APPLICATION OF BIOENERGY ASH AS A FERTILIZER FOR CONIFER SEEDLINGS IN A SUB-BOREAL REFORESTATION SITE IN THE CENTRAL INTERIOR, BRITISH COLUMBIA

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Abstract

In the Central Interior, British Columbia, bioenergy generated from wood wastes is increasingly popular. To mitigate the ash surplus, two trials (seedling pot and field) examined conifer seedlings (lodgepole pine and hybrid spruce) subjected to treatments comparing two bioenergy ash types (gasifier and boiler), combined with nitrogen or alone. Two placement techniques, broadcast spread and teabag, plus two rates of application (2 tonnes ha^{-1} and 4 tonnes ha^{-1}) were also compared. After 51 weeks, seedling pot results suggested both species benefited from ash with nitrogen. In the field trial, after 57 weeks, the gasifier ash, which was high in mineral content compared to the charcoal-filled boiler ash, had increased spruce height, without nitrogen; this ash also spurred the highest soil pH increase, especially when broadcast spread. Also, the low dose of ash was preferred. It is likely ash application can improve reforestation success, providing site conditions and species are compatible.

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Chapter 1 Introduction

The conversion of wood wastes into biofuels and bioenergy is an ideal way to offset the use of fossil fuels, or other non-renewable energy sources. However, as bioenergy gains popularity, particularly in British Columbia (B.C.), there is a need to address the growing amount of ash produced by this energy sector. Currently, ash residuals are either being stockpiled or landfilled, which are practices that are increasingly outdated and discouraged (Emilsson, 2006; Hannam et al., 2017, 2018). While the current regulatory structure in B.C. does not promote recycling wood ashes (Hannam et al., 2017, 2018), there is an opportunity to utilize this “waste” ash, as a fertilizer or soil amendment. Other parts of the world, namely Scandinavian countries, and only some parts of Canada, have recognized the benefits of ash, which is especially high in selected plant essential nutrients, such as calcium, potassium, phosphorus and magnesium. Wood ash residuals have been integrated into forestry and agriculture as a means to raise soil pH (e.g. as a liming agent) and to supply some nutrients to plants. This study was initiated to increase our understanding of ash and attempt to find value in utilizing ash in the forests of the Central Interior, B.C.

In countries where ash fertilization is implemented, the objectives of the ash amendment vary from improving soil nutrient deficiencies to replenishing the exported nutrients harvested with the forest stand. Although high in some plant nutrients, bioenergy ash lacks nitrogen, an important plant nutrient, and one that is frequently deficient in the forests of central B.C. To improve the performance of ash as a fertilizer, nitrogen supplements can be added with the dose of ash (Jacobson, 2003). However, ash is more often applied as a liming agent to neutralize acidic soils (Hannam et al., 2016). Substituting ash for synthetic nutrient input is arguably a function better served by industrial manmade fertilizers (Wang et al., 2007). On the other hand, there are a number of arguments for applying ash on forestlands in the Central Interior of B.C. Aside from diversion from the landfill, ash also acts as a natural soil conditioner and is ubiquitous to the soils of B.C.

When considering ash for land application as a fertilizer or soil amendment, there are certain factors that should be considered. First, the contents of the fuels burned should remain purely plant or wood-derived to avoid any problematic trace element levels. In the case of wood ash accessible to this sub-boreal region, the woody biomass burned to generate bioenergy mainly consists of wood wastes leftover from pulp and lumber milling. Heavy metals, such as cadmium and chromium, occur naturally in tiny amounts in ash, providing there has been no contamination of the bioenergy woody feedstock (Carlton et al., 2008). Furthermore the levels of trace metals (e.g.: Cr, Cd, Pb, Ni, Cu, and Zn), solubility and nutrient levels of ash can also fluctuate (Hannam, 2016; Jacobson, 2003). The physical texture and chemical properties of ash can also vary depending on the type of incineration system used in the bioenergy production, the type of fuels burned, and the temperature at which they were burned (Augusto et al., 2008; Pitman, 2006). Other factors to consider when planning a large-scale ash application include the conditions of the receiving site, such as soil type, vegetation abundance and proximity to waterways (Hannam et al., 2016).

The history of wildfire on the landscape, and forest health agents such as bark beetles, are important drivers of B.C. ecosystems, contributing to forest dynamics and the distribution of nutrients, especially in the Central Interior of B.C. In recent decades the impact of bark beetles, namely the mountain pine beetle (MPB), coupled with wildfire, has forever altered the province's and the regions' forest ecosystems. Timber harvesting, although an "artificial" disturbance, has long impacted forests in the Central Interior of B.C. After harvesting is complete, and after other large-scale forest disturbances, reforestation is undertaken in order to regenerate forests back to a productive ecosystem. It is at the reforestation stage where an opportunity of introducing ash residuals back into the forest ecosystem is presented. Bioenergy ash essentially represents ash that would otherwise be introduced by wildfire or decaying beetle wood. Considering the fuels burned to generate bioenergy originate from regional forests, returning clean ash residuals, as a form of fertilizer or liming agent, back to their origin should be a manageable and encouraged practice.

Utilizing ash at the reforestation stage has not been widely explored. If the initial years of a seedling's life are the most vital, and ash can contribute certain essential plant nutrients, it seemed fitting to examine the use of ash to fertilize conifer seedlings grown in a controlled (seedling pots) and a natural (field) setting. Situated in the Sub-Boreal Spruce (SBS) biogeoclimatic ecological classification (BEC) zone of the Central Interior of B.C., the trials were carried out in a forestry context. However, it is expected the outcomes could easily be rendered in other sectors, such as agriculture or mining and for other applications, such as land reclamation and rehabilitation.

Background

Forest disturbance and ash

Wildfire

For millennia, fire has played a fundamental role in shaping our landscapes (Bowman et al., 2009) and when man began employing it as a tool, the natural sequence of fire intervals was forever altered (Agee, 1996). On account of British Columbia's wildfire history, ash is pervasive in the province's soil landscape. Even so, it is rather foreign to think of fertilization using ash derived from bioenergy production (AshNet, Natural Resources Canada, 2017). In the Sub-Boreal Spruce (SBS) BEC zone of the Central Interior, wildfire is a common ecological disturbance (Steen & Coupé, 1997). The resulting post-fire ash composition can depend largely on tree species and growing conditions (Pitman, 2006); the amount of ash is a result of site conditions, such as aspect, topography, soil properties (e.g.: soil moisture), and climate (Aronsson & Ekelund, 2004; Augusto et al., 2008). In the boreal forest, a burned upper soil organic layer will yield 0.7 to 2.0% in charcoal (Fritze et al., 1994). Charcoal, the remnants of fire, is an oxidized form of dense carbon that can eventually benefit the soil's structure and water-holding capacity (González-Pérez et al., 2004). Not only can charcoal withstand biochemical breakdown for a long time, it can also retain Ca^+ and Mg^+, essential nutrients for plant growth, through adsorption (Hart & Luckai, 2013).

Ash is an incredibly variable material, especially ash occurring as a result of wildfire. The rate and duration of wildfire, as well as the drastic shifts caused by extreme changes in wind direction, are all aspects that add to the variations of wildfire ash (Raison, 1979). Wildfire ash can be wettable and help to reduce post-fire erosion and runoff by preventing soil sealing (Larsen et al., 2009). However, depending on the plant species burned and the conditions of the burn (e.g.: temperature of combustion), ash can influence the wettability of soil by making it water repellent (Bodí et al., 2011). Bodí and colleagues (2011) found that soil wettability was improved when a wettable ash was added, but was decreased when a water-repellent ash was added to a wettable soil.

These contrasts can be attributed to differences in both site and soil conditions, not to mention the intensity of the fire (Bowman et al., 2009). Fire intensity can ultimately determine to what extent the wildfire ash will interact with the soil, native vegetation and the surviving plants as well. Some of these plant species have inherent adaptations to fire (e.g.: thicker bark, serotinous cones or resprouting abilities) that are said to be linked to the repetitive occurrence of fire, or a fire regime (Keeley et al., 2011; Pausas & Keeley, 2009). If these traits are indeed fire-related adaptations, it can be assumed that these species are also accustomed to having ash present in the soil profile. The natural presence and tolerance, or adaptation to, the presence of naturally-occurring ash makes a strong case for utilizing bi-product ash to fertilize seedlings after timber harvest. Essentially it would be to substitute the missing component of what would have been, a natural disturbance. For comparison, low intensity burns can assist in releasing base cation oxides tied up in soil organic matter and initiate a change in physicochemical soil traits similar to a small dose of ash at a rate of 1 tonne ha^{-1} (Fritze et al., 1994; Levula et al., 2000).

Bark beetles

Bark beetles (Coleoptera: Curculionidae, Scolytinae) are native pests to North America and play an important role in forest stand dynamics. Probably the most important beetle in recent decades for B.C., the mountain pine beetle (MPB; *Dendroctonus ponderosae*) has historically played a major function in shaping this region's forests (Taylor & Carroll, 2003). However, with climate change contributing to the severity and frequency of the outbreaks (Carroll et al., 2003; Taylor & Carroll, 2003), the passing MPB outbreak has undoubtedly left its mark on the province's forests. Impacting millions of hectares, British Columbia will undergo a 53-70% loss of merchantable timber by 2021 (Special Committee on Timber Supply, 2012).

Much like wildfire, the MPB has long been a driver of stand dynamics. As host trees die, they gradually lose needles, branches and crowns, altering ground and ladder fuel types, and the subsequent path of fire (Jenkins et al., 2012). However, as Axelson et al. (2009) found, since fire was suppressed throughout most of the 20th century, MPB outbreaks in the Southern Interior of B.C. took over for the absent fire regime. Also, over time, the forest stand, likely originating from a stand-replacing fire, converted from an even-aged cohort of trees, to an uneven-aged stand due to the gradual fall-down of beetle-killed pines (Axelson et al., 2009).

Due to the socio-economic and environmental implications of this blow to the province's timber supply, recommendations for increasing fiber production were made by the Special Committee on Timber Supply (SCTS) in 2012. One recommendation included escalating silvicultural practices, such as fertilization, to encourage the growth of juvenile stands, namely those aged 15-30, and 30-70 years old. According to Brockley (1996), lodgepole pine stands originating from wildfire, aged 25-30 years, have the highest potential for volume gain from fertilization. Older stands that were not thinned, or where fire was prevented from naturally thinning, are not ideal candidates for fertilization due to the limits to crown growth (Brockley, 1996).

Timber harvesting

Besides wildfire and beetles, timber harvesting is another typical forest disturbance in the Central Interior of B.C. With bioenergy potentially becoming a mainstay energy source, the amount of wood debris removed from the harvest site could become worrisome (Hannam et al., 2017). Retaining adequate amounts of coarse woody debris (CWD) is vital for providing food and habitat for forest flora and fauna, for promoting soil stability and carbon storage, all which essentially contribute to a healthy ecosystem (Harmon et al., 1986; Stevens, 1997). Biomass removal as a result of timber harvest can have repercussions for the ecosystem, and the extent in severity and duration can depend on a number of factors associated with site, plant species and climate (Thiffault et al., 2010). In some Swedish forests, whole-stem harvesting, the most intensive harvesting practice, can impact site productivity for up to 15-16 years afterward (Olsson et al., 1996). Moreover, the removal of biomass can cause soil acidification due to leaching of important base cations (Levula et al., 2000). Much of a conifer’s nutrient stores are associated with the soil-root interface so when the forest stand is removed, these plant nutrients are liable to leach away due to less adsorption occurring at the root surface (Persson & Ahlström, 1990). This leads to a depletion in soil nutrient levels and can induce soil acidification (Federer et al., 1989; Olsson et al., 1996). The mineralization capacity and organic matter inputs are also altered after timber harvest, with the severity of these soil conditions depending largely on the intensity of timber removal (Olsson et al., 1996). This nutrient shortfall is the challenge faced by forest managers and planners tasked with reforestation. To offset this imbalance, fertilization at the time of planting could offer a source of nutrition. However, if considering ash application as an alternative to synthetic fertilizer, it has been widely suggested that application to seedlings should be avoided (Augusto et al., 2008). By adding ash as an amendment, the modification of the seedling's environment may be too drastic, especially when the seedling has not had enough time to establish some resilience (Augusto et al., 2008).

Ash fertilization

Ash composition

In general, wood ash is valued for its levels of Ca^{2+}, K^{+}, Mg^{2+} and P (Hannam, 2016; Pitman, 2006; Pöykiö et al., 2004; Steenari et al., 1999; Vance, 1996). Calcium, which makes up 10 to 30% of ash (Emilsson, 2006), is a fundamental nutrient that contributes to the structural integrity of plant cell walls (van den Driessche, 1991). Calcium deficiency in plants causes an inability to allocate resources for protecting its root tips from toxic levels of metals, such as aluminum (Kimmins, 2004), which is another component in ash.

There are many factors that influence the levels of plant macronutrients (K, Ca, Mg, P and S), micronutrients (i.e. Fe, Mn and Cl), and trace elements in bioenergy ash. For one, tree species can influence the composition of ash, with hardwoods yielding ash with higher levels of macronutrients than conifers (Pitman, 2006). Bark and foliage yield higher ash content than the inner white wood (Werkelin et al., 2005). Also the combustion temperature will impact important elements (e.g.: potassium) and metals (e.g.: aluminum) with 500-900°C being optimal for macronutrient retention (Pitman, 2006).

The collection zone of the ash (i.e. fly or bottom), also plays a crucial role in ash composition (Demeyer et al., 2001; Pitman, 2006). Fly ash contains the lighter particles that gather in the flue of the incinerator and is collected from the electrostatic precipitators (or bag houses) built into the bioenergy system to mitigate air pollution (Dahl et al., 2010). Bottom ash (also called grate ash) is the heavier charred fragments that fall through, and is usually collected from underneath the incinerator or boiler bed (Dahl et al., 2010). While both ash types differ in texture, chemistry and nutrient levels, heavy metals are typically higher in fly ash (Dahl et al., 2010; Pitman, 2006). One of the primary concerns surrounding ash for land application is the potential for high levels of trace heavy metals, such as As, Cd, Cr, and Hg. Fly ash, which is the ash prone to higher heavy metal content, can still be a viable fertilizer, providing these levels are checked before land use (Pöykiö et al., 2004); Pitman (2006) on the other hand recommended that fly ash be avoided for land application altogether. This is somewhat contradictory to the guidelines set out under the *Environmental Management Act* and the *Public Health Act*, in the *Code of Practice for Soil Amendments* (CoPSA). The CoPSA has only listed criteria for fly ash, and no guidelines for bottom ash (Government of British Columbia, 2007). According to a Best Management Practices report released by the Ministry of Environment (MOE), the application of bottom ash would require a waste discharge permit issued by the MOE (SYLVIS Environmental, 2008).

To avoid issues with trace metals in ash, first and foremost, it is important to know the origin of the bioenergy feedstock that produced the ash (Karltun et al., 2008). Low levels of heavy metals occur naturally in wood ash, but contaminants can be introduced by way of wood containing preservatives, insecticides and other chemicals (Karltun et al., 2008). Saltwater-laden wood wastes can introduce dioxin emissions into the atmosphere during incineration (Luthe et al., 1997). Ash produced from saltwater-contaminated wood wastes, when applied as an amendment, can induce salt phytotoxicity, potentially disrupting growth in conifers (Staples & Van Rees, 2001).

When ash is applied in its loose form, the sudden abundance of important soluble cations (i.e. Ca^{2+}, K^+ and Na^+) has short-lived benefits, similar to a quick-release fertilizer, and can induce an abrupt pH change (Jacobson, 2003). Finer, loose particles of ash are liable to dissipate quicker than those of the ash with a higher content of char (Hart & Luckai, 2013). Therefore, the stabilization of fine ash into solidified pellets or granules has been widely incorporated into practice to counteract this rapid leaching (Jacobson, 2003). Granulated ash not only helps to regulate the release of important cations, it can also help to stabilize the reactivity of the ash (Steenari et al., 1999; Jacobson, 2003; Karltun et al., 2008). Processing ash in this way can also render it less soluble than loose ash (Nieminen et al., 2005), which can provide a longer supply of nutrients similar to a slow-release fertilizer (Jacobson, 2003). The extent of the nutritional cation abundance and pH change can depend largely on the soil properties and application rate (Pitman, 2006).

To help alleviate some of the challenges faced with the handling and large-scale distribution of ash, aggregation or granulation of loose ash into a hardened or pelletized form is usually recommended (Pitman, 2006). This pre-application process can help to minimize fine ash dust that can easily become airborne. This ash particulate can be a workplace hazard for labourers tasked with manually applying the ash (SYLVIS, 2008). It is advised to take necessary precautions, such as wearing appropriate personal protective equipment (i.e. face mask, gloves) to prevent any adverse effects to breathing and contact with eyes and skin.

Ash application

The earliest research on ash fertilization in forests originated in Finland, from the 1930s (Emilsson, 2006). In Finland, ash fertilization has been used to balance for K and P depletion from timber harvesting, which typically occurs on millions of hectares of drained peatlands (Nieminen et al., 2005). Essentially ash fertilizer has been used to enhance the tree volume in typically nitrogen-rich, drained and dried land (Emilsson, 2006). The Danish rationale for applying bioenergy ash has been to balance the nutrient export caused by timber harvesting (Ingerslev et al., 2011). To determine the amount of ash needed to compensate for the removal of the forest stand, Ingerslev et al. (2011) found that the varying elemental levels of the bioenergy ash would prevent all nutrient levels from being satisfied completely, and at the same time. Adding supplements for S, K, Fe and Zn has been suggested to improve the quality of ash as a fertilizer (Ingerslev et al., 2011). In other words, to fully compensate for the loss of the stand, additional nutrient inputs would be needed, over and above what the ash can supply.

In Northern Germany, Rumpf et al. (2001) applied a weathered mixture of fly and bottom ash to a 50 year-old *Pinus sylvestris* stand. The maximum Ca level in the soil solution occurred after 4 months and elevated K occurred up to a depth of 100cm in the soil. In the upper horizons of the soil, increases were observed in exchangeable Ca and Mg, as well as the cation exchange capacity, nineteen months post-application (Rumpf et al, 2001).

Sweden has utilized ash generated from bioenergy production for “vitality and compensatory” fertilization, a need that arises post-harvest. Since 1998 this practice was also a means to curb the amount of bioenergy ash being landfilled (Emilsson, 2006). Incorporating ash application into forest practices has been considered a measure to compensate for the loss of nutrients occurring as a result of timber harvest, and therefore an “ecological measure” (Emilsson, 2006; p. 30).

The effectiveness of ash can last for upwards of 5 years, which was documented by Solla-Gullón et al. (2008) in a *Pinus radiata* stand in northern Spain, a temperate region. Their fly and bottom ash mixture, which had been incorporated into the upper soil horizons prior to planting the seedlings, increased growth in the initial stand establishment stage (Solla-Gullón et al., 2008).

In general, the main objectives for ash application have been to counteract the post-harvest nutrient slump and soil acidity. However, when considering the variability between study sites, soils, climate, and ash types, there are challenges in generalizing the use of ash (Hannam et al., 2017), especially considering the various BEC zones within B.C. alone. In 2008, the MOE compiled the province’s legislation regarding land application of residuals into a Best Management Practices guidebook (SYLVIS, 2008). The guide refers to the CoPSA (or the Soil Amendment Code of Practice), as well as the *Organic Matter Recycling Regulation* (OMRR; Government of British Columbia, 2002). To apply ash residuals on land, they must comply with strict criteria including levels of trace elements, for example arsenic and cadmium, as well as pH (8.9-13.5) and electrical conductivity (16-50 dS m^{-1}).

Provided that nitrogen is not limiting, ash application can improve soil conditions for plant growth (Jacobson et al., 2014; Hannam et al., 2018), due in part to the base cations (i.e.: Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}) readily available for plant roots (Saarsalmi et al., 2001). Optimal ash fertilization has often been reached with the addition of a nitrogen supplement (Saarsalmi et al., 2001; Jacobson, 2003; Park et al., 2005). In northern Finland, a long-term study of ash fertilization in a 60 year-old Scots pine (*Pinus sylvestris*) stand found volume was significantly increased by ash applied with N, compared to just nitrogen or ash alone (Saarsalmi et al., 2006).

Ash and soil pH

The alkaline pH and the buffering capacity of bioenergy ash has made it an effective agent for neutralizing acidic soils (Augusto et al., 2008). In Canada, wood ash has been used more often as a liming agent than a fertilizer (Hannam et al., 2016). On account of the acid-buffering hydroxides present in wood ash, ash can buffer or neutralize soil acidity (Saarsalmi et al., 2001). The neutralizing capacity of the ash will greatly depend on the amount of Ca^{2+}, K^{+}, Mg^{2+}, Na^{+} present in the ash as hydroxides and oxides (Saarsalmi et al., 2001). Increasing the soil pH of an acidic soil can improve soil nutrient availability for plants, the optimal range being between pH 5.5-7 (Brady & Weil, 2007).

The buffering capacity of ash is not only valued in forestry, but also in agriculture and reclamation (SYLVIS, 2008). The use of ash for liming has been employed in agricultural sectors in Alberta, B.C., New Brunswick, Nova Scotia, and

Quebec, and forestry sectors in B.C. and New Brunswick (Hannam et al., 2016). Pure ash, or completely combusted green fuels, can have a pH between 9-13 and the buffering capacity can be the equivalent of 50 to 70% of pure limestone (Emilsson, 2006). Ash is primarily composed of calcium, in the form of $CaCO_3$, which is the agent that prompts the liming effects of ash (Augusto et al., 2008; Steenari & Lindqvist, 1997).

Clearcut harvesting withdraws nutrients contained in the trees that would otherwise contribute to site's soil nutrient levels. Depending on the amount of biomass removal, the input from other organic sources may not compensate for the loss (Olsson et al., 1996). When living trees are removed, the negative charges associated with the root surface are reduced, thereby decreasing the cation exchange capacity (CEC) of the soil (Kimmins, 2004; p.295). This withdrawal of nutrients can induce an acidic soil environment, the extent dependent on the amount of harvest removal (Olsson et al., 1996). Soil acidity is an issue due to the potential for the mobilization of aluminum (McHale et al., 2007), which has been a concern in northern Europe, since the 1960s (Emilsson, 2006). This is because aluminum is liable to leach into freshwater and groundwater, harming stream quality and subsequently, fish populations (Emilsson, 2006; McHale et al., 2007). Limiting the mobilization of Al is another advantage to neutralizing an acidic soil by channeling the liming capacity of bioenergy ash.

Ash and soil communities

Macro and mesofauna

The input of ash is liable to disrupt biological processes that drive the food and habitat cycles of organisms that reside in soil. Qin et al. (2017) documented mesofauna, namely collembola, being negatively impacted by ash applied at high application rates (i.e. 17 tonnes ha^{-1}). In those cases, the ash effect was essentially temporary, but depending on soil type, osmotic stress could be the main factor in this mesofauna decline, as opposed to the rise in pH (Qin et al., 2017).

Conversely in Central Ontario, Gorgolewski et al. (2016) set up a study in a mixed-deciduous (sugar maple, and American beech) stand to determine the impact of ash application on the abundance of Eastern Red-backed Salamander. Native to the region's forests, the salamanders seemed to benefit from the increased soil pH and the moisture retention caused by the fly ash application, compared to the bottom ash treated areas and the controls (Gorgolewski et al., 2016). Ash is considered hydrophilic and can retain water through capillary action (Etiégni & Campbell, 1991, as cited in Pitman, 2006), which can be an advantageous property of soils that host many diverse forest mesofauna.

Microfauna and microflora

Soil microbes can either proliferate or dwindle, depending on the rate of ash applied (Bääth et al., 1995). Perkiömäki and Fritze (2002) found wood ash (3 tonnes ha^{-1}) increased microbial activity and soil respiration, which can be attributed to the decrease in soil acidity (Fritze et al., 1994). Yet Bååth and colleagues (1995) found an application rate of 2.5 tonnes ha^{-1} decreased microbial activity, with the fungi impacted more than the bacteria. Nevertheless, depending on the concentration of base cations in the ash, the rise in microbial activity could be short-lived (Perkiömäki & Fritze, 2002; Zimmermann & Frey, 2002).

If applied without adhering to best management practices, damage can occur to foliage, fine roots (Persson & Ahlström, 1990), and also mycorrhizae (Erland & Söderström, 1991). Regarding mycorrhizae, the abrupt pH change associated with ash fertilization can hinder the function of those associated with some berry shrub species (Moberg & Tidström, 1985 as cited in Levula et al., 2000). Even so, mycorrhizal colonization of hardened ash has been reported (Mahmood et al., 2002; Hagerberg et al., 2005). In Hagerberg et al.'s (2005) study, the presence of Ca in *Piloderma* sp., a prevalent fungi in coniferous and hardwood forests, extended from where the ash was applied to farther extremities of its fungal structure. This translocation of Ca in fact exceeded that of P and K (Hagerberg et al., 2005). The observation could be attributed to the proclivity of ectomycorrhizae to reinforce its hyphae with a calcium sheath, possibly in an effort to prevent desiccation (Arocena et al., 2001). Aside from Ca, Mahmood et al. (2002) emphasized the importance of *Piloderma*'s role in the mobilization of P from ash.

Ash and ground vegetation

When applying ash via broadcast application, in the absence of mechanical site preparation, ash is likely to be intercepted by ground vegetation, such as mosses, forbs, and shrubs. Depending on the rate of application, ash can interact immediately with the ground vegetation. In a Scots pine fertilization trial study performed in Lithuania, the moss *Pleurozium schreberi,* was impacted up to 2 years after ash and nitrogen application at a rate of 5 tonnes ha^{-1} (Ozolinčius et al., 2007). In the B.C.'s Central Interior, certain ash types mixed with urea were detrimental to some forbs and grasses, but beneficial for some shrubs and bryophytes (Hart, B.Sc. Undergraduate Thesis, University of Northern B.C., 2017). To minimize any unfavorable effects from ash, it is usually recommended to stabilize or harden the ash prior to application (Jacobson, 2003; Hannam et al., 2018). Another recommendation would be to consider the timing and seasonality of the ash application (Hannam et al., 2018). For example, ash could be applied in parallel with mechanical site preparation prior to reforestation, or during thinning and other silviculture operations, to minimize the amount of entries into the site (Hannam et al., 2018)

In Central Sweden, Norström et al. (2012) studied wood ash application of a 50-80 year old Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris* L.) stand treated with 6 tonnes ha^{-1} (with 50% moisture content equating to 3 tonnes ha^{1}). The contents of bilberries (*Vaccinium myrtillus* L.) were examined two years prior and post-application of self-hardened ash and found the levels of trace metals were unchanged (Norström et al., 2012). An increase in K in the soil solution was noted, which is a prevalent observation in many ash fertilization studies. Interestingly, boron was the only elemental level significantly higher than that of the control berries (Norström et al., 2012).

In Central Finland, after the 1986 Chernobyl accident, radiation levels in the berries and fungi were closely studied. Because of evidence showing the potential of radioactive caesium (Cs), or radiocaesium, entering the food chain, Levula et al. (2000) set up trials in 100-year-old Scots pine stands. They compared ash fertilization and prescribed burning and found both practices decreased the Cs levels in the berries several years after application (Levula et al., 2000). These findings could have implications for areas suitable for reforestation where radiation fallout is an issue.

Application in forest industry

Tree growth and forest fertilization

The success of forest fertilization will depend on many factors, such as site characteristics, fertilizer formula, the seedling stock, the application rate and the placement of the fertilizer (van den Driessche, 1991; Rose & Ketchum, 2002). Typically, the objective of fertilization in forestry is to improve a nutrient deficiency, either caused by poor land management practices or just a nutrient deficiency typical of most forest soils (Smith et al., 1997). For large-scale soil nutrient deficiencies, fertilization is usually considered too expensive, and usually requires more than just one application for it to be worthwhile (Smith et al., 1997). Repeated applications of fertilizers, complemented by another treatment such as pre-commercial thinning or brushing, can help increase volume, particularly in lodgepole pine (Lindgren et al., 2007). Ideally, to regenerate a site successfully, conditions and growing space should favour the preferred crop species, rather than the adjacent competitive species (Smith et al., 1997). Limiting competitive vegetation for the seedling could help alleviate pressures on soil moisture supply, one of the most important site factors for predicting fertilization success. If soil moisture is limited, and depending on the formula of fertilizer, excess nutrients can surround the root tips, causing saline conditions in the soil environment. This increase in salinity could lead to irreparable damage to the root system, essentially limiting the growth of the seedlings (Jacobs et al., 2004; Rose & Ketchum, 2002). Comparably, ash application can be predisposed to high salinity concentrations, even in established stands (SYLVIS, 2008).

Fertilization studies from B.C. Central Interior pine forests have documented nutrient deficiencies, with the most renowned likely being nitrogen (Brockley, 1990, 1996). This shortage is said to be attributed to the volatilization of nitrogen occurring as a result of a frequent fire regime, which were typical of pine forests in this region (Brockley, 1990). Deficiency of nitrogen in plants can impact the plant's ability to process chlorophyll, leading to the yellowing of foliage, and eventual mortality (Kimmins, 2004). Nitrogen fertilization is a common practice in some regions where moisture is not limiting, like in the Pacific Northwest for instance (Smith et al., 1997). However, the application of nitrogen can be futile if soil moisture and phosphorous levels are inadequate (Smith et al, 1997). Typical silviculture fertilizers include diammonium phosphate (at a rate of 56kg $P \cdot ha^{-1}$) and ammonium nitrate (at a rate of 225kg $N \cdot ha^{-1}$;Stovall et al., 2012). As Brockley (2012) pointed out, when assessing the needs for fertilization, ratios of P, K and Mg with N (i.e. N:P, N:K, N:Mg) are more important than the absolute values of the nutrient alone.

Aside from nitrogen, deficiencies in sulphur, as well as boron, have been documented in older pine stands in the B.C. Interior (Brockley, 1996, 1990; Sanborn et al., 2005). Sanborn et al. (2005) found in a single application of fertilizer (100kg $S \cdot ha^{-1}$ + 400kg $N \cdot ha^{-1}$), elemental S (S^0) provided a long-term sustained S level at an S-deficient site for up to 12 years. Nitrogen and sulphur are closely linked and both rely on soil microbial activity to become available for plant uptake (Kimmins, 2004). The balance of the two is important because they are both associated with certain plant processes and therefore when the levels of both are ideal (i.e. N:S), both are optimized (Brady & Weil, 2007).

Application rate determination

Ash composition and properties of the receiving site are important factors to consider when determining an appropriate ash application rate. Essentially the maximum rate of application is constrained by the levels of 11 trace elements (arsenic, cadmium, chromium, cobalt, copper, mercury, molybdenum, nickel, lead, selenium and zinc), which must be verified and within acceptable ranges when considering ash for land application (Hannam et al., 2016). Other factors sometimes considered are ash pH, moisture content, and potential contaminants, most notably dioxins and furans (Hannam et al., 2016). The level of indicator nutrients, such as phosphorous or potassium, is another tool for determining an application rate for ash (Pitman, 2006; SYLVIS, 2008; Hannam et al., 2016). For example, in Denmark, 30kg per hectare of phosphorus contained in the ash is a typical guideline (Pitman, 2006).

On the basis of the receiving site, to assess the need for fertilization of any kind, foliar analysis is a useful tool for determining what nutrients are required, potential reasons for nutrient deficiencies, and which stands will respond best to treatment (Brockley, 1996, 2001). While this technique typically applies to established conifer stands, this method does not take into consideration the needs of seedlings. Using ash to fertilize seedlings has not typically been encouraged (Augusto et al., 2008). Nevertheless, when considering ash for fertilization, as previously mentioned, the literature on the effects of ash does not always agree. For instance, Bååth et al. (1995) found an application rate of 2.5 tonnes ha^{-1} decreased microbial activity, with the fungi more impacted than the bacteria. Meanwhile a slightly higher rate of 3 tonnes ha^{-1} initiated an increase in microbes and soil respiration, as reported by Perkiömäki and Fritze (2002). Differing site conditions and ash type may have contributed to the divergent responses.

In Finland, the allowable rate of ash application for the drained and nitrogen-rich peatlands is between 3-5 tonnes ha^{-1} (Emilsson, 2006). In Southern Finland, Saarsalmi et al. (2001) studied a loose ash application of 3 tonnes ha^{-1} in a young, 5-6 year-old, Scots pine and Norway spruce stand. They found the neutralizing and fertilizing properties of the ash lingered up to 16 years after application (Saarsalmi et al., 2001). Increases in cation exchange capacity (CEC), pH and base saturation induced by ash also resonated 16 years later, with levels of exchangeable Ca and Mg still prevalent in the humus and mineral layers (Saarsalmi et al., 2001). Saarsalmi et al. (2001) suggested that 4 tonnes ha^{-1} is the optimum rate of application. Pitman (2006) explained that application rates exceeding 10 tonnes ha^{-1} tend to cause excessive dieback. On the other hand, Vance (1996) insisted that a single application of ash at a rate of 10 tonnes ha^{-1} could replace most of the nutrients that were exported through harvest.

In Canada, due to the fact fertilization using ash is in its infancy, there are no maximum limits set for application rate for forests (Hannam et al., 2018). Instead the limits set are by agricultural standards and far exceed even the highest recommended rates in Europe (Hannam et al., 2018). For instance, in Alberta, the allowable ash dosage on agricultural soils is 45 Mg ha^{-1} (cumulative) compared to a maximum of 7 Mg ha^{-1} allowed for the life of a stand rotation in Lithuania (Hannam et al., 2018).

Fertilizer placement

Generally, the most efficient way of dispersing a large quantity of ash is by mechanical ground spreader, or aerially, by helicopter (Emilsson, 2006). Ground application, likely the most cost-effective (Emilsson, 2006), is not necessarily ideal in a forest due to variable and uneven terrain; also the spacing between the trees may not accommodate a machine. While these application methods are suitable for established stands, where seedlings are involved, the method of application should limit disturbance to the seedling. The stage at which fertilization should take place has been debated, whether prior to planting or when vegetation has already been established (Emilsson, 2006; Hannam et al., 2018). Moreover, there have been fertilization delivery techniques currently used in forestry that have not yet been explored for ash.

Integrating ash application into a reforestation strategy will need consideration of the method of application, and the terrain of the area of application. In forestry, there is a method of fertilization that utilizes teabags packed with pellets of fertilizer (Reforestation Technologies Inc.). These fertilizer teabags can either be placed within the same hole as the seedling or adjacent to it, usually on the “uphill” side in a different hole. For a seedling trial in Saskatchewan, teabags with 20-6-12-6 (N-P-K-S) controlled-release fertilizer were placed in the same hole as the seedlings, 5-7cm away from the root plug (Hangs et al., 2003). This method required the treeplanter to dig a hole large enough to insert the teabag at the bottom, cover it with soil, and then inserting the seedling over top of the teabag, and closing the hole. Using the teabag method, Fan et al. (2002) used a slightly different method whereby the fertilizer teabag was placed in a separate hole on the uphill side of the microsite, 8cm away from the seedling, at a depth of 15cm. Both of these localized fertilization methods should be considered on sites where competitive species may be an issue. In comparison, a broadcast application of fertilizer could contribute to the success of non-target species, compromising the success of the conifer seedlings (Staples et al., 1999). Considering ash is typically spread by broadcast method, it may not be an ideal technique for reforestation sites where competitive species are abundant.

Study Objective and Research Questions

The main objective for the two study trials (the seedling pot study and field trial) was to determine which factors were important when utilizing ash sourced from local bioenergy generators to fertilize lodgepole pine and hybrid spruce seedlings in the sub-boreal zone of B.C. To determine this, seedlings were grown in pots outside a greenhouse and the same two species were also planted in a natural field scenario (i.e. in a harvested cutblock). Both sets of seedlings were subjected to site conditions of British Columbia’s Central Interior Sub-Boreal Spruce (SBS) biogeoclimatic zone. Monitored for the initial few growing seasons, the two study trials differed in detail, length of growing time, and number of measurable parameters. After one growing season and one winter, the seedling pot trial allowed for in-depth analysis, owing to the deconstruction of the seedlings at the end of the study period. By separating the stem with needles, root system, and soil samples, we were able to collect data for the root and shoot masses, foliar chemistry, as well as soil analyses. The field trial lasted for two growing seasons and both trials allowed for height and diameter measurements and were designed to examine the influence of these five main factors:

1- tree species
2- ash type
3- ash placement method
4- rate of application
5- nitrogen addition

To address each factor, the research objectives were framed into three questions:

1- Does the species of seedling influence the seedling's growth response to bioenergy ash application in conifers planted in the SBSwk1 BEC zone?

Two seedling species used in the study were chosen based on recommendations from the Aleza Lake Research Forest resident forester (M. Jull, RPF) and the Ministry (Steen & Coupé, 1997). The first, *Pinus contorta* (var. *latifolia*), or lodgepole pine (shorthand, Pl), was designated a preferred species for the SBS zone in this region of the Central Interior. The second species, *Picea glauca x engelmannii*, or hybrid spruce (Sx), also a preferred species for the Willow (wk1) variant of the SBS (Steen & Coupé, 1997), was selected as a species to contrast the pioneering pine.

Both species were planted in soils originating from a SBSwk1 site and fertilized with different combinations of ash and nitrogen; height and diameter growth were measured, after one growing season and one winter, and in the field, after almost a whole year (51 weeks). In the seedling pot trial, seedling growth (height and root collar diameter), root and shoot masses, nutrient levels in the foliage, soil pH and a visual vigour assessment were recorded; soil pH was also taken in the field trial. It was hypothesized that the ash-induced growth response would depend significantly on the tree species, given the conditions of the pot study and the field.

2- *Does the ash type influence seedling growth and did nitrogen addition enhance the growth response?*

We compared two ashes differing in bioenergy system of origin, but the woody fuels, or bioenergy feedstock, for both were comparable in composition. The ashes were sourced from a gasifier plant (UNBC) and a boiler system (CPLP, described later) and due to differing efficiencies of each combustion system, the ashes contrasted greatly in physical and chemical properties, including moisture content. The finer-textured UNBC ash (mainly mineral matter), with very little moisture, was predicted to have an immediate short-term effect compared to the CPLP ash (relatively high in charcoal), which consisted of larger, coarser fragments.

In substituting fertilizer for ash, the benefits of mixing in a nitrogen supplement to make up for the deficiency in ash have been well documented in the literature. It was hypothesized seedling growth would be significantly increased by ash application coupled with a nitrogen supplement. Height and diameter growth, root and shoot mass, as well as foliage chemistry were measurements taken to analyze whether adding ash with nitrogen improved the suitability of ash as a fertilizer by increasing seedling growth. Analysis of the soil pH and the seedling foliage assisted in determining whether ash type also influenced seedling growth.

3- *Does the method of ash application and the rate of application impact the growth response of the conifer seedling?*

After establishing whether ash with or without nitrogen initiated a growth response, the method of distributing ash and the rate at which it was applied were the next factors examined. The first of the two placement techniques was the broadcast (Bc) method, whereby the ash was spread evenly over the ground around the seedling basal area. The second type of ash delivery was adopted from a technique already employed in forestry, and involved placing ash in a sealed filter pouch, or teabag (Tb). The ash-filled teabag was then placed in an adjacent hole to the planted seedling, buried in the soil. It was hypothesized the placement or delivery mode of ash would have a significant influence on seedling growth. To determine whether the Bc and Tb placements influenced growth, the seedling stem height and diameter were measured in both trials. In the extensive seedling pot trial, in addition to the foliar nutrients and soil pH, the above and belowground growth and masses were also recorded.

Contrasting application rates to test in the study were determined by first researching allowable application limits set by local and provincial legislation, and also countries with similar temperate climates. The capacity of the teabag and the surface area of the seedling pots were also factors in the decision. In consideration of the phosphorus content contained in the UNBC and the CPLP ash, the rates within the allowable range were 3 and 5 tonnes ha^{-1} respectively. By compiling these recommendations, the high rate used in the study was 4 tonnes ha^{-1} and a halved dose was the low rate, at 2 tonnes ha^{-1}. The analyses of the height and diameter, as well as foliar chemical analysis, assisted in determining whether the rate of application was an important factor for seedling growth initiated by ash fertilization.

Chapter 2 Seedling pot trial: Conifer seedlings fertilized with ash and nitrogen grown for one year

Introduction

Addressing the ash residuals generated by the bioenergy industry is a necessary step to improving the sustainability of this form of renewable energy. Currently, most bioenergy ash is landfilled in B.C., but considering its potential applications in forestry, exploring the value-added benefits of ash should be encouraged. Bioenergy ash produced through the combustion of wood wastes from paper mills has the potential for use as a liming material and as a dilute fertilizer (Naylor & Schmidt, 1989). A source of several macro- and micronutrients, ash could provide a valuable boost to conifer seedlings, which can be important during the initial establishment stage. Although ash application of seedlings has not been well explored, introducing ash into the reforestation stage could be a novel way of utilizing waste ash.

Bioenergy technologies, the origin site of the woody feedstocks used for bioenergy production, and post incineration handling of the ash are just some of the factors that add to the variation of ash types (Hope et al., 2017). The utilization of ash as a forest fertilizer requires a certain degree of handling, which adds to the challenges of applying it on a large scale. It is especially more complex in a forestry scenario compared to an agricultural one (Hannam et al., 2017), considering the constraint of access and terrain in a forest, compared to a farm field. Ash applied to agricultural fields is easily incorporated into the upper layer of soil, which is not always practical in forestry. Despite the differences, both agriculture and forestry scenarios must deal with the dust and particulate that is generated by ash application. This can pose occupational hazards to workers and can also make it difficult to apply ash at the target application rates. Off-site receptors may be impacted when ash dust moves into unintended areas. In consideration of these issues, two methods of ash delivery to young conifer seedlings were considered in this trial. The broadcast (Bc) method can be labour-intensive and the exposure to the ash dust can be excessive, when applying at a large scale. To contrast this method, a more localized technique that uses a teabag to contain the ash was tested. A method of fertilization already employed in forestry, this teabag delivery method essentially replicates a method that has been successfully employed in reforestation strategies throughout B.C. It is inserted alongside the conifer seedling as it is being planted by the treeplanter. The teabag, usually containing slow-release fertilizer, is placed either inside the same hole as the seedling, or an adjacent one. By substituting the fertilizer in the teabag with ash, we were able to explore a fertilization method already in practice, which also minimizes the need for extra training of treeplanters.

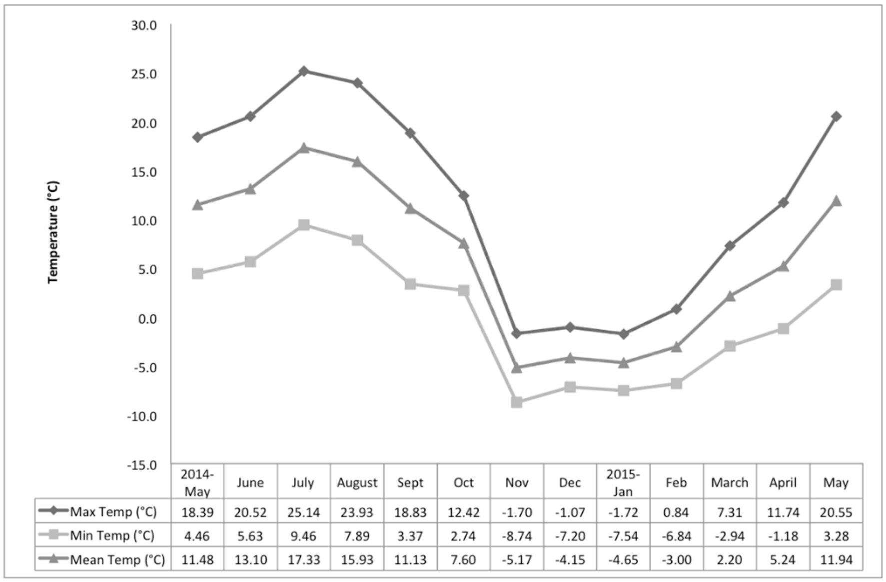
The seedling pot trial was initiated to determine if ash applied in teabags would have benefits over non-amended controls or surface-applied ash. A pot study offered more experimental control over the parallel field trial installed at a reforestation site, described later in this thesis. Although the environmental conditions of the seedlings were somewhat controlled in the pot study, the seedlings were placed outdoors and therefore, were subjected to the natural weather conditions of the seasons. After 357 days, or 51 weeks, deconstructing samples (i.e.: biomass harvest and soil sampling) allowed for detailed chemical analyses, not necessarily allowable in a field trial site intended for reforestation. Nonetheless, by breaking down the seedlings into foliage and root system, inferences on the uptake and dispersal of the ash within the specimen could be made. In an attempt to learn more about ash behavior, chemical analysis of the soil allowed for a deeper examination of the changes occurring in the soil substrate, as a result of ash additions.

Specifically, the main objective of this seedling pot trial was to determine which factors, whether ash type, method of application (broadcast surface spread or teabag), rate of application and nitrogen addition, were main drivers of seedling growth, or nutrient status of the seedling. The two types of ash chosen for our trials originated from different bioenergy systems. The fine-textured gasifier ash was compared with a high carbon (mostly charcoal) ash generated from the boiler of a local pulp mill. It was hypothesized that the low carbon ash would be better suited for land application due to its greater mineral content and liming potential. Due to the fact nitrogen combined with ash has been known to improve the impact of ash application, it was anticipated that nitrogen-treated seedlings would achieve the greatest height and diameter growth, compared to seedlings not treated with nitrogen.

Materials and Methods

Site description and trial design

Located in Prince George, British Columbia, on the campus of the University of Northern B.C., the I.K. Barber Enhanced Forestry Laboratory (EFL) was the site for the seedling pot trial. Ninety-five lodgepole pine seedlings and 95 hybrid spruce seedlings with soil modified with ash and/or nitrogen were grown in pots outside in the fenced compound at the EFL, situated on the north aspect of the compound. From May 2014 to May 2015, the seedlings were observed for almost a full year (357 days). The weather data for the time period of this trial is plotted in Figure 1.



	2014-May	June	July	August	Sept	Oct	Nov	Dec	2015-Jan	Feb	March	April	May
Max Temp (°C)	18.39	20.52	25.14	23.93	18.83	12.42	-1.70	-1.07	-1.72	0.84	7.31	11.74	20.55
Min Temp (°C)	4.46	5.63	9.46	7.89	3.37	2.74	-8.74	-7.20	-7.54	-6.84	-2.94	-1.18	3.28
Mean Temp (°C)	11.48	13.10	17.33	15.93	11.13	7.60	-5.17	-4.15	-4.65	-3.00	2.20	5.24	11.94

Figure 1: The mean, maximum and minimum temperature data collected from the weather station located at the Prince George Airport (YXS; 53°53'03" N:122°40'39" W), elevation 691m (Government of Canada, 2015).

An outline of the trial design is given in Table 1, which lists the factors (i.e.: tree species, method of ash application, ash type, and rate of application) and the associated codes for each level within the factor. A second set of samples was treated with nitrogen, the fifth factor. A total of 19 treatments were replicated 5 times, totaling 95 seedling samples for each species (for full list of treatments, see Appendix A). The first set of measurements took place from May 21st to May 23rd, 2014 (i.e. when the treatments were put in place) and the final measurements were taken after one growing season and one winter, on May 6th, 2015.

Table 1: The attributes of the trial design, with all levels for each factor associated with the treatments and the corresponding code (in parentheses). For a complete list of treatments, refer to Appendix A.

Attributes	**# of states**	**Details**
Species	2	1- *Pinus contorta* var. *latifolia* (Pli) 2- *Picea engelmannii x glauca* (Sx)
Treatment		
Ash types	2	1- Gasifier (UNBC) 2- Boiler (CPLP)
Ash placement	2	1- Broadcast (Bc) 2- Teabag (Tb)
Rate of application	2	1- High, 4 tonnes ha^{-1}(H) 2- Low, 2 tonnes ha^{-1} (L)
Nitrogen	2	With or without
Controls	3	1- Control (Cont) 2- No ash; with nitrogen (N-Only) 3- No ash; with teabags (Tb- Only)
Seedlings/replicate	5	
Total number of seedlings planted	190	Pli 95, Sx 95
Growth recordings	2	4 and 51 weeks

Soil collection and preparation

Located 60 km east of Prince George B.C, the soil for the seedling pot trial was collected at the Aleza Lake Research Forest (ALRF; 54°07′ N, 122°04′ W), on November 2nd, 2013. Just off the West Branch Road of the research forest (Figure 2), on a harvested cutblock (called Block 25), a total of 20 buckets (capacity 18-19L) were filled with the silt loam (the upper 20 cm of mineral soil was collected; forest floor was not included). The soil collection site was chosen based on its proximity to the field trial, located in Block 26 (see Appendix B for Overview map). The buckets of soil were placed in an unheated 15m x 15m storage shed located at the EFL, and were stored in mostly frozen conditions for the winter.

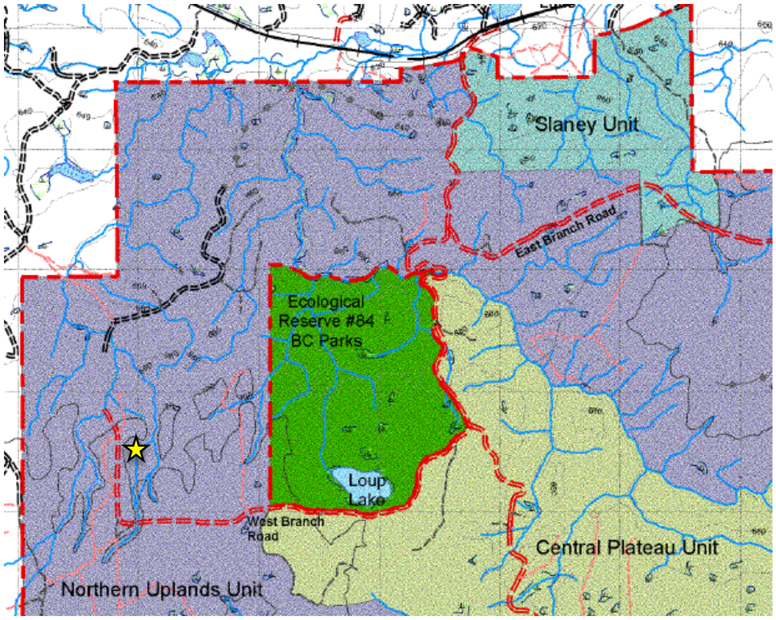


Figure 2: The general area for the soil collection from Aleza Lake Research Forest is indicated by a star symbol. (Map source: http://alrf.unbc.ca/wp-content/documents/maps/Exhibit-E-Management-Units-Tabloid.pdf)

Prior to potting the seedlings, the frozen soil was prepared for the pots by mixing it all together to reach a homogenous substrate. On March 17th, 2014, the buckets of soil were moved from the EFL storage garage into the greenhouse cooler (4°C) to allow it to gradually thaw. Once thawed and partially air-dried, the substrate was passed through a 4mm sieve to remove large debris and coarse fragments, such as rocks, gravel, bark and root wads. The soil from all the buckets was then placed on a large plastic sheet and, was well mixed, using a shovel. To reduce the risk of compaction and settlement of the soil (when potted), perlite, a white, irregularly-shaped, “popped” volcanic material, was added upon the advice of the greenhouse curators. Added at a ratio of 4:1 (soil: perlite, by volume), the porous nature of this all-natural inert product vastly improved the drainage of the potted soil. Four composite samples (each made up of 10 subsamples) of soil without perlite and four composite samples of perlite-soil mix (also consolidated from 10 subsamples) were collected, air-dried, and sent for analysis to the B.C. Ministry of Environment in Victoria, B.C (for partial description, see Table 2; full analysis in Appendix F). Overall the two soils were similar with the exception of the inorganic C level, which was higher in the soil-perlite mix. Soil moisture content was determined by oven-drying (OD) 5 samples of each soil type, at 105°C for 48 hours; the silt loam was 8.8% (g H_2O $100g^{-1}$ OD soil) moisture at the time of experimental set up.

Table 2: Selected chemical properties of the soil used in the seedling pot trial before and after the perlite was added (n= 4). Each set of values represents a mean (standard deviation in parentheses). More complete characterizations are given in Appendix G. (n = 4)

	No perlite	**With perlite**
Sand (%)	13.9 (1.24)	14.9 (0.02)
Silt (%)	69.0 (0.75)	68.6 (1.24)
Clay (%)	17.1 (0.64)	16.4 (1.23)
pH (1:1, mL H_2O, g solid)	4.96 (0.005)	4.69 (0.005)
CEC ($cmol^+$/kg)	13.9 (0.361)	13.7 (0.211)
Available P (mg/kg)	125.3 (9.806)	124.2 (2.851)
Inorganic C (%)	< 0.07 (na)	0.2 (0.10)
Total C (%)	3.4 (0.15)	3.2 (0.05)
Total N (%)	0.181 (0.006)	0.170 (0.004)
Total S (%)	0.023 (0.002)	0.022 (0.004)
B (mg/kg)	5.5 (0.29)	4.7 (0.20)
Ca (%)	0.600 (0.004)	0.582 (0.010)
K (%)	0.267 (0.007)	0.249 (0.010)
Mg (%)	0.572 (0.007)	0.571 (0.009)

Ash types and application rates

The two ashes chosen for the trial differed in bioenergy system of origin and also demonstrate the physical and chemical variations that exist between ash by-products (for brief overview, see Table 3). The UNBC ash originated from the Nexterra Bioenergy Plant (4.4 MW updraft gasifier) located on the Prince George campus of the University of Northern B.C. (UNBC). A mixture of mainly bottom ash with a fly ash component, the ash was produced from waste wood (hog fuel) generated from local lumber milling operations. The UNBC ash was sourced from the collection bin of the gasification system on July 13th, 2012. High in pH, the UNBC ash had low carbon and moisture content compared to the second ash, which was produced from the milling residues of a pulp mill. The full description of the UNBC ash is given in Appendix C.

The Canfor Pulp Limited Partnership (CPLP) supplied the second ash type, which originated from the collection bin of a boiler bioenergy production system located in the PG Pulp mill in Prince George B.C. Referred to as the CPLP or Canfor ash, it was collected from the facility on April 27th, 2012 (ash used in this study) and on January 10, 2013 (ash used in field study). The Canfor ash was primarily composed of bottom ash and contained more charcoal compared to the UNBC ash. Chemically, the UNBC ash had lower concentrations of total C, organic C, total S and N than the CPLP ash (Table 3). But, the UNBC ash exhibited a slightly higher pH, K, B and Mg than CPLP ash. Both ashes exhibited similar $CaCO_3$ equivalent (Table 3 for brief overview; full description in Appendix C).

Table 3: Chemical properties of the UNBC and CPLP ash types used in the seedling pot trial. For full characterization, refer to Appendix C.

Analyte	**UNBC Ash**	**CPLP ash #1**
pH (in water, 1:2)	11.9 (0.127)	11.1 (0.063)
$CaCO_3$ Equivalent (%)	46.3 (1.33)	28.3 (0.345)
EC (mS/cm, 1:5)	10.1 (0.445)	5.56 (0.140)
Moisture content (%)	0.13 (na)	32.5 (na)
Inorganic C (%)	1.89 (0.950)	3.28 (0.338)
Total C (%)	6.65 (0.480)	58.8 (2.62)
Total N (%)	0.037 (0.001)	0.165 (0.003)
Total S (%)	0.190 (0.008)	0.371 (0.006)
Macronutrients		
B (mg/kg)	212.3 (13.6)	145.0 (18.3)
Ca (%)	18.65 (1.111)	9.758 (0.062)
K (%)	5.1 (0.26)	2.7 (0.03)
Mg (%)	2.7 (0.13)	1.1 (0.01)
P (%)	0.8 (0.05)	0.5 (0.01)

In Table 4, trace elemental concentrations of the two bioenergy ashes used in this study were compared to the concentration limits given in the B.C. Code of Practice for Soil Amendments (CoPSA; Government of B.C., 2007). Both ash types used in this study had trace element concentrations that fell below the maximum criteria under the CoPSA (Table 4), despite the UNBC ash containing some fly ash.

Table 4: Concentrations (means with standard deviations, n=4) of trace elements in UNBC gasifier and CPLP boiler ashes relative to limits within BC Code of Practice for Soil Amendments (2007). CPLP ash #1 was used in the seedling pot trial (this chapter) and CPLP ash #2 was used in the field trial (next chapter).

	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
B.C. Allowable Limits* (μg g^{-1}dw)	**75**	**20**	**1060**	**150**	**2200**	**500**	**5.0**	**20**	**180**	**14**	**1850**
UNBC Nexterra (mg/kg)	<1.0	2.6 ± 0.05	30.6 ± 1.01	23.2 ± 3.26	81.5 ± 3.73	< 0.4	2.4 ± 1.9	6.4 ± 0.40	55.8 ± 1.48	<10	470.6 ± 18.67
CPLP ash #1 (mg/kg)	<1.0	5.1 ± 0.04	13.2 ± 0.589	19.7 ± 1.49	46.4 ± 4.73	< 0.4	1.5 ± 0.13	2.1 ± 0.50	18.3 ± 0.703	<10	641.2 ± 16.24
CPLP ash #2 (mg/kg)	<4.0	14.1 ± 1.63	10.6 ± 1.53	3.8 ± 0.90	52.2 ± 3.56	2.6 ± 0.41	<2.0	4.6 ± 0.68	13.1 ± 1.42	< 2	1206.1 ± 62.90

To determine the amounts required for each ash type, the gravimetric moisture content (MC) of the ash and the surface area of the planting pot were taken into consideration. The ash amounts were corrected based on the gravimetric MC (ω) to achieve the same application rate (dry basis) for both ashes. To do so, the moisture content of the ashes was measured by oven-drying 5 ash samples of each type at 105°C for 48 hours. Using the mean of the 5 samples, the following formula was applied to determine the gravimetric MC:

$$\omega = Mw/Md, \qquad \text{(Equation 1)}$$

(where Mw is the total amount of water lost from the samples during oven-drying and Md is the mass of the oven-dried sample)

A unitless ratio, the gravimetric MC was calculated and integrated into the formula given in Appendix D. This calculation was used to determine the amount of ash needed on an as-is basis, by taking into consideration the different moisture contents of the UNBC ash and the CPLP ash. A second CPLP ash (#2) was introduced (critical trace metals given in Table 4; more detail given later), due to the amount of ash needed for the field trial. Therefore the moisture content for the CPLP ash was based on the second CPLP ash type (Appendix D). This CPLP ash (#2) contained approximately 76% moisture, compared to the UNBC ash, which had 0.13% (Table 3).

Another basis in choosing the application rates was the capacity of the teabag. Due to the moisture content of the CPLP ash, it was a heavier material, but contained less mineral content than the UNBC ash. Taking all these factors into account, the maximum capacity for the CPLP ash in the teabag was approximately 6-7g. Given the area of a single pot was equal to 1.767×10^{-6} ha, the low rate application corresponded to 2 tonnes ha^{-1} and for the high rate, 4 tonnes ha^{-1}, if extrapolated over a larger area. To keep consistency between the two trials, and in an effort to isolate the seedling, the amount of ash remained the same for the field trial (refer to Appendix D for more detail).

Teabag and broadcast application methods

Made from compostable paper derived from a blend of thermoplastic, abaca (a plant fiber) and other cellulosic fibers (Special Tea Company, 2014), the pouches used for the teabag (Tb) application method were purchased from Amazon (www.amazon.ca). Measuring 62.5mm x 57mm (2.5”x 2.25”) in size, a given amount of the ash was filled into the teabag and to seal the bag, a heated flat iron, one typically used for hair straightening, was pressed onto the opening of the teabag. To seal the pouch, the seam was heated for 2-3 seconds, or until the teabag was properly sealed (Figure 3).

Figure 3: The flat iron, heated to medium-high heat, was pressed along the seam for 2-3 seconds to seal the teabag closed.

For the broadcast (Bc) method, each application was spread evenly over the surface area of the pot. For the samples treated with nitrogen, each dosage was carefully added on the soil surface near the basal area of each seedling. For the nitrogen application, ammonium nitrate was dissolved in water and applied at a one-time rate of 200kg N ha^{-1}. Based on the surface area of the pot (1.767×10^{-6} ha), this totaled 0.35g N per pot. Given the total N in ammonium nitrate is 35%, approximately 1g of NH_4NO_3 (weighed out accurately as per requirements) was dissolved in 100mL of deionized water and poured over the surface area of the pot for each nitrogen-treated seedling.

Seedling potting and treatment placement

The lodgepole pine (Pl) and hybrid spruce (Sx) seedlings used in the seedling pot trial were sourced from the Pacific Regeneration Technologies (PRT) nursery located in Telkwa B.C. (PRT Summit). Both species were sown in 2012, grown for one year in the nursery in a substrate high in peat moss. Separated by cells in a tray of dense polystyrene, or Styrofoam, within each cell the roots grew and bound around the substrate creating a root “plug”. These particular containers, known as plug-styroblock (PSB) containers, yielded seedling stock with root plugs 4cm in diameter and 12cm in height; hence the shorthand 412A PSB (PRT, 2014). The seedlings were extracted, or lifted, from the styroblocks in November 2013 and stored in a freezer for the winter.

On March 11th, 2014, the frozen seedlings were received at the EFL and stored in the walk-in cooler (4°C) to allow them to thaw slowly for a few weeks. During the potting phase, from March 26th to 27th, 2014, bundles of ten seedlings were gradually taken out of the cold storage (Figure 4). In total, 95 pine and 95 spruce seedlings were randomly selected for potting. The pots were 155mm X 175mm in size (similar to #1 Black Poly Can manufactured by Anderson Die and Manufacturing, Portland, Oregon) and received a layer 5-7 cm in thickness of pebble-sized, expanded clay aggregates (produced by Grotek). These lightweight and pH-neutral clay balls, which were placed at the base of each pot, helped to conserve the amount of soil needed per pot and improve soil drainage.
When placed in the pot, each seedling was positioned slightly off-center and approximately 1300 grams (dry weight basis) of soil were gradually added to the pot, packed lightly around the root plug until it was submerged entirely by soil. The seedlings were all planted as straight and upright as possible (Figure 4).

Figure 4: Examples of the spruce seedling stock (412A PSB) selected for the trial and how each sample was potted.

After being potted, the 190 seedlings occupied a section in one of the compartments of the EFL greenhouse. Placed in a random block design with species intermixed, the pots were shuffled around the holding shelf and repositioned every two weeks to avoid confounding effects from light and temperature (Gotelli and Ellison, 2013). For approximately 6 weeks, from March 26th and 27th, 2014 to May 14th, 2014, the seedling pots were kept in cool conditions, usually above 11.5°C or outdoor ambient temperatures. Maintaining cool temperatures were intended to (1) discourage growth without the ash treatments in place and (2) to wait out winter conditions for more suitable outplanting temperatures.

On May 14th, 2014, when the outside risk of frost had subsided, the seedlings were moved from inside greenhouse to the EFL outdoor compound. The seedlings were first placed in a shady section, near the EFL building, to minimize the shock of direct sunlight. During partly cloudy weather conditions, the pots were situated in a more permanent area in the compound yard. Though sheltered from wind, the high exposure to sunlight throughout the growing season demanded regular watering of the pots by EFL staff, in addition to rain events (Table 5).

Table 5: The monthly precipitation, maximum, minimum and mean temperatures for the summer of 2014, collected from the Prince George Airport (YXS) weather station (Government of Canada, 2014)

Month	Amount of rain precipitation (mm)	Max. temp	Min. temp.	Mean temp.
May	28.7	17.3	3.0	10.3
June	28.5	20.5	5.6	13.1
July	29.2	25.1	9.5	17.3
August	24.5	23.9	7.9	15.9
September	52.8	18.8	3.4	11.1
October	63.2	12.4	2.7	7.6

The ash treatments were implemented on May 21st and May 22nd, 2014, and the nitrogen treatment was administered May 28th, 2014. For the teabag (Tb) samples, to insert the ash teabag into the pot, a small amount of soil was first excavated using a small “auger” (Figure 5). This was done carefully to minimize disturbance to the seedling plug on the side with the widest surface area. Seedlings receiving the low rate of application had one teabag filled with ash buried beside the seedling, and for the high rate, two ash-filled teabags were placed in two separate holes. To ensure a consistent amount of disturbance for all the Tb seedlings, two holes were excavated in each pot, equidistant from the seedling. That is, in the case of the low rate ash treatments, one teabag of ash was buried, and a second teabag filled with an equivalent volume of soil was placed in a second hole. Both teabags were buried at least 0.5-1cm below the soil surface of the pot. Figure 5 shows the approximate location of the first teabag, relative to the position of the seedling stem.

Figure 5: Images showing the insertion of the teabags into the seedling pots. Approximately 3-3.5 cm from the stem, the auger was inserted and twisted gently into the soil.

The broadcast (Bc) method of application involved an even spread of the ash over the surface area of the pot. When the pots were watered (using tapwater), it was necessary to ensure the water penetrated the pot, so as not to overflow and cause the runoff of the broadcast ash. Throughout the growth period, to minimize any growth influenced by non-representative lighting, watering or temperature conditions, the pine and spruce pots were intermixed and each row of pots was rotated and randomly sequenced every 4 to 8 weeks, prior to snow coverage.

On November 10th, 2014, with winter approaching, the pots were placed closer together and sawdust was packed around the outside of all the pots to insulate them (Figure 6a). The seedlings overwintered outside until May 2015, where the snow cover had melted off by mid-March (Figure 6b).

a) b)

Figure 6: (a). The seedlings, on-site at the EFL compound, as they appeared after a snowfall on December 9th, 2014. (b) By the middle of March, all of the snow had melted off and the seedlings were again exposed to the weather conditions (picture taken March 15th, 2015).

Seedling vigour assessment

On May 13th, 2015, prior to measuring the heights and diameters of the seedling samples, the vigour for each seedling was visually assessed using a scale where one represented dead and no vigour, while the highest value of four represented a lively, green seedling. There were slight physiological differences between the tree species to take into account. For the pine samples, one dead seedling, with predominantly brown or red needles, was assigned a 1 for vigour (Figure 7a). Conversely, the highest vigour of 4 signified a live pine with deep green needles throughout the whole stem (Figure 7d). For the spruce, where no samples died, vigour 2 was the lowest value assigned and it represented spruce that had a dead or irregularly-shaped leader, and faded green needles (Figure 8a). The most vigourous spruce had new needles flushing from the bud, and the older needles were deep green in colour (Figure 8c).

a) b)

c) d)

Figure 7: Representative pine samples are shown to give the scale used to assess vigour in the pine samples. Image a) shows a vigour of 1, red needles dominating the stem, b) vigour 2, reduced growth and faded green needles, c) vigour 3, good growth but faded green needles and d) vigour 4 is deep green in colour, with newly or close to bursting buds.

a)


b)


c)

Figure 8: The representative spruce samples for vigour assessment shows a Vigour 2 (a) with a stunted leader and the sample with Vigour 4 (c), deep green in colour with new needles emerging.

Stem and needle harvest

To determine the yield of aboveground biomass, the pine and spruce stems were harvested on May 13th, 2015 (59 weeks following planting, 51 weeks following the ash and nitrogen treatments). Using very sharp needle-nose shears, the stems were cut just above the swelling of the root collar. Most of the live needles, plus the whole stem trimmed to size, were placed into labeled, brown paper bags. Needles from the current year growth were targeted and harvested from the stem and set aside for foliar chemical analysis. The stem and needle bags were oven-dried at 70°C for 48 hours and dry weights were recorded as the samples were removed from the oven. Pots containing soil and root biomass were stored at 4ºC until roots could be separated from associated soil in the pots (described below).

Collecting the foliage for the chemical analysis involved selecting four random samples of a possible 5 replicates from each of the 19 treatments. The needles chosen for collection were from the leader and the upper lateral branches. For the pine samples, 1-2 g (dry weight) of needles, and for the spruce, 0.8- 1g were retrieved from the new growth of each stem. After oven-drying at 70°C for 24 hours, the foliar material was pulverized to a very fine grain using a mortar and pestle, and placed into small, labeled glass vials.

In September 2015, the foliar samples were sent for chemical analysis to the Ministry of Environment (Environmental Sustainability and Strategic Policy Division), located in Victoria, British Columbia. A complete listing of the foliar nutrient data is presented in Appendix E.

Root harvest and soil sample collection

Seedling root biomass was separated from associated soil samples (for pH analysis) during late June to early July 2015. To release the soil from the pot, the pot was inverted and, by hand, the roots were carefully separated from the soil left to soak momentarily in a tray filled with water. By hand, the roots were carefully agitated and as the water in the tray became too dark with soil, it would be replaced by fresher water. Once the water in the tray remained relatively clear, the stem and roots were then placed on paper towel to absorb as much water as possible and then placed in labeled, brown paper bags. After the root samples were oven-dried at 70°C for 48 hours, the biomass was weighed to determine the total yield of belowground material.

To collect the soil pH samples, the pot was visualized as 3 sections, and because the stem was off-center and the teabags were situated approximately 3-3.5cm from the stem (Figure 9), the soil extraction points were away from the teabags to avoid tearing them open and contaminating the soil. For the broadcast samples, the extraction points were the same and a relatively even amount from each section was loosely combined into one pile and 200g was removed, placed in labeled, plastic bags and temporarily stored in the walk-in cooler (4°C), until just prior to the pH analysis. For samples treated with the teabag application method, while the teabag usually remained intact within the soil column, it was important to prevent the contamination of the soil sample with the ash from the teabag. To do so, the teabags were carefully removed and set aside so the remaining soil could be excavated for the sample.

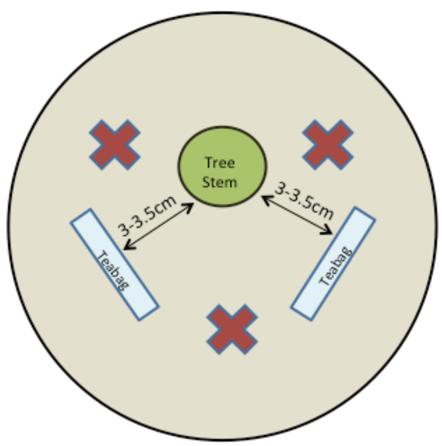


Figure 9: The pH soil samples were extracted from 3 points (marked by X) and consolidated into one sample for each seedling pot.

Four of the pots treated with teabags (Sx/UNBC/Tb/H/noN, Sx/UNBC/Tb/H/N, Pl/UNBC/Tb/H/noN, Pl/UNBC/Tb/H/N, see Table 1 or Appendix A for the shorthand treatment codes) were chosen for a more in-depth pH analysis; these samples were included in the complete pH analysis as well. For each of the four UNBC/Tb/H pots, pH readings for the soil column were done by dividing it into 6 sections instead of 4: 2 levels (Upper and Lower) divided into three sections (A, B, C) (i.e.: Upper ABC, Lower ABC). The further pH analysis for these samples was intended to explore the movement of ash solution from the teabag to the surrounding soil, for anecdotal purposes. However, there were no apparent trends observed and therefore were not examined in this thesis. Also the seedling samples were not excluded from the complete pH analysis however.

For the pH analysis performed in the lab at UNBC, 10g of soil was placed into a small cup with deionized water at a 1:2 soil-to-solution ratio. Similar to the procedure outlined in Kalra and Maynard (1991), for the first 30 minutes, each mixture was stirred a few times and, for another 30-minute period, the mixtures were left undisturbed to allow for settling. After this period, the electrode of the Thermo Orion pH meter (Model 550A) was submerged and a reading was recorded when the meter stabilized on a certain value.

Data analysis

Using a factorial design, the 5 factors were treated as fixed effects in the analysis of variance (ANOVA). The factors were ash type (UNBC, CPLP or no ash), method of ash application (Bc and Tb or no- Tb), application rate (low and high), and nitrogen (with and without). Pine and spruce seedling data were pooled and tree species was treated as the fifth factor. For a complete list of the treatments, refer to Appendix A.

The response variables analyzed in the complete factorial ANOVAs included both the aboveground and belowground units of the seedling. Foliar nutrient levels, soil pH and vigour assessment were other variables in the analysis. The aboveground variables consisted of the final mean height, mean total stem growth (Equation 2) and mean shoot mass. The belowground variables were comprised of the final mean root collar diameter (RCD), mean total root collar growth and the mean root mass. To examine the relationship between the above and belowground variables, the mean root to shoot ratio (R:S) and the height to diameter ratio (HDR) were also analyzed, as well as the total biomass.

$$\text{Total growth} = \text{end of season height} - \text{initial height} = \boldsymbol{\Delta}\ \text{height} \qquad \text{(Equation 2)}$$

Using RStudio Inc. software (R Core Team, 2014), the distribution of the data was tested with the Shapiro-Wilk test. Not all data were normally distributed, however, the boxplots used to plot the data give an impression of the distribution of the data because they represent the median, range, outliers, as well as first and third quartiles.

The data analysis began by first examining the Control treatments (i.e.: no ash, N- only and Tb-only) to determine if any effects associated with nitrogen and placement alone, exclusive of ash, impacted seedling growth. Once the extent of these 2 factors was determined, the ash type, nitrogen and species were examined in a separate ANOVA to isolate any growth associated with the ash x nitrogen treatments. The remaining secondary factors (i.e. application rate and placement) were integrated into the factorial design for the complete 5-factor ANOVA.

While the statistical data output from R-Studio will point out whether a factor or interaction of factors is significant, it does not show at which level this occurs (e.g. high vs low, Pl vs Sx). To better interpret the output, any response variables deemed significant by the ANOVA output were plotted using boxplots to better interpret at which level the significance was likely to have occurred.

Results

Aboveground growth and mass

First, the placement and nitrogen factors were tested by analyzing the no-ash (Tb-only, N-only) controls and the no-treatment controls (i.e. no ash, no N). In both cases, species was an important factor for stem growth and shoot mass, but not for the final mean height (Tables 6 & 7). However, placement was not an important factor (Table 6). Contrarily, nitrogen addition increased the mean shoot mass of the N-only control seedlings (Table 7), which was evident for both species, but especially in the N-treated pine (Figure 10).

Table 6: Factorial ANOVA output for the Control samples (n= 10) compared to the Tb-only samples (n = 10). **Bolded** values are significant.

Factor	Final height		Stem growth		Shoot Mass	
	F Value	*p* value	F Value	*p* value	F Value	*p* value
species	0.021	0.885	22.86	**< 0.001**	6.002	**0.026**
placement	0.0001	0.990	0.880	0.362	0.006	0.941
species x place	0.357	0.559	1.902	0.187	0.302	0.590

Table 7: Factorial ANOVA output for the Control samples (n= 10) compared to the N-only samples (n = 10). **Bolded** values are significant.

Factor	Final height		Stem growth		Shoot Mass	
	F Value	*p* value	F Value	*p* Value	F Value	*p* Value
species	0.201	0.660	44.93	**< 0.001**	20.97	**< 0.001**
nitrogen	0.618	0.443	2.006	0.176	33.50	**< 0.001**
species x N	0.009	0.925	4.095	0.060	3.837	0.068

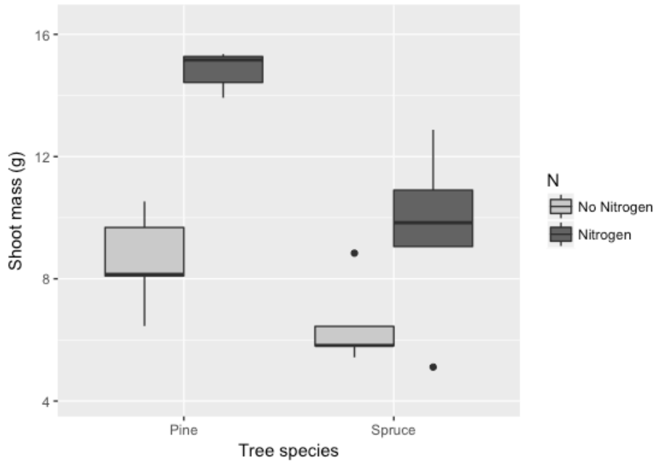


Figure 10: The median shoot mass for the Nitrogen-only and Control (No-Nitrogen, no treatment) samples compared by species and N addition (P, n = 10; S, n = 10).

To determine if ash combined with nitrogen impacted aboveground growth, the species, ash, and N factors were tested using a third-order factorial ANOVA (Table 8). Nitrogen without ash was significant for all the response variables and only the final mean height was significantly increased by ash x nitrogen interaction (p = 0.03, F value = 3.50). Specifically, the UNBC ash with N combination had a strong impact on the mean height of the pine, and less so for the spruce seedlings (Figure 11).

Table 8: The statistical summary for the ash X nitrogen factorial ANOVA ($p < 0.05$). The abbreviation “ns” represents values that were not significant. **Bolded** values are considered significant.

Factor	Final height		Stem growth		Shoot mass	
	F Value	*p* value	F Value	*p* value	F Value	*p* value
species	ns	ns	187.1	**<0.001**	77.7	**< 0.001**
ash type	ns	ns	ns	ns	3.2	**0.04**
nitrogen	3.76	0.05	4.8	0.03	309.4	**< 0.001**
species x ash	ns	ns	ns	ns	ns	ns
species x N	ns	ns	ns	ns	30.6	**< 0.001**
ash x N	3.50	**0.03**	ns	ns	ns	ns
species x ash x N	ns	ns	ns	ns	ns	ns

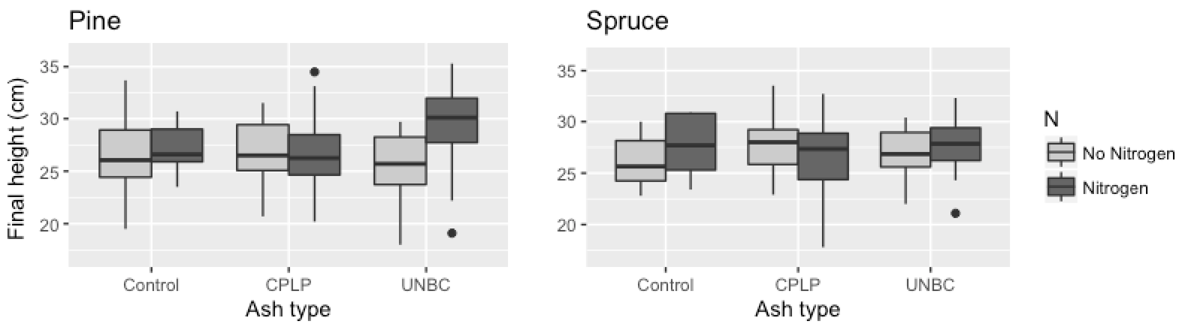


Figure 11: The final median height of the pine and spruce seedlings treated with ash x nitrogen compared to the Control samples.

Incorporating the remaining factors (application rate and placement method) into the ANOVA was limited to second-order interactions. Aside from species and nitrogen, ash type and placement of ash were significant factors to the shoot mass, but only slightly (Table 9). Also the rate x nitrogen had an interaction effect in all the variables, but again with corresponding low F-values (Table 9).

Table 9: The 5 factors and 10 interactions tested using a factorial ANOVA for the height, growth and mass variables. The abbreviation "ns" represents values that were not significant. **Bolded** values are considered significant.

Factor	Final height		Stem growth		Shoot mass	
	F Value	*p* value	F Value	*p* value	F Value	*p* value
species	ns	ns	187.1	**<0.001**	78.9	**< 0.001**
ash type	ns	ns	ns	ns	3.20	**0.04**
placement	ns	ns	ns	ns	5.24	**0.006**
rate	ns	ns	ns	ns	ns	ns
nitrogen	3.53	**0.05**	4.78	**0.03**	304.1	**< 0.001**
species x ash	ns	ns	ns	ns	ns	ns
species x place	ns	ns	ns	ns	ns	ns
species x rate	ns	ns	ns	ns	ns	ns
species x N	4.21	**0.04**	ns	ns	28.9	**< 0.001**
ash x place	ns	ns	ns	ns	ns	ns
ash x rate	ns	ns	ns	ns	ns	ns
ash x N	3.50	**0.03**	ns	ns	ns	ns
place x rate	ns	ns	ns	ns	ns	ns
place x N	ns	ns	ns	ns	ns	ns
rate x N	4.60	**0.03**	4.65	**0.03**	9.02	**0.003**

Belowground growth and mass

In the initial analysis of the placement and nitrogen factors for the controlled groups, none of the belowground variables (final RCD, total mean RCD growth and root mass) were significantly impacted by teabag placement. On the other hand, nitrogen impacted all three response variables (Table 10). The species x nitrogen interaction was significant for the root mass (Table 10), with increased root mass occurring in the N-treated pine controls, compared to the pine without N, and spruce altogether (Figure 12). This increase in mass attributed to the N addition was similar to the aboveground results (see Figure 10).

Table 10: Factorial ANOVA output for the Control samples (n= 10) compared to the N-only samples (n = 10). **Bolded** values are significant

Factor	Final RCD		Root Collar growth		Root Mass	
	F Value	*p* value	F Value	*p* Value	F Value	*p* Value
species	1.64	0.218	1.39	0.255	10.5	**0.005**
nitrogen	14.6	**0.001**	18.1	**0.0006**	17.1	**0.0008**
species x N	0.198	0.662	0.226	0.641	6.251	**0.024**

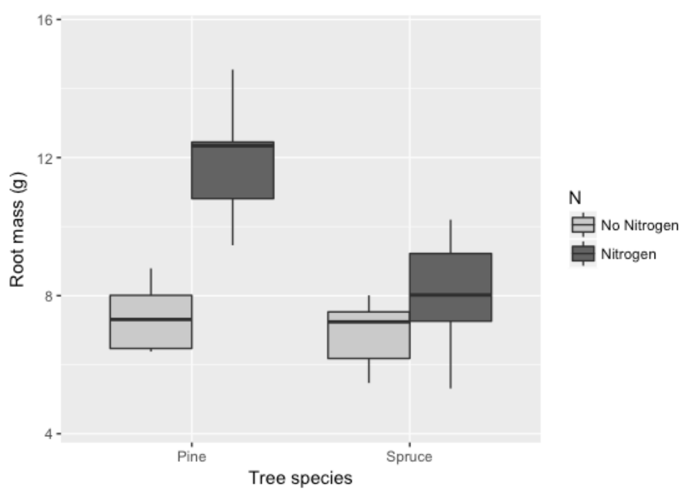


Figure 12: The median root mass for the Nitrogen-only and No-Nitrogen (Control, no treatment) samples compared by species. (n = 5)

As expected, in the three-factor ANOVA (species, ash, N), species and nitrogen were resoundingly significant for all the belowground variables (Table 11). For the final median RCD, additionally ash type, and species x ash, were significant (Table 11). An increase in median RCD was observed in the spruce treated with the CPLP ash, plus nitrogen (Figure 13). The spruce gained RCD growth from both ash x N combinations, while, conversely, the RCD of the pine seedlings, did not see any improvement with the ash and/or N addition. In fact, ash may have decreased the median RCD of the ash-only treatments, in particular, the pine treated with the UNBC ash, no N (Figure 13).

Table 11: Summary statistics for the three-factor ANOVA ($p < 0.05$) performed for the belowground variables. The abbreviation “ns” represents values that were not significant. **Bolded** values are considered significant.

Factor	Final RCD		Root collar growth		Root mass	
	F Value	*p* value	F Value	*p* value	F Value	*p* value
species	142.1	**< 0.001**	45.7	**<0.001**	47.1	**< 0.001**
ash type	5.20	**0.006**	ns	ns	ns	0.06
nitrogen	232.3	**< 0.001**	266.3	**<0.001**	178.1	**< 0.001**
species x ash	4.58	**0.011**	ns	ns	ns	ns
species x N	ns	ns	ns	ns	28.1	**< 0.001**
ash x N	ns	ns	ns	ns	ns	ns
species x ash x N	ns	ns	ns	ns	ns	ns

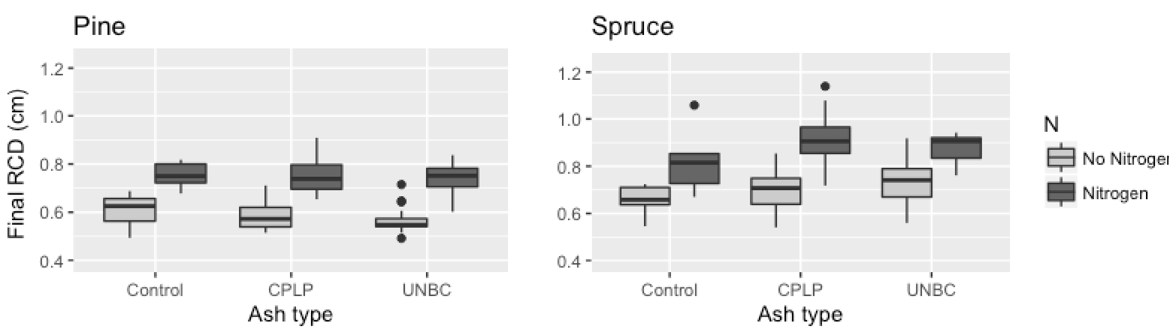


Figure 13: The final median root collar diameter (RCD) of the pine and spruce seedlings treated with ash x nitrogen compared to the Control samples.

When adding the additional factors (i.e. placement and rate) into the ANOVA, the species and nitrogen again were significant. Also the application rate x nitrogen interaction was significant for all the belowground variables, particularly the total RCD growth (Table 12). The RCD growth of the spruce and pine seedlings was improved by the low application rate of ash, combined with nitrogen (Figure 14). On the other hand, for the pine the high rate of ash without the nitrogen reduced RCD growth, when compared to the no-nitrogen pine control (Fig. 14).

Table 12: The 5 factors and their second order interactions tested using a factorial ANOVA for the final RCD measurement, RCD growth and root mass. The abbreviation "ns" represents values that were not significant. **Bolded** values are considered significant.

Factor	Final RCD		Root Collar growth		Root Mass	
	F Value	*p* value	F Value	*p* value	F Value	*p* Value
species	139.2	**<0.001**	47.6	**<0.001**	48.8	**< 0.001**
ash type	5.09	**0.007**	ns	ns	ns	ns
placement	3.28	**0.040**	4.45	**0.013**	6.66	**0.002**
rate	ns	ns	ns	ns	ns	ns
nitrogen	221.1	**<0.001**	269.2	**<0.001**	177.4	< **0.001**
species x ash	4.49	**0.013**	ns	ns	ns	ns
species x place	ns	ns	3.45	**0.034**	ns	ns
species x rate	ns	ns	ns	ns	ns	ns
species x N	ns	ns	ns	ns	27.4	**< 0.001**
ash x place	ns	ns	ns	ns	ns	ns
ash x rate	ns	ns	ns	ns	ns	ns
ash x nitrogen	ns	ns	ns	ns	ns	ns
place x rate	ns	ns	ns	ns	ns	ns
place x N	ns	ns	ns	ns	ns	ns
rate x N	5.70	**0.018**	10.9	**0.001**	4.78	**0.030**

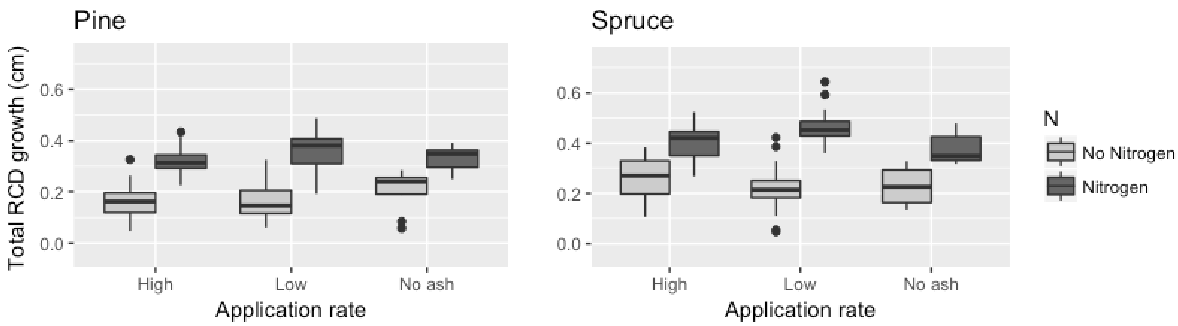


Figure 14: The median RCD growth of the pine and spruce seedlings compared by ash application rate and nitrogen addition. (n=10)

The placement factor was also significant for the RCD growth (Table 12). An increase in total root collar growth was observed in spruce seedlings treated with teabag (Tb) placement (Figure 15). The pine treated with the broadcast (Bc) application method had a slightly more elevated mean RCD growth, relative to the other pine samples (Fig. 15). These results were supported by the root mass when plotted, where an increase was observed in the mass of the pine seedlings treated with the Bc application method (Figure 16).

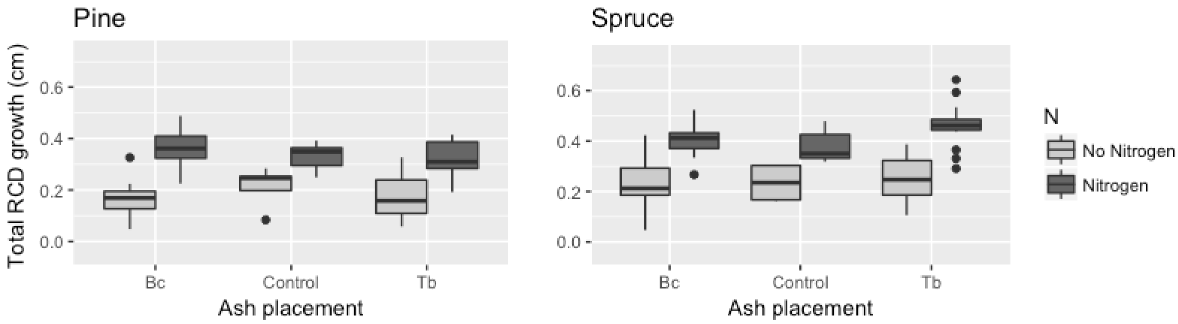


Figure 15: The median RCD growth of the pine and spruce seedlings compared by placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n=10)

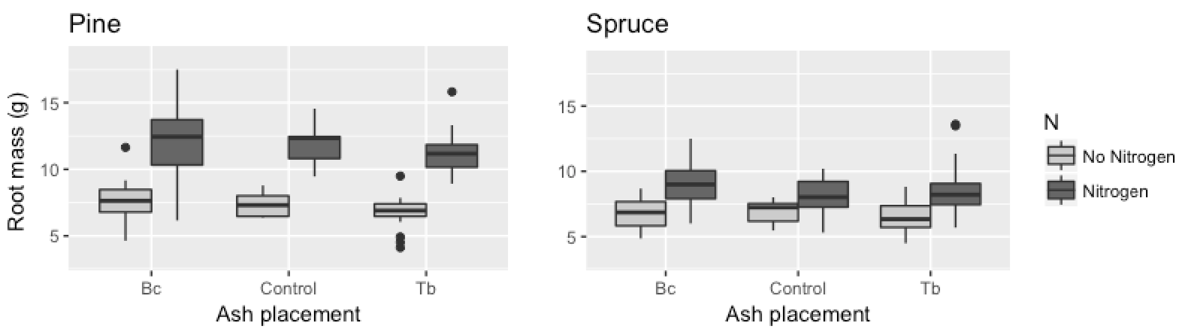


Figure 16: The median root mass of the pine and spruce seedlings compared by placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n=10)

Ratios and total biomass

Species and nitrogen were notable factors throughout the three-factor ANOVA of the root to shoot ratio (R:S), height to diameter ratio (HDR) and the total biomass (Table 13). Ash type significantly impacted all variables in some way, either alone or interacting with species (Table 13). This is evidenced by the decreased HDR values of the spruce samples treated with CPLP and N (Figure 17). In comparison, the pine N-only samples appeared to have the most decreased HDR (Figure 17).

Table 13: Summary statistics for the three-factor ANOVA ($p < 0.05$) performed for the combined above and belowground variables. The abbreviation "ns" represents values that were not significant. **Bolded** values are considered significant.

Factor	R:S		HDR		Total mass	
	F Value	*p* value	F Value	*p* value	F Value	*p* value
species	5.73	**0.018**	81.3	**<0.001**	80.2	**< 0.001**
ash type	ns	ns	ns	ns	3.6	**0.03**
nitrogen	23.9	**< 0.001**	107.2	**<0.001**	312.7	**< 0.001**
species x ash	4.73	**0.009**	3.45	**0.034**	ns	ns
species x N	ns	ns	ns	ns	37.7	**< 0.001**
ash x N	ns	ns	4.53	**0.012**	ns	ns
species x ash x N	ns	ns	ns	ns	ns	ns

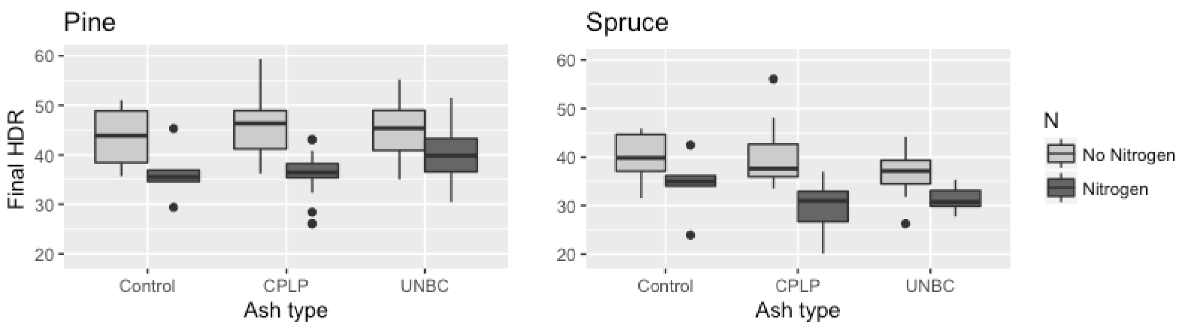


Figure 17: The final median HDR of the pine and spruce seedlings compared by ash type and nitrogen addition. (n = 10)

In the five-factor ANOVA, as well as in the previous three-factor ANOVA, the interaction species x N was a significant factor for the total mass (Tables 13 & 14). This is evidenced in the lodgepole pine, which experienced a significant increase in median total mass in the N-treated samples, particularly when compared to the non-N pine and all of the spruce samples (Figure 18). Ash placement was significant for the R:S and total mass (Table 14). For the R:S, the Tb application method reduced the median ratio, particularly in the pine samples (Figure 19).

Table 14: The 5 factors, and their second order interactions tested using a factorial ANOVA for the Root to Shoot ratio (R:S), Height to Diameter (HDR) and the total biomass (g). The abbreviation "ns" represents values that were not significant. **Bolded** values are considered significant.

Factor	R:S		HDR		Total mass	
	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value
species	6.18	**0.014**	79.9	**< 0.001**	80.2	**< 0.001**
ash type	ns	ns	ns	ns	3.56	**0.031**
placement	5.37	**0.005**	ns	ns	5.77	**0.004**
rate	ns	ns	ns	ns	ns	ns
nitrogen	25.9	**<0.001**	103.3	**< 0.001**	302.1	**< 0.001**
species x ash	5.10	**0.007**	3.39	**0.036**	ns	ns
species x place	ns	ns	ns	ns	ns	ns
species x rate	ns	ns	ns	ns	ns	ns
species x N	ns	ns	ns	ns	35.3	**<0.001**
ash x place	ns	ns	ns	ns	ns	ns
ash x rate	3.98	**0.048**	ns	ns	ns	ns
ash x nitrogen	ns	ns	4.36	**0.014**	ns	ns
place x rate	ns	ns	ns	ns	ns	ns
place x N	ns	ns	ns	ns	ns	ns
rate x N	ns	ns	ns	ns	8.63	**0.004**

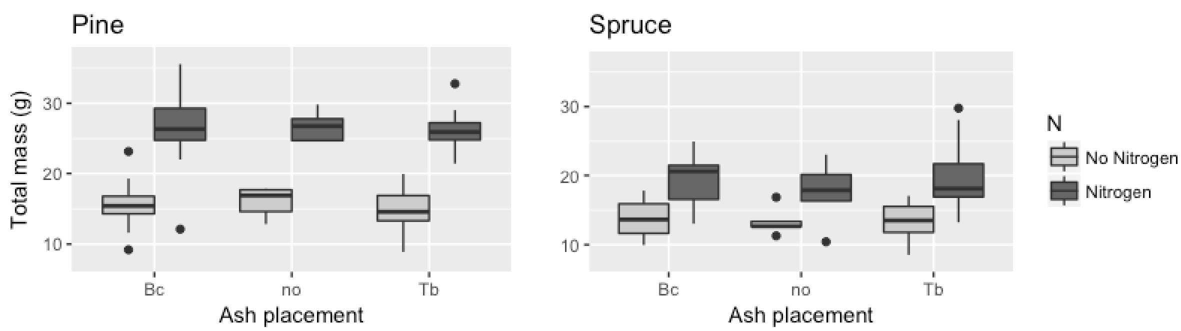


Figure 18: The median total mass of the pine and spruce seedlings compared by placement method and nitrogen addition. (n = 10)

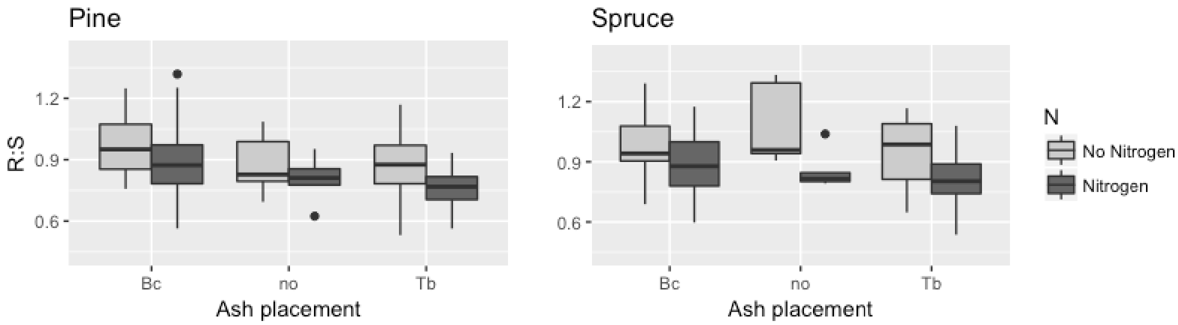


Figure 19: The median root to shoot (R:S) ratio of the pine and spruce seedlings compared by placement method and nitrogen addition. (n = 10)

Foliar analysis

Of all the factors, the two influencing most of the elemental levels in the foliage (i.e. Al, B, Ca, Cu, Fe, K, Mg, Na, N, P, S, Zn) were species and nitrogen (Table 15). To better deduce deficiencies in levels of C, K, Mg, S and P, the ratios of C:N, N:K, N:Mg, N:S, N:P were interpreted using Brockley's (2012) revised foliar nutrient criteria (given in Appendix E). With the exception of Zn, N, S and N:Mg, species type dictated the majority of nutrient percentages in the foliage, most significantly those of Ca and Al (i.e. the highest F-value; Table 15). Boron, potassium and magnesium levels were the most susceptible to the experimental factors. Boron in particular was significantly impacted by the ash type ($p = 0.001$) and the rate of application ($p = 0.007$). Increased B levels were observed in the pine and spruce seedlings treated with the UNBC ash, where nitrogen was absent (Figure 20). The N-treated pine and spruce samples were generally lower in B levels (Figure 20).

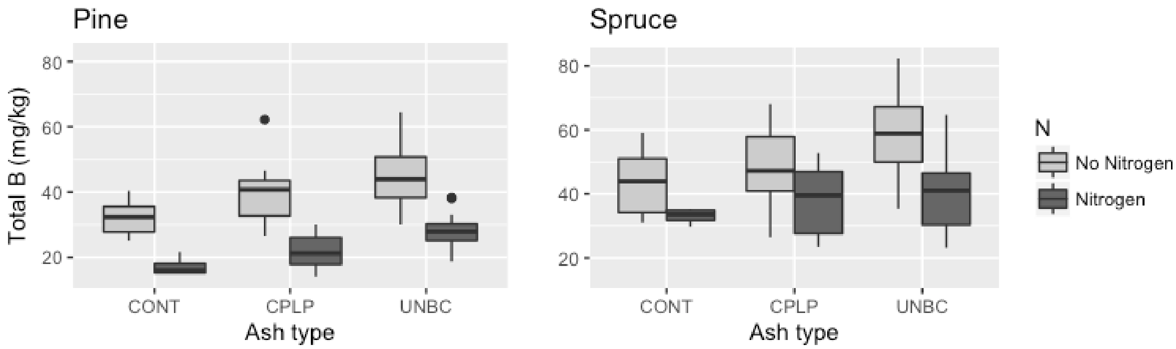


Figure 20: The median total boron (mg/kg) of the pine and spruce seedlings compared by ash type and nitrogen addition. (n = 8)

After the species and nitrogen factors, placement was the next most important factor, influencing levels of Al, K, Mg, P and Zn (Table 15). For Al in particular, the placement ($p < 0.001$) and the species x place ($p < 0.001$) were significant, which is evident in Figure 21. The total Al contained in the foliage of the non-nitrogen pine was high, especially when compared to the Control and the Bc pine sample (Figure 21; Appendix E). The Al levels of the spruce were negligible compared to the pine (Fig. 21).

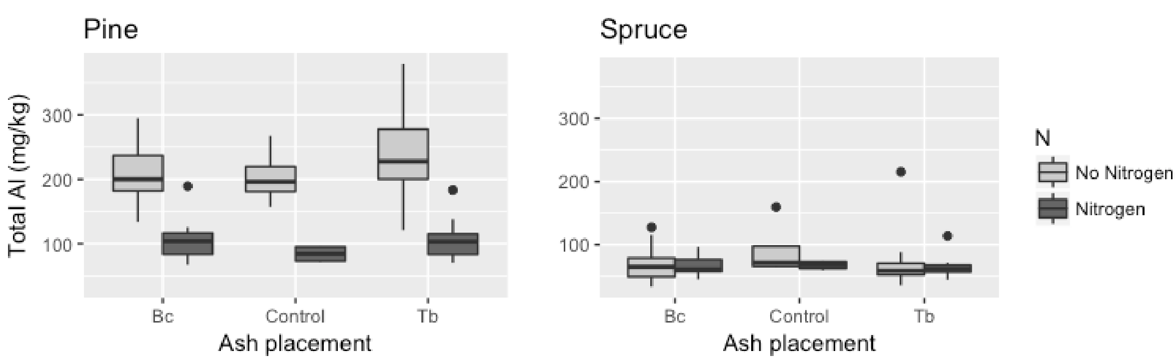


Figure 21: The median total Al (mg/kg) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

Similar to the Al levels, the nitrogen addition inversed the levels of potassium (K; Figure 22) and the K levels were also impacted by the ash placement (Table 15). The foliage of non-N pine seedlings had sufficient K levels (greater than 0.4; Figure 22), according to Brockley's foliar concentration interpretation (2012). When given as the ratio with nitrogen (i.e. N:K), the majority of the nitrogen-treated pine and spruce were deficient in K (Pl, > 2.5, Sx, > 2.0; Figure 23); the samples that had adequate levels of K were the Bc and Tb spruce, with no nitrogen (Pl, < 2.5, Sx, < 2.0; Figure 23).

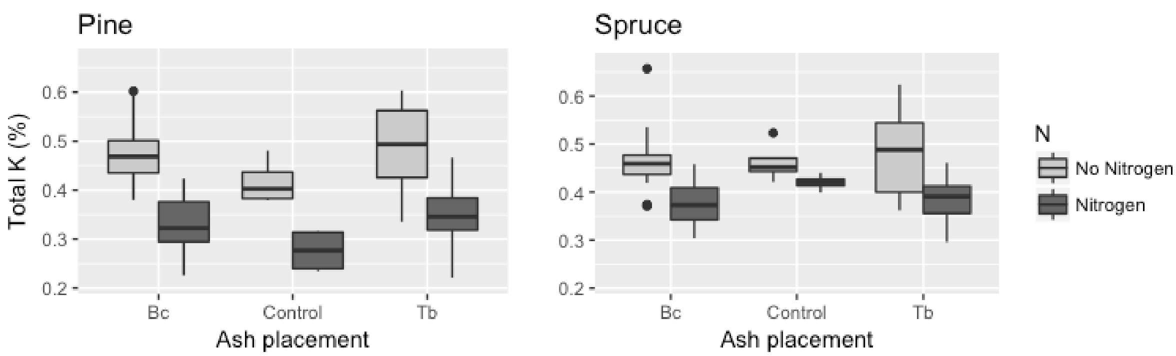


Figure 22: The median total K (%) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

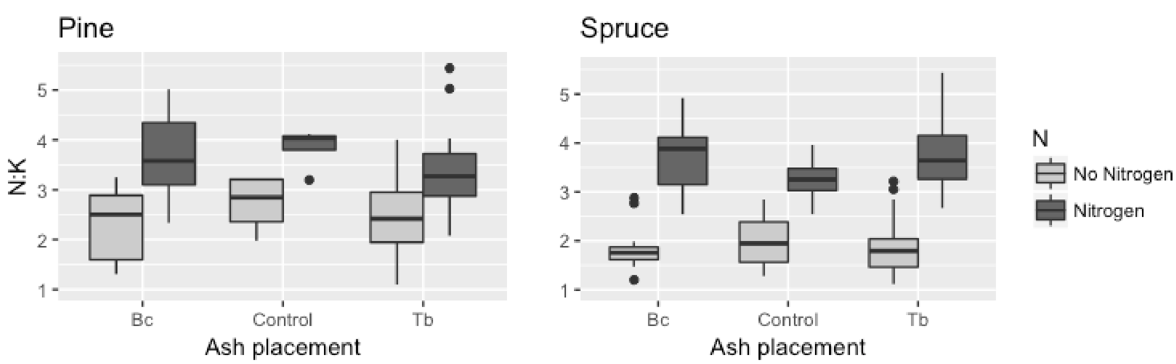


Figure 23: The nitrogen and potassium ratio (N:K) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

According to the foliar nutrient ratios set out by Brockley, only some of the N-only spruce seedlings were nearly deficient of Mg, but the remaining samples were all within adequate levels (< 15; Figure 24). Most of the nitrogen-treated samples in both species were severely deficient in phosphorus (< 10, Figure 25). With regards to the nitrogen and sulphur ratio (N:S), a slight to moderate S deficiency occurred in the spruce treated with nitrogen, according to Brockley's interpretation of foliar nutrients (N:S = 15- 20, Figure 26; Appendix E).

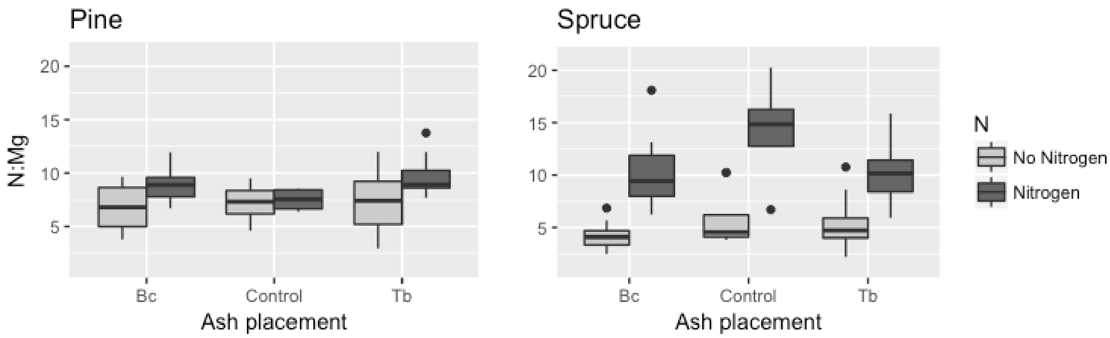


Figure 24: The median nitrogen and magnesium ratio (N:Mg) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

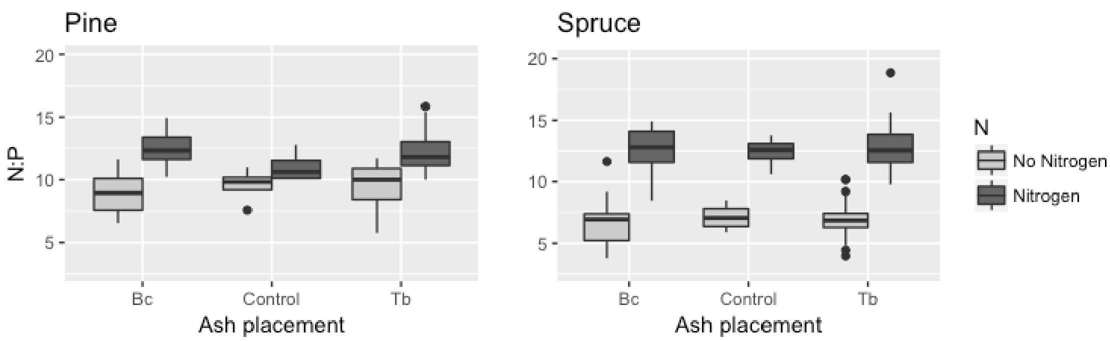


Figure 25: The median nitrogen and phosphorus ratio (N:P) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

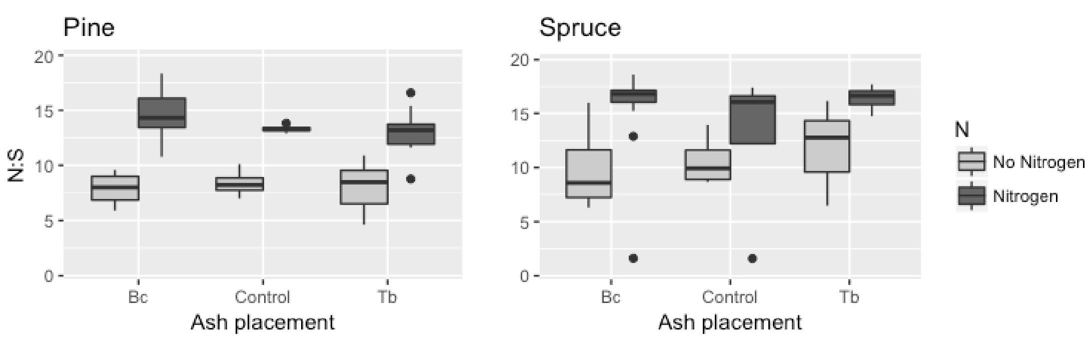


Figure 26: The median nitrogen and phosphorus ratio (N:S) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

With regards to the nitrogen levels, the most seedlings with adequate levels of N were the spruce treated with nitrogen, the greatest increase seen in the CPLP with N samples (Figure 27).

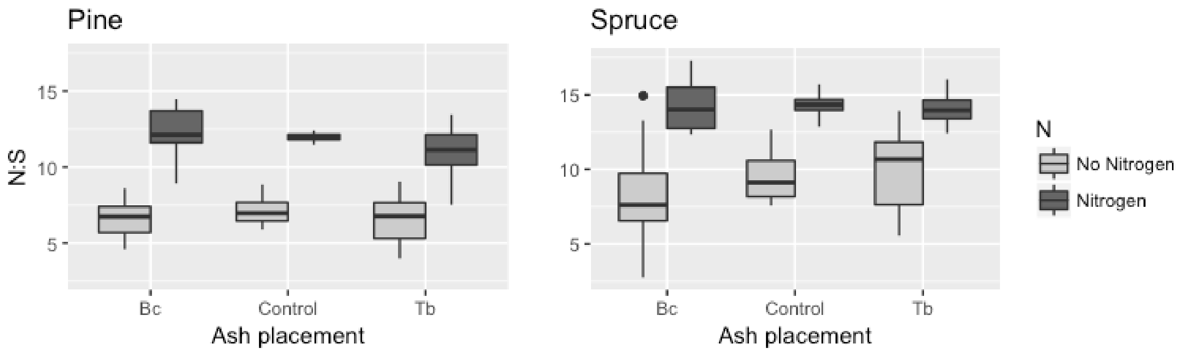


Figure 27: The median nitrogen and sulphur ratio (N:S) of the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition. (n = 8)

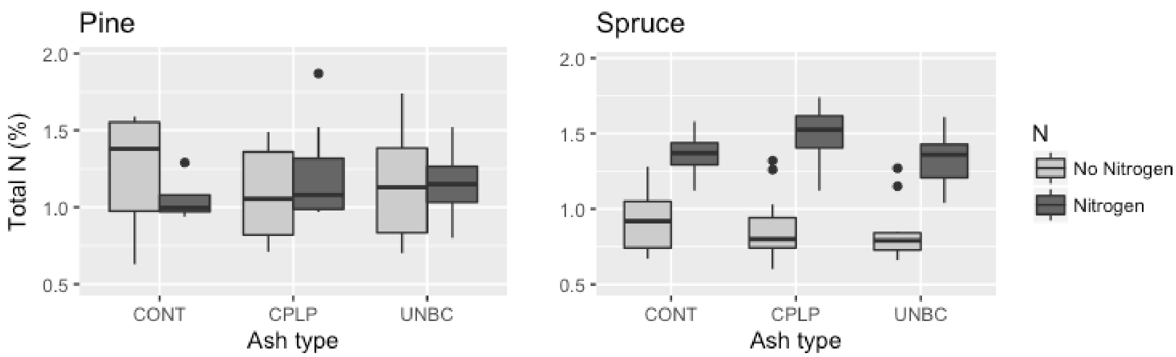


Figure 28: The median total nitrogen of the pine and spruce seedlings compared by ash type and nitrogen addition. (n = 8)

Table 15: The 5 factors, and their second order interactions tested using a factorial ANOVA for the mean nutrient percentage for the foliar chemical analysis. Asterisk (*) signifies data that were normalized according to Brockley, 2012. The abbreviation "ns" represents values that were "not significant." (n= 4)

	Al		B		Ca		Cu		Fe		Na		Mg		Zn	
	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value
species	266.8	< 0.001	75.9	< 0.001	420.7	< 0.001	14.2	< 0.001	3.60	0.060	10.8	0.001	13.05	0.0004	ns	ns
ash type	4.43	0.014	11.0	< 0.001	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
place	10.4	< 0.001	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	2.97	0.054	5.45	0.005
rate	ns	ns	7.61	0.007	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nitrogen	90.8	< 0.001	101.6	< 0.001	30.5	< 0.001	9.242	0.002	3.850	0.052	ns	ns	54.2	< 0.001	73.7	< 0.001
sp x ash	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
sp x place	12.0	<0.001	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	3.56	0.031
sp x rate	ns	ns	3.94	0.049	4.33	0.039	ns	ns	ns	ns	ns	ns	7.35	0.008	7.02	0.009
sp x N	75.2	<0.001	ns	ns	18.8	<0.001	16.8	<0.001	ns	ns	ns	ns	ns	ns	ns	ns
ash x place	ns	ns	4.1	0.05	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	5.75	0.018	ns	ns
ash x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
place x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
place x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
rate x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	4.27	0.041	ns	ns	ns	ns

	N*		K		P		N:Ca		N:K		N:Mg		N:P		N:S		S (ICAP)*	
	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value	F Value	*p* Value
species (sp)	ns	ns	4.94	0.028	14.40	0.0002	318.6	< 0.001	4.43	0.037	ns	ns	12.8	0.0005	32.4	< 0.001	ns	ns
ash type	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	4.03	0.02	ns	ns	ns	ns
place	ns	ns	13.9	<0.001	6.59	0.001	ns	ns	3.11	0.05	ns	ns	3.08	0.049	ns	ns	ns	ns
rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nitrogen	52.4	< 0.001	117.9	< 0.001	42.4	< 0.001	50.9	< 0.001	162.7	< 0.001	103.9	< 0.001	224.9	< 0.001	164.3	< 0.001	ns	ns
sp. x ash	ns	ns	3.031	0.052	ns	ns	ns	ns	3.35	0.038	ns	ns	ns	ns	ns	ns	ns	ns
sp. x place	ns	ns	ns	ns	ns	ns	3.07	0.05	ns	ns	3.68	0.028	ns	ns	4.74	0.01	ns	ns
sp. x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
sp. x N	41.1	< 0.001	9.19	0.003	ns	ns	4.96	0.03	7.74	0.006	22.77	< 0.001	24.0	< 0.001	ns	ns	12.1	< 0.001
ash x place	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x N	ns	ns	2.68	0.072	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
place x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
place x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
rate x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Soil pH

All factors (i.e. species, ash, placement, rate and N) were significant in the soil pH factorial analysis (Table 16). The UNBC ash initiated higher pH values in both pine and spruce samples, most significantly in the non-N samples (Figure 28). Of the interactions, species x ash, species x place, and species x rate were significant, asserting that placement, ash type and rate were significant for the flux in pH (Table 16).

Table 16: The 5 factors, and their second order interactions tested using a factorial ANOVA for the mean soil pH values. The abbreviation "ns" represents values that were "not significant." **Bolded** values are considered significant. (n=3)

Factor	pH	
	F Value	*p* Value
species	9.15	**0.003**
ash type	28.8	**< 0.001**
placement	40.8	**< 0.001**
rate	8.55	**0.004**
nitrogen	49.5	**< 0.001**
species x ash	6.09	**0.003**
species x place	7.67	**0.0006**
species x rate	14.9	**0.0002**
species x N	ns	ns
ash x place	ns	ns
ash x rate	3.97	**0.05**
ash x nitrogen	ns	ns
place x rate	ns	ns
place x N	ns	ns
rate x N	ns	ns

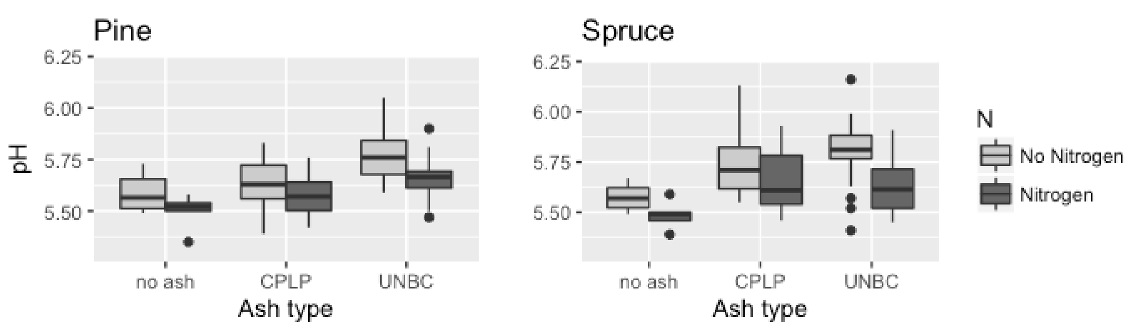


Figure 29: The median soil pH for the pine and spruce seedlings compared by ash type and nitrogen addition.

The Bc placement increased the pH for both species, especially where nitrogen was absent (Figure 29). The pH increase was more prominent in the spruce seedlings (Figure 29). In contrast, the Tb placement had little impact on the pH, especially where N was added (Figure 29).

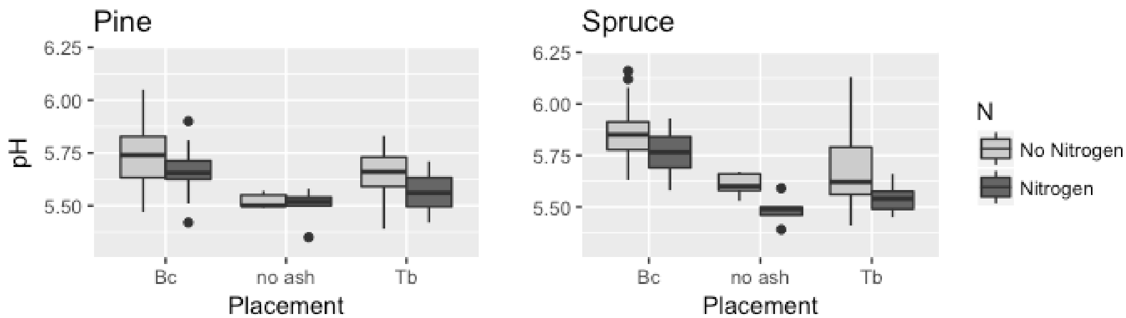


Figure 30: The median soil pH for the pine and spruce seedlings compared by ash placement (Bc= Broadcast; Tb= Teabag) and nitrogen addition.

Vigour assessment

The tendency for the nitrogen-fertilized samples to be more vigourous than their non-nitrogen counterparts was supported by the analysis of the visual vigour assessment (Table 17). The N factor was the most significant, yielding a mean vigour grade of 3.5 in the N-treated samples compared to 2.4 mean vigour for the non-N samples (Table 17). The other significant factors included the rate and the species x ash ($p < 0.05$) (Table 18).

Table 17: The mean vigour grade for the pine and spruce seedlings based on the attributes listed in Table 1.

Attribute	Feature	Mean vigour	Std dev
Species	Pl	3.0	0.6
	Sx	2.9	0.6
Ash type	CPLP	3.0	0.6
	UNBC	2.9	0.6
Placement	Bc	3.0	0.6
	Tb	2.9	0.6
Rate	H	3.1	0.6
	L	2.9	0.6
N	N	3.5	0.6
	no N	2.4	0.6
Control	No ash	2.9	0.6
	N- only	3.5	0.4
	Tb only	2.6	0.7

Table 18: The 5 factors, and their second order interactions tested using a factorial ANOVA for the mean vigour grade (n= 5). The abbreviation "ns" represents values that were not significant. **Bolded** values are considered significant.

Factor	Vigour grade	
	F Value	*p* Value
species	ns	ns
ash type	ns	ns
placement	ns	ns
rate	4.7	**0.03**
nitrogen	166.1	**< 0.001**
species x ash	3.7	**0.03**
species x place	ns	ns
species x rate	ns	ns
species x N	ns	ns
ash x place	ns	ns
ash x rate	ns	ns
ash x nitrogen	ns	ns
place x rate	ns	ns
place x N	ns	ns
rate x N	ns	ns

Discussion

The objective of the seedling pot trial was to determine what factors would be a function in treating conifer seedlings with bioenergy ash treatments. Of the five factors tested (species, ash type, placement, rate, nitrogen), the initial findings suggested that species and nitrogen addition were the two most influential, although ash type, application rate and placement method also played roles. The ash x N combination increased seedling height in lodgepole pine, while the hybrid spruce benefited by the ash x N treatment in diameter. Notably, the important factor for the belowground growth, the foliar analysis and soil pH was the ash placement method. This study attempted to use different methods of application to determine whether planted seedlings would respond to ash delivered closer to the root plug. Fertilizer delivery via teabag is said to reduce the transplant shock that occurs soon after a conifer seedling has been planted (Reforestation Technologies International, Gilroy, California 2018). Therefore incorporating ash with a placement method currently in use in B.C., such as teabags, could help to improve the viability of bioenergy ash use in the forest industry, which is the ultimate goal to this research.

To answer the first research question (whether species respond differently to ash application), the difference in growth between the species was resounding throughout the trial. This disparity in response between the species was attributed to the different resource capacities of the trees. Lodgepole pine is known to respond well to N fertilization (Brockley, 1996), which was apparent in this trial, observed in the plots of the shoot and root masses for the controls alone (Figs. 10 & 12). Also, pine may have had an advantage over the shade-tolerant spruce because the environmental conditions of the trial period likely favored the pine, a species also capable of enduring harsh environments (MacKinnon et al., 1999). Yet, despite the better height growth in the pine, the foliar analysis revealed that the N-treated spruce had adequate levels of N (Figure 27), while the N-treated pine had slightly to moderately deficient levels (Appendix E). This suggests that the pine expended its N resources early on, through extension of stem height, essentially giving it an advantage over competitive plant species. While this can be seen as a benefit in terms of overcoming competition (Grossnickle, 2012), water stress can occur if the root system is unable to sustain adequate water levels, which would induce transplant stress in the young seedling (Grossnickle, 2005). This can be difficult for the seedling to overcome during these vulnerable first years of its life span.

With respect to the shade-loving spruce, it is a species not predisposed to quick growth in the juvenile stage (Smith et al., 1997). Relevant to the second research question (whether ash type and nitrogen influence seedling growth), hybrid spruce appeared to prefer the CPLP ash treated with nitrogen through its growth in root collar (Figure 13), while the pine favoured the UNBC ash with nitrogen (Figure 11). It was hypothesized that the ash type would be influential on seedling growth, and that the high-carbon CPLP ash would act somewhat similar to a slow-release fertilizer compared to the finer-textured UNBC ash, which would resemble a fast-release fertilizer. Therefore we could infer that the species would have opposite preferences when considering ash types, bearing in mind that spruce has been unresponsive to ash treatments in the past. For example, the 5 year-old Norway spruce (*Picea abies*) stand in southwest Sweden (Wang et al., 2007) and the white spruce (*Picea glauca*) seedlings in Saskatchewan, Canada (Staples and Van Rees, 2001) did not respond well to ash application. As Staples and Van Rees (2001) found, spruce seedlings preferred the low rate of ash, while a high rate (5 Mg ha^{-1}) resulted in a decrease in spruce growth. The preference of a low rate of application was also represented in this study by the increased root collar diameter observed in both species treated with a low rate of 2 tonnes ha^{-1} (Figure 14).

The presence or absence of nitrogen was undoubtedly a significant factor throughout the seedling pot trial and it was expected that nitrogen would have a positive interaction with the ash (Jacobson, 2003; Saarsalmi et al., 2006). This was represented in the final median height of the pine seedlings treated with UNBC x N, and also the final median RCD of the hybrid spruce treated with CPLP x N. The addition of ash in conjunction with nitrogen can increase stand volumes of older pine and spruce stands in poor quality sites, such as the N-deficient sites in Finland (Saarsalmi et al., 2014). Another advantage to combining the two is that ash can prolong the effects of the nitrogen addition (Saarsalmi et al., 2014). However, it is hard to predict how long the ash x N combinations will persist and, in this case, it could depend on the ash type. For instance the UNBC ash could have short-lived result, due to its fine texture. Ash that has not been aggregated into pellets or solidified in a more contained state is prone to increased leaching of calcium over time (Steenari et al., 1999; Pitman, 2006). As the calcium dissipates, the pH lowers, causing P, Mg and other metals to release and leach more rapidly away (Steenari et al., 1999).

The third research question addressed the application technique, or placement, as well as the rate of application. The placement technique of the ash has not been widely studied and broadcast application seems to be the typical ash delivery system. Broadcast spreading of ash could be optimized by incorporating the ash into the upper soil horizons, for example, in the agricultural setting where a cultivator can be used to mix in the ash into the upper 10cm of the soil (Lupwayi et al., 2009). However, this is not always practical in a forestry setting. By employing the teabag method, which is a fertilization practice that has assisted in reforestation success (RTI, 2018), we could attempt to determine whether placing the ash closer to the root plug would improve the seedling chances at survival. Belowground variables were particularly susceptible to the placement factor, with root mass and final mean RCD impacted. A small increase in the RCD of the spruce treated with the Tb placement was contrasted by the minor increase observed in the pine treated with the Bc spread. As such, when considering the method of ash dispersal, not only should the site and accessibility be considered, but also whether it is compatible with the species selected for reforestation.

Although all the factors had some impact on soil pH, after nitrogen the ash placement by broadcasting (Bc) or by teabag (Tb) method, was the next most dominant factor. Soil pH increases were observed in both species where seedlings received the Bc method, with no nitrogen added (Figure 29). The difference in ash concentration between a broadcast spread over the surface of the pot, compared to pots containing a compact and submerged ash teabag, would likely contribute to the soil pH increase. The teabags, though weathered at the end of the study period, may have needed further decomposition (i.e. dissolution) over time to allow the ash to infiltrate the soil enough to influence the soil pH. Considering this, the teabag method could be a favourable dispersal method if a delay in nutrient release is advantageous. However, compared to the process of granulating or self-hardening ash, inserting ash into teabags may not be appealing. However, ash teabags could help to minimize dust issues associated with ash dispersal, one of the many challenges associated with ash application.

Similar to Domes et al. (2018), increased soil pH was observed where a low-carbon ash (similar to the UNBC ash type in this trial), was applied to young, 18 and 25-year old spruce stands. Our results suggested the N addition stabilized the pH somewhat. This was likely attributed to the oxidation of the N- fertilizer by soil microbes, that is, the conversion of ammonium to nitrate (i.e. nitrification), which can generate strong acids, inducing a lower, more acidic soil pH (Brady & Weil, 2007). The neutralizing capacity of the ash coupled with an ammonium-based fertilizer could be ideal for reforestation, especially on N-deficient sites, like those renowned throughout the Central Interior B.C.

Ash placement also influenced some important elements in the foliage, such as Al, B, K, Mg and P (Table 15). This has implications for the Al that can be mobilized in an acidic soil environment, which can be problematic for waterways (McHale et al., 2007) and introducing this element through ash in areas prone to acidity, may not be the best practice. However, for all the ash types used in these trials, the Al levels were quite low in the CPLP ashes and, with regard to the UNBC ash, resembled the Al levels of the potting soil (and field trial soil). The nitrogen factor was undoubtedly a player in minimizing the Al uptake in the foliage, or perhaps it could be attributed to the pH change, because the non-N pine samples were all quite high in Al (Figure 21).

Another interesting trend observed in the foliar analysis was the B and K levels, which appeared to be influenced by the nitrogen addition. Both elements had increased levels in the non-nitrogen treated samples, but only the pine seedlings that did not receive nitrogen had adequate levels of K, according to the ranges set out by Brockley (2012). Where ash is deficient in K, a supplemental application (e.g. potassium chloride, K fertilizer or biotite) can help to enhance the ash as a fertilizer. Moilanen et al. (2012) found that adding a K supplement to peat ash, an ash with low K content, was an improvement to stand volume. The increase in growth was greater when the peat ash was combined with KCl, a result slightly higher than the biotite supplement, but both more effective than ash alone (Moilanen et al., 2012).

All samples had adequate levels of B (Figure 20), and in fact, the N addition appeared to have reduced the B intake for both species, particularly those treated with UNBC ash. While stands in the Central Interior of B.C. are known to have B deficiencies, perhaps omitting the N application will enhance the input of B in an ash fertilization application, depending on the aim of the treatment. However, these levels of adequacy may be short-lived, because unlike Ca and P, which persist in ash fertilizers, boron is one of the elements easily released from ash, along with K, sodium (Na) and sulphur (S) (Nieminen et al., 2005). Other notable elements in the foliage included the Ca levels in the lodgepole pine, which differed from those of the spruce. While neither species was deficient, the levels of Ca in the spruce were consistently twice as high as those from the pine, based on the levels set out by Brockley (2012).

The levels of nutrients in the foliage of two very opposite species would have been interesting to contrast with a third species type, for example, Douglas-fir (*Pseudotsuga menziesii*). The challenges with establishing Douglas-fir in field situations, could be aided by the input of ash. Perhaps tree and plant species, like the Douglas-fir and the lodgepole pine, originating from wildfire-prone regions are better adapted to capitalizing from the input of ash.

There were some limitations associated with the seedling pot study. Firstly, the time period relative to the entire life of a conifer was quite short. However, with the more intensive analysis of the seedling structure, it was worth it to determine, if any, the translocation of ash nutrients within the initial stages of seedling establishment. Further studies could examine the translocation of the ash nutrients within the seedling and soil over a longer period of time.

Essentially the initial years of establishment are the most crucial for a seedling, and maximizing survival for planted seedlings is a goal for forest managers and silviculturalists. There are increasingly more and more factors to consider, such as the spacing or density of the seedlings, the seedling stock (e.g. species or size) selected for planting, and also if a fertilizer would benefit the seedling in the long-term.

Chapter 3 Field trial: Conifer seedlings fertilized with bioenergy ash and nitrogen in SBSwk1 harvest cutblock

Introduction

With the production of bioenergy increasing in Canada (Bradburn, 2014), the management and disposal of the subsequent ash by-products need to be taken seriously. In 2009, the Government of Canada created the Pulp and Paper Green Transformation Program, which incentivized pulp and paper mills to integrate cogeneration bioenergy power plants into their infrastructure (Bradburn, 2014). With the encouragement for more of this energy source, there also needs to be concessions made for the expense of disposal or utilization of ash. The economics of utilizing ash on forestlands will depend largely on the pre-disposal treatment (i.e.: ash stabilization), transportation costs and costs for ash dispersal (Hope et al., 2017). In addition to the arduous and logistically difficult nature of actual ash (Hannam et al., 2016), if ash-spreading machinery is being used, there will also be higher transport costs and extra planning will be needed (Hope et al., 2017). As it stands, landfilling ash is more cost-effective, although ash application in forests, presumably clear-cuts, can be competitive provided that the distance from source to site is within 100km (Hope et al., 2017). Also if costs can be reduced in the pre-treatment, in transportation or in the ash dispersal phase, the appeal of ash application will only be enhanced (Hope et al., 2017). Improving our practices and developing innovative methods to help save costs would be one of the objectives for studying the use of ash on a large scale in the forests of Central Interior BC.

If the popularity of bioenergy continues to rise, not only does the surplus of ash become an issue, but it could also have implications for harvesting intensities.

As some Scandinavian countries have found, removing the majority of the biomass associated with the forest stand can be detrimental to the long-term productivity of the site (Olsson et al., 1996; Saarsalmi et al., 2010). Satisfying a demand for bioenergy by increasing the removal of important coarse woody debris (CWD), which plays fundamental roles in the nutrient cycling of a forest ecosystem (Harmon et al., 1986; Stevens, 1997), should be avoided. Presently, many woody materials already go unused in the forest industry, beginning at the road-building and harvesting phases. According to the Forest Practices Board of BC, between 2004-2008, 15 million cubic meters of harvested wood became waste, which equated to 4.3% of the total volume harvested annually during that time period (Forest Practices Board, 2010). These wood wastes range from debris scattered throughout the cutblock, or along road right-of-ways, or wood that cannot be removed due to safety concerns (FPB, 2010). Some of this debris contributes to the CWD content, however, the wood wastes that are piled and burned on-site are the wasted resource. The utilization of woody residuals from harvest blocks for energy, as well as the milling wastes that currently make up the feedstock for bioenergy, and returning the pure ash back to the site of origin, would be a holistic and advanced approach to forestry in B.C.

The ultimate goal in ash utilization is to use the most ash that is operationally and economically feasible, and with the least detriment and most benefit to the ecosystem. By recreating the seedling pot trial in the field, we were able to revisit our study objectives, but in a natural setting and on a larger scale. Located in the Aleza Lake Research Forest, a cutblock harvested in Winter 2013 was the site for the field trial. In Spring 2014, two native conifer species were planted and subjected to the same 19 treatments as the seedling pot trial (Appendix A) to determine whether ash enhances seedling growth. Hybrid white spruce (*P. glauca x engelmannii*) and lodgepole pine (*Pinus contorta,* var. *latifolia*) were treated (via ash and/or N addition to soil) shortly after being planted out and measured before and after two growing seasons. Analyses performed on the growth increment, as well as height and diameter measurements, were intended to help determine whether the factors (tree species, ash type, ash placement, application rate, nitrogen) influenced the growth response, if any occurred. It was hypothesized that ash and nitrogen combined would increase seedling growth and responses would differ with species. Secondary factors such as ash placement method and application rate were also expected to impact the response of the seedlings to the ash treatments.

Materials and Methods

Site description

Located within the traditional territory of the Lheidli T'enneh First Nation, the Aleza Lake Research Forest (ALRF; 54°07′ N, 122°04′ W) is an approximately 9000-hectare tenure situated at the foothills of the Cariboo Range in the northern Canadian Rocky Mountains. The Biogeoclimatic Ecological Classification (BEC) zone that dominates the ALRF is the Sub-Boreal Spruce (SBS), wet- cool subzone (wk), called the Willow variant (1). The SBSwk1 zone is known to be the wettest, snowiest and coolest of the SBS zones in the Cariboo Range (DeLong et al., 2003).

Between 600-750 m above sea level, the ALRF consists of rolling terrain, with gullies throughout, and wetlands along the floodplains of the Bowron River: the area has a mean annual temperature of 3.1°C and a mean annual precipitation of

894.9mm (Jull & Karjala, 2005). The dominating coniferous species in the Willow variant include hybrid white spruce (*Picea glauca x engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus* contorta var. latifolia), with scattered Douglas-fir (*Pseudotsuga menziesii*) in the drier sites (DeLong et al., 2003; Jull & Karjala, 2005). Deciduous species include paper birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*) and black cottonwood (*Populus balsamifera ssp. trichocarpa*); species such as Devil's Club (*Oplopanax horridus*), black twinberry (*Lonicera involucrata*), thimbleberry (*Rubus parviflorus*), black currant (*Ribes lacustre*) and oak fern (*Gymnocarpium dryopteris*) make up some of the ground vegetation that dominated the study site.

The soils at ALRF are generally fine-textured, of glaciolacustrine origin and mainly Luvisols with a prominent Bt horizon resulting from clay particles migrating down from the upper soil horizons (Jull & Karjala, 2005). Upper soil layers are made up of a thin organic layer overtop a granular soil horizon, promoting ideal drainage if on sloping terrain (Jull & Karjala, 2005). According to the edatopic grid from the *Land Management Handbook* (LMH) for the Southeast portion of the Prince George Forest Region, the site series (SS) that encompassed the trial site was SS8 (Appendix H: Edatopic Grid). Soils occurring in SS8 are "rich to very rich" soils and "subhygric" soil moisture regime (Steen & Coupé, 1997; DeLong et al., 2003).

The site for the field trial was located in Block 26 (Appendix B), which was a cutblock harvested in 2013 using the clearcut system, with reserves. On May 22nd 2014, a section of the block approximately 3.1ha in size was partitioned off for this project (see Figure 31a; full map in Appendix B). The study site had relatively flat ground, homogenous plant species and the soils were primarily silt loams (Appendix

G). The boundary was marked with orange flagging ribbon and wooden stakes were posted at each of the four corners as markers. The site was then divided into 6 sub-sections, with approximately the same area, three sections for each tree species (see Figure 31b; full map in Appendix B).

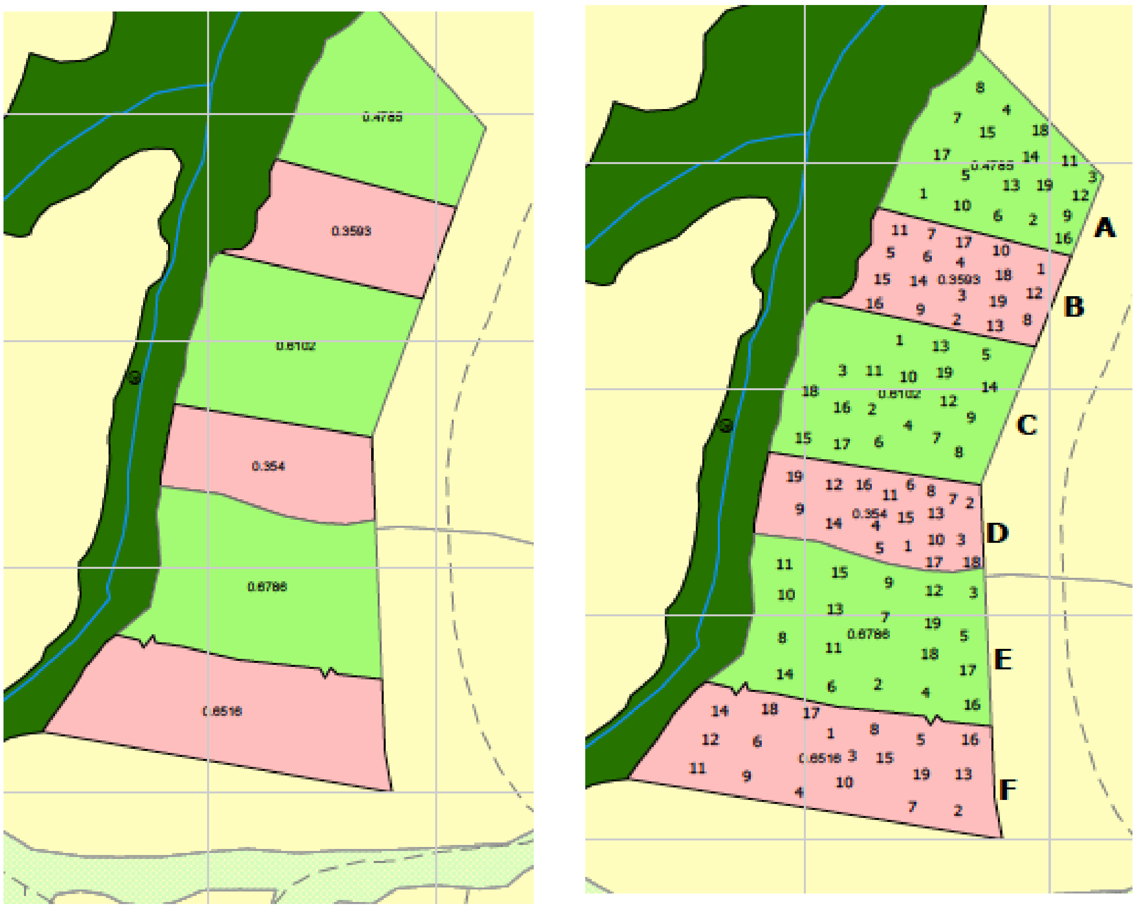


Figure 31: a) The field trial area bordered a Riparian Reserve, referred to as a Wildlife Tree Reserve (WTR) in the legend of the complete map in Appendix B. Green sections (A, C and E) were planted with lodgepole pine (Pl), and pink sections (B, D, F) represent where hybrid spruce (Sx) were planted. b) The approximate location of all the plots, each number corresponding to the treatments listed in Appendix A.

Trial design

The same experimental treatments employed in the seedling pot trial were incorporated into the field trial (see Appendix A for list of treatments). The tree species (lodgepole pine, Pl and hybrid spruce, Sx), types of bioenergy ash (UNBC and CPLP), two methods of application (Broadcast, Bc and Teabag, Tb), and the application rates (low, 2 tonnes ha^{-1} and high, 4 tonnes ha^{-1}, dry basis) remained unchanged for the larger-scaled field trial. For simplicity, the pot size used in the seedling pot trial (i.e. surface area for calculating application rates) was adopted for the field trial to keep uniformity in the amounts of ash, particularly for the teabag treatments.

The section of Block 26 allocated to the field trial was divided into 6 sub-sections and 19 plots were established, for a total of 114 plots over the whole 3.1ha trial area (Figure 31b). In the northernmost parcel (Section A), lodgepole pine was planted, with spruce planted in the adjacent section to the south (Section B). The species planted was alternated through the remaining 4 sections, ending with spruce in Section F (Figure 31b).

In each plot, six seedlings received a treatment that was randomly selected from one of the 19 different combinations by pulling numbers from a hat (see Appendix A for list of each number and the corresponding treatment); control seedlings received no treatment and were independent of the treatments, on account of their distance from the treated samples. A total of 684 seedlings were tracked over the course of two growing seasons (Summer 2014 and 2015) and a winter season (Winter 2014-2015).

Seedling planting and plot set-up

On May 23rd 2014, the hybrid spruce seedlings were planted in three of the parcels (Sections B, D and E) allocated to the field trial on Block 26 (see map in Appendix B). The seedlings, which were sourced by the timber sale licensee, were planted by professional treeplanters from a silviculture company based in Prince George, B.C. Starting June 5th 2014, three ALRF research associates planted the lodgepole pine seedlings in the remaining three sub-sections (A, C and E). The pine seedlings were sourced from the PRT Red Rock nursery, located in Red Rock B.C., 25 km south of Prince George, B.C. and were a similar stock as the seedlings from the pot trial (i.e. 412A PSB, see page 38 for more information). During the time when the seedlings were outside on the cutblock (prior to planting), they were stored in waxed nursery boxes and placed under a Silvicool tarp (Bushpro Supplies Ltd, Vernon, B.C.). The Silvicool tarp is intended to keep the seedlings at a constant temperature close to that of "deep shade" (Bushpro, 2018).

The lodgepole pine and hybrid spruce seedlings were planted at a density of 1800 stems per hectare, which equates to 2.5m spacing between each seedling. The spacing between the seedlings was checked using a 3.99m plot representing 0.005ha or 50m^2. The equivalent density for 1800 stems ha^{-1} per 3.99m plot is 9 seedlings. This plot size was also used as the metric for establishing the study plots in each of the six planted sections.

Treeplanters wore a set of treeplanting bags, which consisted of three 14" soft, vinyl "buckets" positioned on both sides of the hips and one in the back (Bushpro, 2018). Each bucket contains a Silvicool sac that held the seedlings and, similar to the tarp, helped to keep them at a cool temperature and prevent them from drying out (Bushpro, 2018). Each bucket carries a manageable number of cellophane-wrapped bundles of seedlings, which contained 10 seedlings each. As the planter would progress, bundles were unwrapped, kept in contact with a moist piece of foam and placed in the most convenient bucket for the planter to pull them from. While walking, the planter would choose a microsite for the seedling, and with the shovel in-hand, the planter would open a hole at a minimum distance of 2.5m from the previous seedling. With a planting shovel in one hand, the opposite hand would grab the seedling and insert the root plug into the hole opened by the shovel. Prior to closing the hole, the planter would ensure the root plug and stem were as straight as possible. To close the hole, a gentle boot kick or closing by hand was usually sufficient.

Once all the lodgepole pine and hybrid spruce seedlings were planted, the plot centers were established. In each section, nineteen plots representing 19 different treatments were placed in a grid-like pattern (see Figure 31b). Using a large measuring tape, 10 to 12m were measured between each plot center to ensure the plots were independent of each other. A metal wire marker with bright flagging tape was placed at the plot center as an identifier. Attached to each marker was a numbered tag chosen at random from a bag, each number representing a treatment (Appendix A).

In each marked plot, six planted seedlings from a possible 8 or 9 within the 3.99m plot were selected for the trial. Each seedling was tagged using an aluminum tag stamped with an identification number, which was tied loosely to the base of the tree stem with a metal twist tie (Figure 32).

Figure 32: A hybrid spruce seedling with an identification tag attached. The cutout of the seedling pot can be seen at the base of the tree, which helped to delineate the area receiving the broadcast spread of ash and nitrogen. The second image shows a pine seedling with some representative site plant species that would represent some potential competition for the seedlings. Photo credit: H. Massicotte

Treatment placement

The two ash types used for the ash treatments were sourced from local bioenergy producers that utilize wood wastes essentially derived from nearby forests. The ash sourced from the UNBC Nexterra gasifier located on campus in Prince George, B.C., was collected on July 13th, 2012 and consisted of both bottom and fly ash. The UNBC ash was compared to an ash originating from a boiler bioenergy system (#2) located at a Canfor Pulp Limited Partnership (CPLP) pulp mill, also in Prince George B.C. Collected on January 10th, 2013, the CPLP ash was much chunkier and more moist than the UNBC ash, which was more fine and with less moisture (Table 19; full description in Appendix C). The second CPLP ash (CPLP #2) was used for this trial (Table 19). Predetermined amounts of the two ash types (see Appendix D for sample calculations) were weighed and placed into either teabags for the Tb method or plastic bags for the Bc technique. A solid form of nitrogen (ammonium nitrate; NH_4NO_3) fertilizer was weighed and inserted into paper envelopes for storage until application in the field. On July 10th, 11th and 15th, 2014, the premeasured ash and nitrogen fertilizer treatments were applied to six designated seedlings within each one of the plots contained in the six sub-sections.

Table 19: Chemical characterization of the two ash types, UNBC and CPLP, used in the field trial. Full description is given in Appendix C.

Analyte	**UNBC Ash**	**CPLP Ash #2**
pH (in water, 1:2)	11.9 (0.127)	10.4 (0.108)
$CaCO_3$ Equivalent (%)	46.3 (1.33)	44.6 (1.44)
EC (mS/cm, 1:5)	10.1 (0.445)	9.09 (0.279)
Moisture content (%)	0.13 (na)	58.8 (1.63)
Inorganic C (%)	1.89 (0.950)	2.81 (0.335)
Total C (%)	6.65 (0.480)	50.5 (2.55)
Total N (%)	0.037 (0.001)	0.190 (0.001)
Total S (%)	0.190 (0.008)	0.51 (0.051)
Macronutrients		
B (mg/kg)	212.3 (13.6)	142.6 (8.431)
Ca (%)	18.65 (1.111)	14.4 (0.625)
K (%)	5.1 (0.26)	3.2 (0.03)
Mg (%)	2.7 (0.13)	1.2 (0.08)
P (%)	0.83 (0.05)	0.60 (0.04)

Placing the teabag treatment into the soil involved prying open a hole, by hand, with a treeplanting shovel approximately 10cm, or the width of the shovel blade away from the seedling (see Figure 33 for an example). Keeping the hole open with the shovel, the teabag was inserted into the hole so that the bottom of the bag was at a depth of about 10cm. Closing the hole, y hand or with a gentle boot kick, would place the top of the teabag approximately 2-4cm below the surface, organic layer included. The high rate of application called for two teabags to be inserted into two different holes, to attain the rate of 4 tonnes ha^{-1} rate (dry basis). Using a shovel, another hole would be cut at a 90-degree angle from the first shovel-cut, equidistant from the seedling.

Figure 33: A planter demonstrates how the teabag treatment was inserted near a pine seedling using a treeplanting shovel and how it appeared after the hole was closed. Photo credit: H. Massicotte

Figure 34: An example of how the broadcast treatment was placed. The ash and/or nitrogen was spread evenly over the surface area of the pot template. Photo credit: H. Massicotte

For the broadcast method of ash application, the ash was applied by spreading it over a cut-out of a pot used in the seedling pot trial to delineate the surface area coverage (Figure 34). For the nitrogen-treated seedlings, the pre-measured dose of ammonium nitrate pellets were scattered around the stem (refer to Figure 34).

Soil collection and characterization

Prior to the ash application in the field, we collected soil samples from nine soil pits randomly selected in order to characterize the baseline soil properties of the site. These soil pits were located at A14, A20, B3, C3, C4, D10, E7, F6, F15 (refer to Figure 31 for approximate locations). Three soil horizons overall were identified (LFH, Ae, Bm, Bg for F15) and samples for each horizon were taken from all nine pits. The 9 samples from the soil pits were organized into 3 separate categories (A/B, C/D, and E/F). Three composite samples were created by combining equal amounts from each of the collection zones, for each soil horizon. Samples were sent away to the Ministry of Environment (Environmental Sustainability Division- Knowledge Management Branch) for analysis in Victoria, B.C. Fairly low in pH, the field site's soil consisted of a thin LFH layer, with silt loam Ae and Bm/Bg horizons (Table 20; refer to Appendix G for full characterization). A relatively acidic soil, the CEC was greatest in the LFH layer, as was the total carbon and boron levels (Table 20). Available P and Mg increased with depth, the highest amounts found in the Bm horizon.

Table 20: Chemical characterization of the soil type found at the field trial site, located in the SBSwk1-Willow variant. For full description, refer to Appendix G.

	LFH n = 3	**Ae n = 3**	**Bm n = 3**
Sand (%)	na	39.9 (10.3)	45.3 (7.48)
Silt (%)	na	49.6 (7.75)	44.8 (7.77)
Clay (%)	na	10.6 (2.65)	9.90 (2.03)
pH (soil: water, 1:1)	4.9 (0.31)	4.7 (0.14)	5.1 (0.12)
CEC (cmol^{+}/kg)	12.5 (1.03)	4.9 (0.94)	4.9 (0.98)
Available P (mg/kg)	27.2 (11.3)	31.6 (24.6)	77.7 (64.2)
Total C (%)	19.1 (7.29)	1.57 (0.130)	2.34 (0.935)
Total N (%)	0.876 (0.330)	0.112 (0.009)	0.134 (0.047)
Total S (%)	0.089 (0.033)	0.011 (0.002)	0.017 (0.007)
B (mg/kg)	5.37 (0.672)	2.43 (0.228)	< 2 (na)
Ca (%)	0.756 (0.085)	0.446 (0.078)	0.497 (0.055)
K (%)	0.256 (0.041)	0.292 (0.014)	0.271 (0.030)
Mg (%)	0.205 (0.042)	0.334 (0.048)	0.605 (0.030)

Measurements and analyses

Measurements of the stem height and root collar diameter (RCD) were recorded twice during the field trial. Initial measurements were taken at the same time the treatments were applied, on July 10th, 11th and 15th, 2014. Final measurements were taken after the second growing season was presumably complete (i.e. after the buds had hardened off) on August 12th, 13th, and 14th, 2015. The height measurement was taken from the base of the stem to the top of the leader bud. To account for the non-circular stem, two RCD measurements were recorded from the lowest possible point of the stem. Seedling vigour was assessed at the time that final measurements were recorded; however, seedling vigour is not presented or interpreted in this chapter due to time constraints.

Data analysis was carried out in a similar manner as that done for the seedling pot study. However, to avoid destructive measurements, such as total belowground mass of the seedling, measurements were limited to growth increment, final height and final root collar diameter. Using R-Studio, the data was analyzed to determine whether any of the factors (tree species, ash type, application rate, ash placement, nitrogen) were significant to the response of the seedlings to treatments. In the initial analysis, only the three control treatments (No ash/No nitrogen, N-Only, Tb-Only) were tested using a factorial ANOVA. Once the effects of placement and nitrogen were isolated in the controls, the ash and nitrogen interaction was tested for all the samples, including the controls. Due to the limited output of R, if a factor (e.g.: ash type) yielded a low p-value ($p < 0.05$), a boxplot was used to interpret at which level this significant effect occurred. The final analysis included the remaining application rate and placement factors to complete the 5-factor multi-factorial ANOVA.

Results

Analysis of control treatments

To determine whether the placement of the teabag and the nitrogen treatments, both exclusive of ash, were significant factors to seedling growth, the control samples (No ash/No nitrogen, N-Only, Tb-Only) were first analyzed for variance (Tables 21 and 22). With respect to the teabag placement, aside from species being a significant factor for most of the response variables (with the exception of the final RCD, Table 21), species x placement interaction had a significant impact on the total height growth (p = 0.02, Table 21). The teabag placement may have reduced lodgepole pine height, and conversely in the hybrid spruce, may have increased it (Figure 35).

Table 21: Factorial ANOVA results for the Control samples compared to the Tb-only (n = 72). **Bolded** values are significant.

Factor	Final height		Total growth		Final RCD		RCD growth		HDR	
	F Value	*p* value	F Value	*p* value	F Value	*p* value	F value	p value	F value	p value
species	6.40	**0.014**	12.07	**0.0009**	0.147	0.702	9.43	**0.003**	11.5	**0.001**
placement	2.38	0.127	0.424	0.517	1.62	0.208	0.510	0.478	0.904	0.345
sp x place	2.95	0.090	5.27	**0.025**	2.95	0.091	1.23	0.272	0.483	0.489

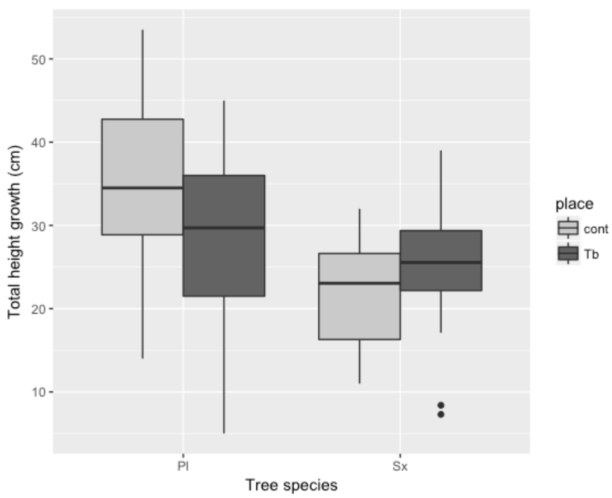


Figure 35: The median total height growth of the pine (Pl) and spruce seedlings (Sx) treated with teabags (Tb-Only) compared to the control (no-ash) seedlings.

Nitrogen was a significant factor for the final height variable and the height to diameter ratio (HDR), but only slightly (Table 22). Interestingly, the nitrogen may have reduced the growth of the N-treated seedlings, in a comparable way for both species (Figure 36).

Table 22: Factorial ANOVA results for the Control samples compared to the N-only (n = 72). **Bolded** values are significant.

Factor	Final height		Total growth		Final RCD		RCD growth		HDR	
	F Value	*p* value	F Value	*p* value	F Value	*p* value	F value	p value	F value	p value
species	1.08	0.302	28.5	**<0.001**	1.03	0.314	14.51	**0.0003**	4.98	**0.029**
nitrogen	3.82	**0.055**	0.531	0.468	0.079	0.779	0.056	0.813	6.75	**0.012**
sp x N	0.035	0.851	1.183	0.281	0.961	0.331	0.011	0.917	0.317	0.575

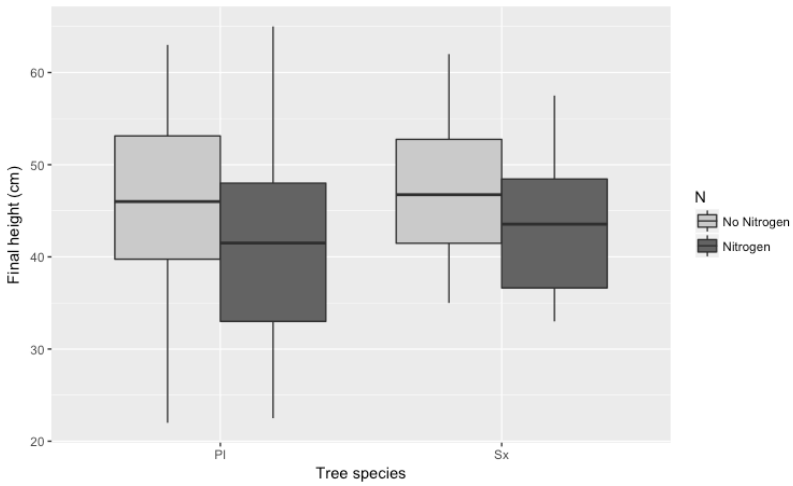


Figure 36: The final median height of the pine (Pl) and spruce (Sx) seedlings treated with nitrogen (N-only) compared to the control (no-ash, no N) seedlings.

Factorial analysis

In the second stage of the ANOVA, where ash and nitrogen factors were analyzed for the pine and spruce, species and nitrogen were the most significant factors, but not for all the variables (Table 23). The total height growth, a variable not heavily influenced by nitrogen alone, was the only variable that was impacted by ash x nitrogen combination (Table 23). Lodgepole pine growth did not appear to be significantly impacted by ash, fertilizer N or the ash x N combination, and, in contrast, hybrid spruce seedling growth responded differently to N addition, depending on the type of ash used (Figure 37). Spruce growth benefited the most when UNBC ash was applied without fertilizer N. The nitrogen added to the CPLP ash also seemed to favour the spruce seedling growth (as compared to non-N treatment, Figure 37).

Table 23: Statistical summary for the three-factor ANOVA (p < 0.05) performed for all the growth variables (final height, total growth, final RCD, RCD growth, HDR).

Factor	Final height		Total growth		Final RCD		RCD growth		HDR	
	F Value	*p* value	F Value	*p* value	F Value	*p* value	F Value	*p* value	F Value	*p* value
species	37.2	**< 0.001**	65.1	**<0.001**	ns	ns	28.7	**<0.001**	48.4	**<0.001**
ash type	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nitrogen	ns	ns	ns	ns	5.07	**0.024**	4.9	**0.03**	9.13	**0.003**
species x ash	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
species x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x N	ns	ns	3.14	**0.044**	ns	ns	ns	ns	ns	ns
species x ash x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

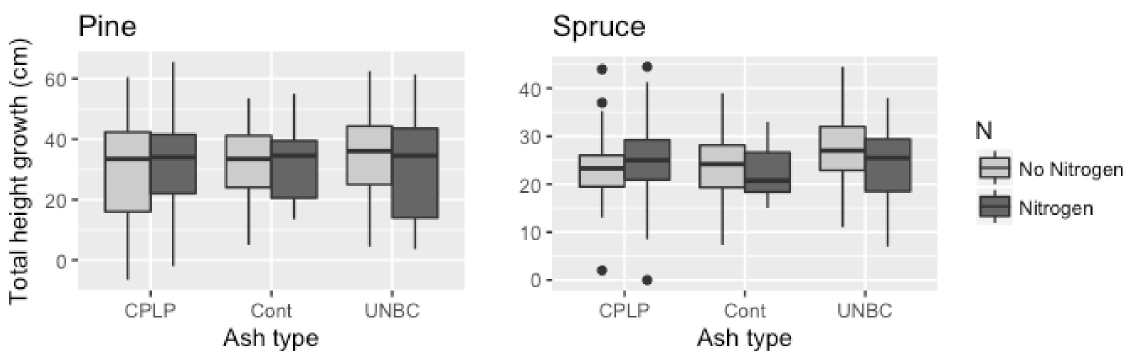


Figure 37: The total median height growth (cm) of the pine and spruce seedlings treated with ash x nitrogen compared to Control (Cont; no ash, no N) samples.

In the final stage of analysis, all the factors were integrated into the multi-factorial ANOVA and it was determined that ash with N (ash x N) became significant for the final height, as did ash type, for total growth (Table 24). Similar to the growth plots in Figure 37, the UNBC ash alone increased hybrid spruce height the most (Figure 38). Similarly the CPLP with N was the only ash x N combination that initiated an increase in hybrid spruce growth over the no-nitrogen counterpart (Figure 38). However, another ash x N combination (UNBC ash x N) increased the final height of the lodgepole pine seedlings, but only slightly compared to the other treatments (Figure 38).

Table 24: The 5 factors and their second order interactions tested using a factorial ANOVA for the final height, total growth, final RCD, total RCD growth and HDR. The abbreviation "ns" represents values that were not significant. **Bolded** values are considered significant.

Factor	Final height		Total growth		Final RCD		RCD growth		HDR	
	F Value	*p* value	F Value	*p* value	F Value	*p* value	F value	*p* value	F value	p value
species (sp)	37.6	**<0.001**	66.1	**<0.001**	3.49	0.062	28.9	**<0.001**	50.2	**<0.001**
ash type	ns	ns	2.5	0.09	ns	ns	ns	ns	ns	ns
placement	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nitrogen	ns	ns	ns	ns	3.97	**0.047**	4.3	**0.04**	9.45	**0.002**
sp x ash	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
sp x place	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
sp x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
sp x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x place	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x rate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
ash x N	3.35	**0.035**	3.30	**0.040**	ns	ns	ns	ns	ns	ns
place x rate	4.51	**0.034**	6.04	**0.014**	4.55	**0.033**	ns	ns	23.6	**<0.001**
place x N	4.45	**0.035**	5.24	**0.022**	ns	ns	ns	ns	4.75	**0.029**
rate x N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

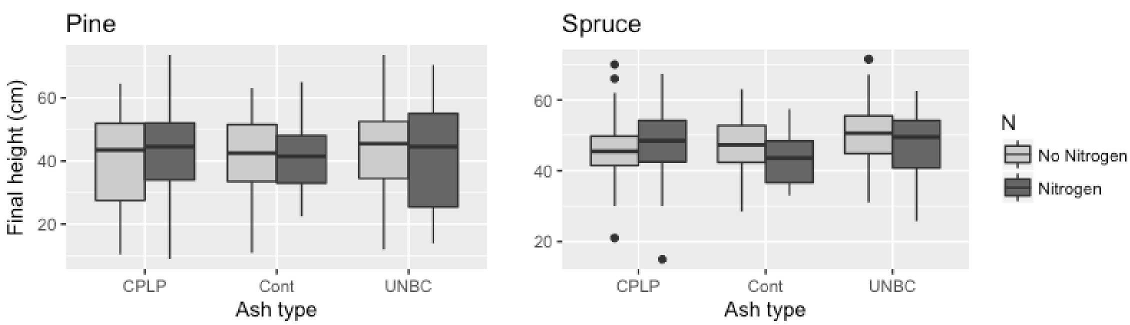


Figure 38: The median final height (cm) of the pine and spruce seedlings treated with ash x nitrogen compared to Control (Cont: no N, with N) samples.

For the final RCD variable, nitrogen and placement x rate were significant factors (Table 24). An increase in RCD growth occurred in the Tb-treated spruce, a growth trend that was first noticed in the analysis of the height of the Controls (Figure 35). The low rate of application, combined with the Tb placement, was the combination that initiated the highest growth response in the spruce seedlings (Figure 39). Conversely, the RCD of the lodgepole pine seedlings did not seem to benefit from either type of placement method, considering the diameter of the untreated Control had the highest increase (Figure 39).

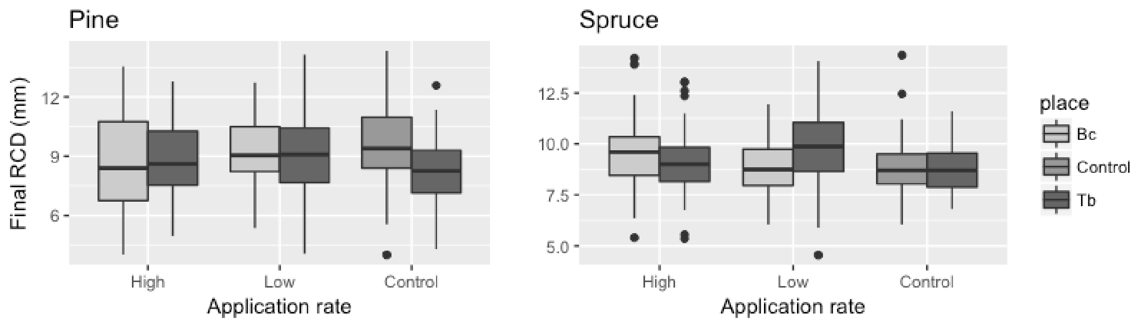


Figure 39: The final root collar diameter (RCD) of the pine and spruce seedlings treated with placement x rate compared to the Controls (no ash and Tb-Only).

Combining the variables into the height to diameter ratio produced the lowest F-value for the placement x rate interaction (Table 24, Figure 40). This provided more evidence for the significant result that occurred in the hybrid spruce seedlings that received the teabag treatment at the low rate of application (Figure 40).

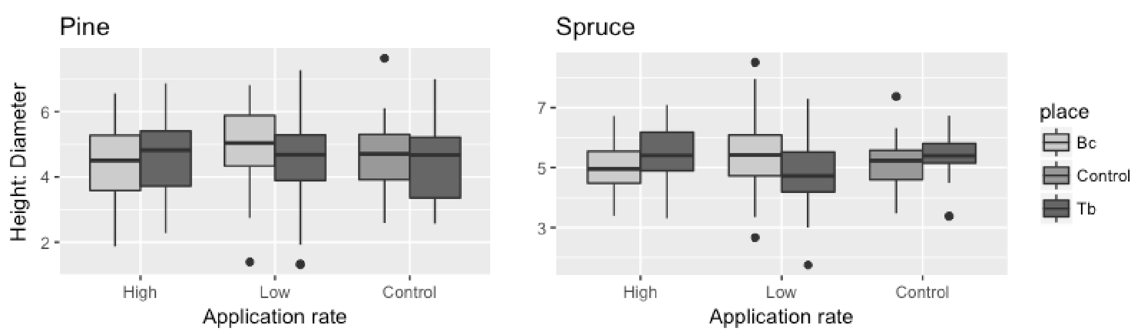


Figure 40: The height to diameter ratio (HDR) of the pine and spruce seedlings treated with placement x rate compared to the Controls (no ash and Tb-Only).

Discussion

The field trial results suggest the response to ash will largely depend on the species of conifer seedling targeted for ash fertilization. Aside from species being an important factor, the rate of application, the placement of the ash, and type of ash may impact the growth of the target species. Nitrogen, a nutrient often deficient in B.C. Central Interior forests (Brockley, 1996), was certainly a factor in determining the effect of ash treatments on both species, but it did not produce the growth enhancement that was expected. The analysis of the controls alone demonstrated increased growth in seedlings that did not receive the nitrogen additive at this particular SBS- Willow site. Generally, the hybrid spruce capitalized the most from ash addition while lodgepole pine did not respond as well as predicted, especially when compared to the pine controls. The only ash treatment that initiated a notable growth response was the UNBC ash, without nitrogen, administered to the hybrid spruce seedlings.

By comparing two tree species we were able to examine the different responses from seedlings with contrasting resource preferences. However, it should be noted that lodgepole pine typically occurs on the drier sites of the Willow variant (DeLong et al., 2003), and the field site may have been outside of the ideal range for lodgepole pine. Although pine can respond favourably to nitrogen addition, particularly at the rate administered in the trial (200kg N ha^{-1}), the responses can be quite variable in the SBS zone (Brockley, 1996). Also, the response of lodgepole pine to N fertilization can be affected by other nutrient deficiencies, namely SO_4 and boron (Brockley, 1996). Sulphur deficiencies are common in the B.C.'s Interior and can be initiated by nitrogen fertilization (Brockley, 2012). The foliar analysis revealed that the sulphur contents in the seedlings were adequate, except in the spruce seedlings treated with ash and nitrogen (Figure 27, page 63). The N fertilization may have contributed to this deficiency, as pointed out by Brockley (2012; Appendix F).

Another possible reason for this lack of growth could be attributed to the broadcast spread of the nitrogen. While the dose was targeted for the seedling, it is possible the competitive species were potentially outcompeting the pine for light and resources. Some figures throughout the Methods and Material section give an impression of the competitive species near the sample seedlings. Although pine is known to take up nitrogen quite readily (Brockley, 1996), the adjacent plant species may have been better suited to the site and, therefore, better equipped to capitalize from the nitrogen, causing the conifer to miss out on the benefits. In reality, lodgepole pine was not necessarily a designated species for the reforestation of this particular SBSwk1 site, and the rest of Block 26, outside of the field trial area, was planted with hybrid spruce. Further, the variation in the planting quality for the lodgepole pine seedlings may have contributed to seedling growth response, survival and mortality. For comparison, the mortality of lodgepole pine was 14.9% (51 of 342 Pl) compared to the hybrid spruce, which was 1.7% (6 of 342 Sx).

The shade-tolerant hybrid spruce seemed to benefit from the ash application, with and without nitrogen. A species indicatively better suited for this SBSwk1 Willow site, the hybrid spruce seedlings gained height with the UNBC ash, without the N added, and increased in diameter with the CPLP x nitrogen treatment. The spruce also responded to the placement and the rate factors, though not as separate factors, but as an interaction (placement x rate). Examining two contrasting application methods allowed us to use an approach dispersing a large quantity of ash, and another that employed a localized dosage placed closer to the root plug. While the former is a typical method of dispersing ash, the latter is a fertilization method already employed in forestry. These two kinds of ash placements were integrated into the study to determine whether the location of the ash would impact the seedlings during a vital establishment phase, particularly where a slump in nutrients can occur post-harvest (Olsson et al., 1996; Thiffault et al., 2010) Depending on the mineral content and texture of the ash, UNBC ash being fine-textured compared to the chunkier CPLP ash, a type of ash stabilization prior to land application might be recommended (Jacobson, 2003). The ashes used in this study were very similar to the gasifier (UNBC) and boiler (CPLP) ashes reported by Domes et al. (2018). The gasifier ash is a high mineral, low carbon ash with a greater calcium carbonate equivalence (i.e. greater neutralizing capacity) and base cation content than the high carbon (mainly charcoal) boiler ash (CPLP). Domes et al. (2018) found that the low carbon gasifier ash was more reactive, increasing soil pH and exchangeable base cations than the higher carbon boiler ash.

The teabag method of ash placement, though somewhat more labour-intensive, acts as a type of pre-application stabilization, due to the fact it was altered from its original form. Essentially the ash (or its dissolved constituents) has to be filtered through a thin paper barrier, and water, or soil moisture, would be the limiting factor to the dispersal rate of ash nutrients and base cations. Interestingly, the teabag placement seemed to promote the greatest growth in the hybrid spruce seedlings, but only where the dose of ash was low. Staples and Van Rees (2001) recommended low application rates for spruce seedlings (white spruce was used in their study), which appeared to be the case in our trial as well. Also, these ashes are quite alkaline and can have a relatively high electrical conductivity (see Appendix C), which is an attribute of fertilization that can inhibit root development (Jacobs & Timmer, 2005).

The method of application would also determine the manner in which ash interacted with other ground vegetation, especially when spread via broadcast application. Not only is it possible that these species intercepted the nitrogen fertilizer intended for the target conifer seedlings, but also some ground species are liable to be negatively impacted by ash application (Hart, 2016). With the teabag method, the ash essentially bypassed the ground species and would be bringing the ash closer to the seedling's root system. While the ash teabag could potentially avert injury to ground vegetation, a dieback of competing vegetation occurring as a result of broadcast ash application, could be an unintended advantage to utilizing bioenergy ash. Because manual brushing or mechanical site preparation is usually coupled with a fertilization treatment, the ash could assist the target conifer species, but indirectly. However, more in-depth research would be needed to determine whether ash-induced dieback would be an alternative to a brushing treatment.

The field study allowed us to examine bioenergy ash application on a larger scale in space and in length of time. Even so, while the initial years of a seedling's life cycle may not amount to a large portion of its entire life, the first two seasons of a seedling's establishment are crucial in determining the success of reforestation. This trial also introduced the complexity and randomness that is typical of any research trial occurring in "natural" field conditions. Wildlife and weather conditions were just some of the unpredictable factors that contributed to the staggering of seedling planting and treatment placement.

Future research could explore whether site preparation or brushing could assist in improving the effectiveness of ash fertilization. Other studies could look at combining broadcast and teabag applications. For example, unprocessed broadcast ash could act as a fast-release fertilizer and could quickly benefit the seedlings. Meanwhile, the ash teabag placed underground could supplement some of the lost biomass contributions from the former forest stand. Due to the contained nature of the ash in the teabag, it would represent a slow-release fertilizer, benefiting the seedling some time in the future. Placing the teabag in the same hole may have encouraged the seedlings to extend roots deeper. More research would be needed to determine what distance from the seedling's roots would be the most beneficial and least likely to cause injury to the seedling. The life span of a teabag buried in soil and also the migration of the ash solution within the soil would also need further investigation.

Finally, more studies are needed to determine what sites are ideal candidates for ash application and which seedling stock is best suited to receive ash fertilizer. Recommendations for ash application of seedlings in the Central Interior of B.C. include ensuring the soil at the site has a low base saturation, and if possible determine whether other soil deficiencies exist, such as nitrogen, boron or sulphur. Nitrogen may not have been required in the field trial because it did not seem to benefit either species, especially with respect to the pine, which seemed to receive the N quite readily in the seedling pot trial. If deficiencies exist, consider the elemental levels of the ash intended for application and whether adding supplements would be suitable, for the site and in practice. Also, if the ash is primarily made up of fine minerals similar to the UNBC ash, and is prone to high levels of dust during application, consider a pre-treatment or stabilization of the ash into a pelleted form or into teabags. These forms will not only lessen the reactivity and solubility of the ash, but it would also help to minimize risk to workers tasked with the ash application.

Chapter 4 General discussion and final conclusions

The ultimate goal of this study was to pursue innovative ways of using bioenergy ash in local forests. By determining the effectiveness of ash as a fertilizer for conifer seedlings, and by integrating information from other countries and current practices within the Canadian forest industry, it is possible that ash fertilization could easily be adopted in B.C., and further afield. Forest fertilization has been practiced in B.C. for many decades but with varying results; this might explain the apprehension of many forest managers and planners to adopt the practice and reach a consensus on whether it is worth the investment. Therefore, trying to encourage ash application in forestry, by either incorporating it as an addition or as a substitute to artificial fertilizers, may not happen readily. However, considering the escalating issue with ash accumulating in stockpiles and landfills, it would be practical to decide a course of action as soon as possible. Incorporating new practices into forest management should be encouraged as knowledge becomes available, and trying new approaches, such as ash fertilization, will help add to the appeal of renewable energy production, which is the ultimate goal to offsetting and divesting from fossil fuel use.

In this study, the aim was to determine what factors would influence the seedling growth response to bioenergy ash application. At the onset of this thesis, three research questions were posed and have been revisited:

> *Did the species of seedling influence the seedling's growth response to bioenergy ash application in conifers planted in the SBSwk1 BEC zone?*

Species was predictably a significant factor in the response to the ash combinations. In both trials, the site conditions tended to favour one particular species, and for that particular species, the ash application was optimized. For instance, the lodgepole pine, a hardy seral species able to endure dry conditions, benefited from the ash x nitrogen at the EFL compound pot study, where conditions were exposed and generally a lot of access to light. In contrast the lodgepole pine did not seem to gain as much in height from the ash addition in the rich field site, where competitive vegetation may have shaded out the pine seedlings. In contrast, the hybrid spruce, the preferred species in the Willow variant, which exhibited little height growth in the seedling pot trial, otherwise thrived in the field site. Perhaps the longer study period of the field trial, or the extra growing time, benefited the establishment of the hybrid spruce, which in fact had sufficient levels of N in the foliage tested from the seedling pot (Appendix E).

Did the ash type influence seedling growth and will nitrogen addition enhance the growth response?

The influence of ash type alone, and with nitrogen, varied across both trials. For the aboveground variables, UNBC ash x nitrogen positively impacted the final median height of the lodgepole pine in the seedling pot trial, but only slightly in the field trial. The UNBC ash enhanced the height and growth increment of the spruce seedlings in the field as well, with the non-N samples having the greatest increase. Contrarily, the CPLP ash and N was beneficial for the final median RCD of the spruce in the seedling pot trial, and also produced the lowest height-to-diameter ratio for the pine. Due to the variability amongst results, it was difficult to infer which ash type or combination acted as the best fertilizer for the seedlings. By examining the characterization of the ash, the UNBC ash, which induced the most immediate growth response, had a higher pH and mineral content compared to the CPLP ash. Also the CPLP ash, which contained higher amounts of carbon (Appendix C), may have been less soluble than the fine-textured UNBC ash. The chemical breakdown of char can take a long time and, therefore, if there were any benefits to growth attributed to the CPLP ash, they may come later on in the life of the seedling, requiring further research. Finally, the UNBC ash induced the greatest soil pH increase for both species of seedling (Figure 29, page 67), adding to the argument that the UNBC ash was the more reactive ash between the ash types.

Did the method of ash application and the rate of application impact the growth response of the conifer seedling?

The outcomes allowed us to see that, aside from species, ash and nitrogen being important drivers, placement method and application rate were actually significant as well. These two factors became more significant over a longer period of time, such as the length of the field trial. Despite being limited to the RCD metric in the field trial, in the seedling pot trial, belowground variables (RCD, RCD growth and root mass) were all influenced by the placement of the ash. The teabag method seemed to be preferred by the spruce in both trials. The teabags also decreased the root-to-shoot ratio for the lodgepole pine planted in pots (Figure 19), which implies the seedling is responding to favourable growing conditions (Harris, 1992). Conversely, the broadcast method induced a notable increase in the root mass of the pine samples in pots. It also stimulated the greatest increase in soil pH, compared to the Tb application method (Figure 30, page 67). With regard to the rate of application, judging by the results of both trials, we could infer that the low application rate (2 tonnes ha^{-1}) was the preferred amount for the spruce, particularly where the teabag method was used (Fig. 14 and 39). The pine RCD growth was mostly responsive to the low rate as well.

Conclusion

The two trials examined just some of the many factors that should be considered when coordinating a successful fertilization using ash in sub-boreal forests. It is important to note that some of the variability presented in this study is representative of the many inconsistencies that exist between sites, ashes and plant responses. By referring to the edatopic grid (Appendix G), it is apparent that even the differences within the Willow variant alone (e.g. soil nutrient and moisture regimes) make it difficult to predict similar results in a different site series. For instance the pine in the field trial did not benefit greatly from the ash addition as it did in the seedling pot trial, but perhaps a site series with a higher soil moisture would induce a more positive response for the pine in the field. The hybrid spruce, which was a far more suitable species for the field trial, was able to deliver better information with a longer study period, compared to the short-term pot study. Not only was the low rate (2 tonnes ha^{-1}) the preferred rate for the spruce, but also the teabag application, even exclusive of ash, promoted growth in the height of the spruce. Emulating the teabag method of application for ash fertilization proved to be an influential factor in the belowground growth response in the seedling pot trial and also for spruce in the field trial. However, if the goal is to raise the soil pH from acidic to more neutral, the broadcast spread of the ash was more appropriate. Also, the UNBC ash prompted the most growth in the spruce especially, and also the pine.

It is important to consider the needs of the site prior to prescribing elemental supplements to add alongside the ash. Supplementing nitrogen or sulphur for example, could improve the performance of ash as a fertilizer. This should only be considered if the site is indeed a candidate for the addition. As noted by Brockley (2012), nitrogen can induce a sulphur deficiency, and through foliar analysis, one can anticipate whether or not adding nitrogen is ideal.

It is evident that implementing ash fertilization in the Central Interior of B.C., and elsewhere, will face its challenges. Whether it is a practice that will indeed become integrated into forestry, it is important to consider the entire supply chain of wood harvested from our forests, from the time of harvest until the wood becomes ash through a bioenergy process. The concept that bioenergy is a renewable and sustainable energy is contradicted when we learn about the ash by-products destined for the landfill or stockpile. By examining bioenergy ash application in a controlled setting and in a natural field setting, we were able to delve into some important aspects of ash utilization in sub-boreal forests. Returning ash to its source, or rather the forest from which the feedstock fiber originated, completes the cycle of nutrients, which is a necessity for ecosystem health.

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Appendices

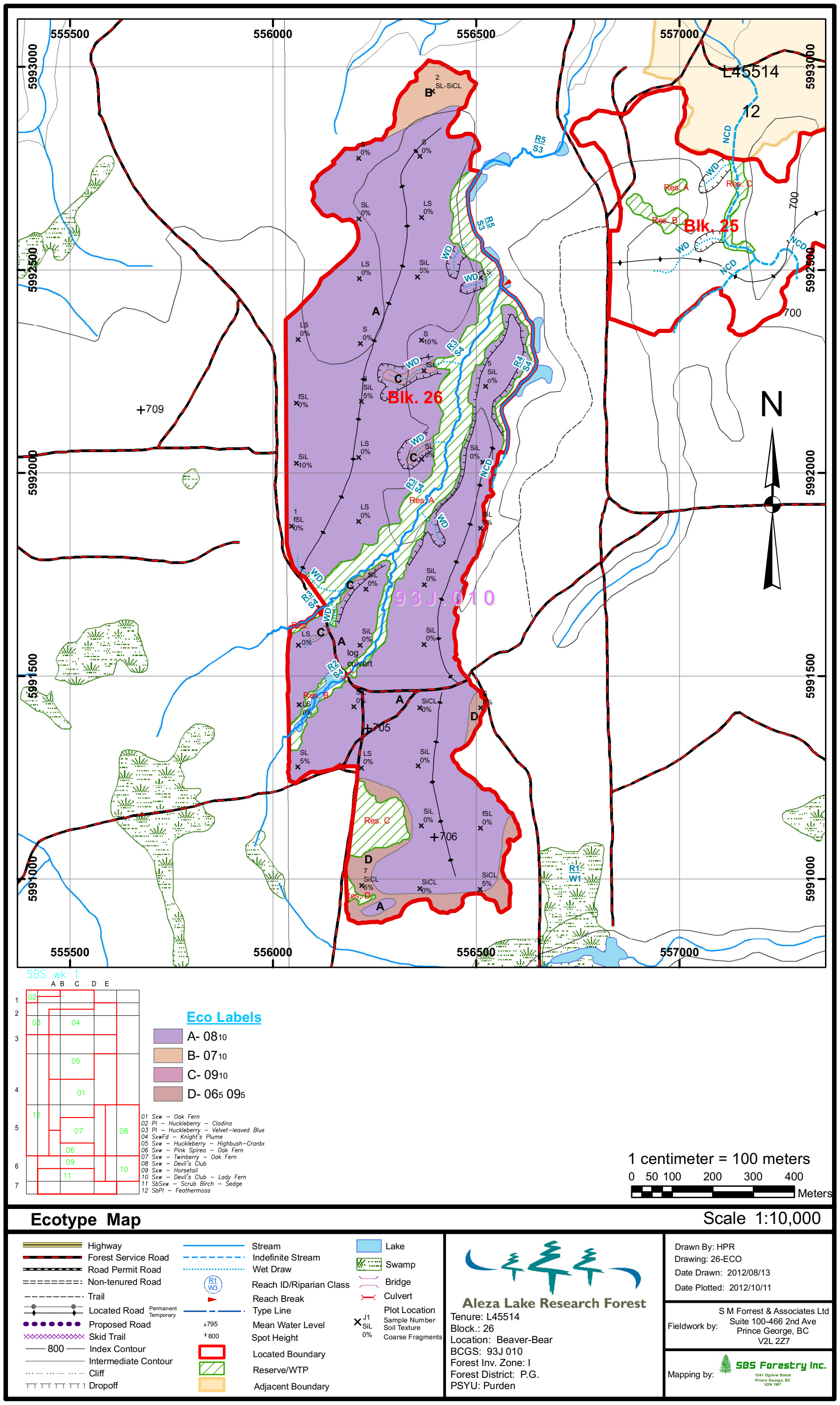
Appendix A: List of treatments used in both trials

	Species		Treatment				
	Sx reps Pot/Field	Pl reps Pot/Field	Ash type*	Placement**	Rate***	Nitrogen	Short Hand
1	5/18	5/18	Control[1]	n/a	n/a	n/a	Control; Cont
2	5/18	5/18	CPLP	Bc	Low	no N	CPLP/Bc/L/noN
3	5/18	5/18	CPLP	Bc	High	no N	CPLP/Bc/H/noN
4	5/18	5/18	CPLP	Bc	Low	with N	CPLP/Bc/L/N
5	5/18	5/18	CPLP	Bc	High	with N	CPLP/Bc/H/N
6	5/18	5/18	UNBC	Bc	Low	no N	UNBC/Bc/L/noN
7	5/18	5/18	UNBC	Bc	High	no N	UNBC/Bc/H/noN
8	5/18	5/18	UNBC	Bc	Low	with N	UNBC/Bc/L/N
9	5/18	5/18	UNBC	Bc	High	with N	UNBC/Bc/H/N
10	5/18	5/18	CPLP	Tb	Low	no N	CPLP/Tb/L/noN
11	5/18	5/18	CPLP	Tb	High	no N	CPLP/Tb/H/noN
12	5/18	5/18	CPLP	Tb	Low	with N	CPLP/Tb/L/N
13	5/18	5/18	CPLP	Tb	High	with N	CPLP/Tb/H/N
14	5/18	5/18	UNBC	Tb	Low	no N	UNBC/Tb/L/noN
15	5/18	5/18	UNBC	Tb	High	no N	UNBC/Tb/H/noN
16	5/18	5/18	UNBC	Tb	Low	with N	UNBC/Tb/L/N
17	5/18	5/18	UNBC	Tb	High	with N	UNBC/Tb/H/N
18	5/18	5/18	Teabag Only[2]	Tb	n/a	no N	Tb- Only
19	5/18	5/18	N Only[3]	n/a	n/a	with N	N- Only
	95/342	95/342					

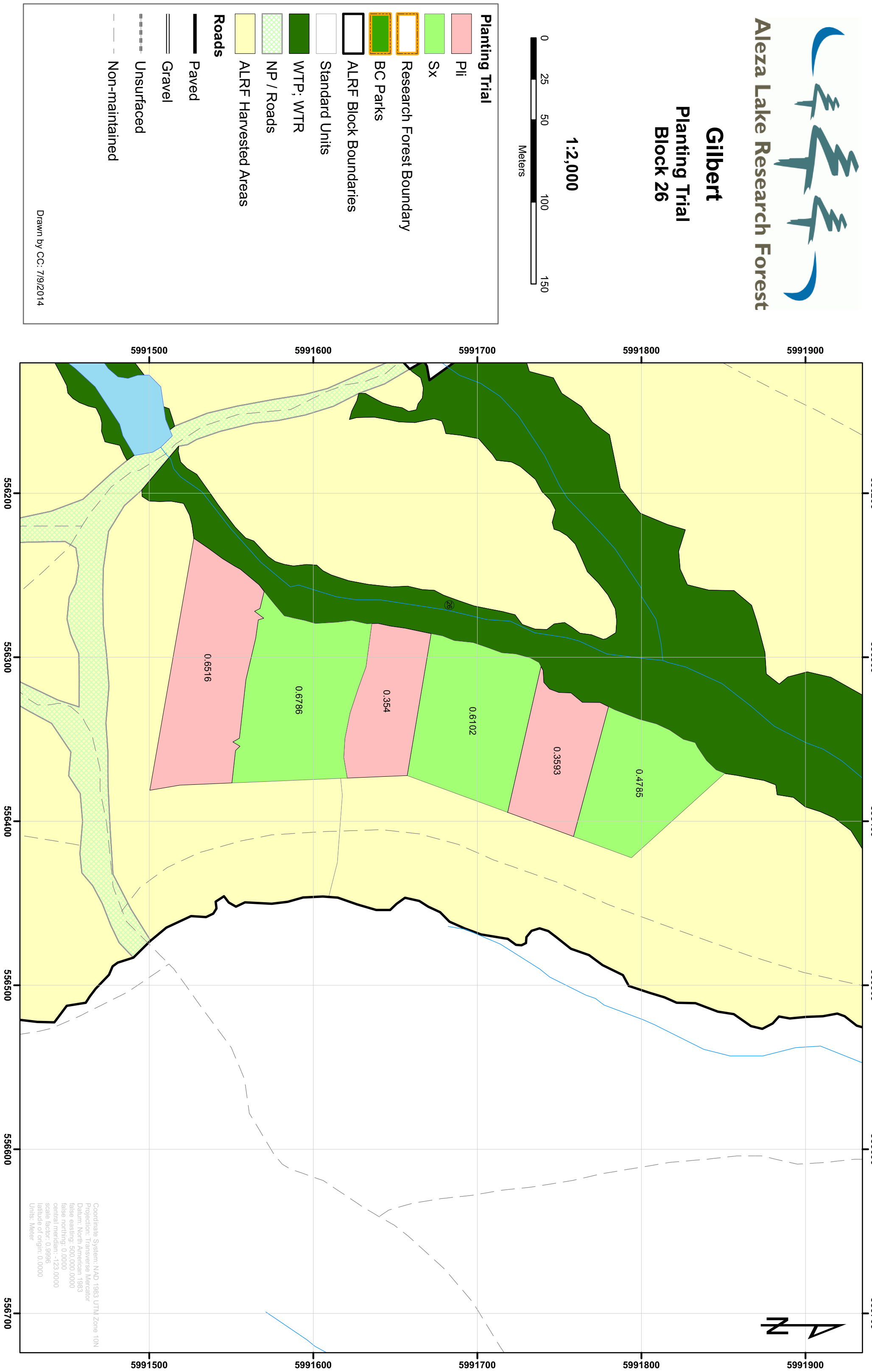
* UNBC = University of British Columbia, CPLP = Canfor
** Bc = Broadcast, Tb = Teabag
*** Low = 2 tonnes ha^{-1}, High = 4 tonnes ha^{-1}
[1] no ash, no nitrogen
[2] no ash, no nitrogen
[3] no ash, with nitrogen

Appendix B

Overview map of Blocks 25 and 26



Overview map of field trial site in Block 26



Appendix C: Chemical properties of ash types

Table 1: The means (with standard deviations in parentheses) for the chemical properties and elemental analysis for all three ash types.

Analyte	UNBC Ash n = 3	CPLP ash #1 n = 3	CPLP Ash #2 n = 3
pH (in water, 1:2)	11.9 (0.127)	11.1 (0.063)	10.4 (0.1)
$CaCO_3$ Equivalent (%)	46.3 (1.33)	28.3 (0.345)	44.6 (1.4)
EC (mS/cm, 1:5)	10.1 (0.445)	5.56 (0.140)	9.1 (0.3)
Moisture content (%)	0.13 (na)	32.5 (na)	58.8 (1.6)
Inorganic C (%)	1.89 (0.950)	3.28 (0.338)	2.8 (0.3)
Total C (%)	6.65 (0.480)	58.8 (2.62)	50.5 (2.6)
Total N (%)	0.037 (0.001)	0.165 (0.003)	0.2 (0.001)
Total S (%)	0.190 (0.008)	0.371 (0.006)	0.5 (0.05)
Available N			
NO_3 (mg N/kg)	na	na	97.8 (4.4)
NH_4 (mg N/kg)	na	na	4.8 (1.02)
Extractable elements 1			
Al (mg/kg)	23990 (1356)	7675 (215)	4470 (404)
As (mg/kg)	< 1.0 (na)	< 1.0 (na)	< 4.0 (na)
B (mg/kg)	212.3 (13.60)	145.0 (18.27)	142.6 (8.4)
Ca (%)	18.65 (1.111)	9.758 (0.062)	14.4 (0.6)
Cd (mg/kg)	2.635 (0.045)	5.103 (0.037)	14.1 (1.6)
Co (mg/kg)	23.22 (3.257)	19.71 (1.490)	3.8 (0.9)
Cr (mg/kg)	30.57 (1.006)	13.20 (0.589)	10.6 (1.5)
Cu (mg/kg)	81.50 (3.729)	46.40 (4.731)	52.2 (3.6)
Fe (mg/kg)	18320 (1152.0)	6583 (277.4)	2993 (353.7)
Hg (mg/kg)	2.4 (1.9)	1.5 (0.13)	< 2.0 (na)
K (%)	5.1 (0.26)	2.7 (0.03)	3.2 (0.03)
Mg (%)	2.7 (0.13)	1.1 (0.01)	1.2 (0.1)
Mn (mg/kg)	11330 (666.9)	6165 (53.5)	6422 (317.9)
Mo (mg/kg)	6.4 (0.40)	2.2 (0.50)	4.6 (0.7)
Na (mg/kg)	7226 (390.0)	2884 (65.5)	2503 (33.2)
Ni (mg/kg)	55.8 (1.48)	18.3 (0.704)	13.1 (1.4)
P (%)	0.8 (0.05)	0.5 (0.01)	0.6 (0.04)
Pb (mg/kg)	< 0.4 (na)	< 0.4 (na)	2.6 (0.4)
S (%)	0.2 (0.01)	0.4 (0.01)	0.7 (0.1)
Se (mg/kg)	< 7.0 (na)	< 7.0 (na)	< 2.0 (na)
Zn (mg/kg)	470.6 (18.7)	641.2 (16.2)	1206 (62.9)

Continued from previous table.

Analyte	UNBC Ash n = 3	CPLP ash #1 n = 3	CPLP Ash #2 n = 3
Extractable elements 2			
Al (mg/kg)	42540 (1249)	14680 (84.3)	1602.5 (160.5)
B (mg/kg)	na	na	72.2 (5.9)
Ca (mg/kg)	2.071×10^5 (1393.0)	1.071×10^5 (1597.0)	8.289×10^4 (5450.0)
Cu (mg/kg)	85.8 (3.5)	39.5 (1.1)	31.9 (3.5)
Fe (mg/kg)	2215 (1252)	7864 (299.0)	865.9 (61.7)
K (mg/kg)	65270 (2152)	29980 (248.8)	26360 (1505)
Mg (mg/kg)	31790 (1415)	11870 (96.9)	8986 (798.3)
Mn (mg/kg)	12250 (814.7)	6534 (95.0)	5140 (424.7)
Na (mg/kg)	14030 (595.4)	5642 (179.5)	1873 (93.4)
P (mg/kg)	9328 (650.0)	5804 (76.9)	1759 (54.3)
S (mg/kg)	2079 (134.2)	3946 (94.1)	3852 (438.2)
Zn (mg/kg)	460.0 (12.2)	632.7 (7.5)	1200 (85.9)

Notes:

CPLP #1 was collected from PG Pulp Boiler #2 on April 27, 2012; this ash was used in the seedling pot study

CPLP #2 was collected from PG Pulp Boiler #2 on January 10, 2013; this ash was used in the seedling field study

Extractable Elements 1 represent elemental concentrations via ICP-OES following US EPA extraction method 3051A: concentrated HNO_3 and HCl; elemental concentrations are more typically reported in the literature using this method than those using method 3052

Extractable Elements 2 represent elemental concentrations via ICP-OES following US EPA extraction method 3052: concentrated HNO_3, HF and H_3BO_3; method 3052 is considered to be a more complete digestion as aluminosilicate minerals are dissolved, unlike method 3051A which does not dissolve aluminosilicates

Appendix D: Calculations for ash application rate

Note: While the low rate is referred to as 2 tonnes ha^{-1} and the high rate as 4 tonnes ha^{-1}, the actual amounts were based on the surface area (A) of the pot from the seedling pot study.

The formula used to determine the equivalent amounts for both ash types, based on the mineral weight and the area of the pot:

Equation 1

$$X \text{ g of ash} = [A \times (\text{rate of application})] \times (1 + \omega)$$

- where X is the amount of ash, A is the area of the pot and ω is the gravimetric moisture content of the ash

The calculation using the above formula to determine the CPLP and the UNBC ash amounts for the low rate (2 tonnes ha^{-1}). The high rate (4 tonnes ha^{-1}) was equal to two doses of the low rate (i.e. one teabag = low rate, two teabags = high rate):

Sample equation for CPLP ash:

$$\begin{gathered} X \text{ g of ash} = [A \times (\text{rate of application})] \times (1 + \omega) \\ = [0.000\ 001\ 767 \text{ ha} \times 2\ 000\ 000 \text{ g/ha}] \times (1 + 0.7589\ \omega \text{ CPLP ash g/g dry weight}) \\ = 3.534\ (1.7589) \\ = 6.216\text{g CPLP ash (for low rate, 12.43g for high rate)} \end{gathered}$$

Sample equation for the UNBC ash:

$$\begin{gathered} X \text{ g of ash} = [A \times (\text{rate of application})] \times (1 + \omega) \\ = [0.000\ 001\ 767 \text{ ha} \times 2\ 000\ 000 \text{ g/ha}] \times (1 + 0.0013\ \omega \text{ UNBC ash g/g dry weight}) \\ = 3.534\ (1.0013) \\ = 3.539\text{g UNBC ash (for low rate, 7.077g for high rate)} \end{gathered}$$

Appendix E: Foliar analysis

Analysis performed by the Ministry of Environment, Environmental Sustainability and Strategic Policy Division (In date: 2015/09/22, out date 2015/10/22). Asterisk (*) signifies data (i.e. N and S values) that has been normalized according to the spreadsheet provided by Brockley 2012.

	Sp.	ash	place	rate	N	N (%)	sd	Al (mg/kg)	sd2	B (mg/kg)	sd3	Total C (%)	sd4	Cu (mg/kg)	sd5	Fe (mg/kg)	sd6	Mg (%)	sd7	Mn (mg/kg)	sd8	Na (mg/kg)	sd9	P (%)	sd10	Zn (mg/kg)	sd11
1	Pl	Cont	Cont	Cont	no N	1.15	0.33	204.2	46.4	33.2	7.3	52.6	0.42	3.96	1.42	71.2	23.3	0.160	0.02	627.0	211.7	3.7	1.9	0.118	0.02	77.6	24.9
2	Pl	Cont	Cont	Cont	yes N	1.06	0.16	84.0	12.9	17.2	3.0	53.2	0.44	3.74	0.58	51.6	4.8	0.142	0.02	309.0	68.3	8.2	7.2	0.096	0.01	45.1	9.3
3	Pl	Cont	Tb	Cont	no N	1.33	0.47	292.9	30.8	31.1	4.4	52.3	0.10	4.47	0.74	69.4	5.7	0.164	0.04	767.8	314.3	7.7	4.3	0.136	0.02	74.7	5.4
4	Pl	CPLP	Bc	H	no N	1.13	0.35	201.2	68.3	38.3	7.7	52.1	0.98	3.66	0.27	80.6	8.6	0.152	0.02	628.6	283.4	2.8	4.7	0.117	0.02	86.6	22.1
5	Pl	CPLP	Bc	H	yes N	1.12	0.27	96.6	26.6	25.0	4.6	52.9	0.51	3.50	0.80	71.6	7.1	0.137	0.03	324.4	94.7	10.4	6.8	0.092	0.01	51.8	17.9
6	Pl	CPLP	Bc	L	no N	1.00	0.32	248.5	44.3	40.0	8.5	52.4	0.67	3.31	0.86	70.5	7.6	0.169	0.02	597.9	125.6	6.2	10.1	0.116	0.02	71.5	22.0
7	Pl	CPLP	Bc	L	yes N	1.23	0.17	97.5	19.8	17.2	2.8	53.2	0.36	3.76	0.55	73.2	6.1	0.113	0.00	314.8	81.0	4.7	4.6	0.093	0.02	43.4	6.6
8	Pl	CPLP	Tb	H	no N	1.16	0.35	179.4	54.9	46.6	10.5	52.0	0.50	3.46	0.77	66.7	3.0	0.183	0.02	617.5	282.6	6.6	6.9	0.117	0.02	68.4	18.0
9	Pl	CPLP	Tb	H	yes N	1.22	0.44	111.0	19.7	25.3	5.3	52.9	0.34	3.51	0.71	64.8	5.8	0.120	0.03	332.4	101.0	5.3	4.0	0.100	0.01	48.3	16.9
10	Pl	CPLP	Tb	L	no N	1.05	0.25	219.3	16.8	32.3	6.2	52.4	0.36	3.59	0.20	75.7	10.0	0.157	0.00	573.6	101.7	4.3	3.9	0.111	0.02	61.5	20.2
11	Pl	CPLP	Tb	L	yes N	1.19	0.19	110.4	50.7	19.8	3.9	52.7	0.46	3.65	0.43	70.2	18.6	0.133	0.01	316.5	107.8	8.2	6.0	0.100	0.01	43.6	14.2
12	Pl	UNBC	Bc	H	no N	1.40	0.23	222.1	37.6	47.5	4.3	51.5	0.52	3.92	0.40	86.4	16.1	0.177	0.02	684.3	193.2	4.3	5.1	0.147	0.02	75.1	7.5
13	Pl	UNBC	Bc	H	yes N	1.33	0.20	125.2	44.0	33.0	5.9	52.4	0.56	3.62	0.71	72.5	19.0	0.161	0.03	398.7	104.1	4.7	4.6	0.103	0.02	55.6	8.1
14	Pl	UNBC	Bc	L	no N	0.95	0.27	167.9	27.6	34.8	4.1	52.0	0.41	3.43	0.34	75.3	11.8	0.168	0.04	372.3	124.9	0.3	0.6	0.117	0.02	72.9	3.6
15	Pl	UNBC	Bc	L	yes N	1.11	0.17	97.6	24.8	23.8	4.1	52.7	0.26	3.45	0.43	69.7	12.2	0.134	0.01	311.9	128.0	2.8	2.4	0.098	0.01	43.7	5.1
16	Pl	UNBC	Tb	H	no N	1.07	0.32	217.8	54.7	54.6	11.3	52.5	0.36	3.65	0.64	84.0	17.6	0.172	0.02	504.5	54.4	5.2	2.0	0.122	0.00	67.1	3.4
17	Pl	UNBC	Tb	H	yes N	1.03	0.17	100.9	26.7	29.0	4.6	53.3	0.43	3.32	0.54	58.1	13.0	0.119	0.02	271.6	65.7	10.1	7.3	0.091	0.01	47.6	16.1
18	Pl	UNBC	Tb	L	no N	1.23	0.38	253.0	100.3	43.0	9.1	51.1	1.40	4.38	1.25	102.4	62.5	0.149	0.04	621.5	386.5	6.2	7.4	0.124	0.03	77.1	33.7
19	Pl	UNBC	Tb	L	yes N	1.14	0.19	96.6	14.5	25.0	3.9	53.7	0.68	3.65	0.29	58.7	4.8	0.106	0.01	292.4	37.5	5.0	3.5	0.083	0.01	42.9	7.7
20	Sx	Cont	Cont	Cont	no N	0.91	0.27	92.1	45.4	48.0	12.2	50.1	0.47	4.07	1.14	93.7	48.5	0.167	0.03	595.6	223.1	18.4	2.3	0.127	0.02	77.3	29.5
21	Sx	Cont	Cont	Cont	yes N	1.36	0.19	67.7	7.0	33.1	2.5	51.1	0.98	4.48	0.10	71.4	2.7	0.112	0.06	712.5	280.6	13.8	3.2	0.112	0.03	26.7	10.1
22	Sx	Cont	Tb	Cont	no N	0.97	0.22	74.6	10.0	40.1	8.8	49.8	0.51	4.01	0.71	87.9	13.5	0.186	0.05	643.5	134.2	16.4	7.1	0.148	0.02	91.9	12.4
23	Sx	CPLP	Bc	H	no N	0.78	0.07	44.6	8.8	38.2	8.3	50.5	0.42	3.45	1.14	59.4	11.9	0.178	0.03	446.3	182.7	7.8	2.5	0.116	0.02	58.7	17.4
24	Sx	CPLP	Bc	H	yes N	1.46	0.24	62.3	23.9	43.3	13.2	50.6	0.67	4.46	0.86	85.8	33.6	0.137	0.01	857.7	325.9	28.3	41.9	0.115	0.03	36.1	17.4
25	Sx	CPLP	Bc	L	no N	0.91	0.28	66.3	22.9	61.3	7.0	50.1	1.28	4.16	1.02	96.9	50.9	0.249	0.03	466.6	33.3	8.5	1.3	0.141	0.03	74.2	31.8
26	Sx	CPLP	Bc	L	yes N	1.51	0.20	62.4	9.5	39.0	5.4	50.4	0.58	4.99	0.63	90.2	9.8	0.195	0.04	909.9	198.5	11.3	5.1	0.117	0.01	42.4	15.4
27	Sx	CPLP	Tb	H	no N	0.93	0.10	57.2	3.6	51.6	11.9	49.8	0.40	3.12	0.16	64.1	7.7	0.170	0.05	682.0	110.9	7.3	4.8	0.116	0.01	59.3	16.0
28	Sx	CPLP	Tb	H	yes N	1.50	0.18	62.7	4.7	40.7	12.0	50.8	0.54	4.45	0.61	71.8	11.0	0.131	0.04	926.6	385.7	9.2	5.0	0.109	0.02	37.7	17.4
29	Sx	CPLP	Tb	L	no N	0.85	0.29	86.9	85.8	45.7	4.4	50.0	0.48	3.12	1.36	112.7	104.3	0.205	0.07	608.9	233.7	10.3	6.7	0.130	0.03	88.6	40.2
30	Sx	CPLP	Tb	L	yes N	1.53	0.20	56.3	9.4	30.2	8.9	51.4	0.26	4.65	0.65	69.1	14.7	0.147	0.02	653.9	205.3	11.2	5.4	0.110	0.03	40.9	22.6
31	Sx	UNBC	Bc	H	no N	0.75	0.08	86.8	21.0	60.2	10.0	49.0	0.27	4.82	1.02	90.9	26.8	0.221	0.03	433.3	120.1	16.7	13.0	0.139	0.02	47.1	13.9
32	Sx	UNBC	Bc	H	yes N	1.21	0.17	64.2	10.8	38.8	8.2	51.3	0.22	4.41	0.33	71.0	12.0	0.110	0.02	605.8	137.6	80.8	132.0	0.101	0.01	35.3	15.7
33	Sx	UNBC	Bc	L	no N	0.92	0.24	79.0	33.9	54.9	9.0	49.5	0.79	3.70	0.67	93.7	46.7	0.176	0.03	438.2	126.1	38.1	51.6	0.125	0.02	54.8	27.1
34	Sx	UNBC	Bc	L	yes N	1.33	0.23	72.1	9.1	30.3	7.6	51.2	1.03	4.67	0.57	78.4	16.9	0.143	0.04	651.7	149.7	15.1	7.7	0.105	0.01	47.1	32.1
35	Sx	UNBC	Tb	H	no N	0.76	0.08	53.3	6.9	60.8	13.9	49.5	0.44	3.28	0.36	59.3	10.6	0.187	0.05	461.8	53.9	13.1	3.2	0.130	0.02	68.8	20.5
36	Sx	UNBC	Tb	H	yes N	1.32	0.12	73.1	27.4	46.7	18.6	51.2	0.90	4.49	0.80	81.8	32.6	0.150	0.06	724.8	93.4	24.2	13.9	0.111	0.01	38.3	13.7
37	Sx	UNBC	Tb	L	no N	0.88	0.19	66.3	7.7	60.5	19.6	49.9	0.65	3.62	0.66	71.1	13.0	0.184	0.06	589.8	180.0	10.9	4.2	0.120	0.01	76.9	18.6
38	Sx	UNBC	Tb	L	yes N	1.43	0.16	65.0	6.5	48.0	13.6	51.0	0.47	4.52	0.61	83.4	12.6	0.160	0.04	759.3	248.7	14.9	6.7	0.128	0.01	53.3	26.7

Continued from the previous table.

Sp.	ash	place	rate	N	Ca (%)	sd	K (%)	sd2	N (%)*	sd3	S (%)*	sd4	Zn (mg/kg)	sd5	N:Ca	sd6	N:S	sd7	N:M	sd8	N:P	sd9	N:K	sd10
Pl	Cont	Cont	Cont	no N	0.325	0.03	0.417	0.05	1.10	0.32	0.129	0.022	77.6	24.9	3.42	1.1	8.4	1.3	6.9	2.0	9.2	1.37	2.61	0.58
Pl	Cont	Cont	Cont	yes N	0.371	0.07	0.276	0.04	1.01	0.15	0.076	0.012	45.1	9.3	2.76	0.4	13.3	0.4	7.2	1.0	10.6	1.21	3.69	0.42
Pl	Cont	Tb	Cont	no N	0.322	0.02	0.520	0.06	1.27	0.45	0.142	0.021	74.7	5.4	3.99	1.5	8.7	2.2	8.4	3.9	9.2	2.47	2.51	0.99
Pl	CPLP	Bc	H	no N	0.386	0.03	0.479	0.09	1.08	0.33	0.140	0.027	86.6	22.1	2.87	1.1	7.6	1.1	7.1	2.0	9.2	1.57	2.33	0.81
Pl	CPLP	Bc	H	yes N	0.451	0.06	0.370	0.04	1.07	0.26	0.084	0.014	51.8	17.9	2.39	0.5	12.8	1.6	8.0	1.6	11.6	1.23	2.92	0.69
Pl	CPLP	Bc	L	no N	0.345	0.08	0.447	0.03	0.95	0.31	0.126	0.035	71.5	22.0	2.75	0.6	7.6	1.4	5.6	1.7	8.2	1.47	2.15	0.76
Pl	CPLP	Bc	L	yes N	0.358	0.08	0.328	0.08	1.18	0.16	0.074	0.014	43.4	6.6	3.37	0.4	16.2	2.1	10.5	1.4	12.9	1.33	3.70	0.57
Pl	CPLP	Tb	H	no N	0.302	0.05	0.481	0.10	1.11	0.34	0.149	0.024	68.4	18.0	3.68	0.9	7.4	1.4	6.2	2.4	9.4	1.07	2.28	0.26
Pl	CPLP	Tb	H	yes N	0.345	0.09	0.397	0.05	1.16	0.42	0.095	0.014	48.3	16.9	3.39	0.7	12.2	3.2	9.5	1.4	11.5	2.54	3.05	1.46
Pl	CPLP	Tb	L	no N	0.344	0.08	0.469	0.11	1.01	0.24	0.126	0.012	61.5	20.2	3.17	1.4	8.1	2.1	6.4	1.4	9.1	2.03	2.34	1.14
Pl	CPLP	Tb	L	yes N	0.356	0.07	0.346	0.04	1.14	0.18	0.087	0.019	43.6	14.2	3.24	0.3	13.3	1.5	8.6	0.7	11.5	0.94	3.32	0.46
Pl	UNBC	Bc	H	no N	0.418	0.08	0.514	0.08	1.34	0.22	0.155	0.025	75.1	7.5	3.36	1.2	8.7	0.5	7.6	1.4	9.2	1.71	2.62	0.29
Pl	UNBC	Bc	H	yes N	0.466	0.05	0.313	0.02	1.28	0.19	0.085	0.015	55.6	8.1	2.75	0.4	15.3	2.3	8.0	1.1	12.5	0.63	4.10	0.66
Pl	UNBC	Bc	L	no N	0.370	0.07	0.481	0.04	0.91	0.26	0.117	0.011	72.9	3.6	2.54	0.8	7.7	1.7	5.6	2.1	7.8	1.56	1.93	0.68
Pl	UNBC	Bc	L	yes N	0.372	0.08	0.318	0.07	1.06	0.16	0.074	0.011	43.7	5.1	2.90	0.3	14.4	1.5	7.9	0.6	10.9	0.72	3.44	0.85
Pl	UNBC	Tb	H	no N	0.350	0.02	0.502	0.05	1.02	0.31	0.156	0.014	67.1	3.4	2.94	0.9	6.7	2.5	6.2	2.9	8.3	2.16	2.08	0.80
Pl	UNBC	Tb	H	yes N	0.373	0.07	0.327	0.03	0.99	0.16	0.077	0.012	47.6	16.1	2.68	0.4	12.9	0.8	8.3	1.2	10.8	0.74	3.06	0.64
Pl	UNBC	Tb	L	no N	0.353	0.06	0.473	0.09	1.18	0.37	0.135	0.043	77.1	33.7	3.29	0.6	8.8	0.8	8.1	2.1	9.5	1.60	2.48	0.48
Pl	UNBC	Tb	L	yes N	0.336	0.03	0.319	0.08	1.09	0.18	0.079	0.011	42.9	7.7	3.23	0.3	13.9	0.8	10.4	2.4	13.2	1.70	3.54	0.86
Sx	Cont	Cont	Cont	no N	0.648	0.15	0.462	0.04	0.87	0.26	0.081	0.006	77.3	29.5	1.34	0.2	10.6	2.4	5.6	2.9	6.8	1.11	1.92	0.66
Sx	Cont	Cont	Cont	yes N	0.838	0.08	0.420	0.02	1.30	0.18	0.269	0.381	26.7	10.1	1.56	0.2	12.8	7.5	13.6	5.3	11.9	1.27	3.12	0.56
Sx	Cont	Tb	Cont	no N	0.753	0.08	0.544	0.03	0.93	0.22	0.065	0.009	91.9	12.4	1.23	0.3	14.1	1.6	5.6	3.2	6.5	2.45	1.72	0.50
Sx	CPLP	Bc	H	no N	0.584	0.12	0.419	0.03	0.75	0.07	0.084	0.034	58.7	17.4	1.31	0.3	9.5	2.3	4.2	0.5	6.5	0.60	1.78	0.10
Sx	CPLP	Bc	H	yes N	0.980	0.20	0.394	0.05	1.40	0.23	0.082	0.011	36.1	17.4	1.44	0.2	17.1	1.1	10.3	2.2	12.3	0.96	3.57	0.60
Sx	CPLP	Bc	L	no N	0.838	0.04	0.477	0.02	0.87	0.27	0.114	0.040	74.2	31.8	1.06	0.4	7.7	0.9	3.6	1.3	6.5	2.14	1.84	0.62
Sx	CPLP	Bc	L	yes N	1.045	0.18	0.378	0.06	1.44	0.19	0.252	0.325	42.4	15.4	1.40	0.2	13.2	7.7	7.5	1.1	12.4	1.38	3.83	0.08
Sx	CPLP	Tb	H	no N	0.676	0.08	0.430	0.07	0.89	0.09	0.075	0.025	59.3	16.0	1.33	0.2	12.8	3.4	5.7	1.8	7.7	1.13	2.12	0.48
Sx	CPLP	Tb	H	yes N	0.968	0.22	0.374	0.03	1.44	0.17	0.085	0.013	37.7	17.4	1.54	0.3	17.0	0.7	11.7	3.4	13.3	1.17	3.84	0.15
Sx	CPLP	Tb	L	no N	0.711	0.31	0.469	0.06	0.81	0.28	0.087	0.030	88.6	40.2	1.21	0.4	10.2	4.4	4.4	2.1	6.2	1.13	1.81	0.88
Sx	CPLP	Tb	L	yes N	0.880	0.24	0.376	0.03	1.46	0.19	0.086	0.011	40.9	22.6	1.72	0.3	17.0	0.3	10.2	2.6	13.8	3.09	3.90	0.54
Sx	UNBC	Bc	H	no N	0.678	0.24	0.441	0.05	0.72	0.08	0.088	0.013	47.1	13.9	1.15	0.3	8.5	2.3	3.3	0.6	5.3	1.29	1.64	0.07
Sx	UNBC	Bc	H	yes N	0.807	0.09	0.387	0.03	1.15	0.16	0.074	0.005	35.3	15.7	1.46	0.3	15.6	2.0	11.2	4.2	11.6	1.87	3.00	0.48
Sx	UNBC	Bc	L	no N	0.776	0.09	0.519	0.10	0.88	0.23	0.072	0.019	54.8	27.1	1.12	0.2	12.6	3.4	5.0	1.2	7.3	2.76	1.76	0.65
Sx	UNBC	Bc	L	yes N	0.838	0.19	0.342	0.04	1.27	0.22	0.076	0.011	47.1	32.1	1.54	0.1	16.7	0.7	9.5	3.0	12.4	2.86	3.82	1.01
Sx	UNBC	Tb	H	no N	0.634	0.07	0.542	0.10	0.73	0.08	0.070	0.016	68.8	20.5	1.16	0.2	10.8	2.5	4.2	1.6	5.7	1.35	1.38	0.29
Sx	UNBC	Tb	H	yes N	0.922	0.26	0.394	0.03	1.26	0.11	0.081	0.009	38.3	13.7	1.45	0.5	15.7	0.7	9.1	2.8	11.4	0.27	3.20	0.12
Sx	UNBC	Tb	L	no N	0.734	0.26	0.423	0.05	0.84	0.18	0.072	0.013	76.9	18.6	1.21	0.3	11.8	2.6	4.7	0.6	7.1	1.82	2.03	0.60
Sx	UNBC	Tb	L	yes N	0.944	0.17	0.403	0.07	1.37	0.15	0.086	0.004	53.3	26.7	1.47	0.2	15.9	1.2	8.8	1.5	10.8	1.92	3.56	1.15

Appendix F: Foliar nutrient interpretative criteria

(Brockley, 2012)

		Threshold value		
Ratio	Interpretation	Lodgepole pine	Interior spruce	Douglas-fir
N:P	Moderate to severe P deficiency	> 13	> 11	> 11
	Slight to moderate P deficiency	11 – 13	10 – 11	10 – 11
	Possible slight P deficiency	10 – 11	9 – 10	9 – 10
	No P deficiency	< 10	< 9	< 9
N:K	Moderate to severe K deficiency	> 4.5	> 4.0	> 3.5
	Slight to moderate K deficiency	3.5 – 4.5	3.0 – 4.0	2.5 – 3.5
	Possible slight K deficiency	2.5 – 3.5	2.0 – 3.0	2.0 – 2.5
	No K deficiency	< 2.5	< 2.0	< 2.0
N:Mg	Moderate to severe Mg deficiency	> 30	> 30	> 30
	Slight to moderate Mg deficiency	20 – 30	20 – 30	20 – 30
	Possible slight Mg deficiency	15 – 20	15 – 20	15 – 20
	No Mg deficiency	< 15	< 15	< 15
N:S	Severe S deficiency	> 25	> 25	> 25
	Moderate to severe S deficiency	20 – 25	20 – 25	20 – 25
	Slight to moderate S deficiency	15 – 20	15 – 20	15 – 20
	No S deficiency[a]	< 15	< 15	< 15

[a]: Sulphur deficiency will likely be induced by N fertilization if N:S > 13

Appendix G: Soil properties

Seedling pot soils

Table 1: The means (with standard deviations in parentheses) of soil chemical properties and elemental analysis.

Parameter	**Soil –no perlite n = 4**	**Soil with perlite n = 4**
Sand (%)	13.9 (1.2)	14.9 (0.02)
Silt (%)	69.0 (0.07)	68.6 (1.2)
Clay (%)	17.1 (0.6)	16.4 (1.2)
pH (1:1, Soil:water)	5.0 (0.005)	4.9 (0.01)
CEC ($cmol^+/kg$)	13.9 (0.4)	13.7 (0.2)
Available P (mg/kg)	125.3 (9.8)	124.2 (2.8)
Inorganic C (%)	< 0.07 (na)	0.2 (0.1)
Total C (%)	3.4 (0.1)	3.2 (0.05)
Total N (%)	0.2 (0.01)	0.2 (0.004)
Total S (%)	0.02 (0.002)	0.02 (0.004)
Al (mg/kg)	25190 (548.4)	24380 (814.2)
As (mg/kg)	< 4 (na)	<4 (na)
B (mg/kg)	5.5 (0.3)	4.7 (0.2)
Ca (%)	0.6 (0.004)	0.6 (0.01)
Cd (mg/kg)	2.9 (0.1)	2.9 (0.1)
Co (mg/kg)	31.1 (2.1)	27.8 (2.5)
Cr (mg/kg)	61.7 (0.5)	60.8 (1.3)
Cu (mg/kg)	19.8 (0.3)	19.7 (0.7)
Fe (mg/kg)	35960 (521.9)	35670 (531.0)
Hg (mg/kg)	< 2 (na)	< 2 (na)
K (%)	0.3 (0.01)	0.3 (0.01)
Mg (%)	0.6 (0.01)	0.6 (0.01)
Mn (mg/kg)	1239 (108.7)	1218 (79.6)
Mo (mg/kg)	0.7 (0.1)	0.7 (0.01)
Na (mg/kg)	435.5 (27.1)	552.4 (27.4)
Ni (mg/kg)	37.7 (0.6)	37.9 (0.7)
P (%)	0.2 (0.004)	0.2 (0.002)
Pb (mg/kg)	6.1 (0.7)	5.6 (0.5)
S (%)	0.03 (0.001)	0.02 (0.002)
Se (mg/kg)	< 2 (na)	< 2 (na)
Zn (mg/kg)	158.6 (2.5)	155.0 (2.9)
Exchangeable cations		
Al ($cmol^+/kg$)	0.6 (0.03)	0.6 (0.03)
Ca ($cmol^+/kg$)	10.7 (0.3)	10.4 (0.1)

Fe ($cmol^+$/kg)	0.02 (0.02)	0.01 (0.01)
K ($cmol^+$/kg)	0.4 (0.01)	0.4 (0.01)
Mg ($cmol^+$/kg)	2.0 (0.1)	2.0 (0.05)
Mn ($cmol^+$/kg)	0.1 (0.01)	0.1 (0.002)
Na ($cmol^+$/kg)	0.1 (0.01)	0.1 (0.004)

Field site soils

Table 2: The means (with standard deviations in parentheses) of soil chemical properties and elemental analysis of the soils from the field trial site.

Parameter	**LFH n = 3**	**Ae n = 3**	**Bm n = 3**
Sand (%)	na	39.9 (10.3)	45.3 (7.48)
Silt (%)	na	49.6 (7.75)	44.8 (7.77)
Clay (%)	na	10.6 (2.65)	9.90 (2.03)
pH (1:1, soil:water)	4.9 (0.31)	4.7 (0.14)	5.1 (0.12)
CEC ($cmol^+$/kg)	12.5 (1.03)	4.9 (0.94)	4.9 (0.98)
Available P (mg/kg)	27.2 (11.3)	31.6 (24.6)	77.7 (64.2)
Total C (%)	19.1 (7.29)	1.57 (0.130)	2.34 (0.935)
Total N (%)	0.876 (0.330)	0.112 (0.009)	0.134 (0.047)
Total S (%)	0.089 (0.033)	0.011 (0.002)	0.017 (0.007)
C:N	21.8 (0.350)	14.0 (0.805)	17.3 (0.990)
Exchangeable elements 1			
Al (mg/kg)	14530 (1764)	20460 (1257)	28460 (5660)
As (mg/kg)	< 2 (na)	< 2 (na)	< 2 (na)
B (mg/kg)	5.37 (0.672)	2.43 (0.228)	< 2 (na)
Ca (%)	0.756 (0.085)	0.446 (0.078)	0.497 (0.055)
Cd (mg/kg)	1.0 (0.3)	< 2 (na)	< 2 (na)
Co (mg/kg)	14.3 (6.0)	24.1 (0.830)	26.8 (6.49)
Cr (mg/kg)	47.9 (7.0)	67.1 (3.08)	75.7 (6.42)
Cu (mg/kg)	8.4 (1.7)	9.07 (1.30)	13.8 (0.889)
Fe (mg/kg)	13700 (4660)	22440 (1530)	3683 (4499)
Hg (mg/kg)	< 1 (na)	< 1 (na)	< 1 (na)
K (%)	0.256 (0.041)	0.292 (0.014)	0.271 (0.030)
Mg (%)	0.205 (0.042)	0.334 (0.048)	0.605 (0.030)
Mn (mg/kg)	< 2 (na)	1694.8 (917.1)	499.4 (86.4)
Mo (mg/kg)	< 2 (na)	< 2 (na)	< 2 (na)
Na (mg/kg)	459.1 (75.7)	544.5 (11.0)	495.5 (12.8)
Ni (mg/kg)	11.5 (1.1)	15.0 (1.4)	36.9 (7.8)
P (%)	0.1 (0.02)	0.07 (0.003)	0.2 (0.03)

Pb (mg/kg)	6.6 (0.8)	5.2 (0.1)	2.8 (0.5)
S (%)	0.08 (0.03)	0.01 (0.001)	0.02 (0.01)
Se (mg/kg)	< 4 (na)	< 4 (na)	< 4 (na)
Zn (mg/kg)	9.8 (1.2)	75.3 (23.1)	117.6 (25.2)
Exchangeable elements 2			
Al ($cmol^+/kg$)	0.3 (0.3)	2.2 (0.4)	1.8 (.04)
Ca ($cmol^+/kg$)	10.1 (1.2)	2.0 (1.1)	2.5 (1.2)
Fe ($cmol^+/kg$)	0.01 (0.01)	0.04 (0.04)	0.03 (0.01)
K ($cmol^+/kg$)	0.3 (0.03)	0.1 (0.03)	0.03 (0.02)
Mg ($cmol^+/kg$)	1.5 (0.2)	0.5 (0.2)	0.5 (0.2)
Mn ($cmol^+/kg$)	0.3 (0.1)	0.1 (0.1)	0.02 (0.003)
Na ($cmol^+/kg$)	0.03 (0.01)	0.03 (0.01)	0.03 (0.01)

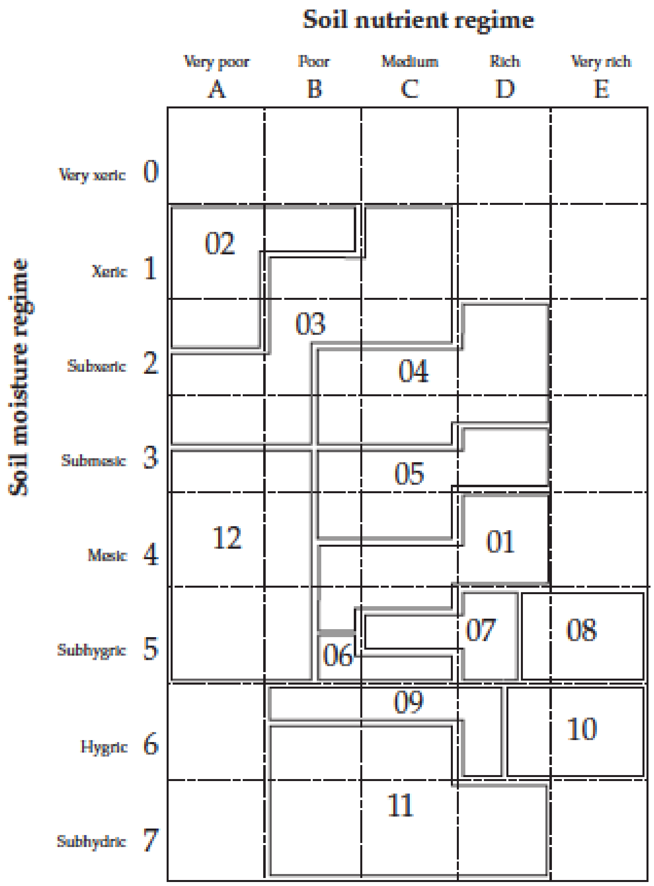
Notes:

Extractable Elements 1 represent elemental concentrations via ICP-OES following US EPA extraction method 3051A: concentrated HNO_3 and HCl; elemental concentrations are more typically reported in the literature using this method than those using method 3052

Extractable Elements 2 represent elemental concentrations via ICP-OES following US EPA extraction method 3052: concentrated HNO_3, HF and H_3BO_3; method 3052 is considered to be a more complete digestion as aluminosilicate minerals are dissolved, unlike method 3051A which does not dissolve aluminosilicates

Appendix H: Edatopic grid for the SBS wk1 (Willow variant)

(DeLong et al., 2003)



Site Series
01 Sxw- Oak fern
02 Pl – Huckleberry - Cladina
03 Pl – Huckleberry - Velvet-leaved blueberry
04 SxwFd – Knight's Plume
05 Sxw – Huckleberry – Highbush cranberry
06 Sxw – Pink spirea – Oak fern
07 Sxw - Twinberry – Oak fern
08 Sxw – Devil's Club
09 Sxw – Horsetail
10 Sxw – Devil's Club – Lady fern
11SbSxw – Scrub birch – Sedge
12 SbPl- Feathermoss

Appendix I: Seedling pot trial data

Table 1: The mean values and standard deviations (sd) for each response variables, final height, total height growth, final root collar diameter (RCD), total RCD growth and height to diameter ratio (HDR), root, shoot and total masses for the Enhanced Forestry Lab seedling pot trial.

#	Sp.	Ash	Place	Rate	N	Final height (cm)	sd	Final RCD (cm)	sd	Total growth (cm)	sd	Total RCD (mm)	sd
1	Pl	Cont	Cont	Cont	no N	25.9	3.39	0.615	0.063	11.2	2.70	0.213	0.078
2	Pl	Cont	Cont	Cont	yes N	27.1	2.79	0.754	0.057	13.9	2.03	0.330	0.057
3	Pl	Cont	Tb	Cont	no N	26.9	5.34	0.600	0.076	13.7	3.36	0.199	0.084
4	Pl	CPLP	Bc	H	no N	26.9	4.04	0.583	0.032	13.1	3.27	0.185	0.028
5	Pl	CPLP	Bc	H	yes N	24.8	2.70	0.733	0.060	11.0	3.95	0.313	0.024
6	Pl	CPLP	Bc	L	no N	26.5	2.53	0.606	0.067	13.5	1.33	0.201	0.074
7	Pl	CPLP	Bc	L	yes N	27.9	5.70	0.796	0.076	15.3	3.11	0.405	0.061
8	Pl	CPLP	Tb	H	no N	28.0	2.45	0.587	0.083	13.4	1.72	0.177	0.071
9	Pl	CPLP	Tb	H	yes N	27.6	2.88	0.744	0.080	13.3	1.88	0.321	0.053
10	Pl	CPLP	Tb	L	no N	25.7	3.42	0.574	0.050	11.1	4.92	0.178	0.078
11	Pl	CPLP	Tb	L	yes N	27.1	4.88	0.724	0.059	13.1	5.27	0.324	0.056
12	Pl	UNBC	Bc	H	no N	25.9	3.42	0.564	0.027	14.4	3.64	0.142	0.060
13	Pl	UNBC	Bc	H	yes N	29.4	6.35	0.735	0.080	12.8	8.31	0.333	0.074
14	Pl	UNBC	Bc	L	no N	23.6	4.42	0.552	0.022	9.26	4.93	0.127	0.062
15	Pl	UNBC	Bc	L	yes N	30.3	1.86	0.786	0.033	14.5	3.35	0.411	0.046
16	Pl	UNBC	Tb	H	no N	25.3	2.68	0.570	0.082	10.8	4.74	0.165	0.095
17	Pl	UNBC	Tb	H	yes N	26.5	2.80	0.735	0.056	13.1	1.45	0.331	0.069
18	Pl	UNBC	Tb	L	no N	27.2	2.08	0.575	0.068	11.9	4.01	0.137	0.058
19	Pl	UNBC	Tb	L	yes N	31.6	2.21	0.709	0.081	15.4	1.48	0.323	0.096
20	Sx	Cont	Cont	Cont	no N	26.7	2.59	0.649	0.066	7.48	0.29	0.235	0.070
21	Sx	Cont	Cont	Cont	yes N	27.6	3.32	0.825	0.149	7.00	1.02	0.381	0.069
22	Sx	Cont	Tb	Cont	no N	25.7	2.67	0.668	0.053	7.00	2.23	0.217	0.081
23	Sx	CPLP	Bc	H	no N	29.1	0.92	0.755	0.071	6.74	1.81	0.266	0.094
24	Sx	CPLP	Bc	H	yes N	26.4	3.34	0.863	0.113	6.96	2.05	0.398	0.097
25	Sx	CPLP	Bc	L	no N	27.3	3.76	0.663	0.058	5.30	2.57	0.166	0.066
26	Sx	CPLP	Bc	L	yes N	27.8	5.84	0.910	0.053	6.08	3.12	0.433	0.057
27	Sx	CPLP	Tb	H	no N	27.2	1.61	0.729	0.101	7.80	0.37	0.271	0.099
28	Sx	CPLP	Tb	H	yes N	26.6	2.31	0.864	0.105	6.32	1.43	0.409	0.058
29	Sx	CPLP	Tb	L	no N	27.0	3.26	0.648	0.069	6.92	1.05	0.217	0.084
30	Sx	CPLP	Tb	L	yes N	25.7	3.22	1.004	0.124	7.18	1.34	0.531	0.083
31	Sx	UNBC	Bc	H	no N	26.5	3.22	0.748	0.118	5.28	2.69	0.268	0.089
32	Sx	UNBC	Bc	H	yes N	26.1	2.88	0.843	0.067	7.76	1.83	0.372	0.034
33	Sx	UNBC	Bc	L	no N	26.1	2.94	0.725	0.106	6.50	1.51	0.215	0.135
34	Sx	UNBC	Bc	L	yes N	28.5	2.87	0.905	0.038	7.98	1.26	0.413	0.024
35	Sx	UNBC	Tb	H	no N	27.5	1.97	0.715	0.080	7.08	2.35	0.245	0.092
36	Sx	UNBC	Tb	H	yes N	27.2	2.54	0.885	0.051	7.08	2.69	0.426	0.077
37	Sx	UNBC	Tb	L	no N	27.6	2.03	0.765	0.071	7.06	1.07	0.277	0.076
38	Sx	UNBC	Tb	L	yes N	28.2	2.29	0.890	0.055	7.94	1.37	0.481	0.036

Continued from previous page.

#	Final HDR	sd	Total mass (g)	sd	Root mass (g)	sd	Total mass (g)	sd	Root: Shoot	sd
1	42.6	7.42	16.0	2.18	7.39	1.03	16.0	2.18	0.878	0.157
2	36.3	5.77	26.8	2.19	11.9	1.91	26.8	2.19	0.804	0.120
3	44.5	4.06	15.2	3.50	7.07	1.65	15.2	3.50	0.873	0.077
4	46.1	6.09	17.0	3.59	8.55	1.92	17.0	3.59	1.007	0.103
5	34.0	4.50	27.8	5.54	14.2	3.37	27.8	5.54	1.053	0.222
6	43.8	3.25	16.2	2.03	7.67	1.10	16.2	2.03	0.911	0.172
7	35.0	6.36	26.4	3.98	10.8	1.68	26.4	3.98	0.710	0.134
8	48.5	7.82	14.5	1.97	6.63	0.65	14.5	1.97	0.853	0.110
9	37.2	1.44	25.7	2.72	10.9	1.43	25.7	2.72	0.743	0.127
10	44.8	5.16	14.9	2.49	6.43	1.15	14.9	2.49	0.801	0.257
11	37.4	5.75	24.8	2.30	10.6	1.22	24.8	2.30	0.758	0.113
12	45.9	5.57	15.0	2.02	7.17	1.26	15.0	2.02	0.911	0.104
13	39.6	5.33	24.4	7.20	11.4	3.51	24.4	7.20	0.904	0.168
14	42.7	7.30	13.7	3.24	6.93	1.81	13.7	3.24	1.029	0.149
15	38.7	3.64	28.2	1.81	12.9	1.13	28.2	1.81	0.846	0.076
16	44.6	2.97	15.0	1.39	7.24	0.40	15.0	1.39	0.946	0.139
17	36.2	4.30	26.5	1.74	11.4	1.36	26.5	1.74	0.753	0.081
18	47.8	6.51	13.9	3.04	6.41	1.33	13.9	3.04	0.882	0.196
19	45.0	5.76	26.8	3.56	11.8	2.51	26.8	3.56	0.777	0.111
20	41.4	5.41	13.4	2.09	6.89	1.04	13.4	2.09	1.087	0.208
21	34.3	6.69	17.6	4.73	8.00	1.88	17.6	4.73	0.859	0.103
22	38.7	5.31	13.4	2.33	6.62	1.23	13.4	2.33	0.988	0.153
23	38.9	4.40	15.8	1.80	7.77	0.57	15.8	1.80	0.994	0.149
24	31.0	5.20	18.0	3.26	8.82	1.44	18.0	3.26	0.982	0.158
25	41.2	4.26	12.6	2.59	6.58	1.58	12.6	2.59	1.090	0.169
26	30.5	5.84	21.0	3.52	10.2	1.59	21.0	3.52	0.946	0.100
27	37.9	5.74	14.2	1.52	7.16	1.23	14.2	1.52	1.014	0.169
28	31.0	2.84	18.2	3.66	8.50	1.08	18.2	3.66	0.912	0.171
29	42.2	8.72	12.1	2.26	5.61	1.02	12.1	2.26	0.885	0.180
30	25.7	2.30	22.9	6.79	10.4	2.99	22.9	6.79	0.859	0.166
31	36.1	6.69	14.0	2.39	6.54	0.87	14.0	2.39	0.893	0.125
32	31.0	2.90	17.9	3.87	8.02	2.23	17.9	3.87	0.818	0.174
33	36.3	3.31	12.9	2.43	6.25	1.38	12.9	2.43	0.940	0.122
34	31.5	2.51	20.7	1.92	8.95	0.75	20.7	1.92	0.776	0.144
35	38.8	4.48	15.7	1.74	7.48	0.99	15.7	1.74	0.925	0.159
36	30.8	1.99	18.6	1.13	7.68	0.73	18.6	1.13	0.719	0.138
37	36.2	2.16	12.4	2.46	6.04	0.71	12.4	2.46	0.980	0.161
38	31.7	1.65	17.8	4.19	7.87	2.15	17.8	4.19	0.785	0.055

Appendix J: Field trial data

Table 1: The mean values and standard deviations (sd) for each response variables, final height, total height growth, final root collar diameter (RCD), total RCD growth and height to diameter ratio (HDR) for the Aleza Lake Research Forest field trial.

Species	Ash	Place	Rate	N	Final height (cm)	sd	Total growth (cm)	sd2	Final RCD (mm)	sd3	RCD growth (mm)	sd4	HDR	sd5
Pl	Cont	Cont	Cont	no N	45.4	10.9	35.2	10.5	9.60	2.63	5.74	2.55	4.88	1.01
Pl	Cont	Cont	Cont	yes N	40.6	11.1	31.2	11.5	9.25	1.94	5.80	2.14	4.44	1.04
Pl	Cont	Tb	Cont	no N	37.4	13.0	28.0	12.7	8.25	1.99	4.94	1.84	4.50	1.29
Pl	CPLP	Bc	H	no N	24.2	13.6	12.1	15.0	6.86	2.23	3.24	2.06	3.50	1.46
Pl	CPLP	Bc	H	yes N	44.1	14.8	34.7	15.2	9.27	2.38	5.70	2.50	4.71	0.89
Pl	CPLP	Bc	L	no N	41.0	12.1	30.5	12.8	8.75	1.84	5.11	1.79	4.64	0.94
Pl	CPLP	Bc	L	yes N	46.2	8.6	36.1	8.1	9.64	2.01	6.13	1.86	4.91	0.97
Pl	CPLP	Tb	H	no N	44.9	15.0	35.6	15.7	9.27	2.32	5.75	2.09	4.76	1.00
Pl	CPLP	Tb	H	yes N	40.9	16.2	30.3	16.6	8.41	1.88	4.91	1.96	4.75	1.33
Pl	CPLP	Tb	L	no N	42.7	10.9	32.3	11.1	9.45	1.76	5.62	1.95	4.57	1.08
Pl	CPLP	Tb	L	yes N	38.1	16.9	28.5	18.1	8.56	1.78	5.01	1.65	4.38	1.71
Pl	UNBC	Bc	H	no N	44.2	17.2	35.2	17.6	9.18	2.13	5.46	2.26	4.67	1.12
Pl	UNBC	Bc	H	yes N	40.4	17.7	29.5	17.2	8.93	2.78	5.34	2.90	4.44	1.19
Pl	UNBC	Bc	L	no N	45.3	13.9	35.9	13.0	9.02	1.44	5.49	1.31	5.02	1.26
Pl	UNBC	Bc	L	yes N	47.7	12.1	36.8	12.2	9.17	1.55	5.58	1.61	5.24	1.22
Pl	UNBC	Tb	H	no N	48.4	12.1	38.3	12.1	9.55	1.53	5.88	1.64	5.06	0.94
Pl	UNBC	Tb	H	yes N	35.2	16.4	25.0	17.2	8.45	1.95	4.71	1.92	4.03	1.31
Pl	UNBC	Tb	L	no N	38.7	10.7	29.5	11.8	8.37	1.73	4.77	1.90	4.64	0.94
Pl	UNBC	Tb	L	yes N	44.0	16.8	33.6	17.7	9.78	2.71	6.09	2.48	4.46	1.13
Sx	Cont	Cont	Cont	no N	47.3	7.4	21.5	6.5	8.65	1.23	3.94	1.10	5.48	0.48
Sx	Cont	Cont	Cont	yes N	43.3	7.4	22.2	5.6	9.23	1.87	4.09	1.64	4.80	0.97
Sx	Cont	Tb	Cont	no N	47.5	8.2	25.1	8.6	8.81	1.19	4.09	1.39	5.41	0.79
Sx	CPLP	Bc	H	no N	44.4	6.6	21.7	5.2	9.48	1.48	4.91	1.35	4.75	0.73
Sx	CPLP	Bc	H	yes N	47.5	8.6	23.7	7.0	9.10	1.37	4.18	1.26	5.24	0.70
Sx	CPLP	Bc	L	no N	45.7	7.8	23.6	5.9	7.98	1.21	3.30	1.22	5.76	0.77
Sx	CPLP	Bc	L	yes N	49.6	8.8	27.6	8.4	9.15	1.41	4.41	1.47	5.52	1.22
Sx	CPLP	Tb	H	no N	48.1	8.2	24.7	6.7	8.38	1.16	4.01	1.04	5.76	0.72
Sx	CPLP	Tb	H	yes N	48.5	8.6	25.0	8.3	9.73	1.62	4.87	1.42	5.07	1.06
Sx	CPLP	Tb	L	no N	46.2	10.1	22.5	6.8	9.31	1.79	4.78	1.47	5.06	1.11
Sx	CPLP	Tb	L	yes N	45.1	12.7	22.5	10.3	10.42	2.37	5.85	2.30	4.39	1.11
Sx	UNBC	Bc	H	no N	52.6	7.5	28.4	7.7	9.35	1.24	4.71	1.37	5.65	0.69
Sx	UNBC	Bc	H	yes N	45.5	9.0	23.5	7.4	10.14	2.26	5.47	2.05	4.58	0.81
Sx	UNBC	Bc	L	no N	48.9	8.0	26.5	7.4	9.11	1.10	4.75	1.10	5.42	0.97
Sx	UNBC	Bc	L	yes N	46.7	9.0	24.5	7.3	9.04	0.88	4.71	0.83	5.19	0.96
Sx	UNBC	Tb	H	no N	50.6	7.9	27.6	6.3	9.21	1.28	4.53	1.24	5.53	0.77
Sx	UNBC	Tb	H	yes N	49.5	9.2	26.2	7.7	8.91	1.72	4.59	1.43	5.61	0.81
Sx	UNBC	Tb	L	no N	49.7	10.0	26.0	7.8	9.58	1.51	4.72	1.44	5.23	0.99
Sx	UNBC	Tb	L	yes N	47.6	8.0	23.4	6.9	9.98	1.38	5.54	1.16	4.81	0.80