Competition Impacts on Hybrid Poplar and Implications for Alternative Establishment Systems

by

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Abstract

The effects of different vegetation control practices on tree-weed interactions and associated establishment and early tree growth were investigated in 1-3 year old hybrid poplar plantations containing Walker poplar (*Populus deltoides* x (*P. laurifolia* x *P. nigra*)) and its progeny Okanese poplar (Walker x (*P. laurifolia* x *P. nigra*)). Two field experiments were established on research sites in northeastern Alberta during two years (2012-2013). Tree survival and growth, herbaceous vegetation cover and composition, soil nutrient availability, soil water content, soil temperature and light availability were measured over two growing seasons. Results showed that an extended full year of chemical and mechanical site preparation prior to tree planting reduced weed impacts on resource availability and improved tree performance. Improved biotic and abiotic growing conditions included the sustained control of understory vegetation, in particular competitive perennial forbs and graminoids, as well as increased availability of light and nutrients. Results also highlighted the need to effectively control perennial rather than annual herbaceous competitors. The findings further demonstrated a spatial and temporal shift in the competitive effects of neighboring vegetation. Trees competed primarily aboveground with weeds (i.e. for light) near the stem (< 50 cm) during the first year, which then shifted increasingly to belowground competition for nutrients later in the establishment period, both near- and far from the tree stem. Okanese also outperformed Walker poplar across all treatments and sites tested, and was more responsive to vegetation control, reflecting its superior performance, higher plasticity, and greater potential for short-rotation-intensive-culture plantations.

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Chapter 1: General Introduction

1.1 Biology of poplars and their importance for plantations

Poplars (*Populus* L.) are the most common deciduous trees in Canada's boreal forest, covering a total of 11.6% of the boreal region, and are second only to spruce (53.2%) and pine (9.3%) in the area covered (Natural Resources Canada 2014). At the same time, poplars play a significant role in the agricultural landscape, particularly over the last century (Richardson et al., 2007). Since 1920, over 32 million poplar trees have been planted in farm and field shelterbelts across the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba, illustrating the important role they play in establishing agroforestry systems (Richardson et al., 2007). In addition to providing ecological diversity, natural and planted poplar stands also play a significant economic role in fibre production across Canada, especially in British Columbia, Alberta, Saskatchewan and Québec (Poplar Council of Canada, 2012).

Poplars are fast-growing deciduous trees with a widespread natural distribution in the Northern Hemisphere, occupying areas with boreal to warm-temperate, and even cool cordilleran climates, and they are adapted to a wide range of ecosite conditions (hydric to mesic) (Dickmann, 2001; Zsuffa et al., 1996). Poplars are relatively short-lived pioneer species (60-120 years) with rapid initial growth, thus differing greatly from the slow-growing conifer species more commonly harvested in the boreal forest (Dickmann, 2001). Poplars demonstrate high volume yields with mean annual growth increments ranging from 6-29 m^3 ha^{-1} yr^{-1} in Canada (Park and Wilson, 2007). Growth of selected hybrid poplar clones (where two or more species are hybridized), measured as increments of diameter at breast height (DBH), peak at three to four years of age in well maintained, weed-free sites (van Oosten, 2004). Growth rates in the Canadian Prairies are assumed to range between 8-12 m^3 per hectare per year on a 20 year rotation length (Anderson and Luckert, 2007). Poplars are shallow-rooted, with roots of young poplars being concentrated within the top 15 cm of soil (Al Afas et al., 2008; Douglas et al., 2010). Additionally, locations close to trees (e.g. 90 cm) were found to have higher values of various root attributes compared to locations further away (e.g. 180 cm) including twice the total root number and total root area ratio (Douglas et al., 2010). However, under favorable conditions roots can extend up to 1.5 m vertically and 4 m horizontally in only two years after planting (Friend et al., 1991; Hansen, 1981). Both sexual and asexual reproduction is widespread in poplars. Vegetative (asexual) propagation of poplar clones from stem or root sections is easy and allows for efficient and low-cost mass propagation as required for industrial-scale plantations (Poplar Council of Canada, 2012).

Hybrid poplar that have been established in plantations on cleared land, usually formerly in agricultural production, and which are intensively-managed are referred to as short-rotation-intensive-culture (SRIC) (Poplar Council of Canada, 2012). Key components of SRIC production systems are a short crop cycle (e.g. less than 25 years for pulpwood production) and an intensive approach to silvicultural management, involving weed control and potentially fertilization (Poplar Council of Canada, 2012).

1.2 Hybrid poplar clones

Poplar species are grouped into six sections: *Aigeiros* (cottonwoods and black poplars), *Tacamahaca* (balsam poplars), *Populus* (aspen and white poplars), *Abaso*, *Turanga*, and

Leucoides (primarily subtropical and tropical species) (Eckenwalder, 1996). Populus species from the *Aigeiros* and *Tacamahaca* sections are used for SRIC production systems because they vegetatively reproduce from stem cuttings. Natural and artificial hybridization among poplar species is very common, predominantly within the afore-mentioned taxonomic sections (interspecific) but also between sections (intersectional). Hybrid poplars occur from both natural or artificial interspecific, intersectional and/or intraspecific hybrids resulting from crossing two distinct species or two individuals within one species with distinct characteristics (Poplar Council of Canada, 2012). Crossing parents from two species can result in hybrid vigour; that is some progeny showing superior growth compared to either parent (van Oosten, 2006). Hybrid vigour and intensive cultural practices contribute to the high productivity of planted hybrid poplar. A reduced rotation length from 60 to 120 years for aspen to less than 25 years for hybrid poplar in the boreal forest illustrates the potential of poplars to contribute to the forest industry in western Canada through improved supply of fibre and wood (Richardson et al., 2007). Across the prairies, there are several hybrid poplar clones available for establishment in SRIC systems, and different clones are known to differ in their growth rates and resource requirements (Berhongaray et al., 2013; DesRochers et al., 2007; Karacic and Weih, 2006; van den Driessche et al., 2007). However, use of these clones in SRIC has only been recent and their performance is currently being tested. Thus, test results for specific clones are limited.

In our study, two economically important and related hybrid poplar clones with contrasting growth forms, Walker (*Populus deltoides* x (*P. laurifolia* x *P. nigra*) and Okanese (Walker *x* (*P. laurifolia* x *P. nigra*), were tested. Both clones were developed in the poplar improvement program of the Agriculture and Agri-Food Canada, Agroforestry Development Centre in Indian Head, Saskatchewan (Schroeder et al., 2013). The Walker and Okanese clones were specifically bred for adaptation to the Canadian prairies and northern Great Plains of the United States (Schroeder et al., 2013). Both clones were originally bred for tolerance to the harsh climate of the Canadian Prairies and their superior growth performance resulted in their widespread use in shelterbelt plantings across the prairies (van Oosten, 2006). Growth rates of both clones are high and can exceed 1.0 m of vertical growth per year (van Oosten, 2006). In addition to their use as shelterbelt trees, both clones have been recommended for use in SRIC plantations, as well as riparian restoration and phytoremediation applications (van Oosten, 2006). Consequently, Walker and Okanese have been used in operational and research plantations by Alberta-Pacific Forest Industries Inc. (Al-Pac), the main operator of SRIC hybrid poplar plantations in Alberta with more than 10,000 ha in operational plantations (Barb Thomas, personal communication, 2015).

Walker and Okanese are intersectional hybrids derived from crossings between poplar species from different sections. Walker poplar is a female clone originating from a three-way cross between a *P. deltoides* female and a hybrid male clone, *P. x petrowskyana* (Lindquist et al., 1977). The female parent *P. deltoides*, known as eastern cottonwood, is native to North America, and belongs to the section *Aigeiros*. The male parent, a *P. x petrowskyana* clone known as Russian poplar, was introduced from Eastern Europe and is a very hardy hybrid obtained from a cross between *P. laurifolia* and *P. nigra* (van Oosten, 2006). *P. laurifolia* from the *Tacamahaca* section and *P. nigra* from the *Aigeiros* section have been widely used in tree hybridization, with *P. deltoides* in particular, as is the case for *P. x Walker* (van Oosten, 2006). Okanese poplar is a male clone derived from a cross between Walker (a female clone) and a *P. x petrowskyana* (*P. laurifolia x P. nigra*) clone (Schroeder et al., 2013).

Walker poplar has been propagated since 1944 (Lindquist et al., 1977; Schroeder et al., 2013) and is the most widely planted shelterbelt poplar in the Canadian prairies (Lindquist et al., 1977; Schroeder et al., 2013). Walker usually has a single stem and very narrow crown. Walker poplar is known to be a poor competitor because of its inability to close the overstory canopy and shade competing understory vegetation (van Oosten, 2006). Moreover, Walker poplar is known to have very specific ecosite requirements and does not reach its potential on marginal planting sites with imperfect growing conditions, commonly defined by soil texture, pH, salinity and fertility (van Oosten, 2006). Best growth for Walker in the Prairie province Saskatchewan was obtained on sandy loam, sandy clay loam and loam soils while poorest growth was reported on sandy clay, clay, silty clay, heavy clay and loamy sand (Schroeder et al., 2002). Optimal pH ranges between 5.0 and 7.5 for poplars, but can vary considerable among different poplar clones (van Oosten, 2004). Moreover, Walker does not tolerate salinity, and electrical conductivity exceeding 2.0 dS/m was found to limit growth and survival (van Oosten, 2004).Walker is considered vulnerable to winter damage showing shoot dieback in northern areas (Lindquist et al., 1977). Walker poplar is also moderately tolerant to drought (Silim et al., 2009) and is rated susceptible to diseases such as stem canker infections (*Septoria musiva* Peck.) (van Oosten, 2006).

Okanese poplar has been propagated since 1986 (Schroeder et al., 2013), and like Walker, is commonly grown in shelterbelts across the Prairies (Kalcsits et al., 2009; Schroeder et al., 2013). Okanese poplar differs dramatically in its growth habit from its mother, Walker, in that it exhibits a moderately broad crown and often develops multiple stems with large lateral branches (Schroeder et al., 2013). The fast growth and broad canopy crown formation of Okanese could lead to a superior potential to shade out competing understory vegetation, thereby rendering it a good competitor. Okanese grows well on a range of soil conditions with the best performance on medium-textured soils with a pH <8.0 (Schroeder et al., 2013). Unlike Walker poplar, Okanese is considered less sensitive to cold damage and is one of the most winter hardy clones available for the Prairies (Kalcsits et al., 2009; Schroeder et al., 2013). Moreover, Okanese is resistant to drought (Silim et al., 2009) and diseases, including Septoria canker (*Septoria musiva* Peck.) and leaf rust (*Melampspora medusae* Thuem.) (Schroeder et al., 2013). Aside from being adaptable to a greater range of site conditions than Walker, Okanese poplar is known to be more responsive to silvicultural treatments (Barb Thomas, personal communication, 2014).

1.3 Economic and environmental benefits of planted poplars

Hybrid poplar grown in SRIC plantations can provide a wide range of services, including wood and non-wood products, on both a small and industrial-scale (Ball et al., 2005). Hybrid poplar has been increasingly cultivated for its high productivity as a source of fibre for the pulp and paper industry, raw material for the composite wood industry such as Oriented Strand Board, Medium Density Fibreboard and plywood, and as a supplier of biomass for energy (Poplar Council of Canada, 2012; Telenius, 1999; Weih, 2004). For small-scale farmers, biomass and wood production from plantations provide the potential for additional farm income while the forest industry gains from a reliable and stable supply of fibre (Richardson et al., 2007). Non-wood products provided by hybrid poplar include fuelwood, as well as the use of young poplar branches and foliage as alternative fodder, particularly during periods of drought (Ball et al., 2005).

Other benefits of planted poplars involve various environmental and ecosystem services such as carbon sequestration, protection from soil erosion, increase of annual crop yield by field shelterbelts, wind reduction by farmstead shelterbelts, and the provision of wildlife habitat, amongst others (Ball et al., 2005). Moreover, poplars (and related species) play an important role in forest reclamation by rapidly stabilizing soils of degraded areas, such as abandoned forestry roads (DesRochers et al., 2004), and are also useful for phytoremediation, e.g. decontaminating polluted soils (Baum et al., 2009). Further benefits include the restoration or improvement of riparian habitats by reducing the negative effects of annual crop agriculture, such as run-off (Schultz et al., 2004).

Besides their potential to supply wood, fibre, energy and various ecosystem services, industrial-scale SRIC hybrid poplar plantations could reduce the harvest pressure on natural forests (Binkley, 1999). By increasing forest productivity on a relatively small area placed under plantation management, SRIC could help meet current wood and fibre needs while simultaneously allowing for increases in the areas of natural forest placed under protection or low intensity ecosystem management (Binkley, 1999; Messier et al., 2003). Such separation of different management intensities among different parts of the landscape is part of the triad approach, where land is divided into (1) protected areas, (2) high intensity production zones, including SRIC hybrid poplar, and (3) extensively managed land allowing for ecosystem based management (Messier et al., 2003).

1.4 Hybrid poplar plantation management in the Prairie Provinces

Currently, the total reported area of hybrid poplar planted to SRIC plantations in Canada is still relatively small, covering approximately 27,559 ha in 2011 (Poplar Council of Canada, 2012).

There are several possible explanations for this, including the high volume and allowable cut of natural poplar stands in Canada (van Oosten, 2004), perceived or actual economic and biological risks involved in the establishment of hybrid poplar plantations (Volney et al., 2005), as well as social constraints such as the objection to changing from traditional annual cropping systems to silvicultural systems (Neumann et al., 2007). However, the area of land within intensively managed plantations is likely to increase in North America (Ball et al., 2005), due to the increasing demand for fibre and the potential for carbon sequestration. For example, 6000 ha of hybrid poplar plantations have been established under the federal afforestation program 'Forest 2020' in Canada in 2004 and 2005 to contribute to greenhouse gas reductions through carbon sequestration (Dominy et al., 2010).

Growing interest in expanding SRIC has led to the assessment of land suitability for the afforestation of woody crops on cleared and cultivated agricultural land, particularly on marginal soils near the forest fringe. Joss et al. (2008) mapped land suitability for the establishment of SRIC with hybrid poplar in the Canadian Prairie Provinces. They found that about 538,000 km^2 of privately owned land is available for afforestation, including all non-forested, privately owned land that can support tree establishment. Of this large eligible land base, 150,000 km^2 were found to be suitable based on key environmental variables representing adequate growing conditions (e.g. growing season precipitation, climate moisture index, growing degree days, and Canada Land Inventory capability for agriculture and elevation) (Joss et al., 2008). These are primarily located in the prairie-boreal forest transition zone. Given the extensive land base both available and suitable, this region stands out for its significant potential for afforestation with SRIC.

Despite the high potential for SRIC, there are three major challenges facing the establishment of hybrid poplar plantations in this region. One challenge to plantation establishment is the harsh climate characterized by long, cold winters and a short growing season with limited precipitation and frequent drought (Bonan and Shugart, 1989). The second challenge is the site quality of land available for SRIC. Poplar plantations are typically being established on marginal agricultural land which may not be suitable for intensive agricultural production because of suboptimal soil and/or geographic factors that result in low and uncertain crop yields (Christersson, 2008; Hofmann-Schielle et al., 1999; Vande Walle et al., 2007). Afforestation on these sites is considered difficult with a major challenge being the costly control of competitive herbaceous vegetation (Hytönen and Jylhä, 2005). The third challenge is the lack of silvicultural information specific to the management of SRIC plantations in the parkland-boreal transition zone (Block et al., 2006). Growth of fast-growing trees on these sites can be limited by intense competition and the resulting lack of nutrients, water and/or light, or by an excess of soil moisture due to insufficient drainage.

Sites typically used for establishment of SRIC plantations are characterized by diverse weed communities containing many herbaceous broadleaf and grass species (Stanturf et al., 2001). Once a site is abandoned, understory vegetation development follows patterns of classical secondary succession, including gradual structural and functional changes in species composition (Wilcox, 1998). Initial early-colonizing pioneer species are typically annual ruderals and generalists, which are progressively replaced by later-successional perennial herb and grass communities (Balandier et al., 2009; Ferm et al., 1994; Wilcox, 1998). Vigorous and rapid plant colonization may be promoted by high nutrient availability and large seed banks characteristic of former agricultural soils, combined with annual soil disturbance that facilitates seed germination (Archaux et al., 2010; Hytönen and Jylhä, 2005). Fast growing, often invasive weedy species typical of repeatedly cultivated land are also common in young hybrid poplar plantations (Sage, 1999).

1.5 Tree-herb interactions

Crop trees continuously interact with neighboring herbaceous vegetation in their efforts to acquire resources simultaneously involving competitive and facilitative interactions (Callaway and Walker, 1997). Competition between young trees and neighboring plants occurs either aboveground for light and space, belowground for water and nutrients, or as a combination of both (Balandier et al., 2006). The high productivity of poplars is strongly associated with their requirements for high resource availability, and consequently depends on the availability of these resources at adequate levels. It is well established that poplars do not reach their full potential on marginal sites (Hofmann-Schielle et al., 1999; Pinno and Bélanger, 2009). Likewise, poplar trees are known to be poor competitors and are unable to obtain adequate light, water, and nutrients when experiencing competition from vigorous weed growth (Coll et al., 2007; Morhart et al., 2013; Stanturf et al., 2001; Welham et al., 2007).

The availability of adequate water is often the most critical factor regulating plantation growth (West, 2006), and numerous studies have found soil moisture to be the key factor reducing success of poplar establishment (Monclus et al., 2006; Silim et al., 2009). Poplars are known to have high water requirements, high stomatal conductance (i.e. water loss), and are sensitive to drought; this reinforces the importance of an abundant and continuous supply of water from the soil (Heilman et al., 1996; Monclus et al., 2006). Moisture availability and conservation is of particular concern where droughts are common such as in the Canadian Prairies, which are characterized by a moisture gradient from sub-humid in the northern boreal forest and central parkland to semi-arid in the southern grasslands (Hogg et al., 2005; Silim et al., 2009). In addition to climate-induced water stress, trees may experience water stress due to competition from weeds for soil moisture, a condition exacerbated during dry periods. For example, Pinno and Bélanger (2009) showed that water availability was reduced in hybrid poplar stands colonized by weeds indicating that water was highly competed for between the poplar trees and neighboring weeds. Likewise, Powell and Bork (2004) found competition for water between trembling aspen and alfalfa and marsh reedgrass.

Plantation productivity can be further limited by nutrient availability. Poplars have relatively high nutritional demands and consequently typically require high nutrient uptake to reach their full growth potential (Heilman et al., 1996). Various studies have reported nutrient uptake by plantation trees grown with and without neighboring weed control, particularly for nitrogen. Coll et al. (2007), for example, reported significant competition for soil nitrogen and highlighted the need to control belowground vegetation to minimize root competition. Similarly, Kabba et al. (2011) found a decrease in hybrid poplar growth due to intense belowground competition for nutrients in the presence of weeds.

Nitrogen is usually the most growth limiting nutrient and the major nutrient used in fertilization treatments. Accordingly, Hangs et al. (2005) reported a stronger relationship between nitrogen supply and growth of young hybrid poplar trees, compared to the supply of other nutrients. Interestingly, nitrogen fertilization of young hybrid poplar trees has yielded mixed results. For example, Coleman et al. (2006), DesRochers et al. (2006), and van den Driessche et al. (2007) found nitrogen fertilization to have positive, negative, and neutral effects on poplar productivity, respectively. Besides nitrogen, phosphorus, zinc, magnesium and calcium may promote poplar tree growth on certain sites (Heilman et al., 1996).

In addition to water and nutrient availability, light interception is closely related to poplar growth (Heilman et al., 1996). Accordingly, poplar clones with high leaf area and rapid canopy closure had a competitive advantage essential for the successful establishment in SRIC plantations (Heilman et al., 1996). As pioneer species, poplars have high light requirements and are intolerant of shading from neighboring vegetation (Sage, 1999; Sixto et al., 2001). Although most studies emphasize the importance of belowground competition for water and/or nutrients in the soil, competition for light also appears to be significant. For example, Sage (1999) attributed reductions in biomass in a willow coppice stand to competition with tall weeds for light in the first year after cutting.

Competition for the aforementioned above and below-ground resources varies temporally with crop and weed growth stages. Young hybrid poplar trees demand high resources as they quickly expand their shoots and roots (West, 2006). At the same time, young poplars are known to be sensitive to competition, and thus dependent on early vegetation control (Hansen et al., 1983; Stanturf et al., 2001). As a result, the establishment phase is particularly critical for growth of young trees. Otto et al. (2010) reported hybrid poplar yield losses as high as 26% in the first year and 8% in the second year after planting due to weed competition. Likewise, Truax et al. (2012) related high yield of hybrid poplar eight years into establishment directly to increased growth early in stand development, thereby emphasizing the importance of ensuring rapid initial growth through use of early vegetation control. Furthermore, the critical period of weed control (CPWC) identified for poplars based on a 5% yield loss lasts as long as 54 days after planting during the first year (Otto et al., 2010). Collectively, these results reinforce the need for weed suppression through post-planting weed control.

There is evidence that the impact of understory vegetation on tree performance varies spatially. Thomas et al. (2001), for example, noted a 37% increase in poplar wood volume when weedy vegetation within a 1-m distance of the tree base was controlled with glyphosate. These 1 m wide strips were left uncultivated because cultivation equipment cannot access weeds close to the tree bole without damaging the trees. Similarly, Powell and Bork (2004) reported that the greatest understory competition on trembling aspen (*P. tremuloides* Michx.) occurred within 0.5 m of aspen saplings. Davies (1988) tested plastic ground sheets to control neighboring vegetation, noting a correlation between the size (i.e. width) of the sheet and its effectiveness in enhancing tree growth, and recommended a minimum size of 1 m^2 around trees. While the aforementioned studies emphasize the need to control vegetation close to trees, Shock et al. (2002) reported negative effects of neighboring vegetation at greater distances (0.5 m and farther) on hybrid poplar growth. In their study, an approximately 1 m wide strip around trees was maintained weed-free through hand-weeding, while seeded alfalfa were allowed to grow within an approximately 3.4 m wide strip between tree rows (Shock et al., 2002).

Perennial weeds, specifically perennial grasses, have been shown to be particularly important in reducing poplar tree performance. For example, Kabba et al. (2007) conducted a pot experiment and reported reduced growth of hybrid poplar in the presence of two perennials, quackgrass (*Elytrigia repens* (L.) Gould) and dandelion (*Taraxacum officinale* F.H. Wigg.), a response they attributed to belowground competition for nutrients. Similarly, Landhäusser and Lieffers (1998) found the perennial marsh reed grass (*Calamagrostis canadensis* (Michx.) P. Beauv.) significantly reduced growth of trembling aspen in a field study. They attributed poor seedling performance primarily to the alteration of microclimate (e.g. cooler soil temperatures), largely brought about by high accumulations of grass litter (Landhäusser and Lieffers, 1998).

Common traits that determine the high competitiveness of perennial grasses include their fast growth rate and well developed fibrous root system that allows for rapid depletion of available water and nutrient resources (Balandier et al., 2006; Hytönen and Jylhä, 2005).

Forbs also effectively compete for resources with crop trees. However, in comparison with grasses, forbs compete more efficiently for aboveground resources such as space, and in particular light, as a result of their large leaf area (Balandier et al., 2006). Detrimental reductions in light interception by trees are observed when forb heights extend above the level of the tree canopy. For example, Sage (1999) attributed reductions in biomass in a willow coppice to competition for light with tall weeds in the first year after cutting. Similarly, Balandier et al. (2009) noted that vegetation composition of a pasture containing forbs such as alfalfa (*Medicago sativa* L.) and dandelion, decreased transmitted light to a level that potentially caused tree seedlings to die. A recent study by Morhart et al. (2013) reported that another forb, field bindweed (*Convolvulus arvensis* L.), exhibited negative effects on poplar performance. The researchers found field bindweed growing particularly vigorously in a non-tillage system where only herbicides were used to control weeds. The climbing growth habit of field bindweed allows it to spiral around young trees, bending them towards the ground, and thereby exposing them to pests and herbivory which potentially contributed to the high tree mortality of 80% (Morhart et al., 2013).

The majority of the above-mentioned studies focuses on competitive interactions and inevitably considers weeds as having a negative impact on poplar growth in SRIC plantations; however, there is also some evidence for facilitative interactions. These can occur directly (e.g. reduction of water or nutrient stress), or indirectly (e.g. displacing competitive weed species) (Hunter and Aarssen, 1988). Modification of the microclimate, increases in nutrient availability, and indirect competitive effects are common facilitative mechanisms functioning in mixed-species systems (Hunter and Aarssen, 1988). Accordingly, Balandier et al. (2009) found seeded cover crops offer tree seedlings protection from extreme soil and air temperatures compared to bare soil. Similarly, Powell and Bork (2004) found aspen saplings surrounded by herbaceous species had decreased insect damage to leaves; further, alfalfa was able to increase soil nitrogen (likely due to N fixation), as well as increase soil moisture availability for short periods. However, of the two herbaceous plants tested, marsh reedgrass and alfalfa, only the latter was found to facilitate soil resource availability, indicating the importance of neighboring species identity in regulating net tree-herb interactive effects (Powell and Bork, 2004a).

Herbaceous plants also play essential ecological roles within agro-ecosystems (Berhongaray et al., 2013). Risk of nutrient leaching is of particular concern during the establishment year of tree plantations when roots of small cuttings are less abundant (McLaughlin et al., 1985; Mortensen et al., 1998). At this time, temporary herbaceous plant cover could offer benefits through retention of nutrients and a reduction in soil erosion. In a study comparing root biomass of young poplars and weeds, root productivity of weeds early in the season was found to be twice that of poplars (Berhongaray et al., 2013). Additionally, these researchers found that while some portions of the soil profile lacked poplar roots (based on observations of individual soil cores), all areas appeared to contain the roots of weeds. These results indicate weeds were distributed more homogenously while roots of young poplars were concentrated closer to the tree bole (Berhongaray et al., 2013). This finding suggests that young poplars are not able to fully stabilize soil early in the establishment period, emphasizing the importance of having alternative ground cover consisting of herbaceous plants, either voluntary or seeded. Knowledge of the potential value of neighboring herbaceous plants (including potential weeds) for agro-ecosystems, as well as their corresponding effect on tree performance, is needed for development of appropriate management tools that could lead to strategic management decisions to selectively remove or add certain species (Storkey, 2006). However, we have limited knowledge of which weed species may have low competitiveness but still fulfill critical ecological functions, and thus be suitable for the optimization of SRIC hybrid poplar plantations.

1.6 Vegetation management

Control of competing vegetation is a standard practice within intensively managed plantations (Hansen et al., 1983; Mead, 2005; Wagner et al., 2005). Conventional vegetation control practices in hybrid poplar plantations aim to reduce weed growth, and ultimately decrease interspecific competition between weeds and trees, through a combination of chemical and mechanical weed control methods both pre- and post-planting (Hansen et al., 1983, 1986). Typical site preparation involves broadcast application with a post-emergent non-selective herbicide (i.e. glyphosate, a non-selective, translocated herbicide effective on nearly all herbaceous vegetation) as well as repeated cultivation (Hansen et al., 1983; Stanturf et al., 2001). Following tree planting, weed control is achieved through broadcast application of a pre-emergent non-selective herbicide prior to tree leaf-out, and is followed up with frequent cultivation (Hansen et al., 1983). In the case of grid planting, cultivation in two directions, i.e. cross cultivation, is feasible allowing for effective in-row as well as between-row weed control (van Oosten, 2004). However, this cultivation treatment does not eliminate neighboring vegetation near the tree bole. Site maintenance typically continues up to four years post-planting (Anderson and Luckert, 2007) until canopy closure (Buhler et al., 1998). Although the overall management input is less intensive than required for traditional annual cropping systems, management practices to control competing vegetation in poplar plantations are associated with high input costs, especially during the establishment period (Anderson and Luckert, 2007). For example, Thomas and Kaiser (2003) reported total costs for silviculture over one rotation being $1231/ha, all of which is required for site preparation and maintenance during the first five years. These calculations are based on cost assumptions for establishing hybrid poplar plantations on an operational basis by Al-Pac in north-central Alberta (Thomas and Kaiser, 2003).

There are three key methods to manage competing vegetation within an agronomic approach to weed control, including mechanical, chemical and cultural practices. The three methods can be applied individually or in combination, and are implemented within an integrated weed management (IWM) framework. IWM is a flexible management system recognizing the dynamic processes of crop-weed interactions, and involves a combination of practices targeted to a specific weed population at a specific site and time to optimize control (Radosevich et al., 2007). Key components of IWM are managing weeds at optimum levels, which is often interpreted as below the economic threshold, while simultaneously minimizing crop yield losses, crop damage, and risks to the environment (Radosevich et al., 2007). Although IWM is commonly practiced within traditional annual cropping systems, this is not the case in SRIC plantations, at least to date.

Chemical weed control may involve the use of various herbicides commercially available and licensed for SRIC plantations. Chemical weed management in SRIC may be used for site preparation prior to tree planting, and for site maintenance post-planting when the tree crop is still dormant or after tree leaf-out (Hansen et al., 1983). Choice of herbicides can be based on their persistence, selectiveness, mode of action, or application type (Morhart et al., 2013). In

Canada, pre-emergent herbicides are registered for use in shelterbelts but are not registered for SRIC plantations (van Oosten, 2006). Several studies have found that herbicide application can effectively decrease weed abundance and increase hybrid poplar tree growth during the early establishment period (Coll et al., 2007; Morhart et al., 2013). The cost efficiency, low labour intensity, and effectiveness of herbicides for vegetation control has led to the current reliance on frequent use of herbicides, and therefore, they remain the most common method of weed control in plantations (Rolando et al., 2011; Wagner et al., 2005). However, accidental herbicide damage to trees is common and cannot be completely excluded (personal observation), emphasizing the importance of using complementary weed control methods.

Mechanical weed control includes practices that physically damage or remove weeds such as cultivation or mowing, and is commonly used in SRIC plantations for initial site preparation and crop maintenance. Cultivation breaks up the dense network of roots common in agricultural fields that have been in pasture or forage production and is used to prepare the soil for planting and to enhance subsequent weed control (Buhler et al., 1998; Hansen et al., 1983). Hybrid poplar is known to perform best in weed-free fields and mechanical weed control practices were found to control weeds, thereby enhancing tree performance (Bilodeau-Gauthier et al., 2011). Compared to chemical weed control, mechanical control methods are more labour-intensive and expensive. Moreover, effects on weeds are short-lived, and early successional and competitive weeds are able to rapidly reinvade (Siipilehto, 2001). Moreover, repetitive mechanical tillage can break up the root system of rhizomatous species, thereby spreading the weeds such as quackgrass, a species known to reduce hybrid poplar growth (Kabba et al., 2011). Furthermore, continuous cultivation increases potential risks to the environment and long-term productivity of a site, including risks of reduced soil fertility through depletion of organic matter and carbon, increased soil moisture loss, and soil erosion. Other detrimental impacts of repeated cultivation may involve direct damage to branches and roots of trees through cultivation equipment, especially at a narrow crop spacing of 3x3 m or less.

Besides the conventional vegetation control methods of herbicide and cultivation, alternative methods such as the use of mulches and cover crops could be used for weed control, decreasing production costs while simultaneously offering environmental benefits. One alternative method to achieve post-planting weed control is the use of a cover crop that would ideally suppress the growth of competitive weeds while not negatively affecting tree performance. Cover crops could prevent sites from becoming colonized by competitive species by rapidly forming a low-growing ground cover without competing for belowground resources with the crop trees. However, in many studies cover crops failed to suppress weeds, and were found to compete with the tree crop and to increase tree mortality (Willoughby 1999, Davies, 1985). For example, Willoughby (1999) reported that established ground cover crops proved to be as competitive as the naturally occurring weed species. A further alternative to chemical and mechanical weed control is the use of mulches to improve early tree growth by suppressing weed seed germination and growth. Other benefits may include reduced water evaporation and subsequent soil moisture conservation along with higher soil temperatures which may promote tree root growth and subsequent nutrient uptake (Davies, 1985; Thomas et al., 2001). In any case, use of alternative methods to control competing understory vegetation within plantations while reducing costs for labour and equipment remain minor (Wagner et al., 2005).

1.7 Research objectives and thesis outline

The development of silvicultural production systems that reduce management costs while increasing the feasibility of plantations will be critical for future establishment of SRIC hybrid poplar plantations, as identified by a recent Delphi survey assessing future deployment of SRIC plantations in Canada (Masse et al., 2014). Despite significant research activities concerning silvicultural management of hybrid-poplar plantations in Canada (Larocque et al., 2013), there is a lack of studies assessing alternative systems that could promote hybrid poplar performance, reduce production costs and enhance ecological functioning within SRIC plantations, especially in the agriculture-boreal forest fringe of the Canadian Prairies. The main objective of this research was to test establishment systems using various alternative vegetation management tools within 1-3 year old hybrid-poplar plantations established in north-eastern Alberta. The results of this study will contribute to our understanding of the key factors influencing hybrid poplar performance and should lead to spatially and functionally targeted weed control strategies that effectively contribute to an optimal IWM plan for operational hybrid-poplar plantations.

In Chapter 2, I compare the effects of three alternative establishment systems to the current business-as-usual system, for their effect on the growth and performance of two hybrid poplar clones within 1-2 year old plantations in north-eastern Alberta. The primary objectives of this study were to:

a) Quantify differences in the abundance and composition of competing understory vegetation neighboring the trees among the establishment systems, and

b) Determine differences in early aboveground growth and survival of the two hybrid poplar clones among the establishment systems and the role of changes in neighboring herbaceous vegetation on this, and

c) Identify key environmental factors related to growth performance of trees in these establishment systems, including nutrient availability, soil temperature, soil moisture and light availability.

In Chapter 3, I assess the spatial impacts of competing vegetation on growth performance of two hybrid poplar clones during early establishment (1-3 years of age), including identification of near-bole (<50 cm) and far-bole (50 cm to 140 cm) competition, as well as above- and below-ground competition. The objectives were to:

a) Test the relative importance of competition near-bole versus far-bole, and above- versus belowground, on growth and survival of two hybrid poplar clones, and

b) Determine whether competition effects vary over time during early establishment in relation to the above factors.

Chapter 2: Effects of alternative establishment systems on resource availability, understory composition, and tree performance in juvenile hybrid poplar plantations

2.1 Introduction

Hybrid poplar (*Populus* spp.) has been increasingly cultivated in short-rotation-intensive-culture (SRIC) plantations for its high productivity and potential to supply wood, fibre, biomass for energy, alternative fodder, and various ecosystem services, including carbon sequestration (Poplar Council of Canada, 2012; Weih, 2004). In the Canadian Prairie Provinces, industrial scale hybrid poplar plantations are mainly established as a source of fibre for the pulp and paper industry on leased agricultural land within the agriculture-boreal forest fringe. Economically viable production of hybrid poplar plantations in this region faces major challenges however, including the harsh boreal climate, the often marginal site quality, and the lack of adequate silvicultural information specific to the parkland-boreal transition zone (Block et al., 2006).

It is well established that the productivity of poplars is strongly associated with their requirements for high availability of resources, including nutrients, water and light. However, typical planting sites are occasionally suboptimal in terms of soil and landscape factors (e.g. poor drainage), and are therefore marginal for intensive annual crop production (Christersson, 2008; Hofmann-Schielle et al., 1999; Vande Walle et al., 2007). The greatest challenge commonly facing establishment of young hybrid poplar on these sites is the diverse weed communities containing fast growing, often invasive herbaceous broadleaf and grass species (Sage, 1999;

Stanturf et al., 2001). Initial survival and growth potential of hybrid poplars can be limited by intense competition with the herbaceous understory, and the resulting lack of nutrients, water and/or light. More specifically, perennial grasses such as quackgrass (*Elytrigia repens* (L.) Gould) are important in reducing poplar tree growth and survival (e.g. up to 50%) through belowground competition for nutrients (e.g. N, P, and K) and water (Kabba et al., 2007). On the other hand, herbaceous plants fulfill critical ecological functions (e.g. retention of nutrients, moisture conservation, reduction in soil erosion) within agro-ecosystems, especially during the early establishment period when young poplar trees are not able to fully stabilize the soil (Berhongaray et al., 2013). However, our knowledge is limited as to which herbaceous species may have low competitiveness with trees while offering environmental benefits, and on which management system(s) could provide the necessary (i.e. selective) suppression of competitive species while retaining or adding species suitable for the optimization of plantation growth (Balandier et al., 2009; Storkey, 2006).

Across the prairies, there are several hybrid poplar clones available for establishment in SRIC production that differ in their growth rates and resource requirements (Berhongaray et al., 2013; DesRochers et al., 2007; Karacic and Weih, 2006; van den Driessche et al., 2007). Of these, the two related intersectional hybrids, the female clone Walker (*Populus deltoides* x (*P. laurifolia* x *P. nigra*) and male clone Okanese (Walker *x* (*P. laurifolia* x *P. nigra*) are two economically important clones originally bred for tolerance to the harsh climate of the Canadian Prairies and superior growth performance (van Oosten, 2006). These two clones differ in their growth form as Walker is characterized by a single stem and very narrow crown, and is usually unable to close its canopy in SRIC (van Oosten, 2004), while Okanese typically has a moderately broad crown and multiple stems with large lateral branches (Schroeder et al., 2013), possibly leading to a superior potential to shade out competing understory vegetation. Moreover, Walker poplar is known to have very specific ecosite requirements and does not reach its potential under sub-optimal site conditions (van Oosten, 2006), while Okanese grows well on a wider range of soils, rendering it more suitable for marginal planting sites (Schroeder et al., 2013). Walker and Okanese were selected for evaluation here due to their economic importance as shelterbelt and SRIC hybrid poplars in the Canadian Prairies and their contrasting growth forms, resource requirements and competitiveness with the herbaceous understory.

Conventional vegetation management within operational plantations strives to reduce tree yield loss and mortality through intensive (i.e. broadcast) weed control during the establishment phase, when young hybrid poplar trees demand high resources and are most sensitive to competition. Current business-as-usual weed control typically involves a combination of chemical and mechanical methods for site preparation starting the fall before tree planting, and subsequent in-stand maintenance up to four years post-planting (Anderson and Luckert, 2007; Hansen et al., 1983, 1986). While chemical and mechanical weed control have been effective in decreasing weed abundance and increasing hybrid poplar tree growth during the establishment period (Bilodeau-Gauthier et al., 2011; Coll et al., 2007; Morhart et al., 2013), there are several limitations associated with the business-as-usual system, including technical, environmental and economic. For instance, the aforementioned methods can pose risks to the tree crop, environment and long-term productivity of a site. These include accidental herbicide damage and/or mechanical damage to trees, as well as risks of reduced soil fertility through depletion of organic matter and carbon with cultivation, and increased soil moisture loss. Furthermore, effects on weeds may be relatively short-lived, necessitating repeated management actions to control rapidly re-establishing weeds (Ferm et al., 1994; Morhart et al., 2013), which in turn, further increases production costs. Reduction of costs for site preparation and plantation maintenance during the establishment period [e.g. $1231/ha over one rotation in north-central Alberta (Thomas and Kaiser, 2003)] has been identified as a critical step for future deployment of SRIC plantations in Canada (Masse et al., 2014).

Besides conventionally used systems, alternative weed control methods such as the use of mulches and cover crops could optimize weed control, decrease production (i.e. maintenance) costs, while simultaneously offering environmental benefits. However, few studies have tested alternative weed control systems and their combined effects on understory cover and composition, environmental conditions and tree performance, especially in the parkland-boreal transition zone of the Canadian Prairies. Morhart et al. (2013), for example, tested different weed control systems on poplar performance in Germany, including the use of ploughing and harrowing, cultivation with ley crop, as well as systems without tillage, but did not report the effects on cover or composition of the herbaceous understory. These researchers found that a combination of tillage and chemical weed control resulted in the best tree establishment, while systems using mechanical vegetation control and the use of mulches resulted in considerable yield losses (Morhart et al., 2013).

In the present study, we evaluated the effects of three contrasting establishment systems for hybrid poplar plantations in north-east Alberta as an alternative to the current business-as-usual system, and their impacts on understory cover and composition, environmental attributes and tree performance. The primary objectives of this study were to: (1) quantify treatment-induced differences in the abundance and composition of competing understory vegetation neighboring trees, (2) determine differences in early aboveground growth and survival between two hybrid poplar clones exposed to different establishment systems, including the role of changes in neighboring herbaceous vegetation, and (3) identify key above- and belowground abiotic factors, including light availability, soil nutrient availability, soil moisture, and soil temperature, that can be related to tree growth within these plantations. This research is expected to provide insight into the development of optimal integrated weed management (IWM) plans by contributing to spatially and functionally targeted weed control strategies for operational SRIC hybrid-poplar plantations throughout the boreal region.

2.2 Methods

2.2.1 Study area

This investigation took place in the Dry Mixedwood Natural Subregion (Natural Regions Committee 2006) of north-central Alberta, Canada ($54^0$53’35.1N, $112^0$51’ 38.5W, 575m above sea level). This area is situated at the interface of the agriculturally dominated Central Parkland to the south and the Central Boreal Mixedwood Natural Subregion to the north. The study was established with the assistance of Alberta-Pacific Forest Industries Inc. (Al-Pac) on research sites that had been natural mixedwood boreal forest and converted to agronomic perennial forages, used most recently for hay production. The area is characterized by a gradual transition from a well-drained upland to an adjacent poorly drained lowland ecosite. Soils are characterized as Typic Fibrisols (Soil Classification Working Group, 1998) in poorly drained areas and Orthic Gray Luvisols in well drained areas (Alberta Soil Information Viewer, 2014).

The climate of the study area is temperate continental with short, warm growing seasons and long, cold winters. The 1981 to 2010 long-term average January and July temperatures were -13.4 °C and 16.6 °C, respectively. Mean annual precipitation was 479 mm over this 30 year period, of which 336 mm (i.e. 70%) falls during the growing season, with a peak precipitation of

105 mm in July (Appendix 2.1). Herbaceous vegetation was dominated by introduced forages, weedy forbs and graminoids. Common annual forbs included *Chenopodium album* L., *Galeopsis tetrahit* L. and *Polygonum convolvulus* L.; common perennial forbs included tap-rooted species such as *Medicago sativa* L. and *Taraxacum officinale* F.H. Wigg., together with creeping species such as *Cirsium arvense* (L.) Scop. and *Equisetrum arvense* L.. The most common graminoid was the creeping perennial *Elytrigia repens* (L.) Gould.

2.2.2 Experimental design

This study was established as a strip-plot design with fifteen blocks, four establishment treatments, and two hybrid poplar clones (Appendix 2.2, Table 2.1). Blocks covered a range of ecosite conditions from upland to lowland areas, but remained internally uniform. The entire study site was fenced with 2.1 m high fencing in 2013 to protect young trees from ungulate browsing. Within each block, four treatments were randomly assigned to four horizontal strip plots, each 11m X 28m in size. Clones were randomly assigned to vertical strip plots orthogonal to the four treatment plots within each block (Appendix 2.2). In the beginning of June 2012, 20 individuals of both poplar clones, “Walker” and “Okanese”, were hand-planted at 2.8 m grid spacing into separate plots (4 x 5 trees in dimension), respectively. This layout provided a single buffer row around all trees monitored and measured (Appendix 2.2). Planting stock consisted of commercially grown over-wintered dormant plugs grown from cuttings at the Smoky Lake Forest Nursery near Smoky Lake, Alberta. Rooted cuttings were packaged in fall 2011 and stored at about -2.5 °C (Dave Kamelchuk, Alberta-Pacific Forest Industries Inc., personal communication, 2014) until planting in June 2012. The four plantation establishment treatments were:

(1) Control – business-as-usual practice involving conventional cultivation prior to planting, and ongoing weed suppression with in-crop herbicides and cultivation following planting.
(2) Fallow – a full year of fallow prior to planting involving repetitive cultivation and herbicide spraying, followed by conventional weed suppression after planting (similar to the business-as-usual).
(3) Cover crop – sowing of a cover crop mixture into prepared fields between tree rows after tree planting.
(4) No-till – planting into untilled fields following localized vegetation suppression using glyphosate herbicide at 5 L ha^{-1} ("No-till") (see Appendix 2.3 for full details on each treatment).

2.2.3 Application of treatments

All four treatments included pre-planting in-row and between-row herbicide application and cultivation, except the no-till treatment, which used in-row and between-row herbicide application but only deep-ripping of in-row strips (see Appendix 2.3 for overview of establishment methods and dates of application for all treatments). Treatment application started in June 2011 for fallow plots. Broadcast herbicide applications of glyphosate (5 L ha^{-1}) occurred during spring and early summer, followed by monthly cultivation until fall of 2011 to attain an extended one year period of herbaceous vegetation control. Final site preparation of fallow plots in the form of cultivation and herbicide application occurred prior to planting of trees in June 2012.

Treatment application for the three other treatments started in September 2011 with an initial glyphosate application (5 L ha^{-1}). For both business-as-usual and cover crop plots, herbicide application was followed by cultivation of the full plot, whereas in no-till plots only the strips designated for tree planting were deep-ripped, without cultivation of 'inter-row' areas.

Seven days after tree planting, cover crop plots were inter-seeded with a mixture of white clover (*Trifolium repens* L.), creeping red fescue (*Festuca rubra* L.), tall fescue (*Festuca arundinacea* Schreb. Cv 'Courtney') and perennial ryegrass (*Lolium perenne* L.). Following tree planting, broadcast application of pre-emergent herbicide (2.16 kg/ha Lorox) was used for business-as-usual, fallow and no-till plots, whereas spot application of Lorox was used within tree rows only within cover crop plots; the latter allowed establishment of interseeded cover crops between-rows. Post-planting herbaceous vegetation control for business-as-usual and fallow treatments was achieved through repeated cultivation at the beginning and end of each successive growing season, while cover crop and no-till plots were mowed annually in August. Mowing was used to reduce standing litter accumulation and habitat for rodents that might feed on young trees, and as a means of supporting the establishment of cover crops.

2.2.4 Data collection

2.2.4.1 Hybrid poplar growth, survival and damage

Initial tree height and basal diameter were measured in June 2012 at planting for the six center trees of each 4 X 5 plot. Each experimental tree was tagged and basal diameter was recorded and trees marked at 3 cm above the ground to allow for repeated measures of basal diameter at the same location. Total height and diameter were measured again for all living experimental trees at the end of the first and second growing seasons in October 2012 and 2013, respectively. Additionally, total height was measured monthly between May and August 2013 for a subset of up to three living trees per plot. Height was measured with a meter stick from ground level to the end of the tallest stem. Trees were straightened out to get a precise measurement. Basal diameter was measured 3 cm above ground in two directions (N-S and W-E) using a digital caliper and recorded to an accuracy of 0.01 mm. Height and diameter increments for each season were calculated by dividing the final growth measurement in fall by the initial measurement in spring. Dieback over the winter of 2012/2013 was assessed through height measurements of the leader in May 2013 and calculated as the difference in height between measurements in fall 2012 and spring 2013.

Tree survival was assessed at the beginning and end of each growing season. Trees were considered dead when the stem was brittle and no green leaves were present; these trees were not included in the analysis of growth increment. Tree survival was expressed as the number of living trees in each plot divided by the total number of trees in the plot and reported as a percentage. Despite fencing the plots, damage occurred from browsing by large ungulates (i.e. deer and moose) and was assessed following the winters of 2012/2013 and 2013/2014, however, only data from the first winter are included in this thesis. Browse damage was recorded as either present or absent, and the amount of browsing calculated as the difference in height from previous fall measurements. Browse frequency was expressed as the number of browsed trees within each intersection plot divided by the total number of living trees, and reported as a percentage.

2.2.4.2 Herbaceous understory cover and composition

Herbaceous understory vegetation was quantified annually around trees between late July and early August 2012 and 2013 (i.e. near peak growth) using a belt transect comprised of three contiguous quadrats (25 cm wide x 35 cm long) to form a 105 cm long belt (Appendix 2.2). Vegetation was sampled using these quadrats at three distances (0-35 cm, 35-70 cm, and 70-105 cm) from the tree base in the four cardinal directions for all living experimental trees in 2012 and for a randomly selected subset of three living trees per intersection plot in 2013. All species of vascular plants were identified in each quadrat and percent cover (0-100%) of above-ground parts of each species visually estimated. Cover estimates were within 5% increments up to 20% cover, and thereafter within 10%. Total cover per quadrat could add up to more than 100% due to overlap of plant canopies. Plant species nomenclature, life cycles, growth forms and origin status are taken from the USDA Plants Database (http://plants.usda.gov/), and Alberta designations were obtained from the Weed Control Act (Alberta Weed Control Regulation 19/2010). For a complete list of plant species identified in the sampling quadrats, see Appendix 2.4. Visual assessments were conducted by the same person across all plots?

2.2.4.3 Soil nutrient availability

Plant Root Simulator (PRS) probes containing ion exchange resin membranes (Western Ag Innovations, Inc., Saskatoon, Canada) were installed in the second growing season (2013) to measure nutrient supply rates. PRS-probes use an absorbing membrane surface of 17.5 cm^2 that is either positively charged (anion) to adsorb all negatively-charged anions such as NO_3^-, PO_4^{3-} and SO_4^{2-}, or negatively charged (cation) to adsorb all positively-charged cations, including NH_4^+, Ca^{2+}, and Mg^{2+}, from the soil. In this study a total of four pairs of PRS-probes, each with one anion and one cation probe, were inserted vertically at each of two different distances from planted trees within each of the four treatment plots of each block containing Okanese, for a total of 124 PRS-samples (15 blocks x 4 treatment plots x 1 clone x 2 distances + 2 additional treatment plots x 2 distances) (Appendix 2.2). Four PRS probe pairs were placed at 20 cm distance from the base of a subset of four trees at the side of the tree facing the main alley (North or South) and four pairs were equally spaced along the center of the main alley (i.e. at 140 cm distance from the base of the trees) (Appendix 2.5). Probes were buried approximately 12 cm deep for a period of nine weeks starting May 28 until July 27 to coincide with the interval between silvicultural maintenance applications to prevent damage of probes from equipment.

After removal probes were cleaned with deionized water and the four pairs per distance were pooled prior to analysis. All probes were promptly shipped to Western Ag Innovations Inc. in Saskatoon, Saskatchewan, and eluted in 0.5 M HCl for an hour prior to analysis, following which the eluate was analyzed for NO_3^-, NH_4^+, PO_4^{3-}, K^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Mn^{2+}, Al^{3+} , Fe^{2+}, Cu^{2+}, Zn^{2+}, B^+ , Pb^{2+}, and Cd^{2+}. NO_3^--N and NH_4^+-N were analyzed colorimetrically with an automated flow injection analysis system and all other nutrients were analyzed using inductively-coupled plasma spectrometry. PRS-probe supply rates are reported as μg of nutrient/10 cm^2/burial length. The equipment and procedure used have analytical method detection limits (MDL, μg/10cm^2/burial length) for each nutrient, indicating the lowest value that is significantly greater than zero, which are as follows: Al= 0.4, B= 0.2, Ca= 2, Cd= 0.2, Cu= 0.2, Fe = 0.4, K= 4, Mn= 0.2, Mg= 4, NH_4^+= 2, NO_3^-= 2, Total N= 2, P= 0.2, Pb= 0.2, S= 2, Zn= 0.2. Nutrients for which the majority of probe values were below the MDL in this study were Cd, Cu and Pb, and therefore data for these nutrients were not statistically analyzed. Further, the nutrients B and Al were excluded from analysis due to incomplete displacement of these ions during probe regeneration for a subset of probes used (Eric Bremer, Western Ag, personal communication, 2013).

2.2.4.4 Soil water content and soil temperature

Volumetric soil water content (%) was recorded on August 28, 2012 and on June 20, July 18, and August 24, 2013, at least two days after measurable precipitation, with a ML2x ThetaProbe soil moisture sensor attached to a HH2 moisture meter (Delta-T Devices, Cambridge, UK). Soil moisture was measured at 5 cm depth at three distances from the tree bole (e.g. 20 cm, 40 cm and 140 cm) for a randomly selected subset of up to three living trees in each intersection plot. Measures at 20 and 40 cm were taken at both the north and south side of the tree, while measurements at 140 cm were equally spaced along the center of the main alley. The two measurements at each distance were averaged prior to analysis. Peak soil temperature (°C) was measured on August 27, 2012, May 09, between June 06 and 18, and on July 21, 2013, between 14:00 and 16:00 MDT, using a 450ATT digital soil thermocouple thermometer (Omega, Laval, PQ, Canada). Soil temperature sampling was at the same locations as soil moisture.

2.2.4.5 Photosynthetically active radiation

Photosynthetically active radiation (PAR; 400–700 nm) was measured on June 14 and July 09, 2013, during a two-hour period around solar noon when weather conditions were stable (either clear sky or completely overcast), using a 80 cm long linear ceptometer (AccuPAR, Decagon devices, Inc., Pullman, USA). Four instantaneously taken measurements were averaged for each of three sampling locations for each tree, for a randomly selected subset of up to three living trees per intersection plot. Sampling locations were: 1) above the tree and weed canopy for an unobstructed sky view, 2) above the weed canopy at the mid crown of the tree for a measure of the tree impact on the surrounding understory, and 3) outside of the tree canopy but within the weed canopy at the vertical midpoint of the shaded portion of the tree crown to measure the effect of competing vegetation in reducing light for the affected tree portion (Appendix 2.6). When no tree leaves where shaded, PAR was measured at the vertical midpoint of the dominant weed layer, which occurred almost exclusively in fallow plots during June (business-as-usual: n=2, cover crop: n=1, fallow: n=32, no-till: n=0). To compare between sampling periods of differing weather conditions and growth, the relative transmittance of each sampled vegetation layer was calculated. Relative PAR transmittance (%) was calculated as the proportion of PAR measured within each respective plant canopy compared to the instantaneous PAR measure taken above the plant canopy, representing proportion of available PAR reaching the respective canopy location.

2.2.4.6 Bud break

Timing of leaf bud break was recorded between May 09 and May 28, 2013 (Julian Day 129-148) on a seven-level bud development scale (0, buds dormant; 1, buds swollen; 2, buds broken; 3, leaves appeared; 4, scales opened; 5, more leaves appeared; 6, leaves fully unfolded) based on Li et al. (2010). During this period all living experimental trees were assigned to one of the seven bud break scores in a two-day interval. The next stage of development was assigned when 50% or more of the buds on each tree reached the next stage of development. Timing of bud break was calculated for each individual tree as the average day of year at which a bud break score of 3 (emergence of the first new leaf) was reached.

2.2.4.7 Soil properties

Ten soil cores were randomly taken from each block in early June 2013. Each core was split into two depths of 0-15 cm and 15-30 cm. All ten samples per depth and block were combined into one composite sample and stored frozen. Samples were analyzed for texture (Sand >50 µm, Clay <2 µm, and Silt 2-50 µm, hydrometer method), pH, electrical conductivity (EC, µs/cm, pH conductivity meter), organic matter (loss on ignition), total nitrogen, ammonium and nitrate (mg/kg air dried soil, colorimetrically on a SmartChem Discrete Wet Chemistry Analyzer) by the Natural Resources Analytical Laboratory at the University of Alberta, Edmonton, Canada. A summary of means for each block and soil depth is presented in Table 2.2.

2.2.5 Statistical analysis

Statistical analyses were performed using both “R” (R Development Core Team 2012) and SAS 9.2 (Sas Institute Inc., Cary, NC) software. Prior to analysis, data for all response variables, including tree, understory and environmental variables, were averaged for all trees within each intersection plot (e.g. clone by treatment interaction) to avoid pseudoreplication. Species composition was expressed by individual species as well as by the following four species groups reflective of growth form and life cycle: 1) annual forbs, 2) perennial forbs, 3) annual grasses, and 4) perennial grasses. Percent cover was calculated as the average cover of each species or functional group of the four respective quadrats within each distance interval for each of the three sampling distances (0-35 cm, 35-70 cm, and 70-105 cm from tree base), and of all 12 quadrats for total cover per tree. Cover crop establishment was quantified simultaneously during assessment of the weedy understory for both growing seasons using the same sampling quadrats and sampling distances.

Differences in poplar tree survival between clones, the four establishment systems and their interaction were tested for each sampling time between October 2012 and May 2014, using the SAS procedure for categorical analysis (proc CATMOD). The final model included survival percentage as the response variable, and establishment systems (business-as-usual, cover crop, fallow and no-till), type of clone (Okanese, Walker) and the interaction between establishment system and clone as fixed factors.

Mixed-model analyses of variance (ANOVA) using the SAS procedure for mixed models (proc MIXED) were used to compare the effects of establishment systems, clones and their interaction, on total tree basal diameter and height, as well as diameter and height increments for each season, total cover of the understory vegetation and cover of each functional group, relative transmittance of photosynthetically active radiation by the understory and the tree canopy, and volumetric soil moisture and soil temperature. The model for all ANOVAs included establishment system (business-as-usual, cover crop, fallow and no-till), type of clone (Okanese, Walker) and the interaction between establishment system and clone as fixed factors, and block as the random term. ANOVAs of tree growth included initial tree basal diameter and height (June 2011) as a covariate to account for variation in tree size at planting. Further, mixed-model ANOVAs were used to compare the effects of establishment systems on soil nutrient supply rates of total nitrogen, NO_3^--N, NH_4^+-N, PO_4^{3-}, K^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Mn^{2+}, Fe^{2+}, and Zn^{2+}, as measured for Okanese poplar, including establishment system as the fixed factor and block as the random term. All response variables were analyzed separately for each sampling distance and each sampling time.

Assumptions of normality and homoscedasticity were tested using plots of residuals. Relative height growth in 2013 and all diameter variables (except initial diameter) in 2012 and 2013 were log transformed; percent cover data of annual forbs, perennial forbs and perennial grasses (except at distance 35-70 and 70-105 cm in 2013) were square root transformed; total volumetric soil moisture (i.e. averaged across all sampling distances) was log transformed, and all soil nutrient supply rates (except Ca and Mg) were log transformed prior to analysis. When significant differences were found, post-hoc pairwise comparisons were performed using a Bonferroni adjustment of α (α/ # of comparisons) to control the family-wise error rate. For example, pairwise comparisons among the four establishment systems used a Bonferroni-adjusted α-value of α_{adj}= 0.05/6= 0.008.

Effects of establishment system, poplar clone and the interaction thereof, on understory vegetation community composition were evaluated with permutational multivariate analysis of variance (perMANOVA) using the R package *vegan* with the *adonis* function (R Development Core Team 2012). Significance testing followed the same method as for the series of ANOVAs.

Indicator species analysis (ISA) was used to determine whether and which understory species (or group of species) were indicators of individual tree establishment systems and combinations thereof (Caceres and Legendre, 2009). Random permutations (n=1000) were used to test the statistical significance of indicator values. ISA was performed using the '*multipatt'* function of the R package 'indicspecies'. Understory vegetation composition was compared among the four establishment systems, using nonmetric multidimensional scaling (NMDS) ordination, using the '*metaMDS*' function in the *vegan* package in R (Oksanen et al., 2014) with a Bray-Curtis (Sørensen) distance measure, which is suitable for non-normal ecological data. Standardization of the data matrix was performed prior to analysis, using a Wisconsin double standardization. NMDS ordinations included cover data (0-105 cm, averaged across all quadrats) of all understory plant species for all assessed experimental trees for the second growing season after planting (2013). Understory variables were added to the ordination post-hoc, using the 'envfit' function (Oksanen et al., 2014) and a Pearson correlation of $r^2 > 0.3$ as the cut-off for all fitted vectors in the final ordination.

Regression tree analysis was used to identify relationships between hybrid poplar clone diameter growth, understory community characteristics, and environmental and management variables - including type of clone and establishment treatment. Diameter growth was used as the response variable, due to confounding factors such as herbivory by native ungulates (moose and/or deer) and winter dieback, which made it inappropriate to assess height growth. Regression tree analysis is well suited to identify primary relationships within complex data sets, involving numerous data types such as categorical, continuous and non-parametric variables (De'ath and

Fabricius, 2000). Univariate regression trees were run separately for the first and second growing season (2012 and 2013, respectively), using the R package *rpart* (R Development Core Team 2012). Predictor variables were selected based on prior significance testing using a series of ANOVAs. In 2012, 20 understory variables, 5 environmental variables, and type of clone and treatment were included. In 2013, 20 understory variables, 32 environmental variables, and type of clone and treatment were included (Appendix 2.11). Data for the understory community included 23 species in 2012 and 37 species in 2013, summarized into 4 functional groups for each of three sampling distances and the aggregate cover of all sampling distances (Table 2.3, Fig. 2.1). Initial regression trees were pruned to minimize cross-validated error. The output is a dichotomous tree diagram that splits data into homogenous groups that can be readily interpreted.

2.3 Results

2.3.1 Understory vegetation

Total understory vegetation cover differed ($p< 0.001$) among treatments during the first two growing seasons after planting, varying from 16% to 38% at the end of the first growing season, and from 35% to 52% at the end of the second growing season (Table 2.3, Fig. 2.1). In 2012, understory cover was generally ranked among treatments in the following order: fallow < no-till < business-as-usual < cover crop (Fig. 2.1); for statistical differences see Table 2.3. Total cover averaged across all sampling distances (0-105 cm) was 22% lower ($p< 0.001$) in fallow than in cover crop, and 11% lower ($p= 0.008$) in fallow than in business-as-usual, reflecting a lower cover of perennial forbs and grasses (Fig. 2.1). Understory vegetation cover increased within all treatments from 2012 to 2013, reflecting largely a universal increase in the cover of perennials, and an increase in annual forb cover within the fallow treatment (Fig. 2.1). Total understory vegetation cover in 2013 was greater ($p< 0.002$) in fallow than in any other treatment, reflective of a rapid increase in annual plant cover (Fig. 2.1); no differences were found among the other treatments that year. Establishment of cover crops was poor in the first season with a total cover of seeded plant species of only 2.4% in the first year, which then increased to 11.4% in the second year (Fig. 2.1). Furthermore, almost no significant differences in understory cover among clones were detected (Table 2.3).

In terms of species composition, perMANOVA tests showed significant differences in understory plant composition among establishment systems (perMANOVA $p= 0.001$) for both 2012 and 2013, whereas no significant differences were found in composition between the Okanese and Walker clones (Table 2.4). Post-hoc pairwise comparisons of treatments showed that understory composition differed among all treatments (perMANOVA $p= 0.001$) (Table 2.4), and this reflected primarily treatment impacts on annual versus perennial plant species. In general, a shift towards perennial species, particularly perennial grasses, was observed for all treatments over time (Table 2.3). However, the proportion of different functional groups (e.g. annual forbs, perennial forbs, and perennial grasses) differed markedly among treatments. For example, the fallow treatment showed the greatest relative proportion of annuals compared to perennials during the first and second year after tree planting, while no-till plots had the greatest proportion of perennial species compared to all other treatments (Fig. 2.1, Table 2.3).

In 2012, the indicator species analysis identified seven significant indicator species associated exclusively with the cover crop treatment, four indicator species for the combination of business-as-usual, cover crop and fallow establishment systems, and three other indicators for the combination of business-as-usual, cover crop and no-till systems (Table 2.5). In 2013, nine significant indicator species were identified exclusively for the cover crop treatment, four species for the fallow treatment, two species for a combination of business-as-usual and fallow, one species for the combination of cover crop and no-till, and two species for the combination of business-as-usual, cover crop and no-till (Table 2.5).

Business-as-usual plots were dominated by a mixture of annual forbs (e.g. *Chenopodium album*, *Polygonum convolvulus*), perennial forbs (e.g. *Taraxacum officinale*, *Medicago sativa*) as well as the perennial graminoid quackgrass (*Elytrigia repens*). Cover crop plots were mostly associated with the seeded cover crop species, as well as numerous perennial forbs and quackgrass. This was unlike fallow plots, which were dominated by ruderal species; indicator species for this treatment were exclusively annual forbs (e.g. *Chenopodium album*, *Thlaspi arvense*, *Polygonum convolvulus*, *Galeopsis tetrahit*) that are shade-intolerant and typical of repeatedly cultivated land. In contrast, indicator species within no-till plots were exclusively perennials, including forbs (e.g. *Potentialla norvegica*, *Taraxacum officinale*) and grasses (e.g. *Elytrigia repens*).

The NMDS ordination showed clear separation among the different plantation establishment treatments based on differences in understory vegetation composition. Additionally, several individual species were identified in the ordinations as being associated with the different establishment systems (Fig. 2.2). In total, seven species were strongly correlated ($r^2 > 0.3$) with the ordination axes, including one perennial grass, two perennial forbs, one annual forb and three cover crop species (Fig. 2.2). A clear gradient from annual dominated to perennial dominated understory species was apparent that directly reflected the plantation establishment systems tested (Fig. 2.2).The final ordination was three-dimensional with a final stress of 0.1484 after 17 iterations.

2.3.2 Hybrid poplar survival and growth

Overall hybrid poplar performance after two growing seasons, including survival, height and diameter growth, were largely affected by poplar clone ($p < 0.001$) followed by the establishment treatment ($p < 0.001$) (Tables 2.6, 2.7). Moreover, significant clone x treatment interactions ($p < 0.001$) indicated that the two related hybrid poplar clones used in this study responded differently to the establishment systems tested (Tables 2.6, 2.7).

2.3.2.1 Survival

No significant differences between clones ($p= 0.744$) and treatments ($p= 0.737$) were found on tree survival after the first growing season (2012) (Table 2.6a). However, in May 2013 after the first winter, survival differed sharply between clones ($p< 0.001$), with Okanese showing greater survival (93%) than Walker (67%); no differences were found among treatments ($p= 0.513$) (Table 2.6b, Fig. 2.3). Clonal differences persisted up to the end of the second growing season ($p< 0.001$), with survival remaining high for Okanese poplar (89%) and dropping even lower for Walker (39%) (Table 2.6b, Fig. 2.3). At the beginning of the third growing season (May 2014) and following the second winter after planting, a clone x treatment interaction ($p= 0.027$) indicated differences in survival existed for each clone among treatments (Tables 2.6a, 2.6c). Survival of Okanese poplar remained high in both the fallow (84%) and business-as-usual (82%) treatments, but decreased to 44% in both the cover crop and no-till treatments (Fig. 2.3). Overall survival of Walker poplar in May 2014 was poor across all treatments, being greatest in the fallow (21%) and lowest in the cover crop treatment (2%) (Fig. 2.3).

2.3.2.2 Diameter growth

Total diameter and diameter increment of Okanese trees was consistently greater compared to Walker trees as measured at the end of the first and second growing season (Table 2.8, Fig. 2.4). Moreover, significant clone x treatment interactions in each year for year-end diameter demonstrated that the clones responded differently to the establishment systems (Table 2.7). Year-end diameter of both clones was always ranked in the following order, regardless of statistical significance: fallow > business-as-usual > no-till > cover crop. However, differences were found in the magnitude of the difference among treatments for each clone, resulting in significant interactions at the end of the first ($p= 0.004$) and second growing season ($p= 0.002$) (Table 2.7).

After the first growing season, final total basal diameter of Okanese trees within the intensively managed fallow plots was greater ($p< 0.001$) than in either of the two less intensive treatments - cover crop and no-till (Table 2.8). Similarly, total basal diameter in business-as-usual was greater than in either no-till or cover crop, though the difference was only significant between the business-as-usual and cover crop ($p< 0.001$) (Table 2.8). No difference was found between the business-as-usual and fallow treatment. At the end of the second growing season, treatment-based differences in total tree diameter of Okanese poplar were more evident; the fallow treatment resulted in total basal diameter that was approximately twice ($p< 0.001$) that of the no-till or cover crop, and also greater ($p< 0.001$) than business-as-usual (Table 2.8). Similarly, trees in business-as-usual grew more ($p< 0.004$) than in either cover crop or no-till (Table 2.8).

Treatment differences for Walker poplar were less pronounced than for Okanese poplar for all measurement times. For example, significant differences in total basal diameter after the end of each growing season were only found between the fallow treatment and the cover crop treatment with an additional difference between the fallow and no-till after the second year (Table 2.8). The business-as-usual treatment, on the other hand, did not differ from either cover crop or no-till. Likewise, differences in total diameter between the business-as-usual and fallow treatments were not significant.

In terms of diameter increment, differences were found between clones, with Okanese outperforming Walker ($p < 0.001$), and among treatments both in 2012 ($p < 0.001$) and 2013 ($p < 0.001$) (Table 2.7). Okanese poplar trees in fallow always showed greater increments ($p < 0.001$) than in either cover crop or no-till, while differences between the fallow and business-as-usual only became significant at the end of the second year ($p = 0.001$) (Fig. 2.4). Interestingly, the fallow treatment was the only treatment exhibiting a doubling of increment from the first to the second year (Fig. 2.4). In contrast, diameter increments decreased in the second growing season within the no-till and cover crop treatments, and remained stable in business-as-usual (Fig. 2.4). Walker trees showed greater increments ($p < 0.003$) in both business-as-usual and fallow than in cover crop after the first year, while trees in fallow showed greater increments ($p <= 0.008$) than in all other treatments during the second year (Fig. 2.4). Notably, Walker poplar showed an increase in diameter growth from the first to the second growing season only in the fallow treatment, while increments in all three other treatments decreased over time (Fig. 2.4).

Initial tree diameter (June 2012) was a significant covariate only in the first growing season ($p = 0.01$) (Table 2.7), indicating that initial conditions of trees only had a short term effect while long-term diameter responses are reflective of the establishment systems tested.

2.3.2.3 Height growth

At the end of the first and through to the end of the second growing season, significant clone x treatment interactions for year-end height demonstrated that the two clones responded differently to the establishment systems (Table 2.7). Similar to clonal differences for diameter, Okanese outperformed Walker in all but the no-till treatment, in that significant treatment differences between clones were only observed late in the assessment period (e.g. August 2013). Differences in height among treatments followed a similar trend as for diameter. At the end of the first growing season, Okanese trees were taller ($p= 0.004$) in business-as-usual than in no-till, and trees in both business-as-usual and fallow were taller ($p< 0.007$) than in cover crop (Table 2.8). Following the first winter, total heights of Okanese trees did not differ among treatments, in contrast to height differences observed the previous fall; this change was attributed to both marked browsing by ungulates and winter dieback (Table 2.8). Differences in height among treatments once again became evident late in the growing season (e.g. June-October 2013), with final total height in October ranking as follows among treatments: fallow > business-as-usual > no-till > cover crop (Table 2.8). In contrast, no differences were found among treatments in total height for Walker poplar, with the exception of measurements from May 2013, which were confounded by browse and winter dieback (Table 2.8).

Height increment for Okanese in the first establishment year ranked (i.e. non-statistically) in the following order: fallow > business-as-usual > cover crop > no-till (Fig. 2.4). Trees grown in both fallow and business-as-usual treatments grew significantly more ($p< 0.002$) than no-till, while no differences were detected between cover crop and the other treatments (Fig. 2.4). Height increment in the second year ranked as follows: fallow > business-as-usual > no-till > cover crop. Trees in the fallow treatment showed greater ($p< 0.003$) height increments than trees in the other three treatments, which in turn, did not differ from one another (Fig. 2.4). Notably, the fallow treatment was the only treatment with a greater annual height increment in the second year compared to the first year, while trees in the cover crop and no-till treatments demonstrated a lower annual height increment in the second year; trees in the business-as-usual had similar annual height increments in both years (Fig. 2.4). In contrast, height increment of Walker did not differ among treatments in the first year but only in the second year, with trees in fallow plots showing greater increments than trees in all other treatments ($p< 0.001$) (Fig. 2.4). Despite the installation of an ungulate fence, extensive browse damage occurred during the winter of 2012/2013 (Appendix 2.7a), and particularly during the winter of 2013/2014 (data not shown). For an overview of browse and dieback effects on height growth during the winter of 2012/2013, see Appendices 2.7a and 2.7b.

Trees in the fallow treatment showed an increase in height growth by nearly 50% at the end of the season (e.g. July to August) compared to previous monthly assessments, regardless of the type of clone, while trees in all other treatments showed similar height increments in each month (e.g. May to August) (Fig. 2.5). Initial tree heights from spring measurements in June 2012 were significant ($p< 0.044$) covariates only for the first growing season after planting, similar to results for initial basal diameter (Table 2.7).

2.3.2.4 Budbreak

Timing of budbreak in mid-May differed between clones with Okanese flushing an average of three days earlier than Walker (Appendix 2.8). Emergence of the first new leaves appeared to be slightly earlier in business-as-usual and fallow compared to both cover crop and no-till, however no statistical significance testing among clones and treatments was done (Appendix 2.8).

2.3.3 Resource availability

Transmittance of available PAR by the understory vegetation to the shaded tree portion (Appendix 2.6, position 3) differed among establishment systems, both early ($p<0.001$) and in the middle of the growing season ($p<0.001$) (Table 2.9). Within the fallow treatment as much as 30% more available PAR was transmitted through competing vegetation to trees compared to all other treatments. Transmission of PAR by the understory decreased from early season to mid-season by 9% and 13% for the fallow and cover crop treatments, respectively, while PAR transmission in both business-as-usual and no-till remained stable over time (Table 2.9). Moreover, there was a difference in light transmission by the clones among different establishment systems, indicated by a significant clone x treatment interaction ($p= 0.003$) in June (Table 2.9). Okanese transmitted the least light to the understory in fallow plots throughout the growing season, with all other treatments being equal (Table 2.9). In contrast, no difference in light transmittance by Walker trees was detected among treatments in June. Notably, during July weeds exceeded the height of Walker trees in most business-as-usual plots, as well as all cover crop and no-till plots, while Walker trees grew above the weeds in most fallow plots (Table 2.9).

Frequent precipitation events resulted in high soil moisture levels throughout the growing seasons, ranging from 24% to 32% volumetric soil moisture during the second growing season (2013) (Table 2.9). Growing season precipitation (May-September) of approximately 327 mm and 200 mm in 2012 and 2013, respectively, indicate that both years were drier than the 30-year monthly average (1981-2010) of 336 mm (Appendix 2.1). However, estimates from 2012 and 2013 were likely underestimates due to missing data at the local weather station. Soil moisture levels at the tree base and up to about 50 cm distance from the trees generally did not differ among treatments (Table 2.10). In contrast, soil moisture levels differed among treatments in the alley between tree rows, with moisture content consistently being greatest ($p < 0.001$) under no-till (Table 2.10). Soil moisture in the alleys under no-till was 8% higher (averaged across all sampling times) compared to moisture content averaged across all other treatments (Table 2.10).

Similarly, soil temperature differed among establishment systems ($p<0.01$) during most sampling times with average temperatures always greatest in fallow and lowest in no-till (Table 2.9). Differences were evident across all three sampling distances, and were greatest in the main alley with soil temperatures in fallow being on average 3.5 °C higher than temperatures in no-till (Table 2.10). Notably, soil temperature was also affected by type of clone in June and July 2013 with average soil temperatures being slightly lower (by 0.5 °C, $p=0.05$) under Okanese than under Walker (Table 2.10).

Total N supply rate, with NO_3^--N being the principal nitrogen form available, differed among treatments ($p<0.001$), ranking in the following order: fallow>business-as-usual>cover crop>no-till (Table 2.9). Notably, total N available for plant uptake in fallow was 107%, 500%, and 635% of that in business-as-usual, cover crop, and no-till, respectively (Table 2.9). Furthermore, total N supply varied by location relative to trees (Table 2.11). More N was available in the main alleys compared to the tree bases. In business-as-usual and fallow this effect was pronounced with an increase of 188% and 92%, respectively. Beside total N, supply rates differed for Ca ($p<0.001$), Mg ($p=0.012$), and S ($p<0.001$), while all other nutrients were not affected by the vegetation control treatments ($p<0.05$) (Table 2.9). Calcium availability was always greatest in no-till and lowest in fallow, both at 20 cm and 140 cm distance from the trees (Table 2.11). Magnesium was lower in business-as-usual and fallow compared to the other treatments at locations close to the trees, while no differences were detected in the alley (Table

2.11). Moreover, sulphur varied among treatments at both distances, with fallow showing the greatest supply rates (Table 2.11).

Results from the regression tree analysis revealed relationships between hybrid poplar performance, understory composition (e.g. functional groups) and resource availability. The final regression tree model for 2012 had 4 nodes explaining 77% of the variation in diameter increment for the first establishment year (Fig. 2.6). The regression tree used clone, treatment, and two understory variables (total cover at 0-105 cm distance and perennial forb cover at 35-70 cm distance). The first split, accounting for more than 50% of the explained variation, was clone type, with Walker poplar being less productive (mean= 2.0 mm) than Okanese poplar (mean= 4.2 mm) (Fig. 2.6). All further splits were to determine diameter growth of Okanese poplar while no further splits occurred for Walker poplar. The greatest diameter increment (mean= 6.4 mm) was associated with Okanese growing on plots with less than 14% total herb cover at 0-105 cm distance to the trees, and less than 0.5% perennial forb cover at 35-70 cm distance to the trees (Fig. 2.6). The lowest diameter increment for Okanese (mean= 3.3 mm) was associated with total cover greater than 14%, as well as with the cover crop and no-till treatments (Fig. 2.6). Notably, Okanese trees in the least productive plots gained only half the diameter increment of those in the most productive plots.

The final regression tree model for 2013 explained 74% of the variation in diameter increment in the second establishment year using four nodes and one understory variable (annual forb cover at 0-35 cm distance), one microclimate variable (PAR transmittance through understory vegetation in June), as well as clone (Fig. 2.7). The first split in 2013 was annual forb cover at 0-35 cm distance from trees (Fig. 2.7). Trees showed greater diameter increments (mean= 5.6 mm) when annual forb cover was greater than 10%, while trees showed lower increments (mean = 1.9 mm) when annual forb cover was less than 10%, regardless of type of clone (Fig. 2.7). Abundance of annuals was inversely correlated with perennial abundance (data not shown), indicating the lower competitiveness of annuals as compared to perennials. Notably, this first split accounted for 55% of the explained variation. The next two splits, accounting for 12.6% and 5.1% of the explained variation, respectively, were clone type, with Walker poplar being less productive than Okanese poplar (Fig. 2.7). The last split was light transmittance by the understory vegetation to determine diameter growth of Okanese poplar, while no further splits occurred for Walker poplar (Fig. 2.7). The greatest overall diameter increments (mean=11.0 mm) were observed when the poplar clone was Okanese, annual forb cover close to trees was greater than 10% and when light transmittance by the understory to the tree exceeded 80% (Fig. 2.7). In contrast, the lowest overall diameter increment (mean= 0.8 mm) was observed when annual forb cover was lower than 10% and the poplar clone was Walker, similar to results from 2012 (Fig. 2.7). Alternative and surrogate splits for regression tree analysis in 2012 and 2013 are reported in Appendices 2.9 and 2.10.

2.4 Discussion

2.4.1 Understory vegetation

The four plantation establishment systems tested varied markedly in their ability to control understory vegetation, both in terms of abundance and composition, as well as in the timing of these impacts (e.g. first year vs second year responses). Although very near complete vegetation suppression was achieved across all treatment plots prior to tree planting, we observed rapid regrowth of understory vegetation from either the remaining seed bank or remaining vegetative propagules during the first growing season, reflecting the relatively short-lived effectiveness of mechanical and chemical (i.e. glyphosate, a non-residual herbicide) control methods. Rapid understory regrowth has been reported by other plantation studies testing mechanical, chemical and alternative weed control methods (Coll et al., 2007; Hytönen and Jylhä, 2005).

Overall, our results indicate that different plantation establishment systems developed unique herbaceous communities. However, the overlap of select understory species with multiple treatments also suggests certain plant functional groups were more associated with particular management practices rather than the establishment treatments *per-se*. For example, annual plant species were largely associated with systems involving tillage for site preparation and/or maintenance (business-as-usual, cover crop and fallow), which in turn, was most pronounced in the intensely cultivated (i.e. fallow) system. In contrast, perennial species were mostly associated with the less intense (e.g. reduced tillage) systems (cover crop and no-till), but interestingly, also appeared within the conventional tillage system (business-as-usual) that continued to rely on herbicide use post-planting. These results suggest the most effective control of perennial competitors during the study was achieved from the extended fallow period conducted prior to planting.

While the current results showed that total vegetation cover was lowest in fallow plots, this effect lasted only for the first growing season. We observed a rapid increase in cover of annual forbs in fallow plots, though perennial cover remained notably lower in the second year compared to all other treatments. As the cover of annuals was not associated with marked losses in tree growth, these findings suggest that the main benefit of the fallow treatment was the significant delay in the establishment of perennial species compared to the other treatments, which in turn, would afford considerable benefit to tree growth, particularly as many previous studies have documented marked yield losses due to perennial herbs (Balandier et al., 2005;

Kabba et al., 2007). Differences in the relative proportion of annual and perennial species in fallow plots can be attributed to the lasting effect of the extended period of mechanical and chemical site preparation on the control of perennial species, as post-planting site maintenance was similar to the control 'business-as-usual'. Perennial forb species are particularly competitive with regard to decreasing light transmission for young trees, primarily due to their tall stems and large leaf area, as opposed to shorter annual forb species (Balandier et al., 2006). The delay of perennial forb species is consequently of particular importance early in the rotation, as poplar trees are highly shade intolerant and young trees may be readily overtopped by neighboring understory species (particularly trees of the Walker clone), and thus exposed to severe light competition.

The cover crop mixture established slowly during the first growing season, even though all understory vegetation was removed during site preparation and maintenance prior to inter-seeding. The slow establishment of cover crop species, particularly during the first year, appeared to be a consequence of the vigorous and rapid colonization of weedy vegetation following the cessation of weed control. Interestingly, plots with interseeded cover crops were more diverse than other treatment plots, similar to findings by Balandier et al. (2009), with several forbs (all nuisance weeds in agricultural crops) such as ballmustard (*Neslia paniculata* (L.) Desv.), whitecockle (*Silene alba* (Mill.) Krause) and white sweetclover (*Melilotus alba* (L.) Medik.) being indicator species. This finding suggests the introduction of these species may have been tied to their entry as accidental volunteers with the seed source in addition to the cover crop mixture itself.

Despite poor establishment in the first year, there is some evidence that the cover crops tested, particularly white clover, did establish reasonably well over time, thus showing some potential for suppressing growth of other weeds. However, more studies are needed, particularly over the long-term, to better investigate complementary weed control strategies that could improve the effectiveness of cover cropping as an alternative establishment and production system for hybrid poplar plantations. For example, extended pre-planting mechanical and chemical vegetation control could suppress competitive weeds, specifically perennial species, while simultaneously facilitating establishment of cover crops, and thereby offer longer-term benefits to both the environment (e.g. reduced soil erosion) and trees (competition).

2.4.2 Tree growth differences among establishment systems

Significant differences were found in both tree diameter and height growth at the end of the first growing season indicating that trees responded rapidly to the vegetation control systems tested. Treatment effects were most pronounced when comparing treatments of sharply contrasting management intensities, reinforcing that effective weed control is necessary to improve poplar performance. This is similar to the findings of Pinno and Bélanger (2009) who reported immediate and large responses of one-year old hybrid poplar trees to competition control, and supports the assertion that early weed control is necessary to improve initial growth (Otto et al., 2010; Stanturf et al., 2001).

The most significant result of this study is the markedly greater growth performance when hybrid poplars were established in plots that received an extended full year of mechanical and chemical weed control prior to planting. Hybrid poplar trees showed better survival and were more productive in fallow plots compared to any other treatment suggesting that a prolonged site preparation phase results in more favorable biotic and abiotic growing conditions for tree establishment. This involved enhanced and more effective control of competing vegetation, especially perennials, as well as improved abiotic growing conditions through significantly greater light levels, increased soil temperatures and much greater soil nitrogen availability (see below). Although the improvements in resource availability were not as large in the second year, established benefits on tree growth appeared to carry over through the second growing season, leading to taller trees with greater diameter growth. As long-term fiber yields of plantations are tied closely to tree performance early in the life of the plantation (Otto et al., 2010), this growth benefit may well translate into improved biomass increments for the remainder of the plantation life cycle, until harvest. Overall, this finding emphasizes the importance for effective site preparation for managing hybrid poplar plantations (van Oosten, 2006), and challenges current operational practices that strive for a relatively short period of site preparation.

Monthly tree measurements revealed that height growth of poplars in the fallow treatment was different from the other treatments since height growth continued to occur late into summer, while in all other treatments height growth was similar or slowed over successive months, suggesting that growing conditions in fallow plots were indeed more favorable for sustained growth. This indicates that competition for resources played a major role late in the growing season and that the impact of vegetation control on height growth can be large when accruing over time.

It should be noted that the fallow system requires higher costs for renting land and site preparation for an extra full year prior to tree planting. However, this may be balanced off, at least in part, by the reduced costs for site maintenance over the life of the rotation, and by increases in early tree growth and accelerated canopy closure. In any case, long-term monitoring is needed to determine if growth benefits as observed in the fallow system will be maintained over the whole rotation. Moreover, an analysis of profitability is needed to determine the financial viability of the alternative establishment systems tested, which is beyond the scope of the current study. According to Anderson and Luckert (2007), a relatively small increase in growth rate would lead to intensive plantation forestry being financially favorable on private land in Alberta. The authors report that a 27% increase in stand volume over one rotation would increase the internal rate of return from 3.6% to 5.1% (Anderson and Luckert, 2007).

2.4.3 Differences between hybrid poplar clones

Despite the two hybrid poplar clones being related (Okanese is the progeny of Walker), differences between them were observed in all of the tree variables assessed. Clonal differences in tree growth were large and manifested rapidly within the first growing season, while differences in tree survival between clones were noted after the first winter. Okanese poplar had better survival and greater productivity across all establishment systems tested as compared to Walker poplar, indicating its greater overall productivity potential on the tested site conditions. Additionally, we observed marked phenotypic differences among treatments for Okanese poplar, emphasizing its ability to respond to vegetation management systems when released from competition.

In contrast, we only observed minor differences in the growth of Walker poplar among the four establishment systems, likely indicating its poor overall initial growth compared to Okanese poplar. The limited growth potential of Walker poplar in the first two establishment years, coupled with the high mortality at the end of the second year and at the beginning of the third growing season, resulted in near complete crop failure for this clone. While soil textures on our study site were likely suitable for this clone, ranging from sandy clay to loam, some blocks had poor drainage, high salinity and relatively high pH, which may have combined with weed competition, impeded the establishment of Walker trees. Walker poplar is known to have very specific ecosite requirements and does not reach its full potential on sub-optimal planting sites (van Oosten, 2006). Moreover, we observed shoot dieback of Walker poplar after the first winter, confirming the assumption that this clone is vulnerable to winter damage (Lindquist et al., 1977). The poor initial growth observed in conjunction with winter dieback also likely increased the high susceptibility of Walker poplar to competition with weeds during the second year when weed competition increased as understory colonization advanced, ultimately exacerbating the poor performance of this clone.

In addition to differences in tree performance between clones, we observed differences in some of the measured environmental characteristics as early as June of the second growing season. Our results showed that Okanese poplar intercepted more available light than the Walker clone, and thereby reduced light transmittance to the understory more effectively. The two clones also differed in their canopy architecture. Okanese showed greater and more rapid canopy development compared to Walker (J. Göhing, field observation); this was expected given its more spreading growth habit and branched architecture, and led to an increased ability to intercept light and consequently shade the understory. It is expected that the greater shading ability of Okanese and its more rapid canopy closure will reduce understory cover sooner in the rotation after planted as compared to Walker, a response that has been reported for other hybrid poplar clones in more mature plantations (Boothroyd-Roberts et al., 2013).

The consistently greater performance (e.g. growth and survival) of Okanese poplar across the varying site conditions tested in this study, including blocks containing poor drainage, demonstrates the greater plasticity of Okanese hybrid poplar compared to Walker. Based on our findings we conclude that Okanese poplar exhibits a superior potential for future use in short-rotation plantations compared to Walker. However, more research is needed to determine whether findings of this study can be applied across a wider variety of soils and greater geographic range. Furthermore, it should be emphasized that we tested growth responses of very young trees, and thus, cannot directly examine the impact of different establishment systems on long-term stemwood production. Consequently, longer term monitoring is needed to test whether growth increases will persist or whether yield losses can be compensated over the whole rotation. It is anticipated that these plantations will experience a Type I pattern in growth response to vegetation control and resulting faster resource capture early in the season. A Type I response equates to improved growth early in the rotation that then carries over into the future without getting larger over time (Mead, 2005).

2.4.4 Resource availability

We demonstrated in this study that competition for light was high between the understory vegetation and two-year old hybrid poplar trees; a finding contrary to most other plantations established on former agricultural or forested land, where competition for light was not considered critical despite the known high intolerance of hybrid poplars to shading (Coll et al., 2007; Pinno and Bélanger, 2009). Light reduction was greatest in no-till and cover crop plots since aggressive, large statured (i.e. perennial) weeds were able to rapidly establish and exceed the height of most trees, particularly those of the Walker clone, and thereby likely contributed to high tree mortality. In contrast, light transmittance was more favorable to tree growth in both the fallow and business-as-usual treatments. Significant differences in light transmittance early in the season highlight the importance of early control of aboveground parts of the understory vegetation. Annual mowing at the end of the season proved insufficient in our study to reduce the negative impacts of neighboring vegetation on light interception by trees, suggesting that mowing may need to take place earlier and/or more frequently in the season. Moreover, mowing suffers from the physical limitation of only being able to treat areas up to a certain distance from the tree base. It should be noted however, that the fallow treatment may have increased light availability directly through the prolonged suppression of tall-growing perennial forb species, and indirectly, by promoting rapid shoot growth of young hybrid poplar trees, potentially helping them reach ‘free-to-grow’ status sooner.

Tree-weed competition for soil moisture may have played a critical role in our study as precipitation during the second growing year was below average during the growing season. However, the lack of treatment differences in soil moisture content at the tree base and up to about 50 cm distance to the tree (e.g. to where roots of young trees were likely concentrated (Douglas et al., 2010), indicates that competition for water between weeds and trees may have been secondary to light and nutrient competition. In contrast, we consistently observed greater soil moisture levels in the alleys under no-till treatments throughout the growing season. Higher soil moisture retention through no-till or reduced tillage practices is surprising, as fallow is often implicated as a tool in agricultural regions to build up soil moisture due to the absence of plants and associated transpiration under repeated weed control (Tanaka and Aase, 1987). The results found here suggest the benefits of reduced evaporation through the maintenance of high accumulations of plant litter on the soil surface and the cooler soil temperatures that result, may have conserved more moisture than those treatments with continuing tillage (Nyborg and Malhi, 1989). Greater moisture conservation on the low disturbance treatments may be beneficial to sustain tree growth on rapidly drained soils but could be disadvantageous on poorly drained soils (Hansen et al., 1986), both of which were present in this study.

Vegetation management systems also influenced soil temperature, particularly at the beginning of the growing season. The no-till treatment in our study delayed soil warming considerably in spring and early summer, likely caused by the insulating plant residue (e.g.

particularly the perennial quackgrass) on the soil surface (Hogg and Lieffers, 1991; Landhäusser and Lieffers, 1998). Consequently, planting trees in no-till areas may reduce tree growth, as has been shown by Hansen et al. (1986). In fact, we observed slightly delayed bud-break in no-till plots, which may have retarded subsequent uptake of soil resources and reduced early-season tree growth. Higher soil temperatures in business-as-usual and especially fallow plots, on the other hand, may have contributed to accelerated bud break, soil water and nutrient mineralization and uptake by trees, and improved tree growth. Both these treatments had routine cultivation of alleys, and the increased bare soil that accompanies this activity would have resulted in greater direct solar radiation, leading to rapid soil warming in spring increasing root activity.

We further demonstrated tree-weed competition for soil nutrients, particularly soil nitrogen. Nitrogen is usually the most growth limiting nutrient for hybrid poplar tree growth (Stanturf et al., 2001) and the major nutrient used in fertilization treatments. Accordingly, Hangs et al. (2005) reported a stronger relationship between nitrogen supply and growth of young hybrid poplar trees, compared to the supply of other nutrients. We found greater N supply rates with increased competition control (e.g. business-as-usual and fallow), a finding similar to Pinno and Bélanger (2009) who reported an increase in hybrid poplar foliar N concentration with control of competing vegetation. The increase in soil N availability was greatest in fallow plots; this was likely due to the extended control of the understory species, specifically perennials, which could have translated in greater tree growth of Okanese poplar, at least during the first two years after planting. Increased N in fallow areas could also arise due to greater soil temperatures, which is known to stimulate N mineralization (Nyborg and Malhi, 1989). Similar results were found by Coll et al. (2007), who reported significant competition for soil N and highlighted the need to control belowground vegetation to minimize root competition. It should be noted that a field study testing NPK fertilization for enhancing hybrid poplar growth in north-central Alberta did not find increases in early tree performance, suggesting that nutrition was not limiting the growth of the three hybrid poplar clones tested (including Walker) in this area (DesRochers et al., 2006). Despite this finding, our results for Okanese poplar, a faster growing clone than Walker, suggest that competition control significantly mitigated competition for soil nutrients between young trees and weeds and may indeed have contributed to the enhanced growth within the fallow treatment.

2.5 Conclusion and operational recommendations

Our results for hybrid poplar plantations in north-central Alberta indicate the need for effective control of competing understory vegetation through a prolonged site preparation phase. We report markedly increased tree growth and survival when poplar trees, specifically Okanese poplar, were established in fallow plots that received extended mechanical and chemical weed control prior to planting. Light and nutrient competition (mainly nitrogen) was substantially reduced in fallow plots, mainly through enhanced control of competing understory species, and particularly the delayed entry of perennial species. The tested alternative establishment systems (cover cropping and no-till) proved less effective for improving biotic and abiotic growing conditions, including light transmittance and soil nutrient availability, which in turn, reduced tree growth and survival. Moreover, we found Okanese poplar outperformed Walker poplar across all establishment systems tested, emphasizing its greater potential for deployment in SRIC plantations across the Canadian Prairies. Overall, our findings provide novel insight into managing hybrid poplar plantations as current operational practices (e.g. business-as-usual) strive for a relatively short period of site preparation, which could neither improve growing site conditions nor benefit tree growth to the extent of the prolonged site preparation phase in the fallow treatment in our study. Based on our results, we recommend the use of Okanese poplar for use in short-rotation plantations in north-central Alberta due to its superior performance across varying site conditions (e.g. plasticity across differing pH and drainage), its ability to rapidly close its canopy and its greater tolerance to competition.

2.6 Tables

Table 2.1– Identity, parentage and section for the hybrid poplar clones used in the study. Also given is the diameter and height measured at the end of 2013 (mean and range), percent survival for the time period June 2012 to May 2014, and the average day of year at which bud-break score 3 (see Methods for details) was reached in May 2013 for the four establishment systems. Standard errors are given in parentheses

Clone	**Genus**	**Female parent species/hybrid**	**Male parent species/hybrid**	**Section**	**Treatment**	**Diameter 2013 (mm)**	**Diameter range 2013 (mm)**	**Height 2013 (cm)**	**Height range 2013 (cm)**	**Survival 2012-2014 (%)**	**Budbreak 2013 (Day of year)**
Walker	*Populus*	*deltoides*	*x petrowskyana (P. laurifolia x P. nigra)*	Aigeiros x (Tacamahaca x Aigieros)	Business-as-usual	7.0 (0.1)	5.1-10.6	56.4 (0.8)	38.5-78.0	14	139 (0.1)
					Cover crop	6.0 (0.1)	4.5-7.8	52.3 (1.0)	32.5-80.0	2	140 (0.1)
					Fallow	8.4 (0.1)	5.3-11.6	61.1 (1.2)	22.0-90.4	21	141 (0.2)
					No-till	6.3 (0.1)	5.3-9.2	59.3 (0.6)	42.5-70.5	11	140 (0.2)
Okanese	*Populus*	*x Walker*	*x petrowskyana*	(Aigeiros x (Tacamahaca x Aigieros)) x (Tacamahaca x Aigieros)	Business-as-usual	12.5 (0.2)	6.6-17.5	104.9 (1.4)	54.0-144.5	82	136 (0.1)
					Cover crop	9.1 (0.1)	7.9-11.2	79.2 (0.8)	54.5-94.8	44	137 (0.1)
					Fallow	18.9 (0.3)	11.4-31.5	129.6 (1.8)	84.4-186.3	84	136 (0.1)
					No-till	9.9 (0.2)	4.6-13.1	85.6 (1.3)	38.3-115.0	44	137 (0.1)

Table 2.2– Summary of soil physical and chemical properties at each of two soil depths across the study area. Values are means of 15 blocks with minimum and maximum values given in parentheses.

Soil variable	Soil depth (cm)	Lowland	Upland
Texture			
Sand (%)	0-15	55.4 (12.4)	43.8 (8.9)
	15-30	56.2 (2.6)	48.1 (9.7)
Clay (%)	0-15	13.6 (4.7)	19.6 (6.5)
	15-30	20.8 (2.5)	22.2 (3.7)
Silt (%)	0-15	31.0 (7.7)	36.6 (3.7)
	15-30	23.0 (4.1)	29.7 (6.7)
pH	0-15	7.5 (0.1)	8.0 (0.2)
	15-30	7.1 (0.4)	8.0 (0.4)
EC (µs/cm)	0-15	2067 (606)	271 (64)
	15-30	2647 (93)	243 (215)
Organic matter (%)	0-15	63.4 (3.0)	13.3 (7.4)
	15-30	73.8 (4.5)	3.9 (1.2)
Total N (%)	0-15	1.53 (0.11)	0.38 (0.12)
	15-30	1.42 (0.28)	0.12 (0.04)
NH_4 (mg/kg)	0-15	10.1 (1.4)	4.0 (1.8)
	15-30	12.6 (2.5)	3.4 (1.1)
NO_3 (mg/kg)	0-15	133.8 (36.8)	14.0 (7.6)
	15-30	54.2 (12.3)	6.9 (8.5)

Table 2.3 –Summary of understory vegetation cover (%) associated with each of four plantation establishment systems for the first (2012) and second (2013) year after planting, grouped by functional group and distance to tree. Values represent mean percent cover ± standard deviation. Also given are p-value results of the ANOVAs showing effect of establishment system (treatment), clone and their interaction. Significant effects are bolded ($p<0.05$). Different lowercase letters in rows indicate significant differences among treatments for a given distance (at Bonferroni adjusted $\alpha_{adj}= 0.05/6= 0.008$).

Year	Understory vegetation cover (%)	Distance to tree (cm)	Establishment system				p-value for treatment effect	p-value for clone effect (Ok>Wa)	p-value for treatment x clone interaction
			BAU	Cover crop	Fallow	No-till			
2012	Total cover	0-35	23.3 (15.9)ab	34.6 (12.0)b	14.7 (19.1)a	16.9 (8.8)a	**<0.001**	0.898	0.699
	Total cover	35-70	29.2 (15.9)bc	39.6 (12.0)c	16.6 (20.2)a	24.7 (10.8)ab	**<0.001**	0.735	0.579
	Total cover	70-105	28.0 (14.7)bc	38.7 (11.2)c	15.4 (19.6)a	25.3 (11.4)ab	**<0.001**	0.576	0.697
	Annual forb*	0-35	12.8 (11.3)b	23.6 (11.2)c	13.8 (19.2)b	3.4 (3.2)a	**<0.001**	0.299	0.645
	Annual forb*	35-70	14.3 (11.6)b	23.7 (10.7)c	15.4 (20.3)b	3.2 (2.7)a	**<0.001**	0.664	0.596
	Annual forb*	70-105	13.4 (10.8)b	22.0 (9.5)c	14.2 (19.6)b	2.7 (2.7)a	**<0.001**	0.234	0.321
	Perennial forb*	0-35	3.7 (5.7)b	4.5 (5.3)b	0.3 (0.6)a	4.5 (9.0)b	**<0.001**	0.107	0.414
	Perennial forb*	35-70	3.6 (5.7)b	5.0 (6.8)b	0.5 (0.8)a	5.7 (10.9)b	**<0.001**	**<0.001**	**0.042**
	Perennial forb*	70-105	3.8 (5.5)b	4.8 (6.5)b	0.5 (0.8)a	6.0 (12.3)b	**<0.001**	0.328	0.198
	Perennial grass*	0-35	6.9 (5.7)b	6.1 (4.8)b	0.4 (1.4)a	9.0 (7.3)b	**<0.001**	0.231	0.555
	Perennial grass	35-70	11.3 (7.5)bc	8.0 (6.4)b	0.6 (2.6)a	15.6 (10.4)c	**<0.001**	0.307	0.462
	Perennial grass	70-105	10.8 (7.5)b	8.0 (6.7)b	0.6 (3.0)a	16.4 (10.3)c	**<0.001**	0.400	0.572
	Cover crop	0-35	N/A	0.5 (0.7)	N/A	N/A	N/A	N/A	N/A
	Cover crop	35-70	N/A	2.7 (1.9)	N/A	N/A	N/A	N/A	N/A
	Cover crop	70-105	N/A	4.0 (2.6)	N/A	N/A	N/A	N/A	N/A
2013	Total cover	0-35	35.3 (13.2)b	31.8 (9.4)ab	53.3 (16.2)c	25.2 (7.3)a	**<0.001**	0.950	0.420
	Total cover	35-70	40.3 (12.5)a	45.6 (9.7)a	54.0 (16.2)b	37.8 (11.2)a	**<0.001**	0.633	0.444
	Total cover	70-105	41.0 (14.4)a	52.4 (12.5)a	49.5 (16.2)a	43.0 (13.5)a	**0.037**	0.966	0.972
	Annual forb*	0-35	12.3 (9.4)b	2.3 (2.7)a	44.2 (20.7)c	0.8 (1.3)a	**<0.001**	0.526	0.568
	Annual forb*	35-70	15.8 (9.9)b	2.9 (3.4)a	47.8 (18.8)c	0.7 (1.0)a	**<0.001**	0.770	0.387
	Annual forb*	70-105	15.6 (10.9)b	2.8 (3.0)a	43.6 (18.1)c	1.2 (2.4)a	**<0.001**	0.186	0.225
	Perennial forb*	0-35	6.2 (7.2)a	15.2 (9.2)b	5.0 (8.1)a	4.8 (5.4)a	**<0.001**	0.086	0.096
	Perennial forb*	35-70	4.6 (5.2)a	14.4 (9.5)b	2.8 (3.3)a	7.1 (12.4)a	**<0.001**	**0.033**	0.099
	Perennial forb*	70-105	4.9 (5.9)ab	14.5 (9.9)c	2.6 (3.3)a	8.0 (14.9)b	**<0.001**	0.103	0.461
	Perennial grass*	0-35	17.0 (9.5)bc	12.0 (7.9)b	3.9 (3.6)a	19.6 (7.5)c	**<0.001**	0.793	0.489
	Perennial grass*	35-70	19.9 (12.4)b	15.9 (12.2)b	3.5 (3.3)a	29.9 (12.0)c	**<0.001**	0.757	0.263
	Perennial grass*	70-105	20.2 (12.7)b	15.5 (12.3)b	2.9 (2.8)a	33.4 (12.8)c	**<0.001**	0.862	0.182
	Cover crop	0-35	N/A	2.3 (4.8)	N/A	N/A	N/A	N/A	N/A
	Cover crop	35-70	N/A	12.4 (8.6)	N/A	N/A	N/A	N/A	N/A
	Cover crop	70-105	N/A	19.6 (10.9)	N/A	N/A	N/A	N/A	N/A

* square root transformed for analysis of variance

Table 2.4 – Results from the perMANOVAs comparing understory vegetation composition (at 0-105 cm from planted poplars) among each of four plantation establishment systems, between the two clones and for the treatment by clone interaction (all at α= 0.05) during the first (2012) and second (2013) year after planting. Also given are results of pair-wise comparisons among the four treatments; these were tested using Bonferroni adjusted α_{adj}= 0.05/6= 0.008. Significant effects are bolded.

Variable	Treatment		Clone		Treatment * Clone	
	F-value	p-value	F-value	p-value	F-value	p-value
2012	18.864	**0.001**	0.905	0.471	0.244	1.000
BAU vs Cover crop	10.274	**0.001**	-	-	-	-
BAU vs Fallow	16.342	**0.001**	-	-	-	-
BAU vs No-till	7.6827	**0.001**	-	-	-	-
Cover crop vs Fallow	18.542	**0.001**	-	-	-	-
Cover crop vs No-till	25.928	**0.001**	-	-	-	-
Fallow vs No-till	34.799	**0.001**	-	-	-	-
2013	31.942	**0.001**	0.805	0.511	0.482	0.959
BAU vs Cover crop	18.138	**0.001**	-	-	-	-
BAU vs Fallow	26.619	**0.001**	-	-	-	-
BAU vs No-till	15.568	**0.001**	-	-	-	-
Cover crop vs Fallow	40.403	**0.001**	-	-	-	-
Cover crop vs No-till	19.435	**0.001**	-	-	-	-
Fallow vs No-till	70.364	**0.001**	-	-	-	-

Table 2.5 – Results of the Indicator Species Analysis evaluating various plantation establishment systems during the first (2012) and second (2013) year after tree planting. Given is the Indicator Value and its significance (at α= 0.05). Only significant indicators are shown. Listed plant species are significant indicators of a given plantation establishment system or combination of systems.

Year	Treatment (group)/ Indicator species	Indicator value	p-value
2012	Cover crop		
	Trifolium repens	100.0	0.001
	Neslia paniculata	92.5	0.001
	Thlaspi arvense	76.8	0.001
	Crepis tectorum	73.0	0.001
	Festuca rubra	73.0	0.001
	Silene alba	56.7	0.001
	Bromus inermis	48.3	0.001
	Business-as-usual + Cover crop + Fallow		
	Chenopodium album	93.4	0.001
	Polygonum convolvulus	86.8	0.001
	Galeopsis tetrahit	79.7	0.001
	Polygonum lapathifolium	50.5	0.010
	Business-as-usual + Cover crop + No-till		
	Elytrigia repens	98.2	0.001
	Taraxacum officinale	69.2	0.001
	Medicago sativa	51.9	0.018
2013	Cover crop		
	Trifolium repens	96.0	0.001
	Trifolium hybridum	75.8	0.001
	Festuca arundinacea	75.6	0.001
	Lolium perenne	70.7	0.001
	Plantago major	54.4	0.001
	Festuca rubra	50.0	0.001
	Silene noctiflora	48.6	0.001
	Melilotus alba	39.9	0.005
	Fragaria vesca	38.6	0.009
	Fallow		
	Chenopodium album	87.0	0.001
	Thlaspi arvense	42.8	0.004
	Polygonum lapathifolium	39.5	0.007
	Crepis tectorum	35.4	0.011
	Business-as-usual + Fallow		
	Polygonum convolvulus	95.7	0.001
	Galeopsis tetrahit	85.3	0.001
	Cover crop + No-till		
	Potentilla norvegica	45.3	0.002
	Business-as-usual + Cover crop + No-till		
	Taraxacum officinale	72.4	0.001
	Medicago sativa	52.4	0.020

Table 2.6 – Results from the categorical analysis on hybrid poplar survival from June 2012 to each of four subsequent sampling times for (a) main effects of establishment treatment, clone and the interaction thereof ($p<0.05$), and (b) pair-wise comparisons between different treatments separately for each clone following a significant treatment by clone interaction for the May 2014 sample period ($p<\alpha_{adj}= 0.05/6= 0.008$). Significant effects are bolded. The significant clone effect in May 2013 and August 2013 was due to greater survival of Okanese than Walker.

(a)

Time	Source	DF	Chi-Square	p-value
Aug 2012	Treatment	3	1.24	0.744
	Clone	1	0.11	0.737
	Treatment*Clone	3	3.04	0.386
May 2013	Treatment	3	5.20	0.158
	Clone	1	64.84	**<0.001** (Ok>Wa)
	Treatment*Clone	3	2.30	0.513
Aug 2013	Treatment	3	6.39	0.094
	Clone	1	166.90	**<0.001** (Ok>Wa)
	Treatment*Clone	3	0.20	0.977
May 2014	Treatment	3	42.79	**<0.001**
	Clone	1	137.70	**<0.001**
	Treatment*Clone	3	9.19	**0.027**

(b)

Clone	Contrast	DF	Chi-Square	p-value
Okanese	BAU vs Cover crop	1	26.58	**<0.001**
	BAU vs Fallow	1	0.15	0.699
	BAU vs No-till	1	26.58	**<0.001**
	Cover crop vs Fallow	1	29.41	**<0.001**
	Cover crop vs No-till	1	0.00	1.000
	Fallow vs No-till	1	29.41	**<0.001**
Walker	BAU vs Cover crop	1	6.21	0.013
	BAU vs Fallow	1	1.77	0.183
	BAU vs No-till	1	0.25	0.615
	Cover crop vs Fallow	1	10.45	**0.001**
	Cover crop vs No-till	1	4.66	0.031
	Fallow vs No-till	1	3.15	0.076

Table 2.7 – Results from the ANCOVAs examining the influence of establishment system, clone, and their interaction on hybrid poplar growth variables, including total height and diameter, and height (HI) and diameter increment (DI) for the first (2012) and second (2013) growing seasons after planting. Initial height and initial diameter (June 2012) were included as covariates; when covariate was not significant, the analysis was re-run without the covariate. Significant effects are bolded (p< 0.05).

Variable	Treatment		Clone		Treatment * clone		Initial height/ diameter	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Height (cm)								
Oct 2012	4.12	**0.012**	46.00	**<0.001**	5.04	**0.005**	11.37	**0.043**
May 2013	7.30	**0.001**	45.30	**<0.001**	3.02	**0.041**	7.39	0.073
June 2013	3.28	**0.039**	54.51	**<0.001**	1.43	0.259	3.74	0.149
July 2013	4.39	**0.013**	110.34	**<0.001**	1.71	0.191	1.06	0.379
Aug 2013	13.84	**<0.001**	127.83	**<0.001**	5.25	**0.006**	0.52	0.522
Oct 2013	13.85	**<0.001**	117.66	**<0.001**	10.78	**<0.001**	0.66	0.477
HI 2012	4.36	**0.009**	45.71	**<0.001**	5.38	**0.003**	24.40	**0.016**
HI 2013*	22.02	**<0.001**	46.01	**<0.001**	1.78	0.170	0.33	0.604
Diameter (mm)								
Oct 2012*	19.23	**<0.001**	167.45	**<0.001**	6.67	**0.001**	34.74	**0.010**
Oct 2013*	28.65	**<0.001**	191.22	**<0.001**	6.37	**0.002**	3.83	0.145
DI 2012*	15.88	**<0.001**	190.91	**<0.001**	1.85	0.153	0.02	0.903
DI 2013*	14.46	**<0.001**	208.20	**<0.001**	0.53	0.664	1.14	0.364

* log transformed

Table 2.8 – Total tree height and diameter across the four plantation establishment systems for the two clones during each sampling period. Different lowercase letters in rows indicate significant differences among establishment systems for a given clone and sampling period; these were tested using the Bonferroni adjusted p-value of $p<\alpha adj= 0.05/6= 0.008$.

		Establishment system			
Clone	Variable	Business-as-usual	Cover crop	Fallow	No-till
Okanese	Height (cm)				
	Oct 2012	73.0 (9.7)b	65.3 (7.7)a	71.6 (9.2)bc	66.3 (6.5)ac
	May 2013	66.2 (9.2)a	61.2 (10.0)a	62.1 (8.2)a	62.1 (9.7)a
	June 2013	74.6 (8.7)b	62.6 (11.1)a	72.4 (15.0)ab	69.2 (7.6)ab
	July 2013	89.9 (13.4)b	73.9 (10.3)a	88.9 (15.9)b	78.6 (10.2)ab
	Aug 2013	107.5 (22.2)b	80.5 (11.5)a	131.7 (27.3)c	86.2 (14.3)a
	Oct 2013	105.0 (22.2)b	79.8 (12.1)a	129.6 (28.1)c	85.5 (19.6)a
	Diameter (mm)				
	Oct 2012*	7.8 (1.1)bc	6.4 (0.5)a	8.7 (1.6)c	7.0 (1.1)ab
	Oct 2013*	12.5 (2.8)b	9.1 (0.9)a	18.9 (5.6)c	9.9 (2.4)a
Walker	Height (cm)				
	Oct 2012	61.6 (5.4)x	56.9 (5.8)x	57.9 (5.3)x	61.7 (5.7)x
	May 2013	52.1 (6.6)y	43.9 (10.1)x	42.5 (7.6)x	52.9 (7.1)y
	June 2013	56.1 (10.0)x	50.2 (12.1)x	47.9 (10.2)x	56.2 (10.1)x
	July 2013	57.5 (11.9)x	48.6 (16.7)x	54.5 (12.8)x	59.3 (9.2)x
	Aug 2013	59.8 (13.4)x	51.2 (20.3)x	66.5 (24.5)x	59.8 (9.5)x
	Oct 2013	56.5 (10.8)x	52.5 (13.6)x	61.3 (18.9)x	59.4 (8.3)x
	Diameter (mm)				
	Oct 2012*	5.3 (0.5)xy	4.9 (0.5)x	5.6 (0.5)y	5.3 (0.6)xy
	Oct 2013*	7.0 (1.2)xy	6.0 (0.9)x	8.4 (1.9)y	6.3 (1.0)x

* log transformed for analysis of variance

Table 2.9 – Summary of above- and belowground environmental attributes of four establishment systems for each sampling time during the first and second growing season after planting. Values represent the mean (± standard deviation in parentheses) of 15 blocks. Different lowercase letters in rows indicate significant differences among establishment systems summarized for both clones for each sampling time; these were tested using the Bonferroni adjusted αadj= 0.05/6= 0.008. Also given are the results from the ANOVAs showing the effect of establishment system, clone and their interaction. Significant effects are bolded. When clone was significant the difference between Okanese and Walker is indicated in parentheses. Nutrient supply rate was only examined in plots with Okanese. See Appendix 2.6 for graphic description of relative PAR transmittance by understory (position 3) and tree canopy (position 2).

Variable	Business-as-usual	Cover crop	Fallow	No-till	p-value for treatment effect	p-value for clone effect	p-value for treatment x clone interaction
Volumetric soil moisture (%)							
August 2012*	18.3 (6.4)a	17.6 (4.8)a	17.4 (4.4)a	22.3 (7.4)b	**<0.001**	0.769	0.498
June 2013*	24.3 (10.4)	23.7 (9.4)	24.1 (9.9)	26.5 (11.1)	0.053	0.272	0.493
July 2013*	25.8 (10.1)a	28.3 (8.8)bc	26.3 (9.3)ab	30.8 (10.6)c	**<0.001**	0.484	0.743
August 2013*	27.7 (9.8)a	30.2 (10.5)b	29.0 (8.5)ab	32.2 (11.5)b	**0.001**	0.574	0.944
Soil temperature (°C)							
August 2012	20.6 (3.7)a	20.3 (3.5)a	21.8 (4.4)b	19.8 (3.6)a	**<0.001**	0.506	0.999
May 2013	13.5 (1.4)ab	14.4 (1.5)b	16.0 (1.8)c	12.9 (1.5)a	**<0.001**	0.204	0.538
June 2013	22.3 (3.3)bc	21.1 (1.8)ab	23.5 (3.7)c	20.1 (2.1)a	**<0.001**	**0.007** (Ok < Wa)	0.158
July 2013	22.1 (2.1)bc	21.1 (2.1)ab	22.3 (2.9)c	21.0 (1.9)a	**0.003**	**0.014** (Ok < Wa)	0.672
Relative PAR transmittance (%)							
by understory vegetation							
June 2013	71.3 (9.6)b	63.5 (10.1)b	85.0 (10.9)c	55.5 (14.8)a	**<0.001**	0.573	0.975
July 2013	72.7 (14.6)b	54.1 (12.7)a	72.1 (17.0)b	56.6 (12.9)a	**<0.001**	**0.001** (Ok > Wa)	0.683
by tree canopy							
June 2013 Okanese	85.1 (4.0)b	89.4 (4.7)b	79.0 (9.3)a	89.6 (5.0)b	**0.012**	**<0.001**	**0.003**
Walker	92.3 (3.5)a	89.2 (3.6)a	92.5 (2.1)a	93.5 (4.2)a			
July 2013 Okanese	91.5 (5.9)b	84.5 (17.0)ab	79.9 (11.0)a	93.7 (5.1)b	**0.003**	N/A	N/A
Walker**	93	N/A	92.4 (4.5)	N/A	N/A	N/A	N/A
Nutrient supply rates (µg of nutrient/10 cm^2/9 weeks)							
Total N*	88.5 (147.1)c	30.5 (70.7)ab	183.1 (228.6)d	24.9 (60.2)a	**<0.001**	N/A	N/A
NO_3^-*	85.9 (146.8)c	27.4 (70.7)ab	180.6 (228.6)d	22.5 (60.1)a	**<0.001**	N/A	N/A
NH_4^+*	2.5 (0.8)	3.0 (2.5)	2.4 (0.7)	2.4 (0.9)	0.369	N/A	N/A
Ca	2553 (243)a	2637 (244)ab	2491 (229)a	2733 (262)b	**<0.001**	N/A	N/A
Mg	254 (48)a	288 (54)b	269 (63)ab	285 (50)b	**0.012**	N/A	N/A
K*	9.9 (6.2)	9.0 (3.7)	10.9 (7.6)	13.7 (8.5)	0.109	N/A	N/A
P*	2.1 (1.0)	1.7 (1.1)	1.8 (1.2)	3.2 (3.1)	0.045	N/A	N/A
Fe*	44.2 (47.7)	31.7 (31.5)	47.2 (55.7)	35.3 (36.6)	0.363	N/A	N/A
Mn*	0.7 (0.3)	0.7 (0.2)	0.7 (0.2)	1.0 (0.9)	0.196	N/A	N/A
Zn*	4.1 (1.9)	3.9 (1.7)	4.6 (2.9)	3.6 (2.2)	0.608	N/A	N/A
S*	385 (432)ab	352 (461)a	451 (492)b	380 (508)a	**0.001**	N/A	N/A
Cu***	0.3 (0.2)	0.2 (0.1)	0.3 (0.2)	0.3 (0.1)	N/A	N/A	N/A
Pb***	0.4 (0.3)	0.3 (0.2)	0.4 (0.3)	0.3 (0.3)	N/A	N/A	N/A
Cd***	0 (0)	0 (0.1)	0 (0)	0 (0)	N/A	N/A	N/A
B****	0.9 (0.7)	0.9 (0.8)	1.0 (0.8)	0.7 (0.7)	N/A	N/A	N/A
Al****	11.5 (7.8)	11.9 (7.4)	14.4 (8.0)	14.1 (9.0)	N/A	N/A	N/A

* log transformed for analysis of variance

** incomplete data because weeds exceeded height of Walker trees in business-as-usual, cover crop and no-till plots

*** excluded from analysis because the majority of probe values were below the MDL

**** excluded from analysis due to incomplete displacement of these ions during probe regeneration

Table 2.10 – Summary of belowground environmental attributes of four plantation establishment systems for all sampling times during the first and second growing seasons after planting. Data are averaged across three sampling distances. Values represent mean (± standard deviation in parenthesis) of 15 blocks. Also given are the results from the ANOVAs showing the effect of establishment system, clone and their interaction. Significant effects are bolded. When clone was significant the difference between Okanese and Walker is indicated in parentheses. Different lowercase letters in columns indicate significant differences among establishment systems summarized for both clones for each sampling time and distance; these were tested using the Bonferroni adjusted α_{adj}= 0.05/6= 0.008.

Distance to tree (cm)	Treatment	Soil moisture (%)				Soil temperature (°C)			
		Aug 2012	Jun 2013	Jul 2013	Aug 2013	Aug 2012	May 2013	Jun 2013	Jul 2013
20	Business-as-usual	15.4 (3.7)	22.0 (9.3)	23.8 (9.2)	24.4 (8.3)a	19.7 (3.3)ab	13.3 (1.4)ab	21.2 (2.7)b	21.5 (1.7)
	Cover crop	15.1 (4.7)	21.4 (8.4)	25.6 (8.4)	25.6 (9.4)ab	19.5 (3.3)ab	14.0 (1.5)b	21.1 (1.9)b	21.4 (2.0)
	Fallow	16.5 (3.1)	22.2 (9.5)	24.4 (8.2)	26.7 (8.0)b	20.2 (3.9)b	15.5 (1.7)c	22.8 (3.4)c	21.4 (2.2)
	No-till	15.5 (4.3)	22.0 (8.8)	26.5 (8.6)	25.6 (7.9)ab	19.1 (3.5)a	12.3 (1.5)a	19.9 (2.3)a	21.3 (1.9)
p-value for treatment effect		*0.203*	*0.684*	*0.073*	***0.029***	*0.054*	***<0.001***	***<0.001***	*0.870*
p-value for clone effect (Ok<Wa)		*0.975*	*0.077*	*0.278*	*0.339*	*0.749*	*0.158*	***0.047***	***0.047***
p-value for treatment x clone interaction		*0.050*	*0.399*	*0.734*	*0.537*	*0.638*	*0.156*	***0.034***	*0.432*
40	Business-as-usual	18.5 (4.1)a	23.4 (10.3)	25.4 (10.2)	27.6 (9.2)	21.2 (3.7)a	13.1 (1.3)a	21.7 (3.0)b	21.4 (1.8)
	Cover crop	17.9 (3.3)a	22.8 (8.8)	28.1 (8.2)	29.0 (9.2)	20.7 (3.5)a	14.4 (1.4)b	21.0 (1.8)ab	20.9 (2.0)
	Fallow	17.2 (3.7)a	23.8 (9.4)	26.7 (9.5)	29.6 (7.9)	22.3 (4.5)b	15.7 (1.7)c	23.1 (3.5)c	21.3 (2.3)
	No-till	23.3 (5.6)b	23.3 (9.9)	28.5 (10.5)	28.6 (9.4)	20.4 (3.7)a	13.0 (1.5)a	20.2 (2.2)a	21.2 (2.0)
p-value for treatment effect		***<0.001***	*0.237*	*0.149*	*0.112*	**0.001**	***<0.001***	***<0.001***	*0.967*
p-value for clone effect (Ok<Wa)		*0.185*	*0.179*	*0.563*	*0.526*	*0.817*	*0.129*	*0.053*	*0.068*
p-value for treatment x clone interaction		*0.280*	*0.790*	*0.518*	*0.070*	*0.867*	*0.297*	*0.093*	*0.674*
140	Business-as-usual	20.9 (8.9)a	27.2 (11.1)a	28.0 (10.7)a	30.7 (10.8)a	21.0 (4.0)a	14.1 (1.2)ab	23.9 (3.6)b	23.5 (2.2)b
	Cover crop	19.9 (5.2)a	26.8 (10.1)a	30.9 (9.2)a	35.5 (10.6)b	20.8 (3.5)a	14.9 (1.4)b	21.2 (1.7)a	20.9 (2.4)a
	Fallow	18.6 (5.8)a	26.3 (10.8)a	27.8 (10.0)a	30.7 (9.2)a	23.0 (4.5)b	16.7 (1.9)c	24.4 (4.1)b	24.1 (3.1)b
	No-till	28.1 (6.1)b	33.7 (10.6)b	36.9 (9.9)b	41.6 (10.1)c	19.9 (3.6)a	13.5 (1.3)a	20.1 (2.0)a	20.7 (1.9)a
p-value for treatment effect		***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
p-value for clone effect (Ok<Wa)		*0.275*	*0.503*	*0.798*	*0.356*	***0.038***	*0.905*	*0.347*	*0.379*
p-value for treatment x clone interaction		*0.485*	*0.918*	*0.357*	*0.507*	*0.871*	*0.381*	*0.420*	*0.512*

Table 2.11 – Nutrient supply rates for the four plantation establishment treatments, measured using PRS-probes from late May to late July 2013. For each treatment and distance to the tree, each value is the mean ± standard deviation of 15 blocks for Okanese poplar. Also given are the results from the ANOVAs showing the effect of establishment system. Significant effects are bolded. Different lowercase letters in columns indicate significant differences among treatments for a given nutrient and distance; these were tested using the Bonferroni adjusted α_{adj}= 0.05/6= 0.008.

Distance to tree (cm)	Treatment	Total N*	NO_3^-*	NH_4^+	Ca	Mg	K*	P*	Fe*	Mn*	Zn*	S*	Cu**	Pb**	Cd**	B***	Al***
		(µg/10 cm^2/9 weeks)															
20	Business-as-usual	45.6 (120.0)a	43.1 (119.3)a	2.5 (0.9)	2623.1 (261.6)ab	251.1 (46.1)a	10.8 (7.8)	2.2 (1.2)	32.3 (18.5)	0.8 (0.3)	3.9 (1.7)	382.1 (459.4)ab	0.3 (0.2)	0.3 (0.3)	0 (0)	0.6 (0.4)	10.7 (8.5)
	Cover crop	44.9 (96.9)a	41.9 (97.0)a	2.9 (3.4)	2687.5 (218.0)ab	286.8 (51.8)b	9.1 (3.7)	1.7 (0.9)	35.7 (40.5)	0.8 (0.3)	3.6 (1.3)	391.3 (471.4)ab	0.2 (0.1)	0.3 (0.2)	0 (0.1)	1.1 (0.9)	14.2 (7.9)
	Fallow	125.4 (174.0)b	122.9 (173.9)b	2.4 (0.7)	2558.3 (230.3)a	267.5 (56.3)ab	11.4 (8.8)	1.8 (1.1)	42.3 (41.8)	0.7 (0.2)	4.9 (3.1)	433.8 (515.2)a	0.3 (0.2)	0.4 (0.4)	0 (0.1)	0.8 (0.6)	13.6 (7.5)
	No-till	27.6 (75.4)a	25.1 (75.2)a	2.6 (0.8)	2798.2 (288.5)b	284.3 (44.8)b	13.1 (7.7)	2.9 (2.4)	29.1 (23.3)	1.0 (1.0)	3.1 (1.4)	368.6 (506.1)b	0.3 (0.1)	0.3 (0.3)	0 (0)	0.6 (0.5)	13.4 (10.0)
p-value for treatment effect		***<0.001***	***<0.001***	*0.164*	***0.006***	***0.009***	*0.359*	*0.077*	*0.843*	*0.910*	*0.262*	***0.030***	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
140	Business-as-usual	131.3 (162.6)y	128.8 (162.4)y	2.5 (0.7)	2482.4 (207.3)xy	256.9 (50.6)	9.1 (4.3)	2.1 (0.9)	56.1 (63.7)	0.7 (0.3)xy	4.3 (2.0)	388.8 (418.1)yz	0.3 (0.2)	0.4 (0.3)	0 (0)	1.2 (0.9)	12.3 (7.2)
	Cover crop	16.0 (22.8)x	12.9 (22.3)x	3.0 (1.1)	2585.9 (264.5)xy	288.3 (57.9)	8.9 (3.8)	1.7 (1.2)	27.7 (19.6)	0.7 (0.2)xy	4.1 (2.0)	311.9 (463.2)x	0.3 (0.1)	0.2 (0.2)	0 (0)	0.6 (0.5)	9.5 (6.3)
	Fallow	240.8 (265.8)y	238.3 (265.8)y	2.4 (0.7)	2424.6 (214.0)x	271.4 (71.0)	10.4 (6.5)	1.9 (1.4)	52.1 (68.0)	0.7 (0.2)x	4.2 (2.8)	467.5 (483.8)z	0.3 (0.1)	0.3 (0.3)	0 (0)	1.1 (0.9)	15.1 (8.7)
	No-till	22.2 (42.4)x	19.9 (42.4)x	2.3 (1.0)	2667.2 (222.2)y	285.2 (55.5)	14.3 (9.5)	3.5 (3.7)	41.6 (46.4)	1.0 (0.7)y	4.1 (2.8)	390.5 (526.7)xy	0.3 (0.2)	0.3 (0.3)	0 (0)	0.8 (0.8)	14.9 (8.0)
p-value for treatment effect		***<0.001***	***<0.001***	*0.088*	***0.010***	*0.079*	*0.146*	*0.084*	*0.132*	***0.017***	*0.820*	***<0.001***	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*

* log transformed for analysis of variance

** excluded from statistical analysis because the majority of probe values were below the analytical method detection limit

*** excluded from statistical analysis due to incomplete displacement of these ions during probe regeneration

2.7 Figures

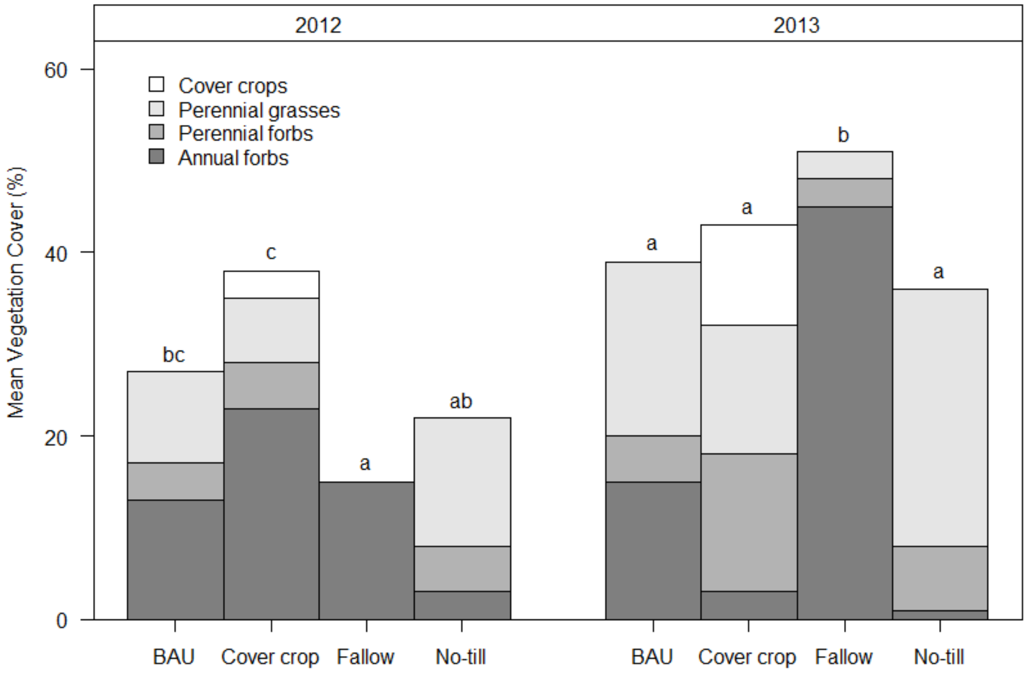
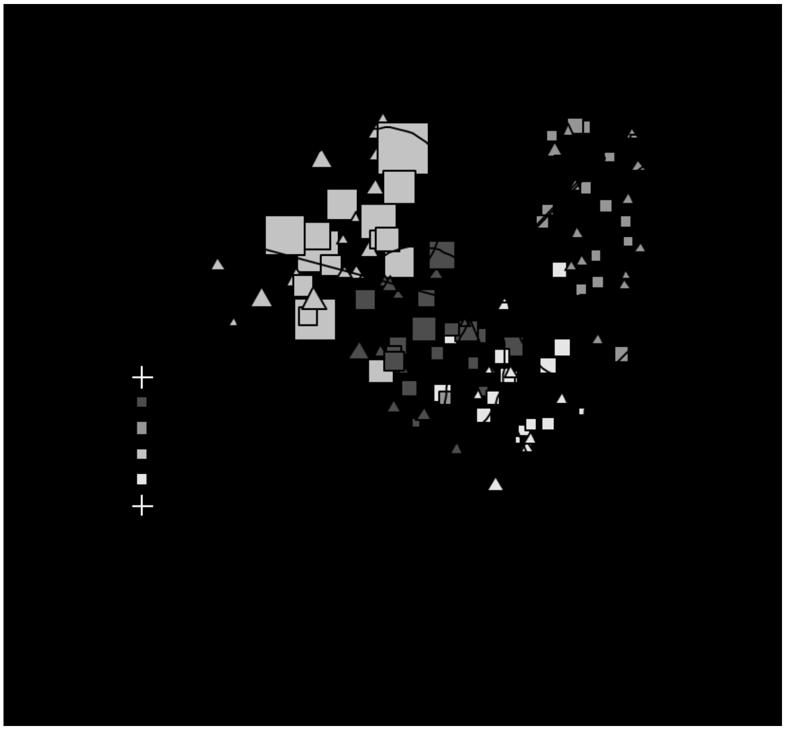


Figure 2.1 – Mean vegetation cover (%, 0-105 cm from planted poplars) of annual forbs, perennial forbs, perennial grasses and seeded cover crops, as affected by the four plantation establishment systems, for the first and second year after tree planting. Different lowercase letters indicate differences in total cover (e.g. all functional groups) among treatments within each growing season (Bonferroni adjusted αadj= 0.05/6= 0.008). Abbreviation: BAU (business-as-usual).



ELRE - *Elytrigia repens*
FEAR - *Festuca arundinacea Schreb. Cv'Courtney'*
LOPE - *Lolium perenne*
MESA - *Medicago sativa*
POCO - *Polygonum convolvulus*
TAOF - *Taraxacum officinale*
TRRE - *Trifolium repens*

Figure 2.2 – NMDS ordination of understory vegetation composition (0-105 cm distance to trees) in 2013. Ellipses indicate 90% confidence intervals for plots of the four establishment systems. Gray shades represent different establishment systems and symbols represent different clones. Only trees that were assessed for vegetation are included in the ordination. Size of each point represents relative diameter increment of trees for the 2013 growing season. Vectors indicate fitted understory species vectors for which the final ordination Pearson correlation was $r^2 > 0.3$. The ordination had a 3-D solution with a final stress of 0.1484 after 17 iterations. For simplicity, only the first two axes are shown.

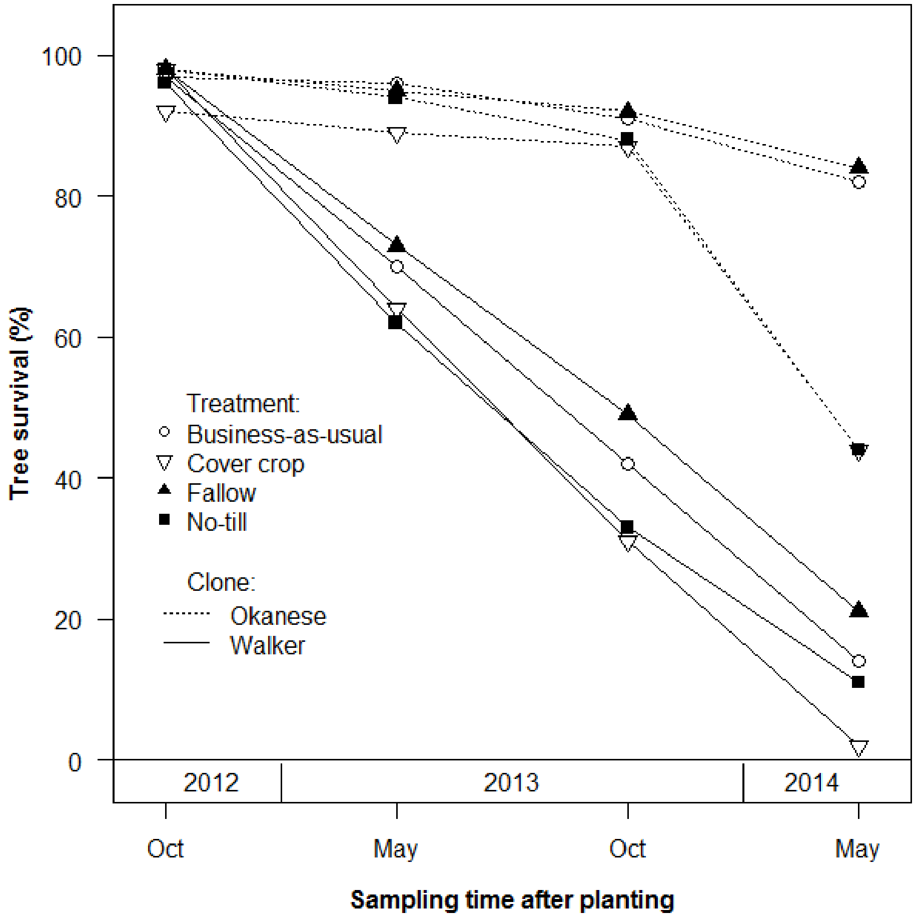


Figure 2.3 – Tree survival (%) as determined after the first year following planting, at the beginning and end of the second year, and at the beginning of the third year following planting. For each treatment and clone, each value is the mean of 15 blocks. Symbols represent different establishment systems and line types represent different clones.

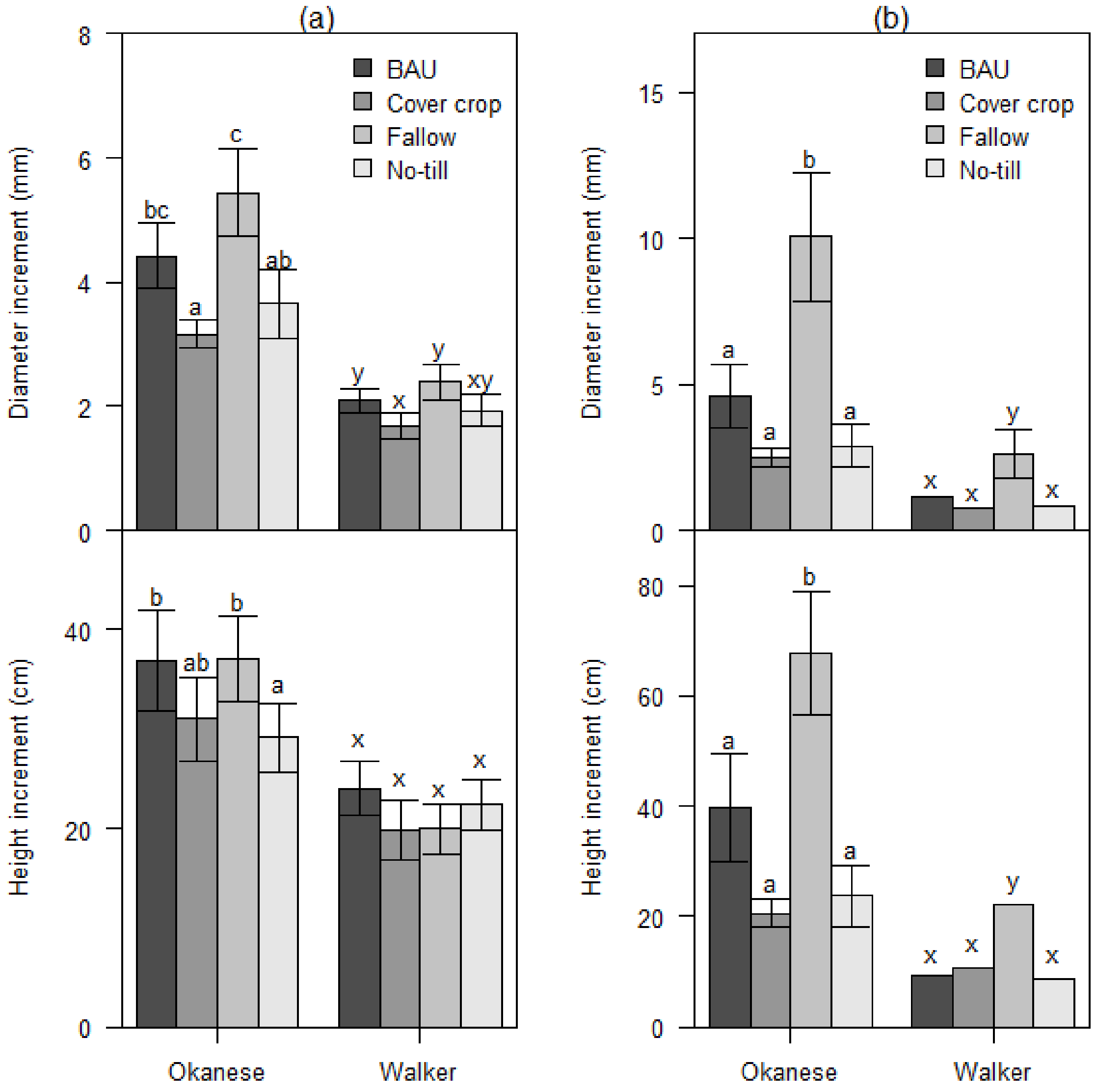


Figure 2.4 – Mean diameter and height increment of Okanese and Walker poplar clones after the (a) first and (b) second year after planting, within each of the plantation establishment treatments. Error bars represent 90% confidence intervals. Different lowercase letters indicate differences among treatments for each clone (at Bonferroni adjusted αadj= 0.05/6= 0.008). All response variables differed between clones for each treatment (Ok>Wa, $p < 0.05$). Abbreviation: BAU (business-as-usual).

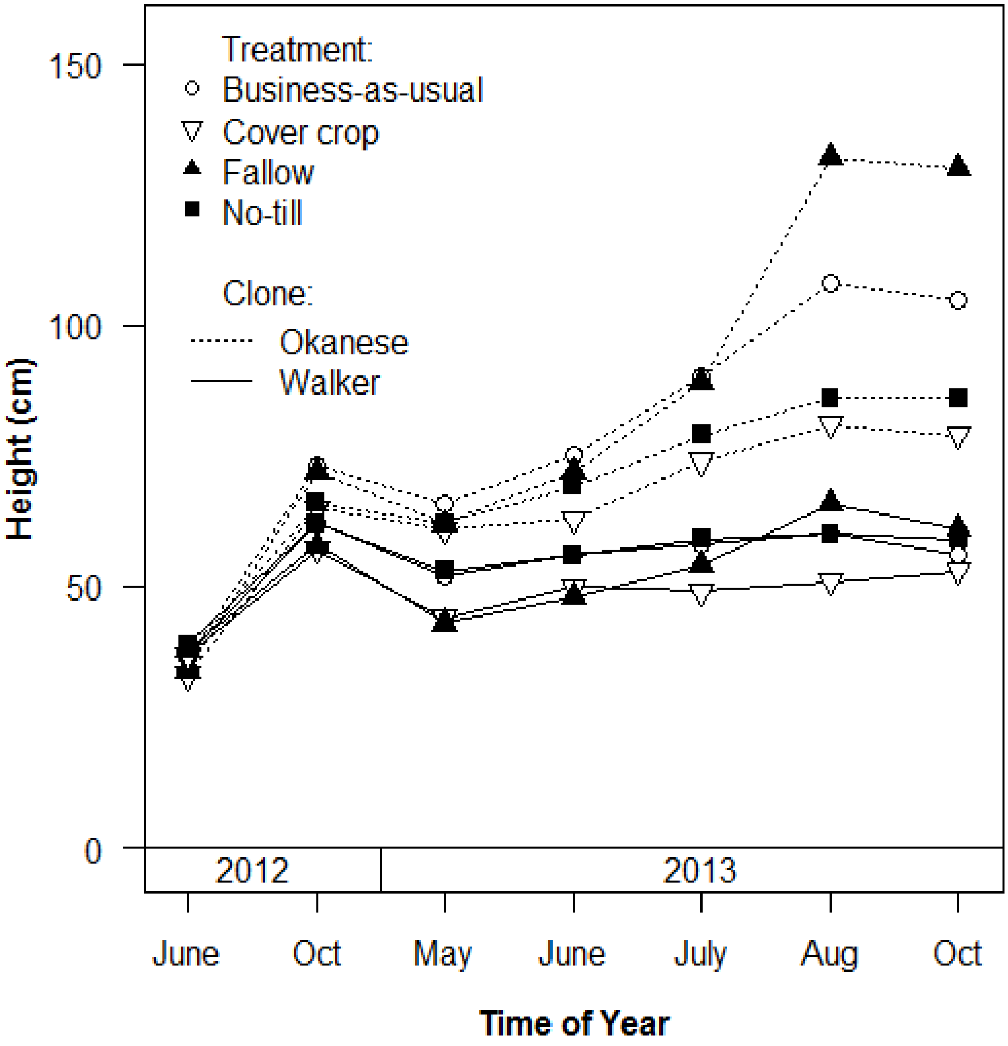


Figure 2.5 – Mean height increment (cm) of Okanese and Walker poplar trees grouped by plantation establishment systems during the first and second year after planting. Symbols represent different establishment systems and line types represent different clones.

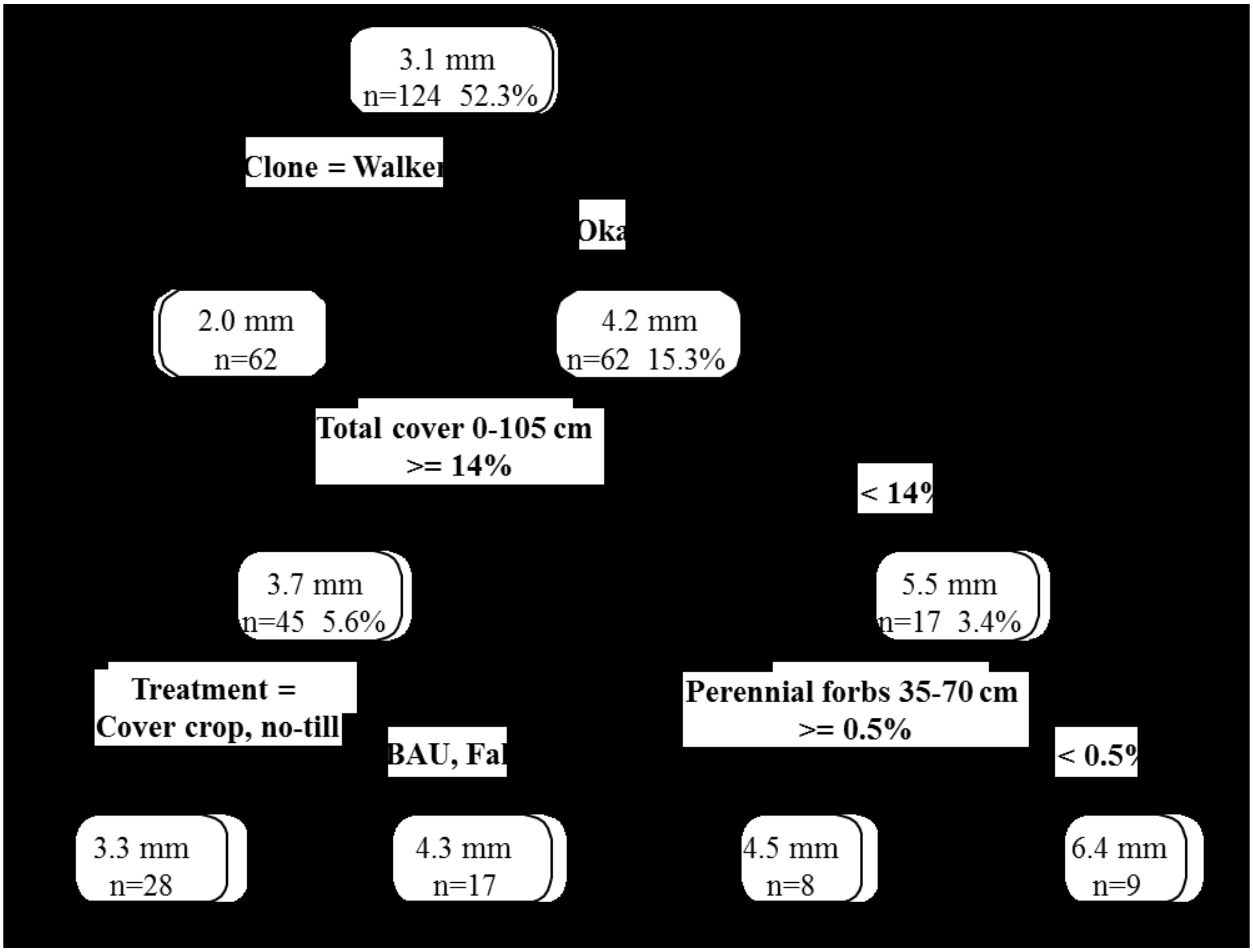


Figure 2.6 – Results of the regression tree analysis explaining hybrid poplar tree diameter increment (mm) for the first growing season (2012). The final regression tree model had four nodes which explained 77% of the variation in diameter increment in 2012 using clone, treatment, and 2 understory variables (total cover at 0-105 cm distance and perennial forb cover at 35-70 cm distance, %). Values shown are estimated diameter increment (mm), the number of trees at each node (‘n=’), and percent variation explained by each split (%).

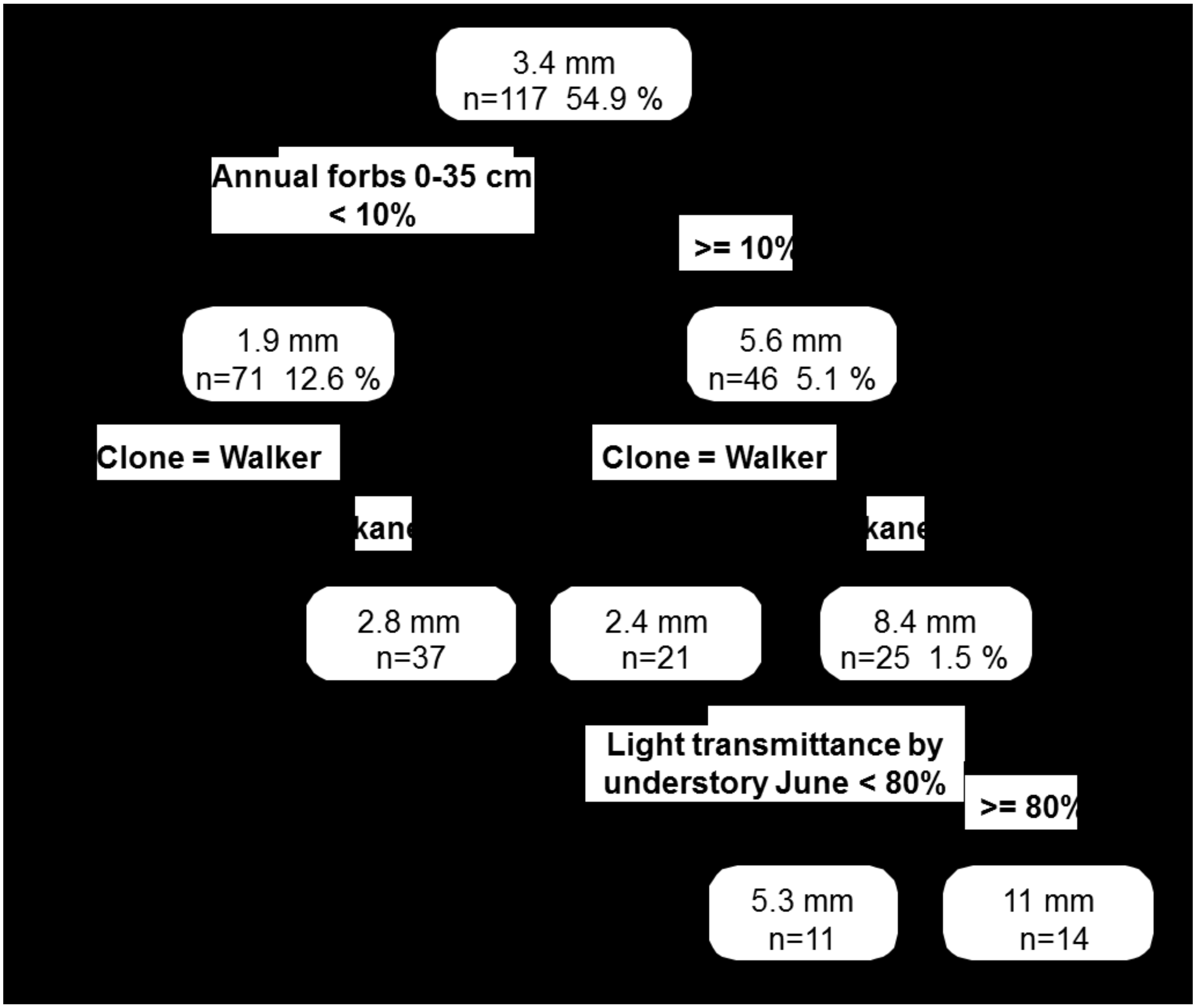
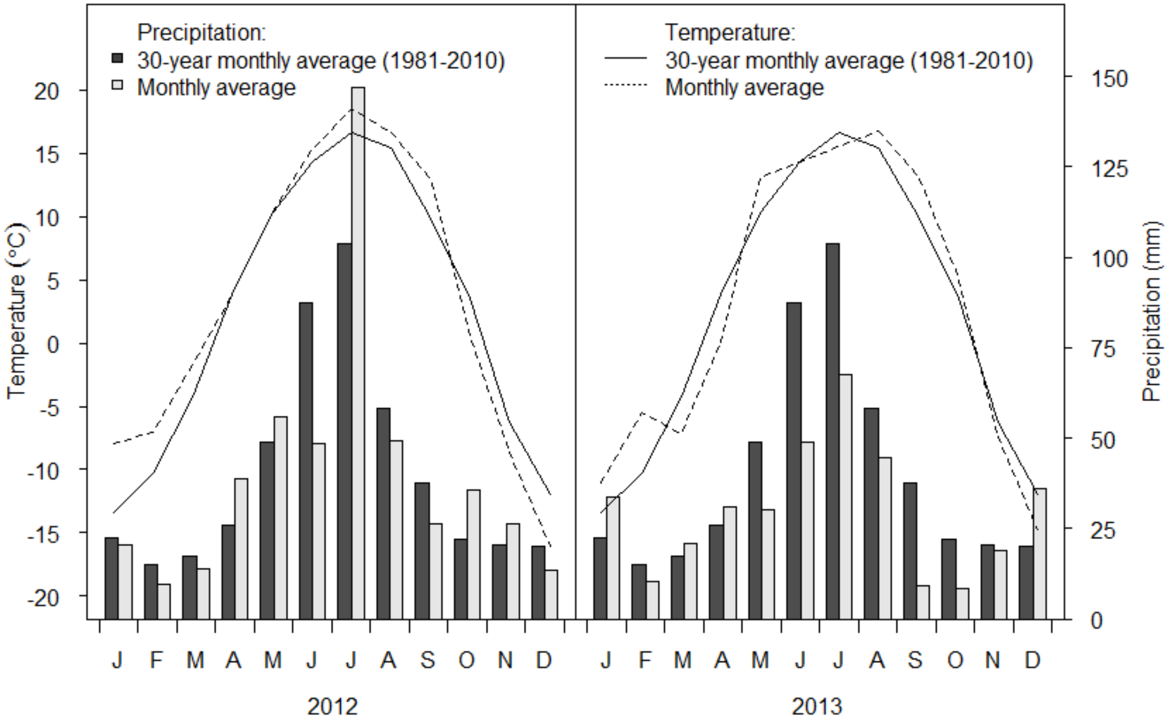


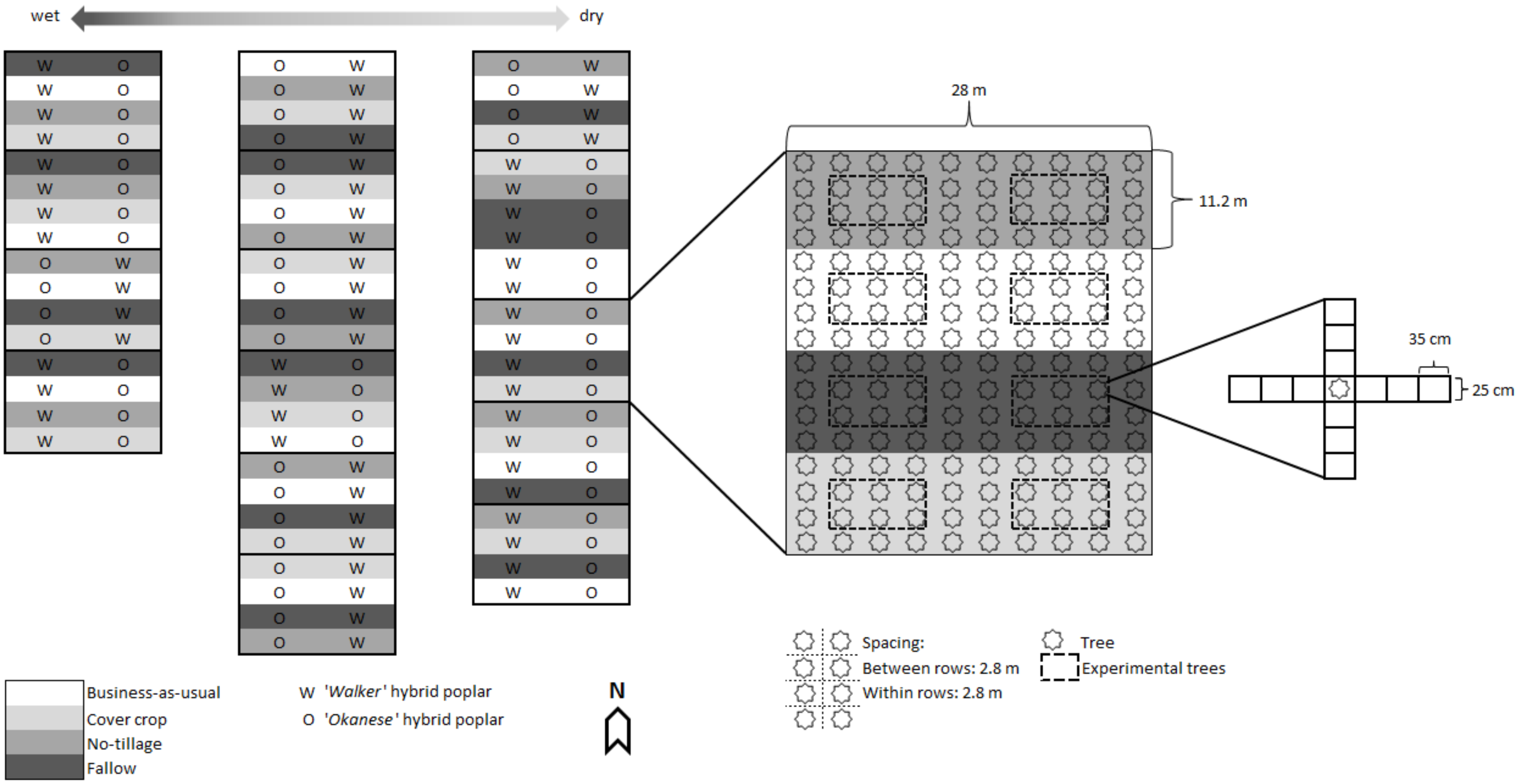
Figure 2.7 – Results of the regression tree analysis explaining hybrid poplar tree diameter increment (mm) for the second growing season (2013). The final regression tree model had four nodes which explained 74% of the variation in diameter increment in 2013 using one understory variable (annual forb cover at 0-35 cm distance, %), clone, and one microclimate variable (PAR transmitted through understory vegetation in June, %). Values shown are estimated diameter increment (mm), the number of trees at each node ('n='), and percent variation explained by each split (%).

2.8 Appendices

Appendix 2.1 – Average monthly temperature, and total monthly precipitation for the sampling years 2012 and 2013, as well as the 30-year average monthly temperature and precipitation for the time period 1981-2010. Climate data were obtained for the Athabasca 2 climate station (Station ID 3060321) based on the National Climate Data and Information Archive (http://www.climate.weatheroffice.gc.ca).



Appendix 2.2 – Experimental plantation layout showing the four establishment systems and two hybrid poplar clones randomized according to a strip-plot design in 15 replicate blocks and the belt transect used for understory vegetation sampling showing the three contiguous quadrats in each cardinal direction. One block on the east site of the plantation contains six instead of four treatment plots, due to one additional plot for both business-as-usual and fallow treatments.



Appendix 2.3 – Plantation establishment systems specifying combinations of chemical, mechanical and/or cultural weed control methods. Management practices were applied to whole plots (e.g. in-row and between-row) if not indicated otherwise.

Management practices	**Establishment system**				**Time**
	Business-as-usual	Cover crop	Fallow	No-till	
Site Preparation					
1st Spraying (2l/acre glyphosate)	---	---	x	---	June, 20 2011
1st Cultivation: discing 2 passes	---	---	x	---	July, 21 2011
2nd Spraying (2l/acre glyphosate)	x	x	x	x	Sep, 08 2011
Planting and follow-up maintenance					
2nd Cultivation: discing*	x (3)	x (3)	x (1)	---	June, 6-7 2012
rototilling 1 pass	x	x	x	---	June, 6-7 2012
Planting	x	x	x	x	June, 6-7 2012
3rd Spraying (2.16 kg/ha lorox)**	x (IB)	x (I)	x (IB)	x (IB)	June, 12 2012
Interseeding cover crop mixture	---	x (B)	---	---	June, 14 2012
Maintenance 1st year					
3rd Cultivation: discing 2 passes	x	---	x	---	Aug, 13 2012
1st Mowing	---	x	---	x	Aug, 14 2012
Maintenance 2nd year					
4th Cultivation: rototilling 2 passes	x	---	x	---	May, 13-14 2013
2nd Mowing	---	x	---	x	Aug, 13-15 2013
5th Cultivation: rototilling 2 passes	x	---	x	---	Aug, 20-22 2013

* Number in parentheses indicates number of passes

** IB= In-row and between-row, I= In-row, B= Between-row

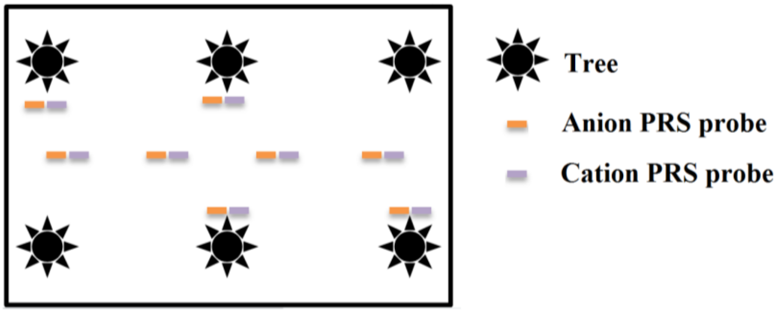
Appendix 2.4 – Plant species identified during sampling, grouped by growth form, life cycle, genus, species, authority, common name, four letter species code, regulatory designation in Alberta, and native status in Canada. Plant species growth forms, life cycles, nomenclature, and origin status were used from the USDA Plants Database (http://plants.usda.gov/); Alberta designations were obtained from the Weed Control Act. The four letter species code was used in the ordination figure.

Growth form	Life Cycle	Genus	Species	Authority	Common Name	Code	Alberta designation	Native Status Canada
Forb	Annual	*Capsella*	*bursa-pastoris*	(L.) Medik.	Shepherd's purse	CABU		Introduced
Forb	Annual	*Chenopodium*	*album*	L.	Lambsquarters	CHAL		Introduced, native
Forb	Annual	*Crepis*	*tectorum*	L.	Narrowleaf hawksbeard	CRTE		Waif
Forb	Annual	*Galeopsis*	*tetrahit*	L.	Hempnettle	GATE		Introduced
Forb	Annual	*Neslia*	*paniculata*	(L.) Desv.	Ballmustard	NEPA		Introduced
Forb	Annual	*Polygonum*	*lapathifolium*	L.	Pale smartweed	POLA		Introduced
Forb	Annual	*Silene*	*noctiflora*	L.	Nightflowering catchfly	SINO		Introduced
Forb	Annual	*Stellaria*	*media*	(L.) Vill.	Common chickweed	STME		Introduced
Forb	Annual	*Thlaspi*	*arvense*	L.	Stinkweed	THAR		Introduced
Forb, vine	Annual	*Polygonum*	*convolvulus*	L.	Wild buckwheat	POCO		Introduced
Forb	Annual, biennial	*Lappula*	*squarrosa*	(Retz.) Dumort.	Bluebur	LASQ		Introduced
Forb	Annual, biennial	*Melilotus*	*alba*	(L.) Medik.	White sweetclover	MEAL		Introduced
Forb	Annual, biennial	*Potentilla*	*norvegica*	L.	Rough cinquefoil	PONO		Introduced, native
Forb	Biennial, perennial	*Silene*	*alba*	(Mill.) Krause	Whitecockle	SIAL	Noxious	Introduced
Forb	Perennial	*Achillea*	*millefolium*	L.	Common yarrow	ACMI		Introduced, native
Forb	Perennial	*Cirsium*	*arvense*	(L.) Scop.	Canada thistle	CIAR	Noxious	Introduced
Forb	Perennial	*Equisetum*	*arvense*	L.	Field horsetail	EQAR		Native
Forb	Perennial	*Equisetum*	*sylvaticum*	L.	Woodland horsetail	EQSY		Native
Forb	Perennial	*Fragaria*	*vesca*	L.	Woodland strawberry	FRVE		Native
Forb	Perennial	*Medicago*	*sativa*	L.	Alfalfa	MESA		Introduced
Forb	Perennial	*Plantago*	*major*	L.	Common plantain	PLMA		Introduced
Forb	Perennial	*Solidago*	*canadensis*	L.	Canada goldenrod	SOCA		Native
Forb	Perennial	*Sonchus*	*arvensis*	L.	Perennial sowthistle	SOAR	Noxious	Introduced
Forb	Perennial	*Taraxacum*	*officinale*	F.H. Wigg.	Common dandelion	TAOF		Introduced, native
Forb	Perennial	*Trifolium*	*repens*	L.	White clover	TRRE		Introduced
Forb	Perennial	*Trifolium*	*hybridum*	L.	Alsike clover	TRHY		Introduced
Forb, vine	Perennial	*Vicia*	*americana*	Muhl. ex Willd.	American vetch	VIAM		Native
Grass	Perennial	*Bromus*	*inermis*	Leyss.	Smooth brome	BRIN		Introduced, native
Grass	Perennial	*Deschampsia*	*cespitosa*	(L.) P. Beauv.	Tufted hairgrass	DECE		Introduced, native
Grass	Perennial	*Elytrigia*	*repens*	(L.) Gould	Quackgrass	ELRE		Introduced
Grass	Perennial	*Festuca*	*rubra*	L.	Creeping red fescue	FERU		Introduced, native
Grass	Perennial	*Lolium*	*perenne*	L.	Perennial ryegrass	LOPE		Introduced
Grass	Perennial	*Phleum*	*pratense*	L.	Timothy	PHPR		Introduced
Grass	Perennial	*Poa*	*palustris*	L.	Fowl bluegrass	POPA		Native
Grass	Perennial	*Poa*	*pratensis*	L.	Kentucky bluegrass	POPR		Introduced, native
Grass	Perennial	*Festuca*	*arundinacea*	Schreb. Cv 'Courtney'	Tall fescue	FEAR		Introduced
Sedge	Perennial	*Carex*	*ssp.**		Sedge	CAssp.		Native
Tree	Perennial	*Populus*	*balsamifera*	L.	Balsam poplar	POBA		Native
Tree, Shrub	Perennial	*Salix*	*ssp.***		Willow	SAssp.		Native

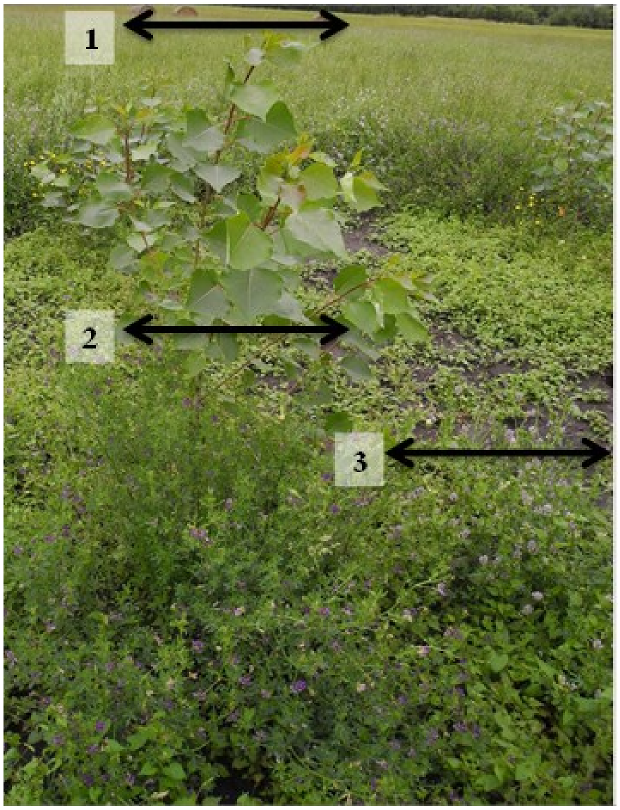
*Carex spp. only identified to genus

** Salix spp. only identified to genus

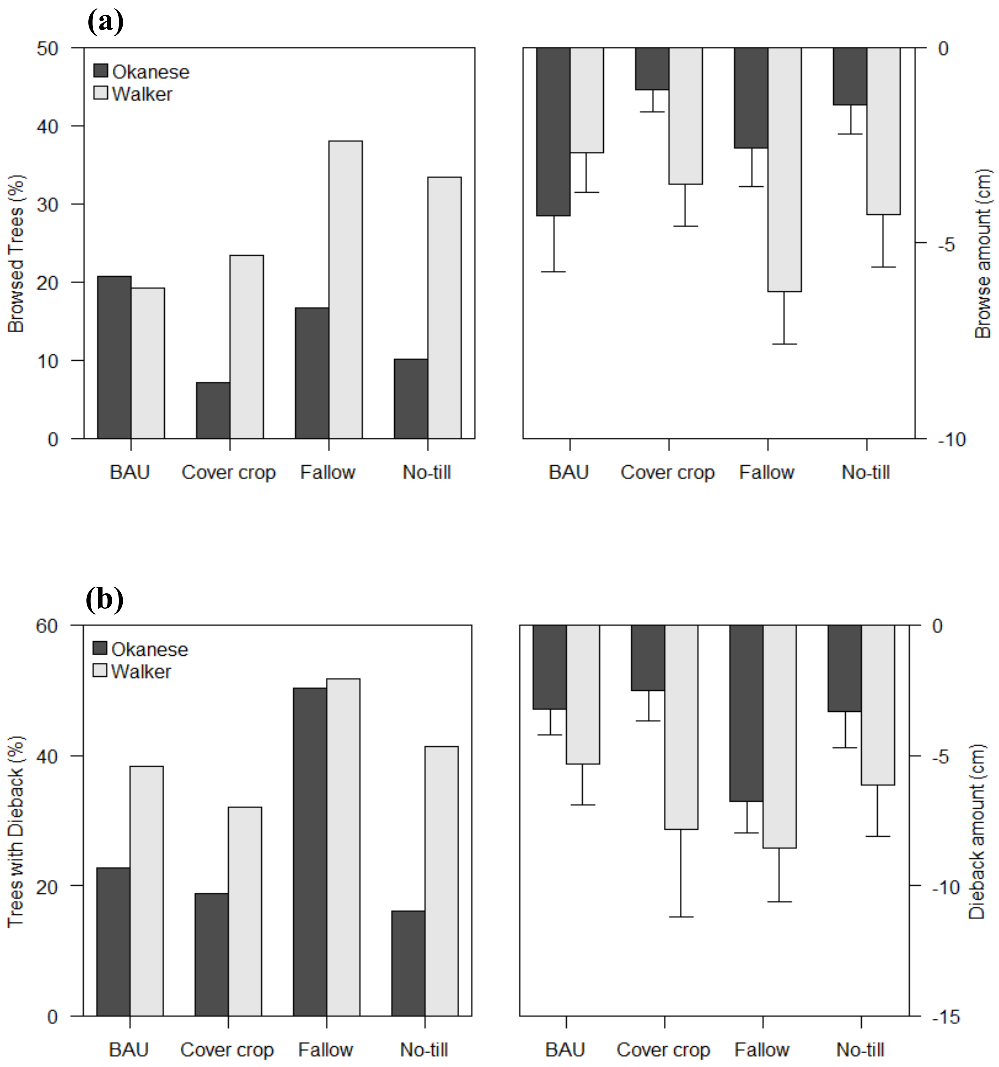
Appendix 2.5 – Layout showing sample locations of PRS probes within each of the four treatment plots of each block containing the hybrid poplar clone Okanese. Spacing between rows and within rows is 2.8 m.



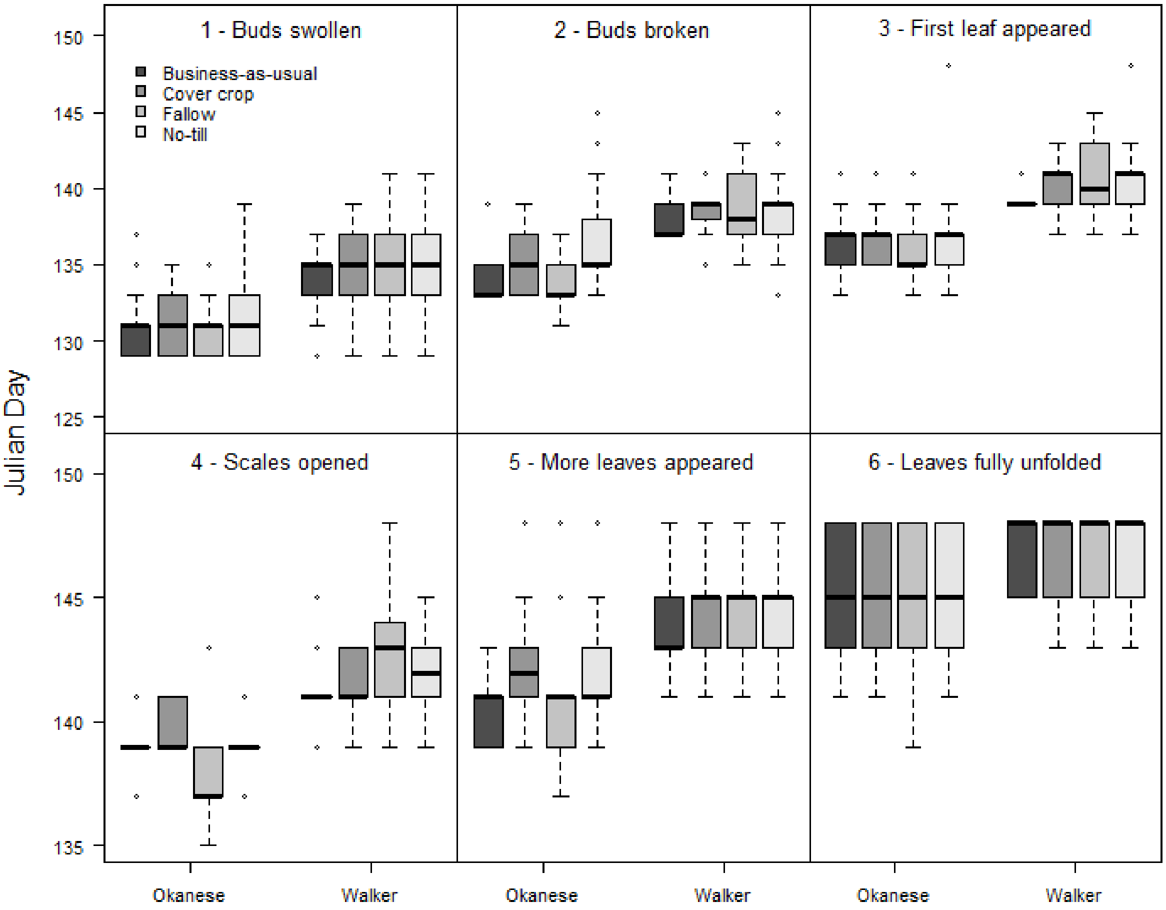
Appendix 2.6 – Layout showing sample locations for measures of photosynthetically active radiation: (1) open sky, (2) tree impact, and (3) herbaceous understory impact.



Appendix 2.7 – Frequency (%) and amount (cm) of damage to hybrid poplar trees over the winter 2012/2013 for (a) browse by moose and/or deer, and (b) winter dieback for each clone and in the different establishment systems.



Appendix 2.8 – Boxplots representing the day of year at which budbreak scores 1-6 were reached during 2013, for each combination of clone by plantation establishment system. The median is shown by the horizontal line inside the box, the interquartile range is represented by the width of the box (75th quartile minus 25th quartile), the 2.5 and 97.5 quartiles are shown by the whiskers, and outliers are indicated by stars.



Appendix 2.9 – Summary of alternative and surrogate splits for each node from the regression tree analysis of diameter increment in 2012. See Figure 2.6.

```
Node number 1: 124 observations, complexity parameter= 0.5232775
Primary splits:
  Clone                     splits as RL                     improve= 0.523
  Total cover 70-105 cm     <16.5           to the right     improve= 0.161
  Total cover 0-105 cm      < 12.5          to the right     improve= 0.156
  Total cover 35-70 cm      < 12.5          to the right     improve= 0.130
  Treatment                 splits as RLRL                   improve= 0.106
Surrogate splits:
  Soil moisture 40 cm August < 17.35        to the left      agree= 0.573
  Perennial forbs 35-70 cm  < 0.5           to the left      agree= 0.573
  Perennial grasses 0-35 cm < 12.5          to the left      agree= 0.556
  Total cover 35-70 cm      <22.5           to the left      agree= 0.556
  Total cover 70-105 cm     < 17.5          to the right     agree= 0.556

Node number 3: 62 observations, complexity parameter= 0.1533778
Primary splits:
  Total cover 0-105 cm      < 13.5          to the right     improve= 0.369
  Total cover 0-35 cm       < 15.5          to the right     improve= 0.335
  Total cover 70-105 cm     < 10.5          to the right     improve= 0.330
  Treatment                 splits as RLRL                   improve= 0.311
  Total cover 35-70 cm      < 16.5          to the right     improve= 0.297
Surrogate splits:
  Total cover 35-70 cm      < 16.5          to the right     agree= 0.984
  Total cover 70-105 cm     < 13.5          to the right     agree= 0.968
  Total cover 0-35 cm       < 9.5           to the right     agree= 0.952
  Treatment                 splits as LLRL                   agree= 0.855
  Perennial grasses 0-105 cm < 0.5          to the right     agree= 0.839

Node number 6: 45 observations, complexity parameter= 0.03436564
Primary splits:
  Treatment                 splits as RLRL                   improve= 0.227
  Soil temperature 20 cm    < 22.1          to the right     improve= 0.151
  Cover crops 70-105 cm     < 0.5           to the right     improve= 0.144
  Cover crops 0-105 cm      < 0.5           to the right     improve= 0.144
  Perennial forbs 0-35 cm   < 29            to the right     improve= 0.131
Surrogate splits:
  Cover crops 70-105 cm     < 0.5           to the right     agree= 0.711
  Cover crops 0-105 cm      < 0.5           to the right     agree= 0.711
  Soil moisture 140 cm      < 15.85         to the right     agree= 0.689
  Perennial grasses 0-35 cm < 1.5           to the right     agree= 0.689
  Cover crops 37-70 cm      < 0.5           to the right     agree= 0.689

Node number 7: 17 observations, complexity parameter= 0.05581875
Primary splits:
  Perennial forbs 35-105 cm < 0.5           to the right     improve= 0.506
  Soil moisture 20 cm       < 18.95         to the right     improve= 0.414
  Soil moisture 140 cm      < 16.8          to the right     improve= 0.267
  Perennial forbs 70-105 cm < 0.5           to the right     improve= 0.233
  Annual forbs 0-35 cm      < 12            to the left      improve= 0.216
Surrogate splits:
  Soil moisture 40 cm       < 14.9          to the right     agree= 0.765
  Soil moisture 140 cm      < 17.65         to the right     agree= 0.765
  Perennial grasses 35-70 cm < 0.5          to the right     agree= 0.765
  Perennial forbs 70-105 cm < 0.5           to the right     agree= 0.765
  Perennial grasses 70-105 cm < 0.5         to the right     agree= 0.765
```

Appendix 2.10 – Summary of alternative and surrogate splits for each node from the regression tree analysis of diameter increment in 2013. See Figure 2.7.

Node number 1: 117 observations, complexity parameter= 0.2745023			
Primary splits:			
Annual forbs 0-35 cm	< 10	to the left	improve= 0.272
Treatment	splits as LLRL		improve= 0.267
Clone	splits as RL		improve= 0.266
Annual forbs 0-105 cm	< 12.5	to the left	improve= 0.257
Annual forbs 75-105 cm	< 14.5	to the left	improve= 0.254
Surrogate splits:			
Annual forbs 0-105 cm	< 12.5	to the left	agree= 0.991
Annual forbs 35-75 cm	< 12.5	to the left	agree= 0.966
Annual forbs 75-105 cm	< 12.5	to the left	agree= 0.957
Treatment	splits as LLRL		agree= 0.880
Total cover 0-35 cm	< 39.5	to the left	agree= 0.863
Node number 2: 71 observations, complexity parameter= 0.0505345			
Primary splits:			
Clone	splits as RL		improve= 0.509
PAR_{Weed} July	< 71	to the left	improve= 0.259
Total cover 75-105 cm	< 25.5	to the right	improve= 0.108
Soil temperature 20 cm July	<20.75	to the right	improve= 0.106
S 20 cm	< 91.74	to the left	improve= 0.091
Surrogate splits:			
PAR_{Weed} July	< 58.5	to the left	agree= 0.662
Perennial forbs 35-70 cm	< 1.5	to the left	agree= 0.634
Annual forbs 35-75 cm	< 7.5	to the right	agree= 0.606
Perennial forbs 0-105 cm	< 2.5	to the left	agree= 0.606
Perennial forbs 0-35 cm	< 4.5	to the left	agree= 0.592
Node number 3: 46 observations, complexity parameter= 0.2745023			
Primary splits:			
Clone	splits as RL		improve= 0.441
Soil temperature 40 cm June	< 24.1	to the left	improve= 0.231
Soil temperature 20 cm June	< 24.55	to the left	improve= 0.230
Soil temperature 140 cm June	< 25.25	to the left	improve= 0.194
Soil moisture 140 cm July	< 23.8	to the right	improve= 0.151
Surrogate splits:			
PAR_{Weed} July	< 61	to the left	agree= 0.696
Perennial forbs 0-35 cm	< 0.5	to the left	agree= 0.674
Annual forbs 75-105 cm	< 28.5	to the right	agree= 0.674
PAR_{Weed} June	< 83.5	to the right	agree= 0.652
Soil temperature 40 cm May	< 14	to the right	agree= 0.652
Node number 7: 25 observations, complexity parameter= 0.1255824			
Primary splits:			
PAR_{Weed} June	< 79.5	to the left	improve= 0.396
Perennial grasses 75-105 cm	< 4.5	to the right	improve= 0.375
Perennial grasses 35-75 cm	< 5.5	to the right	improve= 0.365
Perennial grasses 0-105 cm	< 5.5	to the right	improve= 0.365
Soil temperature 20 cm June	< 22.4	to the left	improve= 0.348
Surrogate splits:			
Perennial grasses 35-75 cm	< 5.5	to the right	agree= 0.92
Perennial grasses 0-105 cm	< 5.5	to the right	agree= 0.92
Perennial grasses 0-35 cm	< 5.5	to the right	agree= 0.88
Treatment	spits as L-R-		agree= 0.84
Perennial grasses 75-105 cm	< 4.5	to the right	agree= 0.84

Appendix 2.11 – Summary of variables that were included during the regression tree analysis in 2012 and 2013.

2012		2013	
Variable	Distance to tree (cm)	Variable	Distance to tree (cm)
Treatment		Treatment	
Clone		Clone	
Annual forb cover	0-35	Annual forb cover	0-35
	35-70		35-70
	70-105		70-105
	0-105		0-105
Perennial forb cover	0-35	Perennial forb cover	0-35
	35-70		35-70
	70-105		70-105
	0-105		0-105
Perennial grass cover	0-35	Perennial grass cover	0-35
	35-70		35-70
	70-105		70-105
	0-105		0-105
Cover crop cover	0-35	Cover crop cover	0-35
	35-70		35-70
	70-105		70-105
	0-105		0-105
Total cover	0-35	Total cover	0-35
	35-70		35-70
	70-105		70-105
	0-105		0-105
Volumetric soil moisture	40	Volumetric soil moisture, June	20
	140		40
Soil temperature	20		140
	40	Volumetric soil moisture, July	20
	140		40
			140
		Volumetric soil moisture, August	20
			40
			140
		Soil temperature, May	20
			40
			140
		Soil temperature, June	20
			40
			140
		Soil temperature, July	20
			40
			140
		Total nitrogen	20
			140
		NO_3^-	20
			140
		Ca	20
			140
		S	20
			140
		Mg	20
		Mn	140
		PAR by understory vegetation, June	
		PAR by understory vegetation, July	

Chapter 3: Spatial partitioning of competitive effects from neighboring vegetation on establishing hybrid poplar

3.1 Introduction

Plantations of fast-growing hybrid poplar trees play a significant economic role for fibre production, as a supplier of wood, biomass for energy, alternative fodder, and ecosystem services such as carbon sequestration (Poplar Council of Canada, 2012; Weih, 2004). In the Canadian Prairie Provinces plantations are mainly being established as a source of fibre on land formerly in conventional agricultural production (e.g. annual crops or forage). Key characteristics of these systems include a reduced rotation length from 60 years for aspen to less than 20 years for hybrid poplar, and intensive silvicultural management, which includes a combination of chemical and mechanical treatments to control diverse and often competitive herbaceous understory vegetation, or weeds (Sage, 1999; Stanturf et al., 2001).

Weed control within plantations aims to reduce tree yield loss and mortality through a reduction in resource competition between trees and weeds, either aboveground for light or belowground for nutrients and/or water (Balandier et al., 2006). Hybrid poplars are known to have high nutritional, water and light requirements and do not reach their full growth potential when experiencing climate-, site- or competition-induced stress through any of these factors. Several studies report plantation productivity to be predominantly under the control of belowground competition for water and/or nutrients, rather than aboveground competition for light (Coll et al., 2007; Pinno and Bélanger, 2009). In other studies, however, poplars have been found to be intolerant of shading by neighboring vegetation (Sage, 1999; Sixto et al., 2001).

Early vegetation control is considered critical to maintain rapid initial growth (Otto et al., 2010) and reduce tree yield losses later into establishment (Truax et al., 2012). Therefore, vegetation management typically focuses on controlling vegetation during the establishment phase when hybrid poplar trees are most sensitive to competition and have particularly high demand for resources (Hansen et al., 1983; Stanturf et al., 2001; West, 2006). In addition to temporal variation in the effects of competing vegetation, there is evidence that the impact of understory vegetation on tree performance varies spatially. Most studies report greater understory competition within the near proximity of trees (e.g. 0.5-1 m) and emphasize the need to control vegetation close to trees (Powell and Bork, 2004b; Thomas et al., 2001). However, widely used mechanical vegetation management methods (cultivation or mowing) suffer from the physical limitation of only being able to treat areas up to a certain distance from the tree base to prevent direct equipment-induced damage to branches, stems, and roots of trees. Little is known about how the spatial relationships among trees and neighboring vegetation influence competitive effects.

This study evaluated the effects of six vegetation control treatments on the performance of two hybrid poplar clones, the female clone Walker (*Populus deltoides* x (*P. laurifolia* x *P. nigra*)) (Lindquist et al., 1977) and male clone Okanese (Walker x (*P. laurifolia* x *P. nigra*)) (Schroeder et al., 2013), established in experimental plantations in north-central Alberta. The two related intersectional hybrids were selected due to their economic importance in shelterbelts, and more recently, in short-rotation-intensive-culture (SRIC) plantations in the Canadian Prairies, and their contrasting growth forms, resource requirements and competitiveness with the herbaceous understory (Schroeder et al., 2013; van Oosten, 2006, 2004).

The objective of this study was to identify the spatial importance of weed competition for resources on tree performance, including the spatial isolation of aboveground and belowground competition as well as competition near and far from the tree bole. The primary objectives of this study were to: (1) test the relative importance of competition near-bole versus far-bole, and above- versus belowground, on growth and survival of two hybrid poplar clones; (2) to quantify vegetation-induced differences in above- and belowground abiotic factors, including light availability, soil nutrient availability, soil moisture, and soil temperature; and (3) to determine whether competitive effects vary over time since planting.

3.2 Methods

3.2.1 Study area

The study area was located in central Alberta, Canada near Boyle (54°90′N, 112°85′W, 570 m above sea level), in the Dry Mixedwood Natural Subregion (Natural Regions Committee, 2006). This area is known as the parkland-boreal transition zone of the Canadian Prairies due to its location north of the agriculturally dominated Central Parkland and south of the largely forested Central Mixedwood Natural Subregion. The climate is temperate continental and characterized by short, warm growing seasons with a thirty year (1981 to 2010) mean July temperature of 16.6 °C, and long, cold winters with a mean January temperature of -13.4 °C. Thirty year normal annual precipitation is 479 mm, of which 336 mm (i.e. 70%) falls during the growing season from May through September (Environment Canada, 2014). The herbaceous vegetation on all sites was dominated by a diverse mix of introduced weedy forbs (annuals and perennials), and graminoids.

3.2.2 Experimental design

The experiment was established in Spring 2011 on research sites managed by Alberta-Pacific Forest Industries Inc., and tree-weed competition dynamics were monitored over a three-year period through fall 2013. The experiment was established as a split-plot design at each of the three sites, with six replicate blocks per site. Two hybrid poplar clones and six vegetation control treatments were included in each block (Appendix 3.1). All three sites were located within a larger fenced area to protect trees from browsing by large ungulates including deer and moose. Study sites included three contrasting topographic locations representing varying moisture regimes including a low-lying area characterized by imperfect drainage (Lowland), a mesic site (Midland), and a rapidly drained upland site with a west-facing aspect (Highland). Soils in the research area are characterized as Orthic Gray Luvisols (Alberta Soil Information Viewer, 2014).

Each block, 28 m X 11.2 m in size, was divided into two split-plots that were randomly assigned to either 25 individuals of Walker or Okanese (Appendix 3.1). Trees were hand-planted in each split-plot at 2.8 m grid spacing in a 5 X 5 configuration, which included an outside buffer row that was not sampled (Appendix 3.1). Within the interior portion of each split-plot (i.e. 3 x 3 grid), the six most uniform trees were randomly assigned to six vegetation control treatments as follows:

(1) No removal of vegetation as the control treatment (NR; no removal),

(2) Removal of aboveground vegetation close (0-50 cm) to the tree bole (AC; aboveground - close),

(3) Removal of aboveground vegetation far (50-140 cm) from the tree bole (AF; aboveground - far),

(4) Complete removal of aboveground vegetation from 0-140 cm (AT; above & belowground - total),

(5) Removal of above- and belowground vegetation close (0-50 cm) to the tree bole (BC; above & belowground - close), and

(6) Removal of above- and belowground vegetation far (50-140 cm) from the tree bole (BF; above & belowground - far).

3.2.3 Application of treatments

To isolate spatial relationships among trees and neighboring vegetation, the various combinations of competition control took place at a 140 cm basic radius around each tree, further divided into the soil zone near the tree (0-50 cm) and soil zone far from the tree (50-140 cm). Removal of aboveground vegetation at each respective soil zone was achieved manually using a hand-held weed whacker to trim aboveground parts of vegetation down to ground level. Resulting litter was left evenly distributed across the respective treatment area. For the removal of both above- and belowground vegetation, hand application of a 10% glyphosate solution was used in combination with the installation of plastic root exclusion barriers. Herbicide was applied during the early morning using hand spray bottles while shielding trees to minimize drift. Root exclusion barriers (150 µm thick clear plastic) were installed in summer 2011 at 50 cm distance from the tree bole to a depth of 15 cm in the last two treatments (i.e. the belowground close and far treatments); barriers prevented root incursion from adjacent uncontrolled vegetation into areas where above- and belowground vegetation was removed. Vegetation control started in June

2011 for all treatments and was repeated periodically (e.g. monthly or as needed), throughout the growing seasons of 2011, 2012 and 2013.

3.2.4 Data collection

3.2.4.1 Hybrid poplar growth, survival and damage

Initial height and basal diameter were measured on the experimental trees in July 2011 shortly after planting. To facilitate repeated sampling of diameter at the same location, stems were marked with a permanent marker at 3 cm height above ground. Total tree height and diameter were measured again for all living experimental trees at the end of the first, second, and third growing season between late September and late October of 2011, 2012, and 2013, respectively. Height was measured with a meter stick from ground level on straightened trees. Basal diameter was measured with a digital caliper to an accuracy of two decimal places and taken in two directions (N-S and W-E), which were then averaged prior to analysis. In the case of the 2011 growing season, height and diameter growth increments were calculated as the difference between the initial and the fall measurements; for 2012 and 2013 increments were calculated as the difference between fall measurements of two consecutive years. Tree survival was recorded at the end of each growing season. Tree survival was calculated for each clone and treatment combination and expressed as a percentage of the original total number of living trees across all 18 blocks. Dead trees were excluded from analysis of tree diameter and height increment.

3.2.4.2 Herbaceous understory cover and composition

Herbaceous understory vegetation was assessed at the end of the second growing season (2012) for all living experimental trees. Sampling was carried out in all four cardinal directions around each tree using a belt transect with two contiguous quadrats along a 100 cm long transect

(Appendix 3.1). Quadrats (25 cm wide x 50 cm long) represented two sampling distances, 0-50 cm, and 50-100 cm from the tree base, and coincided with the near and far treatments, respectively. Within each quadrat, all vascular plant species were identified and percent cover (0-100) of above-ground parts of each species was visually estimated in 5% intervals for estimates up to 20%, and in 10% intervals for estimates above 20%. Total cover per sampling quadrat could add up to more than 100% due to overlap of different plant species. For a list of all plant species identified in the study see Appendix 3.2. Species composition was further assessed by grouping plant species into one of the following four groups, based on growth form and life cycle: 1) annual forbs (including winter annuals and biennials), 2) perennial forbs, 3) annual grasses, and 4) perennial grasses. Total percent cover of neighboring herbaceous vegetation per tree was calculated as the average cover of each species and functional group of all eight quadrats per tree, and total percent cover per distance was calculated as the average of the four respective quadrats within each of the two sampling distances (close: 0-50 cm, and far: 50-100 cm).

3.2.4.3 Soil nutrient availability

Nutrient availability was quantified using Plant Root Simulator (PRS) probes containing ion exchange resin membranes (Western Ag Innovations, Inc., Saskatoon, Canada) that were installed in the second and third growing seasons (2012 and 2013, respectively). Four (out of six) blocks were randomly selected at each site and probes were inserted adjacent to the four treatment trees involving removal of aboveground competition. Thus, only the following treatments were assessed: 1) no removal of vegetation as the control treatment, 2) removal of aboveground vegetation near (0-50 cm) the tree bole, 3) removal of aboveground vegetation far (50-140 cm) from the tree bole; and 4) complete removal of aboveground vegetation from 0-140 cm. PRS-probes (each containing one anion and one cation probe) were vertically inserted into the soil at two different distances from the stem (25 and 95 cm) for each clone within each selected block, for a total of 192 PRS-samples (3 sites X 4 blocks X 4 treatments X 2 clones X 2 distances). At each distance, one pair of PRS probes was buried at each cardinal direction for a total of four pairs per distance and eight pairs per tree. Probes were installed approximately 12 cm deep before the first vegetation control treatment was applied, and left in place for 10 weeks in 2012 (June 18 to August 23), and for nine weeks in 2013 (May 21-24 to July 20). After removal from the soil, probes within each distance at a given tree were combined for analysis. All probes were cleaned with deionized water and shipped to Western Ag Innovations Inc. and analyzed for NO_3^-, NH_4^+, PO_4^{3-}, K^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Mn^{2+}, Al^{3+}, Fe^{2+}, Cu^{2+}, Zn^{2+}, B^+, Pb^{2+}, and Cd^{2+}. PRS-probe supply rates are reported as µg of nutrient/10 cm^2/burial length. Cd, Cu, and Pb were nutrients for which the majority of probe values were below the analytical method detection limit (MDL, µg/10cm^2/burial length), indicating the lowest value that is significantly greater than zero, and therefore these were not subject to statistical analysis. Further, the nutrients B and Al, as measured in 2013, were excluded from analysis due to incomplete displacement of these ions during probe regeneration for a subset of probes used in this study (Eric Bremer, Western Ag, personal communication, 2013).

3.2.4.4 Soil water content and soil temperature

Volumetric soil water content (%) was measured on August 18, 2012 and on June 05, July 04, and August 17, 2013, with a ML2x ThetaProbe soil moisture sensor attached to a HH2 moisture meter (Delta-T Devices, Cambridge, UK), at least two days after significant precipitation. Three equally spaced measures of soil moisture were taken at each of two distances from the tree bole (e.g. 25 cm and 95 cm) at random directions for all experimental trees. The three measurements at each distance were averaged prior to data analysis. Peak soil temperature (°C) was measured on July 24, 2012, and on June 02, July 24, and August 17, 2013, between 14:00 and 16:00 MDT, using a 450ATT digital soil thermocouple thermometer (Omega, Laval, PQ, Canada), following the same approach (i.e. sub-sampling intensity and location) used for soil moisture.

3.2.4.5 Photosynthetically active radiation

Photosynthetically active radiation (PAR; 400–700 nm) was measured on June 11 and July 04, 2013, using an 80 cm long sunfleck ceptometer (AccuPAR, Decagon devices, Inc., Pullman, USA). PAR was recorded during a two-hour period around solar noon during stable weather conditions (either clear sky or completely overcast). Four instantaneously taken measurements were averaged for each of three sampling locations for all experimental trees, including measurements: 1) above the tree and weed canopy for an unobstructed sky view, 2) above the weed canopy at the mid crown of the tree for a measure of the tree impact on the surrounding understory, and 3) outside of the tree canopy but within the weed canopy at the vertical midpoint of the shaded portion of the tree crown to measure the effect of competing vegetation in reducing light for the affected portion of the tree canopy. To compare between sampling periods of differing weather conditions and growth, the relative PAR transmittance (%) of each sampled vegetation layer was calculated as a proportion of the PAR measure taken above the plant canopy.

3.2.4.6 Soil properties

Ten soil cores were randomly taken across all six blocks per site in August 2012, and each core was split into two depths of 0-15 cm and 15-30 cm. Prior to analysis, all sub-samples within a depth and site were combined into one composite sample and stored frozen. Samples were analyzed by the Natural Resources Analytical Laboratory at the University of Alberta, Edmonton, Canada for texture (Sand >50 µm, Clay <2 µm, and Silt 2-50 µm, %, hydrometer method), pH, electrical conductivity (EC, µs/cm, pH conductivity meter), organic matter (%, loss on ignition), total nitrogen (%), ammonium and nitrate (mg/kg air dried soil, colorimetrically on a SmartChem Discrete Wet Chemistry Analyzer).

3.2.5 Statistical analysis

Statistical analyses were performed using “R” software (R Development Core Team 2012) and SAS 9.2 (SAS Institute Inc., Cary, NC). We conducted mixed-model analyses of variance (ANOVA) using the SAS procedure for mixed models (proc MIXED) to compare the effects of clone, vegetation control treatment, site and their interactions on basal diameter and height increments for each year. Initial tree basal diameter and height (June 2011) were included as a covariate to account for variation in tree size at the time of planting. Similarly, we used mixed-model ANOVAs to compare the effects of clone, vegetation control treatment, site and their interactions on total cover of the understory vegetation and cover of each functional group, relative transmittance of photosynthetically active radiation by the understory and by the tree canopy, volumetric soil moisture and soil temperature, as well as soil nutrient supply rates of total nitrogen, NO_3^--N, NH_4^+-N, PO_4^{3-}, K^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Mn^{2+}, Fe^{2+}, and Zn^{2+}. The model for all ANOVAs included vegetation control treatment (NR, AF, AC, AT, BF, BC), type of clone (Okanese, Walker), site (Lowland, Midland, Highland) and the interactions thereof as fixed factors, and block, the clone x block interaction and block nested within site as the random terms. All response variables were analyzed separately for each sampling time and sampling distance, where applicable.

Response variables were tested for the assumption of normality and equal variances using plots of residuals, and transformed when necessary. Data on percent cover of annual and perennial forbs were square-root transformed, perennial grass cover was log transformed, and the majority of soil nutrient supply rates were log transformed prior to analysis. Following significant effects of ANOVA tests, post-hoc pairwise comparisons were carried out applying a Bonferroni adjustment (α/ # of comparisons) to control the family-wise error rate. For example, pairwise comparisons among the six establishment systems used a Bonferroni-adjusted α-value of $\alpha_{adj}= 0.05/15= 0.003$.

3.3 Results

3.3.1 Hybrid poplar survival and growth

3.3.1.1 Survival

Both clones showed 100% survival after the first growing season in 2011 (Fig. 3.1). Survival remained high for Okanese poplar during the second and third years after planting, at 100% and 99%, respectively. Similarly, survival of Walker poplar was high (94%) through the second year after planting, but then dropped to 84% at the end of the third year (Fig. 3.1). Moreover, at the end of the third growing season, overall survival of Walker trees was more variable among treatments, ranging from 61% in the treatment removing above- and belowground vegetation close to trees, to 100% in the treatment involving above-ground vegetation removal far from trees (Fig. 3.1).

3.3.1.2 Diameter growth

Diameter growth increment was impacted by initial tree diameter in 2011 ($p= 0.001$), but not in subsequent years ($p> 0.12$) (Table 3.1), suggesting that longer-term diameter responses are reflective of the vegetation treatment effects rather than initial conditions of the young trees.

Significant effects of treatment ($p< 0.001$) and site ($p= 0.012$) on diameter growth were detected as early as the first growing season in 2011, even after adjusting for the effect of initial diameter (Table 3.1). The greatest diameter increment at that time was obtained in any treatment that included the control of aboveground vegetation close to trees (AC, BC, AT); all these treatments had greater diameter growth than treatments lacking any vegetation control (NR) and those involving any type of vegetation control beyond 50 cm (AF, BF) (Fig. 3.2). Further, diameter increment in the first growing season differed among sites ($p= 0.012$) with greater increments in the lowland than the midland site (Fig. 3.3).

In the second (2012) and third (2013) growing seasons clone ($p< 0.001$), treatment ($p< 0.001$), and site ($p< 0.03$) had significant effects on diameter increment (Table 3.1). Furthermore, significant site x clone and clone x treatment interactions for diameter increment in the second and third growing season indicated that the vegetation control and site impacts on diameter increment differed by clone (Table 3.1). Overall, Okanese poplar outperformed Walker poplar in diameter growth across all treatments and sites during the second and third growing seasons (Figs. 3.2 and 3.3). Moreover, significant differences were found among sites and treatments for Okanese, whereas no differences were found for Walker. Okanese grew significantly better on the midland site compared to both the lowland and upland during each of the second and third growing seasons (Figure 3.3). Moreover, diameter increment of Okanese differed significantly among treatments during this time. At the end of the second growing season, the greatest diameter growth was obtained in the treatment controlling above- and belowground vegetation close to trees, while the least growth was found in those trees lacking any vegetation control (Figure 3.2). However, treatments that included belowground vegetation control either near or far from the tree tended to result in greater diameter growth than those limited to aboveground removal only, although this benefit was similar to that provided by the removal of all aboveground vegetation out to 140 cm. While these patterns generally held true during the third and final year of monitoring (Figure 3.2), one important change from the year prior occurred in that trees experiencing removal above- and belowground vegetation close to the bole had poorer diameter growth compared to the removal of above- and belowground vegetation far from the tree (Figure 3.2). Treatments that controlled aboveground vegetation near or far from the tree continued to have the lowest diameter growth, although the former led to a slight diameter increase relative to the untreated control.

3.3.1.3 Height growth

Significant clone x treatment interactions on height increment in the first (2011, $p = 0.014$) and second (2012, $p = 0.036$) year after planting demonstrated that the two clones responded differently to the vegetation control treatments (Table 3.1). Height increment of Okanese trees did not differ among treatments during the first growing season (2011), while differences became evident during the second year (2012) (Fig. 3.4). In 2012, height increment of Okanese poplar was greater ($p < 0.003$) in the treatments involving above- and belowground vegetation removal at either distance (BC, BF) and the treatment with complete aboveground vegetation removal (AT) as compared to the control (NR) and the treatment using aboveground removal far from trees (AF); height increment in the AC treatment was intermediate (Fig. 3.4). Differences among treatments in height increment for Walker poplar were significant at the end of the first year after planting, with complete aboveground vegetation removal (AT) resulting in greater height increments compared to all other treatments, except the treatment removing aboveground vegetation close to trees (AC) (Fig. 3.4). Contrary to the Okanese clone, no differences in height increment were found at the end of the second year for Walker poplar (Fig. 3.4). Height increment for the third and final year of monitoring (2013) differed among treatments ($p < 0.001$) and between clones ($p < 0.001$) but there were no significant interactions (Table 3.1). Height increment was greater in plots receiving aboveground or above- and belowground control far from the bole, and those with all aboveground vegetation controlled out to 140 cm, and no differences were found among them, compared to those with belowground control close to trees (Fig. 3.4). Notably, the treatment with no control remained similar in height growth to all treatments except the treatment where all aboveground vegetation was removed, with the latter exhibiting greater height increment. Further, Okanese outperformed Walker across all treatments in 2013 (data not shown).

Additionally, height increment differed among sites in the first ($p = 0.044$) and second ($p = 0.008$) growing season, with greater increments in the lowland than the midland site in 2011, whereas the opposite was true in 2012 (data not shown). Initial tree heights from spring measurements in 2011 were significant ($p < 0.05$) covariates for the first two growing seasons after planting (2011 and 2012) but not for the third season (2013) (Table 3.1).

3.3.2 Understory vegetation

Understory vegetation was largely affected by the vegetation control treatment effect (Table 3.2). Total understory cover (e.g. averaged across the two sampling distances 0-100 cm) at the end of the second growing season (2012) ranked among the six vegetation control treatments in the following order: BC < BF < AC < AT < AF < NR although the belowground control treatments did not differ from one another, and neither did the last two (for complete statistical differences see Table 3.3). Total understory cover differed significantly ($p < 0.001$) among treatments, varying from 21% in the BC treatment to 37% in the NR treatment (Table 3.3). Both the BC and BF treatments involving above- and belowground vegetation control using herbicides, resulted in lower ($p< 0.003$) total cover than in any other treatment; understory cover herein was on average 11% lower compared to treatments involving mechanical control of aboveground vegetation only (AC, AC, AT), and 15% lower than the control treatment (NR) (Table 3.3). Interestingly, no differences in total understory cover were found when comparing two of three treatments involving aboveground vegetation removal (AF, AT) with the control (NR) (Table 3.3). For total understory cover close to trees (0-50 cm) the treatments ranked in the following order: BC < AC < AT < NR < BF < AF (Table 3.3). Understory cover at this distance was significantly lower ($p< 0.003$) in the treatment using chemical removal of above- and belowground vegetation (BC) compared to any other treatment (Table 3.3). Notably, understory cover in the BC treatment was on average 20% lower compared to the two other treatments involving mechanical removal of aboveground vegetation (AC, AT), and 27% lower than in the three treatments without any vegetation removal close to trees (Table 3.3). For total understory cover far from trees (50-100 cm) the treatments ranked in the following order: BF < BC < AC < AT < AF < NR (Table 3.3). Understory cover was once again lowest ($p< 0.003$) in the treatment using chemical vegetation removal at this distance (BF); cover was on average 24% lower here than in any other treatment, and almost no differences were found among the other treatments (Table 3.3). Total understory vegetation cover also differed among sites ($p= 0.002$) (Table 3.2), and was on average 13% lower at the highland site compared to both the lowland and midland sites, mainly reflecting a lower cover of perennial forbs (data not shown).

Understory vegetation composition also differed among the vegetation control treatments at the end of the second growing season, primarily reflecting treatment effects on perennial plant species (Table 3.3). The relative proportion of plant functional groups differed when comparing the treatments involving both above- and belowground control using herbicides (BC, BF) at distances close and far from the tree bole with all other treatments. The BC and BF treatments resulted in the lowest relative proportion of perennial grasses close and far from the tree bole, respectively, compared to all other treatments (Table 3.3). Interestingly, the treatments that used mechanical removal of aboveground vegetation (AF, AC, AT) generally did not differ in the relative proportion of the different functional groups present compared to the control treatment, indicating that the latter treatments did not induce changes in species composition (Table 3.3).

3.3.3 Resource availability

Overall transmittance of available PAR by the understory vegetation to the shaded tree portion was high, ranging between 78% and 89% in June and between 71% and 99% in July of the third growing season (Table 3.4). Available PAR transmittance by the understory also differed among vegetation control treatments, both in June and July of 2013 (Table 3.4). PAR transmission by the understory during the early-season was greater in the BC treatment that removed all vegetation using herbicides, compared to any of the other treatments, except the control (Table 3.4). Interestingly, no differences were found among any of the other treatments suggesting that neighboring vegetation in the treatments lacking removal did not reach heights capable of shading trees early in the growing season (Table 3.4). However, later in the season (e.g. July) treatments that controlled vegetation close to trees (AC, AT, BC) resulted in an average of 22% higher PAR transmittance compared to two of the three treatments lacking near-bole vegetation removal (NR and AF); the BF treatment did not differ from either the AC or AT treatments (Table 3.4). PAR transmission by the tree canopy to the understory vegetation also differed among treatments (Table 3.4). Trees transmitted the least light to the understory in the BF treatment, while trees growing in the control transmitted the most light, both in June and July (Table 3.4). In general, the AC, AT and BF treatments resulted in less light being transmitted to the understory compared to the control (NR) early in the growing season, while later on only the BF treatment was capable this. Furthermore, the two clones differed in the amount of light transmitted to the understory, with Okanese transmitting on average 14% and 13% less light to neighboring vegetation than Walker during the early ($p<0.001$) and mid-season ($p<0.001$), respectively (data not shown).

All measured environmental belowground attributes, including soil temperature, soil moisture and soil nutrient supply rates, were largely affected by the site and treatment effects (Table 3.2). While the lowland and midland sites were largely similar with regard to texture, pH, EC, and organic matter content, both of these differed markedly from the highland site (Table 3.5). Both lowland and midland sites had soils with a higher percentage of silt and clay particles (e.g. finer soils) in comparison to the highland site (Table 3.5). Similarly, pH, organic matter and nitrogen values were greater within both the lowland and midland compared to the highland (Table 3.5). For a detailed summary of means of measured soil characteristics for each site and soil depth see Table 3.5.

Soil temperatures differed ($p< 0.001$) among vegetation control treatments during all sampling times (Tables 3.4 and 3.6). Monthly vegetation removal significantly increased soil temperatures with temperatures being on average 2 °C warmer directly within zones where vegetation was removed compared to zones without vegetation removal, regardless of removal method (Tables 3.4 and 3.6). Soil temperatures were always lowest in the control treatment and consistently highest in the zone where the treatment had removed above- or belowground vegetation, either mechanically or using herbicides, indicating that either removal treatment is capable of increasing bare soil and facilitating soil warming (Tables 3.4 and 3.6). Soil temperatures also differed among sites during all sampling periods, with the highland site showing greater temperatures than both the lowland and midland sites; and no differences were found between the latter two sites during most sampling times (Table 3.7). Differences among sites were large with the highland showing an average of 6 °C greater temperature in August 2012 than the midland and lowland sites (Table 3.7).

Moreover, soil moisture levels differed ($p < 0.04$) among vegetation control treatments during all sampling times at the tree base (25 cm from trees) (Table 3.4), and during August 2012 and July 2013 at the distance further from trees (95 cm from trees) (Table 3.6). Soil moisture content close to trees was greater in the BC treatment (chemical removal of above- and belowground vegetation) than the NR during two of the four sampling times, and lower than the NR at one other time (Table 3.4). Notably, outside of the BC treatment, no differences were found among the other treatments during all sampling times (Table 3.4). In August 2012 moisture levels at the 95 cm distance from trees were greatest in the BF treatment but this was not different from the control treatment (Table 3.6). In contrast, moisture content in the AF and AT treatments were lower than that of the control at that time. By July 2013 soil moisture was lower in the BF treatment compared to the control, with no further differences evident among the other treatments (Table 3.6). Similar to site differences in soil temperature, volumetric soil moisture differed among sites during all sampling times of the second and third growing season (Table 3.7). Soil moisture levels ranged between 16% on the highland site and 29% on both the low- and midland, during the middle portion of the third growing season (2013) (Table 3.7). The lowland and midland sites both showed an average of 11% greater ($p < 0.003$) soil moisture content compared to the highland (Table 3.7).

Supply rates for the majority of nutrients differed among vegetation control treatments during both sampling years (Tables 3.4 and 3.6). Availability of these nutrients was greater in soil zones where aboveground vegetation was mechanically removed compared to zones without vegetation removal (Tables 3.4 and 3.6). This trend applied to both sampling distances, with nutrient availability being greatest in the AC and AT treatments close to trees (Table 3.4), and in the AF and AT treatments far from trees (Table 3.6), compared to the treatments without vegetation removal within the same soil sampling zone. Overall, the greatest difference in the nutrient supply rates among treatments was between complete vegetation removal (AT) and the control treatment (NR) (Tables 3.4 and 3.6). Furthermore, differences among treatments and distances were more pronounced in 2012 (when trees were younger) compared to 2013 (when trees were older) (Tables 3.4 and 3.6).

Nutrient supply rates also differed among sites ($p< 0.01$) for the majority of nutrients tested in this study during the second and third growing season after planting (Table 3.7). Differences in nutrient supply rates among sites were largest when comparing the lowland and midland sites with the highland site (Table 3.7), paralleling differences found among sites for soil texture, pH and organic matter content (Table 3.5). Total N supply rate, with NO_3^--N being the principal nitrogen form available, did not differ among sites in either sampling year; however, NH_4^+-N supply rates differed among sites in 2012 ($p= 0.001$) (Table 3.6). NH_4^+-N was lower ($p< 0.003$) on the lowland site compared to both the midland and highland in 2012 (Table 3.7). Supply rates also differed among sites for Mg ($p< 0.001$), K ($p< 0.001$), P ($p< 0.001$), Fe ($p< 0.001$), Mn ($p< 0.040$), and S ($p< 0.001$) in both 2012 and 2013, and additionally for Ca ($p< 0.001$), Zn ($p= 0.007$), and B ($p< 0.001$) in 2012 (Table 3.7). No differences among sites were found for any of the other nutrients (Table 3.7).

3.4 Discussion

3.4.1 Tree growth differences among vegetation control treatments

Hybrid poplar productivity was greatly improved by the control of competing vegetation and highlights the importance of weed control measures for improving tree growth on typical planting sites containing diverse herbaceous weed species, similar to those tested in our study. Notably, our results revealed marked differences in the effectiveness of vegetation removal methods targeting near-bole (0-50 cm) versus far-bole (50-100 cm), and above- (i.e. partial) versus belowground (i.e. complete: above- + belowground) control (Appendix 3.3). Further, our results showed that neighboring vegetation suppression effects on tree performance varied over time since tree planting (Appendix 3.3).

We observed that first year tree growth was improved through selective in-row vegetation control close to trees, regardless of whether vegetation removal was achieved aboveground (i.e. mechanically) or above- and belowground (i.e. chemically). Of particular note was that no further improvements in tree growth were observed by adding control of vegetation farther from the tree bole, while between-row vegetation control (i.e. far from trees) and the control (no vegetation removal) resulted in poorer tree growth at the end of the first year. Similarly, results from the second year indicated that near-bole vegetation control led to increased poplar diameter growth compared to far-bole control efforts.

The initial importance of controlling vegetation near the tree bole (above- or belowground), as shown in 2011 and 2012, reflects the high resource requirements of hybrid poplars during the early establishment period and the strong competitive effects of nearby vegetation. The specific mechanism for this improved early growth remains unclear, however, the similar impact of above and above- and belowground vegetation control near the tree stem suggests at least a portion of the benefit to young trees may have been through increases in light associated with canopy removal. Moreover, although continued presence of live herbaceous roots within the AC and AT treatments would be expected to maintain uptake of water and nutrients, our results indicated greater soil moisture following nearby vegetation removal occurred only from herbicides, which would conserve water by entirely eliminating herbaceous roots. We also are unable to rule out the benefit of increased nutrient availability however, as mechanical suppression of aboveground vegetation markedly increased nutrient supply compared to the non-treated control.

Interestingly, our findings suggest that, unlike conventional (i.e. business-as-usual) plantation management at this time, between-row control of neighboring herbaceous vegetation did not appear to enhance tree growth in the first two years after tree planting. Instead, greater benefits would be afforded by concentrating weed control efforts on the suppression (either before planting, or after planting) of vegetation likely to occupy areas immediately surrounding the stems of newly planted poplar trees, similar to findings by Davies (1988) and Thomas et al. (2001). In contrast, results from the third and final year of monitoring showed that removal of above- and belowground vegetation close to the tree bole did not necessarily result in the best tree performance; instead, tree growth tended to be maximized when aboveground vegetation was controlled out to a distance of 140 cm from the bole. This finding suggests that the competitive effects of neighboring vegetation is shifting from near the tree to further away (i.e. beyond 50 cm) two years after planting, which in turn, would necessitate between-row control of vegetation at that time. This finding may reflect the fact that larger trees may be expected to extend their root systems out further from the tree (Friend et al., 1991), which would then be susceptible to direct competition for resources, particularly from highly competitive species such as perennial grasses.

Lower tree growth in the treatment involving near-bole control using herbicide may reflect tree responses to unintended herbicide damage, either through accidental application to trees themselves, or through root uptake following the translocation of glyphosate into the soil and subsequent exudation into the rhizosphere where it can be taken up by trees (Neumann et al., 2006; Tesfamariam et al., 2009). Reductions in growth and survival of poplar trees due to herbicide damage have been shown in other studies (i.e. Broeckx et al., 2012), revealing the challenge of using herbicide applications, particularly when applied close to trees and during the active growing season (e.g. after leaf-out). Herbicide applications in this study were done using manual application, representing a best case scenario for avoiding incidental herbicide contact with the trees, while industrial applications with commercial equipment may result in more unintended contact. Overall, our findings challenge current operational practices that strive for early between-row weed control, but do not eliminate neighboring vegetation near the tree bole (at any time) because of the risk of damaging tree branches and roots by cultivation equipment and herbicide damage.

Interestingly, our results also showed that tree growth was impacted by initial diameter and height only in the short-term. Initial diameter was found to be a significant covariate only in the first year and initial height was a significant covariate in the first two years after planting, indicating tree growth rapidly became a function of the vegetation control treatments tested rather than initial tree size. Thus, these results suggest that longer-term growth responses within commercial plantations can be primarily explained by ongoing silvicultural practices.

Importantly, our results also showed that the aforementioned treatment effects on tree growth differed markedly between the two hybrid poplar clones, despite the close relatedness of the clones (i.e. Okanese is the progeny of Walker). We observed clonal differences in tree growth as early as the second year after planting and differences in survival at the end of the third year. Okanese poplar demonstrated greater overall productivity across all three sites and additionally showed distinct increases in tree growth when released from competition, indicating that this clone was highly responsive to the vegetation control treatments tested. In contrast, Walker poplar had lower productivity, and did not typically respond to the vegetation control treatments evaluated, confirming results from chapter 2. Furthermore, we observed differences in tree survival between clones; survival of Okanese remained exceptionally high (99%) after three years, while survival of Walker decreased to 84% during this time. Interestingly, survival of Walker was lowest in the two treatments that used herbicide application to remove above- and belowground vegetation either close to or far from the trees. Although none of the treatment differences for survival of Walker poplar were significant, our data, in conjunction with damage assessments, indicate that accidental herbicide damage (particularly near the base of the tree stem) may have led to increased mortality of Walker poplar within these two treatments, raising the possibility that this clone is more susceptible to herbicide.

3.4.2 Understory vegetation

The use of herbicide (BC, BF) proved most effective in providing in-row and between-row control of understory vegetation in our study, a response similar to the findings by Coll et al. (2007) and Morhart et al. (2013). Notably, herbicide applications offered long-term control throughout each growing season, reflecting the high efficacy of frequent herbicide applications used in this study. In contrast, understory vegetation cover in the treatments comprised of mechanical vegetation control (AC, AF, AT) did not generally differ from the control that had no vegetation removal, based on vegetation assessments one month after the last treatment application. This finding highlights the rapid regrowth potential of herbaceous understory vegetation following aboveground mechanical control in this region, and ultimately, the relatively short-lived effects of mechanical control on competing vegetation, despite the high frequency of treatment applications. A similar short-term response of mechanical vegetation control was reported by Coll et al. (2007) and Siipilehto (2001). Notably, we did not find differences in vegetation regrowth between the two sampling distances (0-50 cm vs 50-100 cm), indicating that the use of a hand-held weed whacker allowed us to accomplish effective, though only short-term, vegetation control close to the tree stems. This is unlike conventional mowing treatments using operational sized equipment (e.g. tow-behind mowers) that generally fails to control near-bole vegetation (e.g. Coll et al., 2007) because equipment cannot access weeds growing close to tree stems without damaging the lower tree branches.

Our results also showed that the treatments involving repeated herbicide applications resulted in the lowest relative proportion of perennial grasses compared to all other treatments, thereby likely contributing to improved tree growth. Even a very low cover of perennial grasses has been shown to reduce hybrid poplar survival and growth (Henkel-Johnson, 2014; Kabba et al., 2007), as grasses effectively compete for available nutrient and water resources belowground through their rapid growth rate and fibrous root system (Balandier et al., 2006). It should be noted that vegetation cover assessments did not factor into vegetation height, which along with plant growth form, would significantly influence light transmission. In fact, our results indicate that vegetation did not differ with regard to transmitted light levels between the mechanical and herbicide treatments near the tree bole (see below).

The effectiveness of the above-mentioned control methods is known to depend on vegetation type; thus, it should be emphasized that vegetation in our study was exclusively herbaceous. Several studies have reported that while mechanical vegetation suppression may effectively suppress woody vegetation (Balandier et al., 2006), they are less able to control early successional and competitive herbaceous weeds (Coll et al., 2007; Siipilehto, 2001). Finally, it should be noted that near-bole herbicide application, as applied in our study, involves the risk of accidental herbicide damage to susceptible poplar trees (Broeckx et al., 2012). This is in accordance with our findings, highlighting the need to test innovative complementary weed control practices, with a special emphasis on developing effective near-bole weed control early in the rotation (Chapter 2).

3.4.3 Resource availability

Our results showed that mid-season (e.g. July) vegetation removal near the tree bole led to increased light levels, regardless of removal method, rendering those treatments (AC, AT, BC) most effective in reducing light competition and hence favoring the growth of highly shade-intolerant poplar trees early in the rotation (e.g. three years post-planting). Moreover, the treatment removing both above- and belowground vegetation close to trees resulted in the greatest light transmission, illustrating once again the effectiveness of repeated herbicide applications in suppressing vegetation regrowth (Morhart et al., 2013; Wagner et al., 2005). It should be noted that by the third year after planting transmittance of available PAR by the understory was high across all treatments, indicating that light competition between weeds and trees may have diminished to low and likely insignificant levels, as most trees had tended to reach heights sufficient to overtop neighboring weeds. Nevertheless, our results indicate that the lack of vegetation removal close to the base of trees was associated with increased shading of trees by the understory, even three years after planting. We therefore conclude that vegetation removal close to trees is of high importance to reduce light competition between weeds and trees, and favor rapid canopy development of young trees, especially during the first three years after planting.

This finding is of particular importance in the presence of tall-growing forbs that, due to their large leaf area, are able to compete efficiently with trees for light (Balandier et al., 2006). For example, vegetation in our study was highly dominated by annual, and more importantly, perennial forbs, particularly on the lowland and midland sites, including the tall growing forbs *Medicago sativa* (volunteer alfalfa), *Cirsium arvense* and *Artemisia biennis* (both noxious weeds). When left uncontrolled, these species were able to exceed the height of young poplar trees in the first years after planting, likely leading to reductions in light transmission to trees, similar to our findings three years post-planting. This observation corresponds with findings by Balandier et al. (2009) who reported on the effects of *Medicago sativa* and *Taraxacum officinale* in decreasing light transmission to a level that potentially caused tree seedlings to die.

A further environmental response to the vegetation control treatments included an increase in soil temperature, and this can be primarily explained by the removal of vegetation, regardless of removal method. The herbicide treatments in particular increased soil temperature towards the end of the third growing season; an expected response as we reported the highest efficiency understory vegetation suppression from these treatments, which in turn would have led to an increase in bare soil, and thus soil warming. Pinno and Bélanger (2009) also reported small increases in soil temperature when vegetation was completely removed. Higher soil temperatures may have contributed to accelerated mineralization of soil nutrients (Nyborg and Malhi, 1989), increased tree root activity, and consequently improved tree growth, while lower soil temperatures may have delayed growth of young trees, particularly early in the season (Hansen et al., 1986).

Similarly, patterns of soil nutrient availability in our study could be explained by the presence or absence of aboveground vegetation, suggesting that mechanical control of aboveground vegetation mitigated belowground competition for nutrients. We attribute this strong belowground response to the high frequency of our aboveground vegetation removal treatments, as aboveground trimming took place repeatedly throughout the growing season, which presumably led to some root dieback of weedy understory vegetation (Bicksler et al., 2012). Additionally, our results showed clear differences in soil nutrient levels between the untreated control and mechanical aboveground removal treatments, both during the second and third year after planting. In a similar study, Coll et al. (2007) did not find significant differences between these treatments. We attribute these contrasting results primarily to differences in the implementation of management practices; the mechanical treatment in our study was repeated periodically within a sampling distance (e.g. near-bole and/or far-bole) leading to significant reductions in aboveground vegetation cover compared to the control, whereas in the study by Coll et al. (2007), mowing was not maintained during the growing season and failed to show effects on understory vegetation cover close to trees, where soil nitrogen was assessed.

Although we did not test soil nutrient availability in the two treatments using herbicide to simultaneously control above- and belowground vegetation either close or far from trees (BC, BF), we assume a similar and even amplified response may have occurred under this more intensive herbaceous vegetation control method. Since the herbicide treatments led to near complete vegetation suppression throughout the growing season, and improved vegetation control compared to the mechanical control treatments, it seems reasonable to consider that the near-absence of roots from competing vegetation would have increased soil nutrient levels and subsequently increased availability for uptake by trees. Accordingly, Coll et al. (2007) showed increased soil nitrogen levels following control of above- and belowground vegetation using herbicide, which led to increased soil nitrogen availability compared to the treatment involving only aboveground vegetation removal by means of mowing, and consequently improved tree growth. Similarly, we observed enhanced tree growth in the herbicide treatment that removed vegetation far from trees; however, this response did not occur until the third year after planting, suggesting that the need to control belowground vegetation for mitigating nutrient competition appears to be important later in the establishment period.

3.5 Conclusion

Results from our hybrid poplar plantation study established in north-eastern Alberta indicate a spatial and temporal shift in resource competition between young poplar trees and the neighboring herbaceous understory vegetation. First and second year growth of hybrid poplar trees was distinctly improved when aboveground vegetation was controlled at locations close to the tree bole, while third year tree growth was enhanced through the removal of both above- and belowground vegetation further away (i.e. between-rows). Moreover, environmental data suggest that aboveground competition for light primarily limited tree growth in the initial years, while belowground competition, primarily for nutrients, tended to restrict tree growth more in subsequent years. We also found Okanese poplar consistently outperformed Walker poplar across all tested treatments, emphasizing its greater potential for deployment in SRIC plantations in the Canadian Prairies. Overall, our study highlights the need for effective control of near-bole vegetation to mitigate aboveground competition for light during the early establishment phase, whereas between-row control becomes necessary later on, primarily to mitigate belowground competition. Future work should address the need to develop practical operational methods to cost-effectively reduce or control vegetation near the tree bole without negatively impacting the tree itself.

3.6 Tables

Table 3.1 – Results from ANCOVAs examining the influence of site, clone, vegetation control treatment and their interactions on hybrid poplar growth variables, including diameter (DI) and height increment (HI) for the first (2011), second (2012), and third (2013) growing seasons after planting. Initial tree diameter and height (June 2011) were included as covariates; when covariate was not significant, analysis was rerun without the covariate. Significant effects are bolded ($p < 0.05$).

		2011				2012				2013			
		DI		HI		DI		HI		DI		HI	
Effects	DF	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Site	2	6.01	**0.012**	3.87	**0.044**	5.97	**0.012**	6.86	**0.008**	3.76	**0.047**	4.13	**0.037**
Clone	1	0.58	0.460	0.10	0.751	170.23	**<0.001**	70.72	**<0.001**	153.67	**<0.001**	48.44	**<0.001**
Site*clone	2	2.67	0.073	0.37	0.692	5.47	**0.005**	2.54	0.083	5.88	**0.004**	0.13	0.875
Treatment	5	9.27	**<0.001**	5.05	**<0.001**	13.68	**<0.001**	8.25	**<0.001**	16.35	**<0.001**	7.05	**<0.001**
Site*Treatment	10	0.90	0.531	1.69	0.090	1.44	0.168	0.82	0.610	0.79	0.634	1.35	0.213
Clone*Treatment	5	1.03	0.403	2.97	**0.014**	4.78	**0.001**	2.47	**0.036**	11.47	**<0.001**	1.65	0.152
Site*Clone*Treatment	10	0.37	0.956	1.80	0.065	0.40	0.943	0.59	0.823	1.06	0.399	1.28	0.247
Covariate	1	11.89	**0.001**	18.39	**<0.001**	not significant		4.14	**0.044**	not significant		not significant	

Table 3.2 – Results from ANOVAs examining the influence of site, clone, vegetation control treatment and their interactions on above- and belowground environmental attributes, including volumetric soil moisture, soil temperature, relative PAR transmittance, understory vegetation cover, and nutrient supply rates averaged across the two sampling distances for each sampling time during the second (2012) and third (2013) growing seasons after tree planting. Significant effects are bolded ($p < 0.05$).

	Site		Clone		Site * clone		Treatment		Site * treatment		Clone * treatment		Site * clone * treatment	
Variable	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
Volumetric soil moisture (%)														
August 2012	53.00	**<0.001**	0.49	0.495	4.39	**0.014**	4.98	**<0.001**	1.70	0.085	1.30	0.267	0.60	0.808
June 2013	65.59	**<0.001**	0.39	0.544	0.33	0.718	2.28	**0.049**	4.40	**<0.001**	2.51	**0.032**	1.11	0.357
July 2013	40.08	**<0.001**	0.96	0.342	0.38	0.685	8.56	**<0.001**	5.26	**<0.001**	1.20	0.313	0.91	0.529
August 2013	28.88	**<.0001**	0.40	0.536	1.38	0.256	2.05	0.076	1.24	0.269	2.21	0.057	0.83	0.605
Soil temperature (°C)														
August 2012	37.94	**<0.001**	0.10	0.754	1.98	0.141	12.21	**<0.001**	3.28	**0.001**	0.17	0.973	0.99	0.457
June 2013	56.75	**<0.001**	1.04	0.324	0.36	0.698	10.97	**<0.001**	1.79	0.067	0.69	0.633	0.42	0.937
July 2013	62.45	**<0.001**	0.62	0.444	1.23	0.297	34.78	**<0.001**	4.98	**<0.001**	0.57	0.719	1.35	0.207
August 2013	5.99	**0.012**	0.13	0.727	1.48	0.231	54.32	**<0.001**	3.48	**<0.001**	1.24	0.296	1.24	0.270
Relative PAR transmittance (%)														
through understory vegetation														
June 2013	5.14	**0.020**	1.82	0.198	2.06	0.131	5.43	**<0.001**	1.64	0.103	0.78	0.564	0.81	0.622
July 2013	0.84	0.450	8.55	**0.011**	1.18	0.311	29.54	**<0.001**	7.25	**<0.001**	1.80	0.118	0.44	0.927
through tree canopy above understory														
June 2013	8.15	**0.004**	90.86	**<0.001**	0.16	0.849	5.70	**<0.001**	0.51	0.881	2.20	0.059	0.48	0.903
July 2013	0.30	0.743	39.43	**<0.001**	1.24	0.294	2.46	**0.037**	2.61	**0.007**	2.06	0.076	1.07	0.390
Understory vegetation cover (%)														
at 0-100 cm distance to trees														
Total cover	9.40	**0.002**	0.23	0.636	0.98	0.377	24.97	**<0.001**	2.80	**0.003**	0.19	0.966	0.40	0.944
Annual forb cover*	1.70	0.216	0.50	0.490	0.10	0.909	10.70	**<0.001**	2.36	**0.013**	0.22	0.952	1.33	0.221
Perennial forb cover*	33.26	**<0.001**	5.44	**0.034**	6.89	**0.001**	12.12	**<0.001**	1.48	0.152	0.49	0.784	0.43	0.931
Perennial grass cover**	0.18	0.834	0.83	0.376	2.10	0.126	7.20	**<0.001**	2.09	**0.028**	0.98	0.430	0.72	0.708

* square-root transformed for analysis of variance

** log transformed for analysis of variance

Table 3.2 continued

		Site		Clone		Site * clone		Treatment		Site * treatment		Clone * treatment		Site * clone * treatment	
Variable		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
Nutrient supply rates (µg of nutrient/10 cm^2/9 weeks)															
2012	Total N**	0.88	0.444	1.79	0.214	7.54	**0.001**	23.19	**<0.001**	2.09	0.057	1.18	0.320	3.99	**0.001**
	NO_3^-**	2.02	0.184	3.07	0.114	8.72	**<0.001**	22.21	**<0.001**	2.54	**0.023**	0.91	0.440	3.24	**0.005**
	NH_4^+	17.81	**0.001**	0.03	0.857	1.79	0.170	4.05	**0.009**	1.58	0.157	0.11	0.957	0.83	0.550
	Ca	30.06	**<0.001**	0.02	0.883	1.29	0.278	3.02	**0.032**	1.33	0.246	0.71	0.547	0.86	0.523
	Mg**	503.77	**<0.001**	0.24	0.635	0.82	0.443	0.28	0.838	1.76	0.112	0.22	0.883	0.43	0.861
	K**	62.29	**<0.001**	1.07	0.327	0.92	0.402	4.47	**0.005**	3.04	**0.008**	1.89	0.133	0.80	0.572
	P**	132.99	**<0.001**	0.10	0.763	1.16	0.315	7.16	**<0.001**	1.58	0.156	1.61	0.189	1.72	0.119
	Fe**	21.46	**<0.001**	1.82	0.211	2.09	0.128	22.09	**<0.001**	2.57	**0.022**	0.59	0.620	0.12	0.994
	Mn**	6.33	**0.017**	0.07	0.804	0.65	0.524	20.68	**<0.001**	1.55	0.166	0.15	0.927	0.11	0.995
	Zn**	8.63	**0.007**	0.30	0.600	0.18	0.839	19.26	**<0.001**	1.61	0.149	0.34	0.799	0.43	0.859
	S**	49.26	**<0.001**	2.64	0.139	1.57	0.212	22.31	**<0.001**	0.36	0.903	1.22	0.303	0.95	0.460
	B	23.40	**<0.001**	2.09	0.182	2.28	0.106	0.49	0.687	0.26	0.955	1.01	0.392	2.80	**0.013**
	Al	3.33	0.078	1.20	0.301	2.61	0.077	3.17	**0.026**	0.85	0.536	1.80	0.149	1.99	0.070
2013	Total N**	2.52	0.130	5.40	0.045	2.89	0.059	23.98	**<0.001**	2.38	0.032	0.02	0.996	1.97	0.073
	NO_3^-**	2.17	0.165	6.70	0.029	3.76	0.026	22.11	**<0.001**	2.24	0.042	0.09	0.967	1.59	0.153
	NH_4^+	5.94	**0.020**	0.92	0.363	0.42	0.658	3.66	**0.014**	1.32	0.251	1.58	0.197	1.48	0.190
	Ca	1.24	0.332	0.09	0.769	0.47	0.628	0.23	0.878	1.02	0.416	3.03	**0.031**	4.41	**<0.001**
	Mg**	153.22	**<0.001**	0.15	0.707	0.69	0.501	0.36	0.781	1.01	0.418	2.33	0.077	1.60	0.150
	K**	32.89	**<0.001**	0.24	0.633	0.18	0.838	11.42	**<0.001**	1.25	0.284	1.28	0.282	1.30	0.263
	P**	98.28	**<0.001**	0.59	0.463	1.26	0.287	6.17	**0.001**	0.76	0.603	1.00	0.395	0.84	0.542
	Fe**	21.19	**<0.001**	1.09	0.324	0.49	0.613	29.99	**<0.001**	1.08	0.374	0.08	0.969	2.78	**0.014**
	Mn**	4.94	**0.032**	3.20	0.107	0.37	0.691	14.41	**<0.001**	1.11	0.361	0.51	0.676	1.24	0.290
	Zn**	4.06	0.051	2.36	0.159	1.14	0.322	17.03	**<0.001**	1.26	0.280	0.86	0.465	2.37	**0.033**
	S**	31.93	**<0.001**	0.09	0.771	0.22	0.803	8.07	**<0.001**	0.92	0.485	1.30	0.275	1.74	0.116

** log transformed for analysis of variance

Table 3.3 – Summary of understory vegetation cover (%) – total cover and by functional group - in the six vegetation control treatments and at three distances to tree as sampled in mid-August during the second (2012) growing season after planting. Values represent mean percent cover ± standard deviation of 18 blocks per treatment. Different lowercase letters in rows indicate significant differences among treatments for a given distance (at Bonferroni adjusted αadj= 0.05/15= 0.003). Also given are results of ANOVAs showing effect of vegetation control treatment with significant effects bolded (at α= 0.05). Abbreviations: NR (no vegetation removal, control), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).

Understory vegetation cover (%)	Distance to tree (cm)	Vegetation control treatment						p-value for treatment effect
		NR	AF	AC	AT	BF	BC	
Total cover	0-50	33.9 (17.0)c	36.4 (14.6)c	24.8 (12.3)b	30.2 (14.0)bc	35.2 (19.2)c	7.9 (6.2)a	**<0.001**
Total cover	50-100	40.5 (17.8)c	36.9 (11.8)bc	34.8 (14.4)bc	35.9 (13.7)bc	11.9 (8.3)a	33.4 (14.4)b	**<0.001**
Total cover	0-100	37.2 (16.8)c	36.6 (12.1)c	29.8 (12.6)b	33.0 (13.3)bc	23.4 (9.7)a	20.6 (7.6)a	**<0.001**
Annual forb*	0-50	12.8 (5.7)b	17.7 (10.3)b	14.0 (9.4)b	16.6 (9.4)b	19.4 (12.1)b	3.9 (5.6)a	**<0.001**
Annual forb*	50-100	14.5 (7.1)b	18.3 (8.3)b	15.7 (8.8)b	19.1 (9.4)b	7.3 (8.1)a	15.3 (11.8)b	**<0.001**
Annual forb*	0-100	13.5 (5.6)bc	17.9 (8.6)c	14.8 (8.5)bc	17.8 (9.0)bc	13.3 (6.7)b	9.5 (6.8)a	**<0.001**
Perennial forb*	0-50	19.8 (16.4)c	16.6 (13.5)c	9.8 (8.1)b	11.9 (12.3)bc	14.8 (12.5)bc	4.1 (4.6)a	**<0.001**
Perennial forb*	50-100	24.1 (16.4)c	16.5 (10.6)bc	17.4 (13.2)bc	14.9 (11.6)b	4.4 (5.3)a	16.9 (12.8)bc	**<0.001**
Perennial forb*	0-100	21.9 (15.6)c	16.4 (10.8)bc	13.5 (10.1)ab	13.2 (11.5)ab	9.6 (8.0)a	10.4 (8.0)a	**<0.001**
Perennial grass**	0-50	1.5 (2.2)bc	2.3 (3.9)c	1.2 (2.2)bc	1.9 (4.4)bc	0.9 (2.4)ab	0.1 (0.5)a	**<0.001**
Perennial grass**	50-100	2.1 (2.8)b	2.4 (4.6)b	1.8 (3.9)b	2.1 (4.8)b	0.3 (1.1)a	1.2 (2.2)b	**<0.001**
Perennial grass**	0-100	1.7 (2.3)c	2.2 (4.1)c	1.3 (2.9)abc	2.0 (4.4)bc	0.6 (1.7)a	0.6 (1.3)ab	**<0.001**

* square-root transformed for analysis of variance

** log transformed for analysis of variance

Table 3.4 – Summary of above- and belowground environmental attributes for the six vegetation control treatments for each sampling time during the second and third growing seasons after tree planting for the sampling distance 25 cm from trees. Values represent mean ± standard deviation of 18 blocks per treatment for soil moisture and temperature and twelve blocks for soil nutrient supply rates. Different lowercase letters in rows indicate significant differences among treatments for each sampling time (at Bonferroni adjusted αadj= 0.05/15= 0.003 for soil moisture, soil temperature and PAR transmittance, and αadj= 0.05/6= 0.008 for nutrient supply rates). Also given are the results from ANOVAs showing the treatment effect with significant effects (p< 0.05) bolded. Abbreviations: NR (control, no vegetation removal), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).

Variable		NR	AF	AC	AT	BF	BC	p-value for treatment effect
Volumetric soil moisture (%)								
August 2012		18.2 (5.2)ab	17.1 (4.5)a	17.1 (4.8)a	16.6 (4.1)a	16.6 (3.9)a	19.0 (5.4)b	**<0.001**
June 2013		19.1 (5.8)a	19.1 (6.3)a	19.5 (6.2)ab	19.6 (6.2)ab	19.6 (5.8)ab	20.4 (6.3)b	**0.034**
July 2013		23.8 (7.5)b	23.9 (7.0)b	23.5 (7.4)b	23.9 (7.7)b	23.0 (6.2)ab	21.7 (6.1)a	**<0.001**
August 2013		17.3 (6.5)a	16.5 (6.2)a	17.8 (6.5)a	17.5 (6.8)a	16.3 (6.5)a	19.0 (6.8)b	**<0.001**
Soil temperature (°C)								
August 2012		22.7 (4.0)a	22.8 (3.8)a	24.1 (2.9)b	24.1 (3.1)b	22.8 (4.1)a	24.2 (3.0)b	**<0.001**
June 2013		23.6 (2.8)a	23.1 (3.1)a	25.0 (2.4)b	24.8 (2.6)b	23.2 (2.6)a	25.3 (2.3)b	**<0.001**
July 2013		21.0 (3.0)a	21.0 (2.9)a	23.6 (2.7)c	23.2 (2.9)c	22.2 (2.4)b	24.1 (2.1)d	**<0.001**
August 2013		19.6 (1.7)a	20.3 (1.8)a	22.7 (2.0)c	22.8 (2.1)cd	21.4 (2.1)b	23.4 (2.1)d	**<0.001**
Relative PAR transmittance								
through understory								
June 2013		83.5 (9.6)ab	78.4 (13.8)a	81.0 (12.4)a	81.7 (12.2)a	81.5 (12.3)a	89.3 (10.2)b	**0.001**
July 2013		71.1 (18.6)a	76.2 (18.6)a	92.0 (13.1)bc	95.4 (8.2)bc	88.3 (14.4)b	99.2 (4.7)c	**<0.001**
through tree canopy above understory								
June 2013		85.8 (9.5)c	83.2 (9.6)bc	77.9 (11.8)ab	77.1 (11.2)ab	75.4 (12.5)a	77.9 (11.4)ab	**<0.001**
July 2013		83.7 (14.4)b	82.7 (11.6)ab	79.5 (12.3)ab	79.3 (14.4)ab	70.0 (16.4)a	78.2 (13.5)ab	**0.037**
Nutrient supply rates (μg of nutrient/10 cm^2/9 weeks)								
2012	Total N*	16.4 (10.7)a	25.5 (14.7)a	60.5 (54.0)b	82.3 (76.3)b	N/A	N/A	**<0.001**
	NO_3^-*	13.3 (10.3)a	22.1 (14.3)ab	56.6 (53.2)bc	79.0 (76.0)c	N/A	N/A	**<0.001**
	NH_4^+	3.1 (1.4)	3.2 (1.4)	3.9 (1.8)	3.5 (1.1)	N/A	N/A	0.084
	Ca	2798.6 (580.7)	2766.8 (412.4)	2886.1 (537.3)	2908.8 (432.1)	N/A	N/A	0.283
	Mg*	263.0 (114.8)	264.1 (107.0)	261.5 (100.0)	263.0 (102.6)	N/A	N/A	0.762
	K*	31.5 (23.3)	31.8 (16.4)	38.8 (26.4)	39.8 (37.0)	N/A	N/A	0.110
	P*	10.7 (9.9)a	10.9 (8.7)ab	14.2 (12.9)bc	16.4 (16.5)c	N/A	N/A	**0.001**
	Fe*	25.3 (24.3)a	23.4 (16.0)a	96.3 (88.8)b	119.5 (125.1)b	N/A	N/A	**<0.001**
	Mn	1.9 (0.8)a	2.0 (0.7)a	4.6 (2.3)b	4.4 (1.6)b	N/A	N/A	**<0.001**
	Zn*	1.4 (0.6)a	1.3 (0.6)a	2.7 (1.7)b	3.1 (1.6)b	N/A	N/A	**<0.001**
	S*	118.8 (100.7)a	115.3 (96.9)a	205.4 (168.2)b	266.7 (260.2)b	N/A	N/A	**<0.001**
	B*	2.3 (1.0)	2.5 (1.1)	2.5 (1.1)	2.4 (1.1)	N/A	N/A	0.887
	Al	45.5 (16.3)	50.3 (18.4)	44.5 (15.6)	43.2 (13.0)	N/A	N/A	0.147
2013	Total N*	14.7 (15.7)a	31.2 (29.0)b	47.8 (62.1)b	96.8 (139.9)b	N/A	N/A	**<0.001**
	NO_3^-*	12.6 (15.8)a	27.4 (26.7)ab	45.2 (61.9)bc	94.3 (140.0)c	N/A	N/A	**<0.001**
	NH_4^+*	2.1 (0.6)a	3.9 (5.7)b	2.7 (0.7)ab	2.6 (0.8)ab	N/A	N/A	**0.003**
	Ca	2728.7 (258.8)	2678.6 (345.2)	2758.1 (284.4)	2634.2 (278.0)	N/A	N/A	0.397
	Mg	234.7 (89.5)	228.1 (86.9)	232.0 (79.4)	233.6 (79.5)	N/A	N/A	0.823
	K*	15.7 (11.9)a	20.0 (11.9)ab	18.5 (11.5)a	25.7 (15.2)b	N/A	N/A	**0.001**
	P*	15.9 (19.8)a	18.5 (21.5)ab	20.6 (23.8)bc	24.4 (32.2)c	N/A	N/A	**0.001**
	Fe*	34.6 (34.7)a	48.2 (63.0)ab	65.6 (60.3)b	120.2 (103.3)c	N/A	N/A	**<0.001**
	Mn*	2.7 (1.8)a	3.2 (2.4)ab	4.2 (3.2)bc	5.3 (3.7)c	N/A	N/A	**<0.001**
	Zn*	2.5 (1.0)a	3.0 (1.7)ab	3.3 (1.1)bc	3.9 (1.5)c	N/A	N/A	**<0.001**
	S*	137.8 (110.7)a	145.3 (139.5)a	172.8 (142.9)ab	232.2 (191.1)b	N/A	N/A	**0.003**

* log transformed for analysis of variance

Table 3.5 – Soil characteristics at two depths (cm) and three study sites (lowland, midland and highland). Values are based on analyses of bulked samples composed of ten sub-samples per site. N/A indicates missing data due to a laboratory error.

Soil variable	Soil depth (cm)	Lowland	Midland	Highland
Texture				
Sand (%)	0-15	24.7	26.0	59.3
	15-30	14.2	33.4	68.8
Clay (%)	0-15	24.9	21.1	9.1
	15-30	44.0	27.9	7.3
Silt (%)	0-15	50.4	53.0	31.6
	15-30	41.8	38.7	23.9
pH	0-15	6.7	6.8	6.4
	15-30	7.4	7.5	6.5
EC (µs/cm)	0-15	117	97	N/A
	15-30	148	88	38
Organic matter (%)	0-15	6.23	5.93	2.97
	15-30	3.85	2.76	1.92
Total N (%)	0-15	0.28	0.24	0.11
	15-30	0.12	0.10	0.07
NH_4-N (mg/kg)	0-15	2.59	2.09	1.66
	15-30	1.51	1.78	1.46
NO_3-N (mg/kg)	0-15	2.36	3.18	1.74
	15-30	0.79	0.32	0.82

Table 3.**6**– Summary of belowground environmental attributes of the six vegetation control treatments for each sampling time during the second and third growing season after tree planting for the sampling distance 95 cm from trees. Values represent mean ± standard deviation of 18 blocks per treatment for soil moisture and temperature and twelve blocks for soil nutrient supply rates. Different lowercase letters in rows indicate significant differences among treatments for each sampling time (at Bonferroni adjusted αadj= 0.05/15= 0.003 for soil moisture and soil temperature and αadj= 0.05/6= 0.008 for nutrient supply rates). Also given are the results from ANOVAs showing the treatment effect with significant effects ($p< 0.05$) bolded. Abbreviations: NR (control, no vegetation removal), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).

Variable		NR	AF	AC	AT	BF	BC	p-value for treatment effect
Volumetric soil moisture (%)								
August 2012		20.3 (5.7)bc	18.7 (4.6)a	19.0 (4.8)ab	18.7 (4.3)a	21.1 (4.8)c	18.8 (4.2)ab	**<0.001**
June 2013		21.6 (6.0)	22.1 (6.8)	22.1 (6.1)	22.0 (6.8)	22.3 (6.6)	21.9 (5.8)	0.540
July 2013		25.7 (7.0)b	25.7 (7.2)b	26.0 (7.3)b	26.8 (7.6)b	23.7 (6.0)a	25.6 (7.4)b	**<0.001**
August 2013		20.4 (7.2)	21.4 (6.9)	21.3 (7.2)	20.3 (7.2)	21.0 (6.9)	19.7 (7.1)	0.176
Soil temperature (°C)								
August 2012		22.8 (4.1)a	23.7 (3.5)b	23.2 (3.7)a	24.3 (3.5)b	24.5 (3.5)b	23.2 (3.7)a	**<0.001**
June 2013		23.0 (3.1)a	24.2 (2.4)b	23.1 (2.9)a	24.8 (2.8)b	25.7 (2.0)b	23.1 (2.7)a	**<0.001**
July 2013		20.9 (2.8)a	23.6 (3.3)b	21.3 (2.7)a	23.6 (3.2)b	24.7 (2.2)b	21.4 (2.7)a	**<0.001**
August 2013		19.3 (1.6)a	22.1 (2.3)c	20.4 (2.0)b	22.4 (2.0)cd	23.2 (2.5)d	20.2 (2.1)b	**<0.001**
Nutrient supply rates (µg of nutrient/10 cm^2/9 weeks)								
2012	Total N*	19.6 (13.1)a	53.8 (41.6)b	26.2 (15.9)a	68.0 (60.9)b	N/A	N/A	**<0.001**
	NO_3^-*	17.0 (13.2)a	50.7 (41.5)b	22.7 (15.7)a	64.4 (60.9)b	N/A	N/A	**<0.001**
	NH_4^+	2.8 (1.4)	3.1 (1.2)	3.5 (1.3)	3.6 (1.9)	N/A	N/A	0.113
	Ca	2918.7 (466.4)ab	2904.0 (525.4)ab	2790.4 (458.5)a	3075.8 (408.1)b	N/A	N/A	**0.011**
	Mg*	264.2 (106.3)	264.1 (109.0)	262.6 (99.7)	278.0 (103.9)	N/A	N/A	0.582
	K*	28.2 (20.3)	29.0 (14.0)	35.5 (29.9)	37.0 (29.7)	N/A	N/A	0.068
	P*	12.7 (11.9)	16.1 (16.5)	13.0 (11.7)	16.2 (17.5)	N/A	N/A	0.102
	Fe*	24.3 (21.8)a	91.8 (83.2)b	30.0 (26.0)a	101.5 (128.2)b	N/A	N/A	**<0.001**
	Mn*	2.0 (0.8)a	3.9 (1.7)b	2.2 (0.7)a	3.9 (1.9)b	N/A	N/A	**<0.001**
	Zn*	1.4 (0.9)a	2.5 (1.4)b	1.5 (0.7)a	2.7 (1.5)b	N/A	N/A	**<0.001**
	S*	120.0 (102.9)a	239.0 (216.5)b	134.0 (109.0)a	251.7 (232.0)b	N/A	N/A	**<0.001**
	B	2.5 (1.3)	2.7 (1.2)	2.3 (1.0)	2.6 (0.9)	N/A	N/A	0.612
	Al	49.0 (18.9)	52.1 (17.9)	45.1 (15.3)	48.7 (15.5)	N/A	N/A	0.305
2013	Total N*	23.7 (27.0)a	72.8 (39.2)b	29.9 (27.5)a	109.5 (119.1)b	N/A	N/A	**<0.001**
	NO_3^-*	21.1 (26.6)a	69.7 (39.1)b	27.3 (27.5)a	106.7 (119.2)b	N/A	N/A	**<0.001**
	NH_4^+	2.6 (0.8)	3.2 (2.4)	2.5 (1.0)	2.7 (0.9)	N/A	N/A	0.113
	Ca	2706.5 (326.4)	2766.2 (277.0)	2626.8 (267.6)	2722.0 (339.6)	N/A	N/A	0.146
	Mg*	236.3 (88.1)	223.4 (87.3)	232.5 (80.9)	235.7 (80.8)	N/A	N/A	0.669
	K*	16.0 (9.6)a	18.4 (11.5)ab	18.3 (12.1)ab	23.0 (14.7)b	N/A	N/A	**0.013**
	P*	15.6 (18.8)ab	24.1 (27.5)ab	17.6 (22.0)a	21.7 (28.6)b	N/A	N/A	**0.016**
	Fe*	36.0 (33.3)a	57.6 (39.2)b	37.8 (25.1)a	95.5 (78.4)b	N/A	N/A	**<0.001**
	Mn*	2.4 (1.5)a	3.7 (1.8)b	3.0 (2.4)ab	4.2 (2.5)b	N/A	N/A	**<0.001**
	Zn	2.3 (0.7)a	3.5 (1.5)b	2.7 (0.9)a	3.5 (1.1)b	N/A	N/A	**<0.001**
	S*	136.7 (122.6)a	167.6 (148.1)ab	139.8 (137.5)a	188.3 (133.6)b	N/A	N/A	**0.008**

* log transformed for analysis of variance

Table 3.7 – Summary of belowground environmental attributes for the three study sites (lowland, midland, and highland) for each sampling time during the second (2012) and third (2013) growing seasons after tree planting. Values represent mean ± standard deviation of six blocks per site for soil moisture and temperature and four blocks for soil nutrient supply rates. Different lowercase letters in rows indicate significant differences among sites for each sampling time (at Bonferroni adjusted αadj= 0.05/3= 0.017). Also given are the results from ANOVAs showing the site effect with significant effects (p< 0.05) bolded.

Variable		Lowland	Midland	Highland	p-value for site effect
Volumetric soil moisture (%)					
August 2012		21.2 (2.7)b	21.1 (2.3)b	13.1 (2.0)a	**<0.001**
June 2013		22.8 (1.6)b	26.3 (2.7)c	13.2 (2.8)a	**<0.001**
July 2013		28.9 (2.3)b	29.0 (2.6)b	16.3 (4.3)a	**<0.001**
August 2013		21.7 (3.4)b	24.3 (2.9)b	11.7 (4.3)a	**<0.001**
Soil temperature (°C)					
August 2012		22.6 (2.4)a	20.4 (1.7)a	27.6 (0.8)b	**<0.001**
June 2013		22.3 (1.4)a	22.8 (1.6)a	27.0 (1.4)b	**<0.001**
July 2013		21.8 (1.9)b	20.3 (1.5)a	25.6 (1.3)c	**<0.001**
August 2013		22.5 (2.1)b	22.0 (1.7)b	20.1 (1.9)a	**0.012**
Nutrient supply rates (μg of nutrient/10 cm^2/9 weeks)					
2012	Total N*	43.2 (55.7)	46.8 (53.0)	40.4 (31.5)	0.444
	NO_3^-*	39.1 (55.3)	44.0 (52.6)	37.3 (31.4)	0.184
	NH_4^+	4.3 (1.4)b	2.7 (1.5)a	3.0 (0.9)a	**0.001**
	Ca	3281.1 (321.6)c	2936.5 (282.2)b	2407.6 (362.3)a	**<0.001**
	Mg*	348.4 (30.8)b	317.8 (40.0)b	124.5 (19.5)a	**<0.001**
	K*	17.3 (5.5)a	26.2 (9.6)b	59.1 (29.6)c	**<0.001**
	P*	2.9 (1.6)a	9.3 (3.7)b	29.5 (12.1)c	**<0.001**
	Fe*	89.5 (98.8)b	87.4 (90.8)b	12.0 (5.3)a	**<0.001**
	Mn*	2.8 (1.6)a	4.0 (2.3)b	2.5 (1.0)a	**0.017**
	Zn*	2.1 (1.2)ab	2.8 (1.6)b	1.2 (0.7)a	**0.007**
	S*	262.9 (202.5)b	246.6 (145.1)b	27.3 (9.8)a	**<0.001**
	B*	2.8 (1.0)b	2.8 (1.0)b	1.8 (0.8)a	**<0.001**
	Al	38.8 (20.9)	56.7 (10.8)	46.4 (10.0)	0.078
	Cu**	0.6 (0.3)	0.7 (0.5)	0.1 (0.1)	N/A
	Pb**	1.1 (0.8)	1.0 (0.7)	0.1 (0.1)	N/A
	Cd**	0.1 (0.1)	0.04 (0.06)	0.1 (0.1)	N/A
2013	Total N*	56.2 (99.7)	62.5 (76.2)	39.7 (44.8)	0.130
	NO_3^-*	53.7 (99.6)	59.0 (76.1)	37.3 (44.7)	0.165
	NH_4^+*	2.5 (0.7)a	3.5 (3.7)a	2.4 (1.2)a	**0.020**
	Ca	2693.4 (307.6)	2609.4 (253.9)	2806.5 (298.7)	0.332
	Mg*	293.4 (31.1)b	279.4 (35.2)b	122.9 (19.0)a	**<0.001**
	K*	9.7 (4.2)a	19.6 (9.2)b	28.9 (13.7)c	**<0.001**
	P*	2.2 (1.8)a	6.9 (3.7)b	50.2 (19.0)c	**<0.001**
	Fe*	90.0 (82.1)b	71.8 (56.8)b	22.3 (20.3)a	**<0.001**
	Mn*	2.4 (1.7)a	4.6 (3.0)b	3.8 (2.5)ab	**0.032**
	Zn*	2.5 (0.9)	3.1 (1.4)	3.6 (1.4)	0.051
	S*	226.0 (127.2)b	231.1 (143.6)b	36.4 (9.9)a	**<0.001**
	B***	1.1 (0.8)	1.0 (0.8)	0.3 (0.3)	N/A
	Al***	16.5 (5.9)	11.9 (9.9)	15.6 (6.7)	N/A
	Cu**	0.7 (0.3)	0.8 (0.4)	0.5 (0.3)	N/A
	Pb**	1.8 (0.8)	1.2 (0.6)	0.3 (0.3)	N/A
	Cd**	0.04 (0.07)	0.1 (0.1)	0.00 (0.02)	N/A

* log transformed for analysis of variance

** excluded from statistical analysis because the majority of probe values were below the analytical method detection limit

*** excluded from statistical analysis due to incomplete displacement of these ions during probe regeneration

3.7 Figures

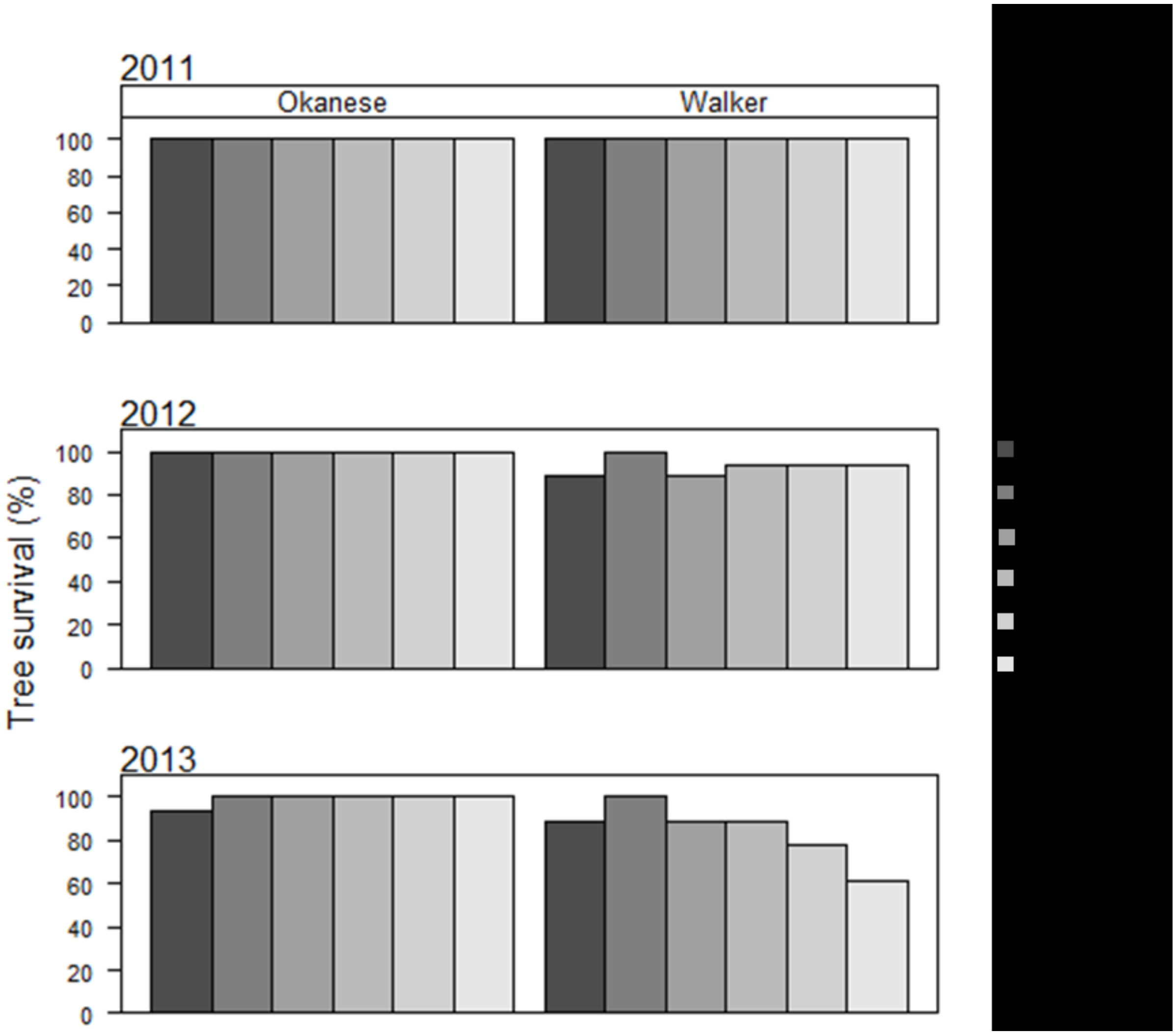


Figure 3.1 – Tree survival (%) as determined after the first (2011), second (2012), and third (2013) year following planting. For each clone and treatment, each value is the mean of 18 blocks. Abbreviations: NR (control, no vegetation removal), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).

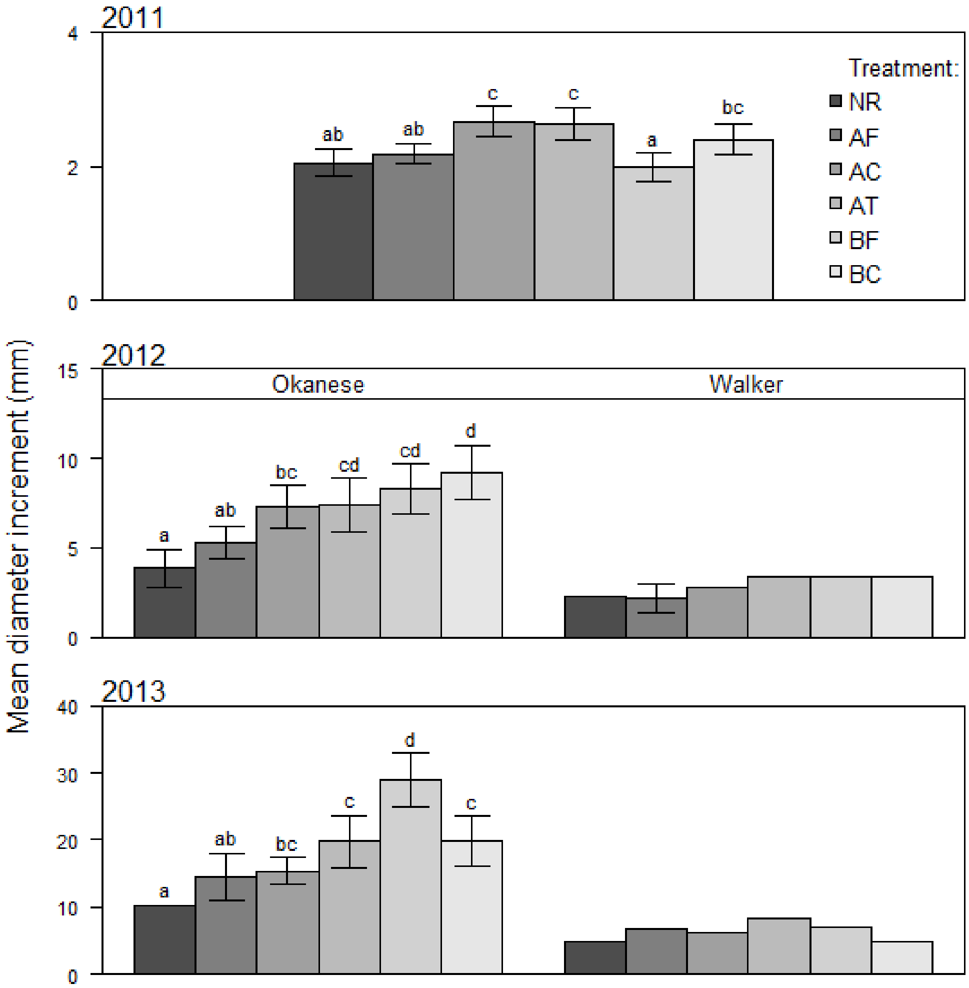


Figure 3.2 – Mean diameter increment (mm) of Okanese and Walker poplar trees during the first (2011), second (2012) and third (2013) growing seasons after planting for six vegetation control treatments. Error bars represent 90% confidence intervals. Different lowercase letters indicate differences among treatments averaged for both clones in 2011 due to the non-significant clone x treatment interaction ($p= 0.403$), and for Okanese poplar in 2012 and 2013 (at Bonferroni adjusted $\alpha adj= 0.05/15= 0.003$). No significant differences were found for Walker poplar. Abbreviations: NR (control, no vegetation removal), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).

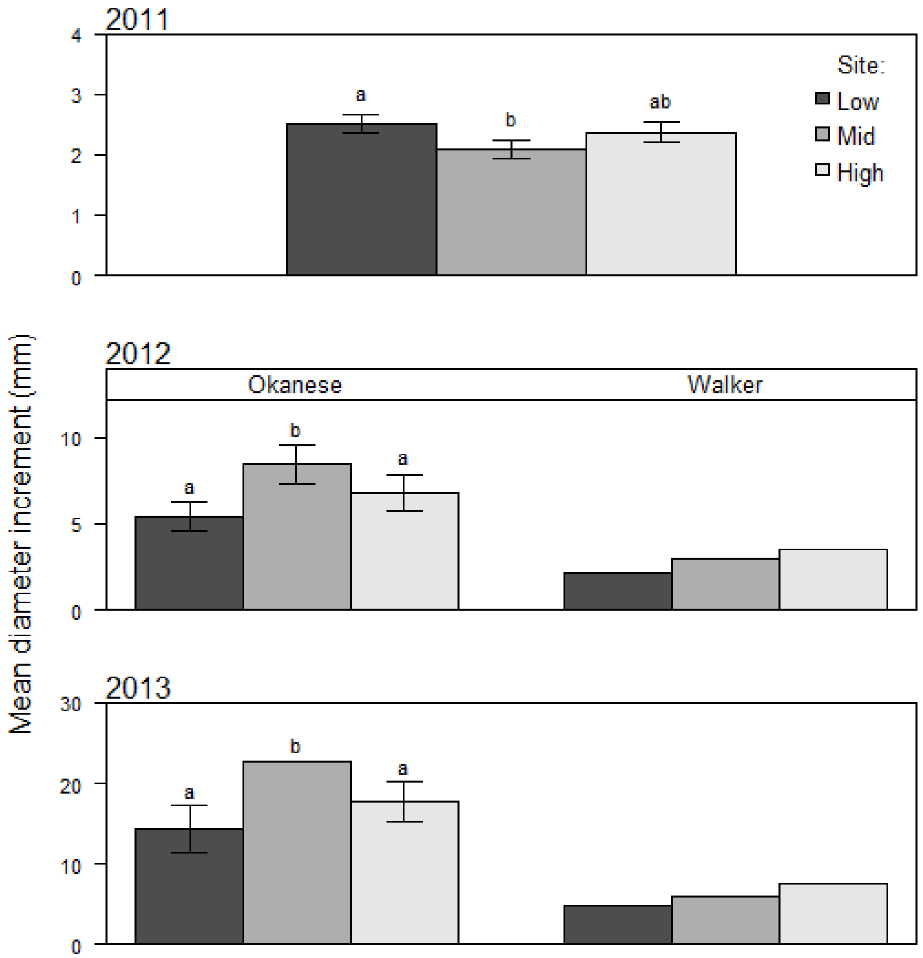


Figure 3.3 – Mean diameter increment (mm) of Okanese and Walker poplar clones at three different study sites during the first (2011), second (2012) and third (2013) growing season after planting. Error bars represent 90% confidence intervals. Different lowercase letters indicate differences among sites averaged for both clones in 2011 due to the non-significant clone x treatment interaction, and for Okanese poplar in 2012 and 2013 (at Bonferroni adjusted αadj= 0.05/3= 0.017). No significant differences were found for Walker poplar.

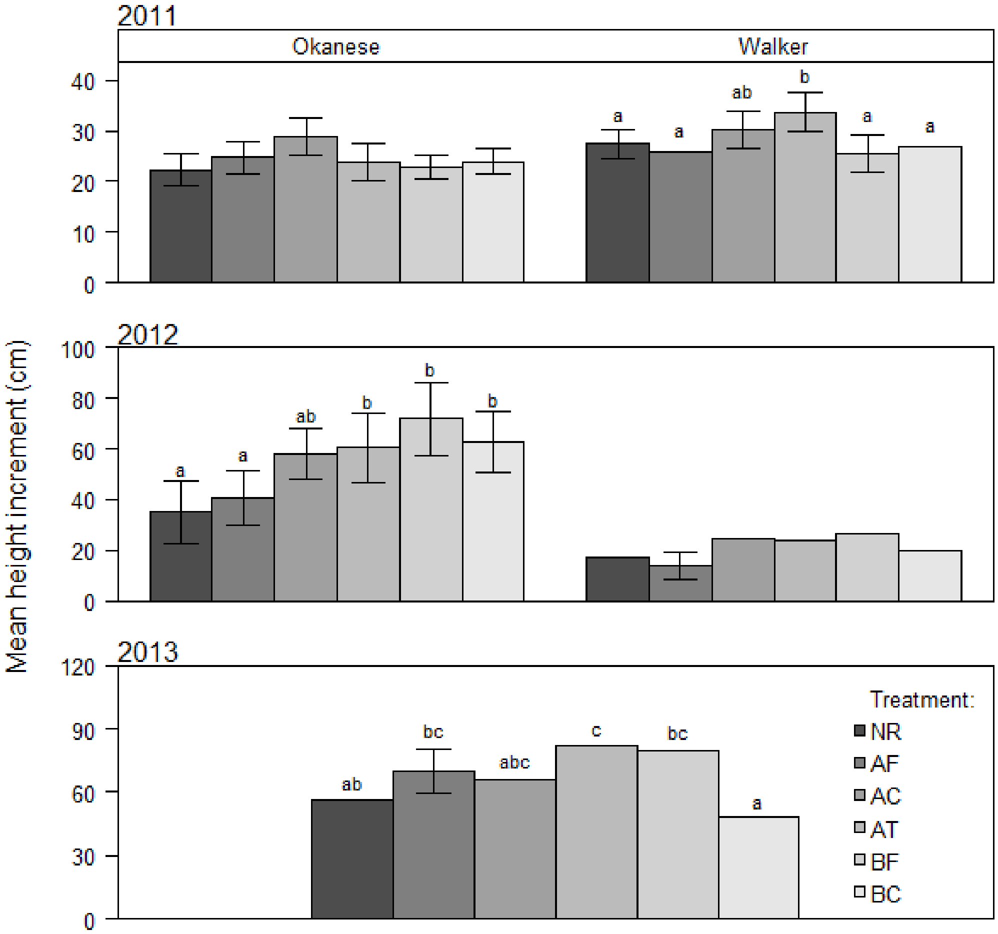
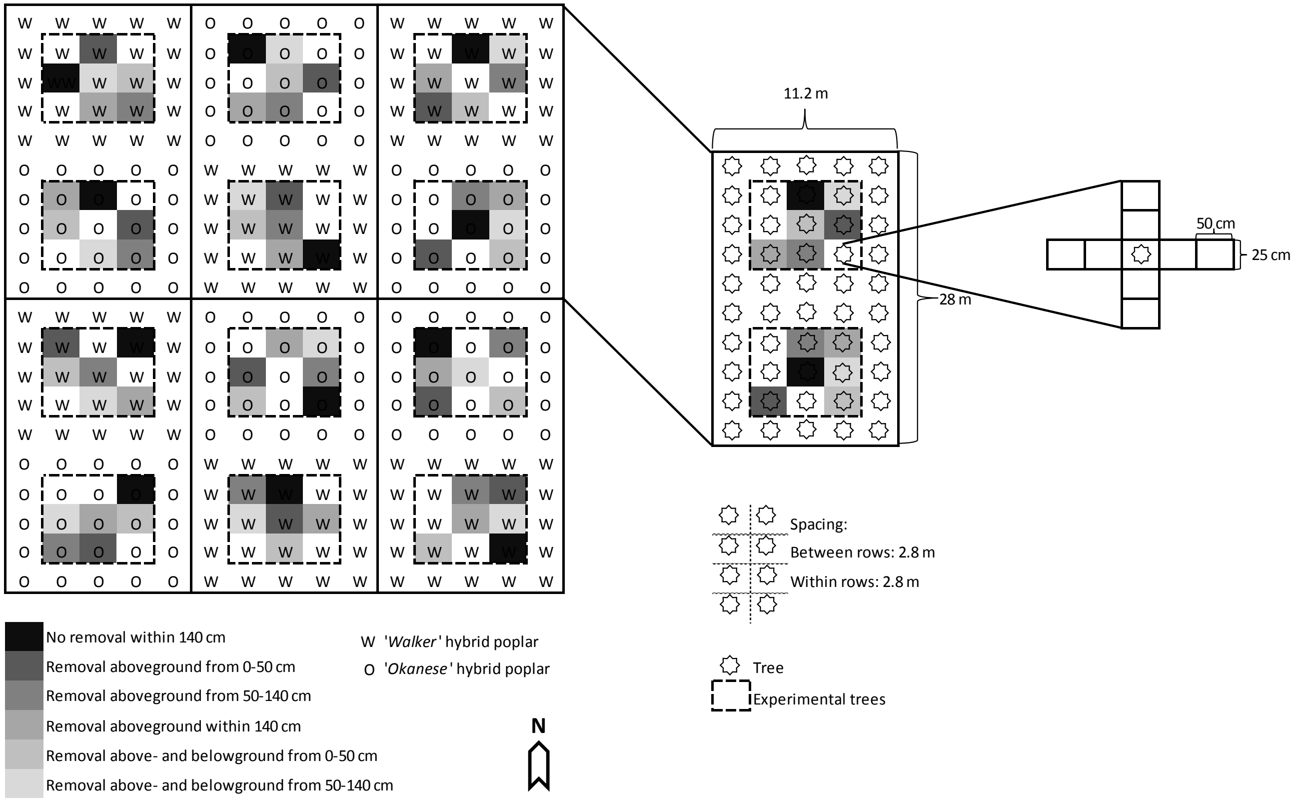


Figure 3.4 – Mean height increment (cm) of Okanese and Walker poplar trees during the first (2011), second (2012), and third (2013) growing seasons after planting for six vegetation control treatments. Error bars represent 90% confidence intervals. Different lowercase letters indicate differences among treatments for each clone separately in 2011 and 2012 and averaged for both clones in 2013 due to the non-significant clone x treatment interaction (p= 0.152) (at Bonferroni adjusted αadj= 0.05/15= 0.003). Abbreviations: NR (control, no vegetation removal), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).

3.8 Appendices

Appendix 3.1– Experimental plantation layout showing the six vegetation control treatments and two hybrid poplar clones randomized according to a split-plot design showing the six replicate blocks that were located at each of three sites and the belt transect used for understory vegetation sampling showing the two contiguous quadrats in each cardinal direction.



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Appendix 3.2– Plant species observed in the sampling quadrats, grouped by growth form. Given is the life cycle, genus, species, authority, common name and regulatory designation in Alberta. Plant species growth forms, life cycles, and nomenclature were based on the USDA Plants Database, and Alberta designations were obtained from the Weed Control Act.

Growth form	Life Cycle	Genus	Species	Authority	Common Name	Alberta designation
Forb	Annual	*Capsella*	*bursa-pastoris*	(L.) Medik.	Shepherd's purse	
Forb	Annual	*Chenopodium*	*album*	L.	Lambsquarters	
Forb	Annual	*Crepis*	*tectorum*	L.	Narrowleaf hawksbeard	
Forb	Annual	*Galeopsis*	*tetrahit*	L.	Hempnettle	
Forb	Annual	*Matricaria*	*discoidea*	DC.	Disc mayweed	
Forb	Annual	*Polygonum*	*lapathifolium*	L.	Pale smartweed	
Forb	Annual	*Silene*	*noctiflora*	L.	Nightflowering catchfly	
Forb	Annual	*Sonchus*	*oleraceus*	L.	Common sowthistle	
Forb	Annual	*Spergula*	*arvensis*	L.	Corn spurry	
Forb	Annual	*Stellaria*	*media*	(L.) Vill.	Common chickweed	
Forb	Annual	*Thlaspi*	*arvense*	L.	Stinkweed	
Forb	Annual, biennial	*Artemisia*	*biennis*	Willd.	Biennial wormwood	
Forb	Annual, biennial	*Erodium*	*cicutarium*	(L.) L'Hér. ex Aiton	Stork's bill	
Forb	Annual, biennial	*Erucastrum*	*gallicum*	(Willd.) O.E. Schulz	Common dogmustard	
Forb	Annual, biennial	*Lappula*	*squarrosa*	(Retz.) Dumort.	Bluebur	
Forb	Annual, biennial	*Potentilla*	*norvegica*	L.	Rough cinquefoil	
Forb	Annual, biennial, perennial	*Dracocephalum*	*parviflorum*	Nutt.	American dragonhead	
Forb	Biennial, perennial	*Silene*	*alba*	(Mill.) Krause	Whitecockle	Noxious
Forb	Perennial	*Achillea*	*millefolium*	L.	Common yarrow	
Forb	Perennial	*Cirsium*	*arvense*	(L.) Scop.	Canada thistle	Noxious
Forb	Perennial	*Epilobium*	*ciliatum*	Raf.	Fringed willowherb	
Forb	Perennial	*Equisetum*	*arvense*	L.	Field horsetail	
Forb	Perennial	*Medicago*	*sativa*	L.	Alfalfa	
Forb	Perennial	*Plantago*	*major*	L.	Common plantain	
Forb	Perennial	*Tanacetum*	*vulgare*	L.	Common tansy	
Forb	Perennial	*Taraxacum*	*officinale*	F.H. Wigg.	Common dandelion	
Forb	Perennial	*Trifolium*	*ssp.**		Clover	
Forb, vine	Annual	*Polygonum*	*convolvulus*	L.	Wild buckwheat	
Forb, vine	Perennial	*Vicia*	*americana*	Muhl. ex Willd.	American vetch	
Grass	Annual	*Avena*	*fatua*	L.	Wild oat	
Grass	Annual	*Beckmannia*	*syzigachne*	(Steud.) Fernald	American sloughgrass	
Grass	Perennial	*Deschampsia*	*cespitosa*	(L.) P. Beauv.	Tufted hairgrass	
Grass	Perennial	*Elytrigia*	*repens*	(L.) Gould	Quackgrass	
Grass	Perennial	*Hordeum*	*jubatum*	L.	Foxtail barley	
Grass	Perennial	*Poa*	*palustris*	L.	Fowl bluegrass	
Grass	Perennial	*Poa*	*pratensis*	L.	Kentucky bluegrass	
Sedge	Perennial	*Carex*	*ssp.***		Sedge	
Tree, Shrub	Perennial	*Salix*	*ssp.****		Willow	

* *Trifolium hybridum* and *Trifolium repens* only identified to genus

** *Carex spp.* only identified to genus

*** *Salix spp.* only identified to genus

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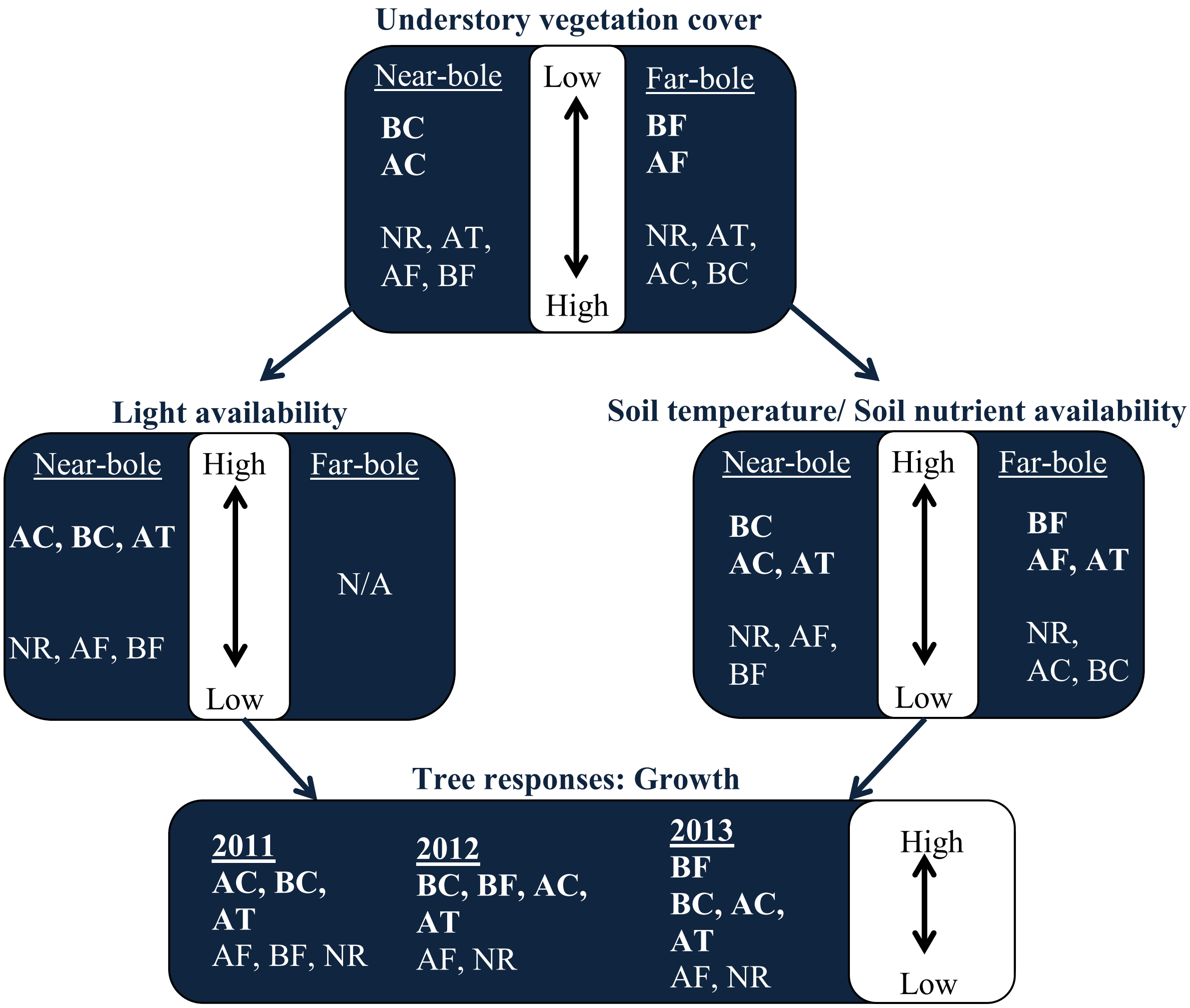
Appendix 3.3– Patterns of responses of understory vegetation cover, environmental variables (light availability, soil temperature and soil nutrient availability) and tree performance to six vegetation control treatments. Tree responses reflect growth of Okanese poplar, because Walker poplar was unresponsive to treatments. Abbreviations: NR (control, no vegetation removal), AF (aboveground vegetation removal at 50-100 cm distance to tree), AC (aboveground removal 0-50 cm), AT (aboveground removal 0-100 cm), BF (above- and belowground removal 50-100 cm), and BC (above-and belowground removal 0-50 cm).



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Chapter 4: Synthesis

This thesis assessed the effects of vegetation control practices on tree-weed interactions and associated establishment and early tree growth in young hybrid poplar plantations based on tree growth responses, understory vegetation as well as environmental resources both above- and belowground. The field experiments were established on research sites in north-eastern Alberta owned by Alberta-Pacific Forest Industries Inc. and was carried out during two consecutive years. Overall, this thesis provided new insights into key processes influencing hybrid poplar performance and advanced our understanding of the effectiveness of current and alternative weed control strategies for operational hybrid poplar plantations in the prairie-boreal forest transition zone.

In the second chapter I evaluated the effects of four different establishment systems on tree-weed interactions within young hybrid poplar plantations with the objective to:

a) Quantify differences in the abundance and composition of competing understory vegetation neighboring the trees, and
b) Determine differences in early aboveground growth performance of two hybrid poplar clones with contrasting growth forms, and
c) Identify key environmental factors impacting tree growth.

This study offered substantial evidence that an extended period of site preparation involving mechanical and chemical vegetation control was the single most important factor for achieving effective and sustained control of perennial weeds, enhancing abiotic growing conditions (light and nutrient availability) and significantly improving the growth of hybrid poplar trees during the early establishment phase. This finding illustrated the high potential for enhancing productivity of these plantations through improved pre-planting weed control as the current operational practice that lacked prolonged site preparation proved less effective for controlling competing perennial vegetation, enhancing growing site conditions, and associated tree growth.

Our study further revealed that high understory cover of annual herbaceous species later in the establishment period, as in the fallow treatment, did not inevitably lead to growth reductions of hybrid poplar trees, highlighting the lower competitiveness of annuals compared to perennial species. This highlights the potential to target weed control efforts on perennial species and retain or add annual species (e.g. as cover crops) to fulfil important ecological functions within hybrid poplar plantations. Our results also specifically demonstrated the value of herbaceous plant cover for soil moisture retention within young hybrid poplar plantations, a finding that is of particular significance in the Canadian Prairies where droughts are common. Although the cover crop and no-till treatments did not prove beneficial for improving tree growth in our study, as competitive effects of perennial species outweighed any positive environmental effects, this finding increased our understanding of the role of temporary plant cover for providing ecological benefits to these plantations.

Results from this study further demonstrated that the two hybrid poplar clones, Walker and Okanese, differed markedly in their growth rates and responses to treatments, offering insight as to their potential for future use in SRIC plantations. Our data revealed that Okanese poplar, a selected progeny of Walker poplar, showed superior growth performance across all treatments tested and across a range of site conditions compared to Walker poplar, indicating its greater suitability for use in heterogeneous landscape environments, including deployment in

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SRIC plantations. Superior performance of Okanese in this study may be attributed to (1) its greater plasticity of performing well under varying growing site conditions, (2) its faster early growth rate and wider crown architecture, leading to earlier crown closure and increased ability to shade competing vegetation, and likely a reduced need for post-planting vegetation management, (3) its greater tolerance of competition, and (4) its greater ability to respond to release from competition, thus offering significant potential for guiding future research activities testing management practices for enhancing hybrid poplar performance. In contrast, findings from this study confirmed that Walker poplar did not perform well on sites with imperfect growing conditions, was highly susceptible to competition from neighboring vegetation, was a poor competitor related to, but not limited to, it's narrow crown and inability to close the canopy, and was less responsive to vegetation control treatments.

In the third chapter I assessed the spatial impacts of competing vegetation on growth performance of two hybrid poplar clones, Walker and Okanese, with the objective to:

a) Test the relative importance of competition near-bole versus far-bole, and above- versus belowground, on the performance of two hybrid poplar clones, and
b) Determine whether competition effects vary over time since planting in relation to the above factors.

Results from this study revealed a combination of aboveground competition for light, primarily during the first three years after planting and which arose from near the tree bole, and belowground competition for soil resources later in the establishment phase, both near and far from the tree-bole. These findings highlight a spatial and temporal shift in the competitive effects of neighboring vegetation and increased our knowledge of tree-weed competition for resources in young plantations. In light of the need to develop practical operational production systems for

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hybrid poplar plantations that reduce management costs while increasing tree performance, these results may be applied to prioritize future plantation management efforts regarding the timing and spatial location of vegetation control relative to trees.

This study further illustrated the superior performance and higher responsiveness of Okanese poplar to vegetation control treatments compared to Walker, confirming results from chapter 2. It is well established that the success of SRIC plantations with hybrid poplar depends on the use of suitable clones (e.g. high performance, high plasticity), in addition to site selection and effective vegetation control management. As current recommendations for clones are based primarily on their performance in shelterbelts across the Canadian Prairies, collective test results from our studies offer new insights on the performance and potential of these clones for SRIC plantations.

Overall, this research increased our understanding of the interactions between young hybrid poplar trees and neighboring herbaceous vegetation as well as the effectiveness of vegetation control practices to mitigate above- and belowground competition leading to the following management recommendations for an integrated weed management plan:

1. Prioritization of resources for site preparation with the objective to achieve effective and sustained control of perennial understory species through an extended full year of weed control prior to tree planting, involving mechanical and chemical weed control methods.
2. Targeting early post-planting weed control efforts on the suppression of near-bole understory vegetation, primarily to mitigate aboveground competition for light between highly competitive annual and perennial forbs and newly planted trees. This may be achieved through a combination of extended pre-planting site preparation (see above), followed by application of a pre-emergent non-selective herbicide near the tree bole prior to tree leaf-out in spring. Alternatively, post-planting weed control may be accomplished

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by means of repeated mowing close to trees starting early in the growing season, for the duration of at least two years after tree planting.

3. Targeting three and four year post-planting weed control on the suppression of understory vegetation far from the tree bole (e.g. between-row) to mitigate belowground competition for soil resources, primarily for nutrients. This may involve shielded herbicide applications between rows using either a post-emergent non-selective herbicide effective on nearly all herbaceous vegetation (i.e. glyphosate) or a selective grass-specific herbicide targeting highly competitive perennial grass species such as quackgrass. Alternatively, between-row vegetation control may be achieved through cultivation.
4. If perennial species are largely absent or effectively controlled, between-row vegetation may be left uncontrolled. Understory cover between-rows may serve important ecological functions including, but not limited to, reduced soil erosion and increased soil moisture retention.

Future research is needed to develop and test practical operational methods to cost-effectively mitigate competition for resources from understory vegetation as well as an economic evaluation of these methods. Particularly, future work needs to extend testing of alternative methods to control vegetation near the tree stem without negatively impacting the tree itself while aiming to minimize the current reliance on herbicides for vegetation control. Moreover, studies on root biology of the hybrid poplar clones tested in this study are needed to quantify belowground responses to competition, varying environmental conditions as well as vegetation management.

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