.1±0.9	0.3±0.08	7.6±0.4
BP3	1.1±0.2	0.6±0.2	7.9±0.1
BP5	0.9±0.08	0.5±0.07	7.7±0.1
SP1	1.1±0.07	0.6±0.11	7.3±0.2
SP2	1.0±0.1	1.5±0.7	5.3±0.7
SP3	1.0±0.07	0.4±0.04	7.5±0.09
SP4	1.0±0.08	0.5±0.05	7.7±0.08
SP5	1.1±0.07	0.4±0.08	7.7±0.3
SP6	0.4±0.07	0.5±0.05	7.1±0.2

SP7	0.9±0.03	0.3±0.04	7.5±0.2

Table 2-4. Top five species ranked from 1-5 with greatest average vegetation cover among of furrowed (left; Stockpiled soil blocks 1, 3-7) and conventionally track-packed soils (right; stockpiled soil block 2 & borrow pit blocks 1-3, 5). Mean ± one standard error (furrowed n=6, conventional n=5).

FURROWED			CONVENTIONAL		
Rank	Species	% cover	Rank	Species	% cover
1	*Trifolium hybridum* (Alsike clover)	5.2±0.3	1	*Melilotus species* (Sweet clovers)	15.7±0.3
2	*Trifolium pratense* (Red clover)	4.9±0.3	2	*Elymus trachycaulus* (Slender wheat grass)	5.7±0.08
3	*Melilotus species* (Sweet clovers)	3.9±0.7	3	*Trifolium hybridum* (Alsike clover)	5.3±0.4
4	*Alnus viridis* (Green alder)	1.5±0.3	4	*Trifolium pratense* (Red clover)	4.8±0.4
5	*Deschampsia caespitosa* (Tufted hair grass)	1.4±0.1	5	*Alnus viridis* (Green alder)	3.3±0.3

Table 2-5. The number of species present at each plot relative to each community vegetation group: grass, native forb, non-native forb, and woody species as well as the total number of species present at furrowed and conventionally track-packed plots. Many of the same species were present at each plot.

Site preparation type	Site Plot	# of grass species	# of native forb species	# of woody species	# of non-native forb species
Conventional	BP1	12	13	6	7
Conventional	BP2	11	8	3	6
Conventional	BP3	10	5	3	8
Conventional	BP5	11	14	10	7
Conventional	SP2	6	4	6	7
Furrowed	SP1	10	8	7	9
Furrowed	SP3	9	6	7	9
Furrowed	SP4	11	9	8	10
Furrowed	SP5	11	8	8	9
Furrowed	SP6	9	10	8	10
Furrowed	SP7	10	9	8	9
Total Conventional		14	20	11	10
Total furrowed		12	17	9	11

Table 2-6. Average nursery hitchhiker seedling aboveground and belowground characteristics of green alder (GA), paper birch (BW), Bebb's willow (SX), and white spruce (SW) grown with fireweed (Fw). Sow dates were compared for each woody hitchhiker species indicated by letters ($p<0.05$). Mean ± one standard error (Controls (C) n=3, hitchhiker seedlings n=4, fireweed grown alone n=9). TN is total nitrogen. SA is surface area.

Species	Sow date	Woody height (cm)	Fw height (cm)	Woody TN (mg)	Fw TN (mg)	Woody total shoot dry mass (g)	Woody stem dry mass (g)	Woody leaf dry mass (g)
GA	0	18.3±3.07^{a}	46.6±2.5^{a}	18.3±3.9^{a}	50.04±9.9^{a}	1.2±0.5^{a}	0.6±0.3^{a}	0.4±0.2^{a}
GA	2	30.9±5.7^{a}	42.4±4.4^{a}	74.1±38.8^{ab}	28.3±8.6^{a}	5.2±2.7^{ab}	3.4±1.7^{ab}	1.8±1.08^{ab}
GA	4	53.1±1.9^{b}	38.0±2.9^{a}	124.8±15.9^{b}	36.3±8.6^{a}	12.7±1.8^{b}	8.8±1.3^{b}	4.0±0.5^{b}
GA	C	55.4±4.2^{b}	46.8±1.6^{a}	61.1±39.0^{ab}	44.2±8.6^{a}	5.08±1.8^{a}	3.9±1.3^{ab}	1.08±0.6^{a}
BW	0	30.4±3.06^{a}	44.0±0.4^{a}	32.5±6.7^{a}	31.2±7.6^{ab}	1.8±0.6^{a}	1.3±0.4^{a}	0.5±0.2^{a}
BW	2	49.1±3.4^{b}	40.8±5.3^{a}	31.4±51.6^{a}	17.4±7.5^{ab}	2.6±0.8^{ab}	2.0±0.6^{ab}	0.6±0.2^{ab}
BW	4	65.9±1.09^{c}	8.5±2.4^{b}	63.1±5.8^{b}	3.4±10.7^{a}	5.09±0.7^{b}	4.0±0.6^{b}	5.9±4.7^{b}
BW	C	64.8±4.2^{bc}	46.8±1.6^{a}	31.05±5.8^{a}	44.2±7.6^{b}	3.0±0.4^{ab}	2.3±0.3^{ab}	0.7±0.1^{a}
SX	0	92.8±2.3^{a}	46.5±1.6^{a}	19.05±3.6^{a}	22.5±7.9^{a}	2.6±0.6^{a}	1.7±0.4^{a}	0.9±0.2^{a}
SX	2	90.0±3.4^{ac}	37.2±3.9^{a}	36.1±3.6^{b}	6.9±9.09^{a}	7.3±0.5^{b}	5.2±0.4^{b}	2.04±0.2^{b}
SX	4	103.2±2.06^{b}	12.4±0.4^{b}	41.7±3.6^{b}	2.8±15.8^{a}	7.0±1.1^{b}	5.01±0.8^{b}	1.9±0.4^{ab}
SX	C	83.3±1.4^{c}	46.8±1.6^{a}	35.7±3.6^{b}	44.2±7.9^{a}	5.0±1.01^{ab}	3.4±0.7^{ab}	1.5±0.4^{ab}
SW	8	12.7±0.9^{a}	35.9±2.7^{a}	5.8±2.4^{a}	21.3±4.4^{a}	0.6±0.1^{a}	0.2±0.06^{a}	0.4±0.09^{a}
SW	10	17.07±1.0^{b}	24.5±1.4^{b}	8.2±2.4^{a}	10.2±4.1^{a}	0.8±0.1^{a}	0.3±0.06^{a}	0.5±0.09^{ab}
SW	C	18.7±1.6^{b}	46.8±1.6^{c}	12.8±2.8^{a}	44.2±4.4^{b}	1.4±0.1^{b}	0.7±0.06^{b}	0.8±0.09^{b}

Species	Sow date	Woody root dry mass (g)	Fireweed root dry mass (g)	Woody root length (m)	Fireweed root length (m)	Woody root SA (cm^2)	Fireweed root SA (cm^2)	Woody Root: shoot
GA	0	0.4±0.2^{a}	2.3±0.6^{a}	0.5±0.2^{a}	1.1±0.3^{a}	35.2±24.5^{a}	73.6±19.4^{a}	0.3±0.05^{a}
GA	2	0.8±0.5^{ab}	2.09±0.8^{a}	0.8±0.3^{a}	0.9±0.3^{a}	49.8±22.9^{a}	62.9±22.01^{a}	0.2±0.07^{a}
GA	4	2.3±0.6^{b}	1.6±0.5^{a}	1.9±0.6^{a}	0.7±0.1^{a}	117.4±22.9^{a}	45.0±9.02^{a}	0.3±0.07^{a}
GA	C	1.6±0.4^{ab}	2.6±0.6^{a}	1.3±0.2^{a}	1.2±0.3^{a}	79.6±22.9^{a}	79.2±20.7^{a}	0.3±0.07^{a}
BW	0	1.4±0.3^{a}	1.5±0.4^{ab}	1.4±0.3^{a}	0.6±0.1^{ab}	93.9±20.8^{a}	39.5±8.6^{ab}	1.2±0.2^{a}
BW	2	1.8±0.5^{ab}	0.5±0.1^{a}	2.1±0.3^{ab}	0.4±0.1^{ab}	139.6±23.3^{ab}	27.9±6.3^{ab}	0.7±0.07^{ab}
BW	4	3.06±0.3^{b}	0.3±0.1^{a}	2.8±0.3^{b}	0.2±0.07^{a}	181.3±19.7^{b}	16.5±2.5^{a}	0.7±0.08^{ab}
BW	C	1.7±0.2^{a}	2.6±0.6^{b}	1.5±0.2^{a}	1.2±0.3^{b}	97.0±12.6^{a}	79.2±20.7^{b}	0.6±0.04^{b}
SX	0	2.3±0.4^{a}	1.06±0.4^{ab}	2.4±0.3^{a}	0.7±0.2^{a}	154.5±18.2^{a}	46.±15.4^{ab}	1.5±0.6^{a}
SX	2	5.8±0.7^{c}	0.3±0.05^{a}	4.1±0.5^{b}	0.2±0.02^{a}	256.9±33.3^{a}	16.4±1.0^{a}	0.8±0.08^{a}
SX	4	5.02±0.7^{bc}	0.2±0.1^{a}	3.5±0.6^{ab}	0.2±0.08^{a}	219.3±36.4^{a}	14.2±4.3^{a}	0.7±0.06^{a}
SX	C	2.8±0.5^{ab}	2.6±0.6^{b}	2.7±0.5^{ab}	1.2±0.3^{b}	174.4±31.3^{a}	79.2±20.7^{b}	0.6±0.06^{a}
SW	8	0.3±0.07^{a}	2.03±0.1^{a}	0.3±0.009^{a}	0.8±0.07^{a}	20.8±0.4^{a}	49.2±5.2^{a}	0.6±0.05^{a}
SW	10	0.3±0.07^{a}	0.8±0.1^{b}	0.4±0.08^{a}	0.5±0.09^{b}	29.5±5.6^{a}	29.6±5.7^{b}	0.4±0.05^{a}
SW	C	0.6±0.07^{b}	2.6±0.6^{a}	0.6±0.09^{a}	1.2±0.3^{ab}	35.6±6.4^{a}	79.2±20.7^{ab}	0.4±0.05^{a}

Table 2-7. Comparison of nursery seedling characteristics of woody plants grown with fireweed at different sow dates prior to out planting at the reclamation sites. Woody plant parameters included height (cm), total shoot dry mass (g), stem dry mass (g), leaves dry mass (g), total root dry mass (g), root length (g), root surface area (cm^2), total nitrogen (N) (g), and root-to-shoot (R:S) ratio. Fireweed grown with woody plants was only measured for height (cm), total root dry mass (g), root length (cm), root surface area (SA) (cm2), and total nitrogen (g). Significant results indicated by * ($p<0.05$). Mean ± one standard error (Controls (C) n=3, hitchhiker seedlings n=4, fireweed grown alone n=9).

Plant	Measurement	Green alder	Paper birch	Bebb's willow	White spruce
Woody	Height (cm)	<0.00010*	<0.00010*	<0.00010*	0.0088*
Woody	Total shoot dry mass (g)	<0.00010*	0.0083*	<0.00010*	0.00033*
Woody	Stem dry mass (g)	0.0010*	0.013*	<0.00010*	<0.00010*
Woody	Leaves dry mass (g)	0.0080*	0.40	0.00020*	0.015*
Woody	Total root dry mass (g)	0.0064*	0.00040*	0.00470*	0.0049*
Woody	Root length (cm)	0.0556	0.0038*	0.039*	0.035!
Woody	Root SA (cm^2)	0.059	0.0052*	0.06	0.037!
Woody	Total N (g)	0.00080*	0.0044*	0.0047*	0.22
Woody	R:S	0.50	0.022*	0.16	0.091
Fireweed	Height (cm)	0.08	<0.00010*	<0.00010*	<0.00010*
Fireweed	Total root dry mass (g)	0.60	0.0016*	0.004*	<0.00010*
Fireweed	Root length (cm)	0.29	0.011*	0.018*	0.017*
Fireweed	Root SA (cm^2)	0.33	0.0052*	0.017*	0.017*
Fireweed	Total N (g)	0.40	0.041*	0.52	0.00011*

! *'emmeans' function corrected for type 1 error and this is not actually significant*

Table 2-8. Statistical comparison of hitchhiker seedling growth characteristics among sow dates under field conditions after 1 and 2 growing seasons. Significant results indicated by * ($p<0.05$). Mean ± one standard error (Green alder n=6, Other species n=11). TN is total nitrogen.

Year	Measurement	Green alder	Paper birch	Bebb's willow	White spruce
1	Woody height (cm)	0.010*	<1E-4*	<1E-4*	<1E-4*
1	Woody increment (cm)	0.09	0.0019*	0.95	0.0030*
1	Fireweed cover (%)	0.071	0.0065*	<1E-4*	0.010*
2	Woody height (cm)	0.005*	1.0E-4*	0.0034	1.0E-4*
2	Woody increment (cm)	0.83	0.79	0.41	0.29
2	Woody total biomass (g)	0.23	1.0E-4*	0.76	1.0E-4*
2	Woody stem biomass (g)	0.15	1.0E-4*	0.032	1.0E-4*
2	Woody leaf biomass (g)	0.38	0.14	0.31	1.0E-4*
2	Woody leaf TN content (g)	0.77	0.29	0.24	1.0E-4*
2	Fireweed cover (%)	0.16	0.10	0.052	0.02
2	Fireweed biomass (g)	0.78	0.79	0.72	0.49

Table 2-9. Leaf total nitrogen (TN) content of hitchhiker woody plants after two growing seasons. Fireweed was grown alone (control) as well as sown with green alder *(Alnus viridis*), paper birch (*Betula papyrifera*), and Bebb's willow (*Salix bebbiana*) at the same time (0-weeks), 2-weeks later, and 4-weeks later. Fireweed was sown with white spruce (*Picea glauca*) at later intervals (8 and 10 weeks). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (Green alder: n=6, Other species: n=11).

Species	Sow date	TN content (g)
Green alder	0	1.4±0.8[a]
Green alder	2	1.6±0.8[a]
Green alder	4	1.6±0.8[a]
Green alder	C	1.7±0.8[a]
Paper birch	0	0.04±0.03[a]
Paper birch	2	0.1±0.04[a]
Paper birch	4	0.09±0.02[a]
Paper birch	C	0.08±0.02[a]
Bebb's willow	0	0.1±0.03[a]
Bebb's willow	2	0.06±0.02[a]
Bebb's willow	4	0.08±0.02[a]
Bebb's willow	C	0.06±0.02[a]
White spruce	8	0.02±0.003[a]
White spruce	10	0.02±0.003[a]
White spruce	C	0.04±0.003[b]

Table 2-10. An evaluation of fireweed spread**.** The average hitchhiker fireweed presence and vegetative cover surrounding the seedlings (8 quadrats, $0.5m^2$), as well as fireweed biomass of 9 quadrats ($0.5m^2$) for each sow date after two growing seasons (Appendix 7)). Fireweed was grown alone (control) as well as sown with green alder *(Alnus viridis*), paper birch (*Betula papyrifera*), and Bebb's willow (*Salix bebbiana*) at the same time (0-weeks), 2-weeks later, and 4-weeks later. Fireweed was sown with white spruce (*Picea glauca*) at later intervals (8 and 10 weeks). Letters indicate sow dates that are statistically different. Presence means with range of standard error, as well as cover and biomass means ± one standard error (Green alder n=6, Other species n=11).

Species	Sow date	Presence (%)	Cover (%)	Biomass (g)
Green alder	0	16.3^a (6.1-37.1)	$0.9±0.4^a$	$12.5±6.8^a$
Green alder	2	14.5^a (35.2-5.1)	$0.6±0.3^a$	$7.1±5.5^a$
Green alder	4	12.0^a (32.4-3.7)	$0.4±0.4^a$	$8.2±5.6^a$
Green alder	C	7.6^a (21.4-2.5)	$0.3±0.2^a$	$7.1±4.5^a$
Paper birch	0	9.4^a (23.4-3.4)	$0.4±0.2^a$	$7.1±4.5^a$
Paper birch	2	12.7^a (27.3-5.3)	$0.8±0.3^a$	$10.5±5.7^a$
Paper birch	4	12.6^a (27.3-5.3)	$0.6±0.3^a$	$9.3±5.1^a$
Paper birch	C	7.6^a (21.4-2.5)	$0.3±0.2^a$	$7.01±4.2^a$
Bebb's willow	0	11.0^a (25.4-4.3)	$0.6±0.3^a$	$9.5±4.6^a$
Bebb's willow	2	10.3^a (24.5-3.9)	$0.5±0.3^a$	$7.07±4.3^a$
Bebb's willow	4	5.3^a (18.7-1.4)	$0.4±0.3^a$	$6.06±4.02^a$
Bebb's willow	C	7.6^a (21.4-2.5)	$0.3±0.2^a$	$7.5±4.0^a$
White spruce	8	12.8^a (27.5-2.1)	$0.9±0.4^a$	$5.9±3.5^a$
White spruce	10	7.0^a (20.6-5.4)	$0.4±0.3^a$	$12.7±5.6^a$
White spruce	C	7.6^a (21.4-2.5)	$0.3±0.2^a$	$7.3±3.5^a$

2.7 Figures

Figure 2-1. Hitchhiker plot locations at the (a) stockpile and (b) borrow pit. Furrowed plots include SP1 and SP3-7. Plots with conventionally track-packed soils include SP2, BP1-3 and BP5.

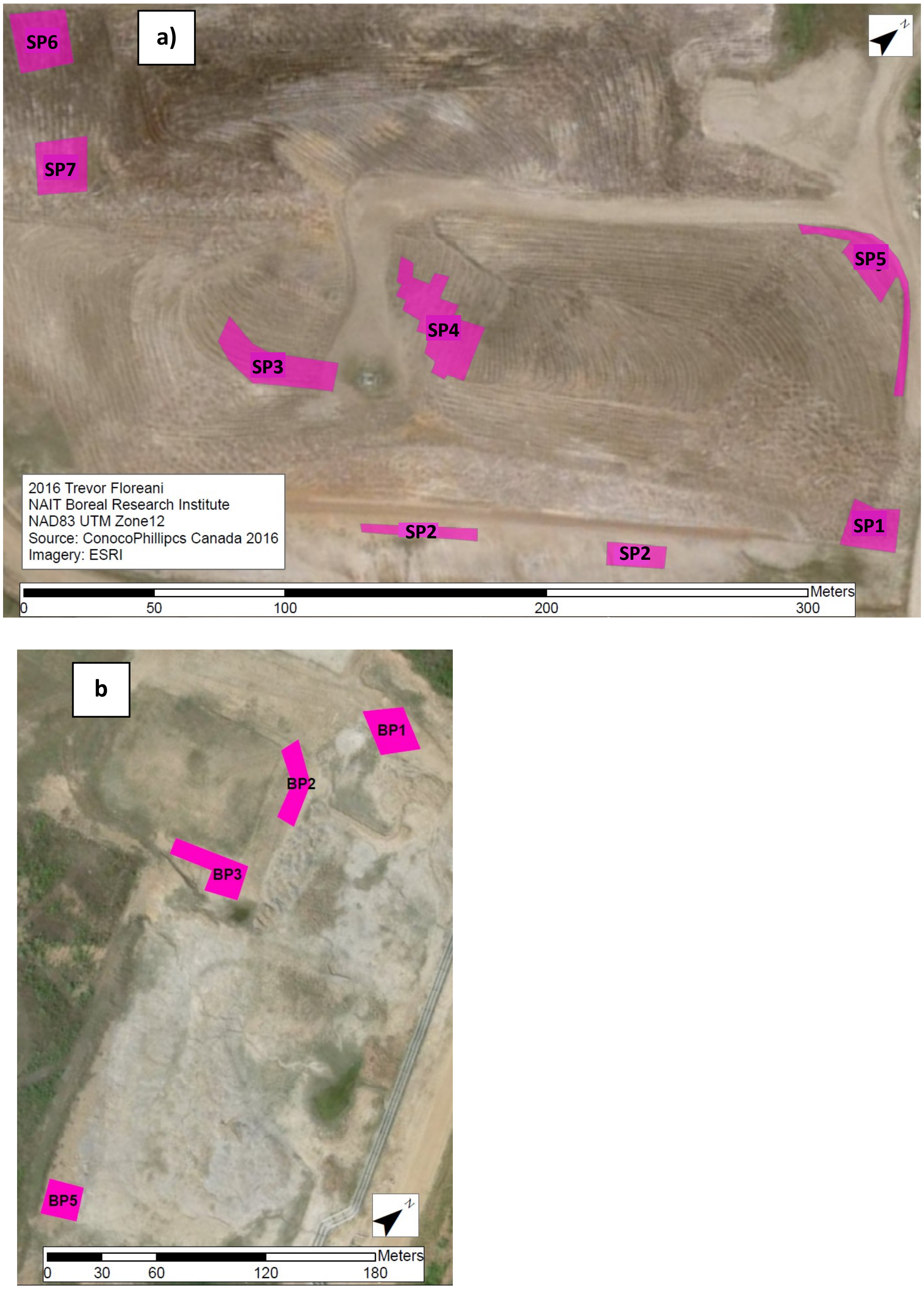


Figure 2-2. Field growth of green alder (*Alnus viridis*) hitchhiker seedlings after one (Yr1) and two (Yr2) growing seasons measured by average (a,b) total shrub height (cm), (c,d) growth increment (inc.) (cm), (e) cumulative survivorship (%), and (f) total, stem, and leaf biomass (g) relative to each sow date. Sow dates included same time (0wk), fireweed (*Chamerion angustifolium*) sown with green alder 2 weeks (2wk) and 4 weeks (4wk) later as well as green alder grown alone (C Ga). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=7).

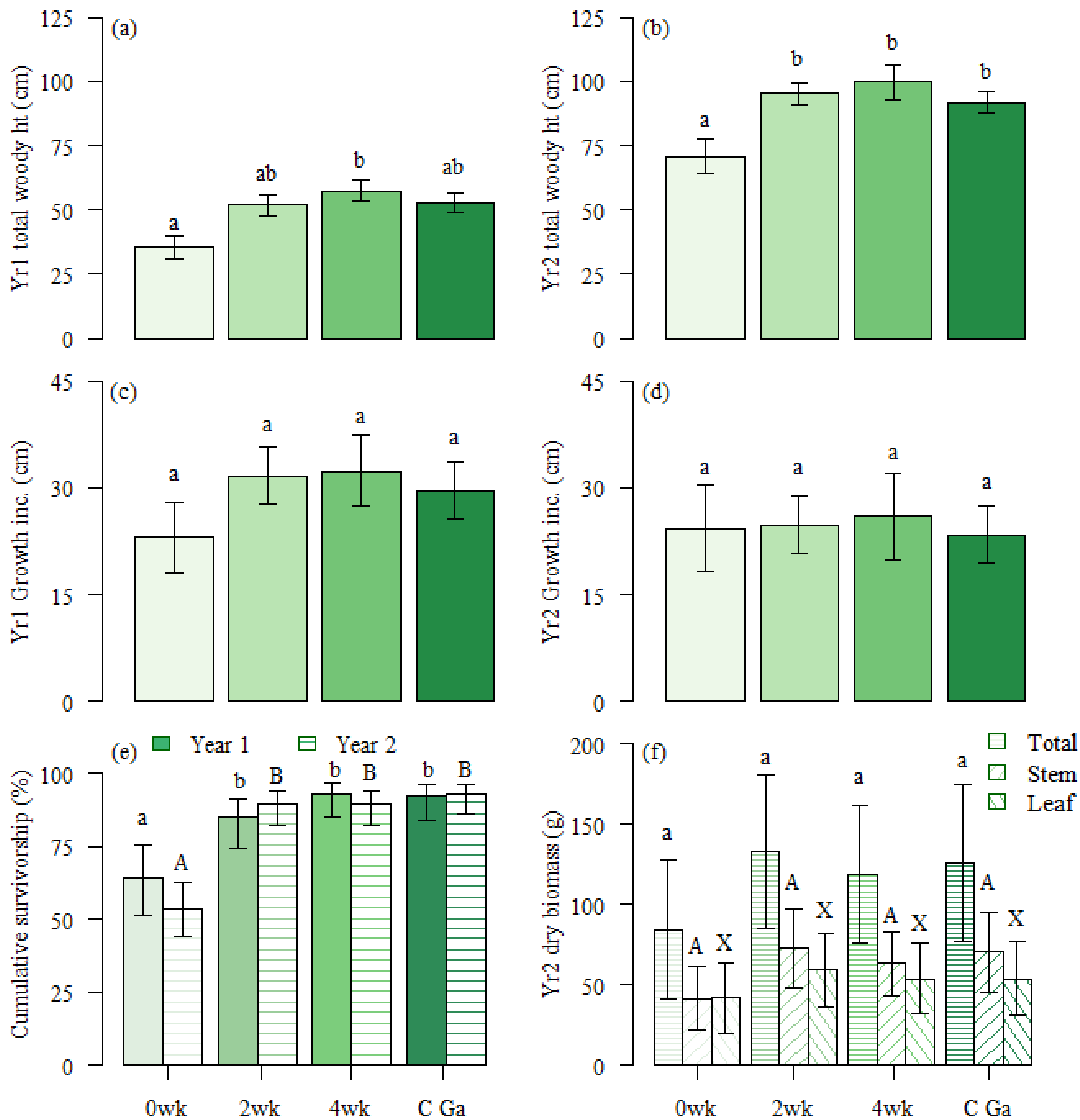


Figure 2-3. Field growth of fireweed (*Chamerion angustifolium*) hitchhiked with green alder (*Alnus viridis*) after the first (Yr1) and second (Yr2) growing season measured by average (a,b) fireweed vegetative cover (%) and (c) fireweed cumulative presence (%) relative to each sow date. Sow dates included same time (0wk), fireweed sown with green alder 2 weeks (2wk) and 4 weeks (4wk) later as well as fireweed grown alone (C Fw). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=7).

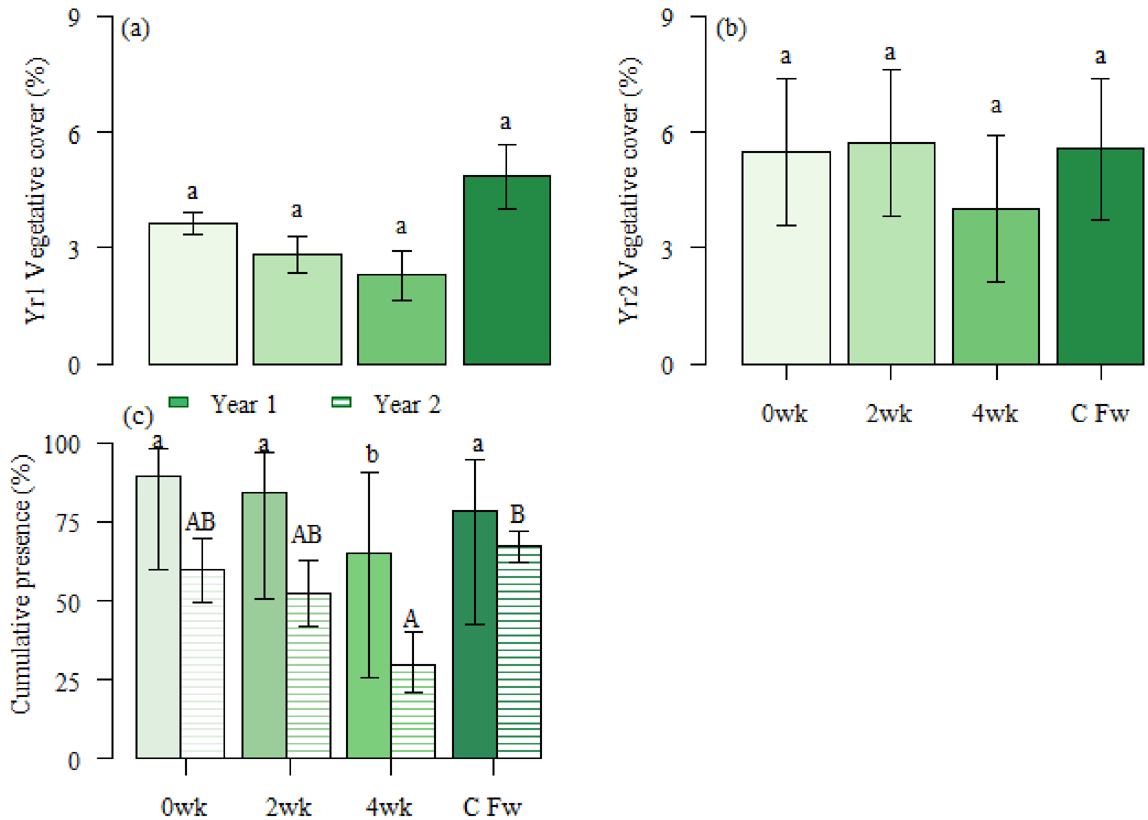


Figure 2-4. Field growth of paper birch (*Betula papyrifera*) hitchhiker seedlings after the first (Yr1) and second (Yr2) growing seasons measured by average (a,b) total tree height (cm), (c,d) growth increment (inc.) (cm), (e) cumulative survivorship (%), and (f) total, stem, and leaf biomass (g) relative to each sow date. Sow dates included same time (0wk), fireweed (*Chamerion angustifolium*) sown with paper birch 2 weeks (2wk) and 4 weeks (4wk) later as well as paper birch grown alone (C Bw). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=11).

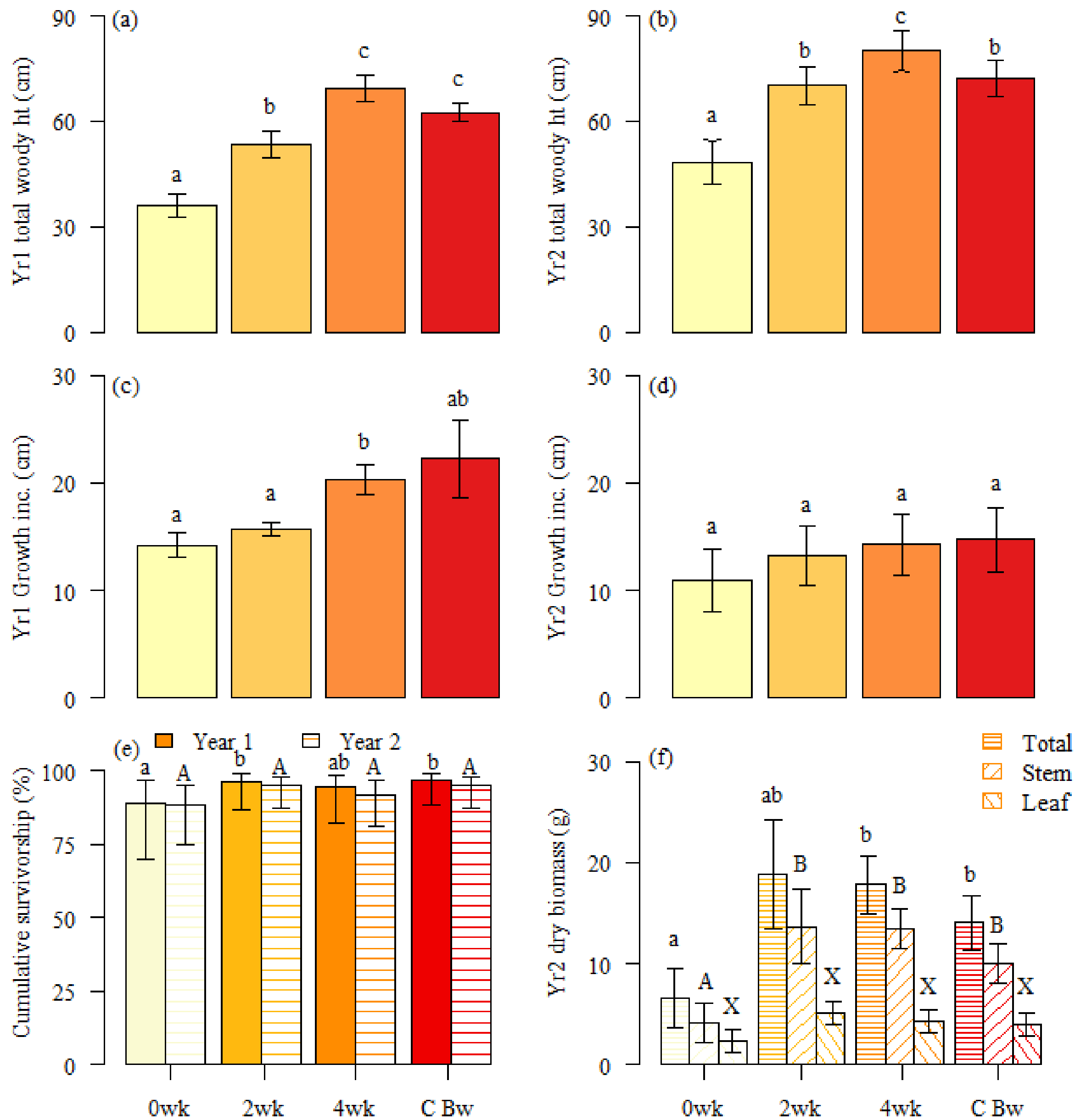


Figure 2-5. Field growth of fireweed (*Chamerion angustifolium*) hitchhiked with paper birch (*Betula papyrifera*) hitchhiker seedlings after the first (Yr1) and second (Yr2) growing season measured by average (a,b) fireweed vegetative cover (%) and (c) cumulative fireweed presence (%) relative to each sow date. Sow dates included same time (0wk), fireweed sown with paper birch 2 weeks (2wk) and 4 weeks (4wk) later as well as fireweed grown alone (C Fw). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=11).

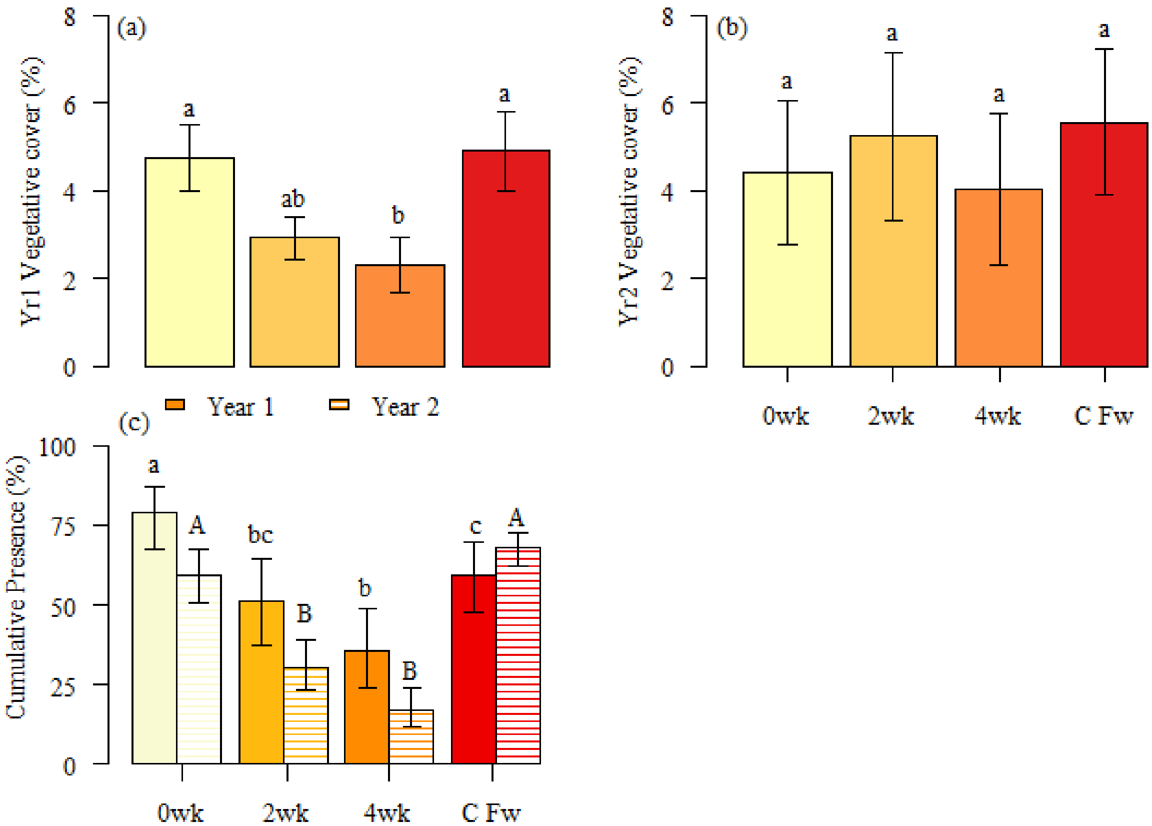


Figure 2-6. Field growth of Bebb's willow (*Salix bebbiana*) hitchhiker seedlings after the first (Yr1) and second (Yr2) growing seasons measured by average (a,b) total shrub height (cm), (c,d) growth increment (inc.) (cm), (e) cumulative survivorship (%), and (f) total, stem, and leaf biomass (g) relative to each sow date. Sow dates included same time (0wk), fireweed (*Chamerion angustifolium*) sown with Bebb's willow 2 weeks (2wk) and 4 weeks (4wk) later as well as Bebb's willow grown alone (C Sx). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=11).

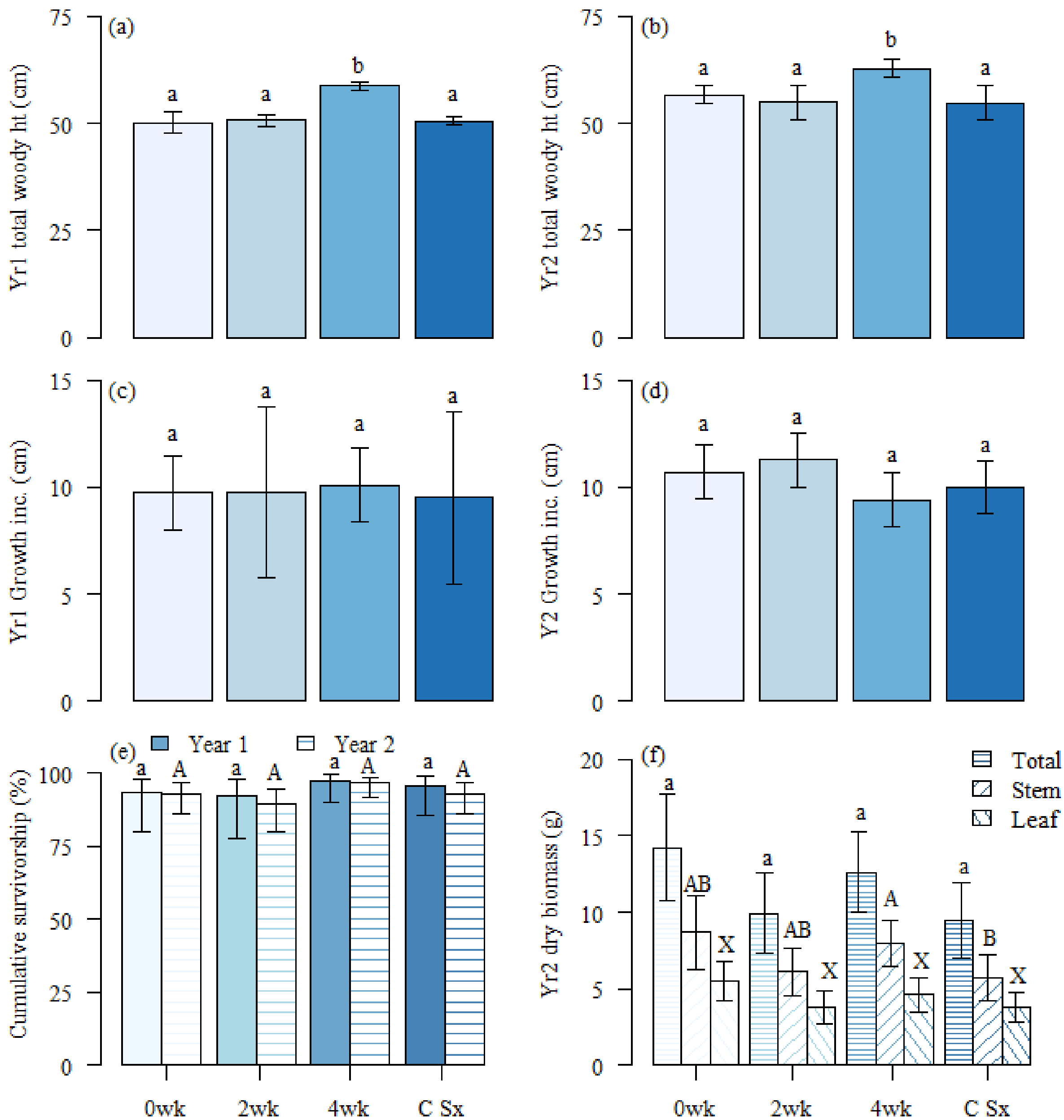


Figure 2-7. Field growth of fireweed (*Chamerion angustifolium*) hitchhiker with Bebb's willow (*Salix bebbiana*) after the first (Yr1) and second (Yr2) growing season measured by average (a,b) fireweed vegetative cover (%) and (c) cumulative fireweed presence (%) relative to each sow date. Sow dates included same time (0wk), fireweed sown with Bebb's willow 2 weeks (2wk) and 4 weeks (4wk) later as well as fireweed grown alone (C Fw). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=11).

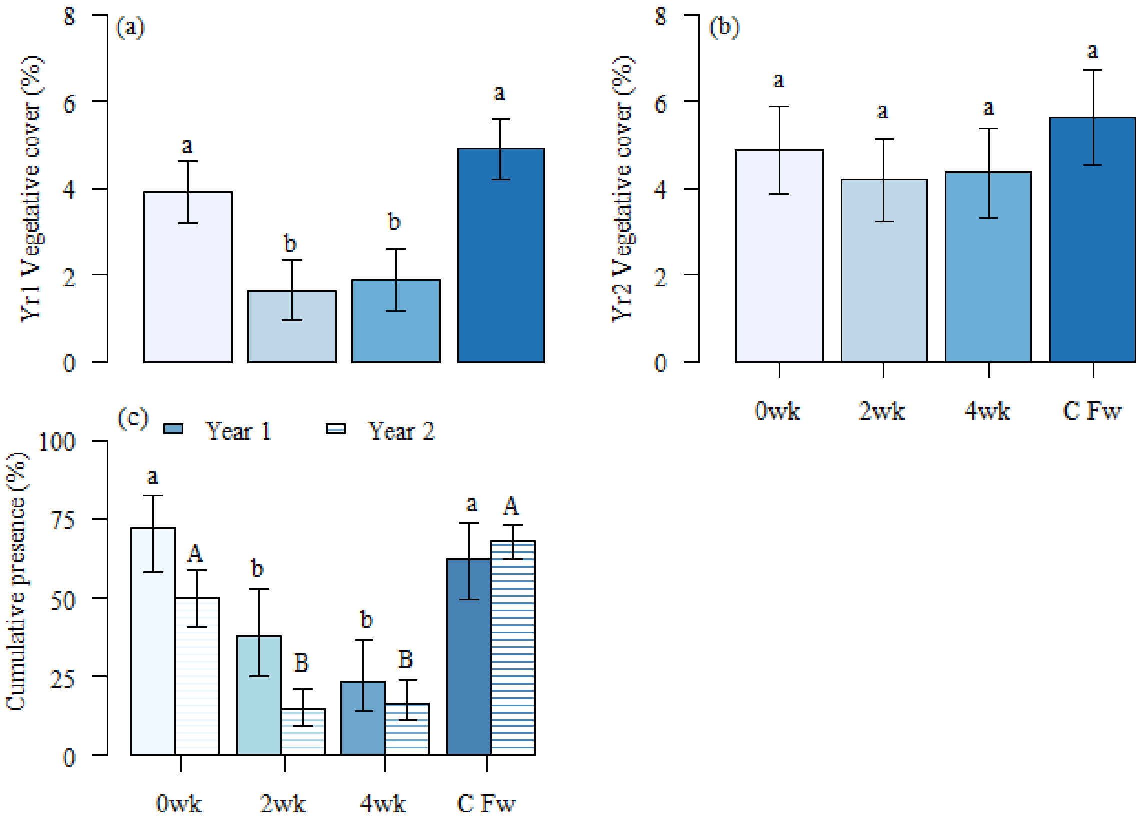


Figure 2-8. Field growth of white spruce (*Picea glauca*) hitchhiker seedlings after the first (Yr1) and second (Yr2) growing seasons measured by average (a,b) total tree height (cm), (c,d) growth increment (inc.) (cm), (e) cumulative survivorship (%), and (f) total, stem, and leaf biomass (g) relative to each sow date. Sow dates included same time (0wk), fireweed (*Chamerion angustifolium*) sown with white spruce 8 weeks (8wk) and 10 weeks (10wk) later as well as white spruce grown alone (C Sw). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=11).

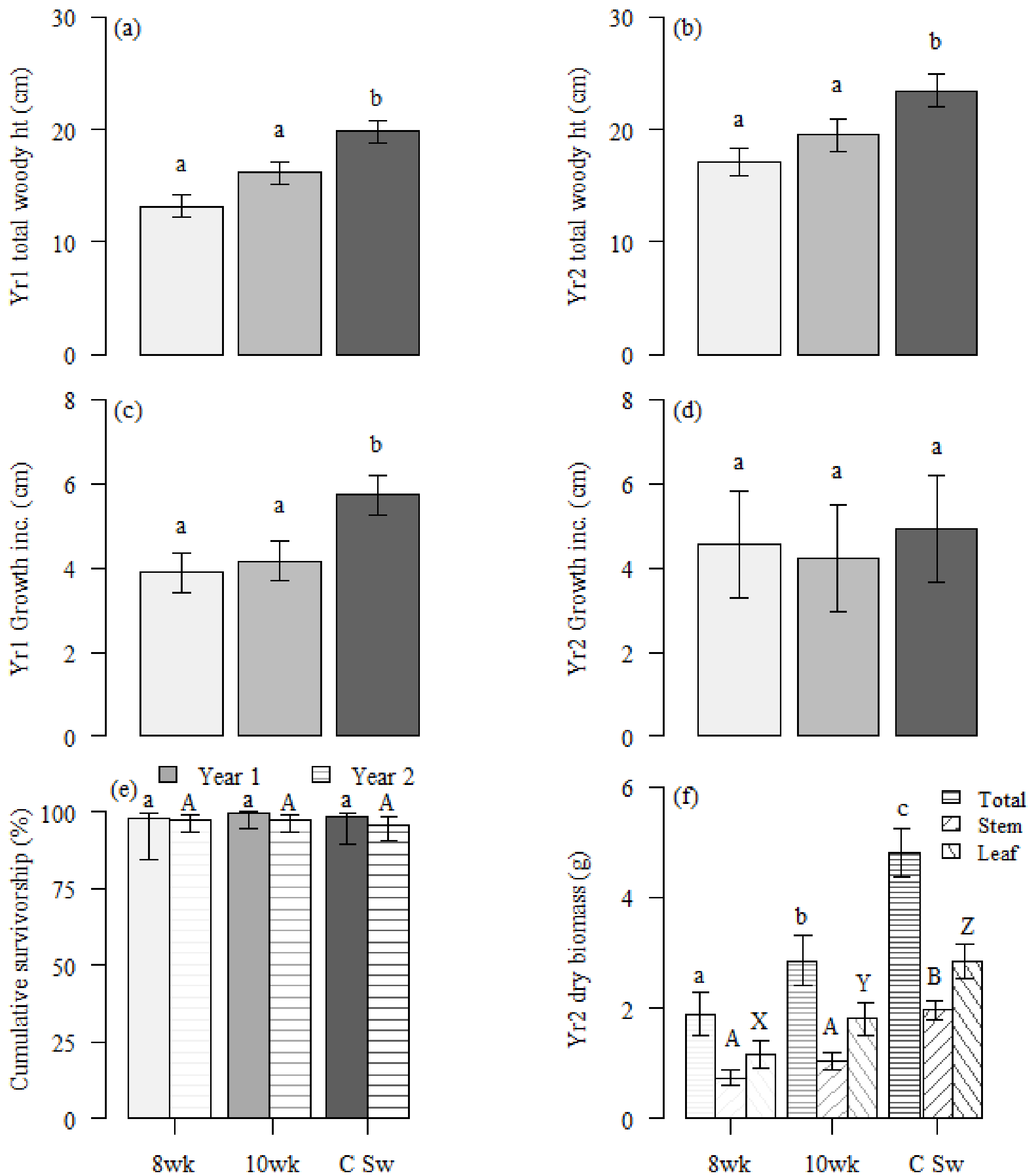


Figure 2-9. Field growth of fireweed (*Chamerion angustifolium*) hitchhiked with white spruce (*Picea glauca*) after the first (Yr1) and second (Yr2) growing season measured by average (a,b) fireweed vegetative cover (%) and (c) cumulative fireweed presence (%) relative to each sow date. Sow dates included fireweed sow with white spruce 8-weeks (8wk), 10 weeks (10wk) as well as fireweed grown alone (C Fw). Letters indicate sow dates that are statistically different. Mean ± one standard error of the mean (n=11).

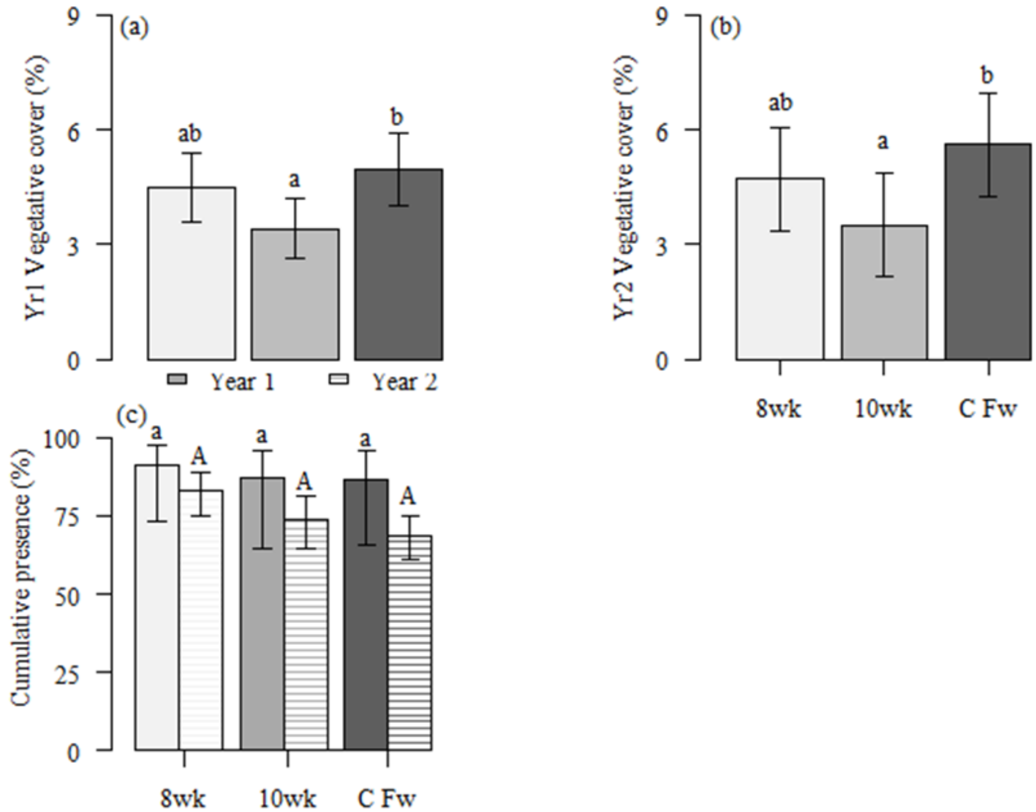
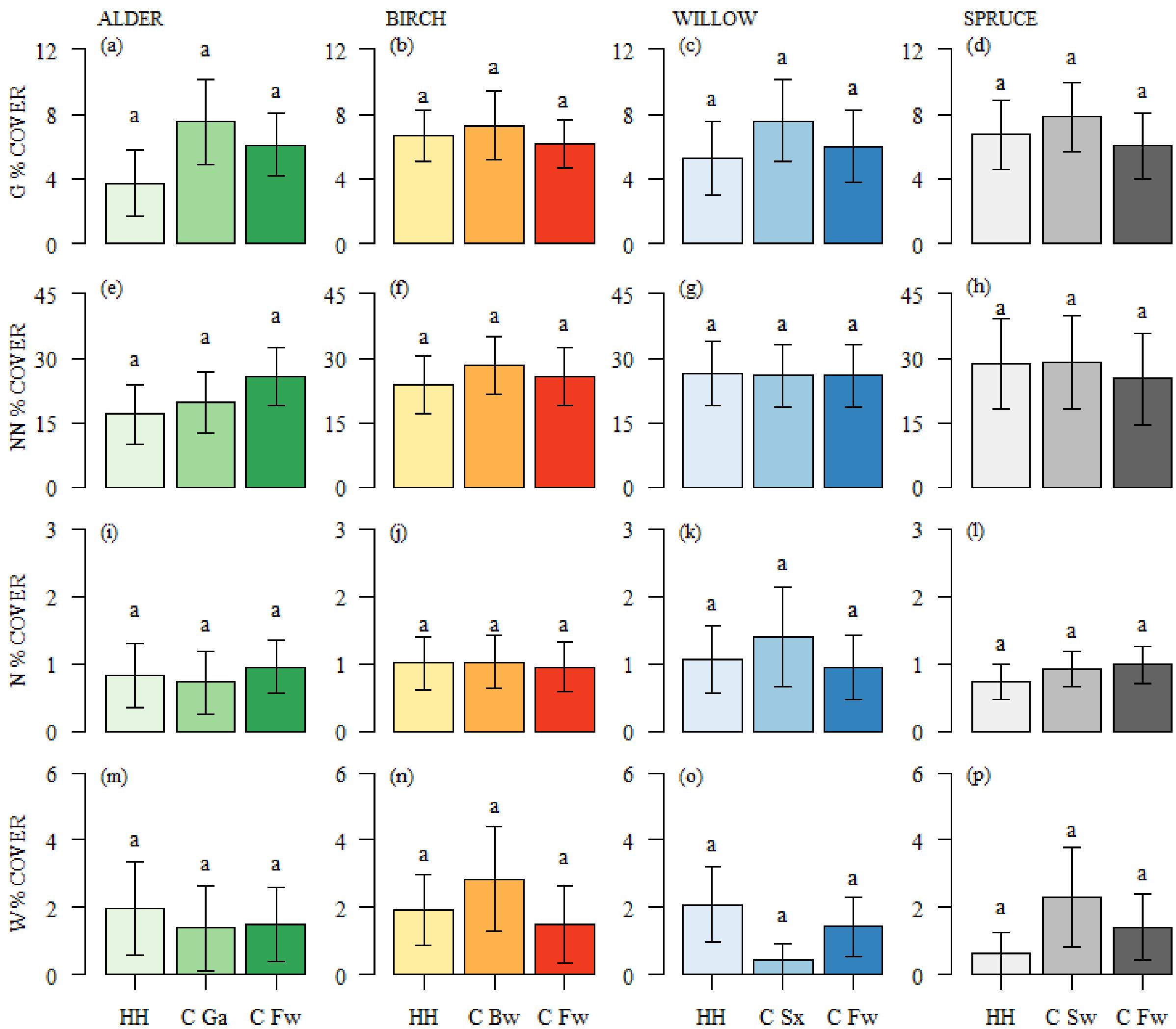


Figure 2-10. Comparison of community vegetation cover surrounding recommended hitchhiker (HH) seedlings as well as woody plants and fireweed (*Chamerion angustifolium*) grown alone (C Fw). Woody plants included green alder (*Alnus viridis*) (C Ga), paper birch (*Betula papyrifera*) (C Bw), Bebb's willow (*Salix bebbiana*) (C Sx), and white spruce (*Picea glauca*) (Sw). The HH seedlings included was 2-week green alder, 2-week paper birch, 0-week Bebb's willow, and 10-week white spruce. Vegetation groups excluded hitchhiker woody and fireweed plants, but included all other native forbs (N), woody (W), grass (G), and non-native forbs (NN). Letters indicate hitchhiker of control seedlings that are statistically different. Mean ± one standard error (Green alder n=7, Other species n=11).



3.0 CHAPTER 3 – Soil-plant interactions in reclaimed soils after two growing seasons

3.1 Introduction

Plant growth and survival at reclamation sites will be different than natural sites. Seedling growth and survivorship at reclamation sites is constrained by a variety of challenges, such as competing vegetation and disturbed soils. Industrial disturbance, such as the creation of oil and gas facilities, involves stripping and stockpiling surface soils. Upon completion of these activities, infrastructure is removed, and the site is contoured to align with the surrounding landscape. Stockpiled soils are placed with bulldozers resulting in relatively smooth soil surfaces. Occasionally, operators may roughen the soil to create greater heterogeneity. By simply moving the soil, a decrease in soil aggregates and loss of organic matter can occur (Wick et al., 2009).

Soil placement may introduce compaction if proper decompaction, such as soil loosening, is not considered (Alberta Environment and Sustainable Resource Development, 2013; Lof et al., 2012). Compaction leaving soils greater than 1.6g/cm^3 can negatively affect the development of plant roots and uptake of water and nutrients (Susnjar et al., 2006; Rohand et al., 2004; Millward et al., 2011; McKenzie et al., 2004). Recently disturbed soils also lead to reduced structure and short-term release of nutrients through mineralization, which promotes the growth of non-native forbs and grasses (Kristenson, et al., 2000). Non-native forbs can establish during soil disturbances and are adapted to harsh conditions, allowing a seed bank of competitive species to develop, and inhibiting the development of native forbs (Radosevich, 1997; Sutton, 1985). In addition, revegetation with native species that can tolerate full sun, variable moisture conditions post-disturbance, and are evolved to recover from natural disturbances may be appropriate (Davis et al., 2017; Gutschick & BassiriRad, 2003). For example, alder species grown in infertile soil was shown to decrease soil erosion and increase community development (Gtari & Dawson, 2011).

Species native to the boreal forest and chosen for this study included: green alder (*Alnus viridis* [Chaix] DC. Subsp. *Crispa* [Aiton] Turill), paper birch (*Betula papyrifera* Marsh.), Bebb's willow (*Salix bebbiana* Sarg.), white spruce (*Picea glauca* [Moench] Voss), and fireweed (*Chamerion angustifolium* L. [Holub.]) (Moss, 1959). These species tend to be found in moist to dry soil conditions, though most would prefer moist, well-drained soils (Bell et al., 2011; Moss, 1959; CEMA, 2009).

Species tolerance stems from adaptability to compete for light, soil moisture, and nutrients (Gatherum et al., 1963). Bebb's willow and green alder are deciduous shrubs that tend to be found in open to partially open areas with moist soils (Moss, 1959). It was expected that green alder and Bebb's willow may be associated with a wider tolerance to nutrient regimes (CEMA, 2009), but green alder in particular has the benefit of nitrogen fixation to establish in nutrient poor conditions (Bosco et al., 1991). Paper birch, a mid-sized deciduous tree, and white spruce, a coniferous tree, tend to be found in mixedwood canopies with moist and moderately nutrient rich soils (Leak, 1978). In addition, these woody species vary in shade tolerance ranging from low to high, respectively: green alder, paper birch and willow, then white spruce (Farrar, 1995).

Fireweed is a herbaceous forb and an early successional species, especially after fire (Moss, 1959), and typically establishes in recently disturbed, moist, nutrient rich soils with good drainage (Pinno et al., 2013; Moss, 1959). It produces more than 5000 seeds per plant, spreads by rhizomes, and tends to compete for light, moisture, and nutrients (Fernald, 1950; Landhausser & Lieffers, 1994; Landhausser et al., 1996; Bell et al., 2001; Moss, 1959). The spread of non-native forbs can be discouraged by fireweed, especially if the soil conditions are favorable to fireweed (Haeussler et al., 1990; Delong, 1991). Fireweed also adds to nutrient cycling through annual litterfall of P and K rich material (Dyrness & Norum, 1983).

Although fireweed has the potential to compete with trees and shrubs, fireweed does not impact shade-tolerant trees, such as white spruce, as much as shade intolerant plants (Ie. *Calamagrostis canadensis*) (Landhäusser et al., 1996; Lieffers & Stadt, 1994; Eis, 1981). An increase in growth of boreal conifers, such as *Picea glauca* (white spruce), has been associated with a decrease in vegetative competition (Brand, 1991). *Betula papyrifera*, *Picea glauca*, and *Populus tremuloides* grew more root when below-ground competition with community was reduced (Hobbie & Chapin, 1998).

Limited research of green alder, paper birch, Bebb's willow, white spruce and fireweed growth and survival responses at reclamation sites have been conducted. Although green alder and willow species have been viewed as competitors having negative effects on the growth of white spruce and lodgepole pine (*Pinus contorta*), a European species, Italian alder (*Alnus cordata*) has been used to successfully revegetate a gravel pit without the addition of topsoil in France (Cartini & Cameau, 2008; Bosco et al., 1991). Although Bebb's willow has not been used for reclamation often, it has been found invading recently burned upland forest sites (Viereck, 1970), mine spoil piles in southeastern British Columbia (Como et al., 1978), as well as recently amended soil with lime and phosphate near Sudbury, Ontario (Winterhalder, 1978). Fireweed has drawn attention as a species with potential for benefiting the recovery of disturbed sites, but the potential as a reclamation species is not yet well understood (Pinno et al., 2013). White spruce is a species that has been relatively common to use for revegetation in Western Canada. It is well known that the combined effect of transplanting stress (Rietveld, 1989; Grossnickle, 2000) and competition with other species, such as *Calamagrostis canadensis* (Lieffers et al., 1993), can negatively affect the success of planted white spruce seedlings during the early phase of seedling growth and survival (Matsushima & Chang, 2006; Sloan & Jacobs, 2013). In addition, it was found that when there was adequate soil moisture, interspecific competition for soil nitrogen often limited white spruce seedling survival (Staples et al., 1999; Robinson et al., 2001).

There is a gap between the knowledge of these species established in natural conditions and the response of these species to disturbed or reconstructed landscapes, particularly for native shrubs and forbs (CEMA, 2009). In this study, two types of industrial disturbance, a reclaimed borrow pit and an existing soil stockpile, supplied a wide range of differing soil parameters that were quantified for planted nursery stock seedlings. It was expected that the aforementioned species will thrive in microsites that capture characteristics similar to natural conditions and develop poorly with greater mortality in microsites with unfavorable conditions, which may vary among species. This assessment will answer the following question:

(1) What soil conditions led to better growth and survival of green alder, paper birch, Bebb's willow, white spruce, and fireweed among a range of reclamation soil conditions and plant community?

3.2 Methods

3.2.1 Seedling production of seedlings

Seeds for this study were collected near Fort McMurray, AB, Canada in seed zone CM3.1 (Alberta Agriculture and Forestry, 2005). Styroblocks (Beaver Plastics Ltd. Acheson, Alberta) facilitated the growth of seedlings starting April 7, 2016 using a completely randomized block design where each block consisted of one species.

Refer to chapter two for detailed production of seedlings (Section 2.2.1). Seedlings grown singly (alone) were selected to assess soil-plant relations, which were grown in 512A styroblocks each with 60 cavities (220mL per cavity). Seedlings were placed outdoors for the month of September to promote dormancy ahead of field out planting. They were transported to the study site and planted over a three-day period during September 26-28th 2016.

3.2.2 Site description

The study sites were located approximately 70 kilometers south of Fort McMurray, Alberta, Canada, located within the boreal mixedwood forest. The average annual temperature and precipitation at these sites was 1.4ºC and 494.4mm, from 1998 to 2017 (Alberta Agriculture and Forestry, 2018). The agricultural growing season length in Alberta is approximately 4 months from seeding date (>5°C air temperature) until fall frost, or about June through September (Agriculture and Agri-Food Canada, 2014). The average daily temperature high of the summer months at the time of planting (2016) and two consecutive years later (2017 & 2018) was 21.2ºC, 21.4ºC, and 18.5ºC (Alberta Agriculture and Forestry, 2018). The accumulated precipitation during summer of 2016, 2017, and 2018 was 381mm, 348mm, and 324mm (Alberta Agriculture and Forestry, 2018).

Two reclamation sites, Surmont Regional Residence (SRR) soil stockpile and a large borrow pit (SMC #110009), were situated 5 km apart within the ConocoPhillips Surmont in-situ facility (Figure 3-1). The soil stockpile was a storage location for the surrounding industrial disturbances (primarily the SRR which was immediately adjacent to the soil stockpile). Most of the stockpile was corner bladed with a dozer to create deep furrows or mounded with an excavator in October 2015, with the exception of one sandy side that was left conventionally track-packed (stockpile plot 2). The second site was a recently reclaimed upland borrow pit. The borrow pit formed a secondary comparison of stock development on soils which had not benefited from surface site preparation. Soil preparation at the borrow pit included placement of subsoil and topsoil with dozers through the summer period in 2016; this created a relatively smooth soil surface compared with the surface heterogeneity created by the furrowing and mounding at the stockpile. Due to the differences in site preparation, site location, and site type, the number and composition of plant species measured August 2018 slightly differed at furrowed and conventionally track-packed sites (Table 3-1, 3-2).

3.2.3 Field study

3.2.3.1 Seedlings

The study design involved a total of eleven independent replicate plots compiled from the SSR stockpile (7 plots) and the borrow pit (4 plots) to evaluate seedling growth across a range of soil conditions (Figure 3-1). Within a single plot, there were 16 lines (4 lines per species) where each line consisted of three plants planted 1.5m apart at a random location along the line (12 plants per plot). Due to shortages of green alder, this species was only planted at the stockpile (6 furrowed and 1 conventionally track-packed plot). Therefore, plots at the borrow pit consisted of 12 lines (4 lines for 3 species). Since fireweed was planted in every single line from the previous study (Chapter 2), two plants per line were planted instead of three (32 plants/plot at stockpile and 24 plants/plot at borrow pit).

To assess the growth of seedlings after two growing seasons, woody survivorship and fireweed presence was recorded. Aboveground biomass was collected for woody plants within $0.5m^2$. To assess growth and spread of fireweed, aboveground fireweed biomass was collected within $1.5m^2$ (3x3 $0.5m^2$ quadrats) centered on the seedling (Appendix 7). Within each plot, only one plant per replicate on each line (woody = 4 per plot, fireweed = 16 per plot) was harvested. This large collection of biomass was initially air-dried for 10 days on metal-mesh benches in the greenhouse followed by oven drying for 12 hours at 70ºC.

3.2.3.2 Soil properties

Soil properties were assessed at the plot level (n=11). During the second growing season (May 9, 2018 to September 29, 2018 - 5 months), soil moisture and temperature data were recorded hourly using DECAGON Em50 Data loggers (METER Group, Inc., Washington, USA). Two logger stations were placed in each plot with each logger containing two soil moisture sensors that measure volumetric water content (METER Group, Inc ECH2O EC-5) and 1 temperature sensor (METER Group, Inc ECT/RT-1) buried 15cm below the surface approximately 1m away from the logger. Sensors were placed with the consideration of diverse microsites. Unfortunately, there were technical errors with some loggers that did not capture data.

Soil sampling occurred in a stratified sampling design with 4 samples per plot. Soil core samples were collected at depths of 0-5cm, 10-15cm, and 25-30cm to analyze bulk density, electrical conductivity (EC), and pH. Soil pits were dug to obtain soil cores at different depths within the rooting zone. Two cores with a total volume of 110.3cm^3 were collected from each depth. Samples were stored in coolers during the collection process and stored for two days in the fridge (4ºC) prior to sample processing at the lab. All soil was oven dried at 65ºC until weight constancy and dry mass determined (for bulk density) and subsequent analysis performed (described below).

EC and pH were measured using a saturated soil paste method (Rhoades, 1996) with pH and EC probes (Orion Versastar V03659, Thermo Scientific, New Jersey, USA).

Additional cores (10cm by 6cm) from the soil surface were collected to assess soil texture, total nitrogen, and organic matter. Litter and vegetation were removed prior to soil sampling. The composite sample of four soil cores was taken 1m away from each soil pit, mixed thoroughly, and subsampled by hand. After oven drying (as described previously), the soil was gently broken up until it passed through a 2mm sieve. One portion of the sieved soil was analyzed for particle size (Laser Defraction Particle Size Analyzer LS 13 320, Beckman Coulter, Indiana, USA).

The second portion of the sieved soil was ground into a homogeneous fine powder and analyzed for total nitrogen (TN) as well as organic matter. Total nitrogen was measured using dry combustion with Flash 2000 Organic Elemental Analyzer (Thermo Scientific, New Jersey, USA) and performed by NRAL at University of Alberta, Edmonton, Canada. I also analyzed the percent organic matter loss occurring between 150ºC and 410ºC (Simultaneous Thermal Analyzer (STA) 6000, PerkinElmer, Massachusetts, USA). This consisted of labile organic matter (LOM) and was more easily burned, just as it is more easily decomposed by soil organisms and microbes and thus more nutrients accessible for plant uptake (Fernandez et al., 2012; Baffi et al., 2007; Bot, 2005).

Three locations per plot were tested for infiltration. Infiltration of unsaturated soils was determined by direct measurement of water infiltration using a Mini Disk Infiltrometer (Model S) (DECAGON Devices, Inc; Washington, USA) (Decagon Devices, Inc., 2012). The infiltrometer was placed on the soil surface, taking care to ensure the entire cylinder was in contact with the soil. Soil surface crusts were not removed, as this would not accurately represent a rain event. The infiltration tests were performed between June 20 to 22 2018 during a period when the soils were unsaturated. The 100 mL cylinder was filled with tap water and the change in water column height was recorded in 30 second intervals until the water had fully infiltrated the soil. The method to calculate infiltration rate was described by Zhang (1997), which requires a series of equations as well as van Genuchten parameters, suction and soil texture (Carsel & Parrish, 1988) (Appendix 10).

3.2.4 Statistical analysis

Ultimately 10 plots were used in the analysis as stockpile plot 2 (SP2) was excluded due native soil having extreme soil characteristics, such as high EC, relative to the rest of the plots (Appendix 11). In addition, little to no community vegetation development was observed (Appendix 12).

R statistical software was used for all analysis and graphing (R Core Team, 2018). Prior to analyzing the response of plant growth to soil conditions, differences in soil temperature (n=2 per plot) and moisture (n=4 per plot) from May to September 2018 was assessed using a single-factor mixed effects model (function 'lme'4) with two nested random factors (plot nested in site) to account for site location as well as site preparation. The assumption of normality for ANOVA was met and unequal variance was accounted for in the lme model by including weights with the function 'varIdent', which provided a better model fit shown by lower AIC values (Konishi & Kitagawa, 2008). Significant differences ($\alpha < 0.05$) between treatment means were separated with a post-hoc multiple comparison test using emmeans function (Lenth, 2018).

There were notable differences in soil characteristics between plots, thus further analysis was done to statistically compare soil characteristics between plots with a one-way ANOVA and a two-way ANOVA with site as a random factor (significance level $\alpha < 0.05$). Soil characteristics included soil moisture high and low, soil temperature high and low, TN, LOM, and infiltration. However, a two-way ANOVA was used to compare bulk density, pH, and EC among plots and depth (plot*depth), and this confirmed that the depths for each parameter were autocorrelated.

Assumptions of normality were met, and unequal variances were accounted for using the lme model by including weights with the function 'varIdent', which provided a better model fit shown by lower AIC values (Konishi & Kitagawa, 2008). The main intention of this portion of the analysis confirmed that (1) there were differences between plots for each soil parameter and (2) the measurements at 3 depths for bulk density, pH, and EC did not differ among depth (p=0.05) (Table 4-6).

Linear regressions were used to describe and analyze the soil and plant relationships. This tested the response of seedling biomass, height of tree species, as well as woody survivorship and fireweed presence to each soil property at the plot level (R Core Team, 2017). Soil properties included infiltration, bulk density, EC, pH, TN, LCOM, soil temperature and soil moisture. Since bulk density, EC and pH did not differ among the 3 measured depths, only the 10-15cm depth was used for regressions, which was anticipated to be a reasonable representation of the root zone. In addition, the relationship between seedling parameters were also evaluated with total vegetation cover as well as vegetation cover categorized by, grass, native forbs, non-native forbs, and woody vegetation surrounding the planted seedlings. Assumptions of normality and variance were assessed graphically; where needed, data was transformed with either log10, log, or square root to meet these assumptions.

The significance alpha level chosen for the regression analysis in this study was 0.1 to better represent biological significance rather than statistical significance given that field trials are inherently variable. Determining biological significance occurs through the evaluation of the data relative to what is conceived to be biologically significant (Matinez-Albrain, 2008). Soil-plant interactions were graphed to show the confidence of the analysis, despite not reporting confidence intervals (Yoccoz, 1991). Significant ($p<0.01$) regressions that have a poor fit due to outliers were not presented as important findings.

3.2.5 Soil characteristics

3.2.5.1 Soil moisture and temperature

Soil temperature and moisture collected from May to September 2018 was compared among months to isolate the months with relatively high and low moisture and temperature regimes. Soil moisture ($p<0.0001$, F=147, df=4) and soil temperature ($p<0.0001$, F=260, df=4) differed among months (Appendix 13). The greatest soil moisture (26±0.7 %VWC) and soil temperature (15±1°C) occurred during July. Soil moisture was lowest during May (19±0.7 %VWC) and June (19±0.7 %VWC). In contrast, the lowest soil temperature occurred during September (7±1°C). Thus, the following months were chosen to correlate with seedling growth and survival; July for HIGH soil moisture, May for LOW soil moisture, July for HIGH soil temperature and September for LOW soil temperature.

3.2.5.2 The range of soil characteristics

Soil characteristics were significantly different between soil stockpile and borrow pit plots (Table 3-3). During the month of HIGH soil moisture, soil moisture ranged from 14 to 30% VWC among plots ($p<0.0001$, F=34, df=10), while the soil moisture LOW ranged from 11 to 22% VWC ($p<0.0001$, F=28, df=10) (Table 3-3). The period of HIGH soil temperatures ranged from 7 to 19°C ($p<0.0001$, F=20, df=8), whereas soil temperature LOW ranged from 2 to 8°C among plots ($p<0.0001$, F=9.4, df=8) (Table 3-3). In addition, the average soil TN ranged from 0.3 to 2.5 $mg \cdot g^{-1}$ ($p<0.0001$, F=29, df=10) and the average LOM widely ranged from 1 to 9% ($p<0.0001$, F=16, df=10) (Table 3-3). The average infiltration rate also varied greatly from $0.9x10^{-4}$ to $16x10^{-4}$ $cm \cdot s^{-1}$ (p=0.0001, F=7, df=10) (Table 3-3). Soil textures were mostly loam, but also clay loam, and sandy loam (Table 5). Given that bulk density, EC, and pH did not significantly differ between the measured depths, it was sufficient to describe the middle depth (10-15 cm) (Table 3-4, Appendix 4). At 10-15 cm depth, bulk density ranged from 0.5 to 1.3 $g \cdot cm^{-3}$ ($p<0.0001$, F=22, df=10) (Table 3-4). There was also a wide range in soil pH from 4.4 to 7.9 ($p<0.0001$, F=11, df=10) and EC from 0.2 to 0.7$dS \cdot m^{-1}$ ($p<0.0001$, F=8, df=10) (Table 3-5, 3-6). Only the 10-15 cm depth was also used in soil-plant correlations.

The relationship between soil characteristics was also visualized with a non-metric multidimensional scaling (NMS) ordination, except for soil moisture and temperature due to missing values. Data was revitalized and ordinate with Sorensen (Bray-Curtis) distance in PC-Ord software (McCune and Mefford, 2011). Stress values were acceptable under Clarke's rules of thumb (McCune et al., 2002); stress less than 5 is excellent, 5-10 is good, and 10-20 is poor.

3.3 Results

3.3.1 Soil-plant & community-plant relations

Green alder biomass was negatively correlated with soil temperature HIGH (Table 3-6, Figure 3-2) while survivorship was positively correlated with bulk density and soil moisture HIGH, which was only correlated with green alder, and negatively correlated with temperature HIGH and LOW (Table 3-6, Figure 3-2). The growth of green alder was not correlated with infiltration, moisture LOW, TN, LOM, EC, and pH (Table 3-6, Figure 3-2). Green alder was the only species that was not correlated with total community vegetation cover or vegetation classes of grass, non-native forbs, native forbs, and woody species (Table 3-7, Figure 3-2).

Paper birch biomass, tree height, and survivorship was correlated to many of the measured soil properties. Paper birch biomass was negatively correlated with pH and positively correlated with soil moisture LOW (Table 3-6, Figure 3-3). Paper birch tree height was positively correlated with TN and LOM, but negatively correlated with pH (Table 3-6, Figure 3-3). TN was only correlated with paper birch growth (Table 3-8). Survivorship of paper birch was positively correlated with pH and soil temperature HIGH (Table 3-6, Figure 3-3). Paper birch was not correlated with infiltration, moisture HIGH, temperature LOW, bulk density, and EC (Table 3-6). Paper birch tree height was positively correlated with woody community vegetation cover, but paper birch survivorship was negatively correlated with total community vegetation cover (Table 3-7, Figure 3-3).

Bebb's willow biomass and survivorship was positively correlated with EC (Table 3-6, Figure 3-4). In addition, Bebb's willow survivorship was negatively correlated with infiltration (Table 3-6, Figure 3-4). Bebb's willow was not correlated with moisture HIGH, moisture LOW, temperature HIGH, temperature LOW, TN, LOM, bulk density, and pH (Table 3-6). Bebb's willow biomass and survivorship was also negatively correlated with woody community vegetation cover (Table 3-7, Figure 3-4).

White spruce survivorship was not correlated with any measured soil properties (Table 3-6, Figure 3-5). However, white spruce biomass and height was positively correlated with LOM and height was positively correlated with temperature LOW and negatively correlated with bulk density (Table 3-6, Figure 3-5). Only spruce growth was correlated with temperature LOW (Table 3-8). White spruce growth was not correlated with infiltration, moisture HIGH, moisture LOW, temperature HIGH, TN, EC and pH (Table 3-6). White spruce biomass was positively correlated with native forbs community vegetation cover (Table 3-7, Figure 3-5).

Fireweed biomass was negatively correlated with bulk density and pH (Table 3-6, Figure 3-6). Only fireweed was shown to be affected by the pH range of the soil conditions (Table 3-8). Fireweed presence was also positively correlated with bulk density, yet negatively correlated with infiltration (Table 3-6, Figure 3-6). Fireweed was not correlated with moisture HIGH and LOW, temperature HIGH and LOW, TN, LOM, EC, or pH (Table 3-6). Fireweed biomass was positively correlated with total vegetation cover, as well as native forbs and woody community vegetation cover (Table 3-7, Figure 3-6). Yet fireweed presence was negatively correlated with woody community vegetation cover (Table 3-7, Figure 3-6).

The ordination of soil parameters (bulk density, pH, EC, LOM, and TN) showed that soil properties at the borrow pit and stockpile overlapped and variability of axis one was driven by LOM and TN (Figure 3-7). Bulk density and pH were autocorrelated and inverse to these were LOM and TN, which were also autocorrelated (Figure 3-7). EC was not associated with the other soil parameters described.

3.5 Discussion

Each of the five species evaluated responded in slightly different ways to soil conditions and community vegetation development; this was not wholly unexpected as these species represented a range environmental tolerances and life history characteristics explained by Bell et al. (2011). Although there were individual species preferences for soil characteristics, as evaluated by greater growth responses, most of these species were still capable of persistence and growth under the range of soil conditions evaluated.

3.5.1 Plant responses to soil physical characteristics (bulk density, infiltration, moisture, temperature)

Bulk density was important for green alder survival, white spruce height and fireweed biomass, as Millward et al. (2011) determined that looser soils promoted root growth, resource capture, and aboveground growth. However, fireweed presence contradicted this trend. Soils with higher bulk density were associated with greater presence (Figure 3-6), which could have been due to the reduction in soil water evaporation (Schwartz et al., 2010). In addition, Fleming et al. (2006) explained, that compaction improves survival and growth by decreasing competition and increasing soil moisture availability.

Lower bulk density has been previously linked with higher infiltration, described by Millward et al. (2011), which was anticipated to be beneficial for plant growth and survival. In this study, infiltration generally had weak positive correlations with biomass and tree height. However, infiltration was negatively correlated with Bebb's willow survival and fireweed presence (Figure 3-4). Soil type may have been influential for fireweed presence (Pinno et al. 2013), but it is more likely that the rationale for the unexpected bulk density results applies here as well. High clay soils with low infiltration, found by Whitson et al. (2005), buffered extreme wet and dry conditions by reducing soil water evaporation.

Soil water is an important requirement for plant growth and survival and this study illustrated that there was likely an optimal soil moisture range linked with improved growth and survival which varied with the tolerance of each species. Green alder survival was greater in soils with higher soil moisture in this study (Figure 3-2), which was also suggested by Moss (1959), Bell et al., (2011), and CEMA (2009). Pinno et al (2017) found that fireweed germination responded with greater biomass when greater watering rates occurred and showed greater mortality to drought. Foote (1983) found that white spruce showed preference to well-drained warm soils, which corresponds to finding greater height of white spruce in warmer soils in this study.

In contrast, CEMA (2009) suggested that paper birch can be found in a range of soil moisture conditions. Biomass corresponded to moist soils (not dry, not saturated), yet survival of paper birch was very good suggesting that moisture may not limit survival and its physiological capacity may be wider than the ecological niche we observe it in. Bosco et al (2016) explained that plant species native range of climatic tolerance (air temperature and precipitation) are larger than anticipated.

3.5.2 Plant responses to soil chemical characteristics (total nitrogen, organic matter, EC and pH)

As nutrients are required for plant growth, it is no surprise that white spruce biomass and height was positively correlated to LOM while paper birch height was positively correlated with TN and LOM. In this study, paper birch grew taller with greater soil TN while Schlatzer (1973) found that paper birch required moderate amounts of sulfur and nitrogen. However, it was unexpected that fireweed and Bebb's willow lacked significant correlation with TN and LOM, although in general TN and LOM had weak positive correlations with plant biomass, tree height, and survivorship or presence. Abundant fireweed growth is often observed in nutrient rich soils (Haeussler et al 1990; Delong 1991), but it may be restricted by soil type when nutrients (NPK) are limiting (Pinno et al., 2013). Brady (1974) found that soil types contained smaller soil particles have higher cation exchange capacity and higher ability to reserve mineral nutrients and be unavailable to plants. In addition, TN and LOM were the only measured nutrient related parameters while Allen et al. (2007) claimed that a lack of other macro- and micronutrients, such as phosphorus, can also limit plant growth. For example, it was determined by Fowells and Krauss (1959) and Gutschick (1978) that low phosphorus can limit energy available to *Alnus viridis* (also called *Alnus crispa*) and affect energy-demanding nitrogen fixation.

It is important to note that nutrient uptake by plants can be affected by other soil parameters, such as pH (Millward et al, 2011; Perry, 2003). Soils with pH between 5.5 and 6.5 are favorable as the majority of micro- and macronutrients are available (Tucker et al., 1987; Perry, 2003). Although soil pH at the soil stockpile and borrow pit were reasonable, Thompson et al. (1997) found herbaceous leaf tissue with positively correlated nitrogen and phosphorus concentrations, and calcium and manganese had positive and negative, correlations with soil pH, respectively.

Fireweed biomass was negatively correlated with higher pH (~7.6), but as mentioned, pH may be an indirect indicator of other soil parameters. For instance, pH can indirectly affect growth by impeding nutrient availability (Tucker et al., 1987; Perry, 2003). Note that bulk density was weakly associated with pH (Figure 3-7), and bulk density was also related to soil type, which impacts nutrient and water retention capabilities and root growth (Millward et al, 2011).

Many boreal species are intolerant of saline soils and the soils at our reclamation sites were considered to be non-saline on average (<2dS/m) (Howat, 2000; Dahnke & Whitney, 1988). Bebb's willow biomass and survivorship had a strong positive correlation with EC, yet there is little knowledge of Bebb's willow salinity tolerance (CEMA, 2009). Since EC is a measure of total charged ions, which can be other ions besides sodium, this correlation could be an indication that Bebb's willow growth and survivorship was being driven by other micro- or macronutrients. Further research to test nutrient requirements of Bebb's willow would be valuable.

3.5.3 Plant responses to community vegetation

Grass and non-native forbs unexpectedly lacked correlation with seedling growth and survival, which suggested that these community species were not prolific enough to negatively impact seedlings. Instead, seedling survival of paper birch, Bebb's willow, and fireweed was negatively affected by naturally establishing woody shrubs and trees, such as *Rubus idaeus* (Wild red raspberry). Disturbance (furrowing or conventionally track-packed) likely reduced emergence of quick establishing weedy species while promoting root development of planted seedlings as Lof et al. (2012) found improved survival and growth of seedlings. In addition, Elmarsdottir et al. (2003) suggested that a lack of microsites equated to a lack of undesirable germination conditions, good moisture and protection for native root propagule and seed emergence. Seedling growth corresponding with native woody and forb species suggested that soil conditions were favorable to overall plant growth (Bell et al., 2011); though it is notable that total community vegetation was negatively correlated with fireweed presence and paper birch survival, suggesting that competing vegetation increased shading of shade-intolerant plants (Maundrell & Hawkins, 2004; Lieffers & Stadt, 1994).

3.5.4 Summary of seedling responses

The following highlighted soil conditions that was associated with greater growth potential:

- Green alder survival was better in moister soils and soils with higher bulk density yet was not inhibited by competing vegetation.
- Paper birch grew best in nutrient rich moist (not saturated or dry) soil conditions where competition was limited.

- Since Bebb's willow unexpectedly had better survival in soils with lower infiltration and soils with higher EC, or possibly a specific available nutrient, soils that provide moisture and nutrient stability may be beneficial.
- White spruce may establish better in looser soils and where native forb vegetation also easily regenerates. However, white spruce also grew well in warm soils and may also benefit from sufficient TN and LOM.
- Fireweed may grow best in looser soils with moderate moisture where native forb vegetation also easily regenerates.

3.6 Limitations and future studies

It is important to consider that soil-plant interactions are affected by multiple abiotic and biotic parameters. The interactions could be further explained with a multivariate approach, such as structural equation modeling (SEM), which has been increasingly used to further explain the complexity of environmental parameters that affect seedling growth. Although soil sampling occurred at the plot-scale in this study, this is a reasonable approach to examine large-scale patterns. Sampling soil adjacent to individual plants or within plant replicates to better correspond to the plant replicate lines and may have allowed for greater resolution in the weaker correlations observed in this study.

An independent study focusing on plant-soil interactions would also give an opportunity to enhance the experimental design. Future trial work aimed at illuminating soil-characteristic driven effects should better control competing vegetation to avoid confounding effects. In addition, the plant-soil relations analysis was confounded by site type (stockpile & borrow pit) and site preparation techniques (furrowing or conventionally-track packed). A large single area encompassing plots with treatments of varying surface loosening techniques and soil characteristics would have eliminated this difference in location and site type; however, it can become difficult to obtain a wide gradient of soil parameters within a single study area.

Green alder was only planted at the stockpile and it would have been beneficial to have green alder planted at the borrow pit as well in order to evaluate green alder growth and survival under a greater cumulative variety of soil conditions. A greater number of plot replicates would have better supported the analysis power and possibly better explain the plant-soil relations.

Lastly, a single soil sampling depth, or a continuous depth profiled from 0-30cm depth, should be considered for similar future studies as the bulk density, pH, and EC measurements with depth were highly correlated and did not provide incrementally useful information. A selected depth representing the root zone would be sufficient in future studies.

3.7 Tables

Table 3-1. Top five species in August 2018 ranked from 1-5 with greatest average vegetation cover among at the soil stockpile (furrowed) and borrow pit (conventionally track-packed) soils. Mean ± one standard error (furrowed n=6, conventional n=5).

STOCKPILE (FURROWED)			BORROW PIT (CONVENTIONAL)		
Rank	Species	% cover	Rank	Species	% cover
1	*Trifolium hybridum* (Alsike clover)	5.2±0.3	1	*Melilotus species* (Sweet clovers)	15.7±0.3
2	*Trifolium pratense* (Red clover)	4.9±0.3	2	*Elymus trachycaulus* (Slender wheat grass)	5.7±0.08
3	*Melilotus species* (Sweet clovers)	3.9±0.7	3	*Trifolium hybridum* (Alsike clover)	5.3±0.4
4	*Alnus viridis* (Green alder)	1.5±0.3	4	*Trifolium pratense* (Red clover)	4.8±0.4
5	*Deschampsia caespitosa* (Tufted hair grass)	1.4±0.1	5	*Alnus viridis* (Green alder)	3.3±0.3

Table 3-2. The total number of species present at the soil stockpile (furrowed) and the borrow pit (conventionally track-packed) for each community vegetation group in August 2018: grass, native forb, non-native forb, and woody species as well as the total number of species present at furrowed and conventionally track-packed plots. Many of the same species were present at each plot.

Site	# of grass species	# of native forb species	# of woody species	# of non-native forb species
Stockpile	12	17	9	11
Borrow pit	14	20	11	10

Table 3-3. Soil properties of each plot at the soil stockpile (SP 1, 3-7) and borrow pit (BP 1-3, 5): soil moisture, temperature, total nitrogen (TN), labile organic matter (LOM), infiltration, bulk density, pH, and electrical conductivity (EC). Mean ± one standard error (infiltration n=3, temperature n=2, others n=4). Some data failed to be collected by instrumentation failure and lack of equipment and is indicated by 'NA'.

Site Plot	Moisture high (Jul.) (%VWC)	Moisture low (May) (%VWC)	Temp. high (Jul.) (°C)	Temp. low (Sep) (°C)	TN ($mg \cdot g^{-1}$)	LOM (%)	Infiltration ($x10^{-4}$ $cm \cdot s^{-1}$)
BP1	30.9±1.5	19.4±0.7	16.5±0.3	7.5±0.6	2.4±0.8	6.7±1.4	5.7±1.9
BP2	25.1±1.2	20.7±0.6	17.8±0.5	5.5±0.7	0.4±0.6	1.5±1.0	1.0±1.4
BP3	20.8±1.4	15.3±0.7	NA	NA	0.5±0.6	1.4±1.0	1.5±1.4
BP5	23.9±1.4	16.6±0.9	NA	NA	1.9±0.6	5.5±1.1	1.4±1.4
SP1	30.4±1.4	22.1±1.5	7.6±1.0	2.6±0.7	0.5±0.6	1.3±1.0	1.9±1.5
SP3	27.2±1.8	16.4±1.3	15.9±0.2	7.2±0.6	0.7±0.6	2.6±1.1	4.1±1.4
SP4	27.9±1.4	17.8±0.7	16.0±0.2	7.6±0.5	0.6±0.6	2.2±1.1	4.5±1.8
SP5	25.7±1.3	20.4±0.7	16.5±0.2	6.9±0.6	0.5±0.6	1.7±1.0	0.9±1.5
SP6	23.4±1.3	20.6±0.7	15.2±0.2	6.9±0.5	2.5±0.7	9.6±1.8	8.7±4.5
SP7	24.4±1.4	19.2±0.6	17.0±0.3	8.3±0.6	0.7±0.6	2.8±1.2	16.4±9.4

Site Plot	BD 10-15 cm ($g \cdot cm^{-3}$)	pH 10-15cm	EC 10-15cm ($dS \cdot m^{-1}$)
BP1	0.9±0.1	7.5±0.3	0.6±0.0
BP2	1.3±0.1	7.5±0.3	0.4±0.0
BP3	0.9±0.1	7.9±0.3	0.7±0.3
BP5	1.1±0.1	7.7±0.3	0.6±0.0
SP1	1.1±0.1	7.2±0.3	0.6±0.0
SP3	0.9±0.1	7.7±0.3	0.4±0.0
SP4	0.9±0.1	7.5±0.3	0.4±0.0
SP5	1.0±0.1	7.8±0.3	0.6±0.0
SP6	0.5±0.1	7.0±0.3	0.5±0.0
SP7	0.9±0.1	7.3±0.3	0.2±0.0

Table 3-4. The *p*-values from comparing bulk density, electrical conductivity (EC), and pH between plots at the soil stockpile and borrow pit (Site Plot), between depths of 0-5cm, 10-15cm, and 25-30cm, as well as the interaction of Site Plot with depth using a two-way ANOVA ($p<0.05$). Average bulk density, EC, and pH for each plot can be found in Appendix 4.

Site Plot	Bulk density	EC	pH
Site Plot	<0.0001	<0.0001	<0.0001
Depth	0.491	0.098	0.171
Site Plot*Depth	0.061	0.763	0.623

Table 3-5. Texture for each sample, used to calculate infiltration, for each plot at the soil stockpile (SP 1, 3-7) and borrow pit (BP 1-3, 5).

Site Plot	Rep	Soil type	Site Plot	Sample	Soil type
BP1	1	loam	SP1	1	sandy loam
BP1	2	sandy loam	SP1	2	loam
BP1	3	loam	SP1	3	loam
BP2	1	loam	SP3	1	loam
BP2	2	loam	SP3	2	loam
BP2	3	loam	SP3	3	loam
BP3	1	clay loam	SP4	1	sandy loam
BP3	2	clay loam	SP4	2	loam
BP3	3	loam	SP4	3	loam
BP5	1	loam	SP5	1	loam
BP5	2	loam	SP5	2	loam
BP5	3	loam	SP5	3	loam
			SP6	1	sandy loam
			SP6	2	loam
			SP6	3	sandy loam
			SP7	1	loam
			SP7	2	sandy clay loam
			SP7	3	loam

Table 3-6. Correlation coefficients between seedling biomass, height, survivorship or presence after the second growing season (2018) and soil properties: soil moisture, soil temperature, total nitrogen (TN), labile organic matter (LOM), and infiltration as well as bulk density (BD), pH, and electrical conductivity (EC) at 10-15cm depth. Bolded and shaded coefficients indicated significant correlations (without outliers) (p<0.1), black coefficients were positive correlations and red coefficients were negative correlations (Alder: n=6, all other species: n=10).

PARAMETER	BIOMASS					HEIGHT	
	Alder	Birch	Willow	Spruce	Fireweed	Birch	Spruce
Infiltration (cm·s^{-1})	0.43	0.02	-0.42	0.32	0.30	0.36	0.49
Moisture High (% VWC)	0.61	0.49	0.03	-0.06	0.33	0.30	-0.49
Moisture Low (% VWC)	-0.46	**0.79**	-0.32	-0.36	0.23	0.00	-0.22
Temperature High (°C)	-0.76	-0.12	0.13	0.17	-0.12	0.08	0.59
Temperature Low (°C)	-0.70	-0.40	-0.08	0.33	0.20	0.22	**0.78**
TN (mg·g^{-1})	0.21	-0.12	0.25	0.65	0.20	**0.75**	0.61
LOM (%)	0.16	0.05	0.13	**0.55**	0.28	**0.83**	**0.64**
BD10-15cm (g·cm^{-3})	0.05	-0.08	0.37	-0.24	**-0.60**	-0.49	**-0.76**
EC 10-15cm (dS·m^{-1})	0.44	-0.35	**0.59**	0.44	-0.12	-0.20	0.04
pH 10-15cm	-0.56	**-0.56**	0.50	0.06	**-0.66**	**-0.70**	-0.14

PARAMETER	SURVIVORSHIP				PRESENCE
	Alder	Birch	Willow	Spruce	Fireweed
Infiltration (cm·s^{-1})	-0.57	-0.35	**-0.69**	-0.35	**-0.69**
Moisture High (%VWC)	**0.92**	-0.17	0.17	-0.02	0.40
Moisture Low (%VWC)	-0.20	-0.03	-0.40	0.19	-0.07
Temperature High (°C)	-0.87	0.67	-0.24	-0.29	-0.32
Temperature Low (°C)	-0.88	0.50	-0.43	-029	-0.47
TN (mg·g^{-1})	-0.52	-0.10	0.02	0.20	-0.19
LOM (%)	-0.57	-0.21	-0.10	0.16	-0.34
BD10-15cm (g·cm^{-3})	**0.78**	0.43	0.49	0.12	**0.68**
EC 10-15cm (dS·m^{-1})	0.40	0.02	**0.65**	0.40	0.44
pH 10-15cm	0.01	0.68	0.50	-0.15	0.39

Table 3-7. Correlation coefficients between seedling biomass, height, survivorship or presence after the second growing and community vegetation cover. Vegetation cover within the immediate vicinity of seedlings consisting of total vegetation cover, grass cover, non-native forb cover, native forb cover, and woody cover. Bolded coefficients indicated significant correlations (without outliers) (p<0.1) where black coefficients were positive correlations and red coefficients were negative correlations (Alder: n=6, other species: n=10).

VEGETATION COVER (%)	BIOMASS					HEIGHT	
	Green alder	Paper birch	Bebb's willow	White spruce	Fireweed	Paper birch	White spruce
Total	-0.16	-0.14	0.51	0.50	**0.58**	0.51	0.33
Grass	-0.41	0.23	-0.33	-0.31	0.18	0.15	-0.05
Non-native forb	-0.22	-0.35	-0.22	0.18	0.46	0.32	0.30
Native forb	0.10	0.36	-0.45	**0.55**	**0.75**	0.52	0.42
Woody	0.35	0.04	**-0.85**	-0.22	0.56	**0.79**	0.28

VEGETATION COVER (%)	SURVIVORSHIP				PRESENCE
	Green alder	Paper birch	Bebb's willow	White spruce	Fireweed
Total	0.09	**-0.57**	-0.21	-0.21	-0.47
Grass	0.33	-0.41	-0.34	-0.42	-0.33
Non-native forb	-0.45	-0.44	-0.11	-0.20	-0.32
Native forb	-0.15	-0.20	-0.26	0.41	-0.31
Woody	-0.41	**-0.47**	**-0.63**	0.07	-0.72

Table 3-8. Summary of plant responses correlated with environmental conditions. Seedling biomass, tree height, or survivorship that was significantly correlated (without outliers) with soil characteristics of community vegetation is indicated with a check mark. A row count shows the relative importance of each soil characteristic or community vegetation group on seedling growth and survival. A column count suggests the relative sensitivity to soil and community characteristics for each species.

Environmental Measurement	Green alder	Paper birch	Bebb's willow	White spruce	Fireweed	*Count*
Infiltration ($cm \cdot s^{-1}$)			✓		✓	2
Moisture High (% VWC)	✓					1
Moisture Low (% VWC)		✓				1
Temperature High (°C)						0
Temperature Low (°C)				✓		1
TN ($mg \cdot g^{-1}$)		✓				1
LOM (%)		✓		✓		2
BD ($g \cdot cm^{-3}$)	✓			✓	✓	3
EC ($dS \cdot m^{-1}$)			✓			1
pH					✓	1
Count	2	3	2	3	3	
Community Measurement	**Green alder**	**Paper birch**	**Bebb's willow**	**White spruce**	**Fireweed**	***Count***
Total vegetation cover (%)		✓			✓	2
Grass vegetation cover (%)						0
Non-native forb vegetation cover (%)						0
Native forb vegetation cover (%)				✓	✓	2
Woody vegetation cover (%)		✓	✓			2
Count	0	2	1	1	2	

** TN is total nitrogen. LOM is labile organic matter. BD is bulk density. EC is electrical conductivity. pH is acidity.*

3.7 Figures

Figure 3-1. Plot locations at the **(a)** stockpile and **(b)** borrow pit. Furrowed plots include SP1 and SP3-7. Plots with conventionally track-packed soils included SP2, BP1-3 and BP5.

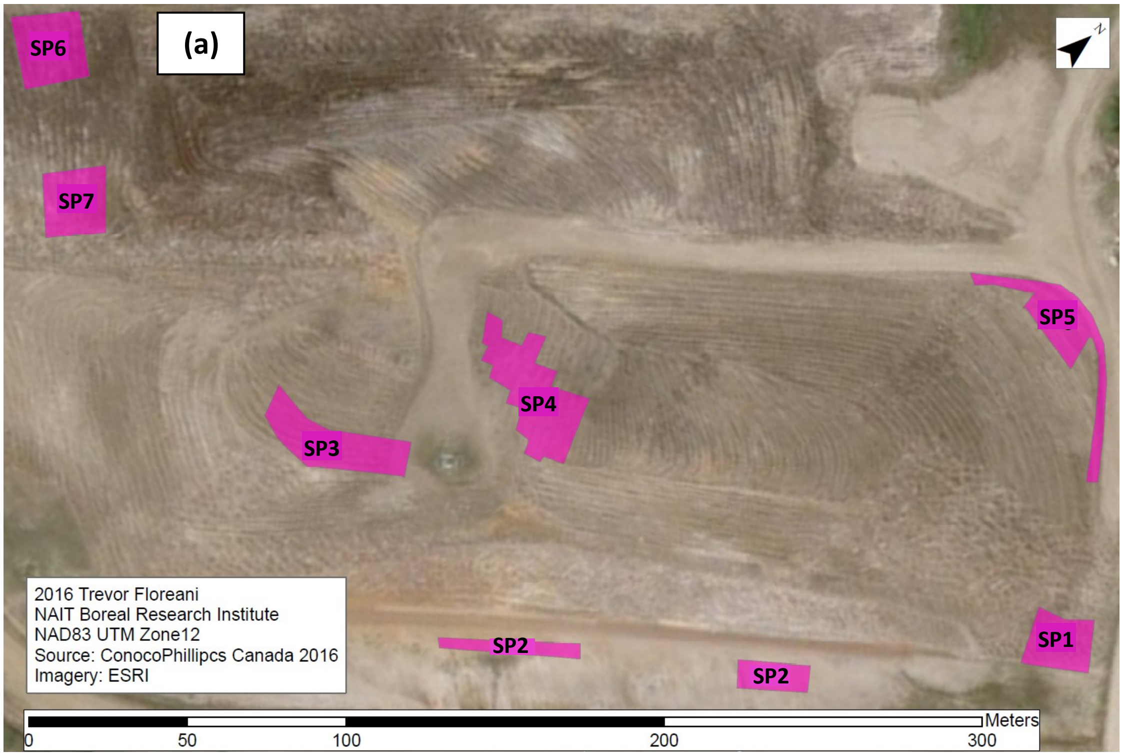


Figure 3-2. Green alder (*Alnus viridis*) biomass was significantly correlated with a) soil temperature high (July) and green alder cumulative (cum.) survivorship was significantly correlated with b) bulk density at 10-15cm depth, c) soil temperature high (July), d) soil temperature low (September), and f) soil moisture high (July). (p<0.1, n=6).

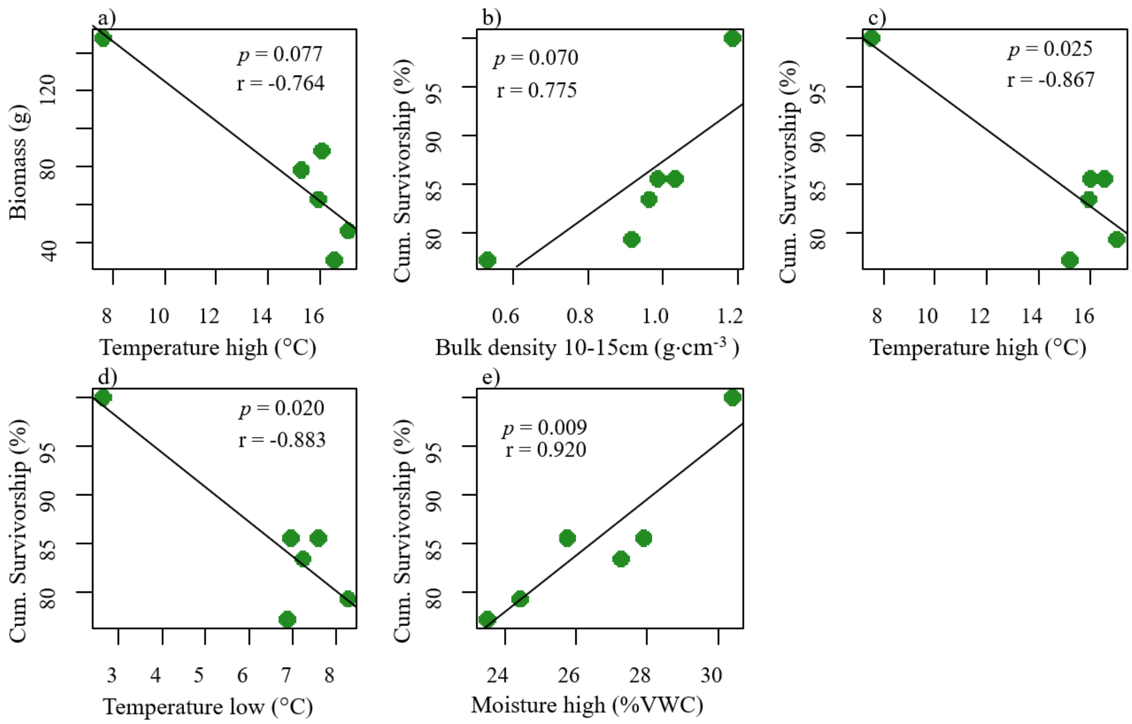


Figure 3-3. Paper birch (*Betula papyrifera*) biomass was significantly correlated with a) pH at 10-15cm depth and b) soil moisture low (May). Paper birch total tree height was significantly correlated with c) total nitrogen, d) LOM, e) pH at 10-15cm depth, and f) woody community vegetation cover. Paper birch cumulative (cum.) survivorship was also significantly correlated with g) soil temperature high (July), h) pH at 10-15cm, and i) total community vegetation cover. (p<0.1, n=10).

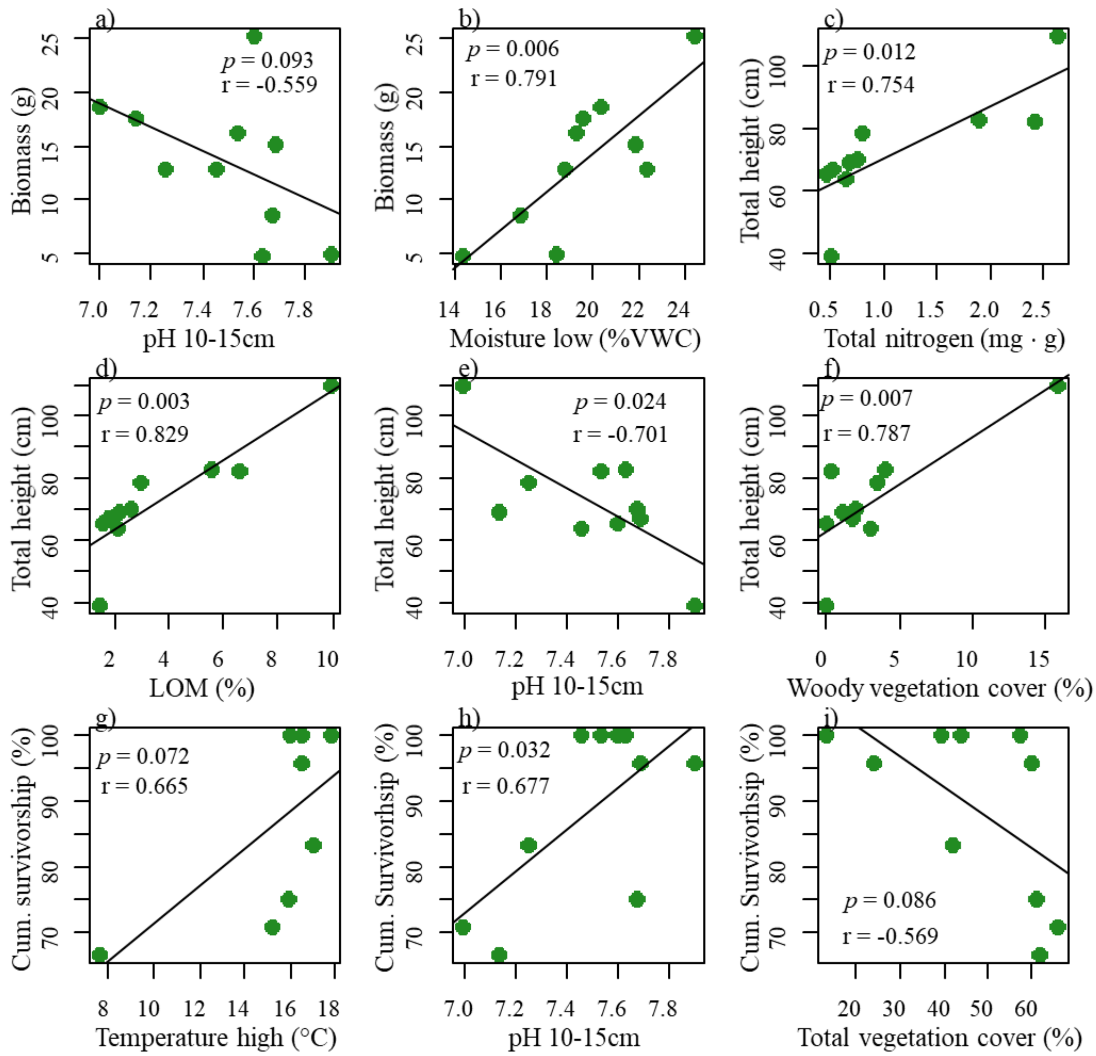


Figure 3-4. Bebb's willow (*Salix bebbiana*) biomass was significantly correlated with a) EC at 10-15cm depth, and b) woody community vegetation cover. Bebb's willow cumulative (cum.) survivorship was significantly correlated with c) electrical conductivity (EC) at 10-15cm depth, d) infiltration, and e) woody community vegetation cover. (p=0.1, n=10).

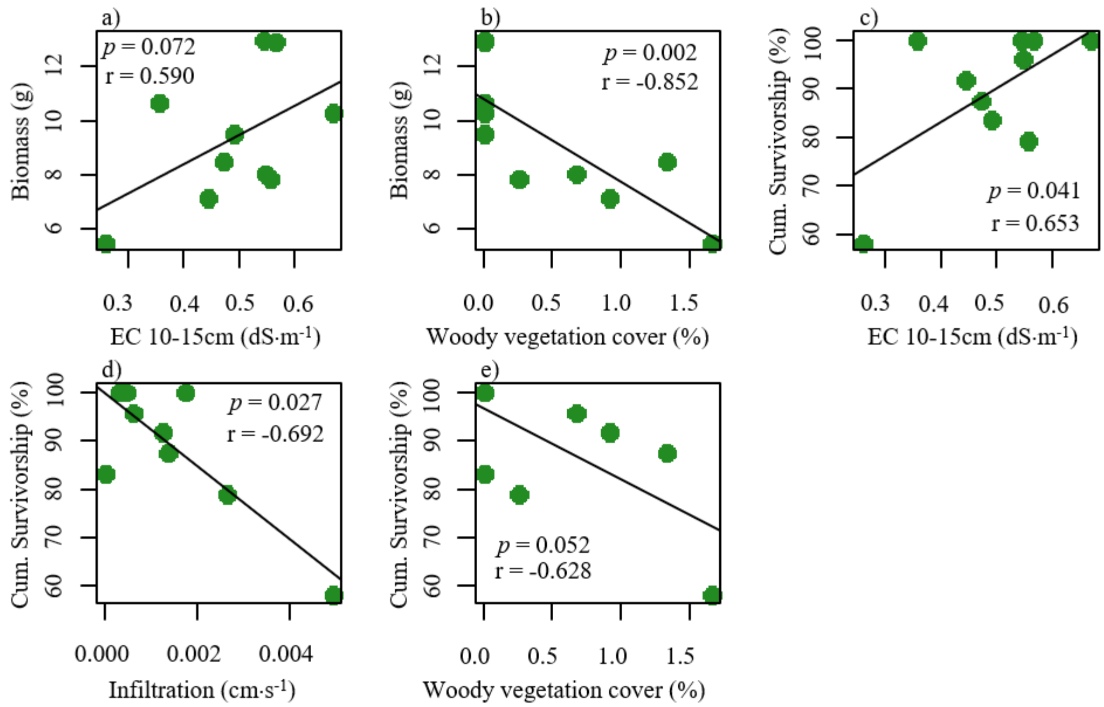


Figure 3-5. White spruce (*Picea glauca*) biomass was significantly correlated with a) labile organic matter (LOM) and b) native forb community vegetation cover. White spruce total tree height was significantly correlated with c) soil temperature low during September, d) LOM as well as e) bulk density at 10-15cm depth. (p<0.1, n=10).

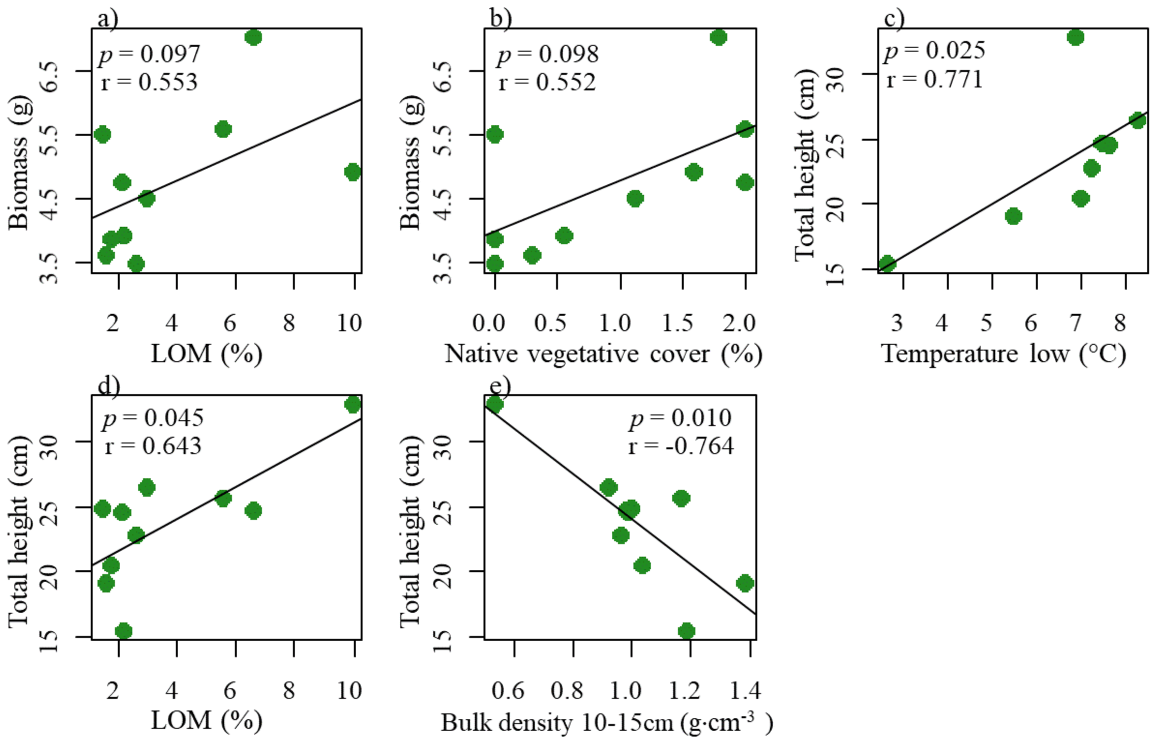


Figure 3-6. Fireweed (*Chamerion angustifolium*) biomass was significantly correlated with a) bulk density at 10-15cm depth, b) pH at 10-15cm depth, c) total community vegetation cover, d) native forb community vegetation cover, and e) woody community vegetation cover. In addition, fireweed cumulative (cum.) presence was significantly correlated with f) bulk density at 10-15cm, g) infiltration, as well as h) woody community vegetation. (*p*<0.1, n=10).

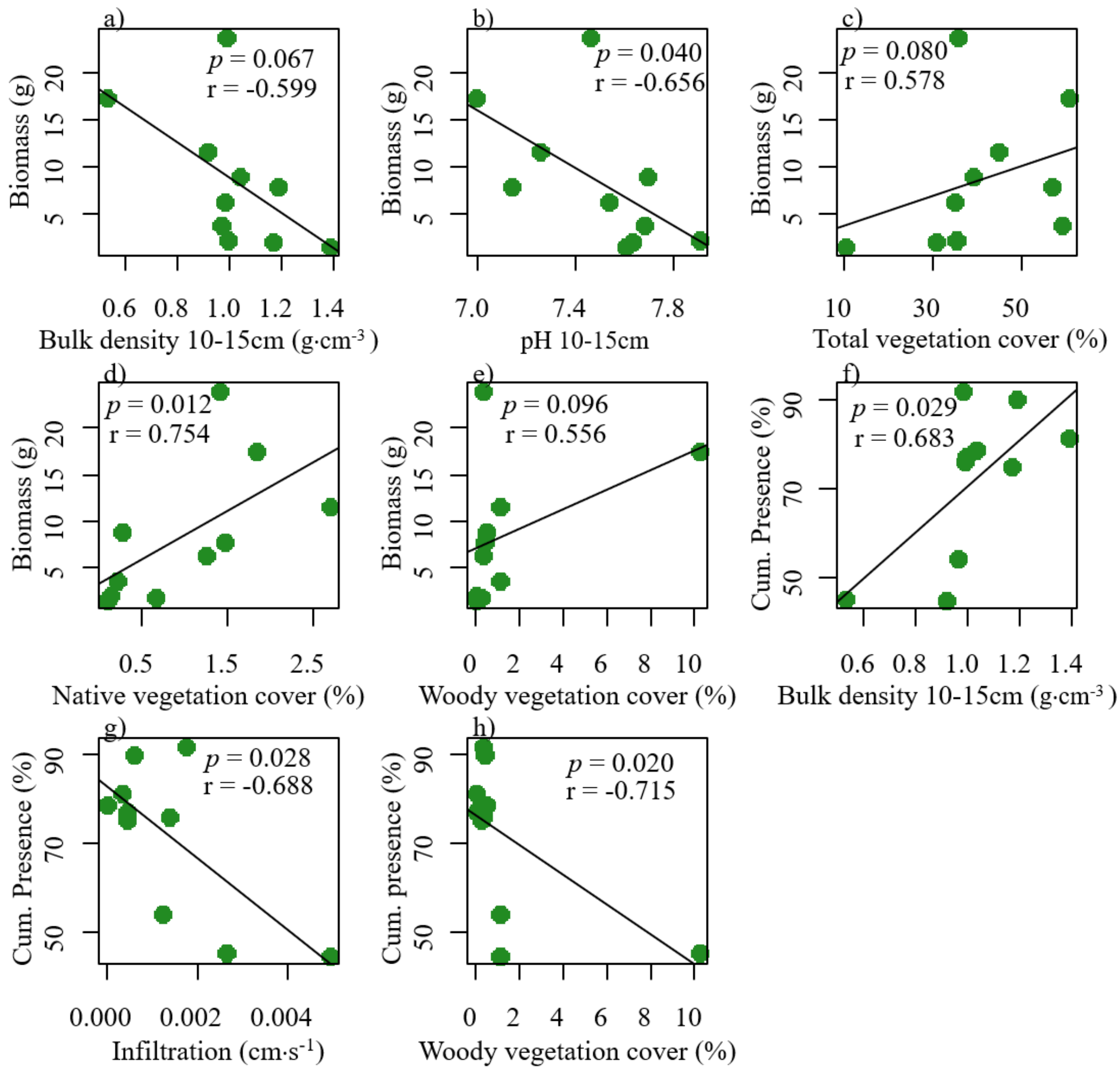
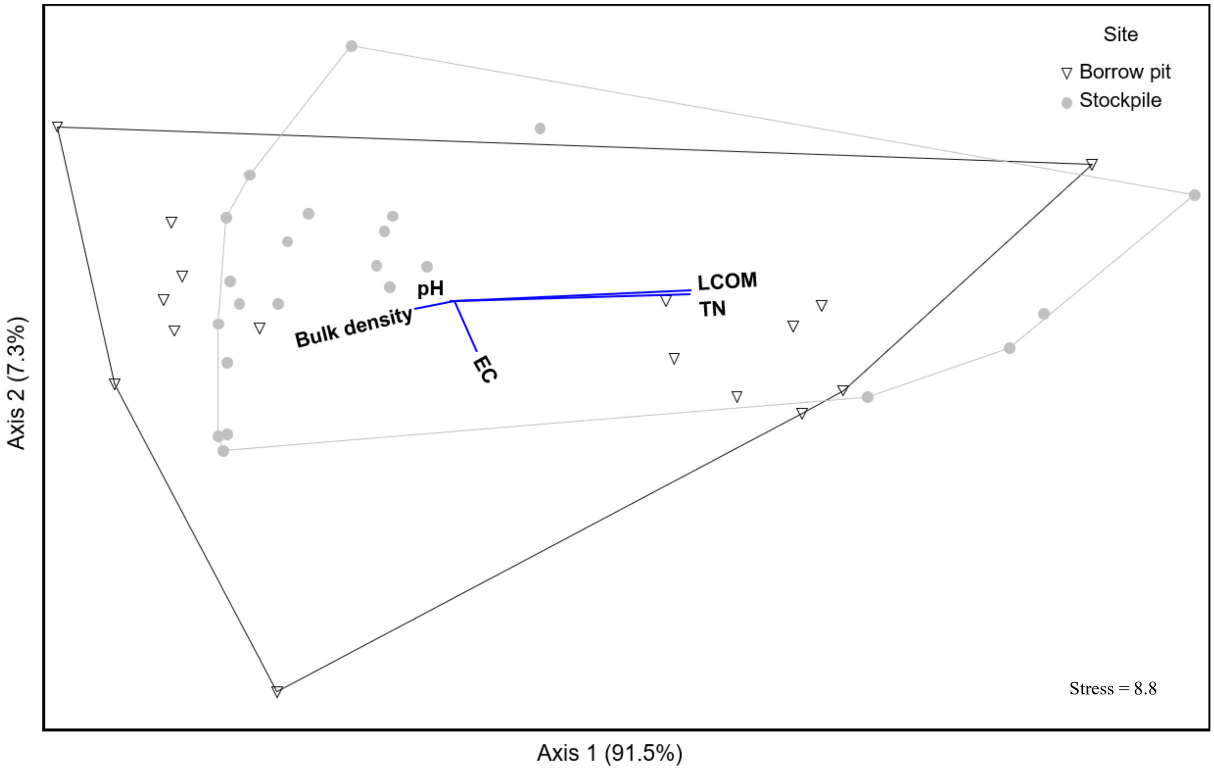


Figure 3-7. Soil properties ordinated with non-metric multidimensional scaling (NMS). Vector length was enhanced by 1000% to better visualize relationships. (n=4).



** pH is acidity. EC is electrical conductivity. TN is total nitrogen. LCOM is labile organic matter.*

4.0 CHAPTER 4 – Technological transfer

4. 1 Introduction

It is agreed that industrial disturbances require human intervention to return the land back to a similar state prior to disturbance (Hobbs and Cramer, 2008; ESRD, 2013). With recent guideline enhancement of requirements for woody density and native herbaceous cover, establishing native herbaceous species remains a challenging reclamation goal (ESRD, 2013; CEMA, 2009). Thus, hitchhiking a native forb to the container with the woody species during seedling production may better support the development of native herbaceous cover as a reclamation tool.

The species used in this study are well understood under natural conditions, yet there is a limited understanding of how these species respond to disturbed or recently reclaimed sites. Although plants can tolerate a wider range of environmental conditions, their growth and survival may be better suited in certain conditions. Green alder, paper birch and Bebb's willow seedlings may be less common to plant at reclamation sites relative to white spruce, jack pine (*Pinus banksiana*), and aspen (*Populus tremuloides*). They have great potential to enhance the process of reclamation and better meet goals of diversity and setting the forest growth trajectory (Native Plant Working Group, 2001; Davies et al., 2017). For example, planting green alder on reclamation sites, with controlled or limited competing vegetation, would contribute to leaf litter, organic matter, soil moisture, and in turn support microbial biomass (Norris, 2013), which results in greater plant available soil nutrients over time (Bot, 2005), ultimately benefiting the development of a forest community.

4. 2 Considerations using hitchhiker seedlings and associated soil conditions

The timing which the forb is sown into the container with the woody species was crucial to the growth and establishment of the hitchhiker plants, especially due to differences in growth rates and life history characteristics. The autecology of each species should be well understood prior to choosing sow dates. Shade tolerant woody species may benefit from quickly growing fireweed, but fireweed has the potential to overtop woody species, especially slow growing conifers (Comeau et al., 1989). Shade intolerant woody species could also be harmed by fast growing fireweed. Thus, ensuring that the woody plant of the hitchhiker seedling has similar height to that of the woody plant grown alone is crucial.

To recap, fireweed (*Chamerion angustifolium*) hitchhiked with green alder (*Alnus viridis*), paper birch (*Betula papyrifera*), Bebb's willow (*Salix bebbiana*), and white spruce (*Picea glauca*) has been shown to successfully grow and establish at a stockpile and reclaimed borrow pit. Although hitchhiker plants and fireweed control did not appear to affect the cover of undesirable species within the local vicinity, native vegetation cover was established through the growth of the hitchhiked fireweed. With greater spread of fireweed in ideal soil conditions, the potential to impact undesirable vegetation remains possible. Of the tested sow dates, at least one sow date was suitable for revegetation, except for paper birch hitchhiked with fireweed which requires further study to optimize this co-grown combination. Recommended sow dates were suggested based on hitchhiker woody and fireweed plants demonstrating similar growth characteristics to the woody or fireweed plant grown alone; thus, 2-week alder, 0-week willow, and 10-week spruce were recommended (Table 4-1).

The 2-week green alder and fireweed hitchhiker seedlings would be best planted at sites with moderate soil moisture and lower bulk density (Table 4-2). Planting shrubs can add desirable forest species and contribute to nutrient cycling with nutrient rich litterfall (Macdonald et al., 2012). Alder have been shown to interact with the establishment of plant communities (Gtari and Dawson, 2011), but this has not been shown in this study and may be shown after a longer period of growth (5 years +).

Willow was proven to be a competitive species during the production of hitchhiker stock. Bebb's willow particularly had overall good height (~50 cm) growth, and cumulative survivorship (~95%), and was unimpeded by being co-grown with fireweed in field conditions, which suggests that Bebb's willow had good revegetation potential provided soil moisture and nutrient stability was ensured. However, Bebb's willow nutrient requirements warrant further investigation as there could be growth limiting micro- or macronutrients. An alternative hitchhiking strategy would be to sow fireweed prior to sowing the willow, by 1 or 2 weeks, to obtain a greater balance of willow and fireweed development; otherwise, sowing a different, more competition tolerant, forb species with willow could be another approach to evaluate in the future.

As mentioned in chapter 2, fireweed sown 1-week prior to paper birch may lead to a more desirable balance of paper birch and fireweed growth characteristics. In addition, paper birch grew best in nutrient rich moist (not saturated or dry) soil conditions where competition was limited. It is recommended to test different forbs hitchhiking with paper birch.

White spruce hitchhiker with fireweed may establish better in looser soils and where native forb vegetation also easily regenerates. However, white spruce also grew well in warm soils and may also benefit from sufficient TN and LOM. It was indicated by Mathison (2018) that showy aster (*Eurybia conspicua*) or fireweed hitchhiked with spruce at a later sow date (10 or 12 weeks) was successfully grown at reclamation sites (Table 4-1) (Mathison, 2018).

Fireweed establishment may be restricted to a certain set of environmental conditions as fireweed was not as prolific as expected (~5% average cover), given the observation in the prior hitchhiker study of fireweed co-grown with white spruce (10-20% average cover) (Mathison, 2018). Fireweed was known to establish in nutrient rich soils (Moss, 1959), but fireweed may grow best in looser soils with moderate moisture where native forb vegetation also easily regenerates. In addition, dry fall planting conditions could have impeded fireweed establishment. The shutdown process in outdoor temperatures may have not been vigorous enough to lead fireweed in complete deep dormancy. Any following activity (transpiration or root growth) could have drained some of the fireweed seedling reserves in dry conditions.

4.2.2 Extending the application with other hitchhiker forbs

The hitchhiker concept should not be limited to the woody species or the single forb (fireweed) tested in this study. Although this study utilized the concept of hitchhiker planting to only a handful of species, there is potential for other forbs and woody species combinations to be successful hitchhiker plants for reclamation. Other species should be considered on a case by case basis as each species has slightly different environmental tolerances and life history characteristics that have implications for successful seedling establishment given favorable site conditions.

Native Plant Working Group (2001) suggested a variety of herbaceous species that could be used for revegetation, such as Canada goldenrod (*Solidego canadensis*) and cream colored peavine (*Lathyrus ochroleucus*). Using native forbs that are found to naturally recolonize reclamation sites would be beneficial as they can tolerate the early successional environmental conditions. For instance, it was found that golden rod (*Solidago sp.*), heart-leaved aster (*Aster divaricatus*), and avens (*Geum canadense*) were found in both forest and reclaimed sites (Holl et al., 2018). Co-growing woody species with a legume may benefit the development of woody species in the container stock as well as lead to establishment of native legumes at reclamation sites. Legumes contribute to nitrogen-rich litterfall and protect young tree seedlings from sunlight and heat during the summer (Peneireiro, 1999; Campos-Filho et al., 2013). A mid-level of legumes has been shown to facilitate decompaction, aeration, and water absorption of the soils (Dubois and Viana, 1994). However, there is also some concern that legumes may outcompete tree species (Dubois and Viana, 1994). Thus, using legumes as hitchhiker forbs must be carefully considered and assessed prior to large scale revegetation applications.

Tall bluebell seedlings were produced for restoration of alpine and subalpine areas of Alaska, USA (Densmore et al., 1990). After one year of growth at the restoration site, tall bluebells were large, vigorous, and flowering (Densmore et al., 1990). It was suggested that the cover could be increased if competition for water and nutrients was reduced (Densmore et al., 1990). Thus, furrowing and tall bluebell hitchhiker seedlings may be a good combination with woody species for hitchhiker seedling production.

4.3 Conclusion

Maximizing the ingress and establishment of native woody and herbaceous species involves a combination of strategies. To start, disturbed sites should be modified to support natural ingress of native woody and herbaceous species. This may involve loosening the soil or creating microsites to support a diversity of species. During the planning process of industrial development, leaving patches of intact forest where possible would supply some native seed sources. Mitigation of competitive grasses and forbs that inhibit the ingress of native species as well as the development of planted seedlings should be considered. Revegetation should include a variety of native woody species, with appropriate densities. However, planted herbaceous seedlings, as hitchhiker seedlings, should be strongly considered if the natural ingress and establishment of native herbaceous forb species is a concern.

4.4 Tables

Table 4-1. Recommended sow dates, or amount of time that woody species grew prior to adding fireweed into the container with woody species, which produced hitchhiker seedlings that were planted at reclamation sites in Alberta thus far. In addition to the 10-week white spruce go-grown with fireweed in this study, Mathison (2018) also suggested 10-week white spruce and fireweed, 12-week white spruce and fireweed, and 10- or 12-week white spruce with Showy aster.

Woody species	Sown with	Recommended sow date
Green alder (*Alnus viridis*)	Fireweed (*Chamerion angustifolium*)	2-weeks
Paper birch (*Betula papyrifera*)	Fireweed (*Chamerion angustifolium*)	-
Bebb's willow (*Salix bebbiana*)	Fireweed (*Chamerion angustifolium*)	0-weeks
White spruce (*Picea glauca*)	Fireweed (*Chamerion angustifolium*)	10-weeks
White spruce (*Picea glauca*)	Fireweed (*Chamerion angustifolium*)	12-weeks
White spruce (*Picea glauca*)	Showy aster (E*urybia conspicua*)	10-12 weeks

Table 4-2. The growth and survivorship responses to soil conditions of singly grown species in field conditions after two years.

Species	Negative response to soil conditions	Positive response to soil conditions
Green alder (*Alnus viridis*)	-	Bulk density, moisture HIGH
Paper birch (*Betula papyrifera*)	pH	Moisture LOW, TN, LOM
Bebb's willow (*Salix bebbiana*)	Infiltration	EC
White spruce (*Picea glauca*)	Bulk density	Temperature LOW, LOM
Fireweed (*Chamerion angustifolium*)	pH, infiltration, bulk density	Bulk density

** pH is acidity. TN is total nitrogen. LOM is labile organic matter.*

REFERENCES

Agriculture and Agri-Food Canada. (2014). Length of growing season in the Prairie Region. Retrieved from http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/climate-change-and-agriculture/future-outlook/climate-change-scenarios/length-of-growing-season-in-the-prairie-region/?id=1363104179472.

Ahlgren, I.F. & Ahlgren, C.E. (1960). Ecological effects of forest fires. *The Botanical Review*, 26(4): 483-533.

Alberta Agriculture and Forestry. (2005). Seed Zones of Alberta (July 2005). Forest Management Branch, Resource Analysis Section. Retrieved from https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/formain15749/$FILE/seed-zones-alberta.pdf.

Alberta Agriculture and Forestry. (2012). Soil moisture and temperature consideration. Retrieved from https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop1272.

Alberta Agriculture and Forestry. (2018). Alberta Information Service, Historical Weather Data. Retrieved from https://agriculture.alberta.ca/acis/township-data-viewer.jsp.

Alberta Energy. (2019a). Oil sands facts and statistics. Retrieved from https://www.alberta.ca/oil-sands-facts-and-statistics.aspx.

Alberta Energy. (2019b). Recovery or extraction. Retrieved from https://www.energy.alberta.ca/OS/AOS/Pages/Recovery.aspx

Alberta Environment. (2010). Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region, 2nd Edition. Prepared by the Terrestrial Subgroup of the Reclamation Working Group of the Cumulative Environmental Management Association, Fort McMurray, Alberta. December 2009.

Ashby, W.C. (1996). Red oak and black walnut growth increased with mine soil ripping. *Int J Mining Reclam Environ*, 10:113–116.

Attiwill, P.M. (1994). The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecology and Management*, 63: 247-300.

Audet, P., Pinno, B.D. & Thiffault, E. (2015). Reclamation of boreal forest after oil sands mining: anticipating novel challenges in novel environments. *Canadian Journal of Forest Research*, 45:364-371. dx.doi.org/10.1139/cjfr-2014-0330.

Baffi, C., Dell'Abate, M.T., Nassisi, A., Silva, S., Benedetti, A., Genevini, P.L. & Adini, F. (2007). Determination of biological stability in compost: A comparison of methodologies. *Soil Biology & Biochemistry*, 39: 1284-1293.

Baligar, V.C., Fageria, N.K. & Elrashidi, M.A. (1998). Toxicity and nutrient constraints on root growth. Proc. Am. Soc. Hortic. Sci. (ASHS) Annu. Conf., 94th, Salt Lake City, Utah, 24 July 1997. *HortScience* 33:960-965.

Bauman, J., Cochran, C., Chapman, J., Gilland, K. (2015). Plant community development following mine restoration treatments on a legacy reclaimed mine site. *Ecological Engineering*, 83: 521-528.

Barbour, M.G., Burk, J.H. & Pitts, W.D. (1987). Terrestrial Ecology. The Benjamin Cummings Publ. Co. Inc., Menlo Park, California. p634.

Barbour, M.G., Burk, J.H., Pitts, W.D., Gilliam, F.S. & Schwartz, M.W. (1999). Terrestrial Plant Ecology, 3rd ed. Benjamin Cummings, Menlo Park, California.

Begon M., Harper, J.L., and Townsend, C.R. (1996). Ecology: Individuals, Populations and Communities, 3rd ed. Blackwell Publ., Oxford, UK., p1068.

Bell, F.W., Kershaw, M., Aubin, I., Thiffault, N., Dacosta, J. & Wiensczyk, A. (2011). Ecology and traits of plant species that compete with boreal and temperate forest conifers: A overview of available information and its use in forest management in Canada. *The Forestry Chronicle*, 87(2), 161-174.

Bell, F.W., Ter-Mikaelian, M.T. & Wagner, R.G. (2000). Relative competitiveness of nine early-successional boreal forest species associated with planted jack pine and black spruce seedlings. *Canadian Journal of Forest Research*, 30(5): 790-800.

Bergeron, Y., Leduc, A., Harvey, B. D. & Gauthier, S. (2002). Natural fire regime: a guide for sustainable management of the Canadian boreal forest. *Silva Fennica* 36, 81–95.

Bloom, A.J., Chapin III, T.S. & Mooney, H.A. (1985). Resource limitation in plants - an economic analogy. *Annual Review of Ecology and Systematics*, 16, 363-392.

Bocso, T., Allen, J.M., Bellemare, J., Kartsz, J., Nishino, M. & Bradley, B.A. (2016). Plants' native distributions do not reflect climatic tolerance. *Diversity and Distributions*, 22: 615-624.

Bosco, M., Buresti, E., Moiroud, A. & Materassi, R. (1991). Biomass production improvement and soil reclamation by nitrogen-fixing actinorhizal plants in two disturbed sites. Proceedings of the International Conferences on biomass for Energy, Industry, and Environment held in Athens, Greece, p 22-26.

Brady, N.C. (1974). The nature and properties of soils, 8^{th} ed. Macmillan, New York.

Brand, D.G. (1991). The establishment of boreal and sub-boreal conifer plantations: An integrated analysis of environmental conditions and seedling growth. *Forest Science*, 37(1): 68-100.

British Columbia (BC) Ministry of Forests. (1998). Provincial Seedling Stock Type Selection and Ordering Guidelines. Ministry of Forests. ISBN 0-7726-3505-6.

Brooker, R.W., Maestre, F.T., Callaway, R.M., Lortie, C.L., Cavieres, l.A., Kunstler, G., Liancourt, P., Tielborger, K., Travis, J.M., Anthelme, F., Armas, C., Coll, L., Crocket, E., Delzon, S., Forey, E., Kikvidze, Z., Oloffsso, J., Pugnaire, F., Quiroz, C., Saccone, P., Schiffers, K., Seifan, M., Touzard, B. & Michalet, R. (2008). Facilitation in plant communities: The past, the present, and the future. *Journal of ecology*, 96(1), 18–34.

Brown, R.L. (2010). Use of woody debris as an amendment for reclamation after oil sands mining. (Unpublished master's thesis). University of Alberta, Edmonton.

Burger, J., Graves, D., Angel, P., Davis, V. & Zipper, C. (2017). The forestry reclamation approach. In: Adams, Mary Beth, (eds.) The Forestry Reclamation Approach: guide to successful reforestation of mined lands. Gen. Tech. Rep. NRS-169. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station: *2-1–2-8.*, 1-8.

Canada's Oil & Natural Gas producers. (2019). Tailings Ponds. Retrieved from https://www.canadasoilsands.ca/en/explore-topics/tailings-ponds.

Comeau, P.G., Watts, S.B., Caza, C.L., Karakatsoulis, J., Thomson, S. & McGee A.B. (1989). Autecology, biology, competitive status and response to treatment of seven southern interior weed species. FRDA Report 093; ISSN 08350572. Victoria, British Columbia: BC Ministry of Forests, Research Branch. 46 p.[9471].

Campos-Filho, E.M., Da Costa, J.N.M.N., De Sousa, O.L. & Junqueira, R.G.P. (2013). Mechanized direct-seeding of native forests in Xingu, Central Brazil. *Journal of Sustainable Forestry*, 32, 7: 702-727.

Carsel, R.F. & Parrish, R.S. (1988). Developing joint probability distributions of soil water retention characteristics. *Water Resources Research*, 24: 755-769.

Callaway, R.M. & Mahall, B.E. (2007). Family roots. *Nature*, 448, 145–147.

Cumulative Environmental Management Association (CEMA). (2006). Land capability classification system for forest ecosystems in the oil sands, 3rd Edition. Alberta.

Como, B.A., L.M. L.avkulich, A.A. Bomke, and J.M. Robbins. 1978. Reclamation of abandoned mine spoils in British Columbia, 1977 - 1978. British Columbia Ministry of Mines and Petroleum Resources, Inspection and Engineering Division. Victoria, British Columbia.

Dahnke, W.C & Whitney, D.A. (1988). Measurement of Soil Salinity. pp. 32-34. In: W.C. Dahnke (ed.) Recommended chemical soil test procedures for the North Central Region. North Dakota Agric. Exp. Stn. Bull. 499.Decagon Devices, Inc. (2012). Mini Disk Infiltrometer User's Manual. DECAGON DEVICES. Washington.

DeLong, S.C. (1991). The light interception index: a potential tool for assisting in vegetation management decisions. *Can. J. For. Res*. 21(7): 1037–1042. doi:10.1139/x91-142.

Densmore, R.V., Dalle-Molle, L. & Holmes, K.E. (1990). Restoration of alpine and subalpine plant communities in Denali National Park and Preserve, Alaska, U.S.A. In: Hughes, HG. and Bonnicksen, T.M., eds. Restoration `89: the new management challenge: Proceedings, 1st annual meeting of the Society for Ecological Restoration; 1989 January 16-20; Oakland, CA. Madison, WI: The University of Wisconsin Arboretum, Society for Ecological Restoration: 509-519. [14720].

Dona, A.J. & Galen, C. (2006). Sources of spatial and temporal heterogeneity in the colonization of an alpine krummholz environment by the weedy subalpine plant Chamerion angustifolium (fireweed). *Canadian Journal of Botany*, 84(6): 933-939.

Dubois, J. C. L. & Viana, V. M. (1994). Da capacidade produtiva da terra. Informativo Agroflorestal, 6(3) editorial.

Dudley, S.A. & File, A.L. (2007). Kin recognition in an annual plant. Biology Letter, 3, 435–438.

Eis, S. (1981). Effects of vegetation competition on regeneration of white spruce. *Canadian Journal of Forest Research,* 11, 1: 1–8. doi:10.1139/x81-001.

Elmarsdottir, A., Aradottir, A.L. & Trlica, M.J. (2003). Microsite availability and establishment of native species on degraded and reclaimed sites. *Journal of Applied Ecology*, 40: 815-823.

Environment and Sustainable Resource Development (ESRD). (2013). 2010 Reclamation Criteria for Wellsites and Associated Facilities for Forested Lands (Updated July 2013). Edmonton, Alberta. 81 pp.

Faget, M., Nagel, K.A., Walter, A., Herrera, J.M., Jahnke, S., Schurr, U. & Temperton, V.M. (2013). Root-root interactions: extending our perspective to be more inclusive of the range of theories in ecology and agriculture using in-vitro analyses. *Annals of Botany*, 112: 253-266.

Fernald, M.L. (1950). Gray's manual of botany. Dudley, Theodore R., gen. ed.; Biosystematics, Floristic & Phylogeny Series; vol. 2. Portland, Oregon: Dioscorides Press. p. 1632.

Fernandez, J.M., Plaza., Polo, A. & Plante, A.F. (2012). Use of thermal analysis techniques (TG-DSC) for the characterization of diverse organic municipal streams to predict biological stability prior to land application.

Fleming, R.L., Powers, R.F., Foster, N.W., Kranabetter, J.M., Scott, D.A., Ponder, F., Berch, S., Chapman, W.K., Kabzems, R.D., Ludovici, K.H., Morris, D.M., Page-Dumroese, D.S., Sanborn, P.T., Sanchez, F.G., Stone, D.M. & Tiarks, A.E. (2006). Effects of organic metter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of long-term soil productivity sites. *Canadian Journal of Forest Research*, 36: 529-550.

Foote, M.J. (1983). Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. Res. Pap. PNW-307. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 108 p. [7080].

Fowells, H.A & Krauss, R.W. (1959). The inorganic nutrition of loblolly pine and virginia pine with special reference to nitrogen and phosphorus. *Forest Science*, 5: 95-112.

Fu, B., Liu, S., Ma, K. & Zu, Y.J. (2004). Relationships between soil characteristics, topography and plant diversity in a heterogenous deciduous broad-leaved forest near Beijing, China. *PlantandSoil*, 261(1):47-54.

Gatherum, G.G., McComb, A.L. & Loomis, W.E. (1963). Effects of light and soil moisture on forest tree seedling establishment, Agricultural and home economics experiment station Iowa State university of Science and Technology, Research bulletin 513, p796-792.

Grant, J., Huot, M., Lemphers, N., Dyer, S. & Dow, M. (2013). Beneath the surface: a review of key facts in the oilsands debate. The Pembina Foundation and The Pembina Institute. Retrieved from: https://www.pembina.org/reports/beneath-the-surface-oilsands-facts-201301.pdf.

Grossnickle S.C. (2000). Ecophysiology of northern spruce species: the performance of planted seedlings. NRC Research Press, Ottawa, p409.

Gtari, M. & Dawson J.O. (2011). An overview of actinorhizal plants in Africa. *Functional Plant Biology*, 38(8): 653–661.

Government of Alberta. (2010). Weed control act. Statutes of Alberta 2008. Chapter W-5.1. Current as of June 17, 2010. Alberta Queens Printer.

Gutschick, V.P. (1978). Energy and nitrogen fixation. *BioScience*, 28:571-575.

Gutschick, V.P. & BassiriRad, H. (2003). Extreme events as shaping physiology, ecology, and evolution of plants: toward a unified definition and evaluation of their consequences. *New Phytologist*, 160, 21–42.

Haeussler, S., Coates, D. & Mather, J. (1990). Autecology of common plants in British Columbia: a literature review. British Columbia Ministry of Forests and Lands, Victoria, British Columbia, FRDA Report No. 158.

Hangs, R.D., Knight, J.D. & Rees, K.C.J.V. (2002). Interspecific competition for nitrogen between early successional species and planted white spruce and jack pine seedlings. *Canadian Journal of Forest Research*, 32: 1813-1821.

Harris, J.A. & Birch, P. (1989). Soil microbial activity in opencast coal mine restorations. *Soil Use and Management*, 5(4): 155-160.

Hobbie, S.E. & Chapin III, S. (1998). An experimental test of limits to tree establishment in Arctic tundra. *Journal of Ecology*, 86: 449-461.

Hobbs, R.J. & Cramer, V.A. (2008). Restoration Ecology: Interventionist approaches for restoring and maintaining ecosystem function in the face of rapid environmental change. *Annual Review of Environment and Resources*, 33:39-61.

Howat, D. R. (2000). Acceptable salinity, sodicity and pH values for boreal forest reclamation. Alberta Environment, Environmental Sciences Division Report ESD/LM/00-2. Edmonton, Canada.

Ilisson, T. & Chen, H.Y.H. (2009). Response of six boreal tree species to stand replacing fire and clearcutting. *Ecosystems*, 12: 820-829. doi: 10.1007/s10021-009-9259-z.

Ingestad, T. (1959). Studies on the nutrition of forest tree seedlings. II. Mineral nutrition of spruce. Physiol. Plant, 12: 568-593.

Johnson, D., Kershaw, L., MacKinnon, A. & Pojar, J. (1995). Plants of the Western Forest. Lone Pine Publishing and the Canadian Forest Service, 2311-96 Street, Edmonton, Alberta.

Kennedy, B.A. (1990). Surface Mining (2nd Ed). Society for Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado.

Kern, C.C., Montgomery, R.A., Reich, P.B. & Strong, T.F. (2014). Harvest-created canopy gaps increase species and functional trait diversity of the forest ground-layer community. *Forest Science*, 60, 335–344.

Kew, G.A., Mengler, F.C. & Gilkes, R.J. (2007) Regolith strength, water retention, and implications for ripping and plant root growth in bauxite mine restoration. *Restoration Ecology,* 15: S54–S64.

Konishi, S. & Kitagawa, G. (2008). Information criteria and statistical modeling. Springer, New York, NY, p 1-104.

Kost, D.A. Vimmerstedt, J.P. & Brown, J.H. (1998). Topsoiling, ripping, and fertilizing effects on tree growth and nutrition on calcareous minesoils. *Forest Ecology and Management*, 103: 307–319.

Kreutweiser, D.P., Hazlett, P.W. & Gunn, J.M. (2008). Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: A review. Environmental Reviews, 16: 157-179.

Lambers, H. & Poorter, H. (1992). Inherent variation in growth rate between higher plants: a search for physiological causes and ecological consequences. *Advances in Ecological Research*, 34: 187-261. doi 10.2016/S0065-2504(03)34004-8.

Landhausser, S.M. (2009). Impact of slash removal, drag scarification, and mounding on lodgepole pine cone distribution and seedling regeneration after cut-to-length harvesting on high elevation sites. *Forest Ecology and Management*, 258, 1: 43-49.

Landhäusser, S.M. & Lieffers, V.J. (1994). Competition between *Calamagrostis canadensis* and *Epilobium angustifolium* under different soil temperature and nutrient regimes. *Canadian Journal of Forest Research*, 24(11), 2244–2250. doi:10.1139/x94-288.

Landhäusser, S.M., Stadt, K.J. & Lieffers, V.J. (1996). Competition between *Calamagrostis canadensis* and three replacement species at different densities and times of seeding. *Journal of Applied Ecology*, 33, 1517–1526.

Lanoue, A. & C. Qualizza. (2000). LFH and shallow mineral horizons as inoculants on reclaimed areas to improve native species catch. 1999 Status Report. Syncrude Canada Ltd., Fort McMurray, Alberta.

Larney, F.J. & Angers, D.A. (2011). The role of organic amendments in soil reclamation: A review. *Canadian Journal of Soil Science*, 92, 1: 19-38.

Le, K. (2017). Evaluating trembling aspen seedling stock characteristics in response to outplanting and competition. (Unpublished masters thesis). University of Alberta, Edmonton, Alberta.

Leak, W.B. (1978). Relationship of species and site index to habitat in the White Mountains of New Hampshire. USDA Forest Service, Research Paper NE-397. Northeastern Forest Experiment Station, Broomall, PA. 9 p.

Lieffers, V.I., MacDonald, S.E. & Hogg, E.H. (1993). Ecology of and control strategies for Calamagrostis-canadensis in boreal forest sites. *Canadian Journal of Forest Research*, 23, 2070–2077.

Lieffers, V. J. & Sidders, D. (2009). Spruce and aspen regeneration following variable retention harvests at EMEND. Edmonton: Sustainable Forest Management Network Ecosystem Management Emulating Natural Disturbance (EMEND) project.

Lieffers, V.J. & Stadt, K.J. (1994). Growth of understory *Picea glauca*, *Calamagrostis canadensis*, and *Epilobium angustifolium* in relation to overstory light transmission. *Canadian Journal of Forest Research,* 24(6): 1193–1198. doi:10.1139/x94-157.

Leatherdale, J.D. (2008). Soil moisture and nutrient regimes of reclaimed upland slopes in the oil sands region of Alberta. (Unpublished master's thesis). University of Alberta, Edmonton, Alberta.

Lenth, R. (2018). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.1.

Lof, M., Dey, D.C., Navarroo, R.M. & Jacobs, D.F. (2012). Mechanical site preparation for forest restoration. *New Forests*, 43:825-848. doi: 10.1007/s11056-012-9332-x

Mathison, A.L. (2018). Improving forb establishment and restoring soil function in disturbed landscapes: Hitchhiker native forbs with white spruce. (Unpublished master's thesis). University of Alberta, Edmonton, Alberta.

Matinez-Albrain, A. (2008). Statistical significance and biological relevance: A call for a more cautious interpretation of results in ecology. ACTA. *Oecologica*, 34: 9-11.

Matsushima, M. & Chang, S.X. (2006). Vector analysis of understory competition, N fertilization, and litter layer removal effects on white spruce growth and nutrition in a 13-year-old plantation. *Forest Ecology Management*, 236, 332–341.

Maundrell, C. & Hawkins, C. (2004). Use of an aspen overstory to control understory herbaceous species, bluejoint grass (Calamagrostis canadensis) and fireweed (Epilobium angustifolium). *Northern Journal of Applied Forestry*, 21, 74–79.

Macdonald, S.E., Quideau, S.A. & Landhäusser, S.M. (2012). Rebuilding boreal forest ecosystems after industrial disturbance. In Restoration and reclamation of boreal ecosystems: attaining sustainable development. Edited by D.H. Vitt and J.S. Bhatti. Cambridge University Press.

McCune, B. & M. J. Mefford. (2011). PC-ORD. Multivariate Analysis of Ecological Data. Version 6.0. MjM Software, Gleneden Beach, Oregon.

McCune, B., Grace, J.B. & Urban, D.L. (2002). Analysis of Ecological Communities. MjM software design. Gleneden Beach, Oregon.

MacKinnon, M.D. & Sethi, A. (1993). A comparison of the physical and chemical properties of the tailings ponds at the Syncrude and Suncor oil sands plants. *In* Proceedings of Our Petroleum Future Conference, Alberta Oil Sands Technology and Research Authority (AOSTRA), Edmonton, Alberta.

McKenzie, N.J., Jacquier, D.J., Isbell, R.F. & Brown, K.L. (2004). Australian Soils and Landscapes An Illustrated Compendium. CSIRO Publishing: Collingwood, Victoria.

Messier, C., Coll, L., Poitras-Lariviere, A., Belanger, N. & Brisson, J. (2009). Resource and non-resource root competition effects of grasses on early- versus late-successional trees. *Journal of Ecology*, 97, 548-554. doi: 10.1111/j.1365-2745.2009.01500.x.

Millward, A.A., Paudel, K. & Briggs, S.E. (2011). Naturalization as a strategy for improving soil physical characteristics in a forested urban park. *Urban Ecosystems*, 14: 261-278.

Moss, E. (1959). Flora of Alberta. Second Edition. University of Toronto Press Incorporated 1983, 1994. Toronto, Ontario, p448-449.

Mosseler, A., Major, J.E. & Labrecque, M. (2014). Growth and survival of seven native willow species on highly disturbed coal mine sites in eastern Canada. *Journal of Forest Research*, 44: 340-349.

Mudrak, O., Hermova, M., Tesnerova, C., Rydlova, J. & Frouz, J. (2016). Above-ground and below-ground competition between willow *Salix caprea* and its understory. *Journal of Vegetation Science*, 27, 156-164. doi: 10.1111/jvs.12330.

Mummey, D.L. Stahl, P.D. & Buyer, J.S. (2002). Soil microbiological properties 20 years after surface mine reclamation: spatial analysis of reclaimed and undisturbed sites. *Soil Biology and Chemistry*, 34 (11): 1717–1725. doi:10.1016/s0038-0717(02)00158-x.

Native Plant Working Group. (2001). Native plant revegetation guidelines for Alberta. Alberta Agriculture, Food and Rural Development. Edmonton, Alberta.

Natural Resources Canada. (2016). Oil sands extraction and processing. Retrieved from https://www.nrcan.gc.ca/energy/oil-sands/18094.

Natural Resources Canada. (2019). Minerals and Metals Facts. Retrieved from https://www.nrcan.gc.ca/mining-materials/facts/20507

Newton, M., Cole, E.C. & White, D.E. (1993). Tall planting stock for enhanced growth and domination of brush in the Douglas-fir region. *New Forests*. 7, 107–121.

Nix, P.G. & Martin, R.W. (1982). Detoxification and reclamation of Suncor's oil san tailings ponds. *Environmental Toxicology and Water Quality: An international Journal*, 7: 171-188.

Noland, T.L., Mohammed, G.H. & Wagner, R.G. (2001). Morphological characteristics associated with tolerance to competition from herbaceous vegetation for seedlings of jackpine, black spruce, and white pine. *New Forests*, 21: 199-215.

Norris, C. (2013). Soil organic matter cycling in novel and natural boreal forest ecosystems. (Unpublished master's thesis). University of Alberta, Edmonton, Alberta.

O'Brien, E. & Brown, J.S. (2008). Games roots play; effects of soil volume and nutrients. *Journal of Ecology*, 96, 438–446.

Oil Sands Magazine. (2019). Oil sands 101: process overview. Retrieved from https://www.oilsandsmagazine.com/technical/oilsands-101.

Pembina. (2019). Mining vs In Situ. Retrieved from https://www.pembina.org/reports/mining-vs-in-situ.pdf.

Peneireiro, F. M. (1999). Sistemas agroflorestais dirigidos pela sucessão natural: Um Estudo de Caso (Unpublished master's thesis). São Paulo University, Piracicaba, SP, Brazil.

Perry, L. (2003). pH for the garden. University of Vermont Extension, Vermont, USA.

Pinno, B.D., Lanhausser, S.M., Chow, P.S., Quideau, S.A. & MacKenzie, M.D. (2013). Nutrient uptake and growth of fireweed (*Chamerion angustifolium*) on reclamation soils. *Canadian Journal of Forest Research*, 44, 1-7.

Pinto, J.R., Marshall, J.D. Dumroese, R.K., Davis, A.S. & Cabos, D.R. (2011). Establishment and growth of container seedlings for reforestation: A function of stocktype and adaphic conditions. *Forest Ecology and Management*, 261: 1876-1884.

Poveda, C.A. & Lipsett, M.G. (2013). The Canadian oil sands: environmental, economic, social, health, and other impacts. *WIT Transactions on Ecology and The Environment*, 173: 575-587.

Province of Alberta. (2016). Environmental Protection and Enhancement Act - Conservation and reclamation regulation. Alberta Queen's Printer, Edmonton, Alberta.

Petroleum Services Association of Canada (PSAC). (2019). Conventional vs. unconventional resources. Retrieved from https://oilandgasinfo.ca/patchworks/conventional-vs-unconventional-resources/.

R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from https://www.R-project.org/.

Radosevich, S.R., Holt, J.S. & Ghera, C.M. (1997). Ecology of weeds and invasive plants: relationships to agriculture and natural resource management, 3rd ed. Wiley & Sons, Inc., Hoboken, NJ. 454p.

Rhoades, J.D. (1996). Salinity: electrical conductivity and total dissolved solids. In: D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, editors, Methods of Soil Analysis, Part 3 - Chemical Methods, SSSA Book Series no.5.3. Madison, WI. p. 417-435.

Rietveld, W.J. (1989). Transplanting stress in bareroot conifer seedlings: its development and progression to establishment. *Northern Journal of Applied Forestry*, 6, 99–107.

Richards, R.T., Chambers, J.C. & Ross, C. (1998). Use of native plants on federal lands: Policy and practice. *Journal or Range Management*, 51: 625-632.

Robinson, D.E., Wagner, R.G., Bell, F.W., and Swanton, C.J. 2001. Photosynthesis, nitrogen-use efficiency, and water-use efficiency of jack pine seedlings in competition with four boreal forest plant species. *Canadian Journal of Forest Research,* 31: 2014–2025.

Rooney, R.C., Bayley, S.E. & Schindler, D.W. (2012). Oil sands mining and reclamation cause massive loss of peatland and stored carbon. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 109, 13: 4933-4937.

Rose, R., Carlson, W.C. & Morgan, P. (1990). The target seedling concept. IN: Target Seedling Symposium: Proceedings, Combined Meeting of the Western Forest Nursery Associations; 1990 August 13-17; Roseburg, Oregon. Gen. Tech. Rep. RM-200. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 286 p.

Rose, R., Haase, D.L., Kroiher, F. & Sabin, T. (1997). Root volume and growth of ponderosa pine and Douglas-fir seedlings: a summary of eight growing seasons. *Western Journal of Applied Forestry,* 12, 69–73.

Rowe, J.S. (1972). Forest Regions of Canada. Dep. Environ., Canadian Forest Services, Ottawa, Ontario Publications. 1300. 172 p.

Rowland, S.M. (2008). Recreating a functioning forest soil in reclaimed oil sands in northern Alberta. (Unpublished master's thesis). University of British Columbia, British Columbia.

Schlatzer, G. (1973). Some experiments with various species in Danish reclamation work. Pages 33-64 IN: R.J. Hutnik and G. Davis, eds. Ecology and reclamation of devastated land, volume 2. Proceedings of a N.A.T.O. Advanced Study Institute on the Ecology and Revegetation of Drastically Disturbed Areas, Pennsylvania State University. Gordon and Breach Scientific Publications. New York.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kogel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S. & Trumbore, S. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478: 49-56.doi:10.1038/nature10386.

Schwartz, R.C., Baumhardt, R.L. & Evett, S.R. (2010). Tillage effects on soil water redistribution and bare soil evaporation throughout a season. *Soil and Tillage Research*, 110(2), 221-229.

Semchenko, M., John, E.A. & Hutchings, M.J. (2007). Effects of physical connection and genetic identity of neighbouring ramets on root-placement patterns in two clonal species. *New Phytologist*, 176, 644–654.

Sloan J.L. & Jacobs D.F. (2013). Fertilization at planting influences seedling growth and vegetative competition on a post-mining boreal reclamation site. *New Forests*, 44, 687–701.

Smreciu, E.A. & Gould, K. 2015. Field emergence of native boreal forest species on reclaimed sites in northeastern Alberta. *Native Plants Journal,* 16(3):204–226.

Society for Ecological Restoration International Science & Policy Working group. (2004). The SER International Primer on Ecological Restoration. Tucson, AZ: Soc. Ecol. Restor. Int.

Sparks, D.L., Page, A.L., Helmke, P.A. & Loeppert, R.H. (editors). (1996). Methods of Soil Analysis Part 3—Chemical Methods. SSSA Book Ser. 5.3. SSSA, ASA, Madison, WI. doi:10.2136/sssabookser5.3.frontmatter.

Stachowicz, J.J. (2001). Mutualism, facilitation, and the structure of ecological communities: Positive interactions play a critical, but underappreciated, role in ecology communities by reducing physical or biotic streses in existing habitats and by creating new habitats on which many species depend. *BioScience*, 51(3), 235-246.

Stocks, B.J., Wotton, B.M., Flannigan, M.D., Fosberg, M.A., Cahoon, D.R. & Goldammer, J.G. (2001). Boreal forest fire regimes and climate change. Kluwer Academic Publishers, Netherlands.

Taiz, L. & Zeiger, E. (2002). Plant physiology, 3rd ed. Sinaur Associates, Inc., Massachusetts.

Tamm, C.O. (1991). Nitrogen in terrestrial ecosystems, ecological studies, no 81. Springer, Berlin.

Thom, D. & Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperature and boreal forests. *Biological Reviews*, 91: 760-781.

Thompson, K., Parkinson, J.A., Band, S.R. & Spencer, R.E. (1997). A comparative study of leaf nutrient concentrations in a regional herbaceous flora. *The New Phytologist*, 136, 4: 679-689.

Toivio, J., Helmisaari, H., Palvianinen, M., Lindeman, H., Ala-Ilomaki, J., Siren, M. & Uusitalo, J. (2017). Impacts of timber forwarding on physical properties of forest soils in southern Finland. *Forest Ecology and Management,* 405:22-30.

Tordoff, G.M., Baker, A.J.M. & Willis, A.J. (2000). Current approaches to the revegetation and reclamation of metalliferous mine wastes. *Chemosphere*, 41:219-228.

Van der Weele, C. M., Spollen, W. G., Sharp, R. E. & Baskin, T. I. (2000). Growth of Arabidopsis thaliana seedlings under water deficit studied by control of water potential in nutrient-agar media. *Water Deficits and Plant Growth*, 51(350), 1555-1562.

Viereck, L.A. (1970). Forest succession and soil development adjacent to the Chena River in interior Alaska. *Arctic, Antarctic, and Alpine Research,* 2(1): 1-26.

Visser, S., Griffiths, C.L. & Parkinson, D. (1983). Effects of surface mining on the microbiology of a prairie site in Alberta, Canada. *Canadian Journal of Soil Science*, 63(2): 177-189.

Volk, T.A. & Kuzovkina, Y.A. (2009). The characterization of willow (Salix L.) varieties for the use in ecological engineering applications: Coordination of structure, function and autecology. *Ecological Engineering*, 35, 8: 1178-1189.

Werner, R.A. & Holsten, E.H. (1982). Mortality of white spruce during a spruce beetle outbreak on the Kenai Peninsula in Alaska. *Canadian Journal of Forest Research,* 13, 96–101.

Whitson, I.R., Abboud, S., Prepas, E.E. & Chanasyk, D.S. (2005). Hydraulic properties of Orthic Gray Luvisolic soils and impact of winter logging. Journal of Environmental Engineering and Science. 2(Suppl. 1): S41-S49. doi: 10.1139/s03-033.

Winterhalder, K. (1978). pH and phosphorus as factors limiting plant establishment on the industrially denuded soils of the Sudbury area, Ontario, Canada. Presented at a joint meeting of the British Ecological Society (Industrial Ecology Group) and the British Soil Science Society entitled "Soil-Plant Relationships in the Reclamation of Derelict Land". University of York, U.K.

Yarmuch, M. (2003). Measurement of soil physical parameters to evaluate soil structure quality in reclaimed oil sands oils, Alberta, Canada. (Unpublished master's thesis). University of Alberta, Edmonton, Alberta.

Yoccoz, N. G. (1991). Use, overuse, and misuse of significance tests in evolutionary biology and ecology. *Bulletin of the Ecological Society of America,* 72: 106–111.

Zipper, C.E., Burger, J.A., Skousen, J.G., Angel, P.N., Barton, D., Davis, V. & Franklin, J.A. (2011). Restoring forests and associated ecosystem services on Appalachian coal surface mines. *Environmental management,* 47:751–765.

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal*, 61: 1024-1030.

Zhang, B., Yang, Y. & Zepp, H. (2004). Effect of vegetation restoration on soil and water erosion and nutrient losses to a severely eroded clayey Plinthudult in southeastern China. *Elsevier*, 57: 77-90.

APPENDICES

APPENDIX 1 (Chapter 2)

Figure A1.1. Green alder (Ga) (*Alnus viridis*) and fireweed (Fw) (*Chamerion angustifoloium*) nursery stock sown April 7, 2016 and photographed June 3, 2016: (a) Fw control, (b) Ga control, (c) Ga+Fw 0 week, (d) Ga+Fw 2 week, (e) Ga+Fw 4 week. *Photo credit: Çağdaş Kera Yücel*.

Figure A1.2. Paper birch (Bw) (*Betula papyrifera*) and fireweed (Fw) (*Chamerion angustifoloium*) nursery stock sown April 7, 2016 and photographed June 10, 2016: (a) Fw control, (b) Bw control, (c) Bw+Fw 0 week, (d) Bw+Fw 2 week, (e) Bw+Fw 4 week. *Photo credit: [Çağdaş Kera Yücel](#)*.

(a)

(b)

(c)

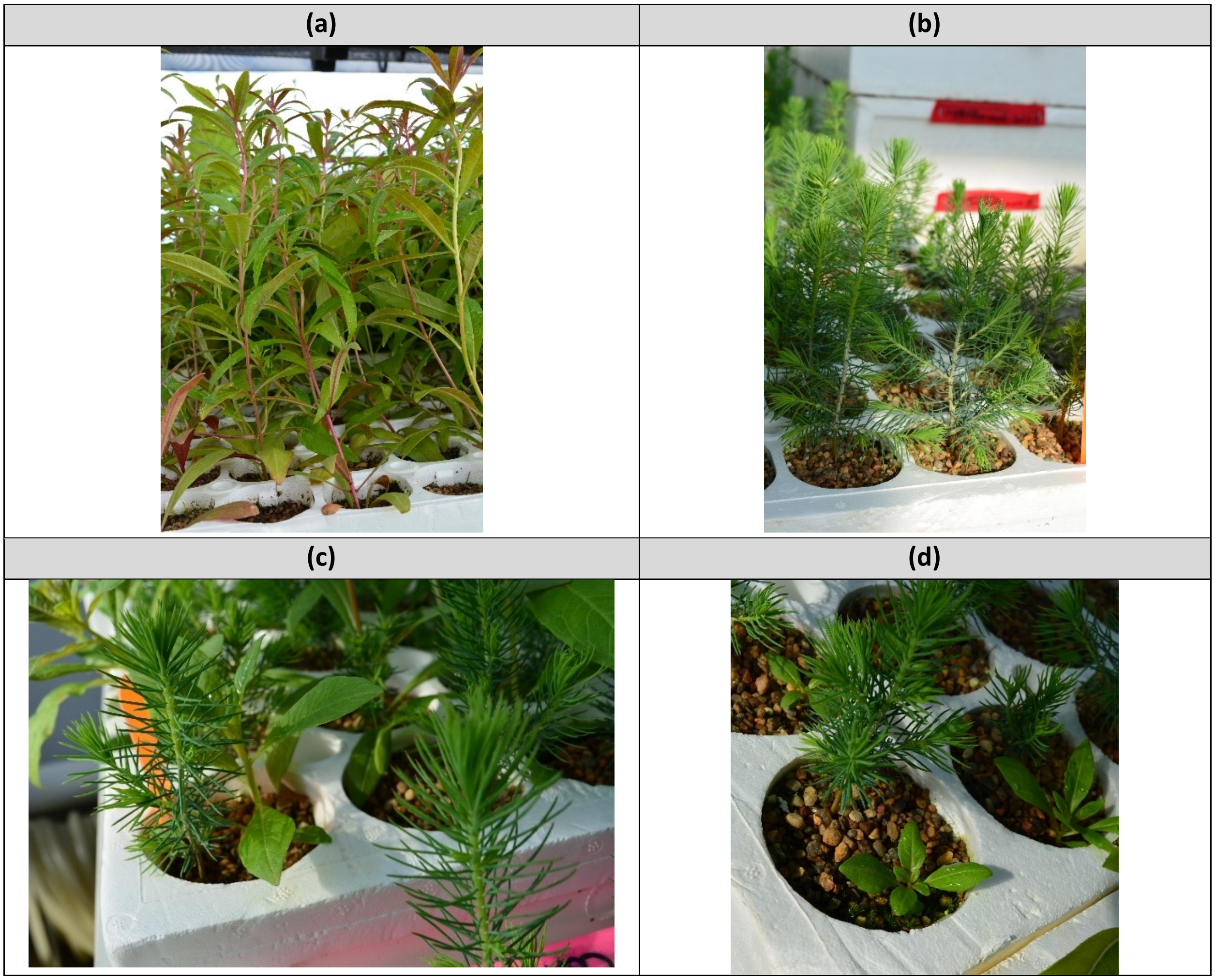
(d)

(e)

Figure A1.3. Bebb's willow (Sx) (*Salix bebbiana*) and firerweed (Fw) (*Chamerion angustifoloium*) nursery stock sown April 7, 2016 and photographed June 3, 2016: (a) Fw control, (b) Sx control, (c) Sx+Fw 0 week, (d) Sx+Fw 2 week, (e) Sx+Fw 4 week. *Photo credit: Çağdaş Kera Yücel*.

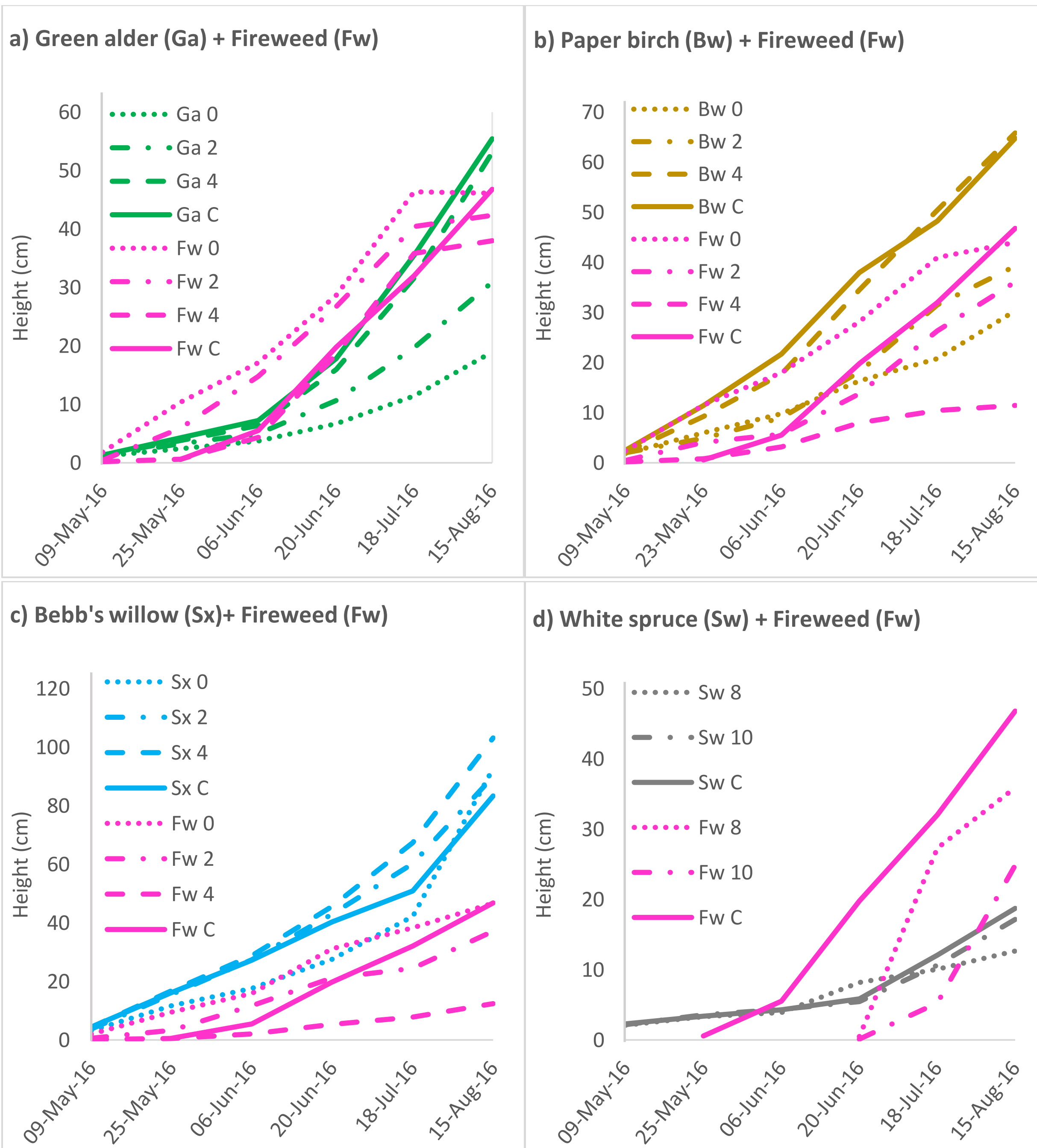
(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A1.4. White spruce (Sw) (*Picea glauca*) and firerweed (Fw) (*Chamerion angustifoloium*) nursery stock sown April 7, 2016 and photographed July 7, 2016: (a) Fw control, (b) Sw control, (c) Sw+Fw 8 week, (d) Sw+Fw 10 week. *Photo credit: Çağdaş Kera Yücel*.



APPENDIX 2 (Chapter 2)

Average height during the production of nursery hitchhiker stock from May 9 to August 15, 2016. Fireweed (*Chamerion angustifolium*) was co-grown with a) green alder (*Alnus viridis),* b) paper birch (*Betula papyrifera*), c) Bebb's willow (*Salix bebbiana*), and d) white spruce (*Picea glauca*). Sow dates of fireweed sown with deciduous woody species included included same time (0wk), fireweed sown with woody species 2 weeks (2wk) and 4 weeks (4wk) later. Fireweed was sown later with white spruce at 8- and 10-weeks. In addition, fireweed and woody plants were grown alone (C).



APPENDIX 3 (Chapter 2)

Figure A3.1. Average root biomass per cavity and average root length per cavity of hitchhiker nursey stock for each plant in the container, which included **green alder** (*Alnus viridis*) and fireweed (*Chamerion angustifolium*). Fireweed was sown with green alder at the same time (0W), 2 weeks (2W) and 4 weeks (4W) later. Fireweed (Fw) and green alder (Ga) were also grown alone (C).

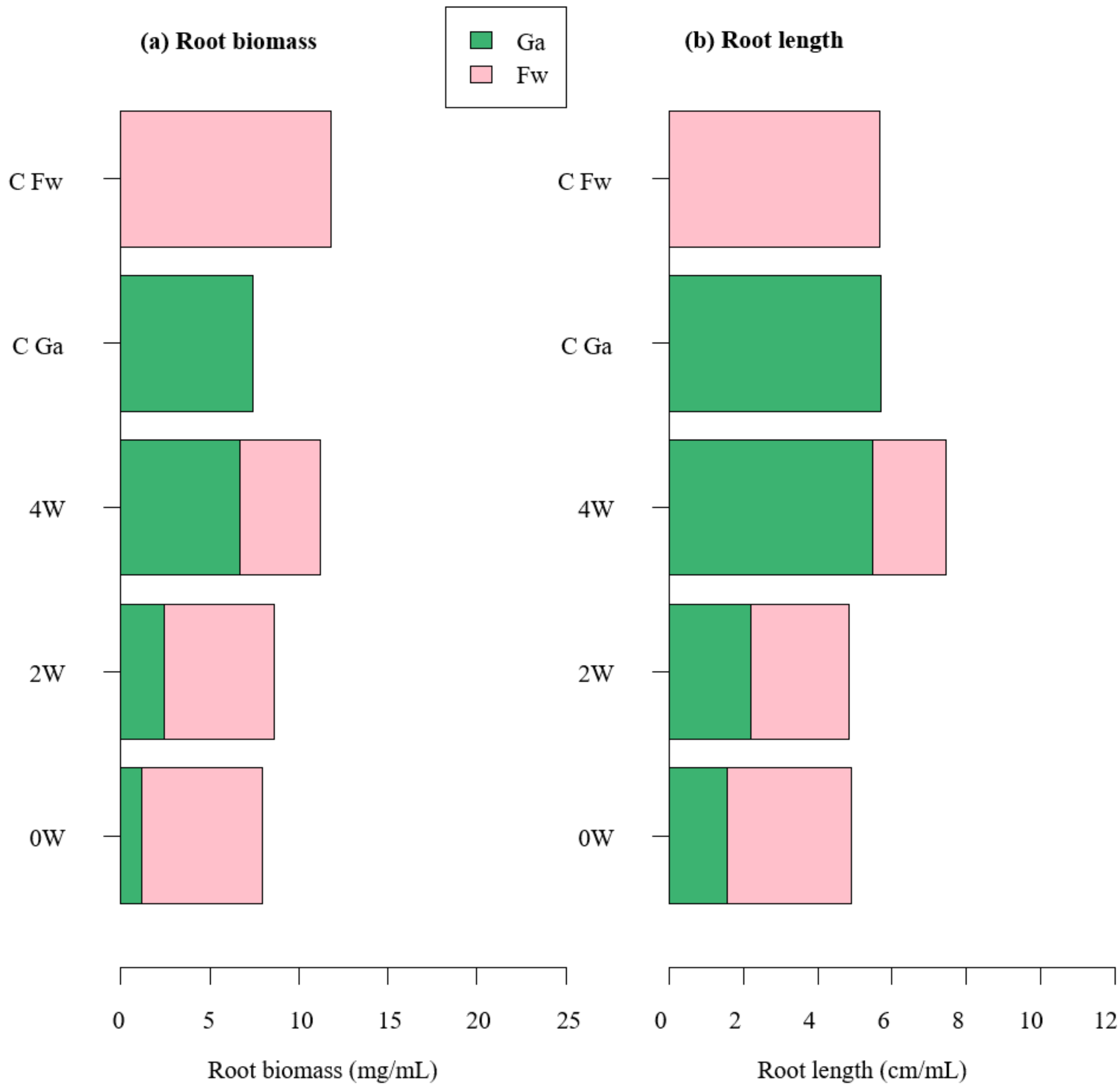


Figure A3.2. Average root biomass per cavity and average root length per cavity of hitchhiker nursey stock for each plant in the container, which included **paper birch** (*Betula papyrifera*) and fireweed (*Chamerion angustifolium*). Fireweed was sown with paper birch at the same time (0W), 2 weeks (2W) and 4 weeks (4W) later. Fireweed (Fw) and paper birch (Bw) were also grown alone (C).

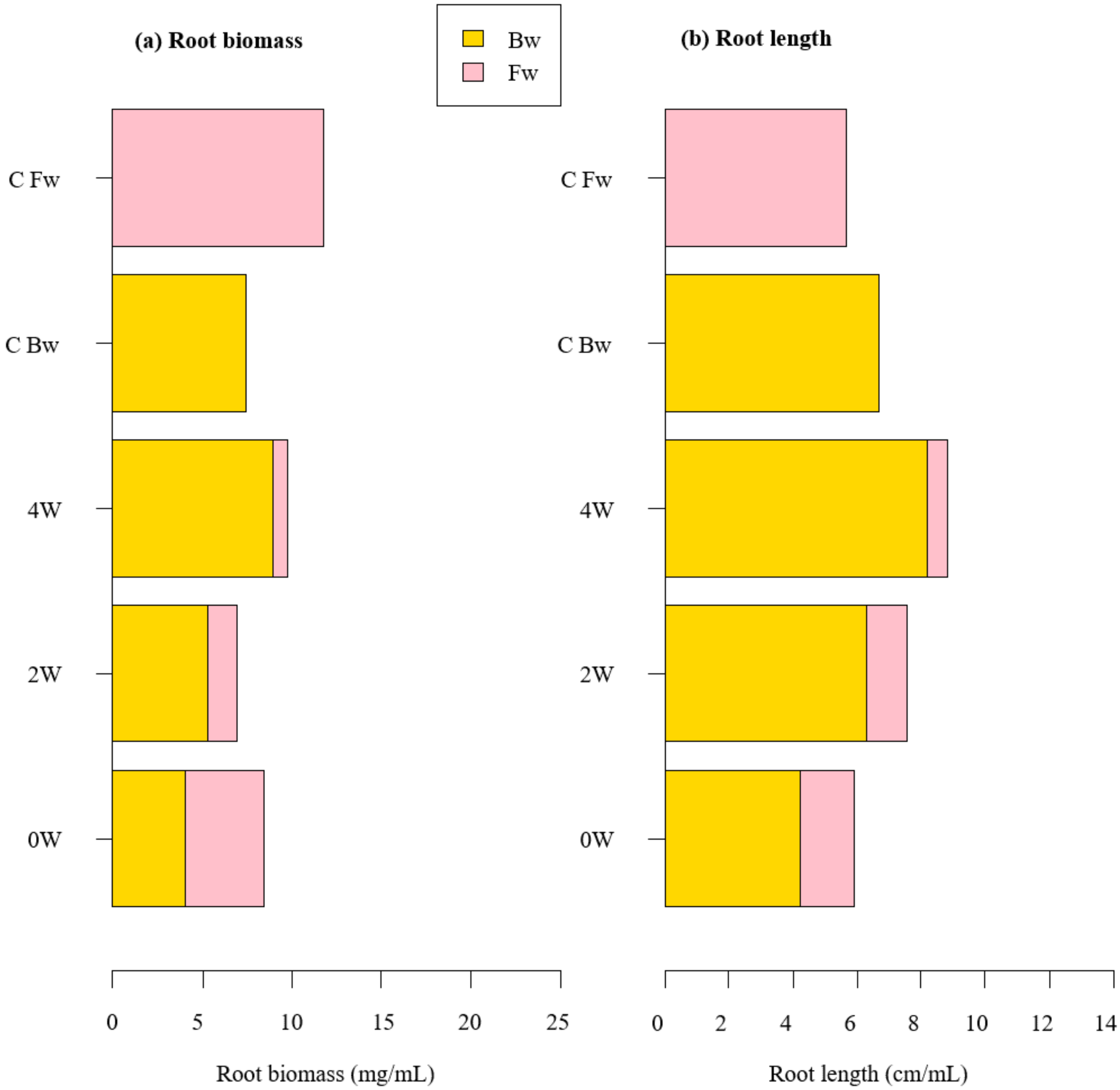


Figure A3.3. Average root biomass per cavity and average root length per cavity of hitchhiker nursey stock for each plant in the container, which included **Bebb's willow** (*Salix bebbiana*) and fireweed (*Chamerion angustifolium*). Fireweed was sown with Bebb's willow at the same time (0W), 2 weeks (2W) and 4 weeks (4W) later. Fireweed (Fw) and Bebb's willow (Sx) were also grown alone (C).

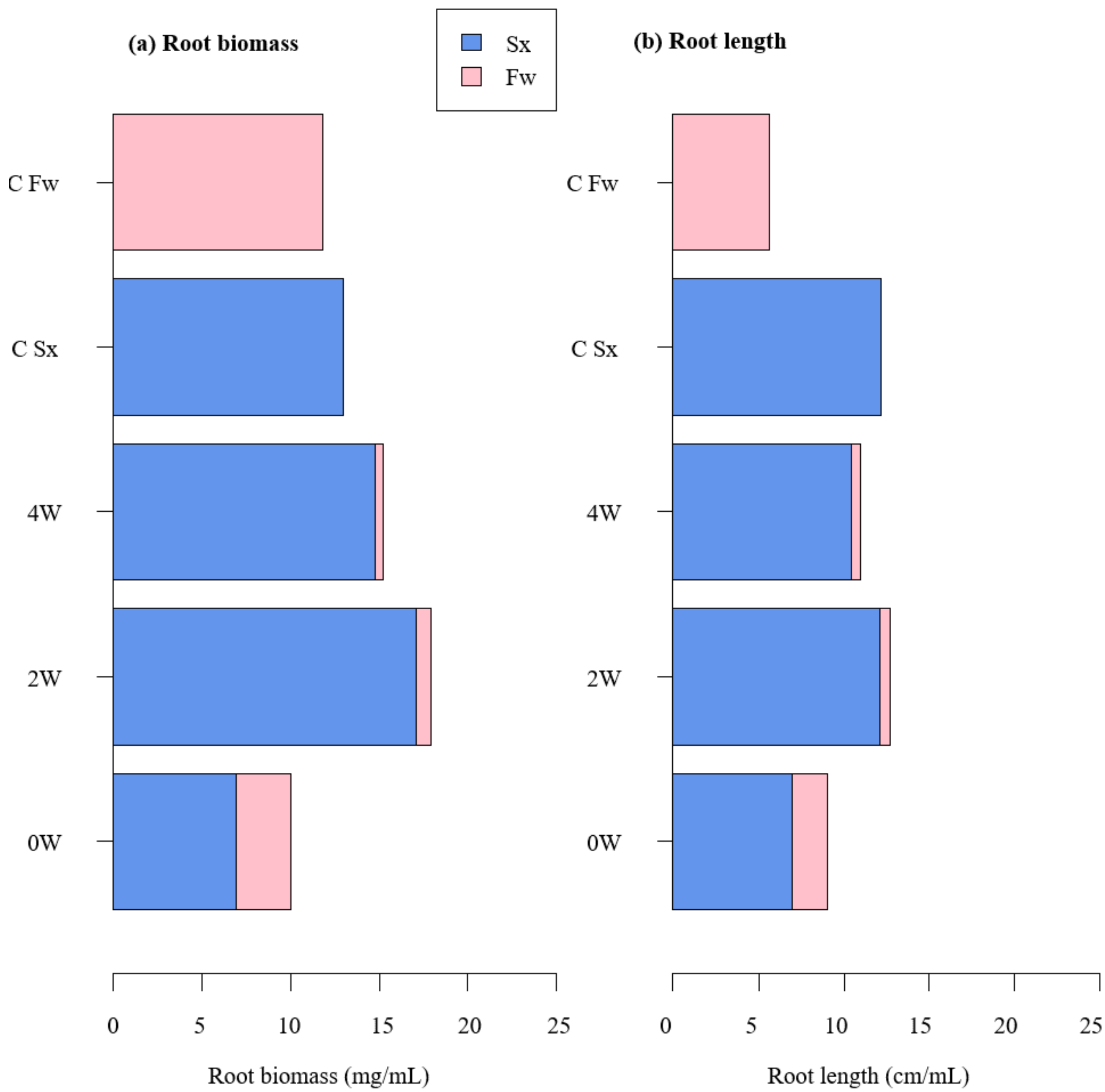
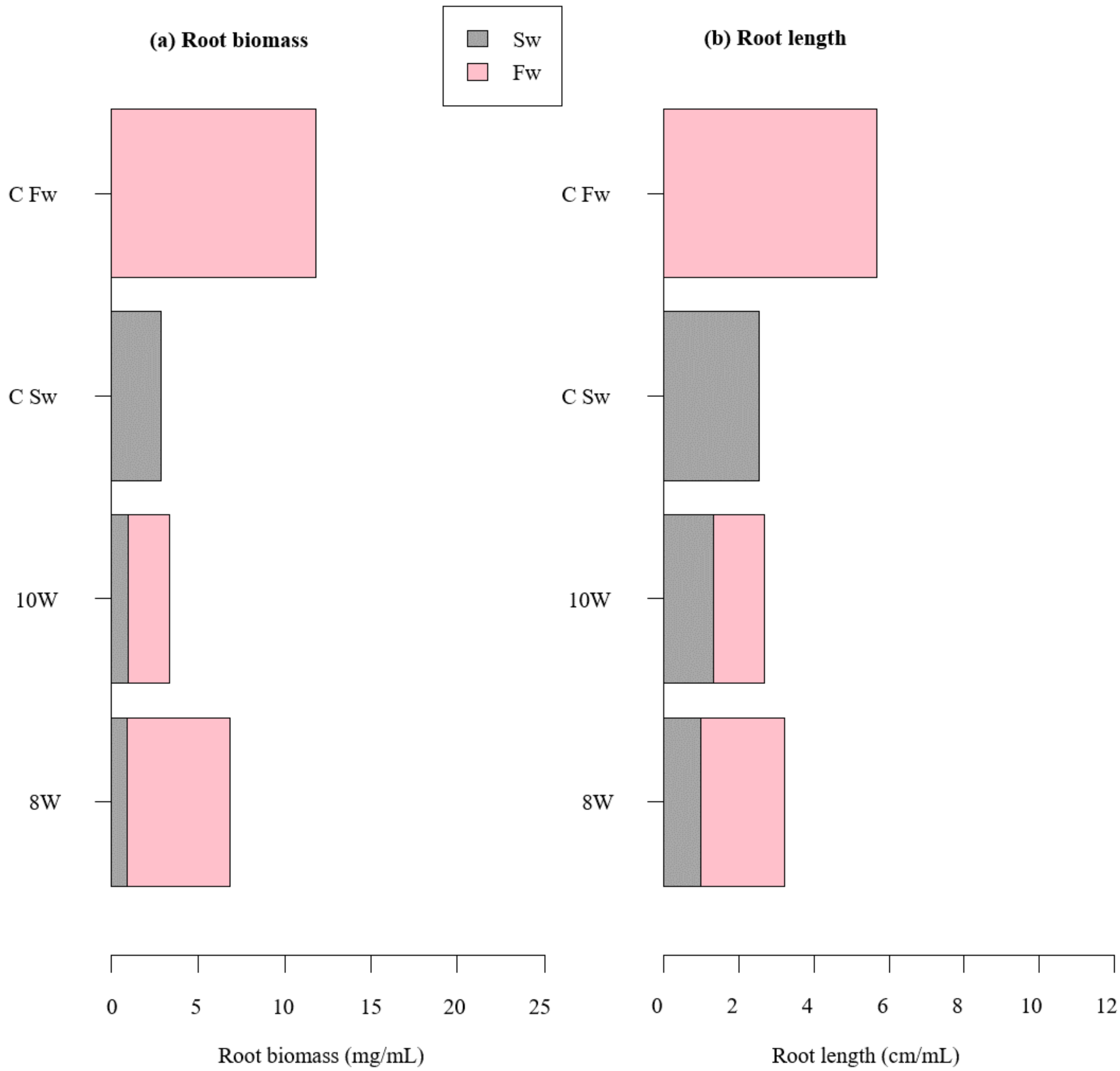


Figure A3.4. Average root biomass per cavity and average root length per cavity of hitchhiker nursey stock for each plant in the container, which included **white spruce** (*Picea glauca*) and fireweed (*Chamerion angustifolium*). Fireweed was sown with white spruce 8 weeks (8W) and 10 weeks (10W) later. Fireweed (Fw) and Bebb's willow (Sx) were also grown alone (C).



APPENDIX 4 (Chapter 2)

Table A4.1. List of models used to compare sow dates for nursery hitchhiker seedling characteristics. The basic model (lm) was used and if the assumptions of normality and homogeneity were violated, then the gls model accounted for this. Fireweed aboveground material was not sampled and therefore no data analysis was done, which is indicated by '-'.

	GREEN ALDER		PAPER BIRCH		BEBB'S WILLOW		WHITE SPRUCE	
Measurement	Ga	Fw	Bw	Fw	Sx	Fw	Sw	Fw
Height (cm)	gls	gls	lm	gls	gls	gls	gls	gls
Root biomass (g)	gls	gls	gls	gls	gls	gls	gls	gls
Root length (cm)	gls	gls	gls	gls	gls	gls	gls	gls
Root surface area (cm^2)	gls	gls	gls	gls	gls	gls	gls	gls
Shoot biomass (g)	gls	-	gls	-	gls	-	lm	-
Stem biomass (g)	gls	-	gls	-	gls	-	lm	-
Leaves biomass (g)	gls	-	gls	-	lm	-	lm	-
Total Nitrogen (g)	gls	lm	lm	lm	lm	lm	lm	lm
Root:shoot	lm	-	lm	-	gls	-	lm	-

Table A4.2. Model type used to compare sow dates of hitchhiker seedling growth 1 and 2 years after planting in field conditions. The basic mixed effects model was lme, which was used if assumptions of normality and homogeneity was met. If assumptions were not met, lme+ indicates that weights with the varIdent function to account for violations of the assumptions. Woody survivorship and fireweed presence was analyzed with glmer.

Year	Measurement	Green alder	Paper birch	Bebb's willow	White spruce
1	Woody height (cm)	lme	lme+	lme	lme+
1	Woody increment (cm)	lme	lme+	lme	lme
1	Woody survivorship (%)	glmer	glmer	glmer	glmer
1	Fireweed cover (%)	lme+	lme+	lme+	lme+
1	Fireweed presence (%)	glmer	glmer	glmer	glmer
2	Woody height (cm)	lme	lme+	lme	lme
2	Woody increment (cm)	lme	lme+	lme	lme
2	Woody survivorship (%)	glmer	glmer	glmer	glmer
2	Woody total biomass (g)	lme+	lme+	lme+	lme+
2	Woody stem biomass (g)	lme+	lme+	lme+	lme+
2	Woody leaf biomass (g)	lme+	lme+	lme+	lme+
2	Woody leaf total nitrogen (g)	lme+	lme+	lme+	lme+
2	Fireweed cover (%)	lme	lme+	lme+	lme
2	Fireweed presence (%)	glmer	glmer	glmer	glmer
2	Fireweed spread cover Q2-9 (%)	glmer	glmer	glmer	glmer
2	Fireweed spread presence Q2-9 (%)	lme	lme	lme+	lme+
2	Fireweed biomass Q1-9 (g)	lme+	lme+	lme+	lme+

APPENDIX 5 (Chapter 2)

Table A5.1. The average total nitrogen concentration of woody plant stems and fireweed root of nursery stock. Species included green alder (*Alnus viridis*) (Ga), paper birch (*Betula papyrifera*) (Bw), Bebb's willow (*Salix bebbiana*) (Sx), and white spruce (*Picea glauca*) (Sw) hitchhiked with fireweed (*Chamerion angustifolium*) (Fw). Fireweed was sown with deciduous woody species at the same time (0), 2 weeks later (2), 4 weeks later (4), as well as woody plants grown alone (Control) whereas fireweed was sown with white spruce 8 weeks and 10 weeks later. Mean ± one standard error of the mean.

Woody hitchhiker Species	Sow date	Species	Woody number of samples (n)	Fireweed number of samples (n)	Woody average total nitrogen concentration (w/w%)	Fireweed average total nitrogen concentration (w/w%)
Green alder	0	Ga	4	3	1.7±0.2	0.8±0.4
Green alder	2	Ga	4	4	1.9±0.2	1.3±0.6
Green alder	4	Ga	3	4	1.5±0.1	1.0±0.5
Green alder	Control	Ga	2	4	1.7±0.3	0.7±0.3
Paper birch	0	Bw	3	4	1.3±0.2	1.1±0.6
Paper birch	2	Bw	5	4	1.6±0.2	1.5±0.8
Paper birch	4	Bw	4	2	1.3±0.1	0.2±0.1
Paper birch	Control	Bw	4	4	1.4±0.1	0.7±0.3
Bebb's willow	0	Sx	4	4	1.1±0.2	1.0±0.5
Bebb's willow	2	Sx	4	3	0.8±0.1	0.4±0.2
Bebb's willow	4	Sx	4	1	1.0±0.1	1.1
Bebb's willow	Control	Sx	4	4	1.0±0.1	0.7±0.3
White spruce	8	Sw	4	4	1.5±0.2	0.2±0.1
White spruce	10	Sw	4	3	1.5±0.1	0.5±0.2
White spruce	Control	Sw	3	4	1.9±0.2	0.7±0.3

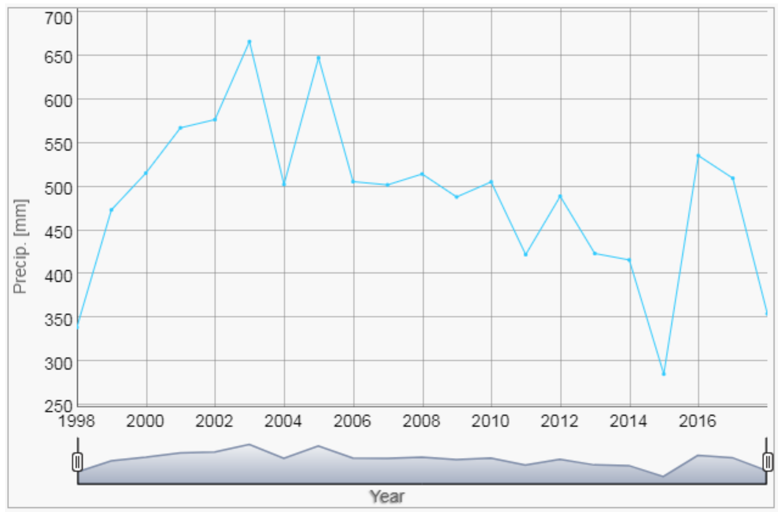
Table A5.2. The average total nitrogen concentration of woody plant leaves after two growing seasons. Species included green alder (*Alnus viridis*), paper birch (*Betula papyrifera*), Bebb's willow (*Salix bebbiana*), and white spruce (*Picea glauca*) hitchhiked with fireweed (*Chamerion angustifolium*). Fireweed was sown with deciduous woody species at the same time (0), 2 weeks later (2), 4 weeks later (4), as well as woody plants grown alone (Control) while fireweed was sown with white spruce 8 weeks and 10 weeks later. Mean ± one standard error of the mean (Green alder: n=6, Other species: n=11).

Hitchhiker species	Sow date	Average total nitrogen concentration (w/w%)
Green alder	0	0.3±0.1
Green alder	2	0.3±0.1
Green alder	4	0.4±0.1
Green alder	Control	0.3±0.1
Paper birch	0	0.4±0.1
Paper birch	2	0.6±0.2
Paper birch	4	0.5±0.2
Paper birch	Control	0.4±0.1
Bebb's willow	0	0.3±0.1
Bebb's willow	2	0.2±0.1
Bebb's willow	4	0.2±0.1
Bebb's willow	Control	0.2±0.1
White spruce	8	0.3±0.1
White spruce	10	0.3±0.1
White spruce	Control	0.2±0.1

APPENDIX 6 (Chapter 2)

Annual precipitation (mm) at the reclamation sites within T083R06W4 (Alberta Agriculture and Forestry, 2018).

Date	Precipitation (mm)
1998	338.81
1999	473.45
2000	515.72
2001	567.51
2002	576.98
2003	666.35
2004	502.69
2005	647.8
2006	505.86
2007	502.15
2008	514.62
2009	488.33
2010	505.56
2011	422.27
2012	489.11
2013	423.55
2014	416.13
2015	285.37
2016	535.73
2017	509.76
2018	354.41



APPENDIX 7 (Chapter 2)

Depiction of the quadrat ($0.5m^2$) arrangement used to assess fireweed development away from the planted seedlings. Quadrat 1 was centered on the planted hitchhiker or control seedling.

2	3	4
5	1	6
7	8	9

APPENDIX 8 (Chapter 2)

Figure A8.1. First growing season (August 2018) of **green alder** (Ga) (*Alnus viridis*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 5, replicate 1): (a) Fw control, (b) Ga control, (c) Ga+Fw 0 week, (d) Ga+Fw 2 week, (e) Ga+Fw 4 week.

(a)	(b)
	
(c)	(d)
	
(e)	
	

Figure A8.2 First growing season (August 2018) of **green alder** (Ga) (*Alnus viridis*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (stockpile, block 2b, replicate 4): (a) Fw control, (b) Ga control, (c) Ga+Fw 0 week, (d) Ga+Fw 2 week, (e) Ga+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A8.3. First growing season (August 2018) of **paper birch** (Bw) (*Betula papyrifera*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 5, replicate 1): (a) Fw control, (b) Bw control, (c) Bw+Fw 0 week, (d) Bw+ Fw 2 week, (e) Bw+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A8.4. First growing season (August 2018) of **paper birch** (Bw) (*Betula papyrifera*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (borrow pit, block 1, replicate 1): (a) Fw control, (b) Bw control, (c) Bw+Fw 0 week, (d) Bw+Fw 2 week, (e) Bw+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A8.5 First growing season (August 2018) of **white spruce** (Sw) (*Picea glauca*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 5, replicate 1): (a) Fw control, (b) Sw control 412A, (c) Sw control 512A, (d) Sw+Fw 8 week, (e) Sw+Fw 10 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A8.6. First growing season (August 2018) of **white spruce** (Sw) (*Picea glauca*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (borrow pit, block 1, replicate 1): (a) Fw control, (b) Sw control 412A, (c) Sw control 512A, (d) Sw+Fw 8 week, (e) Sw+Fw 10 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A8.7. First growing season (August 2018) of **Bebb's willow** (Sx) (*Salix bebbiana*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 5, replicate 1): (a) Fw control, (b) Sx control, (c) Sx+Fw 0 week, (d) Sx+Fw 2 week, (e) Sx+Fw 4 week.

(a)	**(b)**
	
(c)	**(d)**
	
(e)	
	

Figure A8.8. First growing seasong (August 2018) of **Bebb's willow** (Sx) (*Salix bebbiana*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (borrow pit, block 1, replicate 1): (a) Fw control, (b) Sx control, (c) Sx+Fw 0 week, (d) Sx+Fw 2 week, (e) Sx+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

APPENDIX 9 (Chapter 2)

Figure A9.1. Second growing season (August 2019) of **green alder** (Ga) (*Alnus viridis*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 3, replicate 2): (a) Fw control, (b) Ga control, (c) Ga+Fw 0 week, (d) Ga+Fw 2 week, (e) Ga+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A9.2. Second growing season (August 2019) of **green alder** (Ga) and fireweed (Fw) hitchhiker seedlings at plot with **no site preparation** (stockpile, block 1, replicate 1): (a) Fw control, (b) Bw control, (c) Bw+Fw 0 week, (d) Bw+ Fw 2 week, (e) Bw+Fw 4 week.

Figure A9.3. Second growing season (August 2019) of **paper birch** (Bw) (*Betula papyrifera*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 6, replicate 2): (a) Fw control, (b) Bw control, (c) Bw+Fw 0 week, (d) Bw+Fw 2 week, (e) Bw+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A9.4. Second growing season (August 2019) of **paper birch** (Bw) (*Betula papyrifera*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (borrow pit, block 1), replicate 3: (a) Fw control, (b) Bw control, (c) Bw+Fw 0 week, (d) Bw+Fw 2 week, (e) Bw+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A9.5. Second growing season (August 2019) of **white spruce** (*Picea glauca*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 6, replicate 2): (a) Fw control, (b) Sw control 512A, (c) Sw+Fw 8 week, (d) Sw+Fw 10 week.

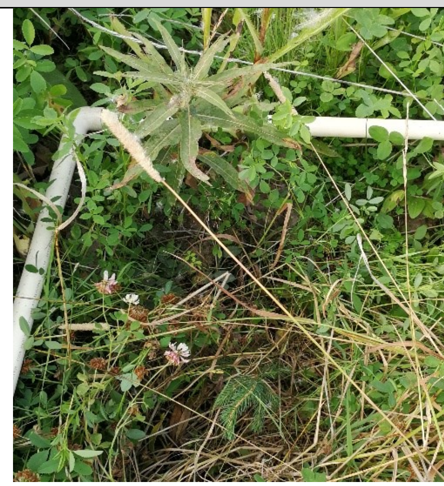
(a)	(b)
	
(c)	**(d)**
 	

Figure A9.6. Second growing season (August 2019) of **white spruce** (Sw) (*Picea glauca*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (borrow pit, block 1, replicate 3): (a) Fw control, (b) Sw control 412A, (c) Sw control 512A, (d) Sw+Fw 8 week, (e) Sw+Fw 10 week.

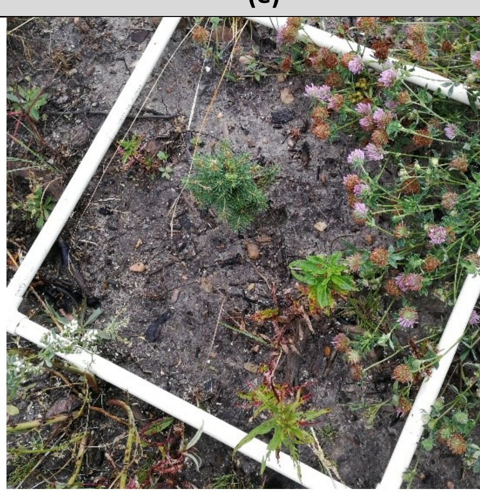
(a)	(b)
	
(c)	**(d)**
	
(e)	
	

Figure A9.7. Second growing season (August 2019) of **Bebb's willow** (Sx) (*Salix bebbiana*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **site preparation** (stockpile, block 7, replicate 3): (a) Fw control, (b) Sx control, (c) Sx+Fw 0 week, (d) Sx+Fw 2 week, (e) Sx+Fw 4 week.

(a)	**(b)**
	
(c)	**(d)**
	
(e)	
	

Figure A9.8. Second growing season (August 2019) of **Bebb's willow** (Sx) (*Salix bebbiana*) and fireweed (Fw) (*Chamerion angustifolium*) hitchhiker seedlings at a plot with **no site preparation** (borrow pit, block 1, replicate 3): (a) Fw control, (b) Sx control, (c) Sx+Fw 0 week, (d) Sx+Fw 2 week, (e) Sx+Fw 4 week.

(a)	(b)
	
(c)	**(d)**
	
(e)	
	

APENDIX 10 (Chapter 2)

List of plant species identified in plots over two growing seasons grouped into woody, grass, native forbs and non-native forbs.

Woody		
Alnus viridis	*Betula papyrifera*	*Betula pumila*
Cornus canadensis	*Larix laricina*	*Picea glauca*
Pinus banksiana	*Populus balsamifera*	*Populus tremuloides*
Rosa acicularis	*Rubus idaeus*	*Rubus pubescens*
Salix spp.		
Grass		
Agrostis scabra	*Agrostis stolonifera*	*Agropyron trachycaulum var. trachycaulum*
Agropyron trachycaulum var. unilaterale	*Aloecurus aequalis*	*Beckmannia syzigachne*
Bromus ciliatus	*Bromus inermis*	*Carex spp.*
Calamagrostis canadensis	*Deschampsia caespitosa*	*Festuca ovina*
Hordeum jubatum	*Koeleria macrantha*	*Phleum pratense*
Poa sp.		
Native forbs		
Achillea millefolium	*Achillia siberica*	*Aralia nudicaulis*
Aster ciliolatus	*Aster conspicuous*	*Aster paniculata*
Cerastium vulgatum	*Chamerion angustifolium*	*Chenopodium album*
Chenopodium capitatum	*Collomia linearis*	*Corydalis aurea*
Dracocephalum parviflorum	*Epilobium glandulosum*	*Equisetum sp*
Fragaria virginiana	*Galiopsis tetrahit*	*Galium triflorum*
Galium borealis	*Gentianella amarella*	*Geranium becknellii*
Hiericium umbellatum	*Juncus bufonius*	*Lathyrus ochroleucus*
Lathyrus venosus	*Lepidium densiflorum*	*Linnaea borealis*
Matricaria matricarioides	*Mentha arvensis*	*Mertensia paniculata*
Petesitis palmatus	*Potentilla norvegica*	*Rhinanthus borealis*
Rumex oxidentalis	*Urtica dioica*	*Vicia americana*
Viola adunca		
Non-native forbs		
Cirsium arvense	*Crepis tectorum*	*Matricaria martima*
Medicago lupulina	*Medicago sativa*	*Meliolotus sp.*
Plantago major	*Polygonum aviculare*	*Sonchus arvensis*
Sonchus oleraceus	*Taraxacum officinale*	*Trifolium hybridum*
Trifolium pratense	*Trifolium rapens*	

APPENDIX 10 (Chapter 3)

Zhang (1997) determined a series of equations to calculate infiltration rate as follows:

(1) Cumulative infiltration $\mathbf{I = C_1 t + C_2 \sqrt{t}}$

C_1($^{\alpha}$m s^{-}1) and C_2(m s$^{-1/2}$) are parameters
C_1: related to hydraulic conductivity
C_2: soil sorptivity
t: time

(2) Hydraulic conductivity for soil (*k*) $\boldsymbol{k = \frac{C_1}{A}}$

C_1: slope of the curve of cumulative infiltration vs square root of time
A: value related to the van Genuchten parameters for a given soil type, the suction rate, and Infiltrometer disk radius (Table A10.1 below)

(3a) Calculate A $$\mathbf{A = \frac{11.65\left(n^{0.1}-1\right)^{[2.92(n-1.9)\alpha h_o]}}{(\alpha r_o)0.91}}$$

(3b) Calculate A $$\mathbf{A = \frac{11.65\left(n^{0.1}-1\right)^{[7.5(n-1.9)\alpha h_o]}}{(\alpha r_o)0.91}}$$

'n' and 'a': van Genuchten parameters for the soil (Table A10.1 below)
r_o: the disk radius
h_o: suction at disk surface

Table A10.1. “Van Genuchten parameters for 12 soil texture classes and A values for a 2.25cm disk radius and suction values from 0.5 to 6cm” obtained from Carsel and Parrish (1988) (Decagon Devices, Inc., 2012).

			h_o						
			-0.5	-1	-2	-3	-4	-5	-6
Texture			A						
Sand	0.145	2.68	2.84	2.40	1.73	1.24	0.89	0.64	0.46
Loamy Sand	0.124	2.28	2.99	2.79	2.43	2.12	1.84	1.61	1.40
Sandy Loam	0.075	1.89	3.88	3.89	3.91	3.93	3.95	3.98	4.00
Loam	0.036	1.56	5.46	5.72	6.27	6.87	7.53	8.25	9.05
Silt	0.016	1.37	7.92	8.18	8.71	9.29	9.90	10.55	11.24
Silt Loam	0.020	1.41	7.10	7.37	7.93	8.53	9.19	9.89	10.64
Sandy Clay Loam	0.059	1.48	3.21	3.52	4.24	5.11	6.15	7.41	8.92
Clay Loam	0.019	1.31	5.86	6.11	6.64	7.23	7.86	8.55	9.30
Silty Clay Loam	0.010	1.23	7.89	8.09	8.51	8.95	9.41	9.90	10.41
Sandy Clay	0.027	1.23	3.34	3.57	4.09	4.68	5.36	6.14	7.04
Silty Clay	0.005	1.09	6.08	6.17	6.36	6.56	6.76	6.97	7.18
Clay	0.008	1.09	4.00	4.10	4.30	4.51	4.74	4.98	5.22

APPENDIX 11 (Chapter 3)

Table A11.1. Bulk density (BD) of the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5) at 0-5cm, 10-15cm, and 25-30cm depths. Mean ± one standard error (n=4). Bulk density significantly differed between plots (*p*<0.0001), did not differ between depths (*p* =0.491), nor had a significant interaction (SitePlot*Depth) (*p* =0.061).

Site Plot	BD 0-5cm ($g{\cdot}cm^{-3}$)	BD 10-15 cm ($g{\cdot}cm^{-3}$)	BD 25-30 cm ($g{\cdot}cm^{-3}$)
BP1	0.8±0.1	0.9±0.1	1.3±0.1
BP2	1.3±0.1	1.3±0.1	1.1±0.1
BP3	1.2±0.1	0.9±0.1	1.0±0.1
BP5	1.0±0.1	1.1±0.1	0.8±0.1
SP1	1.1±0.1	1.1±0.1	1.1±0.1
SP2	1.0±0.1	1.0±0.1	0.9±0.1
SP3	1.0±0.1	0.9±0.1	1.0±0.1
SP4	1.0±0.1	0.9±0.1	0.9±0.1
SP5	1.0±0.1	1.0±0.1	1.1±0.1
SP6	0.5±0.1	0.5±0.1	0.4±0.1
SP7	0.9±0.1	0.9±0.1	0.9±0.1

Table A11.2. Soil pH of the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5) at 0-5cm, 10-15cm, and 25-30cm depths. Mean ± one standard error (n=4). The pH was significantly different between plots (*p* <0.0001), but did not differ between depths (*p* =0.171) nor had a significant interaction (SitePlot*Depth) (*p* =0.623).

Site Plot	pH 0-5cm	pH 10-15cm	pH 25-30cm
BP1	7.2±0.3	7.5±0.3	8.0±0.3
BP2	8.0±0.3	7.5±0.3	7.6±0.3
BP3	7.7±0.3	7.9±0.3	7.9±0.3
BP5	7.5±0.3	7.7±0.3	7.7±0.3
SP1	7.3±0.3	7.2±0.3	7.3±0.3
SP2	4.7±0.3	4.4±0.3	5.3±0.3
SP3	7.3±0.3	7.7±0.3	7.5±0.3
SP4	7.4±0.3	7.5±0.3	7.6±0.3
SP5	7.2±0.3	7.8±0.3	7.7±0.3
SP6	7.0±0.3	7.0±0.3	7.0±0.3
SP7	7.4±0.3	7.3±0.3	7.5±0.3

Table A11.3. Electrical conductivity (EC) of the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5) at 0-5cm, 10-15cm, and 25-30cm depths. Mean ± one standard error (n=4). The EC was significantly different between plots (p <0.0001), but EC did not differ between depths (p =0.098) nor was the interaction effect (SitePlot*Depth) significant (p =0.763).

Site Plot	EC 0-5cm ($dS \cdot m^{-1}$)	EC 10-15cm ($dS \cdot m^{-1}$)	EC 25-30cm ($dS \cdot m^{-1}$)
BP1	0.5±0.0	0.6±0.0	0.5±0.0
BP2	0.3±0.0	0.4±0.0	0.3±0.0
BP3	0.4±0.0	0.7±0.3	0.6±0.2
BP5	0.6±0.0	0.6±0.0	0.5±0.0
SP1	0.5±0.1	0.6±0.0	0.6±0.1
SP2	1.0±0.3	0.2±0.6	0.2±0.7
SP3	0.4±0.0	0.4±0.0	0.4±0.0
SP4	0.4±0.0	0.4±0.0	0.5±0.0
SP5	0.4±0.1	0.6±0.0	0.4±0.0
SP6	0.5±0.0	0.5±0.0	0.5±0.0
SP7	0.3±0.0	0.2±0.0	0.3±0.0

APPENDIX 12 (Chapter 3)

Table A12.1. Average vegetative cover of community species within the local vicinity of Green alder (*Alnus viridis*) at the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5). Mean ± one standard error (n=4).

Site Plot	Total	Grass	Native	Non-native	Woody
BP1	na	na	na	na	na
BP2	na	na	na	na	na
BP3	na	na	na	na	na
BP5	na	na	na	na	na
SP2	47.1±16.4	1.3±0.7	0.0±0.0	0.0±0.0	0.0±0.0
SP1	55.5±5.3	12.8±6.2	1.0±1.0	17.3±4.6	0.5±0.3
SP3	66.7±13.5	7.8±2.5	0.0±0.0	45.9±12.2	0.5±0.5
SP4	43.7±10.0	3.0±0.8	1.3±0.9	17.2±2.4	3.9±1.5
SP5	58.1±13.8	19.1±9.9	0.0±0.0	21.7±12.3	0.0±0.0
SP6	54.8±12.0	5.3±2,6	1.5±0.6	29.5±14.5	7.0±6.1
SP7	48.2±5.1	10.2±5.4	2.4±1.3	20.6±3.1	0.7±0.7

Table A12.2. Average vegetative cover of community species within the local vicinity of Paper birch (*Betula papyrifera*) at the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5). Mean ± one standard error (n=4).

Site Plot	Total	Grass	Native	Non-native	Woody
BP1	39.3±6.6	6.1±2.6	0.8±0.6	24.1±6.8	0.3±0.3
BP2	13.4±2.7	4.3±0.7	0.3±0.3	5.0±2.3	0.0±0.0
BP3	24.1±4.3	4.8±1.5	0.3±0.2	16.7±3.6	0.0±0.0
BP5	57.2±7.0	5.7±4.3	0.6±0.4	41.5±12.8	4.0±4.0
SP2	7.6±2.2	1.2±0.5	0.2±0.2	1.7±1.7	0.0±0.0
SP1	61.8±7.9	17.5±13.2	1.0±0.8	39.6±10.9	1.1±1.1
SP3	60.9±12.1	4.8±1.7	0.1±0.1	50.8±12.6	1.2±0.9
SP4	44.0±5.4	2.3±0.3	0.7±0.3	32.9±7.9	3.0±2.2
SP5	60.0±10.5	18.7±13.6	0.8±0.7	33.1±13.7	1.8±1.01
SP6	66.0±7.4	6.2±3.2	3.0±1.5	33.1±8.87	15.9±13.4
SP7	42.0±9.6	8.08±1.8	3.1±1.4	23.7±7.1	3.5±2.7

Table A12.3. Average vegetative cover of community species within the local vicinity of Bebb's willow (*Salix bebbiana*) at the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5). Mean ± one standard error (n=4).

Site Plot	Total	Grass	Native	Non-native	Woody
BP1	38.7±5.3	5.8±3.0	1.0±0.6	24.1±4.3	0.0±0.0
BP2	12.5±1.5	5.1±0.9	0.0±0.0	2.3±1.04	0.0±0.0
BP3	35.4±9.9	3.8±1.5	0.1±0.1	27.0±11.3	0.0±0.0
BP5	39.3±8.8	8.7±6.1	0.3±0.2	24.1±7.8	0.0±0.0
SP2	5.6±0.8	1.4±0.6	0.0±0.0	0.0±0.0	0.0±0.0
SP1	70.3±3.2	16.6±7.1	6.9±6.6	41.6±12.0	1.1±0.7
SP3	58.5±9.7	9.2±5.0	0.4±0.4	44.7±10.0	0.9±0.6
SP4	38.2±11.8	1.8±0.5	2.0±0.9	26.7±8.7	1.3±0.5
SP5	51.4±13.9	10.4±5.0	0.0±0.0	38.6±15.2	0.0±0.0
SP6	35.8±15.5	4.4±2.9	2.3±0.9	26.3±11.8	0.3±0.3
SP7	45.8±8.2	16.9±9.6	2.0±1.1	18.5±3.5	1.7±1.1

Table A12.4. Average vegetative cover of community species within the local vicinity of White spruce (*Picea glauca*) at the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5). Mean ± one standard error (n=4).

Site Plot	Total	Grass	Native	Non-native	Woody
BP1	37.0±8.9	5.7±2.1	1.8±0.8	24.8±7.9	0.0±0.0
BP2	10.1±2.1	4.7±0.8	0.3±0.2	2.3±2.1	0.0±0.0
BP3	29.3±7.6	2.3±1.0	0.0±0.0	24.6±8.6	0.0±0.0
BP5	39.3±8.4	9.5±4.0	2.0±0.8	24.1±5.5	0.0±0.0
SP2	7.5±2.7	2.8±2.4	0.0±0.0	2.3±2.3	0.3±0.3
SP1	60.0±6.5	9.3±0.9	0.6±0.5	42.1±8.3	5.0±2,8
SP3	59.7±13.0	10.3±4.0	0.0±0.0	47.5±10.8	0.9±0.3
SP4	50.3±3.9	4.0±0.5	2.0±0.8	36.8±4.9	3.3±1.34
SP5	44.9±7.3	9.5±5.0	0.0±0.0	32.1±9.4	0.7±0.7
SP6	87.5±22.1	6.5±3.0	1.6±0.8	60.7±25.7	15.1±14.1
SP7	46.1±8.6	22.0±8.1	1.1±0.5	19.2±4.5	1.0±1.0

Table A12.5. Average vegetative cover of community species within the local vicinity of fireweed (*Chamerion angustifolium*) at the soil stockpile plots (SP 1-7) and borrow pit plots (BP 1-3, 5). Mean ± one standard error (n=16).

Site Plot	Total	Grass	Native	Non-native	Woody
BP1	34.6±4.0	5.4±1.3	1.3±0.4	23.3±5.0	0.3±0.2
BP2	10.4±1.9	3.9±0.9	0.1±0.1	4.0±1.5	0.0±0.0
BP3	35.0±8.0	4.1±1.1	0.1±0.1	28.9±8.1	0.0±0.0
BP5	30.7±6.0	5.1±1.7	0.7±0.3	22.8±5.2	0.2±0.2
SP2	2.7±0.6	0.6±0.1	0.0±0.0	0.5±0.4	0.2±0.1
SP1	56.8±5.8	9.6±2.4	1.5±0.9	38.2±6.6	0.3±0.2
SP3	59.1±6.7	8.7±1.4	0.2±0.1	46.6±6.4	1.1±0.4
SP4	35.5±4.6	2.9±0.7	1.4±0.4	23.5±3.6	0.3±0.2
SP5	39.1±6.2	10.3±2.6	0.3±0.2	24.5±5.8	0.4±0.2
SP6	60.4±6.7	5.6±1.5	1.8±0.6	39.1±8.2	10.3±4.8
SP7	44.4±5.5	11.3±2.7	2.7±0.7	23.9±5.2	1.1±0.9

APPENDIX 13 (Chapter 3)

Table A13.1. Soil moisture each month at each block during the summer of 2018. Mean ± one standard error (n=4). A month with a high and low average (bolded) were chosen to use for correlations with seedling establishment. The month with the greatest soil moisture was July (bolded). The month with the lowest soil moisture was May and June, but May was chosen.

Site Plot	**May**	June	**July**	Aug.	Sept.
BP1	**19.5±1.7**	19.3±1.3	**31.0±4.5**	24.1±2.6	29.2±4.2
BP2	**20.8±1.4**	24.4±1.6	**25.1±1.7**	22.8±1.1	23.5±1.4
BP3	**15.4±2.3**	18.4±1.3	**20.9±2.3**	17.5±3.1	20.4±2.1
BP5	**16.6±3.4**	14.4±1.8	**24.1±4.0**	20.8±3.0	22.5±3.0
SP1	**19.9±2.6**	19.6±2.7	**30.4±3.3**	22.9±2.1	31.2±8.1
SP2	**11.7±4.3**	13.0±4.1	**14.5±4.3**	12.8±4.7	12.9±3.9
SP3	**16.4±5.5**	16.9±4.9	**27.3±7.1**	17.8±4.6	18.7±5.3
SP4	**17.9±1.9**	18.8±2.2	**27.9±4.1**	20.4±2.8	21.8±3.4
SP5	**20.5±1.7**	21.8±1.9	**25.7±2.4**	20.0±1.4	22.7±2.5
SP6	**20.7±1.6**	20.3±2.0	**23.5±1.9**	19.3±1.8	21.8±1.6
SP7	**19.2±1.2**	22.3±2.3	**24.4±3.5**	20.0±2.5	22.9±2.7

Table A13.2. Monthly soil temperature at each block during the summer of 2018. Mean ± one standard error (n=2 [SP 1,4-6]; n=1 [BP1-3,5, SP2,3,7]). A month with a high and low average (bolded) were chosen to use for correlations with seedling establishment. The month with the greatest soil temperature was July and the month with the lowest soil temperature was September.

Site Plot	May	June	**July**	Aug.	**Sept.**
BP1	14.2	15.2	**16.6**	15.8	**7.5**
BP2	15	15.8	**17.8**	16.4	**5.5**
BP3	NA	NA	**NA**	NA	**NA**
BP5	NA	NA	**NA**	NA	**NA**
SP1	4.1±5.5	5.5±5.8	**7.6±5.8**	6.0±6.0	**2.6±2.9**
SP2	19.3	17.8	**19.6**	18.7	**7.8**
SP3	14.1	14.9	**16**	14.2	**7.2**
SP4	14.3±0.4	14.8±0.3	**16.0±0.3**	15.0±0.2	**7.6±0.2**
SP5	13.8±0.2	15.0±0.4	**16.6±0.4**	15.3±0.5	**7.0±0.2**
SP6	12.4±0.3	13.8±0.1	**15.3±0.0**	14.1±0.2	**6.9±0.3**
SP7	14.3	15.4	**17.1**	16.3	**8.3**