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Factors regulating tree-herb competition in young hybrid poplar plantations

by

David Henkel-Johnson

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Dedication

In memory of my grandfather, Donald F. Henkel – mentor, artist, outdoorsman, spinner of yarns, and liar of fish sizes. His love of all things outdoors he passed on to me, without of which I would not be here today. You will be missed Grandpa.

Abstract

Hybrid poplar plantations have the potential to produce large amounts of biomass for the forest industry, but the young trees are sensitive to competition. This research attempted to quantify the influence of factors regulating competition in hybrid poplar plantations under four years old. The effects of competition varied with growing site, indicating an interaction with abiotic conditions. Nonetheless, perennial grasses overall appeared to be highly detrimental to tree growth in comparison to most forb species, especially for younger trees. Additionally, vegetation directly adjacent to the tree stem (within 0.5 m) was responsible for most of the competition for above-ground resources, and controlling near-stem vegetation resulted in large growth increases, but only for the fast-growing 'Okanese' clone. These results suggest that plantation managers should prioritize control of grasses while reducing above-ground biomass of all vegetation within 0.5 m of the tree stem for maximum productivity.

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Chapter 1: Introduction and literature review

1.1 Hybrid poplar plantations

In northern latitudes plantations of fast-growing tree species are receiving increasing attention due to their potential for high fibre yields under short rotations (Balatinecz et al. 2001; Ward 2001). The primary species used in short rotation forestry (SRF) are hybrid poplar (*Populus* ssp.) and willow (*Salix* ssp.); both are popular due to their cold hardiness, high growth rate, ease of propagation, and small genome size, the latter of which facilitates hybridization and genetic improvement by plant breeders (Park and Wilson 2007; Wullschleger et al. 2002). For the duration of my thesis I will primarily be concerned with hybrid poplar.

Growing interest in hybrid poplar plantations stems from increasing global demand for wood products, including roundwood, fuelwood, biofuels, pulp, and paper - coupled with the inability of boreal forests to grow quickly enough to meet the large demand (Park and Wilson 2007; Weih 2004). Canada's hybrid poplar plantations can help meet that demand by producing large amounts of biomass with mean annual increments (MAI) in the range of 6 to 29 $m^3ha^{-1}year^{-1}$, which is comparable to plantations found in more temperate regions (Christersson 2010; Park and Wilson 2007; Weih 2004). The initial growth rate of hybrid poplar plantations is also quite high, which permits rotation cycles of less than 20 years, whereas plantations of native conifers and hardwoods may require rotations of 40-60 years (Yemshanov et al. 2005). Short rotations and high yields can make hybrid poplar plantations quite profitable, and by establishing plantations on marginal agricultural lands near processing facilities, the forest industry gains other financial benefits such as reduced transportation costs, afforestation carbon credits, and preserving provincial land for non-timber interests such as recreation and biodiversity values (Anderson and Luckert 2007; Yemshanov et al. 2005).

In addition to high yields, hybrid poplar plantations offer other benefits regionally and globally. Plantations in otherwise monotypic agricultural landscapes increase spatial diversity across the landscape by providing alternative wildlife habitat (Christian et al. 1997; Christian et al. 1998; Elek et al. 2010; Giordano and Meriggi 2009) and facilitate the re-colonization of native understory woodland species (Boothroyd-Roberts et al. 2013). Under Canada's TRIAD approach to forest management hybrid poplar plantations provide a zone of intensive management that would allow for conservation of other areas of native forest (Messier et al. 2003; Park and Wilson 2007). Hybrid poplar can also fulfill other conservation roles through their use in shelterbelts (Zsuffa et al. 1996) or riparian buffers (Fortier et al. 2010). Hybrid poplar plantations may additionally be used as sites for phytoremediation of municipal wastes, contaminated soils, and industrial sludge (Burken and Schnoor 1997; Felix et al. 2008; Sebastiani et al. 2004).

On a global scale, hybrid poplar plantations help ameliorate high levels of atmospheric carbon dioxide by sequestering large amounts of carbon in their biomass (Liberloo et al. 2006; Vitousek 1991) and underlying soil (Hansen 1993). Arevalo et al. (2009) estimated a 9 year old hybrid poplar plantation in northern Alberta contained a carbon stock of 174 Mg C ha^{-1}, which was greater than that of agricultural land (132 Mg C ha^{-1}) and grassland (121 Mg C ha^{-1}). Hansen (1993) found than the soil under a hybrid poplar plantation on former agricultural land located in the prairies of the north-central United States accrued soil carbon at 1.63 Mg ha^{-1} yr^{-1} faster than adjacent row crops/mowed grassland.

1.2 Plant competition

In order for the benefits and advantages of hybrid poplar plantations to be fully realized, a plantation must first exhibit good survival and growth during its early establishment period (years 1-3 following planting). Unfortunately, many *Populus* species and their hybrids have high resource demands and numerous accounts confirm that they are very sensitive to competition (Block et al. 2009; Hansen and Netzer 1985; Landhausser and Lieffers 1998; Marino and Gross 1998; Pinno and Belanger 2009; Powell and Bork 2004a, b; Stanturf 2002). This intolerance is supported by evidence that poplar experience rapid growth when released from competition after vegetation control measures are applied (Bilodeau-Gauthier et al. 2011; Bowersox et al. 1992; Buhler et al. 1998; Coll et al. 2007; Fitzgerald and Selden 1975; Marino and Gross 1998; Otto et al. 2010; Thomas et al. 2001). Young trees are especially susceptible to competition. In a hybrid poplar yield loss study, Otto et al. (2010) recorded fiber yield losses due to competition that were as high as 26% and 8% in the first and second years following planting, respectively. Moreover, trees that experienced early yield losses due to competition in a coppice plantation with two-year rotations did not recover these losses, even with complete weed control for the remainder of the rotation (Otto et al. 2010). Aside from yield loss and mortality, competition may change the branching architecture of hybrid poplar, causing trees to have fewer living branches, with those live branches remaining having more outward spread (Marino and Gross 1998). An altered crown architecture is undesirable because canopy structure is an important determinant of productivity (Isebrands and Nelson 1982).

Competition between weeds and hybrid poplar trees is temporally and spatially variable and occurs either above-ground for light and space, or below-ground for nutrients and water (Balandier et al. 2006; Grace and Tilman 1990). As an early successional species, *Populus* and their hybrids are less shade-tolerant than other trees, and are highly susceptible to light competition (Landhausser et al. 2007; Sixto et al. 2001). While theoretically less of a problem in open areas like plantations, during the first year or two following establishment neighboring vegetation can be as tall as developing trees, although competition for light becomes less important once trees overtop the neighboring vegetation (Sage 1999).

Below-ground competition for water and nutrient resources is similar in response to water or nutrient deficits in the soil (Nambiar and Sands 1993). Soil and site characteristics will often govern the availability of these resources (Pinno et al. 2010) in addition to climate and site history (Connell et al. 1995; Sands and Mulligan 1990). As hybrid poplar are sensitive to drought, competition for soil moisture is likely to be more common in arid regions, leading to considerably reduced growth (Burgess et al. 1996; Shock et al. 2002). In areas with adequate rainfall, trees may still experience competition for soil moisture if excessive weed cover reduces soil moisture through interception and transpiration; in these instances vegetation control aids in alleviating water stress (Nambiar and Zed 1980).

Competition for nutrients will likewise hinder hybrid poplar growth. While nitrogen is the principal limiting nutrient for hybrid poplar (Coll et al. 2007; McLaughlin et al. 1987; Stanturf 2002), phosphorous has similarly been found to be limiting (Pinno and Belanger 2009; van den Driessche et al. 2003). Nitrogen is one of the primary controllers of plantation productivity because of hybrid poplar’s greater need for nitrogen than other plantation trees (Stanturf 2002) and historically low nitrogen mineralization rates found in northern climates (Binkley and Hogberg 1997; Carlyle 1986; Reich et al. 1997). Available soil nitrogen, increases productivity in native *Populus* and hybrid poplar stands by promoting root growth (Pregitzer and Friend 1996), fine root density (Heilman et al. 1994), and leaf nitrogen concentration (van den Driessche et al. 2008). In spite of these observations, fertilization with nitrogen has not been found to benefit certain hybrid poplar clones, and may even be harmful when the trees are young (DesRochers et al. 2006). Moreover, the form of available nitrogen influences tree growth, as some hybrid poplar clones appear to be better adapted to take up nitrogen from ammonium (NH_4) rather than nitrate (NO_3) sources (DesRochers et al. 2007).

A number of studies have attempted to look further into the relationship between hybrid poplar trees and weeds by investigating the influence of certain weed species and/or weed types on tree performance. To this end Kabba et al. (2007) used a pot experiment to observe that the presence of quackgrass (*Elytrigia repens*) and dandelion (*Taraxacum officinale*) decreased growth of hybrid poplar trees through competition for nutrients. In this case allelopathy may have also been playing a role because quackgrass is capable of producing allelopathic substances (Korhammer and Haslinger 1994) that are known to be detrimental to other species (Schulz et al. 1994). Another perennial grass known to affect *Populus* growth is marsh reed grass (*Calamagrostis canadensis*), which when grown in association with trembling aspen (*Populus tremuloides*) was found to 'crowd' the root system of trees. Additionally, the abundant litter produced by the grass kept soil temperatures cool, resulting in aspen shoots developing more slowly with lower growth rates of shoots, roots, and leaf area (Landhausser et al. 2001; Landhausser and Lieffers 1998; Landhausser et al. 2007). Both of these examples support the assertion by Balandier et al. (2006) that trees in general are especially susceptible to competition by grasses, and particularly perennial grasses, when the former are young.

Traits that make perennial grasses effective competitors are their high growth rate and dense root system with its high ability to acquire water and nutrients (Frochot et al. 2002). Grasses also can form a dense sod layer less than 1 m deep, which is where much of the fine root and total root biomass of hybrid poplar trees is located (Al Afas et al. 2008; Friend et al. 1991). In this situation the root system of grasses crowds out the roots of trees near the surface and prevents trees from accessing rainfall and nutrients located near the soil surface (Balandier et al. 2006). Messier et al. (2009) supported these assertions by observing early-successional trees, hybrid poplar included, experienced significant resource and non-resource root competition (i.e. space) with a grass mixture.

Forbs also compete effectively for resources, and are particularly efficient at intercepting light, owing in part to their relatively large leaf area index (Balandier et al. 2006). Growth form and life cycle may play a key role in determining the competitiveness of forbs. Otto et al. (2010) observed that plantations dominated by early emerging annual weeds are effective at hindering hybrid poplar growth, while Pinno and Belanger (2009) noticed similar effects with Canada thistle (*Cirsium arvense*), which is a large creeping rooted and invasive perennial forb capable of forming very thick infestations.

Aside from neighboring vegetation composition, proximity (i.e. spatial location of neighbors) also plays a role as a factor influencing competition as well, and weeds as near as 20 cm or less away from young *Populus* trees negatively affect tree growth, even when controlled everywhere else (Otto et al. 2010; Powell and Bork 2004a). Controlling weeds between rows and near to the tree stem (i.e., within ~ 0.5 m) increased four year old hybrid poplar yields in British Columbia by 37% compared to untreated and inter-row control treatments only (Thomas et al. 2001). Conversely, alfalfa (*Medicago sativa*) grown at distances of 0.5 m and greater also reduced hybrid poplar growth for up to three years following tree planting (Shock et al. 2002).

1.3 Vegetation control

Typical plantation management practices for controlling competition and increasing yields in hybrid poplar plantations involves a combination of site preparation activities (e.g. cultivation and pre-plant herbicides) to reduce weed populations while preparing the planting bed (Hansen et al. 1983; Hansen et al. 1984; Mead 2005). This is followed by yearly regimens of herbicide (Hansen and Netzer 1985; Netzer and Noste 1978; Sixto et al. 2001) and in-row cultivation (Bowersox et al. 1992; Buhler et al. 1998) to control competing vegetation. These activities usually continue for the next three to four years (Anderson and Luckert 2007; Buhler et al. 1998), which coincides with the period that hybrid poplar are most vulnerable to weed competition (Bowersox et al. 1992; Buhler et al. 1998; Otto et al. 2010; Shock et al. 2002). After this period the tree becomes sufficiently large to compete with weeds through canopy shading, and a well-developed root system facilitates rapid access to soil resources (Buhler et al. 1998; Heilman et al. 1994).

While vegetation control is essential for overall plantation success (Balandier et al. 2006; Thompson and Pitt 2003), it also comes with a host of consequences. Specifically, repeated cultivation typically leads to losses in soil carbon and fertility (Davidson and Ackerman 1993; Mann 1986) while promoting erosion (Gregorich and Anderson 1985) and may further spread perennial weed species (Lauringson et al. 1999). Extensive use of herbicides can lead to herbicide-resistant weed populations (Tranel and Wright 2002) and residual accumulation in the soil (Horowitz et al. 1974). Use of these practices to tightly control weed populations perpetuates the ‘monoculture model’ of agriculture which reduces wildlife habitat (Christian et al. 1997). Furthermore, vegetation control costs can be high relative to the projected value of the harvested tree crop. Alberta-Pacific Forest Industries Inc. (Al-Pac), which is the largest operator of hybrid poplar plantations in Alberta, experiences vegetation control costs of about $150 CAD ha^{-1}yr^{-1}(Dave Kamelchuk, senior research technician, Alberta-Pacific Forest Industries Inc., personal communication, 29 October, 2013) for the first three to four years following planting, depending on the competiveness of the planted clone.

In order to maximize income while keeping vegetation control efforts low, an integrated weed management (IWM) plan is needed. IWM is a weed control approach that combines biological, chemical, cultural, or physical control tactics to provide the crop with the greatest advantage over the weeds, while doing so at minimal cost (Harker and O'Donovan 2013; Radosevich et al. 2007). In hybrid poplar plantations managers following an IWM plant would be more discriminating than those following current management plans in terms of when and where (relative to the tree bole) vegetation control measures are applied, so as to optimize tree growth relative to the amount of intervention, hence maximizing plantation profitability. This would be done by primarily targeting the most damaging weeds, and intervening when and where they are causing the most damage. Regrettably, an IWM plan does not yet exist for hybrid poplar plantations on former agricultural land in the northern latitudes. Before an IWM plan can be developed, the biological characteristics and ecological behavior of weeds, and their interaction with the desired crop, must be understood – this is the basis upon which successful weed control techniques can be developed (Harker and O'Donovan 2013).

1.4 Objectives

The studies mentioned above have primarily worked individually with weed presence/absence, composition, and proximity as independent variables influencing hybrid poplar growth. However, little research has investigated the relative importance of those variables and the effects of their possible interactions. It is my objective to improve on the work of previous research and develop a further understanding of weed-tree relationships by using multivariate techniques to analyze the interactions of vegetation abundance, composition, and proximity as elements of weed communities influencing hybrid poplar growth. I aim to accomplish this using data gathered by the observation and manipulation of weed communities and associated tree growth responses in young hybrid poplar plantations (2-3 years old) in north-central Alberta. The results of this research will greatly aide in the formation of an IWM plan to be implemented in future silvicultural practices.

The remainder of my thesis is organized as follows:

Chapter 2: Influence of weed composition, abundance, and spatial proximity on young hybrid poplar growth –using a combination of observational and manipulative experiments, I determine which weed types are most detrimental to hybrid poplars, quantify hybrid poplar yield losses to weed abundance, and identify the spatial context within which most competition is occurring.

Chapter 3: Comparison of effects of competing proximal and distal above-ground vegetation for two hybrid poplar clones – through the removal of above-ground competition at proximate (0-0.5 m) and distal (0.5-1.4 m) distances from the stem of two hybrid poplar clones, I examine the extent to which the proximity of above-ground herbaceous vegetation influences competition on hybrid poplar trees.

***Chapter 4: Synthesis* -** in the final chapter I will summarize my research with a general conclusion and discussion section along with recommendations for management and future research.

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Chapter 2: Influence of weed composition, abundance, and spatial proximity on young hybrid poplar growth

***Abstract* –** Hybrid poplar plantations have the potential to produce large amounts of biomass for the forest industry, but they are sensitive to competition for resources by neighboring vegetation when they are young. Intensive vegetation control as a way to mitigate yield losses is neither economically nor ecologically desirable, thus identifying the characteristics of competing vegetation most detrimental to tree growth is essential to creating an integrated weed management plan. To help create this plan, a cooperative research project was undertaken during the growing seasons of 2011 and 2012. The goal of this study was to quantify the influence of weed composition, abundance, and spatial proximity on the growth of 2-3 year old hybrid poplar trees within four operational plantation sites in northern Alberta. A secondary goal was to compare the effectiveness of four different vegetation control treatments: 1) cultivation, 2) cultivation + spot herbicide starting in second growing season, 3) cultivation + spot herbicide starting in third growing season, and 4) cultivation + broadcast herbicide. Regression tree and Nonmetric Multidimensional Scaling (NMDS) analyses indicate that perennial grasses in general, and *Elytrigia repens* in particular, are highly detrimental to hybrid poplar growth – especially for two-year old trees. Planting site also plays a large role in determining individual tree productivity, although it is difficult to quantify its influence relative to competition because site was greatly confounded with the surveyed vegetation communities. Increasing intensiveness of vegetation control treatments did not increase tree survival rates in any of the sites and did not result in a commensurate tree growth increase in half of the sites. Of the remaining sites, early intensive vegetation control with herbicides dramatically increased tree growth on the site dominated by *Elytrigia repens.* Using only cultivation as a form of vegetation control was the least effective option, and allowed for persistence of perennial grasses compared to other treatments. These results suggest prioritizing control of perennial grasses by means of herbicides over other forms of competition control.

2.1 Introduction

In Canada plantations of fast growing tree species such as hybrid poplar (*Populus ssp.*) are of increasing interest to the forest industry and private landowners due to their potential for high fibre yields under short rotations (Balatinecz et al. 2001; Ward 2001). Hybrid poplars are gaining popularity due to their cold hardiness, high growth rate, and ease of propagation (Park and Wilson 2007). Biomass produced in poplar plantations is used for pulp, paper, energy, construction wood, and fodder (Weih 2004). With proper management, hybrid poplar plantations at northern latitudes can achieve yields comparable to plantations in more temperate regions (Weih 2004) with mean annual increments in the range of 6-29 $m^3ha^{-1}year^{-1}$(Christersson 2010; Park and Wilson 2007).

Currently hybrid poplar plantations are well established in several regions throughout Canada (Larocque et al. 2013), including marginal agricultural lands (Anderson and Luckert 2007). Afforestation of agricultural land has environmental benefits such as provision of wildlife habitat (Christian et al. 1997), facilitating the re-colonization of native understory woodland species (Boothroyd-Roberts et al. 2013), protecting forest ecosystems by reducing harvest pressure (Messier et al. 2003), and increasing soil carbon (Hansen 1993). Reduced transportation costs can be achieved if the plantations are established close to the processing area (Anderson and Luckert 2007). Unfortunately, former agricultural lands commonly harbor large resident weed populations, and optimizing growth of hybrid poplars requires weed control. Hybrid poplar are thought to be sensitive to competition, and vegetation control is considered essential for plantation success (Block et al. 2009; Pinno and Belanger 2009). Without this vegetation control, trees will be stunted and exhibit higher mortality (Hansen and Netzer 1985; Otto et al. 2010). Aside from yield loss and mortality, competition can also change the branching architecture of hybrid poplars, causing them to be shorter and possess fewer living branches, with those branches that remain being shorter and more outwardly spread (Marino and Gross 1998). An altered crown architecture may be undesirable because canopy structure is an important determinant of productivity (Isebrands and Nelson 1982).

In order to control weed populations, plantations are initially exposed to site preparation treatments (Hansen et al. 1984; Mead 2005), which is followed by post-planting vegetation control (Balandier et al. 2006; Thompson and Pitt 2003). Vegetation control is needed most during the three to four years following planting when hybrid poplars are at greatest risk of competition effects (Buhler et al. 1998; Shock et al. 2002). After this period, trees become sufficiently large to compete with weeds through overstory canopy shading and a well-developed root system to facilitate access to soil resources (Buhler et al. 1998; Heilman et al. 1994). Nevertheless, the vegetation control needed in plantations during these early stages can be costly; Alberta-Pacific Forest Industries Inc. (Al-Pac), which is the largest manager of hybrid poplar plantations in Alberta, incurs vegetation control costs in plantations of about \$150 CAD ha^{-1} yr^{-1} for the first three to four years following plantation establishment (Dave Kamelchuk, senior research technician, Alberta-Pacific Forest Industries Inc., personal communication, 29 October, 2013).

To maximize income while keeping costs of vegetation control efforts low, an integrated weed management (IWM) plan is needed. Integrated weed management is an approach that combines biological, chemical, cultural, or physical suppression tactics to provide the crop with an advantage over the weeds (Harker and O'Donovan 2013; Radosevich et al. 2007). In hybrid poplar plantations managers following an IWM plant would be more discriminating than those following current management plans in terms of when and where (relative to the tree bole) vegetation control measures are applied, so as to optimize tree growth relative to the amount of intervention, hence maximizing plantation profitability. This would be done by primarily targeting the most damaging weeds, and intervening when and where they are causing the most damage. Unfortunately, an IWM plan does not yet exist for hybrid poplar plantations in northern latitudes. Before an IWM plan can be developed, the biological characteristics of weeds, ecological dynamics of weed communities, and their interaction with the desired crop must be understood, and is the basis upon which successful weed control techniques can be developed (Harker and O'Donovan 2013). To this end numerous studies have investigated the relationships between weeds and hybrid poplar trees. For example, Kabba et al. (2007) used a pot experiment to observe that the presence of quackgrass (*Elytrigia repens*) and dandelion (*Taraxacum officinale*) decreased growth of hybrid poplar trees through competition for nutrients. Other studies have observed that early emerging annual weeds such as lamb's quarters (*Chenobodium album*) as well as creeping perennial forbs such as Canada thistle (*Cirsium arvense*), have a detrimental effect on poplar growth (Otto et al. 2010; Pinno and Belanger 2009). It was hypothesized by Balandier et al. (2006) that trees in general are susceptible to competition by grasses when young. Messier et al. (2009) partially confirmed this assertion by observing that early-successional trees, hybrid poplar included, experience significant resource and non-resource root competition with a grass mixture. Proximity may also play a role in competition; weeds within 20 cm of young *Populus* trees negatively affect tree growth, even when controlled everywhere else (Otto et al. 2010; Powell and Bork 2004a). Conversely, alfalfa (*Medicago sativa*) grown at distances of 0.5 m and greater can also reduce hybrid poplar growth for at least three years following tree planting (Shock et al. 2002).

The studies mentioned above have primarily examined vegetation presence/absence and composition as variables influencing hybrid poplar growth, while the proximity of competing vegetation has only occasionally been addressed. It is our aim to improve on previous work and gain further understanding of weed-tree relationships by using multivariate techniques to address the following questions:

Question 1: How do vegetation composition, abundance, and spatial proximity regulate the effects of competition on hybrid poplar growth?

Question 2: How effective are vegetation suppression treatments with regards to hybrid poplar growth? What is the response of the vegetation community to the treatments?

We answered these questions through observation, manipulation of weed communities, and monitoring of associated tree growth in juvenile hybrid poplar plantations (two to three years old) in north-central Alberta. The results of this research should greatly aide in the formation of an IWM plan to be implemented in future silvicultural operations of hybrid poplar plantations.

2.2 Materials & methods

2.2.1 Research sites and description

This research was carried out within operational hybrid poplar plantations in central Alberta, Canada near the town of Athabasca (Lat 54°43’N; Long. 113°17’W), which is situated near the border of the Dry Mixedwood and Central Mixedwood natural subregions of the boreal forest (Beckingham et al. 1996). The area has a cool continental climate with short, warm summers and long, cold winters. The average annual temperature of this region over the past 30 years is 2.3°C, with an average of 480 mm of total precipitation, of which 335 mm falls during the growing season of May to September (Appendix 2-1).

Soils in the area are predominantly Orthic Grey Luvisols and Dark Grey Luvisols in addition to some Dark Gray Chernozems (Alberta Agriculture 2005). Much of this region is utilized for the production of grains, canola, and forage (hay and pasture). Nevertheless, early to mid-seral forests remain common, and are largely composed of an overstory dominated by trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.). Common understory species include beaked hazelnut (*Corylus cornuta Marsh.*), prickly rose (*Rosa acicularis* Lindl.*)*, and red osier dogwood

(*Cornus stolonifera* Michx.). The terrain is flat to gently undulating with elevations between 520-700 m.

Two sites were selected for this study within each of two hybrid poplar plantations (n=4 sites total) located on privately leased land maintained by Alberta-Pacific Forest Industries (Al-Pac). The two plantations were approximately 17 km apart and known as the 'Seim' and 'Berquist' plantations (after the cooperating landowners). Both locations were leased to Al-Pac in 2009 and immediately underwent site preparation procedures consisting of repeated passes by a disc cultivator and herbicide applications (see Appendix 2-2 for an overview of the silvicultural practices undertaken at each site). Prior to conversion the 'Seim' plantation was in pasture/hay crop and 'Berquist' was planted to alfalfa.

Each plantation contained two study sites. The Seim plantation contained sites 'Homestead' and 'Rockpile', which were located about 500 m apart. The Berquist plantation contained sites 'Farmyard' and 'Back40' which were located about 300 m apart. Soils at all sites were Dark Grey Luvisols and contained an A horizon of 17 cm, 20 cm, 25 cm, and 25 cm for the Homestead, Rockpile, Farmyard, and Back40 sites, respectively. Each site was internally uniform in ecosite (i.e. slope, aspect, visible soil conditions, drainage, etc.), and the four sites represented a range of growing conditions typical for plantations in the region. The initial weed community also differed among sites in terms of general plant composition and abundance, although within each site the specific composition of competing vegetation neighboring individual poplar trees also varied. Both plantations were planted in June 2010 with rooted cuttings of the hybrid poplar clone 'Walker' (*Populus deltoides* × (*P. laurifolia* x *P. nigra*)) in a systematic grid pattern with 2.8 m spacing. The study began in spring 2011 and continued through autumn 2013, although the data reported here are only continues through 2012.

2.2.2 Experimental design

The study was a randomized complete block design with each site being treated as a block. Each site consisted of a permanently marked grid of approximately 25 x 25 trees. In each site (Fig. 2-1) 140 trees were selected (i.e. as plots) and 35 were assigned to each of four weed control treatments (n=35 per treatment). Treatments included: 1) cultivation-only during the growing season (CULT), 2) periodic cultivation + spot application (by hand) of herbicide to remaining vegetation within 1.4 m of the tree base (HERB), 3) cultivation in 2011, followed by cultivation + spot herbicide in 2012 (i.e. delayed herbicide treatment; DHERB), and 4) business-as-usual (BAU). The BAU treatment included periodic cultivation + broadcast spray application of linuron and/or glyphosate in spring when trees were dormant, and later, additional applications of sethoxydim or glyphosate as needed. See Appendix 2-2 for a complete description of treatments and BAU herbicide applications.

As the BAU treatment was started prior to all other treatments in 2011 and had a longer time period over which to influence tree growth than the other treatments, the BAU treatment was not included in the analysis of the 2011 data. Also in 2011, the DHERB treatment had not taken place yet, and therefore, for analysis of 2011 data trees within that treatment was considered to be part of the CULT treatment.

Due to operational constraints, trees from the CULT, HERB, and DHERB treatments were selected from within a protected grid of 14 x 14 trees where broadcast spray herbicide was not applied but in-row cultivation still occurred. Trees with the BAU treatments were randomly selected from rows immediately surrounding the aforementioned grid, with at least one tree row between them to safeguard against possible herbicide drift into the protected grid (Fig. 2-1). Cultivation for all treatments was accomplished with a 2 m wide disc plow and consecutive passes were alternated between north-south and east-west alley directions. For HERB and DHERB treatment trees, neighboring vegetation was sprayed around each tree with a 10% solution of glyphosate out to a distance of 1.4 m. Application was done using hand sprayers in conjunction with shields to minimize drift and damage to nearby trees.

2.2.3 Sampling

2.2.3.1 Tree measurements - During spring 2011, all study trees were measured for height and basal diameter at ground level. Basal diameter was measured in both north-south and east-west directions to calculate a mean diameter. Some trees had co-dominant stems, in which case the height and basal diameter for each stem was measured. Additionally, other trees had forked stems branching above the root collar, in which case height was calculated as an average of the height of the two stems. Tree measurements were repeated in autumn of 2011, spring and autumn of 2012, and again in the spring of 2013 (to assess height losses due to winterkill and moose browsing). Stems were initially marked with a permanent marker to ensure subsequent diameter measurements were taken at the same location on each tree. Repeated measures over time were then used to calculate height and stem diameter increments. Due to complications from significant moose browse and winter stem dieback, tree height increment could not be used as a response variable in the analysis, see Appendix 2-3 for a summary of the extent of moose damage on tree height. Additionally, as many trees had co-dominant stems, basal diameter increment could not be used as a response variable. Therefore the primary response variable in the analysis was basal area increment (BAI) of individual trees, which is unaffected by multiple stems and not as directly influenced as height by damage to the tree leader. Early successional deciduous species, including *Populus*, may even have the ability to compensate for infrequent winter browsing of the shoots (Carson et al. 2009; Danell et al. 1994), hence negative influences of browsing on BAI were not expected. BAI was calculated as the net increase in the aggregate basal area of all stems on a given tree over a year as calculated from the average diameter of each stem with the following formula:

$$\mathrm{BAI} = \sum_{i=1}^{n}[\pi((\bar{x}_i)/2)^2\ ]_{\mathrm{autumn}} - \sum_{i=1}^{n}[\pi((\bar{x}_i)/2)^2\ ]_{\mathrm{spring}}$$

where n equals the total number of stems on the tree and $\bar{x}_i$ represents the average diameter of the i^{th} stem.

2.2.3.2 Vegetation measurements - Assessments of neighboring vegetation were performed in mid-June and late August of both 2011 and 2012 for a total of four assessments. In 2011 only trees from the CULT and DHERB treatments were assessed, which expanded in 2012 to include trees from all treatments. Neighboring vegetation was visually assessed for percent cover (by plant species) using a 105 cm x 25 cm area separated into three equal and consecutive quadrats of 35 cm x 25 cm, with the narrow side of the quadrat situated next to the tree (Fig. 2-1). Assessments were made at every sample tree in each of the cardinal directions and the resulting cover data averaged by quadrat location [near (0-35 cm from stem of tree), mid (35-70 cm) or far (70 -105 cm)], and also across all quadrats to quantify total aggregate cover from the tree base to a 105 cm distance. See Appendix 2-4 for a complete list of plant species encountered.

Following the vegetation assessment in August 2011, weeds near DHERB treatment trees were harvested by cutting at ground level to quantify above-ground biomass. Vegetation was harvested from the same quadrats sampled for cover, sorted to combinations of growth form and longevity (i.e. perennial grasses, perennial forbs, or annual forbs; annual grasses were absent or present in trace amounts only, and were therefore not harvested). Forbs with a variable annual or biennial life cycle were relatively scarce and grouped with the annual forbs. Biomass samples were oven-dried at 50°C to stable mass and weighed. Spearman rank correlations of the August weed assessments indicated strong correlations between visual assessments of cover and the biomass measurements; ρ=0.67 ($p < 0.0001$), 0.67 ($p < 0.0001$), and 0.85 ($p < 0.0001$), for annual forbs, perennial forbs, and perennial grasses, respectively. Total biomass per site ranged between 400-800 g m^{-2} (Fig. 2-2).

2.2.3.3 Soil sampling - Soil samples were taken from each site in August 2012. Ten soil cores were taken systematically from across each site, and separated into soil depths of 0-15 and 15-30 cm. Within each site, cores were bulked by depth class, frozen, and later analyzed at the Natural Resources Analytical Laboratory at the University of Alberta. The measured properties and analytical methods employed were as follows: organic matter – loss on ignition; pH and electrical conductivity – pH conductivity meter; total nitrogen, ammonium and nitrate – colorimetric determination on a discrete auto-analyzer; soil texture – particle size analysis with a hydrometer. Soil physical and chemical properties for each site and depth are reported in Table 2-1.

2.2.3.4 Tree damage assessments - In 2012 a number of trees appeared to be under attack from sawfly larvae, which are the immature form of wasps from the *Symphyta* sub-order. Sawfly larvae are notorious defoliators of forests, and in the conditions found in hybrid poplar plantations they can be especially devastating (Sulz 2011). In order to account for damage from sawfly larvae each tree was inspected twice during the growing season in 2012 and assigned damage designations of light (1-25%), moderate (25-50%), severe (50-75%), or very severe (75-100%) defoliation.

Herbicide damage in the form of wilting, leaf cupping, and chlorosis was also observed on some HERB and BAU trees – most likely due to herbicide drift during application despite preventative efforts. Trees were assigned damage designations on the same scale as insect damage (i.e. in 25% intervals), except as percent of foliage affected rather than percent defoliation. Any tree that experienced insect damage of severe or greater (n= 30; 5.4 % of all trees), and herbicide damage of moderate or greater (n=7; 1.3

%) was excluded from analysis. Other trees excluded from analysis were those that were later found to be clones other than ‘Walker’ that were mistakenly mixed in with the planting stock (n= 9; 1.6 %), and trees that died from other forms of non-competitive damage such as mechanical injury by the cultivator (n=3; 0.5 %).

2.2.4 Data analysis

2.2.4.1 Effects of neighboring vegetation on tree growth – To first quantify tree growth in relation to neighboring vegetation composition, abundance, proximity, and combinations thereof, we used only trees that had not received any herbicide treatment to avoid its additional influence on vegetation cover. Analysis of 2011 data for this purpose included trees from both DHERB and CULT treatments because herbicide application had yet to start for the DHERB treatment, but in 2012 only CULT trees were used for this analysis. The response variable was BAI and the predictive variables were site, neighboring vegetation composition, abundance, proximity, and their combinations. Table 2-2 presents the mean cover values of the vegetation variables. In these models vegetation composition was percent cover by plant growth form rather than individual species (Appendix 2-4). Our rationalization for this approach is that plant species of the same growth form have similar competitive mechanisms for resources and are therefore likely to have similar effects on crop trees (Balandier et al. 2006). In addition, as weed control measures in silvicultural applications are likely to vary by growth form, this approach maintains linkages to subsequent plantation management.

The analysis was conducted using univariate regression trees generated by the *rpart* package with R version 2.2.1. software (R Devopment Core Team 2013). Regression trees along with classification trees, collectively known as CART (Classification and Regression Trees), were first developed into a software program by Breiman et al. (1984), but have since been adopted by other statistical packages. The primary advantage of tree-based models is that they are able to capture relationships difficult to detect with conventional linear models due to their ability to use unbalanced and non-parametric data with collinear variables, as well as a mix of categorical, continuous, and rank variables within a single analyses (De'ath 2002; De'ath and Fabricius 2000; McCune and Grace 2002). The output of tree models is a decision tree diagram that is easy to interpret visually, and is used for purposes of predicting and understanding the influence of multiple predictor variables on a response. Regression trees differ from classification trees by having a continuous response variable, whereas classification trees feature only categorical responses.

Regression tree analyses were performed for each of the 2011 and 2012 growing seasons. Each regression tree was first grown to its full size, but then pruned to minimize the cross-validated relative error so as to avoid overfitting of the data. Alternative primary splits and surrogate splits are produced for each tree node and reported in Appendix 2-5. Examination of the alternative splits allows comparison of the split strength of the selected explanatory variable to that of the best splits of the remaining variables (De'ath and Fabricius 2000). Surrogate splits are used in cases when the selected primary split is missing, but a surrogate variable which closely agrees with the primary split for the division of cases into two groups can be utilized as a substitute (De'ath and Fabricius 2000). As a part of the *rpart* routine, each time a variable was used as part of either a primary or surrogate split, a goodness of split measure was calculated and later summed to calculate variable importance (Therneau and Atkinson 2013). The variable importance indices were scaled to 100 and later converted to dot plots to visually represent variable importance, and are presented along with each tree.

To identify specific plant species - rather than growth form - as potential determinants of tree growth, we used ordination analysis applied to a dataset of trees from the CULT treatment. This was first done with all sites combined and then again on a site-by-site basis. The purpose for analysis of individual sites was to view tree BAI-species relationships independent of possible site influences. Aggregate cover data (0-105 cm) of neighboring vegetation averaged over all assessed quadrats for each tree from both the 2011 and 2012 growing seasons was used as the species dataset in the ordinations. To provide insight into the relationship between tree growth and neighboring vegetation, symbol sizes for individual trees in the ordination plots were adjusted to be directly proportional to BAI. The ordination method used was Nonmetric Multidimensional Scaling (NMDS) with a Bray-Curtis (Sørensen) distance measure, which is a powerful distance-based ordination technique that uses an iterative process to fit the original data into a best-fit ordination (McCune and Grace 2002). It is well-suited for analyzing community data and can handle non-normal datasets containing many zero values with ease. Analysis used the "isoMDS" and "metaMDS" function in the *vegan* package in R (R Devopment Core Team 2013), which rotates the resulting axes so that site variance is maximized along the first axis. Prior to analysis the community data were standardized using a Wisconsin double standardization, a process which often improves ordination quality (Oksanen 2013). In order to determine the appropriate dimensionality of the final configuration, scree plots were constructed to assess the number of dimensions versus their corresponding stress values. This initial analysis was completed with a step-down procedure utilizing 1-10 dimensions, up to 50 runs, and random starting locations to avoid local minima and search for a global solution. The initial runs indicated that a three dimensional solution was optimal. The final run used a three dimensional solution, with up to 1000 runs and random starting locations. Final stress values were between 0.10 and 0.19, which is in the acceptable range for reliable NMDS configurations (Clarke 1993). A Pearson correlation value with the axis of $|r| > 0.3$ was used as a cut-off for inclusion of species vectors in the ordination plots. To assist with interpretation of the plots an estimation of species variance as captured by each axis was obtained by calculating the correlation with axis loadings and the original dissimilarity matrix.

Indicator Species Analysis (ISA) was used in conjunction with NMDS to identify specific plant species associated with the different sites (De Caceres and Legendre 2009; Dufrêne and Legendre 1997). A total of 9999 permutations were run to test the results for significance. The ISA method used followed the original IndVal function of Dufrêne and Legendre (1997). For this analysis we used the "multipatt" function in the *indicspecies* package in R (R Devopment Core Team 2013).

2.2.4.2 Effectiveness of vegetation suppression treatments **-** The effectiveness of vegetation suppression treatments on tree survival and growth was assessed using categorical analysis and a mixed model ANCOVA, respectively, both performed with SAS 9.2 software (SAS institute Inc. 2008). Tree survival was analyzed using the PROC CATMOD procedure for the period encompassing spring 2011 to autumn 2012, with 'site', 'treatment', and 'site*treatment' interaction as fixed factors. Tree growth was analyzed for each of the 2011 and 2012 growing seasons to evaluate differences in mean BAI ($\alpha = 0.05$) using the PROC MIXED procedure. Initial tree basal area from the beginning of the growing season was used as a covariate in these analyses to account for variation in BAI means as a reflection of initial tree size. Due to large differences in vegetation composition among sites, each site was analyzed separately for tree growth responses. Visual assessments of residual distributions and scatterplots of predicted versus residual values determined that in all cases but one, assumptions of normality and homogeneity of variance were met. Data from the 'Farmyard' site in 2012 were highly non-normal and it was not possible to achieve normality through transformations. Thus, a

Kruskal-Wallis test was employed on data from the ‘Farmyard’ site to test for differences among treatments. If a significant treatment effect was found in a site, then a Tukey’s Honest Significant Difference (HSD) post-hoc test was used to test for differences among treatments.

Indicator Species Analysis (ISA), using the same methods as before, was performed to identify specific plant species associated with the individual treatments. An additional series of NMDS ordinations, also utilizing the same procedure as described above, was done for trees in all treatments to examine detailed patterns of weed communities (including specific species) as a function of sites and treatments. The data used in the analysis came from the aggregate cover data (0-105 cm) of neighboring vegetation averaged over all assessed quadrats for each tree from the 2012 (i.e. final) growing year when all trees received assessments. A BAI vector was overlaid on the ordinated community data to make an indirect gradient analysis to visually observe how both treatments and species composition were related to tree growth.

To ascertain differences in composition of the competing vegetation among treatments, we used distance-based permutational multivariate analysis of variance (PerMANOVA) to test for differences in vegetation composition among the treatments; this was completed for each site separately using the 2012 vegetation data - the same vegetation data as the NMDS analysis (Anderson 2001; McArdle and Anderson 2001). This analysis was appropriate for testing these data as it requires no assumptions of normality. Analysis was performed with a Bray-Curtis distance measure on average species cover with 10,000 permutations to calculate significance. Significant results were followed by post-hoc tests consisting of pair-wise comparisons among treatments in each site with a Bonferroni correction of alpha. The PerMANOVA analysis was completed using the “adonis” function in the *vegan* package in R (R Devopment Core Team 2013).

2.3 Results

2.3.1 Question 1 – Effects of vegetation composition, abundance, and spatial proximity

Tree growth in these plantations was highly influenced by site, but competing vegetation – notably perennial grasses – was also important. Regression tree analysis of the 2011 data indicated that site was the primary variable which explained the most variation in tree BAI (Fig. 2-3). The first split in the regression tree was to divide the trees as belonging to either the more productive sites (Homestead and Back40) or the less productive sites (Rockpile and Farmyard). Note that the splits do not align with the soil data which suggest that Homestead and Rockpile are more similar to each other, and Back40 and Farmyard are also similar, indicating that competing vegetation must be playing a role in determining site productivity. Examination of the alternative and surrogate splits (Appendix 2-5) suggested that perennial grass cover in any of the assessed quadrats could be alternatively used to split the trees into more or less productive individuals, indicating a negative collinearity between perennial grass cover values and tree growth, regardless of the proximity of perennial grass cover to the tree base. In all cases involving the use of perennial grass cover as a splitting variable in place of site, the critical splitting point occurred when grass cover was above or below 7 %.

Following the initial split into sites, the next factor determining tree growth in the less productive group was whether the total cover of all competing vegetation in the entire 0-105 cm assessment strip was greater than 11.6 % (Fig. 2-3). Trees with this level of competing vegetation or higher, had BAI values as little as 0.81 cm^2, which represented a 69 % yield loss compared to trees in the same sites with lower levels of neighboring vegetation. As an alternative or surrogate split, cover of all competing vegetation species, or just the cover of perennial grass species in any of the individual quadrats, could potentially be utilized in place of total aggregate cover. When using the cover values of all species to split the dataset, critical values occurred between about 8 and 15%, although with perennial grass cover the selected splitting points all occurred at less than 4% cover. All other individual splits in the regression tree model for the 2011 data explained only 3% or less of the total variation in BAI. The variable importance measure for the 2011 data (Fig. 2-4) suggested that site was clearly the most important variable determining tree BAI, and that presence of perennial grass cover in any of the quadrats was highly important as well. Total cover in the furthest quadrat (70-105 cm) was similarly determined to be highly related to tree growth. It is important to mention that although site was determined to be highly important, we cannot definitively separate site effects from vegetation effects, as vegetation composition and abundance was highly confounded with site.

In 2012 the variable ‘site’ remained the primary variable explaining most of the variation in tree BAI, about 26.4 %, although it seemed to have less influence than in 2011 (Fig. 2-5) when it could potentially explain 51.3 % of the variation in tree BAI. Regression tree analysis of the 2012 data also differed from 2011 in that the lone productive site was Homestead, while Back40 was grouped with the less productive Rockpile and Farmyard sites. The alternative and surrogate splits (Appendix 2-5) suggested that perennial grass cover of any of the assessed quadrats could have been used in place of site for that first node, with the critical values being between 10% and 20%, depending on distances from the tree base.

After using site to split the trees into more or less productive individuals, the next factors used in determining splits for the less productive sites in 2012 were the total cover of all species in the furthest (70-105 cm) quadrat (Fig. 2-5). Trees in those sites with cover greater than or equal to 15.8 % at this proximity had BAI values 63 % less than those trees which had less cover in that quadrat. The slightly weaker splits found by the alternative and surrogate splits (Appendix 2-5) use cover values from perennial grasses or total species cover in any of the measured quadrats to divide the data. The critical values for total species cover were between 15 and 30 %, and for perennial grasses they were between 8 and 20%, which suggests that on a per unit area that grasses may be more detrimental to tree BAI than total cover. In the 2012 variable importance measure (Fig. 2-4), site was again identified as the most important variable, and total species cover in the 70-105 cm quadrat as the next most important.

Due to similar explanatory power of different vegetation variables - as suggested by the alternate and surrogate splits (Appendix 2-5) - it is difficult to pinpoint exactly which variables are most influential on tree BAI. However, judging from the collective results of the regression trees, alternative and surrogate splits, and variable importance measure, it is likely that perennial grass is the form of competing neighbor vegetation that is most detrimental to hybrid poplar growth, a result that occurred largely at the Rockpile site. It is also notable that the point at which the critical cover values of perennial grasses occurred was lower in less productive sites than in all sites combined. Lastly, the higher critical values of the 2012 data and compared to 2011, along with the reduced ability of the 2012 regression tree to explain variation in tree growth as a product of competing vegetation, indicates that younger trees are more susceptible to competition while older trees are less influenced by their presence.

It should be mentioned that while the site was confounded by vegetation (hence possible non-independence of effects), that site was likely no longer an important variable in the regression tree in both years following the initial split into the more or less productive sites. This is because upon examination of the alternative and surrogate splits (Appendix 2-5) site was never again found to be a variable that could be used to explain more than small variations in tree growth, whereas the vegetation variables were found by the analysis to be much better than site in explaining subsequent variation in tree growth.

Specific species, *Elytrigia repens* (quackgrass) and *Cirsium arvense* (Canada thistle) in particular, in addition to growth forms, were also identified as being detrimental to hybrid poplar growth. This was not true across all sites, however, because tree growth and neighboring vegetation communities in CULT trees were highly dependent on site, as was evident from the NMDS of all sites combined (Fig. 2-6). Axes 1, 2 and 3 accounted for 41.4 %, 17.6 % and 4.2% of species variance, respectively. A total of 19 species were strongly ($|r| > 0.3$) correlated with the NMDS ordination axes (Table 2-3), which included a mix of perennial grasses, as well as both annual and perennial forbs. Ordinations depicting tree BAI- species relationships indicated that BAI followed a gradient negatively associated with the *Elytrigia repens* species vector, and positively with the *Taraxacum officinale* (dandelion) vector when all sites are included in the same ordination (Fig. 2-6).

The ISA showed significant indicator species for all four sites (Table 2-4). Indicators included three perennial forbs, one perennial grass, and eight annual forbs at the ‘Homestead’ site (Table 2-4). In ‘Rockpile’ two perennial forbs, two perennial grasses, and two annual forbs were identified as significant (Table 2-4). In ‘Farmyard’ one perennial forb, one perennial grass, and three annual forbs were found to be indicators (Table 2-4). Lastly, in Back40 indicator species included only one perennial forb and one annual forb (Table 2-4). The contrasting importance of specific species among individual sites may help to explain differences in BAI between the locations, especially the affinity of *Elytrigia repens* for the Rockpile site and correspondingly low BAI values (Fig. 2-6).

Further NMDS analyses performed individually for ‘Homestead’, ‘Rockpile’, ‘Farmyard’, and ‘Back40’ sites obtained final stress values of 0.1648, 0.1125, 0.1482, and 0.1663, respectively (Fig. 2-7). Pearson correlations ($|r| > 0.3$) between species vectors with the ordination axes uncovered numerous correlations (Table 2-5). *Cirsium arvense* was associated with reduced BAI in the Homestead and Rockpile sites, *Elytrigia repens* was related to low BAI values in the Homestead, Rockpile, and Farmyard sites, and *Thlaspi arvense* appeared to be negatively associated with BAI in the Rockpile site (Fig. 2-7).

Definitive evidence of facilitation between neighboring vegetation and tree growth was not clearly evident. In only a few of the selected splits of the final regression trees (Fig. 2-3 and 2-5) and in the summary of alternative and surrogate splits (Appendix 2-5) did increasing vegetation increase tree growth. In these cases the splits had either very little explanatory power or were used simply as a surrogate for planting site. The results of the NMDS analysis also did not identify specific species as facilitators, as what might be expected with nitrogen-fixing species (e.g. *Trifolium* ssp. and *Medicago sativa*). Consistent, positive relationships between BAI and a species or growth form among the sites is required before we can conclude that facilitation was present.

2.3.2 Question 2 – Influence of suppression treatments on trees and vegetation

By autumn of 2012, 41 hybrid poplar trees (7.3% of all trees) had died, not including those that died due to non-competitive injuries (insect, herbicide, or cultivator damage). No significant effects of treatment, site, or site*treatment were found to influence tree mortality (Table 2-6), and both the ‘Homestead’ and ‘Back40’ sites had 100% survival. When the analysis was re-run including only the Rockpile and Farmyard sites (where mortality did occur), no significant effects of treatment, site, or site*treatment were observed (Table 2-6), suggesting mortality of hybrid poplar was consistent regardless of silvicultural treatment.

The impact of the vegetation suppression treatments on tree growth was highly dependent on site and was not significant until the end of the second growing season following treatment application. In 2011 no effects of the treatments were observed at any of the sites (Fig. 2-8), although initial basal area (BA), as measured in the spring of 2011, was a significant covariate across all sites (Table 2-7). These results differed from the 2012 data when vegetation suppression treatments were found to be significant at both the 'Homestead' and 'Farmyard' sites ($p = 0.003$ and $p < 0.0001$, respectively), but not the 'Farmyard' and 'Back40' sites ($p = 0.17$ and $p = 0.20$, respectively) (Table 2-7). Pairwise comparisons using Tukey HSD post-hoc tests revealed that trees in 'Homestead' that received the CULT treatment had lower BAI than trees in all other treatments (Fig. 2-8). In 'Rockpile', the HERB treatment trees had significantly greater BAI than all other treatments, and the CULT treatment trees at this location had lower BAI than the HERB and BAU, but not the DHERB, treatments (Fig. 2-8). Initial BA, as measured in the spring of 2012, was again used as a covariate and found to be significant for both the Homestead and Rockpile sites (Table 2-7).

An ISA suggests that the effect that the treatments had on the vegetation communities was for most species to be eliminated in the HERB and DHERB treatments, while perennial grass species became most closely associated with the CULT treatment (Table 2-8). Indirect gradient analysis of 3-dimensional NMDS ordinations obtained final stress values of 0.1964, 0.1753, 0.1474, and 0.1101 for the 'Homestead', 'Rockpile', 'Farmyard', and 'Back40' sites, respectively (Fig. 2-9). Pearson correlations ($|r| > 0.3$) between species vectors and the BAI vector with the ordination axes uncovered frequent correlations (Table 2-9). Species negatively associated with BAI included *Cirsium* *arvense* in Homestead, *Elytrigia repens* in Rockpile and Farmyard, and *Poa palustris*, *Phleum pratense* and *Trifolium* ssp. in Rockpile. With the exception of *Cirsium arvense*, all species negatively linked with BAI were also significant indicators for the CULT treatment, thereby providing evidence for why trees in the CULT treatment had the lowest BAI values of all treatments when significant differences were detected.

PerMANOVA tests verified that all sites had differences in vegetation composition between treatments ($p < 0.0001$) (Table 2-10a). Post-hoc comparisons of treatments with Bonferroni adjusted alpha revealed that most treatments had significantly different vegetation communities, with the exception of the HERB and DHERB treatments in the 'Homestead' site, and between the BAU and CULT treatments at 'Farmyard' (Table 2-10b).

2.4 Discussion

This study is unique from previous investigations examining competition with hybrid poplar trees in that it exploited operational field conditions and relied on iterative and regression processes with large datasets to find patterns of association between trees and complex assemblages of neighboring vegetation. Much previous work either took place under highly controlled conditions such as pot experiments (Kabba et al. 2007; Messier et al. 2009) or else competition was simply broadly quantified as the presence or absence of certain species (Otto et al. 2010; Pinno and Belanger 2009). However, despite our efforts to discern relationships between competing vegetation and tree growth, the primary determinant of tree productivity in this study was planting (i.e. site) conditions, followed by perennial grass abundance, and then total neighboring vegetation.

2.4.1 Influence of planting site, vegetation composition, abundance, and proximity on tree growth

2.4.1.1 Site effects - The selected study sites were unique both in terms of vegetation and abiotic conditions; thus, separating the influence of the two is difficult because most of the measurements were focused on the biotic environment. Soil measurements potentially explained some of the variation in tree growth among sites. The most productive site overall was Homestead, which possessed edaphic conditions most closely aligned to those identified for peak productivity under the climatic conditions of Alberta's boreal forest region (Pinno et al. 2010). The work of Pinno et al. (2010) identified the most productive sites for hybrid poplar clone Brooks 6 (*Populus deltoides* x (*P. laurifolia* x *P. nigra*) as those with relatively high sand content (55-70%) and soil pH of approximately 6. They hypothesized that this soil texture maintained ideal conditions of adequate moisture with good drainage and aeration, while soil pH optimized nutrient availability. Despite this, in our study the Rockpile site, which had soil conditions similar to Homestead, in addition to a greater sand content that brought it closer to the 'ideal', was the least productive. We speculate that the reduction in growth at Rockpile was due to the intense competition caused by abundant perennial grasses (see below), but also because this location was situated on imperfectly drained land at the bottom of a slope, which is considered less suitable for hybrid poplar growth (Stanturf 2002). Additionally, while the genetic backgrounds between the Walker clone used in this study, and the Brooks6 clone used in the study by Pinno et al. (2010), are similar, they are not identical, and therefore are likely to respond differently to abiotic conditions.

Differences in soil nutrition among sites may also explain the variation in tree growth. Trees in the Farmyard site, despite having access to high levels of available soil nitrogen, grew less than trees in all other sites, with the exception of those at Rockpile.

This is possibly due to the fact that a large proportion of the available nitrogen in the Farmyard site was in the form of nitrate (NO_3), which previous fertilization studies have found may adversely influence growth of the ‘Walker’ clone (DesRochers et al. 2006; DesRochers et al. 2007). It is also possible that the trees in the Rockpile site grew less because of the high abundance of perennial grasses and annual/biennial forbs in that site that would have competed for soil resources.

2.4.1.2 Influences of competition- Our finding of the detrimental impact of perennial grass cover on tree growth is well supported in the literature. Pot experiments with hybrid poplar have shown a negative influence of grasses on tree growth, and this is due to reduction of nutrient uptake (Kabba et al. 2007) and competition for root space resulting in reduced fine root growth and root branching (Messier et al. 2009). Other studies in natural *Populus tremuloides* forests grown in association with *Calamagrostis canadensis*, a common perennial grass in Alberta’s boreal forest, found that the grass reduced available light, soil moisture, and nutrient resources (Powell and Bork 2004a, b), and produces an insulating mat of litter that reduces soil temperatures (Hogg and Lieffers 1991), and consequently decreases tree growth (Landhausser and Lieffers 1998). This is not unlike some areas of the study sites examined here where perennial grass cover was extensive and dead shoots formed a thick layer of matted litter.

One species of perennial grass is particular, *Elytrigia repens* (quackgrass), appeared to be especially deleterious for hybrid poplar growth. This effect was noted among CULT treatment trees in the Homestead, Rockpile, and Farmyard sites; *Elytrigia repens* was not present in the Back40 site. The key morphological characteristic of *Elytrigia repens* that makes it an effective competitor is its ability to form a dense sod from aggressively spreading rhizomes (Werner and Rioux 1977); this sod can efficiently tie up soil nutrients (Kabba et al. 2007; Werner and Rioux 1977) and also produce allelopathic substances known to reduce the growth of other species (Schulz et al. 1994).

Another competing species that was linked with reduced tree growth in this study was *Cirsium arvense* (Canada thistle), a widespread invasive perennial forb and among the most frequently recognized noxious weeds in North America (Skinner et al. 2000). Among the sites containing moderate populations of *Cirsium arvense* (i.e. Homestead and Rockpile), a negative relationship between its abundance and tree growth was detected. The marked competitive ability of *Cirsium arvense* arises from its extensive root system, which permits efficient capture of soil nutrients and moisture (Donald 1990), and its large aerial shoots, which help it intercept available light (Moore 1975). *Cirsium arvense* is also similar to *Elytrigia repens* in that it may exhibit an allelopathic effect on other plants (Stachon and Zimdahl 1980). Finally, observation of trees near which *Cirsium arvense* was growing revealed noticeable damage to bark tissue on saplings, possibly a result of friction with *Cirsium arvense*'s characteristic thorns or well lignified stems and branches when they mature at an approximate height of 30-150 cm (Moore 1975). While remaining untested here, we speculate that this weed may interrupt the translocation of water and nutrients within the trees, and warrants further investigation.

In contrast with perennial grasses there was relatively less affiliation between tree growth and the overall total abundance of annual or perennial forbs. At the species level, with the exception of *Cirsium arvense* (see above), no other forbs were definitively linked with reduced BAI values. Our overall finding that hybrid poplar tree growth is more susceptible to competition from perennial grasses than forbs is consistent with studies done on other tree species, including seedlings of *Fagus sylvatica* (Coll et al. 2003), *Betula pendula* (Willoughby et al. 2006) and *Pinus ponderosa* (Elliott and White 1987).

The lower critical cover values of perennial grass abundance compared to total vegetation abundance, in both 2011 and 2012, is further testament to our conclusion that perennial grasses are the most detrimental form of competing vegetation for hybrid poplar trees. These low critical values (< 7 % of perennial grass cover in 2011 and 7-20 % of perennial grass cover in 2012) represent a threshold between relatively high and low impacts and attests to the importance of controlling vegetation abundances before they reach highly growth-damaging levels. Additionally, the overall lower critical cover values in 2011 than 2012 suggests that hybrid poplar are more sensitive to competition when younger, a conclusion also reached by others (Otto et al. 2010; Shock et al. 2002). Shock et al. (2002) observed that by the third year of growth hybrid poplar were less affected by competing weeds. This may account for why the regression tree analysis explained less variation in tree growth as a product of competing vegetation in 2012 than the year before, as 2012 was the third year of growth for our trees.

The relatively high importance value of total competing vegetation abundance in the 70-105 cm quadrat in both 2011 and 2012 (Fig. 2-4) was somewhat surprising. Coll et al. (2007) emphasized the importance of local vegetation control (0-0.5 m from tree base) in newly planted hybrid poplar plantations, which resulted in about the same amount of tree growth as total vegetation control. Similar conclusions were reached for hybrid poplar plantations in coastal British Columbia (Thomas et al. 2001), as well as for other species, such as *Pseudotsuga menziesii* (Rose and Rosner 2005) and *Pinus radiata* (Woods et al. 1992). As young hybrid poplar roots can reach well into the alleyways between trees (Friend et al. 1991) where competition for soil resources with inter-row vegetation is likely to occur, it is not surprising that competition extend out to that distance. However, it is also unclear whether the relationship observed represents a negative causal impact of vegetation on tree growth, or if competing vegetation may have proliferated to a greater extent in that distance interval because smaller trees would impose less competition on neighboring vegetation beyond 70 cm. Furthermore, rank correlation analysis revealed that vegetation abundance within 70-105 cm from the tree stem was highly correlated with total vegetation abundance at 0-105 cm from the tree stem (data not shown). For this reason, the results of the variable importance measure should be viewed with caution. Further manipulative experiments to assess the impact of proximal and distal vegetation impacts on hybrid poplar are needed.

2.4.2 Comparison of weed suppression treatments

The lack of a same-year tree growth response to vegetation control treatments in the first year of treatment is not unusual within young hybrid poplar plantations (Coll et al. 2007). In addition to biological time lags associated with tree growth following competition release, we speculate the lack of differences is also partly due to the fact that the HERB and CULT treatments did not commence until early July of 2011. The following year there was a continued lack of response among trees to treatment in the Farmyard and Back40 sites (both located at the Berquist plantation), despite the nearly complete removal of all vegetation in 1.4 m radius around each HERB and DHERB treatment tree. Given our limited knowledge of the abiotic conditions the definitive cause for the lack of response in the Farmyard and Back40 sites cannot be determined; however, as previously discussed, the edaphic conditions for at least the Farmyard site are not ideal for hybrid poplar growth. On low quality sites such as Farmyard, previous research suggests that competition intensity is low, and consequently, the benefits of vegetation control may be less than on high quality sites (Pinno and Belanger 2009). Additionally, the high availability of nitrogen on the Farmyard and Back40 sites may help alleviate competition between the trees and weeds, possibly explaining why no differences between the vegetation suppression treatments were observed.

In 2012 the two sites that did show differences among vegetation suppression treatments - Homestead and Rockpile - were both located in the Seim plantation. In both cases, trees in the CULT treatment demonstrated the least amount of growth, with the exception of the DHERB treatment trees in Rockpile. Controlling vegetation using only cultivation, as was the case with the CULT treatment, not surprisingly was ineffective for reducing weed biomass near the tree base (Coll et al. 2007). Additionally, cultivation may even help propagate some of the more harmful creeping perennial weeds such as *Elytrigia repens* and *Cirsium arvense* (Moore 1975; Werner and Rioux 1977). The association of numerous perennial grass species with the CULT treatment in those sites (Table 2-8) lends further support to this suggestion of why trees in the CULT treatment grew the least out of all the treatments.

One of the most telling results in this entire study is that trees in the HERB treatment at the Rockpile site grew more in 2012 than any other treatment at that location, including trees in the DHERB treatments, which received total vegetation control from the beginning of the third (2012) growing season. This suggests an important positive influence exists of early weed control from herbicides, and also that trees which experienced early yield losses are unable to rapidly make up for lost growth, a result mirrored by Otto et al. (2010). Longer term data is needed to test whether the trees can compensate for early yield losses given time to do so. We hypothesize that the extreme differences in tree growth among treatments in the Rockpile site can be attributed to high competition intensity between the trees and large abundance of neighboring perennial grasses, particularly *Elytrigia repens*, in that site. Netzer and Noste (1978) noticed similar results when using herbicides in vegetation suppression treatments that gave the most dramatic results on a sod-bound grassy site dominated by *Elytrigia repens*.

2.4.3 Challenges and future recommendations

Considerable unforeseen challenges in the form of widespread moose browse, late (and uneven) starting times of treatments, lack of detailed microclimatic and soil data, multiple-stemmed trees, and extensive correlations among independent variables, collectively imposed substantial limitations in the execution of this study and subsequent interpretation of results. Recommendations for future work are as follows:

1. Fence around field-scale research plantations to keep large browsing mammals out and allow for the accurate quantification of tree height and stem volume in addition to basal area.
2. Start tree measurements and vegetation suppression treatments immediately after tree planting to help reduce the variability in initial tree size.
3. Collect detailed measurements of soil moisture, temperature, nutrient availability, and available photosynthetically active radiation (PAR) around individual trees, as this information would greatly help in explaining the intensity of resource competition and specific causes for variability in tree growth.
4. Investigate if multiple-stemmed trees and single stem trees with equivalent starting basal areas accrue basal area at the same rate under identical conditions. If they do not, then only include single-stemmed trees in future studies.

2.4.4 Conclusion

Planting site was found to be highly important for determining hybrid poplar growth, although we cannot definitively state the magnitude of its importance because site was confounded by vegetation composition – each site had notably different community assemblages and dominant species. Among competing vegetation forms, perennial grasses were the most detrimental to tree growth, whereas with the exception of a few species, forbs as a group were generally less important competitors. Specific plant species that were particularly unfavorable for hybrid poplar trees were *Elytrigia repens* and *Cirsium arvense*. Hybrid poplars were also found to be more sensitive to competition when younger, and become more resistant to herbaceous competition as they get older. Using cultivation alone (the CULT treatment) to control competing vegetation was the least effective treatment option, and this practice tended to favor perennial grasses over treatments involving herbicide. However, on half of the sites no differences in growth were found between trees in the CULT treatment and any of the other treatments. On those sites where no growth differences were found, In sites where the competition intensity remained high, initiating vegetation suppression treatments early maximized tree BAI growth, and trees that received delayed vegetation control (i.e. when older) were not able to rapidly recover from the initial damage caused by competition.

Table 2-1. Physical and chemical properties of soils at the various study sites taken in late summer 2012.

Plantation	Site	Soil depth(cm)	Organic C (%)	pH	EC (mS/cm)	Total N (%)	NH_4 (mg/kg)	NO_3 (mg/kg)	Clay (%)	Silt (%)	Sand (%)
Seim	Homestead	0-15	4.6	5.9	118	0.19	2.35	12.83	18	50	33
		15-30	2.6	5.8	79	0.07	2.22	5.72	25	41	35
	Rockpile	0-15	4.6	6.4	108	0.21	3.36	12.05	16	50	34
		15-30	2.2	6.8	60	0.06	1.86	2.48	36	22	42
Berquist	Farmyard	0-15	10.9	7.6	396	0.49	1.59	60.16	25	54	20
		15-30	4.1	8.1	266	0.12	1.55	22.59	43	46	12
	Back40	0-15	6.2	7.5	413	0.27	1.47	37.67	26	51	22
		15-30	3.1	8.0	249	0.10	2.13	23.07	43	43	14

Table 2-2. Vegetation variables included in the regression tree models for hybrid poplar basal area increment (BAI). Values shown are mean percent cover ± standard deviation. Values are split between the sites and years that they were observed, in addition to their quadrat location (proximity) from the trees which received vegetation assessments. Refer to Appendix 2-4 for the growth forms of specific species.

Growth form	Proximity (cm)	Homestead		Rockpile		Farmyard		Back40	
		2011	2012	2011	2012	2011	2012	2011	2012
Total cover	0-105	15.4 ± 6.3	27.8 ± 6.0	34.1 ± 7.2	38.4 ± 6.5	12.4 ± 5.2	30.0 ± 10.7	7.9 ± 5.6	21.9 ± 9.3
Total cover	0-35	20.9 ± 11.9	32.5 ± 10.2	41.1 ± 10.5	42.3 ± 8.6	17.3 ± 11.8	36.4 ± 13.8	11.7 ± 11	28.3 ± 18.7
Total cover	35-70	14.0 ± 6.4	25.9 ± 7.0	33 ± 7.3	36.8 ± 6.3	11.9 ± 5.6	29.6 ± 12	8.1 ± 6.7	22.1 ± 8.9
Total cover	70-105	11.3 ± 5.2	24.9 ± 5.6	28 ± 7.7	36.2 ± 7.6	8.0 ± 4.5	24.0 ± 10.8	4.0 ± 3.8	15.3 ± 5.6
Perennial grass	0-105	2.7 ± 2.9	8.3 ± 6.8	19.9 ± 8.1	28.8 ± 7.4	2.9 ± 3.6	13.3 ± 9.9	0.2 ± 0.3	0.8 ± 1.7
Perennial grass	0-35	3.3 ± 5.1	8.8 ± 7.7	21.9 ± 11.9	31.1 ± 10.3	5.1 ± 8.0	16.1 ± 10.6	0.2 ± 0.4	1.9 ± 4.2
Perennial grass	35-70	2.6 ± 3.0	8.9 ± 7.8	20.7 ± 8.3	29.2 ± 6.4	2.5 ± 3.1	13.7 ± 11.7	0.2 ± 0.3	0.5 ± 1.3
Perennial grass	70-105	2.1 ± 1.9	7.3 ± 6.4	17.1 ± 7.6	26.0 ± 7.4	1.2 ± 1.8	10.0 ± 9.5	0.2 ± 0.3	0.1 ± 0.3
Perennial forb	0-105	6.7 ± 6.8	11.5 ± 6.3	4.4 ± 4.0	8.2 ± 3.6	3.3 ± 4.6	6.4 ± 5.4	6.1 ± 5.6	13.3 ± 10.2
Perennial forb	0-35	10.0 ± 12.5	14.0 ± 9.0	5.9 ± 5.7	9.7 ± 6.0	6.7 ± 10.5	11.2 ± 10.8	9.4 ± 10.7	20.1 ± 18.5
Perennial forb	35-70	5.8 ± 6.8	10.1 ± 6.8	3.8 ± 4.1	6.8 ± 4.0	2.4 ± 3.9	5.9 ± 6.0	6.0 ± 6.7	13.9 ± 11.0
Perennial forb	70-105	4.3 ± 4.9	10.4 ± 6.4	3.4 ± 3.7	8.2 ± 2.6	1.0 ± 3.0	2.3 ± 3.2	2.8 ± 3.5	5.8 ± 5.2
Annual forb	0-105	6.0 ± 3.9	7.8 ± 6.0	9.8 ± 4.5	1.4 ± 0.9	6.1 ± 3.6	10.3 ± 6.4	1.7 ± 2.4	7.8 ± 5.9
Annual forb	0-35	7.5 ± 6.6	9.4 ± 8.2	13.4 ± 7.9	1.4 ± 1.0	5.5 ± 5.7	9.1 ± 7.5	2.1 ± 4.8	6.3 ± 9.9
Annual forb	35-70	5.7 ± 4.5	6.9 ± 6.7	8.6 ± 4.4	0.9 ± 1.0	7.1 ± 4.7	10 ± 6.8	1.9 ± 2.6	7.8 ± 5.1
Annual forb	70-105	4.9 ± 3.0	7.2 ± 4.8	7.5 ± 3.9	2.0 ± 1.6	5.9 ± 3.4	11.7 ± 6.6	1.0 ± 1.4	9.5 ± 5.9

Table 2-3. Pearson correlations of species vectors with each axis from the NMDS ordinations represented in Fig. 2-6. Vectors with |*r*| > 0.3 were considered to be correlated and are bolded.

	NMDS ordination axis		
	Axis 1	Axis 2	Axis 3
Species	*r*	*r*	*r*
Plant spp. variance explained	41.4%	17.6%	4.2%
Cirsium arvense	-0.203	0.180	**0.401**
Crepis tectorum	0.173	**0.400**	0.045
Descurainia sophia	0.219	**-0.429**	0.257
Draba nemorosa	**-0.366**	-0.138	**-0.415**
Dracocephalum parviflorum	-0.133	0.036	**0.305**
Elytrigia repens	**-0.530**	**-0.619**	-0.255
Galeopsis tetrahit	-0.206	0.025	**0.362**
Gnaphalium palustre	-0.101	**0.310**	0.068
Medicago sativa	**0.532**	0.015	**-0.373**
Phleum pratense	**-0.451**	-0.292	**-0.376**
Plantago major	**-0.478**	0.075	-0.227
Poa palustris	**-0.302**	0.072	0.293
Poa pratensis	0.245	-0.123	**0.317**
Potentilla norvegica	**-0.798**	0.120	0.030
Silene alba	-0.045	0.109	**-0.342**
Silene noctiflora	-0.215	-0.062	**-0.330**
Taraxacum officinale	-0.171	**0.764**	-0.145
Thlaspi arvense	**0.706**	**-0.384**	0.126
Trifolium ssp.	**-0.515**	-0.263	**-0.399**

Table 2-4. Results of indicator species analysis (ISA) based on site. Data are drawn from the aggregate cover data averaged over all assessed quadrats (0-105 cm) from the 2011 and 2012 growing seasons from the CULT treatment trees. Listed are all indicator species with corresponding indicator values. Significant indicator values are bolded ($p < 0.05$).

Species	Homestead	Rockpile	Farmyard	Back40
Cirsium arvense	**46.3**	0.5	0.0	0.0
Dracocephalum parviflorum	**41.1**	0.0	0.0	0.1
Galeopsis tetrahit	**48.6**	2.9	7.9	0.1
Geranium bicknellii	**12.7**	0.6	0.0	0.0
Gnaphalium palustre	**27.6**	0.0	0.0	5.2
Melilotus officinalis	**22.9**	0.0	0.0	0.0
Plantago major	**39.4**	34.7	0.0	0.0
Poa palustris	**58.7**	8.9	21.2	6.4
Polygonum convolvulus	**41.1**	1.5	21.3	9.1
Polygonum lapathifolium	**17.1**	0.0	0.0	0.0
Potentilla norvegica	**67.1**	32.9	0.0	0.0
Taraxacum officinale	**50.7**	10.8	1.3	36.1
Draba nemorosa	0.3	**67.7**	0.0	1.0
Elytrigia repens	16.9	**53.3**	27.0	0.0
Phleum pratense	0.1	**92.3**	0.5	0.0
Silene noctiflora	0.7	**25.2**	0.1	0.8
Trifolium ssp.	9.2	**84.9**	0.2	0.1
Vicia americana	3.6	**26.6**	0.0	0.0
Chenopodium album	2.2	9.4	**52.6**	7.5
Desurainia Sophia	0.7	0.0	**88**	0.1
Poa pratensis	0.1	0.0	**42.3**	18.5
Thlaspi arvense	3.4	1.8	**53.1**	40.8
Urtica dioica	0.0	0.2	**13.7**	0.2
Crepis tectorum	20.4	11.1	0.4	**42.4**
Medicago sativa	0.3	0.1	25.7	**55.1**

Table 2-5. Pearson correlations of species vectors with each axis from the NMDS ordinations represented in Fig. 2-7. Vectors with |*r*| > 0.3 were considered to be correlated and are bolded.

		NMDS ordination axis		
		Axis 1	Axis 2	Axis 3
Site	Species	*r*	*r*	*r*
Homestead	Plant spp. variance explained	25.9%	19.4%	0.04%
	Bromus inermis	**-0.429**	0.069	-0.067
	Chenopodium album	**-0.701**	0.006	0.012
	Cirsium arvense	**-0.854**	-0.156	0.061
	Crepis tectorum	0.175	0.043	**0.449**
	Descurainia sophia	0.095	-0.056	**0.365**
	Dracocephalum parviflorum	**-0.315**	-0.171	-0.106
	Elytrigia repens	0.080	**-0.748**	-0.137
	Equisetum arvense	0.053	-0.081	**-0.516**
	Equisetum palustre	0.087	-0.092	**-0.533**
	Geranium bicknellii	0.043	**-0.463**	**0.381**
	Gnaphalium palustre	**0.333**	0.186	**0.689**
	Medicago sativa	**-0.357**	0.156	-0.028
	Plantago major	0.115	**0.637**	-0.173
	Poa palustris	**0.502**	0.071	-0.226
	Polygonum convolvulus	-0.007	**0.492**	0.083
	Polygonum lapathifolium	0.060	-0.002	**-0.449**
	Potentilla norvegica	**0.470**	0.001	-0.193
	Silene noctiflora	-0.033	**0.470**	**-0.301**
	Stellaria media	0.143	**-0.550**	0.019
	Taraxacum officinale	0.110	**0.688**	0.087
	Thlaspi arvense	-0.080	**0.363**	-0.163
	Trifolium ssp.	**0.428**	-0.022	-0.232
	Veronica peregrina	**0.461**	-0.267	0.066
Rockpile	Plant ssp. variance explained	20.7%	0.1%	10.7%
	Artemisia biennis	0.222	0.178	**-0.435**
	Carex ssp.	0.160	**0.302**	0.020
	Chenopodium album	-0.086	-0.176	**-0.381**
	Cirsium arvense	**0.598**	**-0.317**	0.073
	Crepis tectorum	**-0.380**	0.298	**0.311**
	Draba nemorosa	**0.364**	**-0.377**	**-0.308**
	Elytrigia repens	-0.188	0.124	**0.679**
	Equisetum palustre	-0.112	**0.420**	-0.144
	Equisetum sylvaticum	**-0.559**	**-0.457**	0.202
	Galeopsis tetrahit	-0.187	-0.145	**-0.331**
	Geranium bicknellii	**-0.330**	0.196	0.252
	Medicago sativa	**-0.549**	-0.045	-0.116
	Phleum pratense	**-0.392**	**0.326**	**-0.721**
	Plantago major	-0.034	**0.327**	-0.036
	Poa palustris	0.216	**0.521**	**-0.443**
	Polygonum convolvulus	**0.443**	0.147	0.009
	Potentilla norvegica	**0.645**	0.104	-0.160

	Silene alba	**0.776**	-0.113	-0.050
	Silene noctiflora	**0.666**	**-0.396**	-0.098
	Taraxacum officinale	**-0.467**	**-0.427**	**-0.300**
	Thlaspi arvense	**0.464**	-0.280	0.218
	Trifolium ssp.	**0.444**	0.178	-0.257
	Urtica dioica	-0.031	**-0.318**	-0.217
	Vicia Americana	-0.267	**-0.34**	-0.195
Farmyard	Plant spp. variance explained	30.3%	2.4%	8.8%
	Chenopodium album	**0.449**	0.150	-0.039
	Crepis tectorum	**0.639**	0.084	-0.090
	Descurainia sophia	-0.269	**-0.495**	-0.029
	Elytrigia repens	**-0.478**	0.017	**-0.637**
	Galeopsis tetrahit	**-0.360**	**-0.398**	**0.460**
	Hordeum jubatum	**-0.318**	-0.092	**0.382**
	Medicago sativa	**0.729**	**-0.326**	-0.252
	Phleum pratense	-0.125	-0.004	**-0.305**
	Poa palustris	0.170	-0.084	**0.323**
	Poa pratensis	**-0.362**	-0.221	**0.453**
	Polygonum convolvulus	0.276	0.153	**0.603**
	Taraxacum officinale	0.200	**-0.710**	0.088
	Thlaspi arvense	-0.165	**0.509**	0.258
	Trifolium ssp.	-0.259	0.038	-0.266
	Urtica dioica	**-0.439**	-0.290	-0.101
Back40	Plant ssp. variance explained	14.2%	18.4%	1.1%
	Artemisia biennis	0.066	**-0.316**	0.092
	Chenopodium album	0.249	0.070	**0.433**
	Crepis tectorum	**0.336**	0.106	**0.763**
	Galeopsis tetrahit	0.223	0.181	**0.482**
	Medicago sativa	0.131	**0.684**	**-0.429**
	Poa palustris	**-0.596**	-0.293	0.023
	Poa pratensis	**-0.458**	**-0.402**	0.276
	Polygonum convolvulus	**-0.331**	-0.153	0.144
	Silene alba	-0.051	-0.249	**-0.356**
	Sinapsis arvensis	0.056	-0.156	**-0.302**
	Stellaria media	**-0.483**	0.128	-0.068
	Taraxacum officinale	**0.667**	**-0.603**	-0.184
	Thlaspi arvense	**-0.624**	0.080	0.242

Table 2-6. Results of tree survival analysis with 'Treatment', 'Site' and 'Treatment*Site' as fixed factors. Site could not be tested as an effect when all sites were included because of 100% survival in the 'Homestead' and 'Back40' sites. Results were re-run with the remaining sites.

Sites	Effects	DF	Chi-square value	P-value
All sites	Treatment	3	0.000	1.0
	Site	3	.	.
	Treatment*Site	9	2.820	0.97
Farmyard and Rockpile	Treatment	3	7.010	0.07
	Site	1	0.000	0.95
	Treatment*Site	3	2.820	0.42

Table 2-7. Results of ANCOVA tests for differences in tree basal area increment (BAI) and initial basal area (BA) as a covariate between the four vegetation suppression treatments at each site. Data reported separately for each of the 2011 and 2012 growing seasons. Farmyard in 2012 was tested for treatment differences using a Kruskal-Wallis* test and returns a chi-squared value (Note: initial basal area could not be included as a covariate). Significant values are bolded ($p < 0.05$).

Year	Site	Effect	Num DF	Den DF	F-/Chi-square value	P-value
2011	Homestead	Treatment	1	101	0.39	0.54
		Initial BA	1	101	107.09	**<0.0001**
	Rockpile	Treatment	1	91	3.62	0.06
		Initial BA	1	91	41.19	**<0.0001**
	Farmyard	Treatment	1	83	0.97	0.33
		Initial BA	1	83	9.00	**0.0036**
	Back40	Treatment	1	99	2.75	0.10
		Initial BA	1	99	62.88	**<0.0001**
2012	Homestead	Treatment	3	133	4.87	**0.0030**
		Initial BA	1	133	74.91	**<0.0001**
	Rockpile	Treatment	3	77	15.52	**<0.0001**
		Initial BA	1	77	101.30	**<0.0001**
	*Farmyard	Treatment	3	110	5.03	0.17
	Back40	Treatment	3	133	1.56	0.20
		Initial BA	1	133	0.31	0.58

Table 2-8. Results of indicator species analysis (ISA) as related to the vegetation suppression treatments within each site. Data were drawn from the aggregate cover averaged over all assessed quadrats (0-105 cm) adjacent to each tree. Listed are all indicator species with corresponding indicator values. Significant indicator values are bolded ($p < 0.05$).

Site	Species	BAU	CULT	DHERB	HERB
Homestead	*Gnaphalium palustre*	**45.8**	0.1	0.0	0.0
	Elytrigia repens	8.7	**68.4**	1.0	0.6
	Melilotus officinalis	1.4	**16.0**	0.2	0.9
	Plantago major	5.8	**47.0**	0.7	0.1
	Poa palustris	1.0	**85.7**	4.5	1.2
	Polygonum convolvulus	18.8	**49.4**	11.9	12.0
	Potentilla norvegica	21.2	**60.5**	4.3	3.7
	Taraxacum officinale	46.1	**48.6**	2.2	1.5
	Trifolium ssp.	3.1	**49.9**	0.5	1.2
Rockpile	*Chenopodium album*	**67.5**	0.1	0.0	3.2
	Crepis tectorum	**38.8**	5.3	0.6	8.7
	Galeopsis tetrahit	**43.2**	0.6	0.0	3.9
	Medicago sativa	**49.8**	0.7	0.0	0.0
	Polygonum convolvulus	**71.2**	1.7	0.0	0.6
	Potentilla norvegica	**61.2**	11.8	3.8	13.9
	Taraxacum officinale	**76.7**	18.5	1.5	2.0
	Elytrigia repens	36	**57.4**	4.2	1.9
	Phleum pratense	0.1	**83.1**	0.4	0.0
	Poa palustris	0.8	**74.3**	0.7	8.8
	Trifolium ssp.	22.2	**64**	5.2	4.7
	Draba nemorosa	0.1	3.9	2.2	**36.5**
	Silene alba	0.5	0.1	0.7	**21.8**
	Thlaspi arvense	16.3	3.9	2.2	**50.8**
Farmyard	*Elytrigia repens*	40.9	**41.5**	8.1	0.2
	Medicago sativa	17.6	**45.7**	1.1	0.0
	Poa palustris	14.5	**37.6**	9.4	0.1
	Polygonum convolvulus	14.9	**29.4**	1.9	0.1
	Taraxacum officinale	14.8	**21.8**	0.5	0.0
	Thlaspi arvense	30.9	**34.6**	12.6	21.9
	Urtica dioica	0.0	**12.8**	0.1	0.3
Back40	*Stellaria media*	**26.7**	1.2	0.0	0.0
	Crepis tectorum	13.2	**26.0**	2.6	2.7
	Medicago sativa	34.0	**35.9**	3.3	0.3
	Poa palustris	0.3	**33.9**	3.8	3.1
	Poa pratensis	0.4	**29.7**	0.0	0.0
	Polygonum convolvulus	0.5	**21.6**	2.1	2.6
	Taraxacum officinale	33.1	**45.5**	8.1	0.5
	Thlaspi arvense	6.9	**35.4**	20.2	33.6

Table 2-9. Pearson correlations of species and BAI vectors with each axis from the NMDS ordinations represented in Fig. 2-9. Vectors with |*r*| > 0.3 were considered to be correlated and are bolded.

		NMDS ordination axis		
		Axis 1	Axis 2	Axis 3
Site	Species	*r*	*r*	*r*
Homestead	Plant spp. variance explained	14.2%	18.4%	1.1%
	Chenopodium album	-0.047	-0.025	**-0.302**
	Cirsium arvense	**-0.501**	0.097	0.130
	Crepis tectorum	**0.426**	-0.280	0.096
	Elytrigia repens	0.083	0.283	**0.432**
	Equisetum arvense	0.041	-0.192	**0.412**
	Gnaphalium palustre	**0.321**	0.189	0.001
	Potentilla norvegica	**0.381**	**0.315**	0.259
	Taraxacum officinale	-0.016	**0.581**	-0.140
	BAI	0.282	0.036	-0.175
Rockpile	Plant spp. variance explained	29.7%	3.4%	7.9%
	Chenopodium album	-0.237	**-0.437**	-0.032
	Crepis tectorum	-0.247	**-0.347**	0.135
	Draba nemorosa	0.220	0.066	**0.323**
	Elytrigia repens	0.081	0.178	**-0.631**
	Medicago sativa	-0.149	**-0.495**	-0.218
	Phleum pratense	-0.066	**0.390**	**-0.382**
	Poa palustris	-0.120	**0.476**	-0.294
	Polygonum convolvulus	0.054	**-0.402**	-0.222
	Potentilla norvegica	**0.331**	**-0.414**	0.111
	Silene alba	-0.012	0.150	**0.315**
	Silene noctiflora	**0.332**	-0.003	0.118
	Taraxacum officinale	-0.249	**-0.622**	**-0.312**
	Thlaspi arvense	-0.239	0.018	**0.539**
	Trifolium ssp.	-0.062	**0.500**	**-0.411**
	BAI	-0.059	**-0.361**	0.257
Farmyard	Plant spp. variance explained	29.9%	7.3%	3.2%
	Descurainia Sophia	-0.101	**0.567**	0.035
	Elytrigia repens	**0.709**	0.274	**-0.326**
	Galeopsis tetrahit	0.000	0.086	**0.314**
	Medicago sativa	**0.451**	-0.213	**-0.372**
	Poa pratensis	0.208	0.007	**0.455**
	Polygonum convolvulus	**0.307**	-0.293	0.292
	Taraxacum officinale	0.259	**-0.395**	0.214
	Trifolium ssp.	0.098	-0.011	**0.423**
	BAI	-0.257	-0.144	-0.055
Back40	Plant spp. variance explained	39.6%	16.9%	4.1%
	Chenopodium album	0.069	0.077	**0.351**
	Crepis tectorum	0.188	-0.132	**0.486**
	Medicago sativa	**0.494**	**-0.568**	-0.180
	Poa palustris	0.028	-0.066	**-0.517**
	Poa pratensis	0.039	0.028	**-0.390**

Taraxacum officinale	**0.677**	**0.440**	-0.011
Thlaspi arvense	**-0.581**	0.022	-0.172
BAI	-0.103	0.054	0.125

Table 2-10. Results for **(a)** PerMANOVA testing for differences in plant communities between the four vegetation suppression treatments, and **(b)** post-hoc comparisons between treatments within sites, different letters in the same row are significantly different using a Bonferroni adjustment of alpha. Analysis was done separately at each site using all treatment trees in the 2012 growing season. Data were drawn from the aggregate cover averaged over all assessed quadrats (0-105 cm) adjacent to each tree. Significant values are bolded ($p < 0.05$).

a)

Site	DF	SS	MS	F-value	P-value
Homestead	3	12.263	4.088	18.267	**< 0.0001**
Rockpile	3	10.537	3.512	23.801	**< 0.0001**
Farmyard	3	6.766	2.255	11.437	**< 0.0001**
Back40	3	8.949	2.983	16.393	**< 0.0001**

b)

Site	CULT	HERB	DHERB	BAU
Homestead	a	b	b	c
Rockpile	a	b	c	d
Farmyard	a	b	c	a
Back40	a	b	c	d

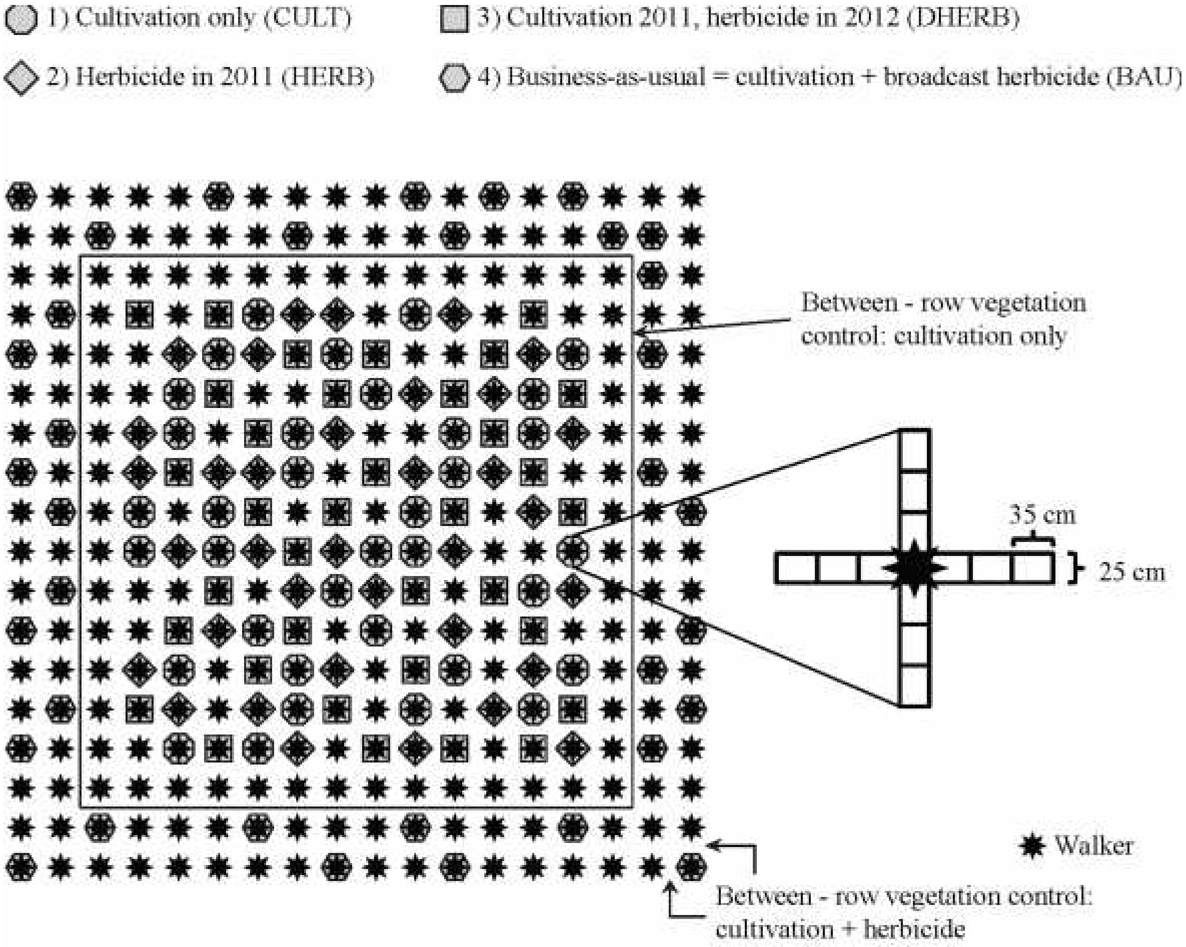


Fig. 2-1. Example of the randomized complete block experimental design layout of plots, and sampling design using strip quadrats for vegetation assessment.

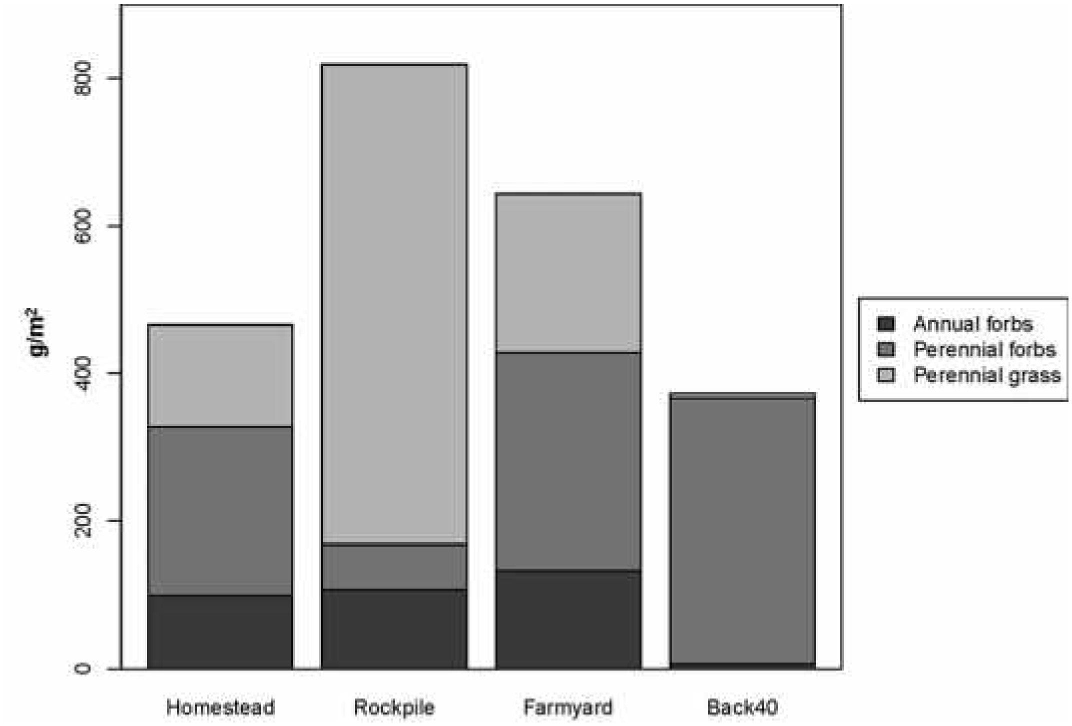


Fig. 2-2. Mean biomass (g/m^2) of weeds by site near trees in the DHERB treatment during August 2011.

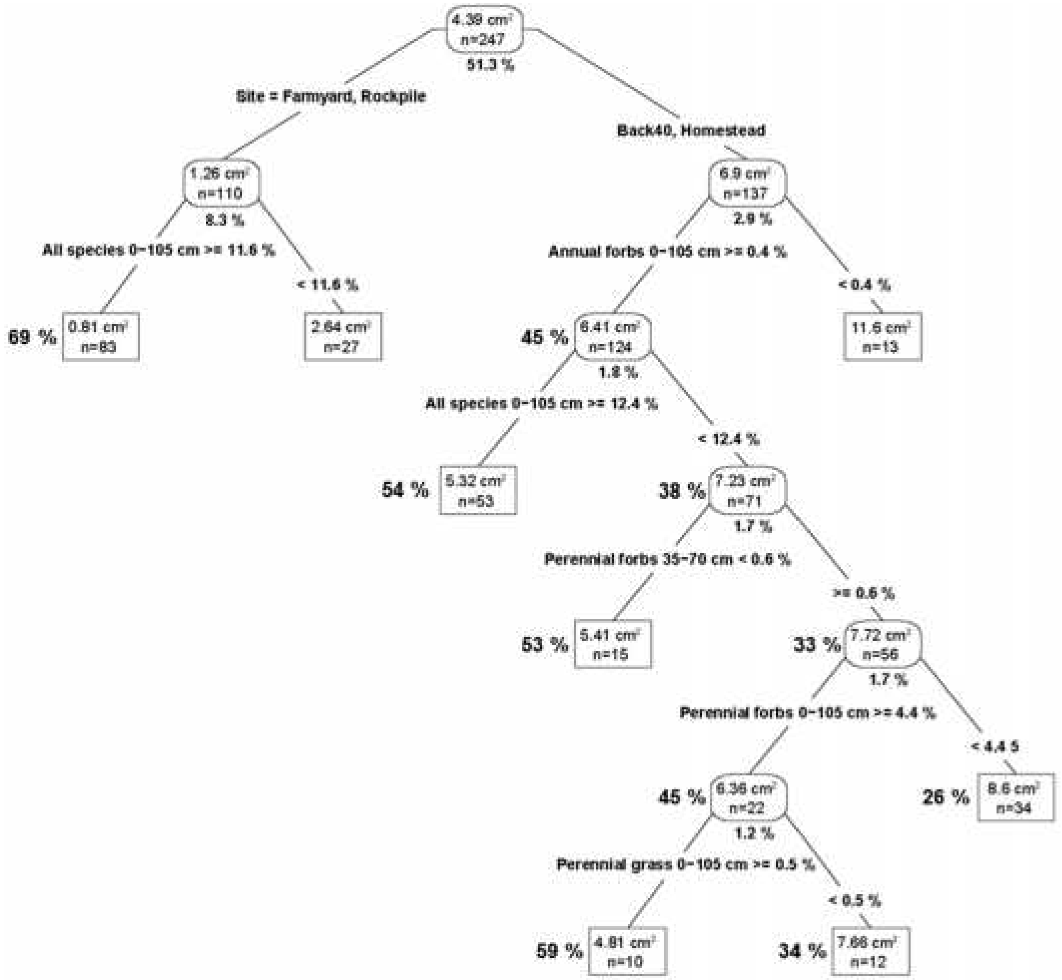
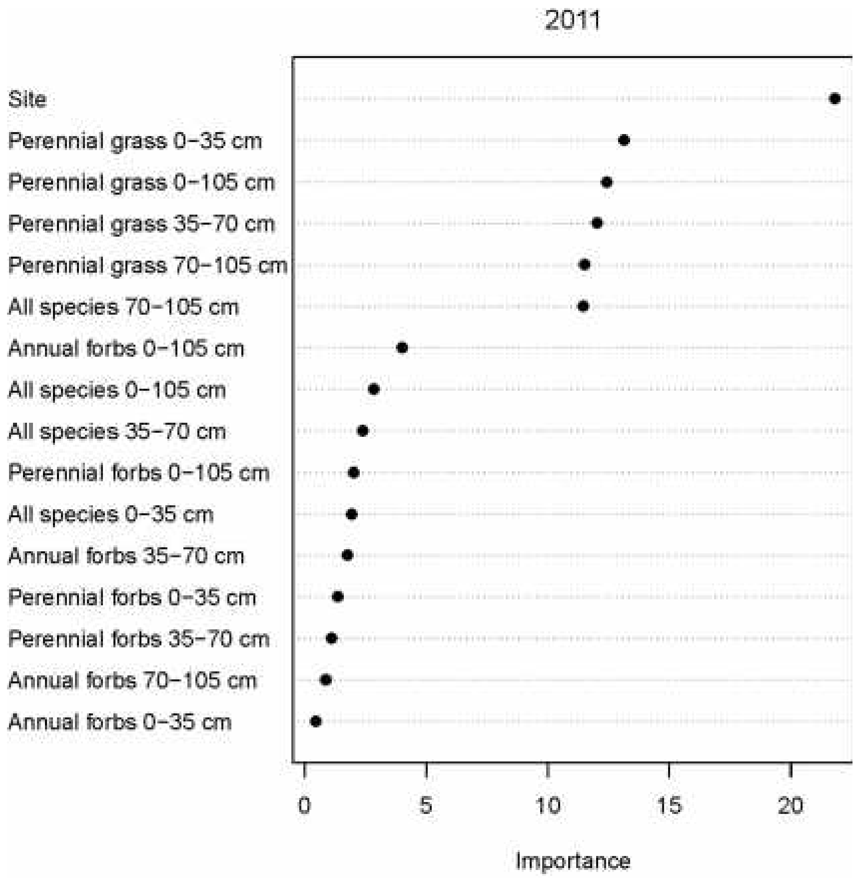


Fig. 2-3. Results of the regression tree analysis of basal area increment (BAI) within the CULT and DHERB treatment trees in 2011. Herbicide applications for the DHERB treatment had not begun in 2011, thus DHERB trees were included with the CULT trees for that year. Each splitting variable is either site or percent cover values of a particular growth form. The top number in each node is estimated BAI in cm^2, 'n=' is the number of trees belonging to each node, and the percentage value below each node with a split represents how much variation is explained by the split. The number to the left of a node is that yield loss for that node when compared to the maximum BAI possible for those sites as defined by the first split.



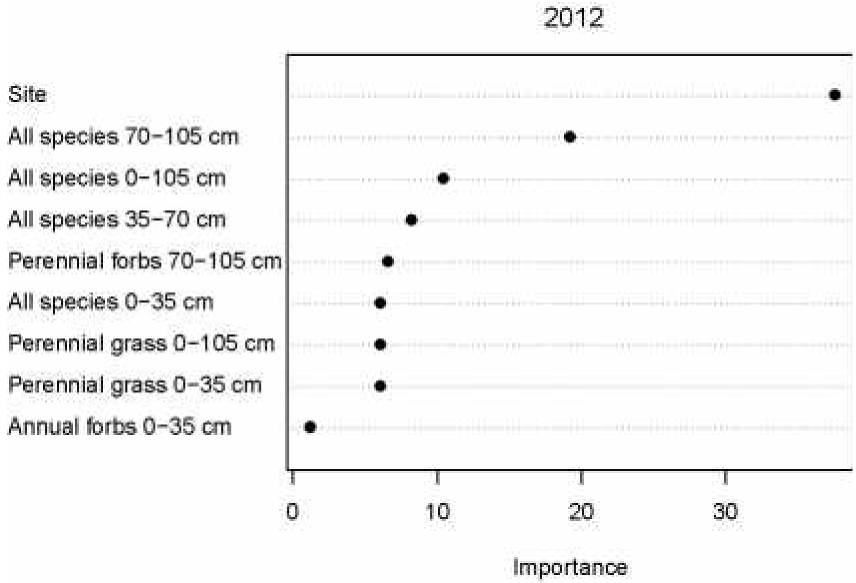


Fig. 2-4. Dot plots of variable importance in the regression trees for analysis of the 2011 and 2012 data (represented in Figs 2-3 and 2-5) and scaled to 100. Dots further to the right indicate the variable was more important for determining tree basal area increment.

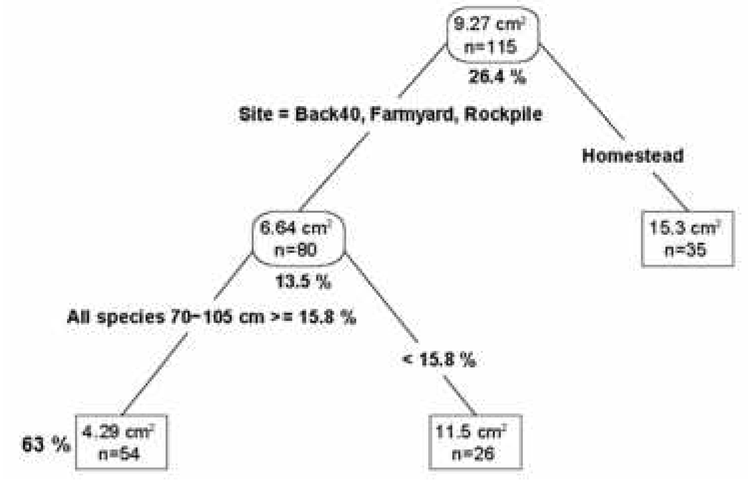


Fig. 2-5. Results of the regression tree analysis of basal area increment (BAI) within the CULT treatment trees in 2012. Each splitting variable is either site or percent cover values of a particular growth form. The top number in each node is estimated BAI in cm^2, 'n=' is the number of trees belonging to each node, and the percentage value below each node with a split represents how much variation is explained by the split. The number to the left of a node is that yield loss for that node when compared to the maximum BAI possible for those sites as defined by the first split.

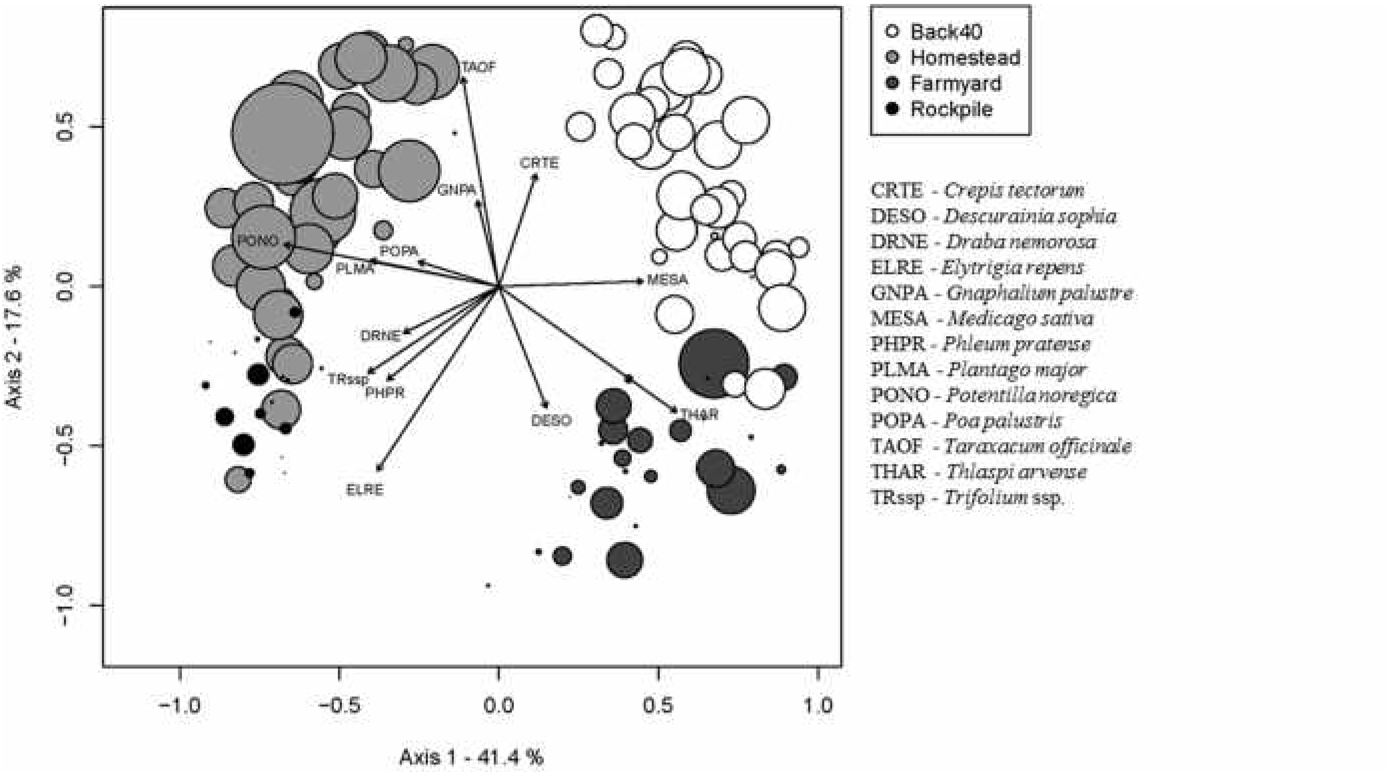
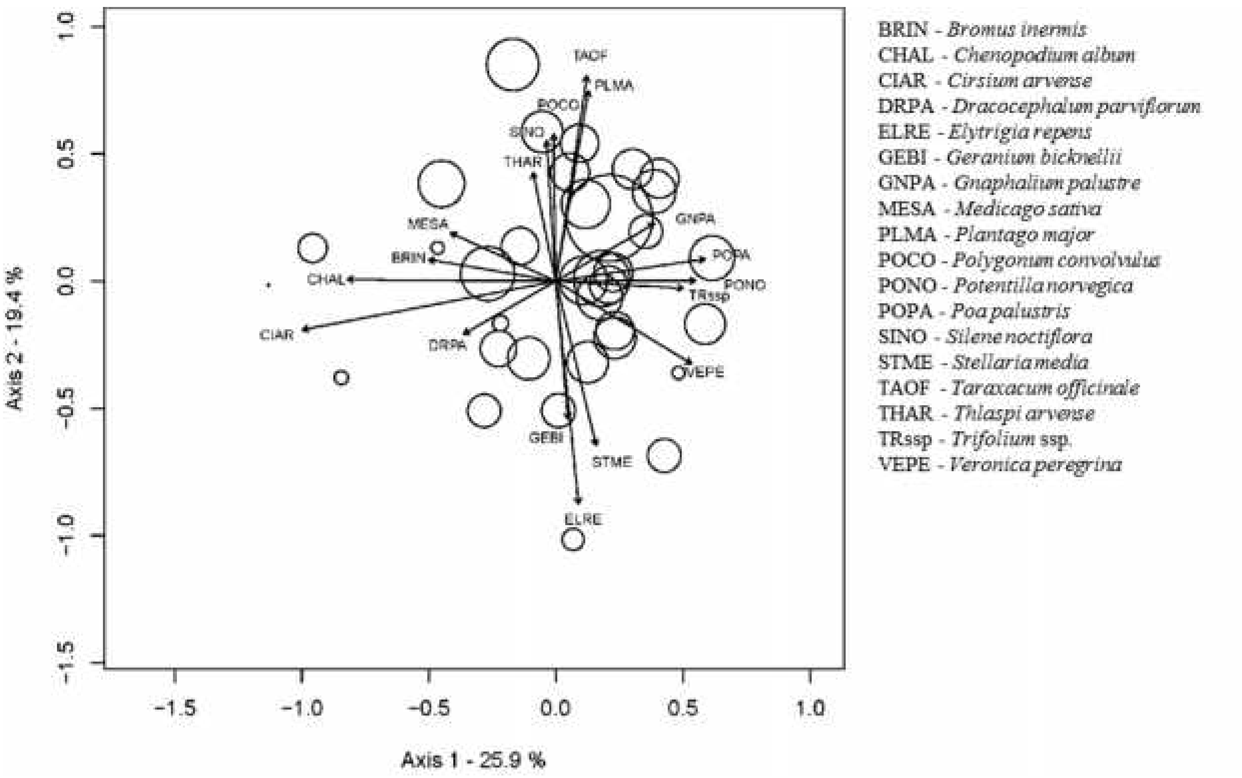
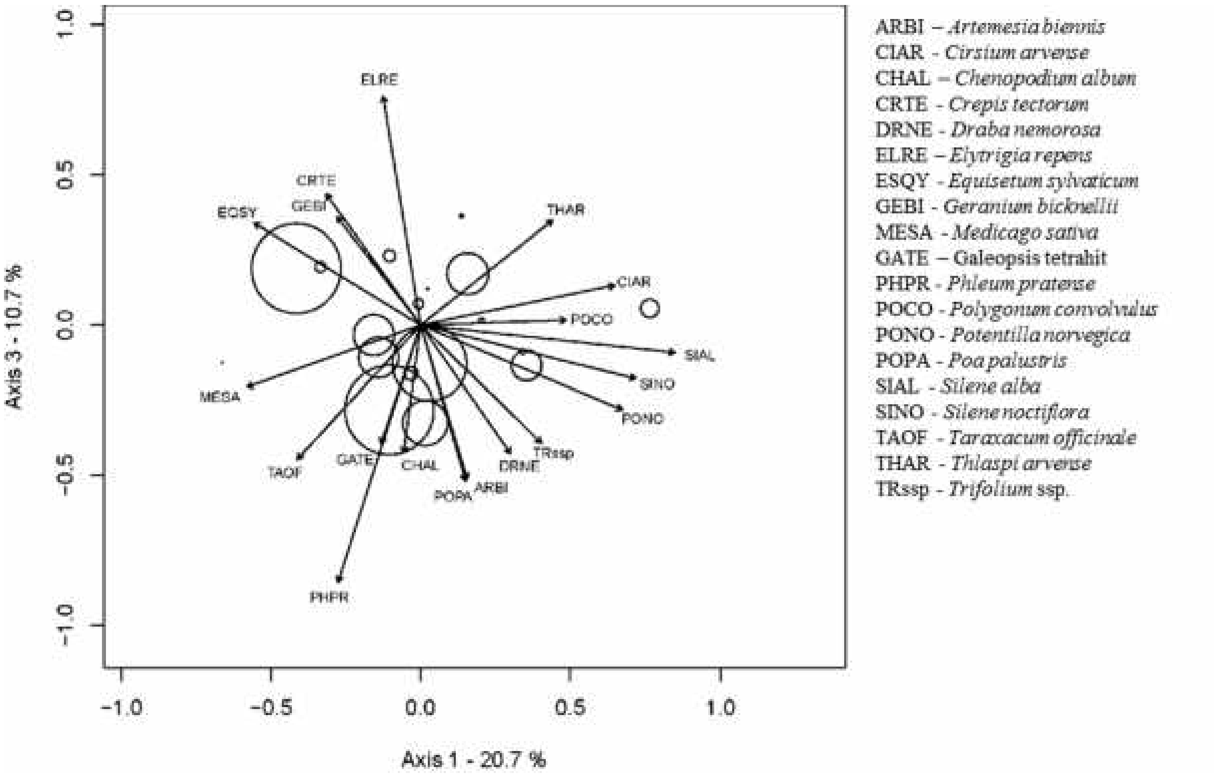


Fig. 2-6. Results of NMDS ordination of the neighboring vegetation composition for CULT treatment trees in all sites. Each point represents a tree and is ordinated by the aggregate cover data (0-105 cm) of neighboring vegetation averaged across the 2011 and 2012 growing seasons. Different color points denote different sites, and point size represents total BAI of the tree near which the vegetation was assessed. The length and direction of the species vectors (see Appendix 2-4 for species codes) indicate their strength of association with the ordination axes. Only the dimensions which explained the most variation in the ordination are shown. The cut-off for display of species vectors was |*r*| > 0.3. Ordination is a 3-D solution with a final stress of 0.1443 after 22 iterations.

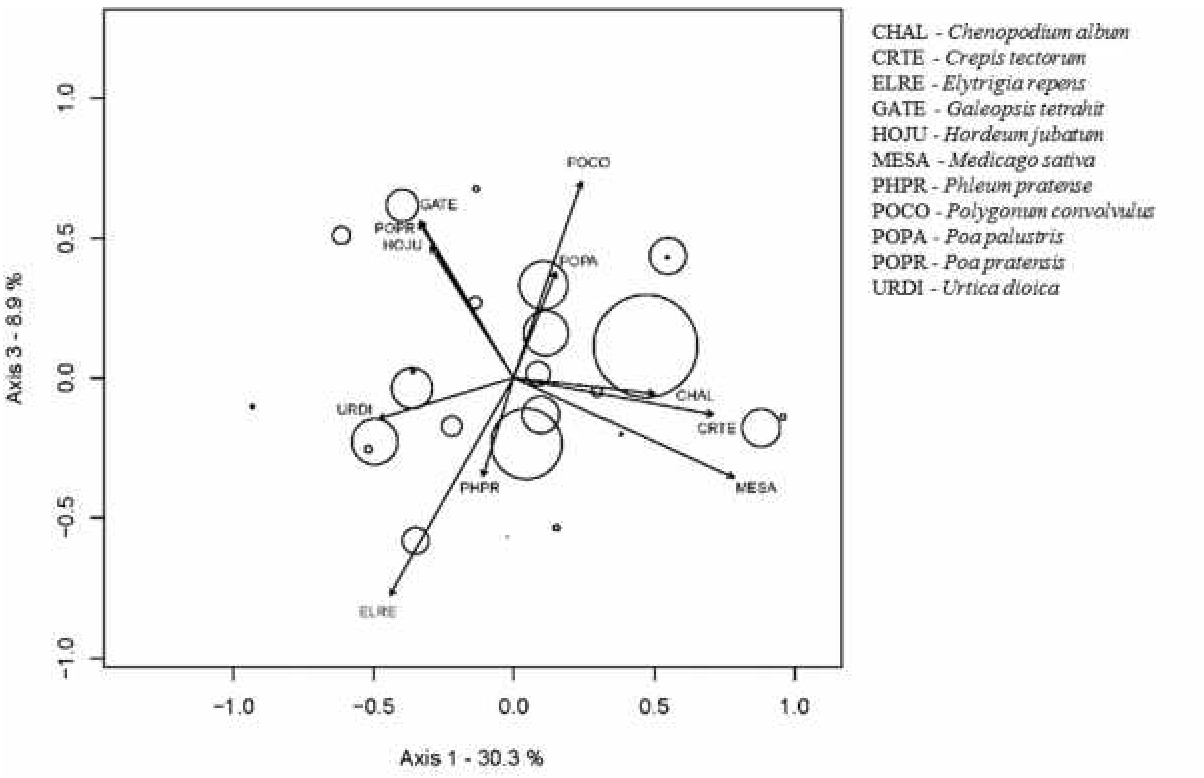
Homestead


Axis 2 - 19.4 %
Axis 1 - 25.9 %
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.5
-1.0
-0.5
0.0
0.5
1.0
TAOF
PLMA
POCO
SINO
THAR
MESA
BRIN
CHAL
CIAR
DRPA
GNPA
POPA
PONO
TRssp
VEPE
GEBI
STME
ELRE
BRIN - Bromus inermis
CHAL - Chenopodium album
CIAR - Cirsium arvense
DRPA - Dracocephalum parviflorum
ELRE - Elytrigia repens
GEBI - Geranium bicknellii
GNPA - Gnaphalium palustre
MESA - Medicago sativa
PLMA - Plantago major
POCO - Polygonum convolvulus
PONO - Potentilla norvegica
POPA - Poa palustris
SINO - Silene noctiflora
STME - Stellaria media
TAOF - Taraxacum officinale
THAR - Thlaspi arvense
TRssp - Trifolium ssp.
VEPE - Veronica peregrina

Rockpile


ELRE
CRTE
GEBI
EQSY
THAR
CIAR
POCO
SIAL
SINO
PONO
MESA
TAOF
GATE
CHAL
POPA
ARBI
DRNE
TRssp
PHPR
1.0
0.5
0.0
-0.5
-1.0
Axis 3 - 10.7 %
-1.0
-0.5
0.0
0.5
1.0
Axis 1 - 20.7 %
ARBI – *Artemesia biennis*
CIAR - *Cirsium arvense*
CHAL – *Chenopodium album*
CRTE - *Crepis tectorum*
DRNE - *Draba nemorosa*
ELRE – *Elytrigia repens*
ESQY - *Equisetum sylvaticum*
GEBI - *Geranium bicknellii*
MESA - *Medicago sativa*
GATE – Galeopsis tetrahit
PHPR - *Phleum pratense*
POCO - *Polygonum convolvulus*
PONO - *Potentilla norvegica*
POPA - *Poa palustris*
SIAL - *Silene alba*
SINO - *Silene noctiflora*
TAOF - *Taraxacum officinale*
THAR - *Thlaspi arvense*
TRssp - *Trifolium* ssp.

Farmyard


POCO
GATE
POPR
HOJU
POPA
CHAL
CRTE
URDI
PHPR
MESA
ELRE
1.0
0.5
0.0
−0.5
−1.0
Axis 3 - 8.9 %
-1.0
-0.5
0.0
0.5
1.0
Axis 1 - 30.3 %
CHAL - Chenopodium album
CRTE - Crepis tectorum
ELRE - Elytrigia repens
GATE - Galeopsis tetrahit
HOJU - Hordeum jubatum
MESA - Medicago sativa
PHPR - Phleum pratense
POCO - Polygonum convolvulus
POPA - Poa palustris
POPR - Poa pratensis
URDI - Urtica dioica

Back40

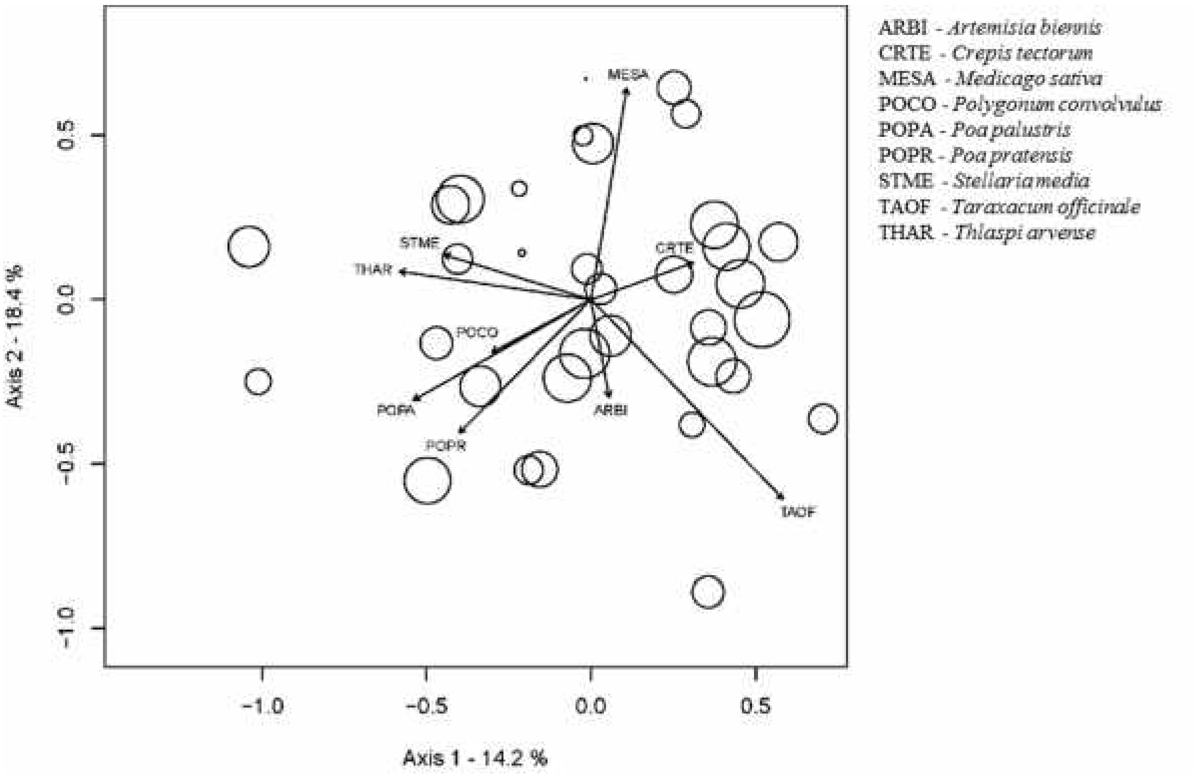


Fig. 2-7. Results of NMDS ordinations of the neighboring vegetation composition for CULT treatment trees in each site. Each point represents a tree and is ordinated by the aggregate cover data (0-105 cm) of neighboring vegetation averaged across the 2011 and 2012 growing seasons. Point size represents total basal area increment of the tree near which the vegetation was assessed. The length and direction of the species vectors (see Appendix 2-4 for species codes) indicate their strength of association with the ordination axes. Only the dimensions which explained the most variation in the ordination are shown for each site. The cut-off for display of vectors was $|r| > 0.3$.

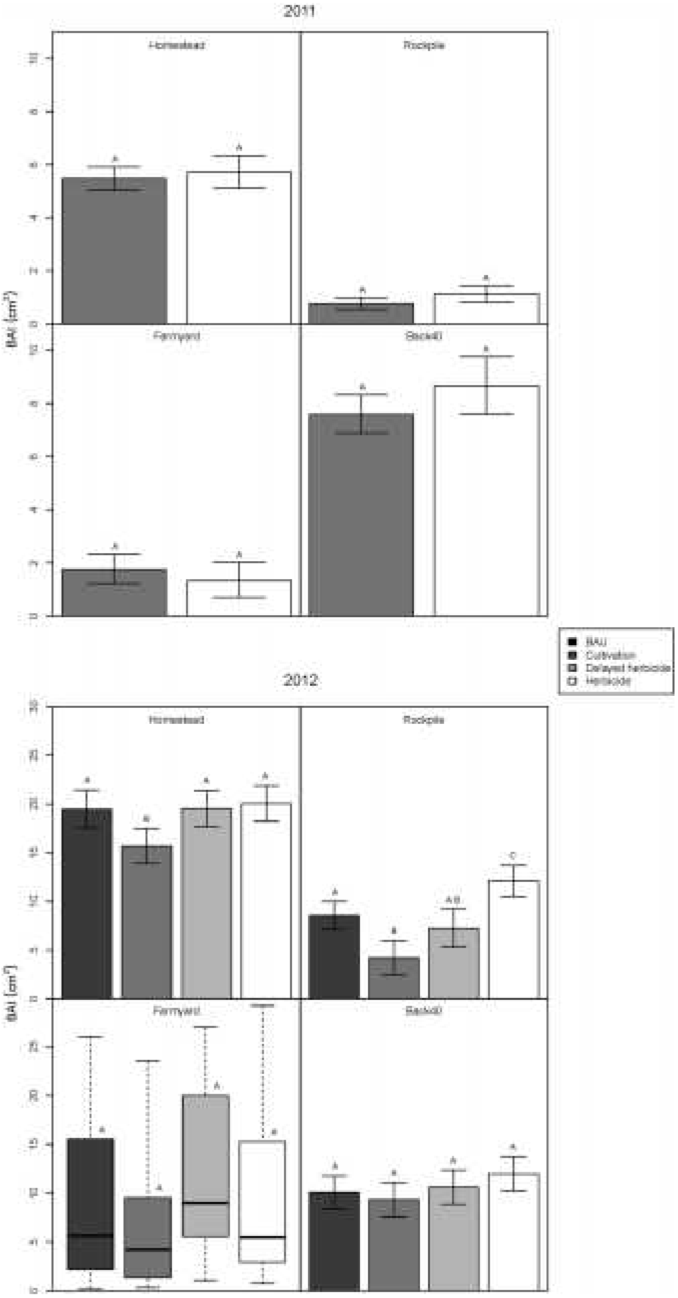
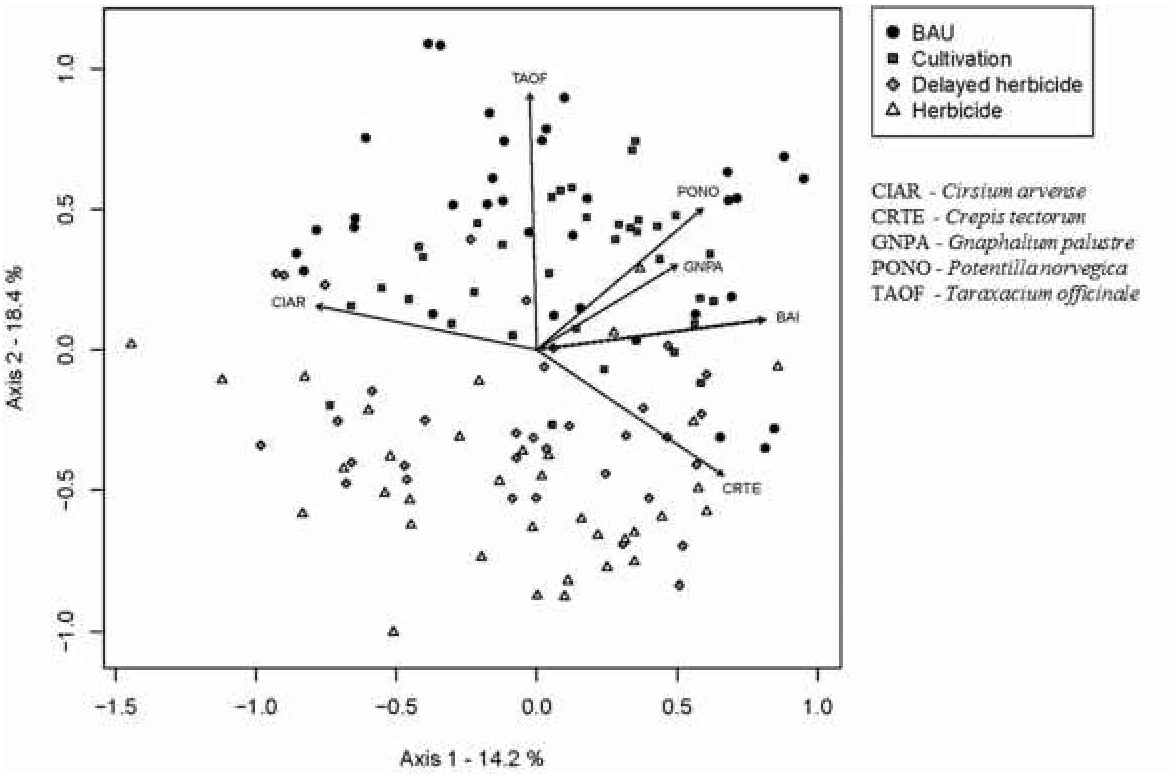


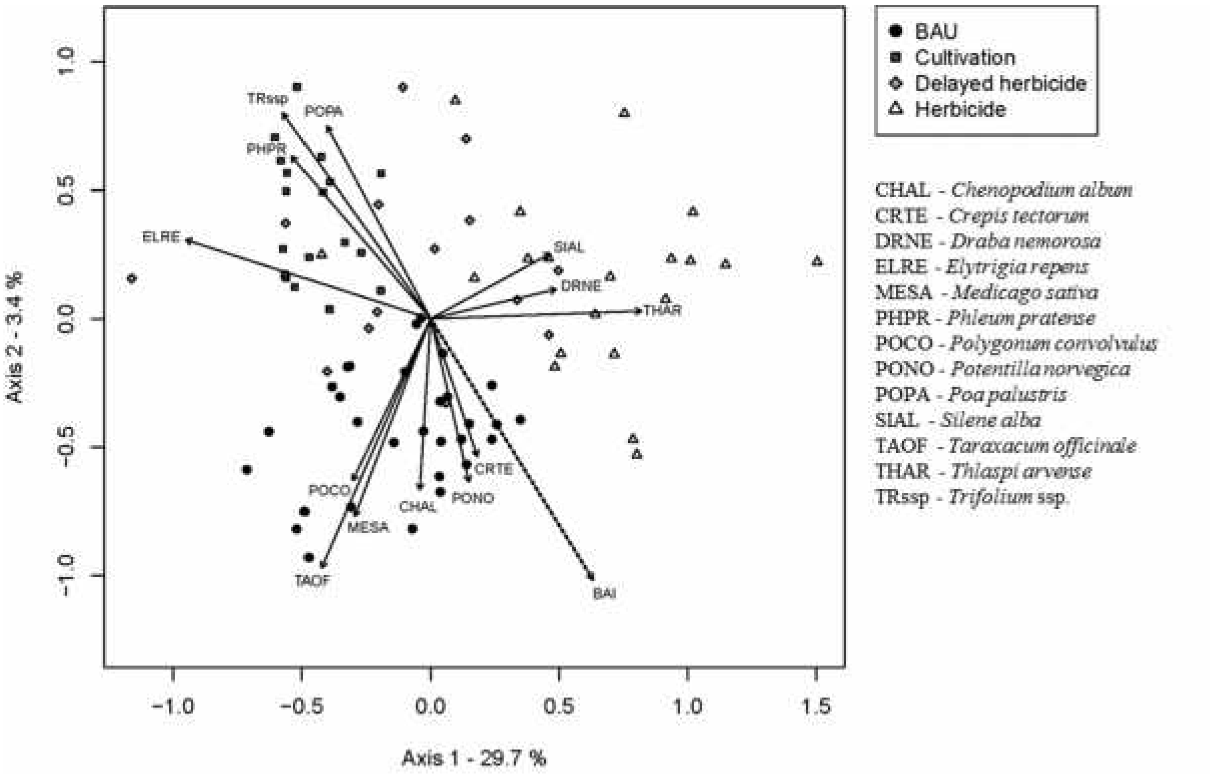
Fig. 2-8. Basal area increment (BAI) of trees in 2011 and 2012 for each of the vegetation suppression treatments, for individual sites. Data for 'Farmyard' 2012 were non-normal, and thus analyzed using a Kruskall-Wallis test and represented here by a boxplot - middle bar is the median, ends of boxes are the 25th and 75th quartiles, and ends of whiskers are the 2.5 and 97.5 quantiles. Error bars on the barplots are 95% confidence intervals. Treatments with different letters in the same site are significantly different ($p < 0.05$) using Tukey's HSD. BAU and DHERB treatments are not shown in the 2011 figure due to the BAU treatment commencing before the other treatments in 2011, and the DHERB treatment did not begin until 2012 – hence trees designated for the DHERB treatment were grouped with the CULT treatments in 2011.

Homestead

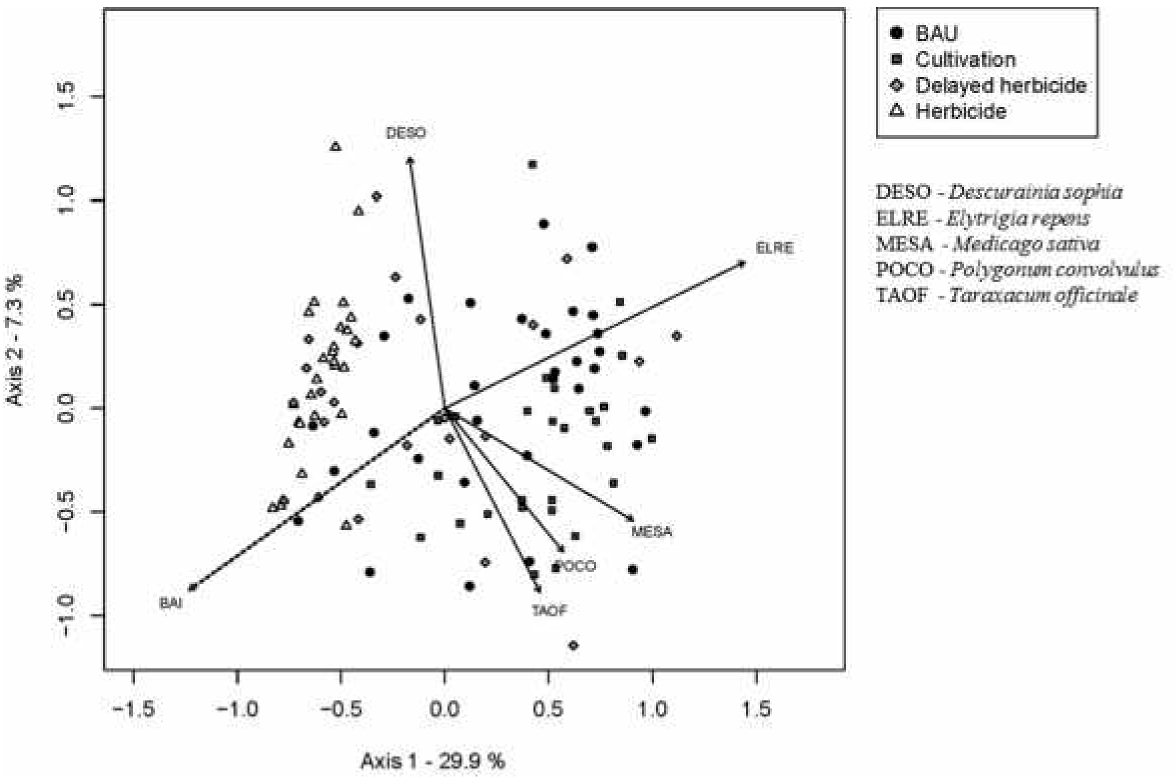


CIAR - *Cirsium arvense*
CRTE - *Crepis tectorum*
GNPA - *Gnaphalium palustre*
PONO - *Potentilla norvegica*
TAOF - *Taraxacium officinale*

Rockpile


● BAU
■ Cultivation
◆ Delayed herbicide
△ Herbicide
CHAL - Chenopodium album
CRTE - Crepis tectorum
DRNE - Draba nemorosa
ELRE - Elytrigia repens
MESA - Medicago sativa
PHPR - Phleum pratense
POCO - Polygonum convolvulus
PONO - Potentilla norvegica
POPA - Poa palustris
SIAL - Silene alba
TAOF - Taraxacum officinale
THAR - Thlaspi arvense
TRssp - Trifolium ssp.
TRssp
POPA
PHPR
ELRE
SIAL
DRNE
THAR
CRTE
PONO
CHAL
POCO
MESA
TAOF
BAI
Axis 2 - 3.4 %
Axis 1 - 29.7 %
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
1.5

Farmyard



BAU
Cultivation
Delayed herbicide
Herbicide
DESO - *Descurainia sophia*
ELRE - *Elytrigia repens*
MESA - *Medicago sativa*
POCO - *Polygonum convolvulus*
TAOF - *Taraxacum officinale*
DESO
ELRE
MESA
POCO
TAOF
BAI
Axis 2 - 7.3 %
Axis 1 - 29.9 %
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

Back40

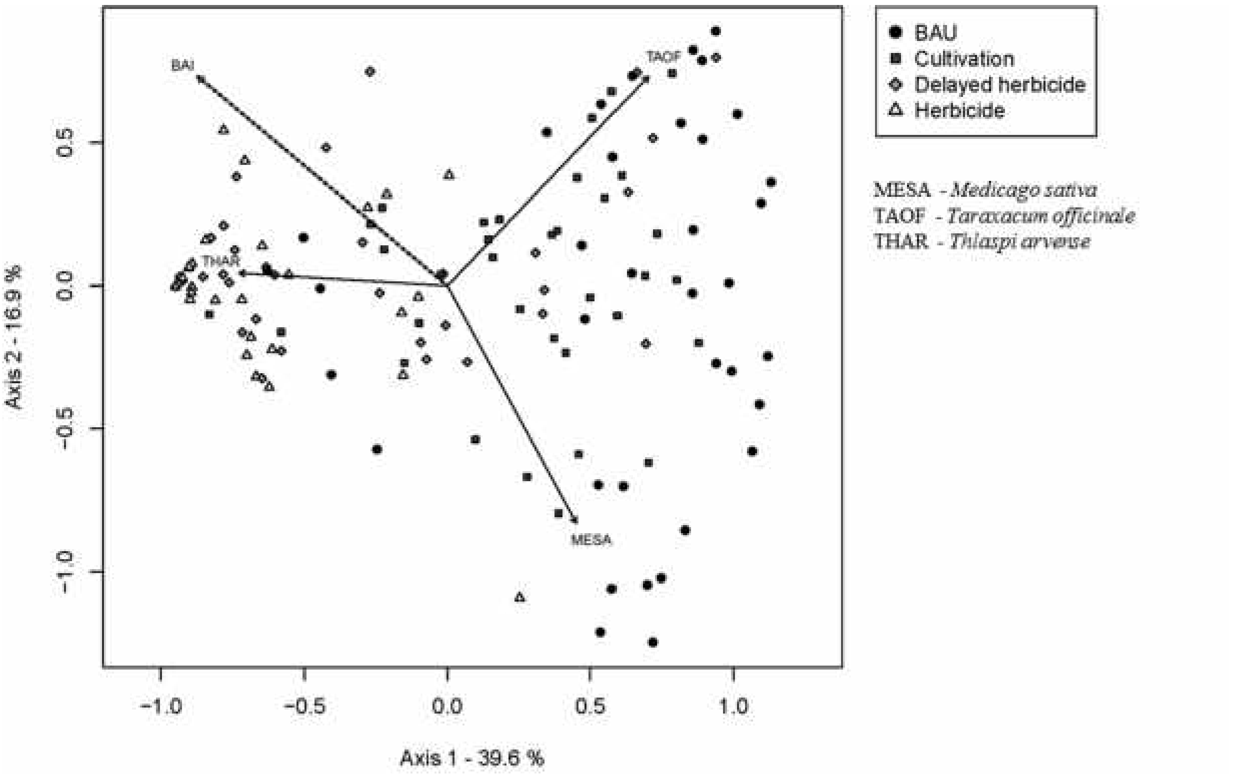


Fig. 2-9. Results of the indirect gradient analysis with NMDS ordination of all treatment trees in each site. Each point represents a tree and is ordinated by the aggregate cover data (0-105 cm) of neighboring vegetation averaged across the 2012 growing seasons. Different point symbols denote different treatments. A bolded and dashed vector representing basal area increment (BAI) is overlaid on the plot. The length and direction of the vectors (see Appendix 2-4 for species codes) indicate their strength of association with the ordination axes. Only the dimensions which explained the most variation in the ordination are shown for each site. The cut-off for display of vectors was |*r*|> 0.3

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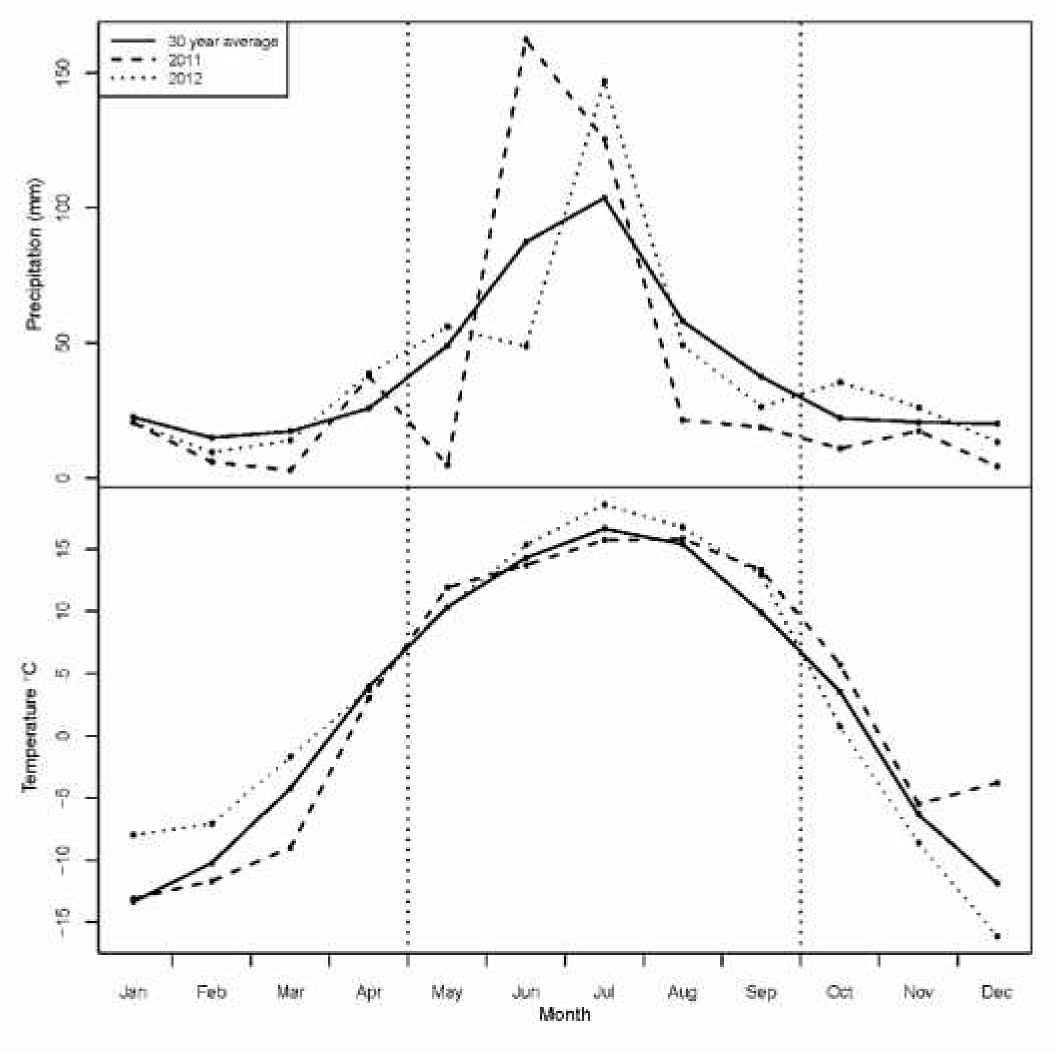
2.6 Appendices

Appendix 2-1. Total monthly precipitation and average temperature during 2011 and 2012, together with the 30 yr average. Area between the dotted vertical lines represents the May-September growing season. All data gathered by weather stations in Athabasca county and accessed from Canada's National Climate Archive. Precipitation data from 2011 and 2012 are likely underestimates of the true value due to missing archive data.



Appendix 2-2. Description of site preparation and vegetation control treatments.

	Treatments			
	Cultivation	Herbicide	Delayed herbicide	Business-as-usual
2009	1.85 L/ha Vantage Plus, 360 g/L glyphosate 1.33 L/ha PrePass, 50 g/L florasulam and 360 g/L glyphosate 2 passes with disc cultivator			
2010	4.5 L/ha Lorax, 480 g/L linuron 1 pass with disc cultivator prior to tree planting Dormant rooted hybrid poplar cuttings were planted in early June 2-4 passes (in-row) with disc cultivator following planting 0.56 L/ha Lontrel, 360 g/L clopyralid 2.0 L/ha Venture, 125 g/L fuazifop-p-butyl (Seim site only) 1.1 L/ha Poast Ultra, 450 g/L sethoxydim (Berquist site only)			
2011	4-5 passes (in-row) with disc cultivator throughout the growing season			
		5 % Roundup Ultra2, 540 g/L glyphosate – one application wiped to vegetation around base of trees 10 % Roundup Ultra2, 540 g/L glyphosate – one application wiped to vegetation around base of trees		4.5 L/ha Lorax, 480 g/L linuron – applied over dormant trees 1.65 L/ha Roundup Transorb, 540 g/L glyphosate – applied over dormant trees (Seim site only) 1.1 L/ha Poast Ultra, 450 g/L sethoxydim (Seim site only)
2012	3-5 passes (in-row) with disc cultivator throughout the growing season			
		10 % Roundup Ultra2, 540 g/L glyphosate – two applications sprayed around base of trees	10 % Roundup Ultra2, 540 g/L glyphosate – two applications sprayed around base of trees	2.47 L/ha Roundup Ultra2, 540 g/L glyphosate – applied with Environmist sprayer

Appendix 2-3. Summary of the frequency of trees browsed (in percent) and amount (in cm ± standard deviation) of tree stems removed by large ungulates (moose and deer) over the winter of 2012/2013. Summary of browse data over the winter of 2011/2012 is not available as we did not differentiate between stem loss due to moose or winter damage in that period.

Frequency

	Treatments			
Site	BAU	Cultivation	Delayed herbicide	Herbicide
Homestead	48.6%	71.4%	73.5%	71.4%
Rockpile	86.7%	76.5%	86.7%	95.7%
Farmyard	100.0%	89.3%	100.0%	93.1%
Back40	100.0%	100.0%	97.1%	100.0%

Browse amounts

	Treatments			
Site	BAU	Cultivation	Delayed herbicide	Herbicide
Homestead	65.8 ± 32.0	62.5 ± 16.9	68.3 ± 23.1	67.3 ± 43.9
Rockpile	51.2 ± 25.1	37.2 ± 20.1	47.1 ± 19.3	47.8 ± 30.7
Farmyard	49.3 ± 17.4	51.3 ± 17.9	52.2 ± 11.4	46.3 ± 13.5
Back40	76.2 ± 26.1	67.5 ± 21.4	72.5 ± 33.6	68.2 ± 29.5

Appendix 2-4. List of neighboring plant species sampled in the study. Plants with annual/biennial cycles were grouped with the annual species for analysis. Species nomenclature from the USDA PLANTS Database.

Code	Species	Longevity	Growth
ACMI	*Achillea millefolium* L.	Perennial	Forb
ARBI	*Artemisia biennis* Willd.	Annual/biennial	Forb
BRIN	*Bromus inermis* Leyss.	Perennial	Grass
BRTE	*Bromus tectorum* L.	Annual	Grass
CABU	*Capsella bursa-pastoris* (L.)	Annual	Forb
CAssp.*	*Carex* ssp.	Perennial	Sedge
CHAL	*Chenopodium album* L.	Annual	Forb
CIAR	*Cirsium arvense* (L.) Scop.	Perennial	Forb
COAU	*Corydalis aurea* Willd.	Annual/biennial	Forb
CRTE	*Crepis tectorum* L.	Annual	Forb
DESO	*Descurainia sophia* (L.) Webb ex	Annual/biennial	Forb
DRNE	*Draba nemorosa* L.	Annual	Forb
DRPA	*Dracocephalum parviflorum* Nutt.	Annual/biennial	Forb
ELRE	*Elytrigia repens* (L.) Gould.	Perennial	Grass
EQAR	*Equisetum arvense* L.	Perennial	Forb
EQPA	*Equisetum palustre* L.	Perennial	Forb
EQSY	*Equisetum sylvaticum* L.	Perennial	Forb
GATE	*Galeopsis tetrahit* L.	Annual	Forb
GEBI	*Geranium bicknellii* Britton.	Annual/biennial	Forb
GNPA	*Gnaphalium palustre* Nutt.	Annual	Forb
HOJU	*Hordeum jubatum* L.	Perennial	Grass
LEDE	*Lepidium densiflorum* Schrad.	Annual/biennial	Forb
MADI	*Matricaria discoidea* DC.	Annual	Forb
MEOF	*Melilotus officinalis* (L.) Lam.	Annual/biennial	Forb
MESA	*Medicago sativa* L.	Perennial	Forb
PHPR	*Phleum pratense* L.	Perennial	Grass
PLMA	*Plantago major* L.	Perennial	Forb
POCO	*Polygonum convolvulus* L.	Annual	Forb
POLA	*Polygonum lapathifolium* L.	Annual	Forb
PONO	*Potentilla norvegica* L.	Annual/biennial	Forb
POPA	*Poa palustris* L.	Perennial	Grass
POPR	*Poa pratensis* L.	Perennial	Grass
SIAL	*Silene alba* Poir.	Biennial/perennial	Forb
SIAR	*Sinapis arvensis* L.	Annual	Forb
SINO	*Silene noctiflora* L.	Annual	Forb
SOOL	*Sonchus oleraceus* L.	Annual	Forb
STME	*Stellaria media* (L.) Vill.	Annual	Forb
TAOF	*Taraxacum officinale* F.H. Wigg.	Perennial	Forb
THAR	*Thlaspi arvense* L.	Annual	Forb
TRssp.**	*Trifolium hybidium* and *repens* L.	Perennial	Forb
URDI	*Urtica dioica* L.	Perennial	Forb
VEPE	*Veronica peregrina* L.	Annual	Forb
VIAM	*Vicia americana* Muhl. Ex Willd.	Perennial	Forb

**Carex* ssp. Indentified only to genus in the field.

***Trifolium hybridium* and *Trifolium repens* identified only to genus in the field and were combined for analysis.

Appendix 2-5. Summary of regression tree alternative and surrogate splits from analysis of the 2011 data on trees from both the CULT and DHERB treatments, and also summary of regression tree alternative and surrogate splits of the 2012 data on trees from the CULT treatment. At each node there is listed the best predictor variables and their associated values or classes which splits the data such that the decrease in deviance with the partition is maximized. The first primary splitting variable listed at each node is that which was used in the construction of the tree, all other primary splits are the alternatives. The next columns indicate which branch to follow if the previous argument is true, and "improve =" indicates the change in the impurity index of that node of the primary splits. The relative size in the improvement value, rather than their absolute value, indicates the comparative utility of the variables. With the surrogate splits "agree =" gives the proportion of agreement of that particular surrogate split with the first primary split.

2011

Node number 1: 247 observations	complexity parameter=0.513		
Primary splits:			
Site	Homestead, Back40	to the right	improve=0.513
Perennial grass 0-35 cm	< 1.9	to the right	improve=0.332
Perennial grass 0-105 cm	< 5.5	to the right	improve=0.300
Perennial grass 35-70 cm	< 4.9	to the right	improve=0.270
Annual forbs 0-105 cm	< 2.4	to the right	improve=0.258
Surrogate splits:			
Perennial grass 0-35 cm	< 1.9	to the right	agree=0.818
Perennial grass 0-105 cm	< 5.5	to the right	agree=0.802
Perennial grass 35-70 cm	< 6.8	to the right	agree=0.802
Perennial grass 70-105 cm	< 4.3	to the right	agree=0.785
All species 70-105 cm	< 19.2	to the right	agree=0.765
Node number 2: 110 observations	complexity parameter=0.018		
Primary splits:			
All species 0-105 cm	< 11.6	to the right	improve=0.272
All species 0-35 cm	< 14.3	to the right	improve=0.265
Perennial grass 35-70 cm	< 1.9	to the right	improve=0.189
Perennial grass 0-35 cm	< 3.3	to the right	improve=0.181
Perennial grass 0-105 cm	< 1.5	to the right	improve=0.179
Surrogate splits:			
All species 0-35 cm	< 14.3	to the right	agree=0.927
All species 35-70 cm	< 10.7	to the right	agree=0.891
Perennial forbs 0-35 cm	< 0.1	to the right	agree=0.873
All species 70-105 cm	< 7.8	to the right	agree=0.855
Perennial forbs 0-105 cm	< 0.2	to the right	agree=0.845
Node number 3: 137 observations	complexity parameter=0.083		
Primary splits:			
Annual forbs 0-105 cm	< 0.4	to the right	improve=0.197
Annual forbs 35-70 cm	< 0.7	to the right	improve=0.118
Annual forbs 0-35 cm	< 1.1	to the right	improve=0.113
Annual forbs 70-105 cm	< 0.7	to the right	improve=0.105
All species 0-105 cm	< 7.6	to the right	improve=0.088
Surrogate splits:			
Annual forbs 35-70 cm	< 0.3	to the right	agree=0.949
All species 35-70 cm	< 1.1	to the right	agree=0.934
Annual forbs 70-105 cm	< 0.1	to the right	agree=0.927
All species 0-105 cm	< 1.4	to the right	agree=0.920
All species 70-105 cm	< 0.3	to the right	agree=0.912

```
Node number 6: 124 observations    complexity parameter=0.029
  Primary splits:
      All species 0-105 cm         < 12.4            to the right    improve=0.122
      Perennial forbs 0-105 cm     < 4.4             to the right    improve=0.107
      All species 0-35 cm          < 14.6            to the right    improve=0.089
      Perennial forbs 0-35 cm      < 22.1            to the right    improve=0.067
      Perennial forbs 70-105 cm    < 11.2            to the right    improve=0.063
  Surrogate splits:
      All species 0-35 cm          < 17.2            to the right    agree=0.911
      All species 70-105 cm        < 8.8             to the right    agree=0.815
      Perennial forbs 0-105 cm     < 10.6            to the right    agree=0.782
      Perennial forbs 0-35 cm      < 14.6            to the right    agree=0.750
      All species 35-70 cm         < 8.7             to the right    agree=0.750

Node number 13: 71 observations    complexity parameter=0.017
  Primary splits:
      Perennial forbs 35-70 cm     < 0.6             to the left     improve=0.122
      Perennial forbs 0-105 cm     < 0.4             to the left     improve=0.070
      Perennial grass 0-35 cm      < 0.2             to the right    improve=0.069
      All species 0-35 cm          < 1.6             to the right    improve=0.063
      All species 35-70 cm         < 2.5             to the left     improve=0.054
  Surrogate splits:
      Perennial forbs 0-105 cm     < 1.6             to the left     agree=0.887
      Annual forbs 0-105 cm        < 7.7             to the right    agree=0.831
      Perennial grass 35-70 cm     < 2               to the right    agree=0.817
      Annual forbs 35-70 cm        < 6.8             to the right    agree=0.817
      All species 35-70 cm         < 1.3             to the left     agree=0.817

Node number 27: 56 observations    complexity parameter=0.017
  Primary splits:
      Perennial forbs 0-105 cm     < 4.4             to the right    improve=0.174
      Annual forbs 35-70 cm        < 3.9             to the left     improve=0.097
      All species 0-35 cm          < 7.2             to the right    improve=0.095
      Annual forbs 0-105 cm        < 5.1             to the left     improve=0.086
      Perennial forbs 70-105 cm    < 0.8             to the right    improve=0.085
  Surrogate splits:
      Perennial forbs 0-35 cm      < 9.7             to the right    agree=0.839
      All species 0-35 cm          < 12.5            to the right    agree=0.804
      Perennial forbs 35-70 cm     < 6.2             to the right    agree=0.786
      All species 0-105 cm         < 6.5             to the right    agree=0.750
      All species 35-70 cm         < 13.4            to the right    agree=0.732

Node number 54: 22 observations    complexity parameter=0.012
  Primary splits:
      Perennial grass 0-105 cm     < 0.5             to the right    improve=0.260
      Perennial grass 0-35 cm      < 0.4             to the right    improve=0.186
      Annual forbs 0-35 cm         < 1.3             to the right    improve=0.155
      Perennial forbs 70-105 cm    < 3.4             to the left     improve=0.126
      Annual forbs 70-105 cm       < 0.8             to the right    improve=0.122
  Surrogate splits:
      Perennial grass 0-35 cm      < 0.1             to the right    agree=0.955
      Annual forbs 0-35 cm         < 1.5             to the right    agree=0.909
      Site                         Back40            to the right    agree=0.864
      Annual forbs 0-105 cm        < 1.0             to the right    agree=0.864
      Perennial grass 70-105 cm    < 0.4             to the right    agree=0.864
```

2012

Node number 1: 115 observations	complexity parameter=0.264		
Primary splits:			
Site	Homestead	to the right	improve=0.264
Perennial grass 35-70 cm	< 20.4	to the right	improve=0.210
Perennial grass 70-105 cm	< 14.8	to the right	improve=0.206
Perennial grass 0-105 cm	< 13.3	to the right	improve=0.205
Perennial grass 0-35 cm	< 11.9	to the right	improve=0.197
Surrogate splits:			
Perennial forbs 70-105 cm	< 9.1	to the left	agree=0.748
Annual forbs 0-35 cm	< 27.6	to the left	agree=0.704
Node number 2: 80 observations	complexity parameter=0.135		
Primary splits:			
All species 70-105 cm	< 15.8	to the right	improve=0.279
All species 0-105 cm	< 29.5	to the right	improve=0.255
Perennial grass 35-70 cm	< 10.2	to the right	improve=0.253
Perennial grass 70-105 cm	< 11.4	to the right	improve=0.238
Perennial grass 0-105 cm	< 11.4	to the right	improve=0.235
Surrogate splits:			
All species 0-105 cm	< 22.7	to the right	agree=0.850
All species 35-70 cm	< 24.1	to the right	agree=0.812
Perennial grass 0-105 cm	< 8.4	to the right	agree=0.775
Perennial grass 0-35 cm	< 11.1	to the right	agree=0.775
All species 0-35 cm	< 31.5	to the right	agree=0.775

Chapter 3: Comparison of effects of competing proximal and distal above-ground vegetation for two hybrid poplar clones

***Abstract* –** Hybrid poplar are a desirable fibre crop frequently planted on former agricultural land, which often contains abundant propagules and seeds of weedy vegetation that later compete with poplar trees. This research trial examines the adverse effects of above-ground competition at differing proximities from the tree stem. As part of an experimental manipulation study, replicated at each of three sites, above-ground vegetation was removed at the following distances from the tree stem of both 'Okanese' and 'Walker' hybrid poplar clones: 0-1.4 m (complete), 0-0.5 m (proximal), 0.5-1.4 m (distal), and a control (no removal). This study was installed in a split-block design at the fenced research fields located at the Alberta-Pacific Forest Industries Inc. mill site in northern Alberta, and took place over the course of two years, including the year of tree establishment. Tree growth responses to the treatments were immediate, and in the establishment year, basal area increment (BAI) was greatest in the proximal (0-0.5 m) and complete (0-1.4 m) suppression treatment. In the following year, both BAI and height increment (HI) of saplings were again greater in the proximal and complete competition suppression treatments than the other treatments, but only for the Okanese clone – which grew much more than the Walker clone in these treatments. The lack of a difference between these two treatments indicates the majority of above-ground competition takes place near (within 0.5 m) the tree stem, and that suppression of above-ground vegetation at distances greater than 0.5 m provides few benefits for young tree growth.

3.1 Introduction

Hybrid poplars (*Populus* ssp.) are among a selection of fast-growing tree species that are being planted extensively as a biomass and fibre crop in North America, Europe, China and Chile. They are typically harvested at less than 20 years of age and are used to produce a wide range of products such as pulp, paper, construction wood, fodder, or energy (Weih 2004). Hybrid poplar are frequently planted on former agricultural land and grown using cultural practices similar to those used on other row crops, including periodic control of competing weedy vegetation that is typically abundant on disturbed landscapes (Bowersox et al. 1992; Hansen et al. 1983). In most tree plantations vegetation control is essential to reduce competition for resources both below-ground (i.e. soil moisture and nutrients) and above-ground (i.e. sunlight and space) (Balandier et al. 2006; Thompson and Pitt 2003).

It is well established that hybrid poplar are very sensitive to below-ground competition (Hansen and Netzer 1985; Kabba et al. 2007). As an early successional species, *Populus* are also sensitive to above-ground competition (Marino and Gross 1998; Powell and Bork 2004a), but in some competition control studies, interspecific above-ground competition was dismissed as unimportant because the weeds were below the height of the tree leaves (Pinno and Belanger 2009; Thomas et al. 2001). Nonetheless, when crop trees are very young, above-ground competition for light and space can be important, and has been observed to be the dominant form of competition during the first year of hybrid poplar (Sixto et al. 2001) and short-rotation willow culture (Sage 1999).

Despite the relatively short period of susceptibility to above-ground competition, it is possible that yield losses early in the life of a hybrid poplar may influence later harvest yields due to the inability of hybrid poplar to compensate for early yield losses (Otto et al. 2010). Early vegetation control is therefore considered essential to ensuring maximum tree (i.e. fiber) biomass, but the relative importance of the proximity of above-ground competitive impacts (i.e. near versus farther away from the tree stem) remain unknown. Mechanical means of weed control, such as mowing or cultivation, are typically limited to the alleyway between tree rows and are ineffective at reducing weed biomass near the tree stem (Coll et al. 2007). Conversely, weed control near the tree stem may be limited to mulching, hand rouging, or targeted herbicide application (Thomas et al. 2001). Given the need to understand the spatial nature of competitive impacts from weeds on young tree plantings, we tested the relative effectiveness of above-ground control at both proximal and distal proximities to the tree stem on tree growth. We did this through the controlled removal of above-ground competition at varying distances from the tree stem of two hybrid poplar clones in their first two growing seasons.

3.2 Materials & methods

3.2.1 Research sites and description

Three research sites were established in early July of 2011 in the fenced Alberta-Pacific Forest Industries' (Al-Pac) research fields (Lat 54°53'N; Long. 112°51'W, 575m), located just south of Al-Pac's processing mill and near the town of Athabasca in northern Alberta, Canada. This area is located near the border of the Dry Mixedwood and Central Mixedwood natural subregions of the Boreal Forest region (Beckingham et al. 1996). The climatic conditions of the region are consistent with that of a cool continental climate characterized by short, warm summers and long, cold winters. The 30 year precipitation average during the growing season (May-September) is 335 mm. During the study years of 2011 and 2012 the area received approximately 333 mm and 327 mm of precipitation during the growing season, respectively, although these values are likely underestimates as the nearby weather station had missing data.

The three study sites were located on landscape positions representing a variety of moisture regimes. The site names of 'Highland', 'Midland', and 'Lowland' corresponded to their respective topographic locations, and were associated with a range of moisture from xeric to sub-mesic. Vegetation in all the sites was entirely herbaceous and composed of pioneer and meadow species. In the Highland site vegetation was fairly sparse and dominated by *Capsella bursa-pastoris* and *Crepis tectorum*, both annual forbs. Vegetation in the Midland and Lowland sites was abundant and was composed primarily of taller perennial/biennial forbs such as *Cirsium arvense*, *Trifolium hybridium*, and *Artemisia biennis*, in addition to some grasses (e.g. *Elytrigia repens* and *Avena fatua* – perennial and annual life cycles, respectively) and shorter perennial forbs (e.g. *Plantago major* and *Taraxacum officinale*). In the latter two sites vegetation cover frequently engulfed part or the entire tree crown when it was allowed to remain next to the tree stem

(Appendix 3-1). Tree growth was generally highest on the Midland site, lowest on Lowland, and intermediate in the Highland site.

Classification of the soils was not performed, although soil samples were taken from each site in August 2012 to measure their physical and chemical properties. Ten soil cores were taken systematically from across each site, and separated into soil depths of 0-15 and 15-30 cm. Within each site, cores were bulked by depth class, frozen, and later analyzed at the Natural Resources Analytical Laboratory at the University of Alberta. The measured properties and analytical methods employed were as follows: organic matter – loss on ignition; pH and electrical conductivity – pH conductivity meter; total nitrogen, ammonium and nitrate – colorimetric determination; soil texture – hydrometer method. Soil physical and chemical properties for each site and depth are reported in Table 3-1.

3.2.2 Experimental design

This study used a randomized split block design that was repeated in each of the three sites. Each site contained six replicated blocks, and each block contained 50 hybrid poplar cuttings planted in a systematic grid pattern of 5 x 10 trees with 2.8 m spacing. Half of each block was planted with rooted cuttings of the hybrid poplar cultivar ‘Walker’ (*Populus deltoides* × (*P. laurifolia* x *P. nigra*)) and the other half with the cultivar ‘Okanese’ (Walker × (*P. laurifolia* x *P. nigra*)) to form two adjacent plots of 5 x 5 trees each. These clones were selected as they are used operationally and therefore of particular interest. Within each 5x5 matrix we randomly selected four of the inner nine trees (i.e. those within the center 3x3 matrix, thereby excluding those around the perimeter) to be assigned to one of four experimental treatments, including: 1) a control with no suppression of competing vegetation within 1.4 m from the tree stem (CONT), 2) suppression of distal above-ground vegetation at 0.5 m to 1.4 m from the stem (DIST), 3) suppression of proximal above-ground vegetation at 0 m to 0.5 m from the stem (PROX), or 4) complete suppression of above-ground vegetation out to 1.4 m from the stem (COMP). Suppression of above-ground vegetation was accomplished by mowing every four weeks starting in June and extending to early September. Mowing was done using a string trimmer and vegetation was clipped to less than 5 cm height from the soil surface; cut vegetation was not removed.

3.2.3 Measurements

Within a week of planting the over-winter dormant rooted cuttings in July 2011, all study trees were measured for maximum height and basal diameter at ground level. Basal stem diameter was measured in both north-south and east-west directions to calculate an average stem diameter. Some trees had co-dominant stems, in which case the height and basal diameter for each stem was measured. Tree measurements were repeated in October of 2011, early May of 2012 (to assess height losses due to winterkill), and again in October of 2012. Stems were initially marked with a permanent marker to ensure subsequent diameter measurements were taken at the same location on each tree. Consecutive measures over time were used to calculate height and stem diameter increments for each tree. Due to complications from some trees having co-dominant stems, basal diameter increment could not be used as a response variable. To account for multiple stems, basal area increment (BAI) was used instead. BAI was calculated as the net increase in total basal area on a given tree over a year as calculated with the following formula:

$$\text{BAI} = \sum_{i=1}^{n}[\pi((\bar{x}_i)/2)^2\,]_{\text{October}} - \sum_{i=1}^{n}[\pi((\bar{x}_i)/2)^2\,]_{\text{May}}$$

where n equals the total number of stems on the tree and $\bar{x}_i$ represents the average diameter of the i^{th} stem

3.2.4 Data Analysis

Height increment (HI) and basal area increment (BAI) were used as response variables to test the influence of clone identity and competition suppression treatment as the fixed effects along with their interaction. Data were run in a mixed model ANCOVA coded for a split-plot design and run in SAS 9.2 software (SAS institute Inc. 2008). Prior to final analysis, site was tested for interactions with the fixed effects with Wald Z-tests and none were found, although tree growth did vary substantially among sites. In the final analysis, site, block nested within site, and clone by block were considered random factors; initial basal area and height from the beginning of each growing season were included as covariates to account for variation in BAI and HI as a reflection of initial tree size. Tree growth was analyzed separately for each of the 2011 and 2012 growing seasons ($\alpha = 0.05$) using the PROC MIXED procedure. Each year was separately analyzed to assess how tree age influences growth responses. Only five trees (out of a total of 144) died by the end of the study, and these were excluded from the 2012 analysis. Assumptions of normality and equal variances were tested with visual assessments of scatterplots of predicted versus residual values, and were met in all cases with the exception of equal variance when BAI was the response in 2012. As a result, for the latter a Satterthwaite approximation of the degrees of freedom was applied to adjust for unequal variances. Post-hoc tests for treatment and clone differences were applied using a Bonferroni correction of alpha. In instances where a clone by competition treatment interaction was found, the orthogonality of the design allowed for the correction to be applied separately when testing treatment differences within each clone (6 comparisons, tested at α=0.083), and also for evaluating clone differences within treatments (4 comparisons, tested at α=0.0125).

3.3 Results

Despite the short period of time over which competition suppression treatments were in place during the establishment year of 2011, there was a significant effect of treatment on tree basal area increment (BAI) (Table 3-2). Trees belonging to either the COMP or PROX treatment had greater BAI values than trees in the other treatments, with no further differences among them (Fig. 3-1A). Height increment (HI) also differed among treatments in 2011, but was further impacted by clone and a clone by treatment interaction. The HI of Walker trees exceeded that of Okanese, but only in the COMP treatment (Fig. 3-1B). Additionally, while HI did not differ among competition suppression treatments for the Okanese clone, Walker trees had greater HI in the COMP treatment than those within the CONT and DIST treatments; HI in the PROX treatment was intermediate (Fig. 3-1B). The initial height of the rooted cuttings during establishment was also found to be a significant covariate (Table 3-2).

Tree growth in 2012 was greater than in the previous year: 2011 - mean BAI = 16.0 mm^2, mean HI = 27.1 cm; 2012 - mean BAI = 60.8 mm^2, mean HI = 34.6 cm. For both BAI and HI responses the clone by treatment interaction was significant, as were individual clone and treatment effects (Table 3-2). Results of post-hoc testing revealed treatment differences similar to those for BAI in 2011 where growth of trees in the COMP and PROX treatments were greater than those in the CONT and DIST treatments, with two key differences; in 2012 these differences among treatments were significant for both BAI and HI responses, and then only within the Okanese clone (Fig. 3-2). No treatment differences were noted with the Walker clone (Fig. 3-2). Among clones, Okanese trees also had greater BAI than Walker trees in the COMP and PROX treatments but not in CONT or DIST (Fig. 3-2A). Okanese trees in all but the CONT treatment had greater HI values than Walker trees in the same treatments (Fig. 3-2B). As a covariate, initial basal area was found to be significant in 2012, and initial height was not, which is the exact opposite of covariate significance in 2011.

3.4 Discussion

Results of this study indicate that the majority of benefit from above-ground control of vegetation comes from removal (clipping) of vegetation near the tree stem (within 0.5 m). Extending the zone of vegetation control out into the alleyway between trees provided no detectable growth benefit. Further, control of competing vegetation only in the distal position provided a marginal and non-significant growth benefit, as compared to no vegetation control. This suggests that above-ground control of the inter-row vegetation during the first couple of years following plantation establishment is unnecessary, at least insofar as above-ground competition is concerned. Herbicide control of the more competitive species of grasses may be beneficial (see Chapter 2). However, as the trees get older and their roots expand further away from their stem they will encounter inter-row competition, thus vegetation control farther from the tree may become necessary. It is also possible that as the trees get older (hence larger) they may decrease neighbor competition via overstory shading, and reduce or negate the need for vegetation control between trees. Additional research is needed to determine whether the suppressive effect of the tree canopy in older trees is great enough to adequately control inter-row vegetation.

It is important to note that the observed gains in growth (and treatment effects as described in the previous paragraph) were primarily for the Okanese clone, whereas the Walker clone was much less responsive to the treatments and less productive overall. Over the course of the entire study period the Okanese clones averaged 125% greater basal area increment (BAI) and 78% greater height increment (HI) than Walker (data not shown). Initial heights and basal areas were also found to influence subsequent growth, but at different tree ages. Initial height of the trees during the establishment year was found to be a significant covariate for HI in the first growing season, but not the second. This suggests that the height of the rooted cuttings prior to planting has a short-term influence on the trees' ability to rise above neighboring vegetation. In contrast, initial basal area was a significant covariate in the second (2012) but not the first (2011) growing season. From this information we speculate that BAI in the establishment year is predominantly a product of external factors such as resource acquisition and competition, because the trees were planted as rooted cuttings or plugs, and therefore had relatively small root systems and limited internal resources to assist them. In the following year, it may be that initial basal area quantitatively represents how well the trees became established and built up their internal reserves, which consequently influenced their ability to grow more and resist competition over the growing season. It is unknown whether this positive feedback will magnify or diminish over time. We hypothesize that the initial treatments during the establishment year may have influenced the trees' ability to increase their below-ground biomass, which in turns impacts BAI the following year.

We presume that the favorable growth response to suppression of above-ground vegetation near the tree stem was primarily because of reduced competition for space, and in particular incoming light. In theory, vegetation closer to the tree stem intercepted more incoming light, and thus competed more effectively for space than vegetation further away from the stem. Trees in this study were relatively young and had much of their canopy engulfed by tall statured herbaceous plants rooted near the tree stem, even during the second year after planting; this competing vegetation would have imposed significant competition for photosynthetically active radiation. This effect may be further aggravated if the competing vegetation is comprised of tall statured forbs with high leaf area, which are generally more effective competitors for light than grasses (Balandier et al. 2006). For example , alfalfa (*Medicago sativa*), a large perennial forb, intercepts nearly twice the light of marsh reedgrass (*Calamagrostis canadensis*), a perennial grass species, when both are grown within 20 cm of young trembling aspen (*Populus tremuloides*) seedlings (Powell and Bork 2004a). It is likely that a similar influence was present in our sites – especially Midland and Lowland – as the vegetation cover was extensive and composed of tall perennial and biennial forbs such as *Cirsium arvense*, *Trifolium hybridium*, and *Artemisia biennis*. When vegetation cover was allowed to persist near the tree stem, these species usually covered the tree crown partly or entirely (Appendix 3-1).

Alternative explanations for the growth response to the treatments include increased soil temperatures due to a reduction of vegetation and soil litter (Hogg and Lieffers 1991), which may increase root and shoot growth directly (Landhausser et al. 2001; Wan et al. 1999), or indirectly through increased nitrogen mineralization (Rustad et al. 2001). Conversely, this was not found to be true in the case of slightly higher soil temperatures associated with weed-free plots compared to unweeded plots in hybrid poplar plantations in Saskatchewan (Pinno and Belanger 2009). Other possible explanations include reduced competition for below-ground resources (water and nutrients) as a consequence of root dieback below the cut vegetation (Bicksler et al. 2012). However, cutting of neighboring herbaceous vegetation may not always relieve below-ground competition, as competitive below-ground interactions between defoliated and non-defoliated vegetation is highly dependent on species (Zhu and Sang 2008). For example, Davies (1985) noted that cutting grasses near crop trees increased drying of the soil, which could increase moisture stress on neighboring trees. Furthermore, Coll et al. (2007) observed soils in both untreated and mowed treatments had lower available nitrogen levels than either cultivation or herbicide treatments; this presumably was due to nutrient uptake by the remaining vegetation within the first two treatments.

Despite the possible negative consequences of mowing as a form of vegetation control, our findings indicate that cutting competing above-ground vegetation near the stem of a young hybrid poplar tree benefits – rather than hinders – tree growth. As a caveat, the benefits of any above-ground treatment were primarily observed for the Okanese clone, whereas the Walker clone seldom displayed a growth response to treatments. The superior growth response of Okanese, particularly in the second year after planting and treatment, suggests this clone has superior growth potential, which in turn, is further expressed when released from competition. Notably, the overall greater effectiveness of proximal (rather than distal) above-ground control in this clone mirrors that of other studies involving hybrid poplar where competition occurred near the stem, though primarily below-ground (Coll et al. 2007; Thomas et al. 2001).

The fact that we observed any positive influence of above-ground suppression differs from studies where no such effect was observed (Coll et al. 2007) but agrees with others (Bilodeau-Gauthier et al. 2011; Czapowskyj and Safford 1993). We attribute the inconsistent results to differences in vegetation types (i.e. herbaceous vs. woody vegetation), hybrid poplar clones, plantation ages (1-10 years), and former land uses (i.e. agricultural vs. forest). Additionally, the mowing treatment of Coll et al. (2007) was not maintained throughout the study period, and it failed to provide above-ground control of vegetation near to the tree stem itself, which our results suggest is essential to elicit a growth response in hybrid poplar trees. The results of our study are fairly unique however, because it found significant treatment differences when the competing vegetation was all herbaceous. In the above-mentioned studies where mowing effects were observed, the trees were planted on formerly forested sites where competing vegetation included woody vegetation (shrubs, young trees, etc.), which is more effectively suppressed by mechanical means of control than is herbaceous vegetation (Balandier et al. 2006).

3.4.1 Conclusion

We observed rapid, same-year responses to removal (by means of clipping) of competing vegetation immediately adjacent to hybrid poplars and responses became even more pronounced one year later. These results indicate that above-ground competition was limiting tree growth for young hybrid poplar trees in this study. Moreover, these results were primarily observed for the superior performing Okanese clone, rather than the slower growing Walker clone. Improvements in tree growth were seen only in treatments that suppressed above-ground neighboring biomass within 0.5 m of the tree stem, suggesting competition occurs near the tree stem in plantations less than two years old. In contrast, cutting of competing vegetation at proximities greater than 0.5 m from the tree stem did not improve growth, and suggests limited benefits may occur from silvicultural treatments targeting these areas within plantations. Similar below-ground competition effects have been shown by previous studies where most of the experienced below-ground competition is due to vegetation immediately adjacent to the trees (Coll et al. 2007; Thomas et al. 2001). On this basis we suggest that inter-rows may initially be left intact to provide soil conservation and biodiversity benefits.

Table 3-1. Physical and chemical properties of soils at the various study sites. N/A indicates data were not available because of a laboratory error.

Site	Soil depth (cm)	Organic C (%)	pH	EC (mS/cm)	Total N (%)	NH_4 (mg/kg)	NO_3 (mg/kg)	Clay (%)	Silt (%)	Sand (%)
Highland	0-15	2.97	6.44	N/A	0.11	1.66	1.74	9	32	59
	15-30	1.92	6.51	38	0.07	1.46	0.82	7	24	69
Midland	0-15	5.93	6.81	97	0.24	2.09	3.18	21	53	26
	15-30	2.76	7.50	88	0.10	1.78	0.32	28	39	33
Lowland	0-15	6.23	6.73	117	0.28	2.59	2.36	25	50	25
	15-30	3.85	7.39	148	0.12	1.51	0.79	44	42	14

Table 3-2. Results of the ANCOVA tests for differences in hybrid poplar growth increment in response to poplar clone type and competition treatment. Initial basal area and initial height were included as covariates for the analysis of basal area increment (BAI) and height increment (HI), respectively. Results are reported separately for each of the 2011 and 2012 growing seasons. Significant values are bolded ($p < 0.05$).

Year	Response	Effect	Num DF	Den DF	F-value	P-value
2011	BAI	Clone	1	17	0.02	0.89
		Treatment	3	101	12.46	**< 0.0001**
		Clone*Treatment	3	101	1.11	0.35
		Initial basal area	1	101	0.57	0.45
	HI	Clone	1	17	0.23	0.64
		Treatment	3	100	4.28	**0.0069**
		Clone*Treatment	3	100	3.54	**0.0185**
		Initial height	1	100	16.57	**< 0.0001**
2012	BAI	Clone	1	17	50.7	**< 0.0001**
		Treatment	3	96	5.41	**0.0017**
		Clone*Treatment	3	96	5.92	**0.0009**
		Initial basal area	1	96	19.69	**< 0.0001**
	HI	Clone	1	17	39.47	**< 0.0001**
		Treatment	3	96	11.23	**< 0.0001**
		Clone*Treatment	3	96	3.13	**0.0290**
		Initial height	1	96	1.96	0.16

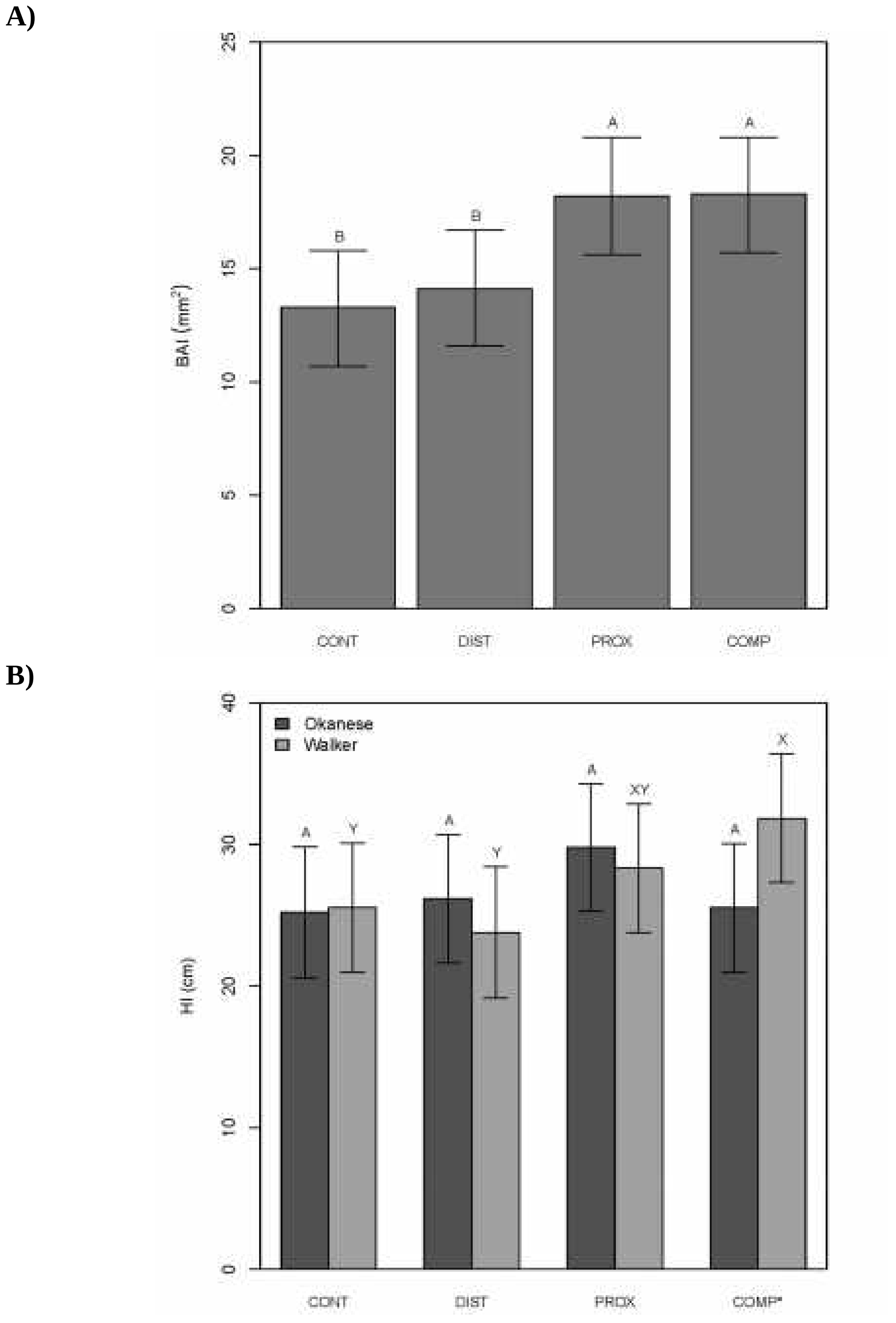


Fig. 3-1. Hybrid poplar growth increments for basal area increment (BAI) **(A)** and height increment (HI) **(B)** for each suppression treatment in 2011; CONT = control (no suppression), DIST = distal (vegetation control 0.5 – 1.4 m from the tree), PROX = proximal (0.0 – 0.5 m), COMP = complete (0.0 – 1.4 m). Error bars are 95% confidence intervals. Treatments with different letters within the same clone are significantly different ($p < 0.05$), and a * next to a treatment name denotes significant differences between clones within that treatment ($p < 0.05$); all post-hoc tests were performed using a Bonferroni correction. Only treatment effects are shown for basal area increment because there was no significant interaction between treatment and clone.

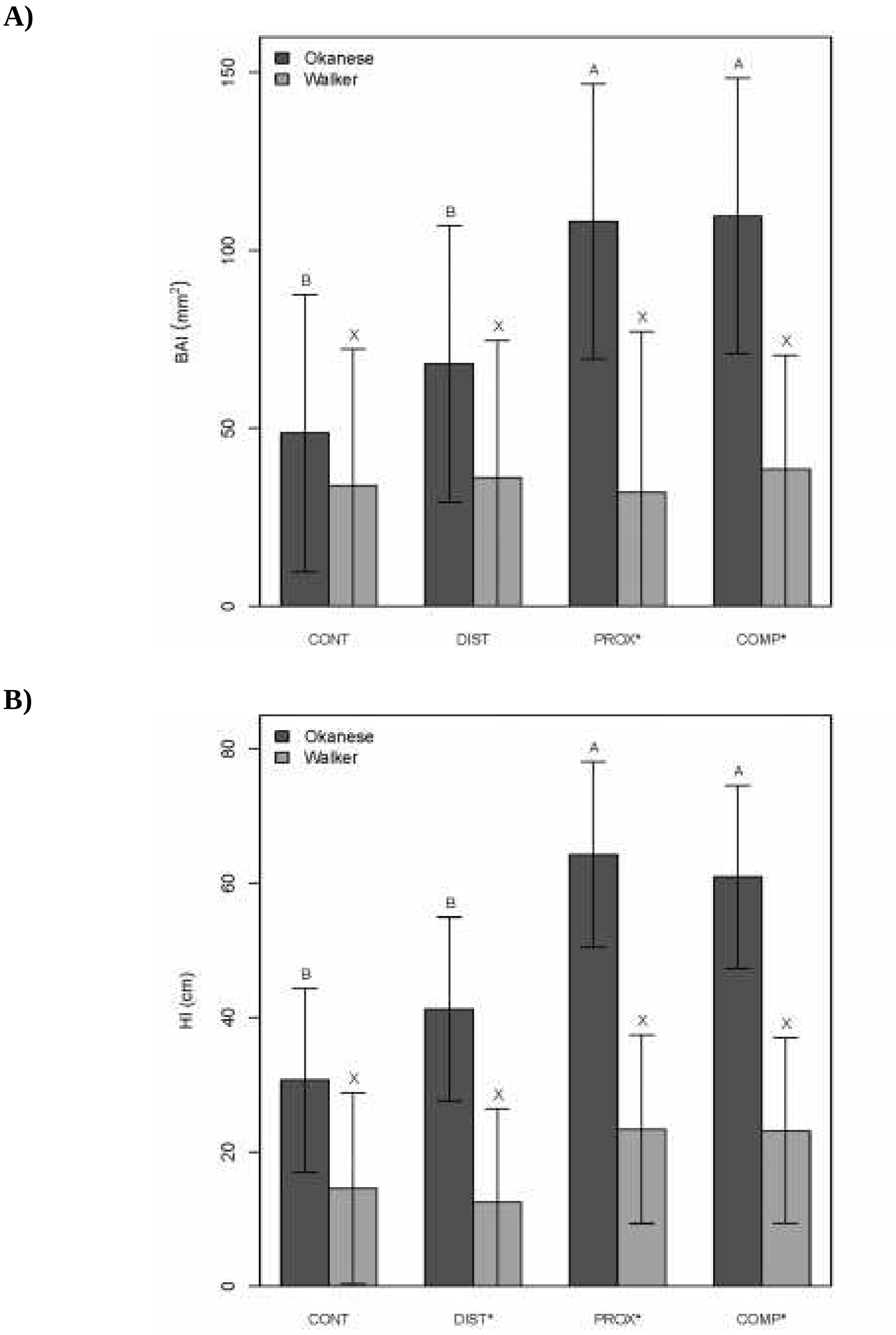


Fig. 3-2. Hybrid poplar growth increments for basal area increment (BAI) **(A)** and height increment (HI) **(B)** for each suppression treatment in 2012; CONT = control (no suppression), DIST = distal (vegetation control 0.5 – 1.4 m from the tree), PROX = proximal (0.0 – 0.5 m), COMP = complete (0.0 – 1.4 m). Error bars are 95% confidence intervals. Treatments with different letters within the same clone are significantly different ($p < 0.05$), and a * next to a treatment name denotes significant differences between clones within that treatment ($p < 0.05$); all post-hoc tests were performed using a Bonferroni correction.

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3.6 Appendices

Appendix 3-1. Photos of a tree in the DIST treatment **(A)** and the PROX treatment for comparisons **(B)**. Note the greater access to sunlight and space by the tree in the PROX treatment.

A)

B)

Chapter 4: Synthesis

One of the primary challenges of managing large-scale plantations consists of maximizing growth and fibre production while under the duress of economic and silvicultural constraints. A prime example of this challenge is faced by the plantation managers for the Poplar Farm Land Lease Program of Alberta Pacific Forest Industries Inc. (Al-Pac), which has installed over 10,000 ha of operational plantations of hybrid poplars within a 200 km radius of their mill in northeastern Alberta. Often the largest management cost in these and other types of plantations is in the control of competing vegetation during the early establishment and growth phase. Given the previously mentioned constraints, understanding the impact of species and location of competing weeds on plantation growth is integral for determining how best to spend limited dollars during this critical early phase. To date, few studies have investigated this competition, and little is known about the factors regulating competition in hybrid poplar plantations. This thesis seeks to remedy that lack of knowledge by investigating the competitive interactions taking place between young hybrid poplar trees and neighboring vegetation; few measurements of available resources were performed and interpretation of the results is based strictly on tree growth responses, although large sample sizes helped to facilitate the detection of tree-herb relationships. To carry out this research, operational plantations were made available for study along with a fenced controlled plot area, both courtesy of Al-Pac. Results of this research will aid in the formation of an integrated weed-management plan for hybrid poplar plantations, and contribute to our understanding of the effectiveness of current silvicultural practices and ecology of plantation forests.

In Chapter 2 I first quantified the impact of competing neighboring vegetation by analyzing tree growth as it relates to herbaceous vegetation composition, abundance, and proximity (i.e. distance from the stem). This study appears to be the first using hybrid poplar that included detailed assessments of herbaceous plant communities for the purpose of explaining variation in tree growth. In Chapter 2 tree growth was defined as basal area increment (BAI), and not basal diameter increment (BDI), because many trees contained co-dominant stems, and I suspect that if average BDI had been used as the response variable, it would have underestimated the true growth of a multi stemmed tree. Height increment (HI) was also not used due to complications from extensive winter moose browse and stem dieback. Overall negative influences on tree growth from browsing are not expected to be severe, however, as previous studies suggest that early successional deciduous species, including *Populus*, have the ability to compensate for winter browsing of the shoots (Carson et al. 2009; Danell et al. 1994). With that being said, the most important factor determining tree growth was site (i.e. growing conditions) rather than any particular vegetation variable. However, because vegetation composition, as well as its impact, co-varied with site conditions, it is impossible to generalize about the impacts of competition across sites. This indicates that with regards to tree growth, site and vegetation are not independent, non-interacting variables, but rather are interdependent variables with a complex relationship, each unique. Future research aimed at clarifying this relationship would be immensely valuable and provide additional context for my results.

Vegetation variables were nonetheless important in explaining variation in poplar growth; perennial grasses overall, as well as specific plant species (e.g. *Elytrigia repens* and *Cirsium arvense*), were identified as being highly detrimental to tree growth. It also appeared that competition played a greater role in influencing tree productivity earlier in the development of the stand (i.e. growth was reduced more for two year old trees than three year old trees).

The role of vegetation proximity from the tree stem in regulating the effects of competition was less clear as different vegetation components at varying proximities explained similar amounts of total variation in tree growth in both two and three year old stands. Nonetheless, total neighboring vegetation abundance within 70-105 cm from the tree stem was identified as an important determinant of individual tree productivity, as determined by the variable importance measure. These results are potentially contradictory to the results of Chapter 3 and previous studies that suggested control immediately adjacent to the tree stem is more important (Coll et al. 2007; Thomas et al. 2001). Furthermore, rank correlation analysis revealed that vegetation abundance within 70-105 cm from the tree stem was highly correlated with total vegetation abundance at 0-105 cm from the tree stem. For this reason, the results of the variable importance measure should be viewed with caution. I hypothesized in Chapter 2 that this result emerged because poplar trees in plantations have a suppressive effect on neighboring vegetation, and that smaller trees impose less competition on neighboring vegetation beyond 70 cm, hence the direction of influence may be opposite to that which the analysis indicated. Another possible explanation is that in that for the trees in this particular analysis, the vegetation was not controlled near to the stem and therefore all the trees are receiving heavy near-stem competition, hence competition farther out – which is controlled to some degree by the disc cultivator – is what explains variations in growth. Additional research is needed in this area to confirm the role of proximity in regulating competition effects.

To further investigate the role of spatial location in competitive effects, I compared the effectiveness of different vegetation suppression treatments around hybrid poplar trees and the effect that each had on tree growth (Chapter 2). Results from that experiment further supported the conclusions reached previously from the observational study of neighboring vegetation and tree growth by providing an observable cause and effect. On half of the sites, those that were in the Berquist plantation, increasing intensity of vegetation control did not result in a commensurate increase of tree growth. This suggests that the productivity of these sites may have been limited in some other way besides competition, or else moose browsing limited our ability to find differences in growth. Of the sites that did show a response to suppression treatments, cultivation as a sole means of vegetation control was inadequate. I hypothesize that the inadequacy of cultivation-only as a vegetation control treatment is partly because grasses, which imposed the greatest reduction in the growth of the trees, were more poorly controlled by the cultivation-only treatment as compared to every other treatment. This is supported by the fact that early vegetation control with herbicides in the Rockpile site (which was dominated by *Elytrigia repens* - quackgrass) resulted in the largest growth increases of any treatment. Overall these results give further credence to conclusions that grasses are highly damaging to young hybrid poplar, and can best be controlled with the use of silvicultural strategies that include herbicides.

Chapter 3 of my thesis differed from the previous chapter by narrowing its focus to an experimental test of above-ground competition and the regulating influence of proximity of neighbor vegetation from the tree stem during early establishment. This study was unique in that it attempted to isolate a source of above-ground competition, and manipulate it independently of other competition sources. It also differed from the study in my second chapter by being a manipulative study, and no quantitative measures of neighboring species composition or abundance were undertaken. Its strength is in its simplicity, and the rapid differentiation of growth responses among treatments during the establishment year can be attributed to immediate changes in above-ground competition brought on by the treatments. Prompt release from competition in young trees has rarely been observed in other competition studies involving hybrid poplar, although in many studies establishment year growth was not measured. Nonetheless, these results are a testament to the importance of above-ground resources for early tree growth. Both clones showed similar positive responses to the treatments that removed vegetation close to the tree, but the Walker clone did not respond to any treatment in the post-establishment year (2012). For Okanese, however, favorable responses to competitive release continued into the post-establishment year, and both basal area increment (BAI) and height increment (HI) displayed identical responses to the treatments. This suggests that Walker trees either have a high susceptibility to competition, or it is an unresponsive clone. Also, Okanese was a faster growing clone than Walker, and may have had more ability to respond to a release from competition.

4.1 Management implications of research

Using the conclusions of my research, an integrated weed management plant should include the following components:

1. A focus on earlier, rather than later vegetation control (in terms of plantation age).
2. Prioritization of vegetation control to target perennial grasses and/or more deleterious plant species such as quackgrass and Canada thistle, where present.
3. Where highly competitive weeds are present, herbicides are needed for maximum effectiveness.
4. Control of all above-ground vegetation within 0.5 m of the tree bole when using Okanese clones, which are faster growing than the Walker clone when control measures are applied. This can be done perhaps using techniques such mulch mats, directed applications of herbicide (perhaps a mix of broad spectrum and pre-emergent herbicides) in the spring prior to tree leaf-out, or a team of

operators with weed trimmers. Previous research suggests that the majority of below-ground competition also occurs nearer to the tree bole, so methods which also control below-ground competition are preferred.

5. Control of perennial grasses in the alleyway between tree rows, perhaps using grass-specific herbicides. If perennial grasses and other highly competitive species are not present, the space between the tree rows may be left intact, or the vegetation there may be adequately controlled using only cultivation.
6. Planting of larger rooted cuttings, which help the trees to resist initial competition following planting.

Application of these research findings will not only benefit tree growth, but also support efforts to conserve soil and promote wildlife habitat. Herbaceous plants classified as 'weeds' can play an important role in maintaining long-term soil fertility (Welham et al. 2007), and contribute to wildlife habitat through diversity (Archaux and Martin 2009).

4.2 Challenges and recommendations for future research

This project, particularly Chapter 2, gave me the opportunity to conduct research under operational conditions and consider the challenges faced by industrial operators. Nonetheless, execution of this research presented substantial unforeseen challenges, both practical and theoretical. To counter these difficulties and assist in the gathering of more informative data, I present the following suggestions and recommendations:

1. Fencing of research areas so as to exclude large browsing mammals. This would allow for accurate quantification of tree height and stem volume in addition to basal area.
    - If some browsing is inevitable, then an investigation into how summer and winter browsing influences hybrid poplar morphology, as well as

how trees compensate for shoot loss would greatly aide future researchers in accounting for browse damage in their results.

2. An investigation into whether multiple stemmed trees accrue height and basal area at different rates than single stemmed trees. If they do, then for future studies *a-priori* selection of trees with a single stem is recommended.
3. Begin tree measurements immediately after planting to better account for variability in initial tree size.
4. Greater frequency of tree measurements in a growing season would provide much needed insight into how tree size, as influenced by competition and vegetation control treatments, interacts with time.
5. Annual tree measurements throughout an entire rotation could help determine if trees can compensate for early growth losses due to competition, and how vegetation control treatments change a plantation's growth curve. Vegetation control can affect the growth curve by either advancing the stage of stand development without changing site productivity (Type 1 growth response) or by inducing a long-term change of site properties to increase productivity (Type 2 growth response) as described by Snowdon (2002).
6. Collect detailed measurements of soil moisture, temperature, nutrient availability, and available photosynthetically active radiation (PAR) around individual trees, as this information would greatly help in explaining the intensity of resource competition and specific causes for variability in tree growth. However, this would require much more manpower and additional workers (or a reduced number of study trees) would be needed.

7. If feasible, careful excavation of hybrid poplar roots at different ages and under different conditions of competition intensity could provide invaluable insight as to hybrid poplars' below-ground growth plasticity.

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