ESTABLISHMENT OF DRIP-IRRIGATED POPLAR IN SEMI ARID BRITISH COLUMBIA

by

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ABSTRACT

The need for research into systems that augment diminishing wood fibre supplies is underscored by escalating pressures on primary forests. In semi-arid forest plantations, small-scale site preparation can reduce competition from non-crop species, but interplanting amongst existing vegetation may create favorable establishment conditions including altered soil water content and hindered deer browsing. The objectives of this thesis are to determine: (1) the impact of mechanical site preparation versus interplanting on the survival and initial growth of *Populus* cuttings, (2) differences in survival and initial growth between four different selectively-bred *Populus* clones and (3) whether there is an interaction between the establishment treatments and the different clones in an intensively managed plantation. In 2016, a drip irrigation system was constructed to deliver approximately 2.5 l day^{-1} of water to cuttings of 4 selectively-bred poplar (*Populus deltoides* x *petrowskyana* (*P. laurifolia* x *P. nigra*)) clone types (Green Giant, Griffin, Hill, Walker) planted across 6 blocks in a 10-hectare plantation on Skeetchestn Reserve west of Kamloops, BC. Before planting, 50% of each block was treated with mechanical site preparation, and 50% was not mechanically site prepared to allow for interplanting of the cuttings with existing vegetation. Watering took place from July-September 2016 and from May-September 2017. In 2016, trees were watered for 48 days, totaling 1.06×10^6 l. In 2017, trees were watered for 96 days, totaling 2.12×10^6 l. At the end of each growing season, non random sampling including measurements of basal diameter, total height and length of longest stems as well as counts of tree survival were conducted. Generalized linear models were constructed to investigate responses of survival, diameter, height and volume index to establishment treatment, clone type and initial cutting size predictors. Significant differences in tree survival, basal diameter, basal diameter increment, total tree height, total tree height increment, volume index and volume index increment were found between clones ($p<0.05$) but not between establishment treatments after the first (2016) and second growing season (2017). No significant treatment*clone interactions were detected.

By fall 2017, the best performing clone was Green Giant with 75% survival, 15.6 mm basal diameter, 0.6 mm two-year diameter increment, 43.6 cm height, 14.3 cm two-year height increment, 0.10 dm^3 volume index and 0.06 dm^3 two-year volume index increment. The worst performing clone was Griffin with 32% survival, 12.0 mm basal diameter, 0.2 mm two-year diameter increment, 38.7 cm height, 4.9 cm two-year height increment, 0.06 dm^3 volume index and 0.03 dm^3 two-year volume index increment. Cuttings with larger initial diameters exhibited significantly better ($p<0.05$) survival, diameter increment, height increment and volume index increment in the first year after planting. With first year survival being paramount to establishment success, cuttings planted in similar conditions should be selected for large basal diameters. The mechanical site preparation establishment treatment showed consistent improvement of establishment and growth parameters over the interplanting treatment, but mixed significant ($p<0.05$) and non-significant ($p>0.05$) results did not support recommending it for future use.

Keywords: forest engineering, irrigation, plantation forestry, *Populus,* silviculture.

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DEDICATION

From a small seed a mighty trunk may grow - Aeschylus

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LIST OF ACRONYMS

AMSL = Above Mean Sea Level
BEC Zone = BioGeoClimatic Zone
BGxh2 = Bunchgrass; very dry hot subzone; Kamloops variant
DI= Diameter Increment
Di = 2017 Basal Diameter measurement
Do = Initial Basal Diameter measurement
ET= Hargreaves Reference Evapotranspiration
GDD= Growing Degree Days
GG = Green Giant poplar
GLM = Generalized Linear Model
HDPE = High Density Polyethylene
HI= Height Increment
Hi = 2016 Height measurement
Hii = 2017 Height measurement
Ho = Initial Height measurement
HSD = Honest Significant Difference
$K_{C(1)}$ = Crop Coefficient for 2016
$K_{C(2)}$ = Crop Coefficient for 2017
LDPE = Low Density Polyethylene
L = Loam
MSP = Mechanical Site Preparation
NOMSP = No Mechanical Site Preparation
PAR = Photosynthetically Active Radiation
PVC = Polyvinyl Chloride
RCB = Randomized Complete Block
SCL = Sandy Clay Loam
SiC = Silty Clay
SiCL = Silt Clay Loam
SL = Silt Loam
SVP= Saturation Vapour Pressure
VI = Volume Index Increment
VIF = Variance Inflation Factor
Vi = 2016 Volume Index
Vii = 2017 Volume Index
Vo = Initial Volume Index
VPD = Vapour Pressure Deficit

CHAPTER 1. GENERAL INTRODUCTION

Poplar Plantations in British Columbia

The history of working with poplar plantations for various commercial applications dates to around the 1950's in British Columbia (BC), Canada (Smith and Blohm 1966; Samson et al. 1999). Some of the more recent plantations in BC have been established for uses that include carbon sequestration, phytoremediation, pulp, paper and panel manufacturing, agroforestry and environmental restoration (Samson et al. 1999; Stanton et al. 2002). Hybrid and native poplar plantations have been in recent operation in Salmon Arm, Vernon, the lower mainland, northeastern BC and the Peace River area (Carlson 1992; Nercessian 1994; van Kooten 1999; Stanton et al. 2002; CFS 2006; Vyse and Simard 2007). There have also been plantations in other areas of the province such as Creston in the Kootenay region (CFS 2006; Vyse and Simard 2007).

The land base for hybrid poplar plantations has been limited to a scattering of small areas across the province due to several constraints, namely ecology (climate), policy and economics (Carlson 1992; Thomas et al. 2001; Barber 2007). Drought and frost have played a large role in determining where the establishment of plantations has been considered in the past (Carlson 1992). The potential for generating negative environmental effects associated with intensively managed plantations (especially during the establishment process) has also been a barrier to a more widespread acceptance across the province (Vyse and Simard 2007). As a result, areas where more intensive management is deemed an acceptable practice are often limited to private land or other areas where zoning or other land use agreements permit such activities (Binkley 1997; Morford and Hutton 2000; Barber 2007). If an area of land is ecologically suited and the status of the land allows for growing intensively managed poplar, the location in proximity to buyers or users of the wood fibre must also be economically viable (Thomas et al. 2000). Transportation costs can quickly reduce potential profits and the overall feasibility of the project (van Oosten 2006; Zhang and Pearse 2011). The cost-benefit relationships associated with establishing and operating poplar plantations have also been subject to fluctuations in wood fibre markets over the years (van Kooten 1999; Park and Wilson 2007).

Today, growing demand for the products and services from hybrid poplar plantations has led to increased interest in establishing plantations that suit the environmental, political and economic landscape of BC (Knudson and Brunette 2015). Plantation grown hybrid poplar can be a versatile crop when clones are correctly selected to fit local ecological conditions and management objectives (Stanton et al. 2002). Hybrid poplar plantations may also represent one solution for meeting growing wood fibre demand while reducing some of the harvest pressure on BC's naturally forested ecosystems that are often subject to competing land use values (Binkley 1997; Park and Wilson 2007; BCMFLNRO 2010).

Poplar Ecology

Limits to Poplar Growth

Several abiotic and biotic factors can affect establishment success, growth, dieback and mortality in plantation grown hybrid poplar. Some important environmental factors for poplar growth include water availability, temperature, nutrient availability and soil conditions, as well as competition for resources from other vegetation.

Ample moisture is required to maximize growth (Strong and Hansen 1991). Irrigation may not be necessary for survival, but significantly increases growth in *Populus* species (although there is a high amount of variation in these increases; Strong and Hansen 1991). For areas receiving less than 300mm of growing season precipitation, guidelines recommend supplemental moisture (e.g. irrigation) to overcome significantly restricted growth. Moisture deficits can come in the form of vapour pressure deficits in the air or in soil moisture deficits (Nash 2009). When exposed to these moisture deficits, morphological responses vary, but results typically take the form of altered allocation or reduced production of biomass (Nash 2009). *Populus deltoides* have been observed showing signs of top dieback resulting from exposure to drought, soil moisture deficit or lowered water table (Rood et al.

2000; Nash 2009). Poplar hybrids have shown variation in tolerance to moisture deficits (Demerrit 1990).

Populus trees are typically thought of as being found in hydric to mesic areas with a variation in ability to colonize a site across the genus and with climate and soil type (Demeritt 1990). In general, hybrid poplars seem to do well in medium textured soils with good moisture holding capacities and a minimum of one meter in depth (Demeritt 1990). Different poplar hybrids have shown the ability to grow in soils with varying pH, though optimum conditions are thought to be around 6.0 to 7.0 (Demeritt 1990).

Low availability of iron and other micronutrients in alkaline soils can lead to chlorosis, poor growth and death (Brady and Weil 2008; Terpsma 2016). Trees that have poor availability of nitrogen can display chlorotic symptoms while over abundances of nitrogen can negatively affect stem morphology (Brady and Weil 2008; Terpsma 2016). Another important macronutrient, soil phosphorus is important to structural tissue strength, root growth, photosynthesis, nitrogen fixation and maturation (Kelly and Ericsson 2003; Brady and Weil 2008; Terpsma 2016).

Injury and death can occur in shallow roots of any age of tree when there is a lack of insulating snow cover to provide protection from frost damage. Trees with damaged roots may be prone to dieback of leaders and branches later in the growing season leading to malformations such as “staghead” (leafless condition of the top area of the tree crown; Zalasky 1978). In addition, freezing and thawing or rapid temperature changes can cause damage to sapwood and bark while killing off limbs and leaders (Zalasky 1978). Loss of vigor and cankering can also occur because of winter drying (Zalasky 1978). The lower and upper boundaries for temperature growing conditions are listed as below -46ºC and above 38ºC for greater than 1 week (Demeritt 1990).

Adequate spacing between planted trees is also an important consideration. This can vary depending on the end use of the trees, but a general recommendation suggests 3 m within row by 4 m between row spacing that works out to a stocking density of 833 stems/hectare (Ménétrier et al. 2005).

Successful establishment of a poplar plantation requires control of competing vegetation especially during the first two years after planting (Demeritt 1990). Shade and thick plant cover such as heavy sod is known to negatively impact tree survival and growth while competition for light, water and nutrients can reduce growth and vigor of crop trees (Demeritt 1990). Herbicides can be used to control competing vegetation but these can negatively affect the trees as well (Demeritt 1990). High material costs along with social and environmental concerns associated with vegetation control treatments have necessitated more study of poplar plantations grown under alternative establishment methods in recent years (Masse et al. 2014). Effectively applied site disturbance and precise delivery of resources (water and nutrients) are fundamental elements of efficient establishment systems (van Oosten 2006). Careful assessment of site ecological conditions can indicate the level of disturbance required for successful establishment (Lof et al. 2012). Small-scale mechanical site preparation (MSP) is a method of creating targeted locations and amounts of physical disturbance to aid in seedling establishment (Thomas et al. 2000). When used effectively, MSP contributes to favorable growing conditions and reduces competition from non-crop vegetation while minimizing disturbance to non-planted areas of a site (Thomas et al. 2000). Interplanting amongst the existing canopy of trees or shrubs (NOMSP) can also be an effective establishment treatment when applied in appropriate ecological conditions (Rousset and Lepart 1999). Crop species in interplanted scenarios benefit from the cover provided by the existing canopy- serving to create milder microclimates and obstruct predation (Rousset and Lepart 1999). Protection from grazing is important to establishment especially in the southern interior of British Columbia where wildlife and domestic animals often occupy the same spaces as forest plantations (Meidinger and Pojar 1991).

A variety of animals can cause damage to poplar trees. Girdling of the bark at ground level and above can be caused by small rodents below the snow line (Zalasky 1978). Hares can cause damage to trees above the snow line (Zalasky 1978). Beavers may harvest large areas of a plantation in short time periods, while porcupines and black bear can damage older trees (van Oosten 2006). Ungulates may browse trees in the early years after planting which can influence overall survival (Truax et al. 2012). Cattle, horses and sheep can cause damage to trees, especially while they are young. Cattle have been reported to use hybrid poplars for a backrub which can cause partial uprooting while horses and sheep may strip the bark from trees (van Oosten 2006).

Several pathogens are of concern to hybrid poplar plantations because of the potential impacts they can have on wood quality, growth increments, and tree survival within a plantation in addition to the potential for propagation and spreading of disease by the plantation itself. Notable pathogens that cause stem canker include *Hypoxylon mammatum* (in *Populus tremuloides* and poplar hybrids in stands with low stocking densities), *Cytospora chrysosperma* (in poplar hybrids and can be encouraged by moisture stress), *Dothichiza populae* (can affect *Populus nigra* by causing declines), and *Septoria musiva* which causes severe stem infections in densely stocked stands (800 to 1000 stems/ha; Demerrit 1990; van Oosten 2006). *Septoria* can cause leaf spots in addition to stem cankers (van Oosten 2006). These cankers can lead to stem breakage and multiple tops that may seriously affect the harvestable volume of the tree (van Oosten 2006). Foliar diseases that can cause problems in hybrid poplars include *Phyllosticta* spp. (leaf spot), *Melampsora medusa* (leaf rust), *Marssonina brunnea* (leaf spot), *Septotinia podophyllina* (oak leaf fungus), *Venturia populina* (shepherd's crook shoot blight) on Tacamahaca poplars and *Venturia macularis* (leaf and shoot blight) on Leuce and Aigeiros poplars (Demeritt 1990).

In North America, *Crysomela scripta* (cottonwood leaf beetle), *Malacosoma disstria* (tent caterpillar), *Ichthyura inclusa* (poplar tentmaker), *Nymphalis antiopa* (morning cloak butterfly) and *Choristoneura conflictana* (large aspen tortrix) are known to cause defoliation of poplars (Demerritt 1990). Foliar damage can be caused by *Zeugophora scutellaris* (leaf beetle), *Phyllonorycter tremuloidiella* (Aspen blotch miner) and *Phyllocnistis populiella* (Aspen leaf miner; Demerritt 1990). *Gypsonoma haimbachiana* (cottonwood twig borer) can kill buds and up to the first 25 cm of shoot tips (Demerrit 1990). *Saperda calcarata* (poplar borer), *Plectrodera scalator* (cottonwood borer), *Agrilus liragus* (bronze poplar borer) and *Agrilus horni* (flatheaded borer) can also cause general damage while *Prodiplosis morrisi* (poplar gall midge) and other small insects can cause reductions in tree growth (Demerrit 1990). *Cryptorhynchus lapathi* (willow borer) was a concern in the Okanagan region and can cause stem damage and breakage of host trees in years 2 and 3 (Chapman and Pypker 2014).

Green Giant Poplar

Also known as Brooks 6, Green Giant poplar is the male offspring of a cross between a female Eastern cottonwood, *Populus deltoides* from southeastern Canada and the male offspring of another cross between Laurel poplar, *Populus laurifolia* from Siberia and European black poplar, *Populus nigra* (Maini and Cayford 1968; Talbot et al. 2011). Its full scientific name is *P. deltoides* x (*Populus laurifolia* x *Populus nigra*). The clone is ranked as having a moderate height growth rate of 0.8-1.0 m / year with a straight and narrow crown with steep branch angles (van Oosten 2006). The Green Giant clone is rated as "not vulnerable" to low temperature damage and reaches maximum cold hardiness rapidly (van Oosten 2006). It has a moderate susceptibility to *Septoria musiva* stem canker and *Melampsora* leaf rust diseases and is recommended for short rotation intensive culture, shelterbelt, riparian, and phytoremediation purposes (van Oosten 2006). The clone was developed in Brooks, Alberta and distributed during the period of 1948-1960 (Talbot et al. 2011).

Griffin Poplar

Griffin poplar, also known as Brooks 1 is also the male offspring of a cross between a female Eastern cottonwood, *Populus deltoides* from southeastern Canada and the male offspring of another cross between Laurel poplar, *Populus laurifolia* from Siberia and European black poplar, *Populus nigra* (Maini and Cayford 1968; Talbot et al. 2011). Its full scientific name is *P. deltoides* x (*Populus laurifolia* x *Populus nigra*). The clone is ranked as having a moderate height growth rate of 0.8- 1.0 m /

year with a straight and narrow crown with steep branch angles (van Oosten 2006). The Griffin clone is rated as "not vulnerable" to low temperature damage and reaches maximum cold hardiness rapidly (van Oosten 2006). It has a moderate susceptibility to *Septoria musiva* stem canker and *Melampsora* leaf rust diseases and is recommended as unsuitable for short rotation intensive culture, shelterbelt, riparian, and phytoremediation purposes (van Oosten 2006). The clone was developed in Brooks, Alberta and distributed during the period of 1948-1960 (Talbot et al. 2011). Griffin Poplar is recommended for the Kamloops area in the Landscape Guidelines for Development within the City of Kamloops (City of Kamloops 2007).

Hill Poplar

Hill poplar, also known as FNS 44-55 is the female offspring of a cross between a female Eastern cottonwood, *Populus deltoides* from southeastern Canada and the male offspring of another cross between Laurel poplar, *Populus laurifolia* from Siberia and European black poplar, *Populus nigra* (Maini and Cayford 1968, Talbot et al. 2011). Its full scientific name is *P. deltoides* x (*Populus laurifolia* x *Populus nigra*). The Hill clone is ranked as having a moderate height growth rate of 0.8-1.0 m / year with a moderately wide crown with wider spreading branch angles (van Oosten 2006). It is rated as "slightly vulnerable" to low temperature damage and has a high susceptibility to *Septoria musiva* stem canker and *Melampsora* leaf rust diseases. It is recommended for short rotation intensive culture, shelterbelt, riparian, and phytoremediation purposes. The clone was developed in Indian Head, Saskatchewan and distributed from 1997 to present day (Talbot et al. 2011).

Walker Poplar

Walker poplar, also known as FNS 44-52 is the female offspring of a cross between a female Eastern cottonwood, *Populus deltoides* from southeastern Canada and the male offspring of another cross between Laurel poplar, *Populus laurifolia* from Siberia and European black poplar, *Populus nigra* (Maini and Cayford 1968; Lindquist et al. 1977; Talbot et al. 2011). Its full scientific name is *P. deltoides* x (*Populus laurifolia* x *Populus nigra*). The Walker clone is ranked as having a fast height growth rate of greater than 1.0 m / year with a straight and narrow crown with steep branch angles (van Oosten 2006). It is rated as “moderately vulnerable” to low temperature damage and has a moderate susceptibility to *Septoria musiva* stem canker and *Melampsora* leaf rust diseases. It is recommended for short rotation intensive culture, shelterbelt, riparian, and phytoremediation purposes. The clone was developed in Indian Head Saskatchewan and distributed from 1956 to present day (Talbot et al. 2011).

Environmental Effects of Poplar Plantations

There is some evidence suggesting that hybrid poplar plantations may provide habitat benefits for raptors as well as corridor functions for small mammals (Moser and Hilpp 2003; Moser and Hilpp 2004; Schultz et al. 2004; Giordano and Meriggi 2009). The results of one study suggested that although plantations themselves were homogenous in terms of structural diversity, they may contribute to overall landscape diversity and may therefore have some beneficial effects for wildlife (Park and Wilson 2007). As well, a riparian buffer provided by a hybrid poplar plantation may provide some benefits to the adjacent Deadman River in terms of shade, coarse particulate organic matter (CPOM) input, erosion control and in stream course woody debris recruitment over time (Fortier et al. 2016).

Potential negative environmental effects associated with poplar plantation establishment and operation include: irrigation causing water losses from the adjacent stream, fencing and road building causing general site disturbance, migration barriers and habitat fragmentation, plowing or disc trenching creating disturbance allowing for colonization by invasive species, displacement of native vegetation and pesticide, herbicide and fertilizer application which may alter nutrient regimes on the landscape and have unintended effects in other trophic levels (van Oosten 2006; Hartmann et al. 2010).

Thesis Objectives

The research scope of this thesis was determined based on input from Sk7ain Ventures Ltd.; a joint venture between Skeetchestn Natural Resources Corporation and Norbord Inc., the Ministry of Forests, Lands and Natural Resource Operations of British Columbia and Thompson Rivers University.

This collaboration allowed for the project to balance social concerns of growing poplar on Skeetchestn land and address the economic goals of Sk7ain Ventures Ltd. It also accommodated the testing of the most appropriate technology for establishing a poplar plantation in a semi-arid environment. This included establishing a large-scale drip irrigation system to supply water individually to each tree along with employing the use of engineered microtopography to contribute to the management of water for individual trees.

Understanding of irrigation and production issues were identified as gaps in the scientific knowledge of poplar plantations in southern interior British Columbia (Morford and Hutton 2000). A need for more information on suitable density, pruning and rotation age for trees grown in the region was also identified along with concerns about the environmental risks of poplar plantations. Concerns included: pests and diseases of poplar plantations and how these might spread, genetic outflow to native species, and how environmental effects of poplar plantations compared to other industry systems (e.g. horticulture, traditional agriculture and forestry; Morford and Hutton 2000). Another recent study identified an interest in more research of systems that reduce management costs and increase feasibility of future poplar plantations established in Canada (Masse et al. 2014). Together, these studies present a case for more investigation into growing poplar under irrigated plantation conditions in southern interior British Columbia.

In this study, two alternative establishment treatments were investigated for their potential as keys to meeting feasibility objectives for future plantations. First, small scale MSP or engineered microtopography can increase productivity by reducing competition from non-crop species (Thomas et al. 2000). Second, interplanting amongst the canopy of existing shrubs or trees (NOMSP) may be associated with more favorable establishment conditions via a reduction in soil temperature and photosynthetically active radiation (PAR), alteration of water content at the soil surface and hindering of grazing (Rousset and Lepart 1999). The specific objectives of this thesis are:

1. Determine the impact of interplanting versus engineered microtopography on the survival and initial growth of *Populus* cuttings.
2. Quantify a difference in survival and initial growth between the four different *Populus* clones Green Giant, Griffin, Hill and Walker.
3. Determine whether there is an interaction between the different clones and different establishment treatments.
4. Provide a model for development for future drip irrigated poplar plantations in semi-arid environments in British Columbia.

During the research project there was also a focus on developing protocols for disease management, reducing predation/grazing/browsing, water management, fertilization regime, crop selection and harvesting.

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CHAPTER 2. DRIP IRRIGATION SYSTEM

Introduction

Growing conditions in marginal poplar plantation sites are poor without management intervention (Thomas et al. 2000). In semi-arid environments, irrigation is a management intervention that is critical to supporting production of healthy above-ground biomass (Shock et al. 2013). In the case of poplar, limited water availability restricts growth and kills trees (Schreiber 2012). When supplied in appropriate amounts, water from irrigation replaces daily crop water use (Shock et al. 2013). In plantations, trees have better resistance to pathogens and develop wood volume with less susceptibility to cavitation, embolism or dieback when there is access to reliable and adequate irrigation (Schreiber 2012). Too much water from irrigation can lead to leaching of nutrients and deep percolation or waste.

While poplar are hardy trees, excessively wet conditions can spread pathogens and cause other forms of stress (Shock et al. 2013). Heavy reliance on irrigation water can make plantations susceptible to drought (Shock et al. 2013). The use of water for the production of wood fibre must also be balanced with the often-competing needs of biological, social and economic systems that rely on the same resource. Robust and efficient irrigation systems are implemented with sustainable water use and irrigation management at their core (Shock et al. 2013). Technological improvements to the sustainable and effective application of irrigation include development of accurate ways to determine plant water requirements and increased precision in water delivery systems such as drip irrigation.

Drip irrigation has historically worked well for small trees, tomatoes and citrus around the world (Benami and Ofen 1984) and it has shown practical and environmental advantages over flood and sprinkler irrigation in intensively managed poplar plantations in the Pacific Northwest of the United States (O'Neill et al. 2014). Infrastructure for conventional systems is expensive to install and comes with high operating costs (e.g. gasoline or electricity to run pumps). Drip irrigation systems have the capacity to be finely calibrated to conserve energy and water. Due to the comparatively lower energy and water requirements, drip irrigation systems are compatible with a wider variety of energy and water sources (electrical, gasoline, ram pumps, water tender). In addition to having reduced energy requirements when compared to conventional systems, well-implemented drip irrigation systems frequently have reduced insect, disease and fungus problems, fewer weeds, less soil crusting, reduced cultivation and less soil compaction interference with harvesting (Israelson et al. 1980). These benefits make drip irrigation an appealing choice for establishing a poplar plantation that minimizes disturbance in areas with fragile ecosystems containing listed wildlife species and important cultural archaeology (McNabb 2016). Efficient irrigation is also crucial to systems supplied by river surface water- where impacts to flows at important times for fish spawning and migration must be minimized. More droughts and higher energy costs in the future mean that efficient delivery and use of water will be even more critical (Tupker et al. 2003).

Slowly applying low pressure water via drip irrigation saves water by directing it to the root zone of the target crop (Shock et al. 2013). Drip irrigation systems can also be designed to directly apply fertilizer to target crops in precise formulations and amounts- further reducing waste and energy expenditures on non-crop plants. Fine adjustments can be made to a system or programmed depending on yearly or seasonal crop water requirements. While drip systems have a lot of advantages over conventional systems, they can still be costly to install and difficult to maintain. Systems need to be well designed and robust to be cost effective. Proper selection of the right system and materials can save time and money.

Due to their simple design microtube emitter systems are an example of a cost effective and more flexible alternative to conventional pressure compensating systems. Microtubes as uniform drip emitter systems were conceptualized in the 1980’s and have since been employed throughout much of the developing world (Vermeiren and Jobling 1980; Keshtgar et al. 2013). Microtube emitter systems cost substantially less than conventional systems (Singh et al. 2009). As well, they can be more precisely tuned than other types of pressure compensating emitter systems, because they have lower coefficients of variability when properly designed (Keshtgar et al. 2013). A microtube emitter system can also deliver water to a non-uniform plantation design, such as one that involves interplanting with existing vegetation and requires the ability to replace or add more emitters with time.

Knowledge Gaps

Canada's agriculture sector used 1600 million m^3 of water which made up 80% of total consumption (withdrawn and not returned to the original source) in 2013 (Environment and Climate Change Canada 2016). Currently British Columbia annually allocates 1 566 849 Dm^3 (1385649 Dm^3 for consumptive use and 181200 Dm^3 for non-consumptive use) surface water for agriculture (10.7% of total volume used in non-water power sectors; British Columbia Environmental Protection and Sustainability 2006). An estimated total of 114064 ha of farmland in BC is reported to be under irrigation (Agriservice BC 2018). Drip and micro-sprinkler irrigation systems have been the subject of studies involving fruit trees and vineyards in the Okanagan region of BC in recent decades (Utkhede 1999; Fentabil et al. 2016). Studies of irrigated poplar plantations in BC reported water delivery systems using spray emitters and conventional irrigation (Carlson 1992). While there is extensive work with drip irrigation in different scenarios in many countries, knowledge is generally limited for growing poplar under true drip or micro-irrigated conditions in the southern interior of British Columbia (Morford and Hutton 2000). In the present work, I detail key elements of the design, establishment and operation of a microtube-emitter drip-irrigated poplar plantation in semi-arid, southern interior British Columbia. The primary objectives of this study were to: (1) estimate seasonal and maximum daily water requirements of 1 and 2 year old planted poplar cuttings, (2) develop a flexible, robust irrigation system capable of providing accurate, efficient water delivery throughout the 2 year study term and for the length of the crop rotation and (3) outline the day to day operation of the system from startup in the spring to shut down in the fall.

Methods

Deadman River Site Description

The plantation site is located in the Deadman River watershed (N 50°45.500' X W 120°54.500'; Appendix A; Figure A.1). The project site is 50 m east of the Deadman River. The river is a second order stream with a discharge range of 0 l s^{-1} in 1919 to 5850 l s^{-1} in 1990 with an estimated long term mean annual discharge of 4600 l s^{-1} using measurement stations above (Water Survey of Canada Station 08LF027) and at Criss Creek (Water Survey of Canada Station 08LF007; Thompson 1999). The stream discharge was measured and calculated on July 27, 2017 at approximately 50 m downstream of the intake for the irrigation system (N 50°45.215' X W 120°54.556') at 350 amsl. The discharge was calculated to be 838 l s^{-1} (Table 2.1).

The Deadman River is home to many important salmonid species. These include: steelhead (*Oncorhynchus mykiss),* coho salmon (*O. kisutch)*, pink salmon (*O. gorbuscha*) and chinook salmon (*O. tshawytscha*; Thompson 1999). As well, pacific lamprey (*Lampetra tridenta*), longnose dace (*Rhinichthys cataractae*), large scale sucker (*Catostomus macroheilus*), mountain whitefish (*Prosopium williamsoni*), cottids (*cottidae*), and northern pikeminnow (*Ptychocheilus oregonensis*) inhabit the Deadman River watershed (Bennett 1998). Adult fish migration (especially that of *O. tshawytscha*) is a key concern throughout the region. Low flow conditions lead to high predation rates, injuries when navigating shallow reaches and adverse effects from potential elevated temperatures. Withdrawals from baseflow during the summer period that are not supported by storage put further stress on migrating fish. Respecting licensed water rights and instream flow needs are recommended for optimizing flow conditions for Deadman River fish and water users (Rich McCleary, personal communication, 2017).

Irrigation Requirements

Given that the proposed plantation was in a location that historically received less than 375 mm of precipitation annually and less than 300 mm of precipitation during the growing season (Appendix A; Figure A.2), it was determined that planted poplar cuttings would have significantly restricted growth without supplemental moisture through irrigation (Schroeder et al. 2002; Vanin and Burgon 2003; van Oosten 2006; Wang et al. 2016).

Water delivery parameters and irrigation scheduling were calculated following guidelines outlined in the Irrigation Industry Association of British Columbia (IIABC) Agriculture Sprinkler Irrigation Scheduling Calculator Users Guide and the British Columbia Ministry of Agriculture Irrigation Water Demand Model (Petersen and van der Gulik 2009; Fretwell 2009). Irrigation was set to deliver water to planted poplar trees in the first and second year of the study using parameters outlined in the literature for clones of similar age and parentage growing in plantations with similar environmental conditions (Gochis and Cuenca 2000; O'Neill et al. 2014).The overall system was designed to have capacity for water delivery over the rotation of the tree crop, using parameters estimated based on estimates for similar poplar clone water demand at age 10 (Zhang et al. 1999).

Equations

Monthly water use rates of first and second season poplar grown at a site in Oregon were used to generate crop coefficients for trees growing in similar climatic conditions to the Kamloops area as local poplar consumptive-use estimates were unavailable (Gochis and Cuenca 2000; O'Neill et al. 2014). These crop coefficients were then used to relate each year of poplar growth to growing degree days (GDD) which were calculated using 1990-2010 climate normals from Wang et al. (2016). The crop coefficients were used to modify the Hargreaves reference evapotranspiration value (also from Wang et al. 2016) for a given day (ET_{TALL}) and the subsequent values were used to program the irrigation (Hargreaves and Samani 1985). Equation 1 calculates the first year crop coefficient based on an adjusted crop curve calculated for a young poplar tree in its first season of growth, Equation 2 calculates the second year crop coefficient based on an adjusted crop curve calculated for a young poplar tree in its second season of growth and Equation 3 calculates the ET value for a given day in a given year of production.

$$K_{C(1)} = 3.93x10^{-1} - 2.58x10^{-5}\left(\sum GDD\right) + 5.39x10^{-8}\left(\sum GDD^{2}\right) - 8.98x10^{-12}\left(\sum GDD^{3}\right) \quad (1)$$

$$K_{C(2)} = 3.71x10^{-1} + 1.38x10^{-4}\left(\sum GDD\right) + 2.95x10^{-8}\left(\sum GDD^{2}\right) - 8.20x10^{-12}\left(\sum GDD^{3}\right) \quad (2)$$

$$ET = K_{C(year)} x\ ET_{TALL} \quad (3)$$

Where:

$K_{C(year)}$= Crop coefficient for a given year;

$\sum GDD$= Cumulative growing degree days; and

ET = Evapotranspiration replacement rate.

Irrigation System

Layout of the irrigation system was planned using a combination of Google Earth and Arcmap 10.2 software. Field layout of the irrigation system and planting locations took place over 11-30 May, 2016. Row orientation was determined by aligning the first row in a block with any continuous straight features located close to the portion of the planting area (Figure 2.1, Figure 2.2).

In 2016, a micro-tube emitter drip irrigation system was established to water trees in a 10 hectare, intensively managed poplar plantation each with approximately 2.5 l day^{-1}.

Intake and Pumps

The irrigation system water intake consisted of a triangular screen fabricated out of steel and fitted with mesh of size and surface area following Fisheries and Oceans Canada (DFO) guidelines (DFO 1995). In adherence to DFO guidelines (DFO 1995), the intake screen was pointed upstream and placed in an area of the river that did not have any backflow or other feature that would have made it an area of refuge for fish. The intake screen was bolted to the upstream end of a 100 m long by 20 cm diameter high density polyethylene (HDPE) drive pipe which fed into a concrete surge tank downstream along the bank of the river (Figure 2.1). The surge tank was installed to absorb sudden rises or drops in water pressure and to allow for some of the sediment load in the irrigation water to settle out and be drained from the system via a drain valve located at the bottom of the tank (Brown 2006). A metal butterfly valve was installed downstream of the surge tank while metal spring check valves and dual gate valves were used to reduce or stop back pressure and backflow from the mainline into the pumps (Figure 2.1).

The irrigation system was originally designed to be pumped at a rate of 0.1 l s^{-1} with water from five modified hydraulic ram pumps (Oasis 320, Glockemann Water Pumps PTY LTD., Queensland, Australia). They were bolted to a cement pad and supplied with water from a polyvinyl chloride (PVC) manifold downstream from the surge tank (Figure 2.1). Hydraulic ram pumps do not require gasoline or electricity (Brown 2006). Instead, a pressure rise created by alternately opening and closing a falling column of water to free flow is used to pump a small volume of water up to an 111360 l polyethylene tank at the highest point in the system (Figure 2.1). When fully functional, this will provide water without the need for any external energy source.

A 12 horsepower, 389 cm^3, 8.8 l s^{-1}, gasoline powered water pump (GX 390, Honda Motor Company LTD., Hamamatsu, Japan) was used for the majority of the 2016 and 2017 growing seasons to provide reliable watering while the ram pumps were being installed and tuned. Downstream from the pump (Figure 2.1), a 15 cm diameter, 130 micron disc filter was installed in the mainline (Arkal, Netafim Ltd., Hatzerim, Israel). This filter was installed to mitigate the transmission of suspended particles that could cause emitter blockages. The filter was equipped with two pressure gauges- one before the filter, and one after the filter. An observed difference in pressure readings between the two gauges indicated when the filter needed cleaning. Debris was cleared from the filter manually several times throughout the growing season for 2016 and 2017, but in 2017- regular back flushing of the filter took place when large differences in pressure between the two gauges were observed. For the month of June 2017, back flushing was done every day, corresponding with high sediment loads in the Deadman River during freshet. Later in June and into July of that same year, back flushing was reduced to every other day, and then to once or twice a week, corresponding to decreasing sediment loads and reduced observations of pressure differences between the two gauges on the filters. Back flushing was carried out by closing a 15 cm diameter manual butterfly valve downstream of the filter and removing the check valve upstream from the filter (Figure 2.1). An 8 cm diameter discharge hose was then fitted upstream of the filter, and the butterfly valve was then opened for approximately 10 seconds or until the water leaving the discharge hose appeared clean. Care was taken to not let back flushed water release sediment into the Deadman River.

Main System

Downstream of the pump and filter, a 323 m long mainline made up of 6.1 m lengths of 15 cm diameter pipe (1103 Kpa Cycle Tough PVC, IPEX Inc., Verdun, Quebec, Canada) supplied water to an 11360 l polyethylene tank at the maximum height of the system (Figure 2.1). Total drop from the tank to the disc filter was 42.7 m (Figure 2.1). The irrigation system was designed to have the pumps fill the tank, allowing for a controlled volume of water to gravity-feed out slowly over 5 different irrigation zones throughout the watering period. Manual ball valves were installed at junctions between the mainline and submains to control the distribution of water to irrigation zones on each bench (Figure 2.1). Relief valves were installed downstream of each manual ball valve to reduce water surging and siphoning during the watering of each irrigation zone (Figure 2.1). Downstream of each manual ball valve and pressure relief valve, north- south oriented systems of smaller diameter PVC pipe submains and manifolds distributed water to the irrigation zones (Figure 2.1).

From 15 June to 29 July, 2016, approximately 180 lengths of 1.27 cm diameter low density polyethylene (LDPE) tubing (Series 160, Polytubes 2009 Inc., Edmonton, Alberta) were connected to PVC water distribution manifolds and laid out in parallel east- west rows (laterals) to form 5 irrigation zones across the 10 hectare plantation (Appendix A; Figure A.1). The average length (run) of a lateral was 100 m. At the junctions between manifolds and laterals, 46 cm sections of rubber flexline were glued on to the manifold at the upstream end and joined with fitting on the downstream end. Laterals terminated at a manual ball valve and approximately 1.5 m of 1.91 cm diameter LDPE tubing as a flush line. Connections at the terminal end were clamped together with 1.27 cm diameter and 1.91 cm hose clamps. Average lateral length was approximately 100 m with maximum lengths of 150 m and minimum lengths of 10 m across the site. Any areas where the lateral was obstructed by vegetation were corrected by rerouting the lateral. As a result, the lateral was not always down the exact middle of a row (Figure 2.2). During the spring of 2017 startup procedures, approximately 20 sections of damaged laterals had to be mended. These lines were likely damaged by coyotes or other small animals (van Oosten 2006). Lines were mended by cleanly cutting off the damaged sections and joining the lateral back together with 1.27 cm diameter hose couplings.

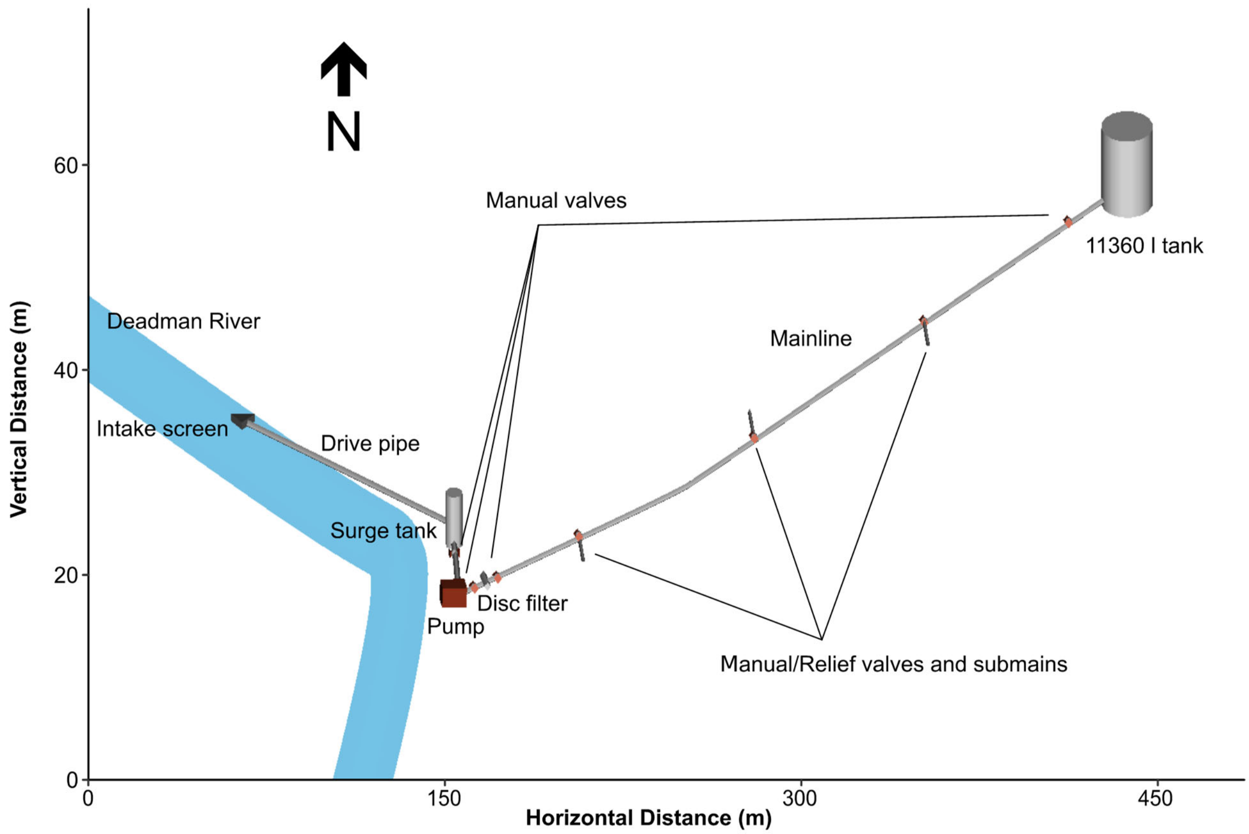

Figure 2.1. Pumpsite and mainline of water delivery system established on the Deadman River in July 2016 to deliver water to approximately 9000 drip irrigated poplar trees. Created with Art of Illusion v3.0.3 Software (Eastman 2008).

Emitters

LDPE capillary tubes of dimensions 0.6 mm internal diameter by 3.2 mm outside diameter were used as emitters (3.2 mm x 0.6 mm capillary tubes, MDC Industries Ltd., Sderot, Israel). Emitters were cut off of a 200 m roll at 45° angles and inserted into laterals approximately every 3 m by creating a hole with a punch and inserting the first 10 cm of the emitter into the opening (Figure 2.2). The length of the cut emitter combined with the length, pressure and topography along the path of the lateral all affected the flow rate of the emitters (Keshtgar et al. 2013). Pressure compensation along a lateral run was achieved by lengthening emitters by 50 to 100% in low areas. Most emitters were 3 m long, but were lengthened by 1 m - 3 m in the lower sections along the run of a lateral. Each zone was systematically inspected once per week for damaged lines or improperly functioning emitters. Emitters became plugged in several different ways- white plastic material from cut PVC pipes, soil or small rocks, and algae. Plugged emitters cause poor water distribution in drip irrigation systems (Vermeiren and Joblin 1980). Removing the plugged emitter from the lateral and plugging it back in the opposite way around usually cleared the emitter of the blockage. In instances where the blockage was not cleared, a syringe fitted with clear vinyl tubing of internal diameter of approximately 3.35 mm was slipped over the blocked emitter and the syringe plunger was pulled back, drawing out the material causing the blockage and restoring normal function to the emitter. If none of the above methods worked to clear blockages, then the emitter was replaced.

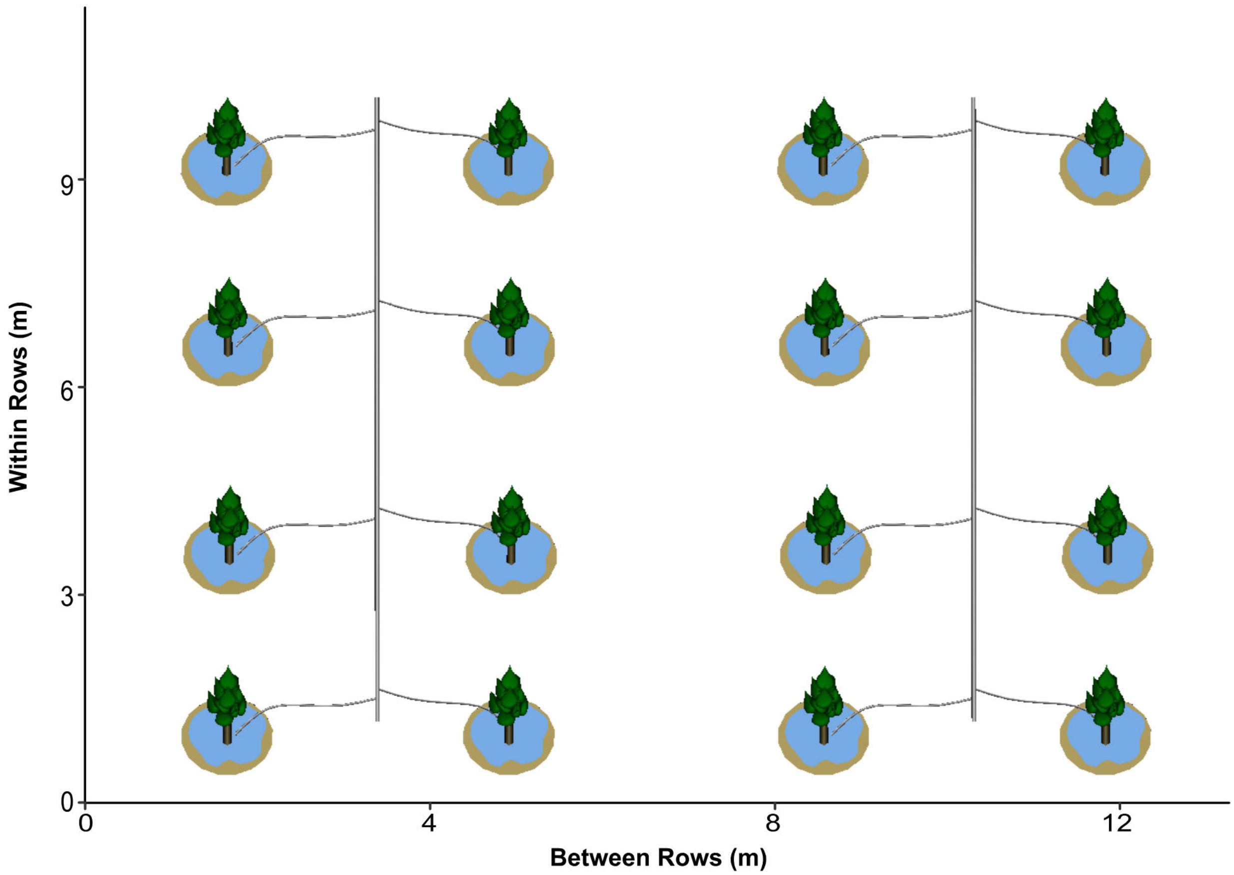

Figure 2.2. Layout example of two laterals with microtube emitters delivering drip irrigation to a typical plot of experimental trees with 3 m spacing within rows by 3.7 m spacing between rows. Created with Art of Illusion v3.0.3 Software (Eastman 2008).

Startup and Shutdown Procedures

Before starting up the system at the beginning of each growing season or after any changes to mainline, submain or manifold routing (especially those involving cutting or installing new PVC pipes), the system was flushed to prevent transport of particles which could lead to blocked emitters or buildup in the laterals. System flushing was carried out one zone at a time and involved separating all laterals at each union between the header and the lateral. Water was then run through the manifold and allowed to drain out of all the uncoupled fittings. After sufficient debris had been flushed from the manifold, fittings were recoupled and each lateral was then flushed with water and drained via a ball valve at its terminal end. Once flushing of the lateral was completed, then the ball valve at the end of the lateral was closed and that lateral was then deemed ready for irrigation. This process was continued in the same order until the whole zone had been completely flushed and was ready for irrigation. The process was repeated for all zones.

At the end of the growing season and before overnight temperatures could cause freezing of water lines, the system was drained of all water by opening all valves and allowing water to drain out of the system. During the fall 2016 shutdown of the irrigation system, some lines were damaged due to the use of compressed air and as a result, modifications were made to the system to allow for adequate water drainage without having to rely on compressed air. Once all lines were sufficiently flushed and drained, any openings in the system were then blocked to prevent intrusion by rodents, other small animals and debris. As much as possible, any infrastructure located near to the high-water mark of the Deadman River was removed and stored for the winter. This ensured that pipes, pumps, fittings and other materials would not be damaged by high flows or freezing along the Deadman River during the spring and winter.

Results

Crop coefficients ($K_{C(1)}$) for the months that corresponded with the first growing season (August and September, 2016) of the planted Poplar cuttings were both calculated to be 0.39 (Table 2.1). Crop coefficients ($K_{C(2)}$) for the months that corresponded with the second growing season were calculated to be 0.43 for June, 0.44 for July and August, and 0.41 for September 2017 (Table 2.1).

Table 2.1. Monthly estimated crop coefficients for 1 ($K_{C(1)}$) and ($K_{C(2)}$) 2 year old poplar trees growing in a 1 m x 1 m area of sandy loam textured soil on the Deadman River plantation site in the 2016 and 2017 growing seasons. . In 2016, the number of days irrigated out of the growing season was 48 days due to the late planting date (29 July to 15 September), and in 2017 the number of days irrigated out of the growing season was 96 days (27 May to 15 September).

Month	$K_{C(1)}$	$K_{C(2)}$
Jun	-	0.43
Jul	-	0.44
Aug	0.39	0.44
Sep	0.39	0.41

For the 2016 growing season, irrigation was started on 29 July (late) and programmed according to the estimated ET demand, with irrigation concluding on 15 September. Cumulative per tree ET for this period was estimated to be 81 mm, while total mean irrigation amounted to 120 mm, plus an additional 64 mm of rainfall (Table 2.2, Figure 2.3). From 29 July to 15 September, 2017 cumulative per tree ET was estimated to be 99 mm, while total mean irrigation amounted to 98 mm, plus an additional 17 mm of rainfall (Table 2.2, Figure 2.3). For the entire 2017 growing season (27 May to 15 September) cumulative per tree ET was estimated to be 314 mm, while total mean irrigation amounted to 240 mm, plus an additional 51 mm of rainfall (Table 2.2, Figure 2.3). The cumulative per tree ET demand for both years was less than that of the June to September cumulative ET from the 1981- 2010 Hargreaves reference ET of 491 mm calculated for the area from ClimateBC data (Figure 2.3; Wang et al. 2016).

Table 2.2. 1981 to 2010 Hargreaves reference and estimated daily mean and seasonal total evapotranspiration (ET; mm), irrigation (mm) and precipitation (mm) for an individual drip irrigated poplar tree growing in a 1 m x 1 m area of sandy loam textured soil on the Deadman River plantation site in the 2016 and 2017 growing seasons. In 2016, the number of days irrigated out of the growing season was 48 days due to the late planting date (29 July to 15 September), and in 2017 the number of days irrigated out of the growing season was 96 days (27 May to 15 September).

	Daily	Season total
Hargreaves Reference ET (mm)		
2016	4.2	203
2017	5.1	491
Adjusted ET (mm)		
2016	1.7	81
2017	3.3	314
Irrigation (mm)		
2016	2.5	120
2017	2.5	240
Precipitation (mm)		
2016	1.3	64
2017	0.5	51

In the 2016 growing season, three zones were watered each day: approximately one tank across the high elevation bench, one half tank across the middle elevation bench, and 3/4 of a tank across the lower elevation bench. This totaled approximately 23000 l per day (Table 2.3). Watering was done in a similar way in 2017, except watering was done on a 6 day per week schedule rather than 7 days per week.

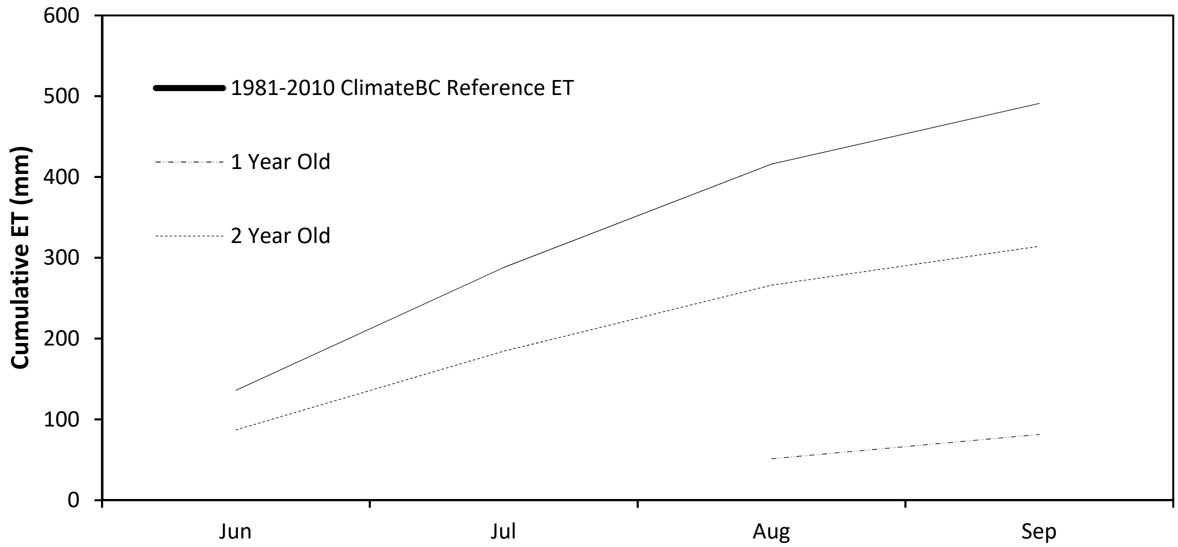

Figure 2.3. Cumulative reference evapotranspiration and estimated evapotranspiration for 1 and 2 year old drip-irrigated poplars near Kamloops, British Columbia in 2016 and 2017, respectively. Reference evapotranspiration is from the 1981-2010 Hargreaves estimate for the area from ClimateBC.

For a typical Poplar tree in the plantation, water was delivered via a single 6.9 x 10-4 l s-1 microtube emitter for approximately 1 hour per day (total = 2.5 l tree-1 d-1; Table 2.3). In the 2016 growing season (29 July to 15 September), a total of 1.2 x 102 l was delivered to a typical individual tree (Table 2.3). In the 2017 growing season (27 May to 15 September), a total of 12.4 x 102 l was delivered to a typical individual tree (Table 2.3).

The long term mean annual discharge of the Deadman River was estimated to be 4.6 x 10^3 l s^{-1} based on data from the measurement stations above (Water Survey of Canada Station 08LF027) and at Criss Creek (Water Survey of Canada Station 08LF007; Table 2.3). The discharge of the gasoline pump used to irrigate the plantation for the 2016 and 2017 growing seasons was estimated to be 8.8 l s^{-1} or 0.2% of the long term mean annual discharge of the river (Table 2.3). The estimated pump discharge of 8.8 l s^{-1} was 1.1% of the 838 l s^{-1} discharge calculated from measurements taken by BCMFLNRO staff for low-flow conditions of the Deadman River on July 27, 2017 at approximately 50 m downstream of the intake for the (not in operation) irrigation system (Figure 2.1). The pump and plantation used an estimated daily volume of 2.3 x 104 l which was 0.006% of the 4.0 x 108 l estimated daily volume of the Deadman River at the point of measurement of the long term mean annual data (Table 2.3).

Table 2.3. Estimated discharge (l s^{-1}), mean daily volume (l) and seasonal volume (l) of water used to irrigate the entire 10 hectare poplar plantation with a gasoline pump and used by an individual microtube emitter for the 2016 and 2017 growing seasons. Discharge for the Deadman River is from the estimated long term mean annual discharge determined from measurement stations above (Water Survey of Canada Station 08LF027) and at Criss Creek (Water Survey of Canada Station 08LF007).

	Discharge (l s^{-1})	Daily volume (l)	2016 volume (l)	2017 volume (l)
Deadman River	4.6 x 10^3	4.0 x 10^8	1.9 x 10^{10}	3.8 x 10^{10}
Pump withdrawal	8.8	2.3 x 10^4	1.1 x 10^6	2.1 x 10^6
Microtube emitter	6.9 x 10^{-4}	2.5	1.2 x 10^2	2.4 x 10^2

Discussion

The estimated crop coefficients of the Poplar cuttings in 2016 and 2017 were lower than predicted 0.30 to 0.70 crop coefficients for similar one and two-year-old poplar clones grown elsewhere in the world (Gochis and Cuenca 2000). This was partly due to an accommodation made by the model for the shorter growing season that the trees in the present study experienced (Gochis and Cuenca 2000; O'Neill et al. 2014). The calculated crop coefficients and ET's may still overestimate water demand in the second growing season for the trees at the Deadman River site since they had less first season growth than the trees used to develop the adjusted models which experienced peak ET's of 121 mm and 181 mm for one and two year old poplar in the month of July (Gochis and Cuenca 2000; O'Neill et al. 2014).

The growing season at the Deadman river site was shorter and had seasonal irrigation taking place over a shorter time period than that of the studies which took place in Oregon and New Mexico (Gochis and Cuenca 2000; O'Neill et al. 2014). The growing season in the Oregon study lasted from 1 April to 21 October, while the growing season in the New Mexico study lasted from 17 April to 16 October. During these periods, the trees in the New Mexico study received 1450 mm in irrigation, plus 127 mm in rainfall. The trees at the site of the Oregon study used 466 mm and 675 mm in the first and second growing seasons, while water received from rainfall was not reported.

Water demand models often operate on several assumptions (Gochis and Cuenca 2000; O'Neill et al. 2014). A more simplistic model with fewer inputs was selected in favor of having to make more assumptions following irrigation system design methods more suited to traditional agriculture (e.g. sprinkler irrigated corn and alfalfa; Petersen and van der Gulik 2009; Fretwell 2009). Among other inputs required by more traditional agricultural methods of determining irrigation requirements, effective rooting depth is described as the area in the soil column where water is most used by the target crop. While destructive sampling of the roots of the planted trees at the Deadman River plantation site was not part of the study, there is some disagreement in the literature about effective rooting depth of poplar (due to clonal differences and different environmental responses in different areas). Root systems of 4-year-old poplar stands in similar textured soils, watered with a similar method in Puyallup, Washington were found to concentrate in the upper 1 m of the soil (“effective rooting depth”) because of the effect of irrigation and higher levels of organic matter and N in the upper soil (Heilman et al. 1994). Another study suggests an effective rooting depth where 95% of all fine roots were located within 1 m in boreal forest ecosystems (Callesen et al. 2016). Maximum rooting depths of 71 cm in 3-year-old hybrid poplar were found in a plantation study near Ontario, Oregon, while root systems of 4-year-old trees extended beyond depths of 3.2 m in a similar plantation (Heilman et al. 1994; Shock et al. 2002). A study of trees in plantations in Mediterranean France found rooting below 3 m depth for 13-year-old poplar, suggesting effective rooting depth should be beyond 1 m as 52-55% of roots excavated were between 2 and 3 m depth (JHA 2017). Poplar are also suspected to be phreatophytic when ground water is nearby (Rood et al. 2003; Schreiber 2012). Assumptions made about rooting depth required by more sophisticated agricultural irrigation models could have resulted in very different water demand outputs.

As young poplar trees become established, their roots explore more of the soil matrix and increase their ability to source water and become less reliant on water from irrigation. Trees planted at the lowest elevation benches of the site may also sub-irrigate in time if roots continue to grow toward groundwater (Chapman and Pypker 2014). Expanding canopies of growing trees shade competition and direct water inputs to the target crops (Perry 1989). Development of more uniform canopies over time also leads to less interaction with the atmosphere and causes proportionally less evaporative water losses than those experienced by the trees when they were smaller (Teklehaimanot et al. 1991; Green et al. 1995). The possibility of reduced dependence on water inputs from irrigation by established trees informed the decision to shorten the watering period from 7 days per week in 2016 to 6 days per week in 2017.

Concomitantly, fast growing trees with more leaf area transpire more, leading to increases in their water use (Tupker et al. 2003). More reliable and abundant water availability ensures that trees bred to have large vessel diameters and less conservative growth than native Aspen would have a lowered risk of drought related cavitation, embolism and dieback (Schreiber 2012). Delivering more reliable water to the trees with the existing system would require adjustment of the irrigation scheduling in order to accommodate the delivery of more water per day in each growing season. The most feasible way to make this adjustment would involve extending the watering period for each irrigation zone. A more complicated adjustment could also be made by altering the water pressure at each zone manifold or lengthening the emitters to allow for altered rates of water delivery to each tree. Care would have to be taken in making these adjustments because optimal soil saturation levels would have to be achieved while continuing to minimize potential runoff, leaching and waste of water lost to the soil column below (percolation).

While the study provided estimates of seasonal and maximum daily water requirements of 1 and 2-year-old planted poplar cuttings, questions remain about the overall sustainability of the plantation over the duration of the rotation- especially in the context of increasing and competing demands for water resources from the Deadman River. Summer maximum crop coefficients of 0.91 adapted from FAO guidelines for adult deciduous trees put individual tree water demand at twice that of the 1 and 2-year-old trees in this study (Doorenbos and Pruitt 1977; Gochis and Cuenca 2000). Estimated future water requirements as high as 18.0 kg tree^{-1} were calculated using peak daily transpiration from sap flow for 6-year-old poplar trees in a study in Britain (Zhang et al. 1999). In a 10-year projection using these inputs, maximum water requirement for a 9000-tree plantation is estimated to be between 10000 to 30000 m^3 year^{-1} at its highest water demand (Zhang et al. 1999). A resident of the nearby city of Kamloops is allotted 135 m^3 per billing cycle (City of Kamloops 2012). The maximum water demand of the plantation would be equivalent to that of 10-30 houses for the summer period. In terms of duty, the poplar plantation water usage is less than 5 cm which is less than 10% of a typical corn duty of ~ 100 cm. Corn at a 100 cm duty uses 9085 m^3 ha^{-1} and the poplar plantation uses less than 38 m^3 ha^{-1}.

Estimates of crop water use are key to the design and management of plantations (Gochis and Cuenca 2000). Despite efforts made to be efficient with water from the planning to the operation of the irrigation system throughout the rotation, there is a possibility that future water availability for irrigating trees will be reduced in order to supply more important uses such as irrigating food crops, domestic use or maintaining flows for adult fish migration (especially that of *O. tshawytscha*). After the establishment phase, water from irrigation may be less critical for the survival of young trees, but continued irrigation would be needed to keep up growth rates for a 10-20-year rotation for oriented strand board fibre (Will Carr, personal communication, 2015). Respecting licensed water rights and instream flow needs is the best way to optimize flow conditions for Deadman River fish and water users (Rich McCleary, personal communication, 2017).

Conclusions and Operational Recommendations

Results from the poplar plantation established in southern interior British Columbia provided estimates of seasonal and maximum daily water requirements of 1 and 2 year old planted poplar cuttings, outlined the development of an irrigation system capable of providing accurate, efficient water delivery throughout the duration of the study and described the day to day operation of the system from startup in the spring to shut down in the fall. The findings of this study also expand our knowledge of the performance of microtube emitter drip irrigation systems set up to service poplar plantations in semi-arid regions of BC.

Future studies should collect more poplar physiology data to inform the precise delivery of drip-irrigation water. Since water conservation was a major objective of the irrigation system, more methods to reduce evaporative water losses should be employed in future work. Future studies of irrigation systems in BC's southern interior region should count on less water being available for these types of plantations as other uses of the water resource are prioritized. This emphasizes the need to create extremely efficient and precise systems that do not waste water or make unnecessary removals from already stressed (over-allocated) systems. This system is a step in that direction, with room for a lot of improvement. Despite making every effort to conserve water, the priority should be on allocating water for endangered salmon populations- this means that the economic risk inherent in establishing a drip irrigated poplar plantation in these conditions will always be high. Planning for the water to be shut-off at some point in the length of the rotation should be a consideration for all future projects.

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CHAPTER 3. EFFECTS OF ESTABLISHMENT TREATMENTS ON THE SURVIVAL AND INITIAL GROWTH OF FOUR POPLAR CLONES

Introduction

When left unmitigated, harsh environmental conditions and competition for resources can severely affect the establishment of poplar cuttings (Demeritt 1990). Combinations of mechanical site preparation (MSP), vegetation management, fertilization and irrigation are used in short rotation intensive management forestry to optimize resource availability and improve seedling success especially when planting sites are marginal (van Oosten 2006; O'Neill et al. 2014). Modern MSP falls into one of three categories: subsoiling/ripping, mounding or scarification/scalping (Lof et al. 2012). Subsoiling/ripping and mounding create more disturbance than scarification, particularly when scarification is done in an intermittent or patch format (also known as scalping). Scalping is carried out in afforestation operations to remove grass sod or other vegetation to expose desirable bare-soil planting spots while minimizing disturbance to soil structure (Lof et al. 2012). MSP techniques that minimize disturbance also reduce opportunities for noxious weeds or other undesirable vegetation to spread across the planting site (Meidinger and Pojar 1991; Lof et al. 2012; McNabb 2016). A combination of MSP and glyphosate-based herbicides are typically applied to reduce competition from established vegetation and create more favourable growing conditions for target crops prior to planting. This is usually followed by repeated vegetation management at intervals throughout the life of the plantation (Demeritt 1990; van Oosten 2006).

Interplanting amongst the canopies of existing vegetation creates microsites that aid in the establishment of young trees (Rousset and Lepart 1999). Obstacle planting and interplanting further aid in establishment by reducing opportunities for damage to trees from predation (Rousset and Lepart 1999). Interplanting treatments with no mechanical site preparation (NOMSP) are worthwhile to explore because they offer the lowest cost and lowest site disturbance when compared to other plantation establishment treatment methods (Lof et al 2012, McNabb 2016).

The plantation site in semi arid British Columbia is culturally and ecologically sensitive while harsh environmental conditions make seedling establishment a challenge. The site is located on Skeetchestn land in the Thompson Plateau of south-central interior of British Columbia (McNabb 2016). A 2016 archaeological assessment of the proposed planting area found multiple cultural depressions and lithic scatters which were important to avoid and preserve for future investigation and analysis by Skeetchestn Natural Resources staff employed in cultural heritage (McNabb 2016). As well, the assessment found the proposed planting site to be a fragile ecosystem with limited plant productivity and soil development (McNabb 2016). This site contained characteristic lichen species forming cryptogamic biological soil crusts, soils made up of silty clay loam to sandy loam textured brown Chernozems and Regosols developed on fluvial or lacustrine deposits (Meidinger and Pojar 1991; McNabb 2016). In addition to sensitive soils and vegetation, the site is also the location for a number of important wildlife species (Hobbes 2013; McNabb 2016). Other characteristics of the challenging planting environment included temperature extremes and low precipitation; creating conditions that must be addressed with management before attempting to establish a plantation. The site experiences only 256 mm with 175 mm as rainfall. The long-term mean temperature (1961 to 1990) for January is -5.2°C but maximum lows are approximately -29°C. Mean summer temperature equals 20.8°C with maximum temperatures reaching 38°C in July (Wang et al. 2016). Hence, it is necessary to select the planting stock that is adapted for this climate.

The hot, dry summers the site experiences necessitate an efficient watering system. Drip irrigation has practical and environmental advantages over flood and sprinkler irrigation in intensively managed plantations in the Pacific Northwest of the United States (O'Neill et al. 2014). While there is extensive work with drip irrigation in different scenarios in many countries, knowledge is generally limited for growing poplar under drip-irrigated conditions in the southern interior of British Columbia (Morford and Hutton 2000). In general, standard intensive management practices disturb the soil and add chemicals to the environment. In water-limited environments, more precise application of irrigation could favor the use of lower intensity management practices and retain target crop establishment benefits comparable to more intensive management scenarios. More research is needed to explore combinations of management alternatives that retain seedling survival and growth improvements and minimize disturbance to areas with fragile ground conditions and/or sensitive ecosystems (Lof et al. 2012).

Clone types differ in their growth rates and resource requirements and in their tolerance to harsh climates (Maini and Cayford 1968; van Oosten 2006; Talbot et al. 2011). The four related intersectional hybrids, the male clone Green Giant (*Populus deltoides* x (*Populus laurifolia* x *Populus nigra*), the male clone Griffin (*Populus deltoides* x (*Populus laurifolia* x *Populus nigra*), the female clone Hill (*Populus deltoides* x (*Populus laurifolia* x *Populus nigra*), and the female clone Walker (*Populus deltoides* x (*Populus laurifolia* x *Populus nigra*) were originally bred for tolerance to harsh Canadian prairie climates and superior growth performance (Maini and Cayford 1968; Lindquist 1977; van Oosten 2006; Talbot et al. 2011). These clones may differ in their growth form with Green Giant, Griffin and Walker clones displaying single stem, straight and narrow crowns while Hill is characterized by a moderately broad crown with wider spreading branch angles (van Oosten 2006), possibly enabling it to better shade out competing understory vegetation. With adequate water, these clones may be adapted to the harsh climate of the research site (Schroeder et al. 2002; Vanin and Burgon 2003; van Oosten 2006). All clones have a history of use in operational and research plantations in western Canada (Morrison et al. 2000; Tupker et al. 2003; Silim et al. 2009; Schreiber 2012). More locally, all clones have grown successfully in Princeton and Sumas, BC (Will Carr, personal communication, 2016).

In the present study, I evaluated the effects of two contrasting establishment systems for poplar plantations in semi-arid, southern interior British Columbia as alternative establishment methods and their impacts on tree performance. The primary objectives of this study were to determine: (1) the impact of interplanting versus engineered microtopography on the survival and initial growth of *Populus* cuttings, (2) differences in survival and initial growth and between the four different *Populus* clones Walker, Griffin, Hill and Green Giant and (3) whether there is an interaction between the different clones and different establishment treatments. This research is expected to provide insight into the development of establishment strategies for poplar plantations in sensitive semi-arid regions of British Columbia.

Methods

Study Area

The study took place approximately 40 kilometers west of the city of Kamloops, British Columbia, Canada and is adjacent to the Deadman River (N 50°45.500' X W 120°54.500') at 350 to 370 amsl (Appendix A; Figure A.1). The nearest weather station (35 km from the site) indicates that the average annual precipitation in the region is 279 mm with 240 mm as rainfall (Appendix A; Figure A.2). June is the wettest month (37.4 mm average, 1981 to 2010) and February is the driest month (5.9 mm average, 1981 to 2010; Wang et al. 2016). The long-term mean minimum temperature (1981 to 2010) for January is -5.9°C with an extreme minimum of -37.2°C. Mean summer temperature equals 19.6°C with extreme maximum temperatures reaching 40.6°C in July (Wang et al. 2016). The vegetation at the site was dominated by big sagebrush (*Artemisia tridentata*), with some prickly pear cacti (*Opuntia fragilis*) and black cottonwood (*Populus trichocarpa*) or balsam poplar (*Populus balsamifera*) interspersed. There was also cheatgrass (*Bromus tectorum*), stiff needlegrass (*Achnatherum occidentale*), crested wheatgrass (*Agropyron cristatum*) and sandberg's bluegrass (*Poa secunda*) on the site (Appendix**Error! Reference source not found.** A; Table A.3; McNabb 2016; Terpsma 2016). The project site Biogeoclimatic (BEC) zone is the BGxh2 which is characterized as the very dry hot subzone, Kamloops variant of the Bunchgrass BEC zone (Nicholson et al. 1991; McNabb 2016). The site is within the ranges of the Northern Pacific rattlesnake (*Crotalus oreganus*), whitetail deer (*Odocoileus virginianus*), mule deer (*Odocoileus hemionus*), bighorn sheep (*Ovis canadensis*) and beaver (*Castor *canadensis*). Moose (*Alces alces*) are well documented in the upper reaches of the Deadman River, but not at the study site (Lemke 1998; BCMOE 2000; Hobbs 2013).

The planting area spanned across three different elevation benches (Figure A.1). The soils in the higher elevation benches were mainly sandy clay loam (SCL), silty clay loam (SiCL) and silty clay (SiC) textured, while most soils in the mid and lower elevation benches were mainly silt loam (SL) and loam (L) textured (Terpsma 2016). Generally, the site lacks a true A horizon and contains a weakly modified “B” horizon (Bm1) with a sandy and rocky “C” horizon beneath (Terpsma 2016). The higher elevation benches had a richer chernozemic “A” horizon above the “Bm” layer, but this covered a limited area (~14% of the site; Terpsma 2016). The lower elevation areas were comprised of rockier and sandier soil due to their proximity to the river and periodic flooding and bank erosion (McNabb 2016).

Mineralizable nitrogen (0.70 – 7.10 mg/kg) and phosphorus (3.80 – 14.30 mg/kg) tended to decrease with depth in the soil pits (Appendix A; Table A.1; Terpsma 2016). Aluminum (0.004 – 0.006 Cmol+/kg), sodium (0.008 – 0.076 Cmol+/kg) and iron (<0.001 Cmol+/kg) were all found to be at low levels throughout the site, while exchangeable cations of calcium (5.83 – 11.87 Cmol+/kg), magnesium (2.01 – 2.25 Cmol+/kg) and potassium (0.23 – 0.56 Cmol+/kg) were all at higher levels (Appendix A; Table A.1; Terpsma 2016). The study site consisting of alkaline soils with higher levels of exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}, and smaller recorded levels of Al^{3+} and Fe^{3+} followed soil nutrient trends in arid and semi-arid environments (Appendix A; Table A.1, Table A.2). Averages for cation exchange capacity (CEC) and pH in the first 15 cm of soil depth were close to the average quantities for soils characteristic of arid regions (Brady and Weil 2008). Additionally, CEC was found to be in a typical range for medium textured soils with low organic matter (Terpsma 2016). The soil was alkaline (7.49 -7.91) which provided reasonable growing conditions (BCMFLNRO 2016). Calcium, potassium, phosphorus and sodium were determined to be within good ranges (BCMFLNRO 2016). Carbon and mineralizable nitrogen averages were both low, but tended to be variable across the site which was likely due to previous land use in the area (e.g. cattle grazing; BCMFLNRO 2016).

The irrigation system consisted of 180 lengths of 12.7 mm diameter polyethylene drip tubing laid out in parallel east- west rows approximately 6 m apart (Figure 2.2, Appendix A; Figure A.1). The average length of a row of tubing was 100 m. Trees were watered approximately 1 hour day^{-1}, using ~ 3 m long, 2.5 l hour^{-1} flow rate, capillary tube-style emitters of dimensions 0.6 mm internal diameter by 3.35 mm outer diameter manufactured by MDC industries. Watering took place from July-September 2016 and from May-September 2017. In 2016, trees were watered every day for 48 days, totalling 1.06 x 10^6 l. In 2017, trees were watered 6 days a week for 96 days, totalling 2.12 x 10^6 l (Table 2.3).

Experimental Design

The study was established as a randomized complete block (RCB) design with 6 blocks, 2 establishment treatments and 4 poplar clones (Figure 3.1, Appendix A; Figure A.1). Each establishment treatment and clone type combination was replicated 3 times in the blocks located in the easternmost part of the site and 3 times again in the western part of the site (Figure 3.1, Appendix A; Figure A.1). In each block were sixteen 400 m^2 plots of 36 trees and within these, the middle 16 trees were sampled. Fifty percent of each block was treated with mechanical site preparation (MSP), and 50% was not treated with mechanical site preparation (NOMSP; 2 MSP and 2 NOMSP plots assigned to each of the 4 clone types per block; Figure 3.1). The 4 clone types were the male clone Green Giant (*P. deltoides* x (*Populus laurifolia* x *Populus nigra*); Maini and Cayford 1968; Talbot et al. 2011), the male clone Griffin or Brooks 1 (*P. deltoides* x (*Populus laurifolia* x *Populus nigra*); Maini and Cayford 1968; Talbot et al. 2011), the female clone Hill or FNS 44-55 (*P. deltoides* x (*Populus laurifolia* x *Populus nigra*); Maini and Cayford 1968; Talbot 2011), and the female clone Walker (*P. deltoides* x (*Populus laurifolia* x *Populus nigra*); Lindquist et al., 1977) were used. In total, 1536 trees were measured across the entire planting site. For each of the 4 clone types, 192 trees were planted in MSP treated areas, and 192 were planted in NOMSP treated areas.

From 16-25 May, 2016, the MSP treatment (Appendix B; Figure B.1) was applied to one half of each block using the toothed portion of a rock bucket (approximately 60 cm wide with five 15 cm long teeth) on a rubber tracked miniature hydraulic excavator (model 35D, John Deere, Moline, Illinois). Within a block, the excavator travelled parallel to the proposed irrigation line layout; stopping every 3 m and inserting the teeth into the soil surface (Appendix B; Figure B.1). With two drags of the soil surface, the bucket produced an approximately 100 cm x 100 cm x 15 cm section of disturbed soil (i.e. “scalp”) that removed competing vegetation and facilitated planting. The goal of this treatment was not to produce a mound. Large vegetation such as big sagebrush removed by the preparation process were left onsite but moved off the section of exposed soil created by the bucket. Once irrigation infrastructure was installed the trees were planted 12-20 July, 2016.

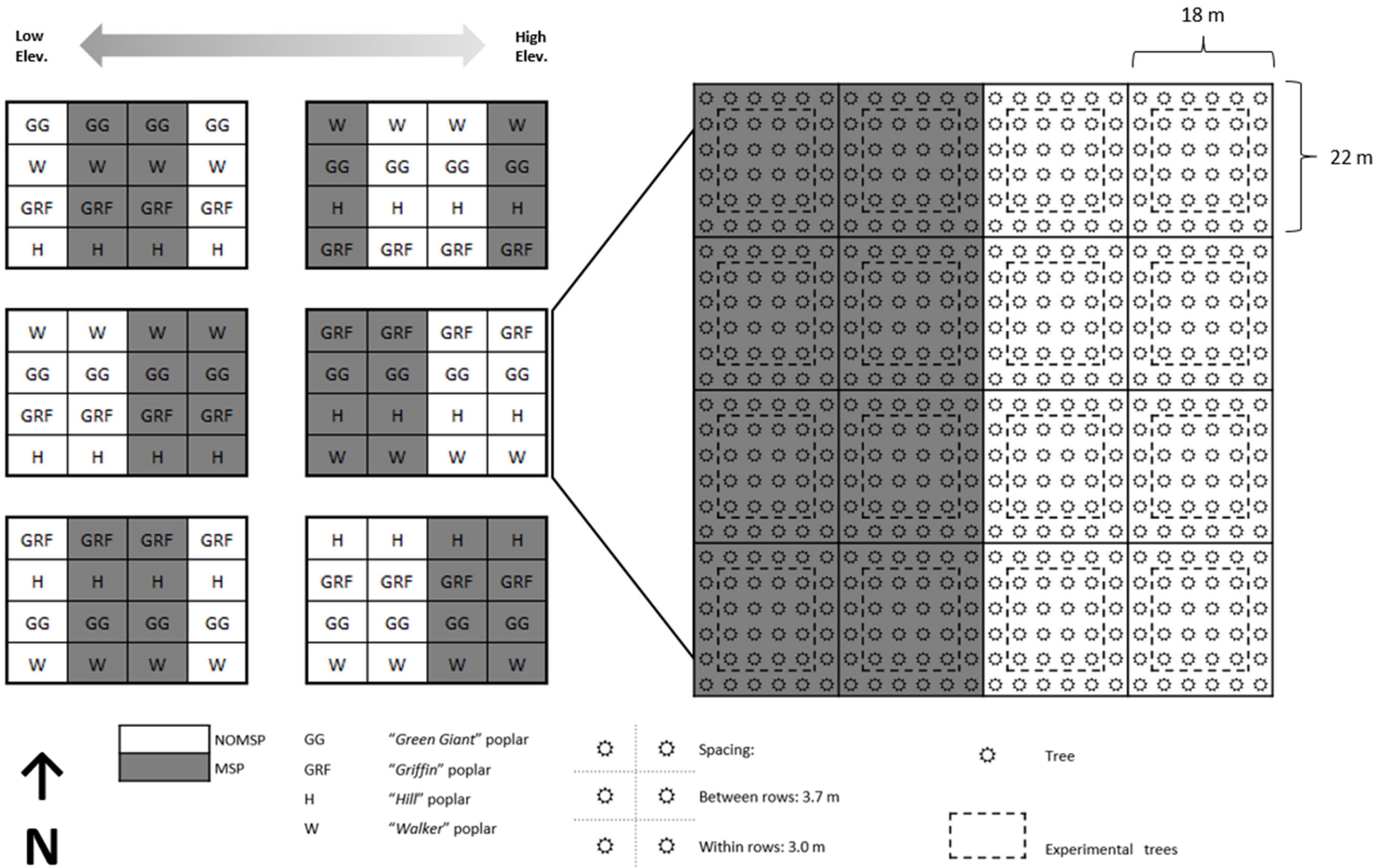

Figure 3.1. Experimental plantation layout showing the four poplar clones and two establishment treatments arranged according to a randomized complete block design showing the sixteen replicate plots that were located within each of the six blocks.

Weather Data

On 9 June 2016, a cellular weather station was installed at the site at the coordinates: N 50°44.917' X W 120°54.593' at 364 amsl (Hobo RX3000 3G, Onset Comp, Bourne, MA, USA). The weather station monitored precipitation (model S-RGB-M002, Onset Comp), air temperature, (°C), relative humidity (%) and dew point (°C) at 1.3 cm height (model S-THB-M002, Onset Comp), wind speed/direction at 2 m (S-WSET-B, Onset Comp), soil temperature at 10 cm depth (model S-TMB-M002, Onset Comp) and soil moisture at 10 and 20 cm (model S-SMC-M005, Onset comp). Onsite weather data were compared to climate normals generated for the area using Climate WNA software (Wang 2016).

In the fall of 2016 and 2017, after the leaves had dropped (i.e. summer growing season was completed), data was collected on experimental trees within six blocks. I measured total overall height, height of cutting above-ground, north-south diameter, east-west diameter, number of stems, leader length, and presence/absence of damage to the tree (e.g. deer browse, mechanical damage to cutting, indicators of disease). Stem diameter measurements were taken using Magnum digital calipers (model K309AF1-1210, Magnum Industrial, Coquitlam, British Columbia) at 3 cm above the soil surface to standardize measurement locations and minimize error caused by non-level calipers or obstructions such as rocks on the soil surface (Appendix B; Figure B.2). The average of the north-south and east-west measurements was calculated to account for stem ovalness.

Absence of above-ground growth was noted as an indicator of mortality and transformed into a percentage of survival for each plot at the end of the 2016 and 2017 growing seasons. Survival data was additionally collected in June 2017 for the experimental trees. This was done to observe if there had been significant mortality over the winter.

Weather and Growth Measurement

Saturation vapor pressure (Pa, SVP) was calculated using the following formula from Murray (1967):

$$SVP = 610.78 * 10^{\frac{7.5T}{(237.3+T)}} \qquad (1)$$

Vapor pressure deficit (Pa, VPD) was calculated using the following formula from Monteith and Unsworth (1990):

$$VPD = \frac{(100 - \mathrm{RH})}{100} * \mathrm{SVP} \qquad (2)$$

For both 2016 and 2017, basal diameter increment (DI), total tree height increment (HI), initial volume index (Vo), final volume index (Vii) and volume index increment (VI) were calculated. Basal diameter increment (DI) was calculated by subtracting the average of the north-south and east-west diameter measurements (mm) from 2016 (Do) from the averages of the same measurements taken in 2017 (Di).

$$DI = Di - Do \qquad (3)$$

Total tree height increment (HI) was calculated by subtracting the initial height measurement (cm) of the planted cutting in 2016 (Ho) from the final overall height measurement of the tree in 2017 (Hii).

$$HI = Hii - Ho \qquad (4)$$

Volume index (dm^3; Vo) was calculated with an equation used by Pontalier et al. (1997) and Wu and Stettler (1998) that consisted of squaring the average of the North-South and East-West diameter measurements from 2016 and 2017 (Do) and multiplying them by the initial height measurement (cm) of the planted cutting in that year (Ho).

$$Vo = \left(\frac{Do}{10}\right)^2 \left(\frac{Ho}{1000}\right) \tag{5}$$

2017 volume index (dm^3; Vii) was calculated with an equation used by Pontalier et al. (1997) and Wu and Stettler (1998) that consisted of squaring the average of the North-South and East-West diameter measurements from 2017 (Di) and multiplying them by the final overall height measurement of the tree in 2017 (Hii).

$$Vi = \left(\frac{Di}{10}\right)^2 \left(\frac{Hii}{1000}\right) \tag{6}$$

Total volume index increment (dm^3; VI) was calculated by subtracting the calculated initial volume index (Vo) from the calculated final volume index (Vii).

$$VI = \left\{\left(\frac{Di}{10}\right)^2 \left(\frac{Hii}{1000}\right)\right\} - \left\{\left(\frac{Do}{10}\right)^2 \left(\frac{Ho}{1000}\right)\right\} \tag{7}$$

Canopy Browse and Dieback

Browse frequency was estimated by averaging counts of the number of trees per plot that had received damage to stems in the form of recently removed (clipped) vegetation. The primary cause of this damage was suspected to have been from browsing by *Odocoileus hemionus* (mule deer) as they were frequently sighted in the plantation area and their fresh tracks were often observed in close proximity to trees that had received recent damage. As well, dieback was quantified as the average amount of vertical height that was lost by trees in each plot between the 2016 and 2017 sampling times. Dieback was defined as a progressive death or loss of tissue originating at the tips of stems. A value for dieback frequency was generated from counts of the trees in each plot that had experienced some form of dieback.

Canopy Architecture

Canopy architecture was evaluated using a count of the number of stems longer than 2 cm branching off the main stem and primary branches and a measurement of the length of the longest branch off the main stem. These data were collected in fall 2016 and fall 2017 and used to calculate averages for each plot.

After the poplar cuttings were planted, dominant competing vegetation was quantified by counting the number of *Artemisia tridentata* shrubs per plot and measuring their height (cm). Counts were used to calculate a density of per hectare (ha) value by dividing the number of shrubs by the area of the plot (0.04 ha). Height data was transformed into an average shrub height per plot value.

Statistical Analysis

Statistical analyses were carried out using “R” software (R Development Core Team 2019). Data for all measured variables and parameters were averaged for all experimental trees within each plot.

Generalized Linear Models (GLM) were developed to compare effects from clone type, establishment treatment and initial cutting diameter on survival, diameter, height and volume increments for each growing season. The model for all GLMs included block, establishment treatment (MSP, NOMSP), type of clone (Green Giant, Griffin, Hill, Walker), the interaction between establishment treatment and clone type, and initial diameter all as fixed factors. According to partial omega squared (ωp^2; Olejnik and Algina 2003) for blocks, the proportion of variability explained by the blocks amounted to more than 2% in most models (Table 3.1). Variability from the blocks was not eliminated from the model because of this reason. Basic assumptions of each model were tested before carrying out the GLM. Assumptions of homoscedasticity and normality were examined using plots of residuals. In addition, assumptions of homoscedasticity were tested for using Breusch-Pagan tests (α=0.05). Fligner-Killeen and Levene’s tests for homogeneity of variances (α=0.05), Durbin-Watson tests for independence (α=0.05), Variance Inflation Factor (VIF) calculations for multicolinearity and Spearman’s rank correlation tests for monotonic relationships between variables were also carried out prior to the GLM. No transformations were required to meet the prerequisites of the GLM so raw data are presented here. Where significant differences were found, Tukey’s honest significant difference (HSD) post-hoc comparisons were performed (α=0.05). The statistical analyses were performed using the statistical packages *car* 3.0, *lmtest* 0.9-36, *sjstats* 0.16.0, *stats* 3.5.1 and *stats4* 3.5.1 (R Development Core Team 2019).

Results

After two growing seasons, significant differences in survival, diameter, height and volume index growth were mostly influenced by poplar clone ($p<0.05$), with mixed significant ($p<0.05$) and non-significant ($p>0.05$) effects from establishment treatment (Table 3.1). There was some presence of a treatment*clone interaction ($p<0.05$) for tree survival, but not for height, diameter or volume growth responses (Table 3.1). Covariates for initial diameter, height and volume all had some effect on corresponding responses for survival, diameter growth, height growth and volume growth, but these effects diminished after the first year and were minimal for the growth increment responses (Table 3.1).

Weather

The temperature in both 2016 and 2017 was warmer than the long-term average produced by Climate WNA (1981-2010; Wang 2016). The 2016 growing season monthly average temperature at 1.3 m above ground (21.0°C, 22.0°C, 13.8°C for July, August and September, respectively) was above the 1981 - 2010 average (20.2°C , 19.6°C , 14.5°C for July August and September, respectively; Appendix A; Figure A.2). The 2017 growing season monthly average temperature at 1.3 m above ground (15.5°C, 20.3°C, 23.9°C, 22.5°C, 17.2°C for May, June, July, August and September, respectively) was between 2.1 to 3.7°C above the 1981 - 2010 average for every month (13.4°C, 17.6°C, 20.2°C, 19.6°C, 14.5°C for May, June, July August and September, respectively; Appendix A; Figure A.2). In 2016, rainfall during the summer period was higher than in 2017. In 2016, frequent rain events resulted in growing season monthly total rainfall (33 mm, 40 mm and 40 mm for July, August and September, respectively) above the 1981 - 2010 average (32 mm, 24 mm, 25 mm, for July August and September, respectively; Appendix A; Figure A.2). Total (July-September) growing season precipitation was 113 mm versus 81 mm historically for the same three-month period indicating that 2016 was wetter than the 30 year monthly average (Appendix A; Figure A.2). 2017 growing season monthly total rainfall (3 mm, 11 mm and 6 mm for July, August and September, respectively) was below the 1981 - 2010 average (32 mm, 24 mm, 25 mm, for July, August and September, respectively; Appendix A; Figure A.2).

Total 2017 (July-September) growing season precipitation was 20 mm versus 81 mm historically for the same three month period indicating that 2017 was drier than the 30 year monthly average (Appendix A; Figure A.2). 2016 growing season soil VWC ranged from 0.14 m^3/m^3 (10 cm depth) and 0.15 m^3/m^3 (20 cm depth) on August 20th, 2016 to 0. 24 m^3/m^3 (10 cm depth) and 0.25 m^3/m^3 (20 cm depth) at its highest on August 22, 2016. For the 2017 growing season, soil VWC was at its highest on May 17th, 2017 (0.17 m^3/m^3 at 10 cm depth and 0.19 m^3/m^3 at 20 cm depth) and at its lowest around the week of August 10th, with values of 0.07 m^3/m^3 (10 cm depth) and 0.08 m^3/m^3 (20 cm depth). In 2016, average VPD ranged from 4.34 Kpa at its highest on July 29th to 1.56 Kpa at its lowest on September 2nd (Appendix A; Figure A.3). Average vapor pressure deficit in 2017 ranged from 4.69 Kpa at its highest on August 29th to 1.42 Kpa at its lowest on September 20th (Appendix A; Figure A.3).

Survival

Significant differences in tree survival were detected as main effects between establishment treatments and clones ($p<0.05$), but not as simple effects between establishment treatments for individual clones after the first (2016) and second growing season (2017; Figure 3.2, Figure 3.3). In fall 2016 averages of both establishment treatments, Green Giant clones showed the greatest survival (83%), followed by Hill (71%), then Walker (69%) and Griffin (40%; Figure 3.3a). By spring 2017, averages of both establishment treatments of survival for all clones had slightly declined to 75%, 64%, 62% and 36% for Green Giant, Walker, Hill and Griffin respectively (36%; Figure 3.3b). In the fall of the 2017, clonal differences ($p<0.05$) persisted with survival dropping for Green Giant (61%), Walker (52%), Hill (48%) and Griffin (32%) again for averages of both establishment treatments combined (Figure 3.3c).

The negligible effect from treatment*clone interaction for all sampling periods indicated that all clones had similar survival responses to the establishment treatments (Table 3.1). In the three sampling periods for all clones, the MSP treatment had a greater main effect, but non-significant simple effect on survival rate (Table 3.1, Figure 3.2, Figure 3.3). For fall 2016, the survival rates ranged from 87% for Green Giant in the MSP treatment to 32% for Griffin in the NOMSP treatment. In spring 2017, the survival rates ranged from 80% for Green Giant in the MSP treatment to 29% for Griffin in the NOMSP treatment. By fall 2017, the survival rates ranged from 68% for Green Giant in the MSP treatment to 22% for Griffin in the NOMSP treatment.

Table 3.1. Results from GLMs examining the effect (ωp^2) of block, establishment treatment, clone and their interaction on poplar survival and growth variables, including survival, total height, diameter and volume with height (HI), diameter (DI) and volume increment (VI) for the first (2016) and second (2017) growing seasons after planting. Initial height, initial diameter and initial volume (November 2016) were included as covariates for the corresponding responses. Initial diameter was also included as a covariate in the survival model. Significant effects are bolded (p<0.05).

Variable	Block		Treatment		Clone		Treatment*clone		Initial height/diameter/volume	
	ω_p^2	p-value	ω_p^2	p-value	ω_p^2	p-value	ω_p^2	p-value	ω_p^2	p-value
Survival (%)										
Nov 2016	-0.004	0.474	0.142	**<0.001**	0.58	**<0.001**	-0.02	0.769	0.158	**<0.001**
Jun 2017	0.126	**0.004**	0.219	**<0.001**	0.538	**<0.001**	-0.021	0.802	0.124	**<0.001**
Nov 2017	0.274	**<0.001**	0.224	**<0.001**	0.345	**<0.001**	-0.027	0.93	0.099	**0.001**
Diameter (mm)										
Nov 2016	-0.001	0.439	0.006	0.21	0.736	**<0.001**	-0.03	0.973	-	**-**
Nov 2017	-0.006	0.498	-0.009	0.69	0.516	**<0.001**	-0.026	0.902	0.292	**<0.001**
DI 2017	0.103	**0.0108**	0.05	**0.0159**	0.238	**<0.001**	-0.022	0.807	-0.005	0.46
Height (cm)										
Nov 2016	0.346	**<0.001**	0.022	0.079	0.168	**<0.001**	-0.014	0.638	0.09	**0.002**
Nov 2017	0.16	**<0.001**	-0.004	0.428	0.196	**<0.001**	-0.024	0.853	0.012	0.144
HI 2016	0.194	**<0.001**	0.102	**<0.001**	0.539	**<0.001**	-0.029	0.962	0.1	**<0.001**
HI 2017	0.052	0.080	0.027	0.0594	0.219	**<0.001**	-0.019	0.753	-0.006	0.501
HI Total	0.323	**<0.001**	0.107	**<0.001**	0.372	**<0.001**	-0.023	0.841	0.056	**0.012**
Volume Index (dm^3)										
Nov 2016	-0.009	0.537	0.019	0.095	0.647	**<0.001**	-0.029	0.976	0.524	**<0.001**
Nov 2017	-0.031	0.833	0.002	0.281	0.346	**<0.001**	-0.03	0.971	0.234	**<0.001**
VI 2016	0.024	0.209	-0.01	0.899	0.346	**<0.001**	-0.021	0.805	0.108	**<0.001**
VI 2017	0.003	0.395	-0.01	0.908	0.108	**0.004**	-0.024	0.869	0.02	0.0908
VI Total	-0.033	0.854	-0.01	0.821	0.238	**<0.001**	-0.031	0.984	0.112	**<0.001**

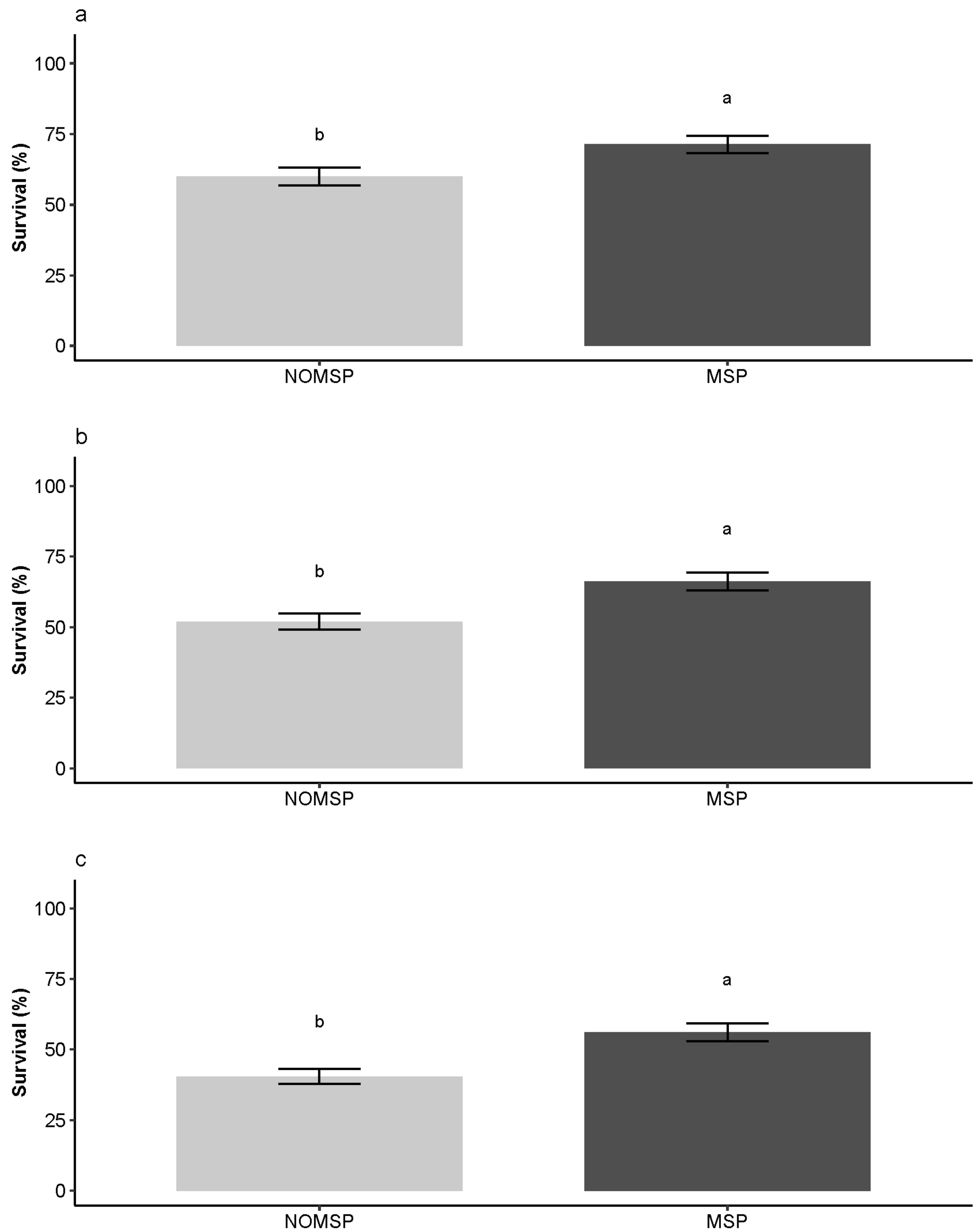

Figure 3.2 Tree survival (%) as determined after the (a) first year following planting (2016) and at the (b) beginning and (c) end of the second growing season (2017). Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

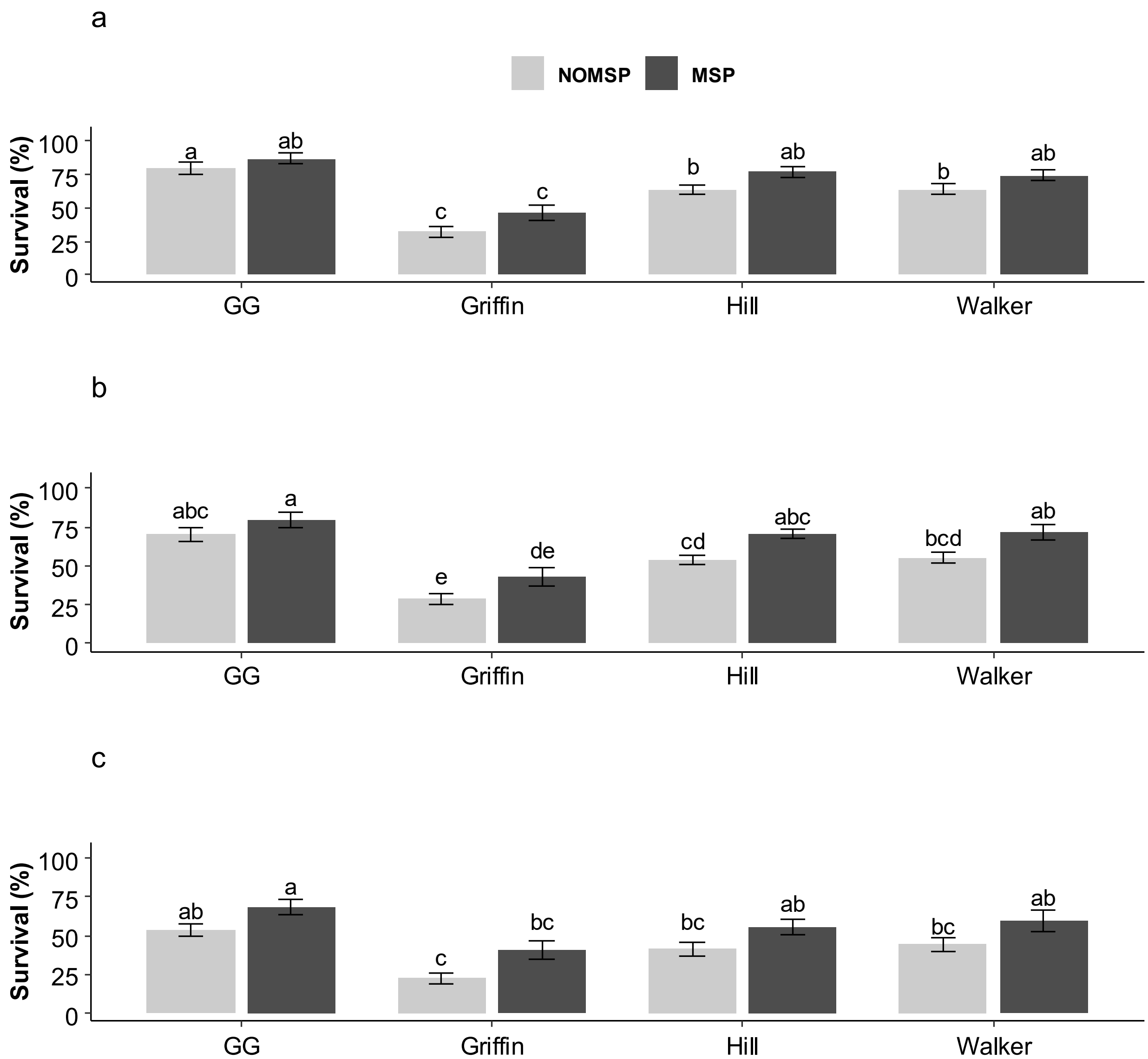

Figure 3.3. Tree survival (%) as determined after the (a) first year following planting (2016) and at the (b) beginning and (c) end of the second growing season (2017). For each treatment and clone, each value is the mean of 12 plots. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

Diameter Growth

Significant differences in basal diameter were found between clones ($p<0.05$) but not between establishment treatments after the first (2016) and second growing season (2017; Figure 3.4). In fall 2016, Green Giant clones showed the greatest basal diameter (14.4 mm), followed by Walker (13.1 mm), then Hill (12.1 mm) and Griffin (9.3 mm; Figure 3.4). In the fall of 2017, significant clonal differences persisted with basal diameters for Green Giant (15.5 mm), Walker (15.3 mm), Hill (14.0 mm) and Griffin (12.0 mm; Figure 3.4). MSP did not significantly increase basal diameter for any clones and no significant treatment*clone interactions were detected, (Table 3.1, Figure 3.4). For fall 2016, mean basal diameters ranged from 14.5 mm for Green Giant in the MSP treatment to 9.3 mm for Griffin in the NOMSP treatment. By fall 2017, the basal diameters ranged from 15.6 mm for Green Giant in the NOMSP treatment to 11.8 mm for Griffin in the NOMSP treatment (Figure 3.4).

Diameter increments calculated from the two sampling times showed significant differences detected as main effects between clones and establishment treatments ($p<0.05$), but not as simple effects between establishment treatments for individual clones, with Green Giant showing the greatest DI from fall 2016 to fall 2017 (0.6 mm), followed by Walker (0.5 mm), Hill (0.4 mm) and Griffin (0.2 mm; Figure 3.7). No significant treatment*clone interactions were detected (Table 3.1). The basal DI from fall 2016 to fall 2017 ranged from 0.7 mm for Green Giant in the MSP treatment to 0.1 mm for Griffin in the NOMSP treatment (Figure 3.4).

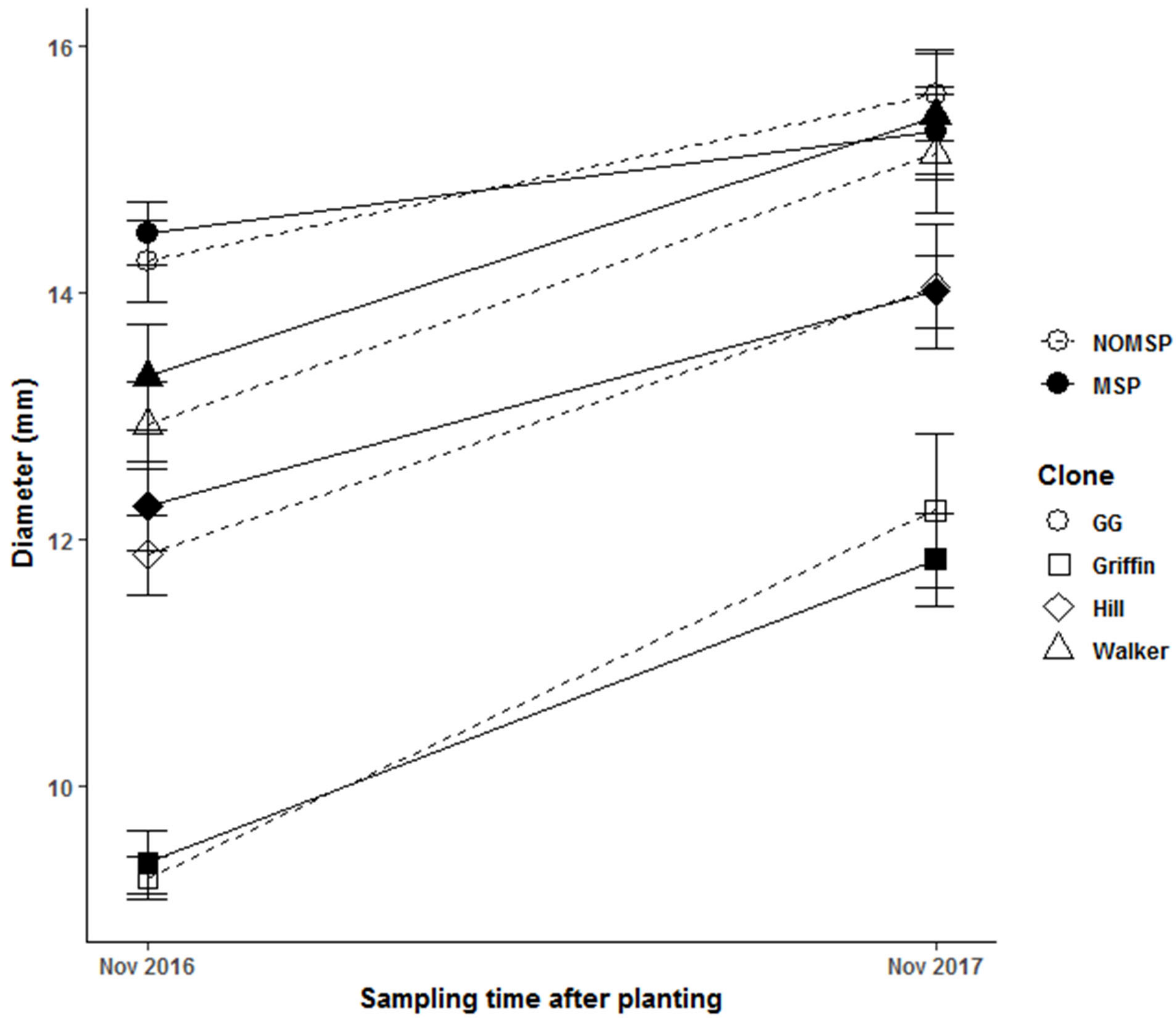

Figure 3.4. Tree mean basal diameter (mm) as determined after the first year following planting and at end of the second growing season. For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Error bars represent standard error.

Height Growth

Significant differences in tree height were found between clones ($p<0.05$) but not between establishment treatments after the first (2016) and second growing season (2017; Figure 3.5). In fall 2016, Green Giant clones showed the greatest overall height (40.9 cm), followed by Hill (40.6 cm), then Walker (39.8 cm) and Griffin (36.5 cm; Figure 3.5). In the fall of 2017, overall heights were greatest for Hill (47.7 cm), followed by Walker (43.7 cm), Green Giant (43.6 cm), and Griffin (38.7 cm; Figure 3.5). MSP did not significantly increase tree height for any clones and no significant treatment*clone interactions were detected. In the two sampling periods for most clones, the NOMSP treatment had a greater, but non-significant effect on overall height (Figure 3.5). For fall 2016, the overall height ranged from 41.8 cm for Green Giant in the NOMSP treatment to 36.4 cm for Griffin in the NOMSP treatment. By fall 2017, the overall heights ranged from 48.1 cm for Hill in the NOMSP treatment to 38.4 cm for Griffin in the NOMSP treatment.

Height increments calculated from the two sampling times showed significant differences detected as main effects between clones and establishment treatments ($p<0.05$), but not as simple effects between establishment treatments for individual clones, with Green Giant showing the greatest height increment (14.3 cm), followed by Hill (12.7 cm), Walker (11.9 cm) and Griffin (4.9 cm; Figure 3.5). MSP did not significantly increase total height increment for any clones and no significant treatment*clone interactions were detected (Table 3.1). The MSP treatment had a greater, but non-significant effect on HI (Table 3.1, Figure 3.5). The HI from fall 2016 to fall 2017 ranged from 15.9 cm for Green Giant in the MSP treatment to 3.1 cm for Griffin in the NOMSP treatment.

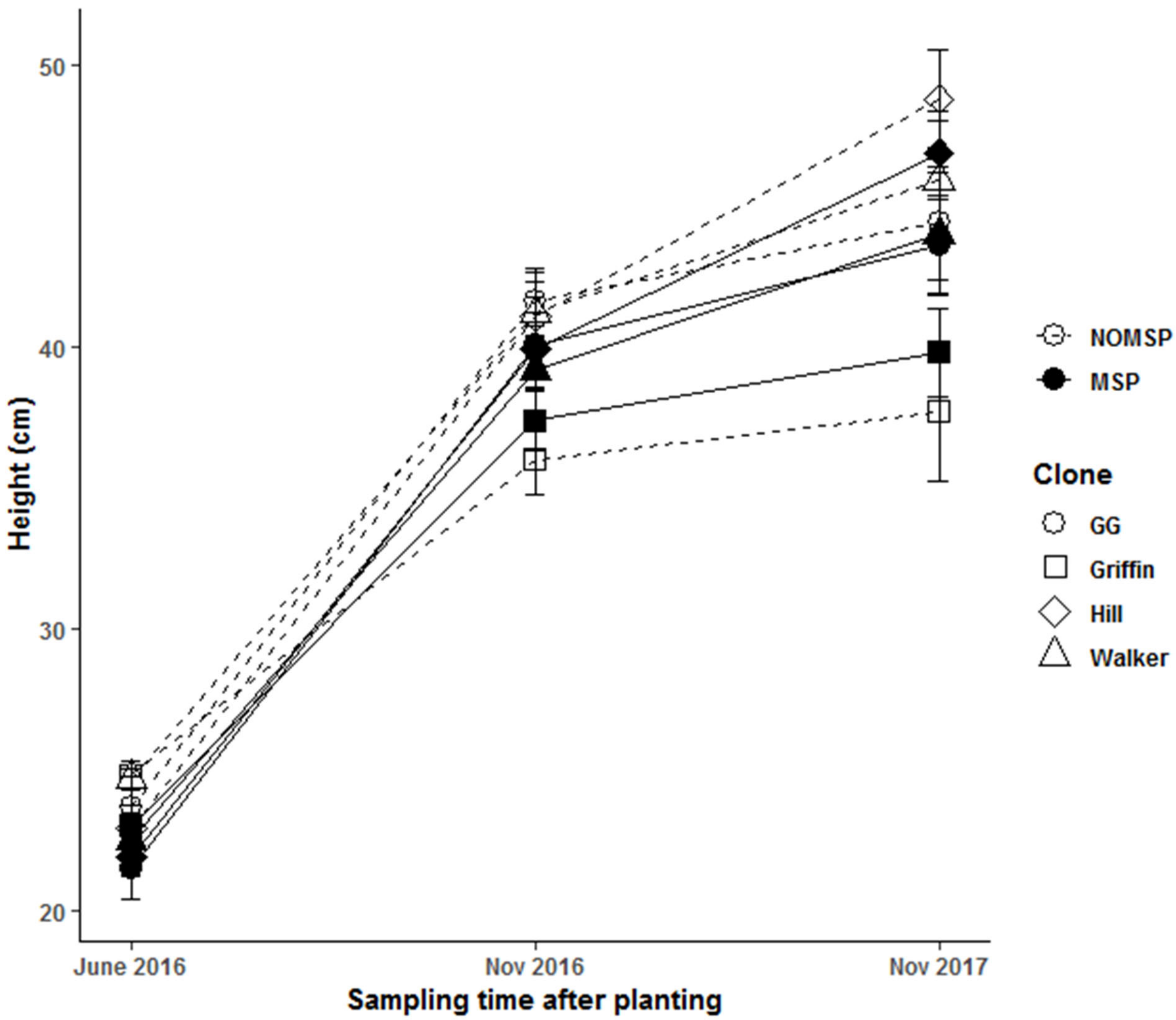

Figure 3.5. Tree height (cm) as determined after the first year following planting and at the beginning and end of the second growing season. For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Error bars represent standard error.

Volume Index Growth

Significant differences in tree volume index were found between clones ($p<0.05$) but not between establishment treatments after the first (2016) and second growing season (2017; Figure 3.6). In fall 2016, Green Giant clones showed the greatest volume index (0.10 dm^3), followed by Walker (0.10 dm^3), then Hill (0.08 dm^3) and Griffin (0.05 dm^3; Figure 3.6). In the fall of 2017, volume indexes were greatest for Walker (0.12 dm^3), followed by Green Giant (0.11 dm^3), Hill (0.10 dm^3), and Griffin (0.06 dm^3; Figure 3.6). MSP did not significantly increase volume index for any clones and no significant treatment*clone interactions were detected (Table 3.1).

In the sampling periods for all clones, there was no significant difference in volume indexes between the MSP and NOMSP treatments (Table 3.1, Figure 3.6). For fall 2016, volume index ranged from 0.10 dm^3 for Green Giant and Walker trees in both the MSP and NOMSP treatments to 0.05 dm^3 for Griffin trees in both the MSP and NOMSP treatments. By fall 2017, volume index ranged from 0.12 dm^3 for Green Giant and Walker trees in the NOMSP treatments to 0.06 dm^3 for Griffin trees in both the MSP and NOMSP treatments.

Volume index increments calculated from the 2016 initial sampling to the final sampling time in fall 2017 showed significant differences between clones ($p<0.05$) but not between establishment treatments, with Green Giant (0.06 dm^3), Hill (0.06 dm^3) and Walker (0.06 dm^3) showing the greatest volume index increments and Griffin (0.03 dm^3) showing the least (Figure 3.7). MSP did not significantly increase volume index increment for any clones and no significant treatment*clone interactions were detected (Table 3.1). In the two sampling periods for most clones, there was no significant difference in volume index increments between the MSP and NOMSP treatments (Figure 3.7). The VI from fall 2016 to fall 2017 ranged from 0.06 dm^3 for MSP and NOMSP Green Giant and Walker to 0.02 dm^3 for Griffin in the NOMSP treatment.

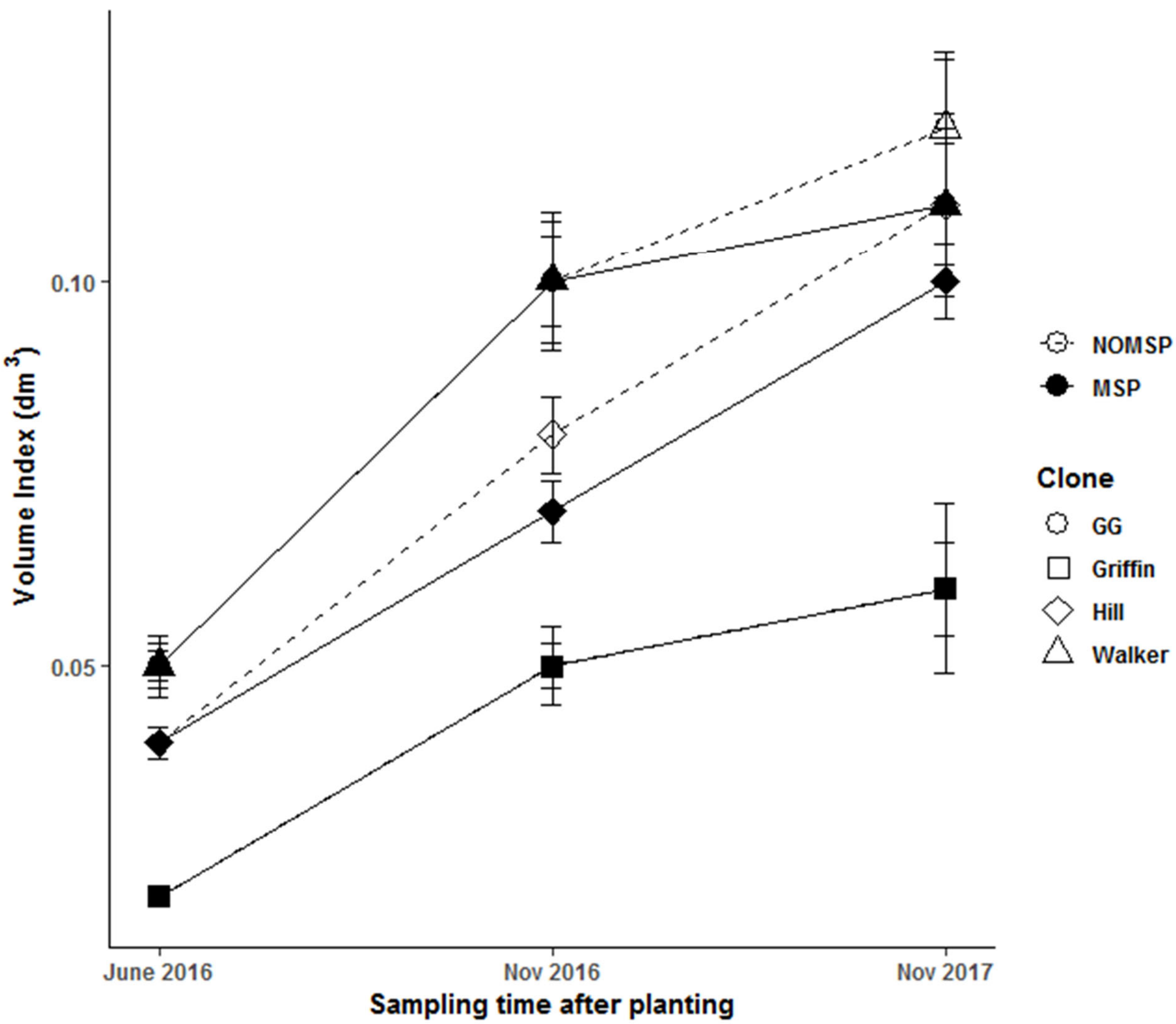

Figure 3.6. Tree volume index (dm^3) as determined after the first year following planting and at the beginning and end of the second growing season. For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Error bars represent standard error.

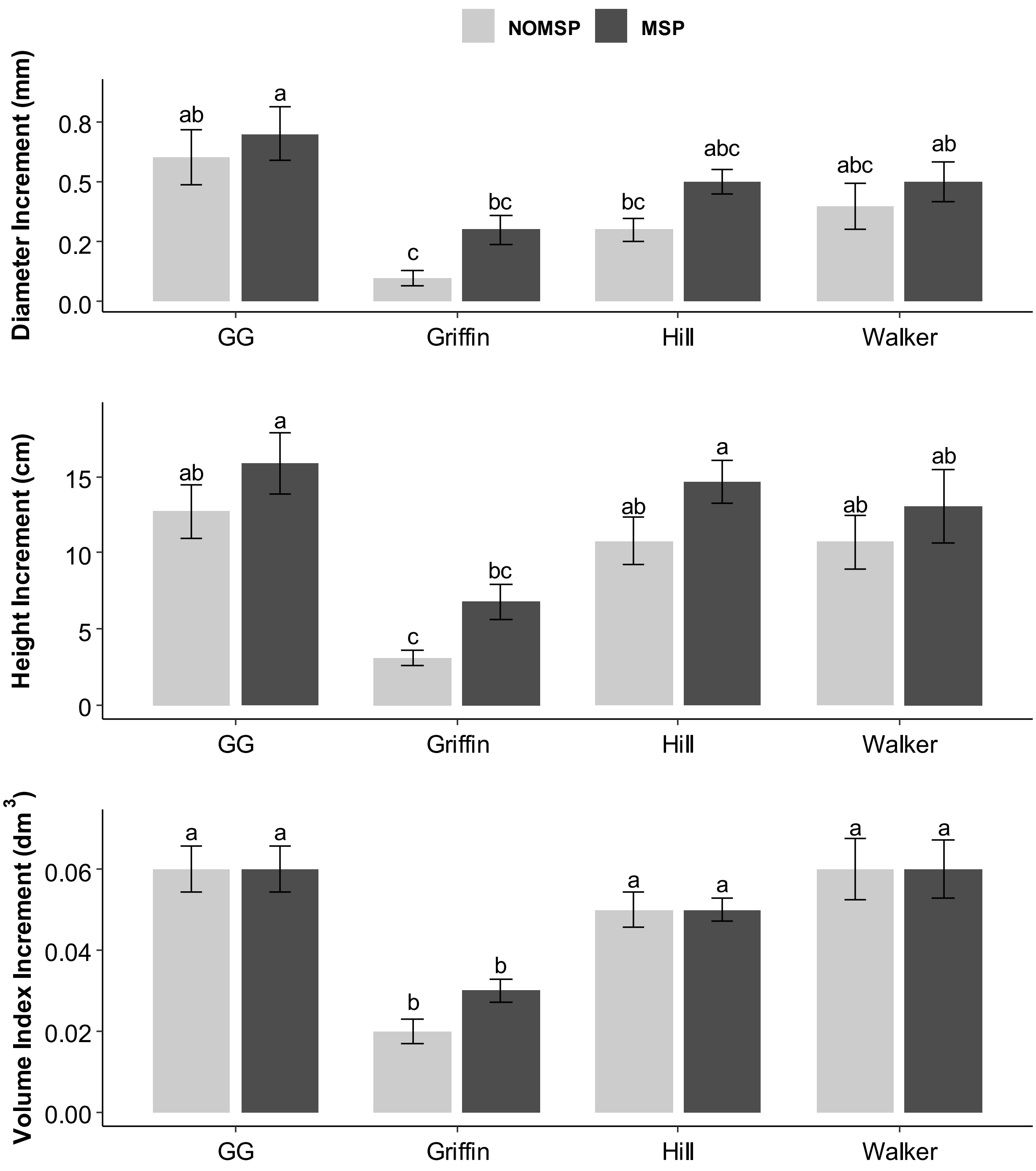

Figure 3.7. Mean diameter, height and volume increment of Green Giant, Griffin, Hill and Walker poplar clones as a two-year total from the (2016) first year after planting to the end of the (2017) second growing season, within each of the plantation establishment treatments. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

Diameter

In the three linear models developed to compare initial (2016) diameter as an independent variable to the dependent variables; survival, height increment and volume index increment, initial diameter was found to be a good predictor of all responses (Figure 3.8, Figure 3.9, Figure 3.10, Appendix C; Table C.3). Significant direct linear relationships were found between initial diameter and the four dependent variables in the first growing season ($p<0.001$, $R^2=0.65$ in NOMSP and $p<0.001$, $R^2=0.64$ in MSP for 2016 survival; $p<0.001$, $R^2=0.74$ in NOMSP and $p<0.001$, $R^2=0.66$ in MSP for 2016 height increment; $p<0.001$, $R^2=0.65$ in NOMSP and $p<0.001$, $R^2=0.64$ in MSP for 2016 volume index increment; Figure 3.8, Figure 3.9, Figure 3.10, Appendix C; Table C.3). By the end of the second growing season the strength of the relationship between initial cutting diameter and the response variables decreased but remained significant ($p<0.001$, $R^2=0.58$ in NOMSP and $p<0.01$, $R^2=0.60$ in MSP for fall 2017 survival; $p<0.07$, $R^2=0.23$ in NOMSP and $p<0.001$, $R^2=0.33$ in MSP for 2017 height increment; $p<0.41$, $R^2=0.13$ in NOMSP and $p<0.06$, $R^2=0.25$ in MSP for 2017 volume index increment; Figure 3.7, Figure 3.8, Appendix C; Table C.3). For all models, trees with larger initial cutting diameters had better performance in the parameter being measured (Figure 3.8, Figure 3.9, Figure 3.10, Appendix C; Table C.3). As well, MSP treated clones consistently displayed better performance than NOMSP treated clones, but this was not statistically significant (Figure 3.8, Figure 3.9, Figure 3.10).

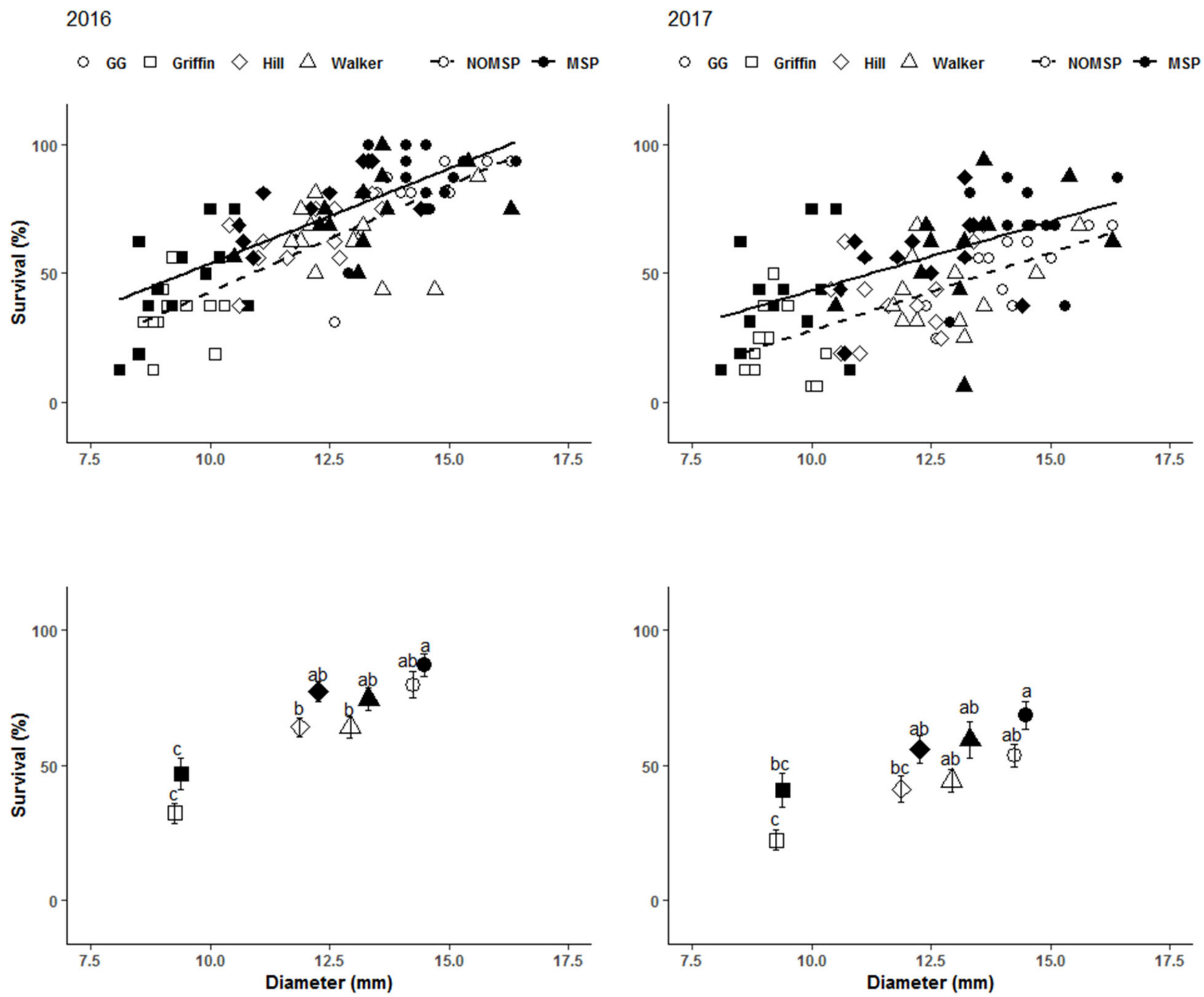

Figure 3.8. Tree survival (%) as a function of initial diameter (mm) as determined after the (2016) first year following planting and at the end of the (2017) second growing season. For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

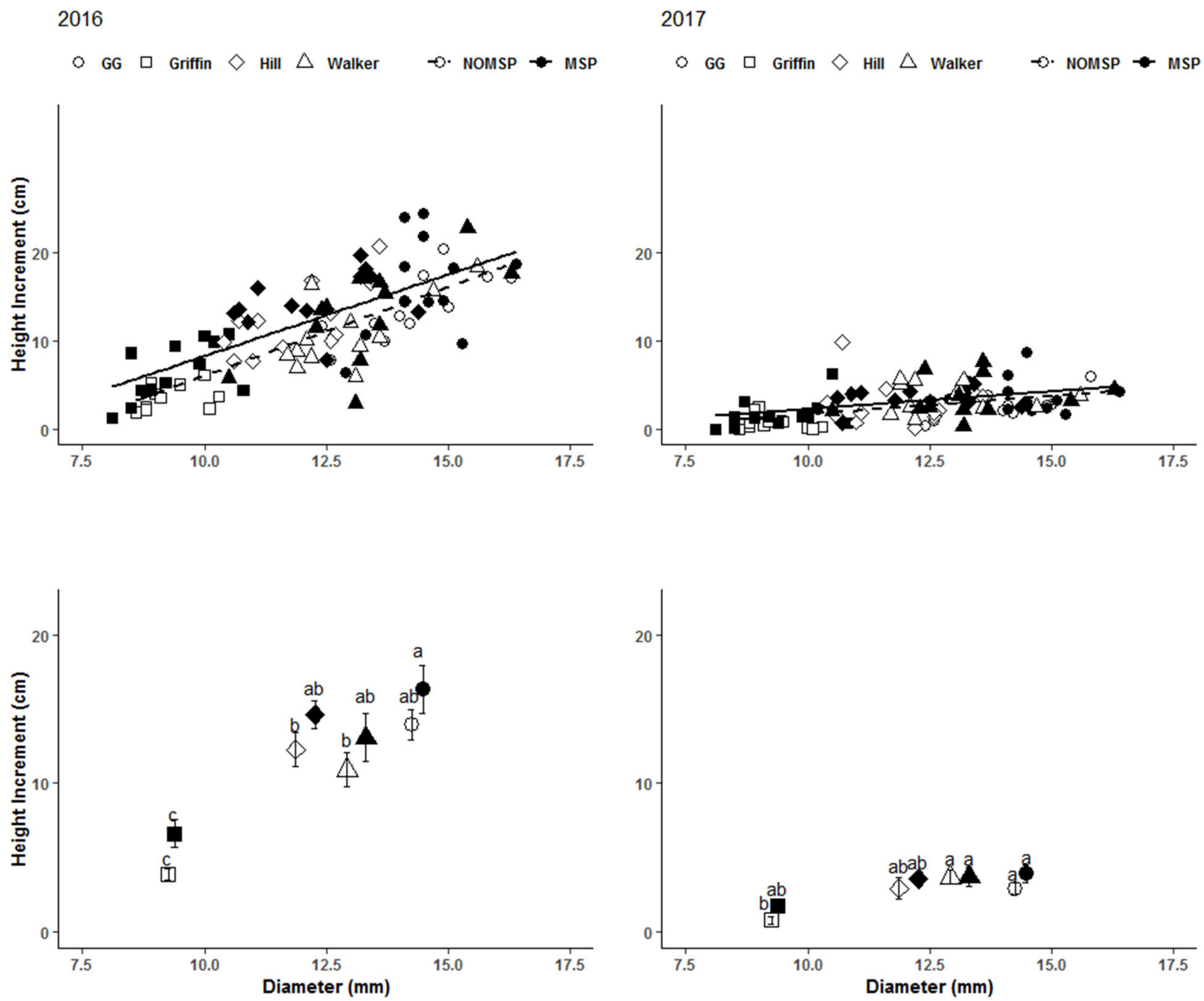

Figure 3.9. Height increment (cm) as a function of initial diameter (mm) as determined by subtracting the cutting height following planting from the total height at the end of the first growing season (2016) and by subtracting the total height at the end of the first growing season from the total height at the end of the second growing season (2017). For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

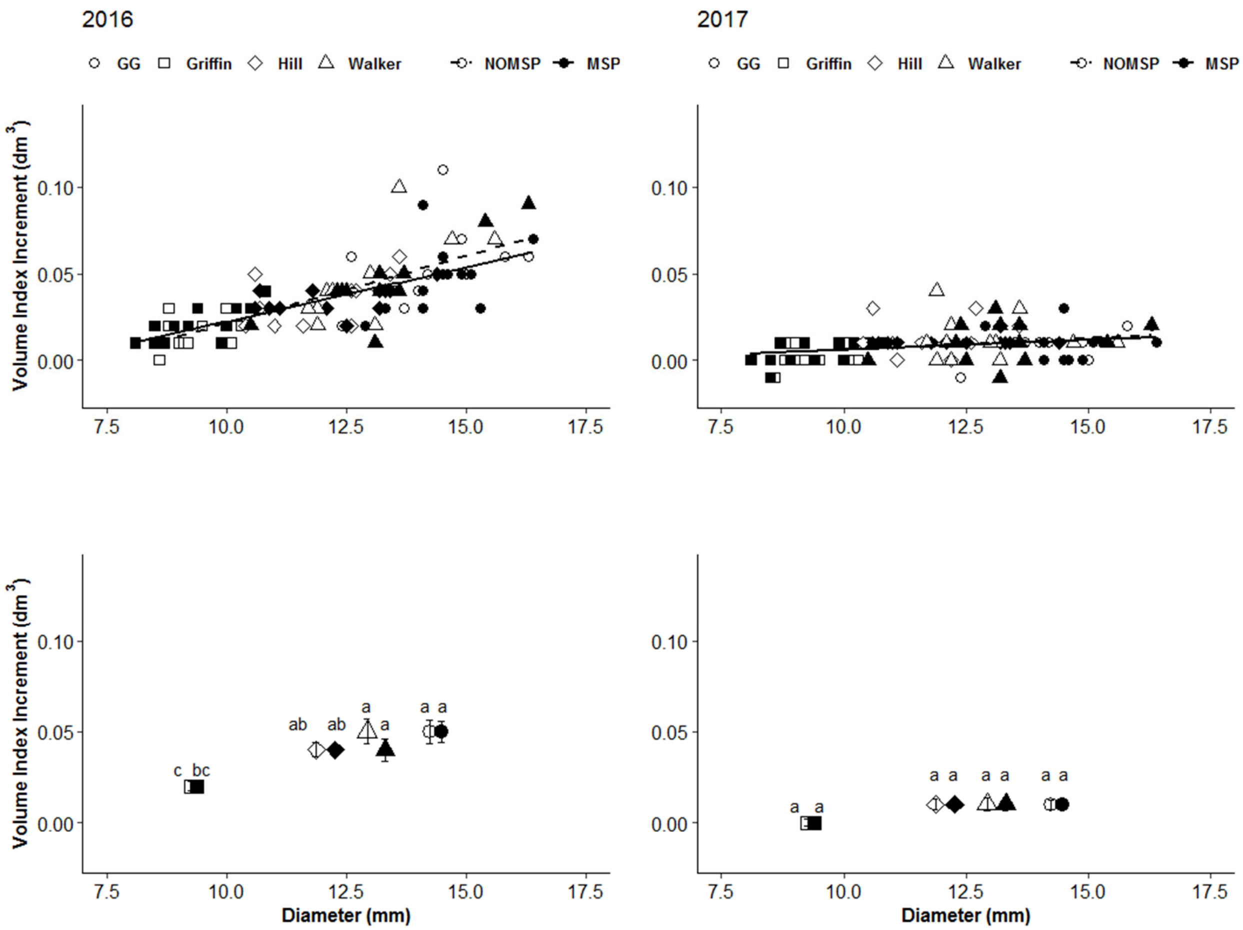

Figure 3.10. Volume index increment (dm^3) as a function of initial diameter (mm) as determined by subtracting the volume index following planting from the volume index at the end of the first growing season (2016) and by subtracting the volume index at the end of the first growing season from the volume index at the end of the second growing season (2017). For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

Browse and Dieback

In the two sampling periods for individual clones, the MSP treatment had a greater, but non-significant frequency of browse (Appendix C; Figure C.2). For fall 2016, the browse frequency ranged from 23% for Green Giant in the MSP treatment to 1% for Griffin in the NOMSP treatment. By fall 2017, the browse frequency ranged from 23% for Hill in the MSP treatment to 5% for Griffin in the NOMSP treatment. Without differentiating between individual clones, there was a significant difference in mean browse frequency for establishment treatment alone, with MSP treated trees being browsed twice as much as those in the NOMSP treatment for both years (Appendix C; Figure C.2). In the time between the 2016 and 2017 samplings, the MSP establishment treatment also experienced a higher, but non-significant frequency of dieback relative to the NOMSP (Appendix C; Figure C.3). Dieback frequency ranged from 16% for Green Giant in the MSP and NOMSP treatments to 6% for Griffin in the NOMSP treatment. During the same time period, the MSP treatment experienced a greater non-significant amount of dieback in terms of mean loss of height (cm) than the NOMSP treatment (Appendix C; Figure C.3). Loss of vertical growth ranged from -6.7 cm for Hill in the MSP to -3.6 cm for Hill in the NOMSP.

Canopy Architecture

Stem count did not differ significantly between establishment treatments or clone types in 2016, but some significant clonal differences ($p<0.05$) were detected in 2017 (Appendix C; Figure C.4). In 2016, all clones had an average of 4 stems longer than 2 cm branching off the main stem and primary branches, while in 2017, this stem count ranged from 8 for Green Giant in the MSP and NOMSP treatments to 4 for Griffin in the NOMSP treatments (Appendix C; Figure C.4). In 2016, the length of the longest stem did not significantly differ between establishment treatments, but ranged from 24.7 cm for Green Giant in the NOMSP treatment, to 17.3 cm for Griffin in the NOMSP (Appendix C; Figure C.4). In 2017, the length of the longest stem again did not significantly differ between establishment treatments, but ranged from 30.4 cm for Hill in the MSP treatment, to 22.6 cm for Griffin in the NOMSP treatment (Appendix C; Figure C.4).

Competing Vegetation

Assessments of the primary competing vegetation showed no significant differences or trends in the density or height of *Artemisia tridentata* among the treatments (Appendix A; Figure A.4). The tallest plants were found in plots with NOMSP Griffin trees (60 cm) with most plants in the 50-60 cm height range (Appendix A; Figure A.4). The highest density of plants was found in the NOMSP Walker treatment (600 plants ha^{-1}) with most plants in the 0.02 to 0.03 plants/m^3 range.

Discussion

Tree Growth Differences among Establishment Systems

The MSP treatment had a minimal effect on the survival and 2-year growth of the planted poplar cuttings. Significant differences were not found in survival, diameter growth, height growth, diameter increment (DI), height increment (HI) or volume increment (VI) between the two establishment systems tested (Table 3.1, Figure 3.7). Over the two seasons, the effect of the MSP treatment on survival, diameter growth and height growth was calculated to be 22% or less, while the effect of the MSP treatment on DI, HI and VI was calculated to be 10% or less (Table 3.1). This suggested that MSP improved tree performance over the NOMSP treatment, but only in a minor way. The small difference in the response of cuttings to the different site preparation treatments may have resulted from conflicting costs and benefits of the MSP and NOMSP treatments to plant growth.

The lack of significant effect of site treatment (MSP vs NOMSP) on seedling survival and growth may result from conflicting benefits of both treatments. For example, the MSP sites may have removed competition, but the intact vegetation in the NOMSP treatment may have created a more favourable microclimate. Effects of MSP on survival and growth were greater, but non-significant, for cuttings that had smaller initial diameters when planted, suggesting that MSP may have aided initial growth of smaller diameter planting stock (Figure 3.8, Figure 3.9, Figure 3.10). The most plausible mechanism by which MSP could have improved growth performance over the two seasons was via the removal of existing vegetation that competed with the planted cuttings for water, light and nutrients and via improved water infiltration which assisted root development (Demeritt 1990; Thomas et al. 2000). These microsites could have experienced greater precipitation inputs via reduced interception loss, but warmer temperatures in summer months would have increased evaporative moisture losses (Pinno and Belanger 2009). MSP treatments were expected to have been associated with less competition for resources from surrounding vegetation although no significant difference in the post-planting height or density of the dominant competing (*Artemisia tridentata*) shrubs was detected between the different establishment treatments

(Appendix A; Table A.3, Figure A.4). In areas dominated by *Artemisia tridentata,* although there was no significant difference in terms of dieback measurements, the intact canopies of the existing vegetation retained in the NOMSP treatment may have allowed planted cuttings to be more protected from deer browse, and were suspected to have contributed to reduced soil temperatures and photosynthetically active radiation (PAR) as well as altered soil surface water contents (Rousset and Lepart 1999). The more uniform canopies in the NOMSP treatment may have been less well-coupled with the atmosphere than the rougher canopies of the MSP treatments- leading to reduced ventilation rates and turbulent exchange which are factors in evapotranspirative water-loss (Teklehaimanot et al. 1991; Green et al. 1995). These microclimates could have shielded the interplanted NOMSP trees from harsh environmental conditions like those experienced in mid-August of the 2016 growing season and mid-July of the 2017 growing season (Appendix A; Figure A.2, Figure A.4; Rousset and Lepart 1999).

Dieback (percent frequency and amount of lost vertical growth) did not significantly differ between clones or establishment treatments, but MSP treated trees showed a similar pattern in the amount of vertical loss of growth to the pattern associated with the percent frequency of browse (Appendix C; Figure C.2, Figure C.3). MSP treated clones with larger growth and larger initial diameters appeared to have been browsed more heavily than smaller clones in NOMSP areas. Dieback was primarily associated with deer browse, but microclimate conditions may have also increased dieback in MSP sites.

Differences between Poplar Clones

A major factor in the survival and growth performance of a planted cutting is the ability to develop roots quickly (Zhao et al. 2014). Initial size affects the ability of a cutting to develop roots by controlling the amount of carbohydrate and hormonal content available for the production of new tissue (Harfouche et al. 2007; Zhao et al. 2014). The part of the parent tree that the cutting was taken from also plays a role in the rooting ability of the cutting (Harfouche et al. 2007). This is because the tissue composition and potential budding ability differ in different structural parts of a parent tree (Harfouche et al. 2007). In particular, cuttings sourced from root suckers (formations developing from roots) and sticklings (complete plants developing from rooted cuttings) are superior at producing roots over those sourced from stump sprouts and reiteration shoots (produced following a break of a branch; Harfouche et al. 2007). Trees that are at a disadvantage when it comes to developing and sending out roots are less able to explore the surrounding soil and are more susceptible to harsh environmental conditions. Cuttings that do not root in the first few weeks after planting are expected to die off quite quickly (Harfouche et al. 2007). Those planted cuttings that did develop roots, but not in adequate numbers, lengths or depths, may have survived the first season only to be killed off over the winter or in the hotter, drier conditions of the second growing season (Zalasky 1978). Trees that struggled to put out roots would have had less water, carbohydrate and other nutrients to put towards above-ground growth which could have manifested in the clonal growth differences that were observed (Zhao et al. 2014). Additionally, smaller diameter cuttings also have thinner bark and higher surface area to volume ratios than larger diameter cuttings, leaving them more susceptible to desiccation (van Oosten 2006).

Establishment treatment (MSP or NOMSP) and clone type were less important predictors than the initial diameter of the cutting when predicting the survival, height growth, DI, HI, and VI (Table 3.1). While there was an interaction between cutting diameter and establishment treatment (MSP seemed to aid smaller diameter cuttings more than larger diameter cuttings), no significant interaction was detected between clone type and establishment treatment. This meant that all clones responded in similar ways to the two establishment treatments. MSP likely helped to reduce competing vegetation, while NOMSP may have allowed for some protection of the planted cuttings against harsh environmental conditions and deer browse via existing *Artemisia tridentata* (Rousset and Lepart 1999). No clones were shown to respond significantly better to one treatment or the other, without taking initial cutting size into account. As a general rule, future plantations using cuttings with initial diameters smaller than 14 mm can expect MSP to improve survival and growth by approximately 10% in similar conditions. If cuttings greater than 14.8 mm initial diameter are used, then survival and growth in MSP and NOMSP would be roughly equal (NOMSP would be more cost effective).

If a tree survived the first year, the cutting diameter became less important. Most initial cutting size related differences in survival and growth performance were diminished by the second year. This suggested that initial cutting size may have been less of a factor in later growth performance if a tree managed to put out adequate roots and survive into the second year after planting. This did not counteract first year survival being paramount to establishment success.

The differences in performance between the four clone types highlight the importance of the procurement of good planting stock. Cuttings must be from clones that are not only of adequate size, harvested correctly from the right tissue and properly handled and planted, but the cuttings themselves must be genotypically suited to the planting conditions (DeBell and Harrington 1993). When it comes to selecting a combination of clone types, planting mixed cultures with more genetic diversity is a way to buffer against potential losses from biotic and abiotic hazards over the length of the rotation (van Oosten 2006). Decisions on which clones to select, how many different types to select, and how to lay them out are also influenced by the rotation length, harvesting method, piece size and end use of the trees (DeBell and Harrington 1993). Often, the answer to the question of how many clone types to select is not simply “more is better,” but instead takes into account the feasibility and priority of the above-mentioned considerations. Having more genotypes that use site resources and respond to conditions differently could be more productive over the rotation, but this is hard to quantify and requires more study (DeBell and Harrington 1993).

Growth Relative to Other Studies

The height growth of the four clones under the two establishment treatments was low compared to reported height measurements of genetically and regionally similar plantations found in the literature. The mean height of all clones in my study was 39 cm after the first growing season and 43 cm after the second growing season (Figure 3.5). In the literature, height was a common performance metric spanning across time periods and geographic regions. A 1977 factsheet on Walker poplar stated an average height after one growing season of 90 cm at Indian Head south Saskatchewan and Hays Alberta (Lindquist et al. 1977). A slightly later study found 2-year-old *Populus tremuloides* trees growing in the Mixedwood and Lower Foothill sections of the Boreal Forest Region in Alberta, Saskatchewan and Manitoba on average grew to a height of 167 cm by the second growing season (Peterson et al. 1982). In a 1992 study in nearby Vernon, BC, *Populus trichocarpa* x *Populus deltoides* clones grew 136 cm in year one and 436 cm in year two (Carlson 1992). The clones were planted from rooted cuttings in plowed, disced and herbicide sprayed land at 1 m x 1 m spacing and were irrigated with effluent water from 29 l min^{-1} sprinklers. A 2000 BC Ministry of Forests extension note stated that poplar grown in the south and mid-coast of BC generally grew 150 cm in the first year and 300-500 cm year $^{-1}$ in the following years (Thomas, Comeau and Brown 2000). A 2010 study of twenty different (20 cm cutting) clones of subsurface-irrigated (1.6 l hour $^{-1}$) poplar trees planted at 1.5 m x 1.5 m spacing in pre-emergent herbicide-treated land in semi-arid Farmington, New Mexico reported a mean height of 120 cm after year one and 340 cm after year two (Shock et al. 2010). The same study also examined twenty-four different (20 cm cutting) clones of subsurface-irrigated (1.6 l hour $^{-1}$) poplar trees planted at 1.5 m x 1.5 m spacing in pre-emergent herbicide-treated land in semi-arid Ontario, Oregon and reported a mean height of 280 cm after year one and 560 cm after year two (Shock et al. 2010). Lastly, a 2017 study reported average height growth of Walker poplar as 60 cm after the first growing season in a plantation located in the Dry Mixedwood Natural Subregion of north-central Alberta (Goehing et al. 2017).

Harsh environmental conditions and the short initial growing season owing to the July planting date may have also affected establishment and growth performance over the course of the study (van Oosten 2006). Among plant responses to resource-poor environments, overall growth and the rate of resource acquisition have been shown to decline as part of a series of integrated physiological processes (Chapin 1991). Periods where this type of stress was highest at the study site would have occurred during the summer months when temperature was at its peak and onsite soil moisture conditions were at their lowest (Appendix A; Figure A.2). In 2016, the period of highest climatic stress occurred in mid-July with average onsite temperatures of 21.0 °C, total monthly precipitation of 20.2 mm, and an average VPD of 1.78 Kpa (Appendix A; Figure A.3). In 2017, the warm, dry period occurred in late July, with an average temperature of 23.9 °C, total monthly precipitation of 3.2 mm, and an average vapor pressure deficit of 2.21 Kpa (Appendix A; Figure A.3). Similar to soil chemical and physical conditions, it is expected that trees with small initial diameters, inadequate root systems or with pre-existing weakened conditions succumbed to the stress of high temperatures and were not able to keep up with high water demand during these periods (Schreiber 2012).

Nutrient availability and overall soil parameters were not found to be too high or too low to be detrimental to the establishment and growth of the poplar trees in the first two years (Terpsma 2016; BCMFLNRO 2016). Overall, soil chemical conditions did not appear to be a major cause of mortality or stunted growth over the two growing seasons. There were no obvious qualitative signs of nutrient deficiencies noted in the experimental trees (e.g. chlorotic leaves, abnormal stem morphology). All clones seemed to respond to these conditions in similar ways in terms of survival and initial growth, except for the Griffin clone, which had very poor survival and initial growth in the site conditions. This was likely due to the small initial size of the cuttings and a failure to put out adequate roots in the cuttings that failed, but it is expected that any soil nutrient deficiencies or sub-optimal soil chemical or texture conditions would have had a larger impact on the already disadvantaged Griffin clones.

Canopy Architecture

Canopy architecture was approximated as an additional indicator of establishment success and growth (Chapin 1991; Wu and Stettler 1998). Trees that had suffered dieback were observed to have diminished canopy architectures (Appendix C; Figure C.3, Figure C.4). As well, a tree with a larger canopy would have more ability to capture resources for growth (Schreiber 2012). A larger canopy would have allowed for better shading of the soil - providing cooler temperatures for delicate roots, better competition with surrounding vegetation and more ability to photosynthesize and store carbohydrate (Schreiber 2012). The most successful Green Giant clones displayed a recurring pattern with the largest initial cutting size, greatest survival, greater height and volume growth and the largest canopy architecture, while Griffin clones displayed the same but opposite pattern with the smallest initial cutting diameter, the poorest survival and growth with the smallest canopy architecture.

Conclusions and Operational Recommendations

Results from the poplar plantation established in southern interior British Columbia indicate that while the engineered microtopography of the MSP treatment consistently improved establishment and growth parameters over the interplanting in the NOMSP treatment, the effect of the improvement was too small to recommend it for future planting in similar conditions. The MSP treatment improved first and second year survival over the NOMSP treatment, showing significant differences detected as main effects between clones and establishment treatments ($p<0.05$), but not as simple effects between establishment treatments for individual clones, while other growth and establishment measures displayed smaller and more variable effects from the treatments over the two seasons. This variability in responses was partially from confounding of height and volume growth results caused by ungulate browsing and partially from conflicting benefits of both treatments. The interplanting method of the NOMSP treatment cost less to implement, resulted in significantly less damage to trees from ungulate browsing, and created fewer disturbed bare soil opportunities for noxious weeds to colonize.

Clonal differences in establishment success between the planted cuttings were overshadowed by physical differences in the quality of the planting stock. Cuttings with larger initial basal diameters outperformed those with smaller initial basal diameters in the first and second growing season. Smaller cuttings were less equipped to deal with environmental stress in the hotter, drier periods of the growing season. They suffered dieback and were less able to put on growth like the larger trees. Despite this, Green Giant clones were found to consistently outperform Griffin clones, emphasizing a greater potential for deployment in semi-arid plantations. Overall, the study highlighted the need to select more uniform cuttings of larger initial size for better survival and establishment in the first two growing seasons in semi-arid plantations.

The findings of this study expand our knowledge of the performance of these poplar clone types in semi-arid regions of BC and contribute to our understanding of their responses to two establishment treatments of differing intensities. Further study over the length of the rotation will give more insight about growth rates and viability of clones in semi-arid conditions. Future studies spanning more years or comparing later stages of the growth of the trees may also indicate more clonal differences in terms of volume growth and canopy architecture. Studies taking place in similar biotic and abiotic conditions should explore more types of intensive establishment treatments, but only on sites where this type of disturbance is environmentally, socially and economically appropriate. If future plantations do make use of more MSP, then fencing or some other means of deterrent should be used to reduce losses to vertical growth caused primarily by deer browse. Conversely, if future plantations do not use MSP because of the marginal effectiveness demonstrated in this study, then future research should seek to better define the beneficial and detrimental aspects of NOMSP interplanting treatments on poplar establishment.

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CHAPTER 4. CONCLUSION

This thesis assessed the effects of two contrasting establishment systems on associated survival and early growth of young trees in a drip-irrigated poplar plantation in a semi-arid environment. The field experiment was established on Skeetchestn Reserve, approximately 40 km west of the City of Kamloops in the southern interior region of British Columbia and was carried out for two consecutive years. Overall, this thesis provided insight into the development of strategies to improve survival and early growth of four young poplar clones under alternative establishment systems and advanced our understanding of operating drip-irrigated poplar plantations in sensitive semi-arid ecosystems.

Discussed in the second chapter are the details involving the design and operation of the water delivery system with the objectives:

1. Estimating seasonal and maximum daily water requirements of 1 and 2-year-old planted poplar cuttings
2. Developing a flexible, robust irrigation system capable of providing accurate, efficient water delivery throughout the 2-year study term and for the length of the crop rotation and
3. Outline the day to day operation of the irrigation system from startup in the spring to shut down in the fall.

Results from the study provided estimates of seasonal and maximum daily water requirements of 1 and 2-year-old planted poplar cuttings, outlined the development of an irrigation system capable of providing accurate, efficient water delivery throughout the duration of the study and described the day to day operation of the system from startup in the spring to shut down in the fall. The findings of this study also expand our knowledge of the performance of microtube emitter drip irrigation systems set up to service poplar plantations in semi-arid regions of BC.

In the third chapter I evaluated the effects of two different establishments systems on tree performance with the objective to:

1. Determine the impact of interplanting versus engineered microtopography on the survival and initial growth of *Populus* cuttings.
2. Quantify a difference in survival and initial growth between the four different *Populus* clones Walker, Griffin, Hill and Green Giant.
3. Determine whether there is an interaction between the different clones and different establishment treatments.

This study offered some evidence that small scale mechanical site preparation did improve survival and initial growth, especially for smaller sized poplar cuttings, but also indicated contrasting effects due to competing benefits in the interplanting method, namely reduced browsing from ungulates and potentially milder microclimates created by existing vegetation during the periods of highest environmental stress during the growing season (Demeritt 1990; Rousset and Lepart 1999; Thomas et al. 2000; Pinno and Belanger 2009). The study also further revealed the importance of selecting cuttings of adequate size, clearly showing improved performance in all parameters assessed with larger initial planting diameters (van Oosten 2006).

Results from this study further demonstrated that the Green Giant, Hill and Walker clones performed similarly to each other in the planting conditions, while the Griffin clones had poorer survival and growth rates in all treatments. The Green Giant, Hill and Walker clones may have greater suitability for deployment in similar plantation conditions in the future. Superior performance of these clones may be attributed to the larger initial size of the cuttings that were planted, greater plasticity of performing well under the site growing conditions and faster initial growth rates (especially in root formation; van Oosten 2006; Harfouche et al. 2007; Zhao et al. 2014).

Future studies spanning more years or comparing later stages of the growth of the trees may also indicate more clonal differences in terms of volume growth and canopy architecture. Studies taking place in similar biotic and abiotic conditions should explore more types of intensive establishment treatments, but only on sites where this type of disturbance is environmentally, socially and economically appropriate. If future plantations do make use of more MSP, then fencing or some other means of deterrent should be used to reduce losses to vertical growth caused primarily by deer browse.

Conversely, if future plantations do not use MSP because of the marginal effectiveness demonstrated in this study, then future research should seek to better define the beneficial and detrimental aspects of NOMSP interplanting treatments on poplar establishment. Further research is needed to collect more poplar physiology data to inform the precise delivery of drip-irrigation water to poplar trees in this environment. Since water conservation was a major objective of the irrigation system, more methods to reduce evaporative water losses should be employed in future work. Future studies of irrigation systems in BC’s southern interior region should count on less water being available for these types of plantations as other uses of the water resource are prioritized.

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APPENDIX A. STUDY AREA

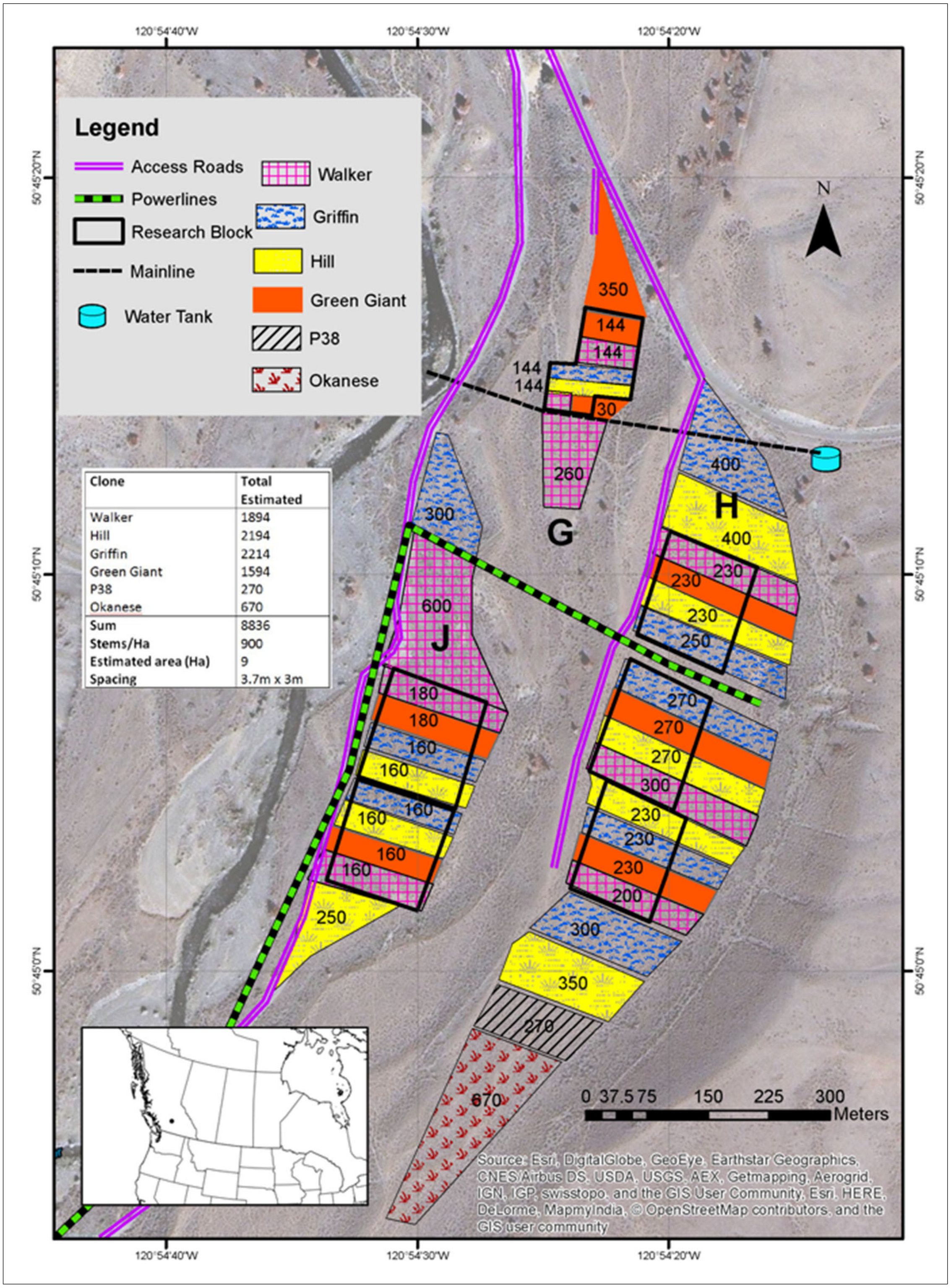


Figure A.1. Experimental plantation layout showing poplar clones arranged according to a randomized complete block design consisting of sixteen replicate plots located within each of the six blocks. Generated using ArcMap 10 software.

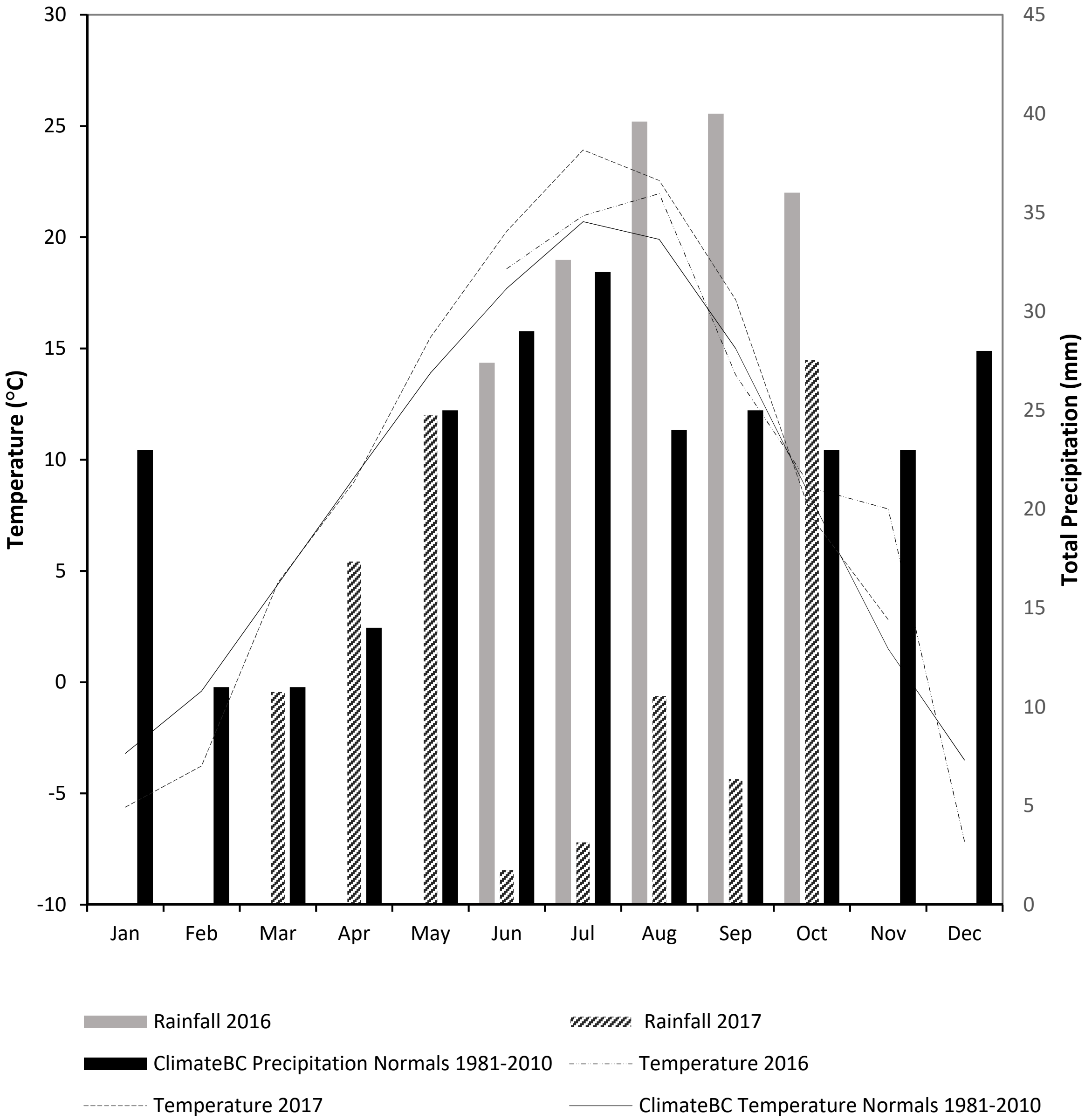
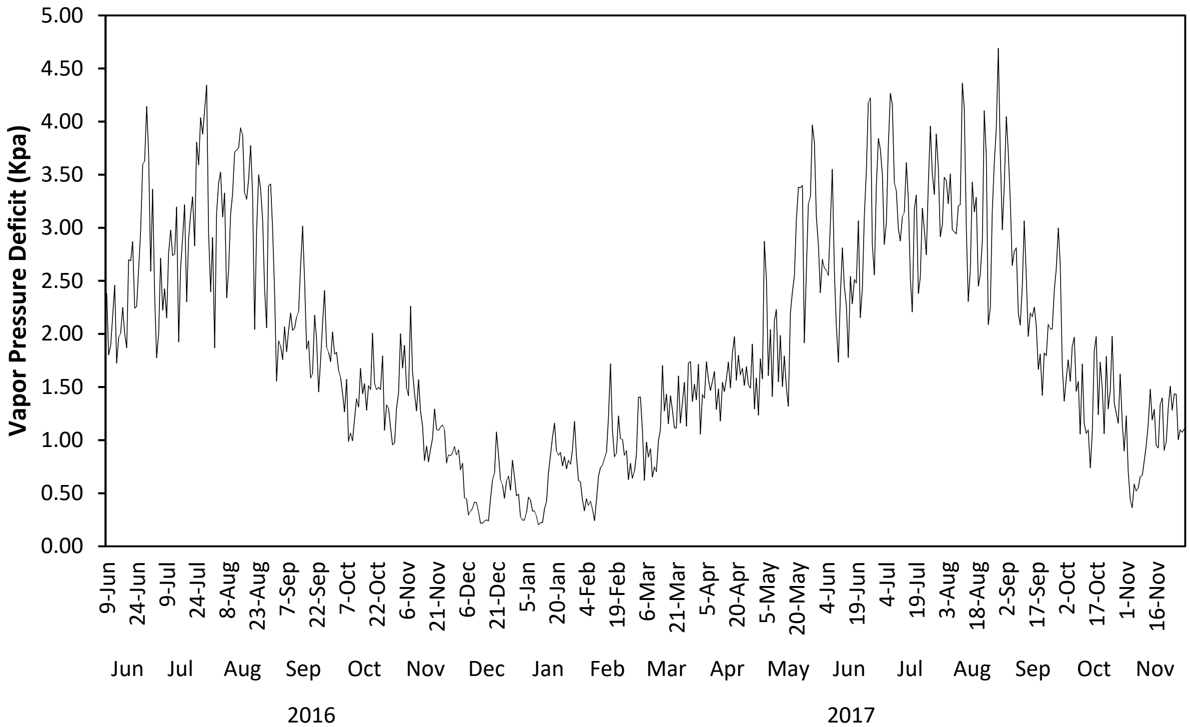


Figure A.2. 2016, 2017 and historic (1981-2010) average monthly temperature (1.3 m) and total monthly precipitation from the Deadman River onsite weather station and ClimateBC. Onsite precipitation removed from weather station dataset winter months.



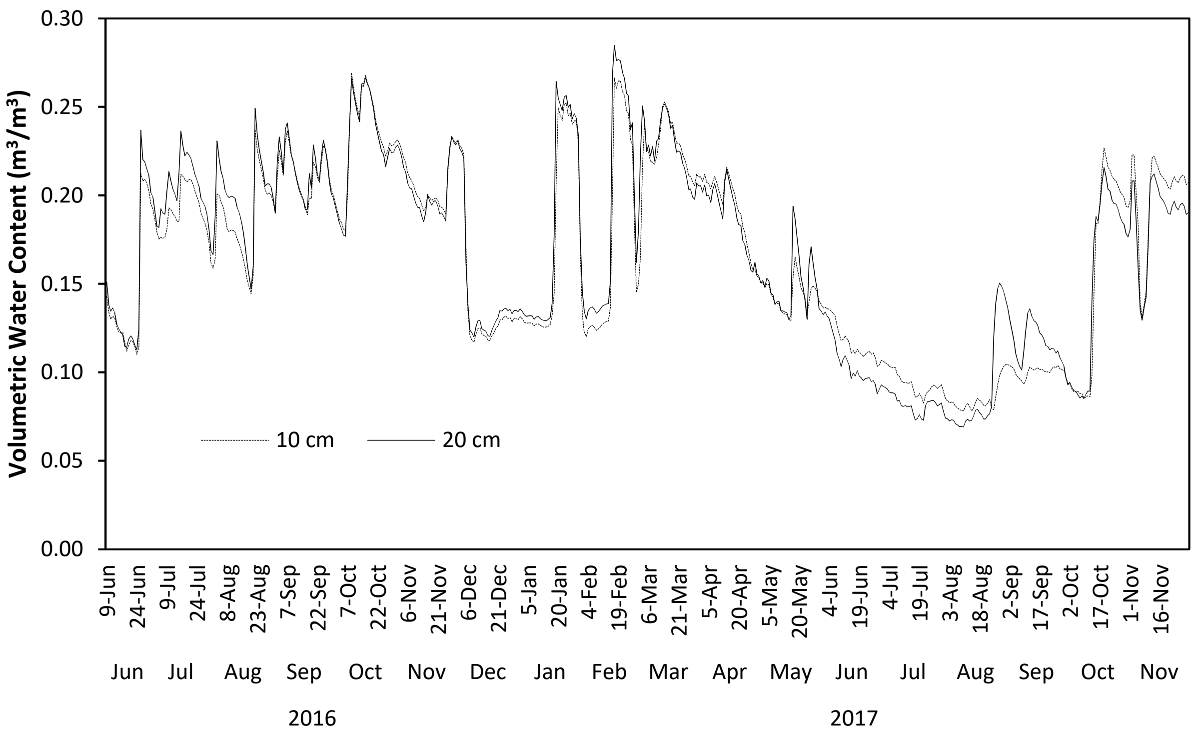


Figure A.3. Maximum daily Vapor Pressure Deficit (VPD) at 1.3 m above ground and average daily soil Volumetric Water Content (VWC) at 10 cm and 20 cm depth from June 2016 to December 2017. VPD calculated from temperature and relative humidity data collected via the Deadman River onsite weather station.

Table A.1. Mineralized nitrogen, available phosphorous, percentage of particles smaller than 2 mm, and soil pH values derived from 58 soil samples sent to the MFLNRO soils lab in Victoria, BC (Terpsma 2016).

Soil Depth (cm)	Mineralizable N (mg/kg)	Available P (mg/kg)	Pass 2mm	pH (CaCl2)
0-15	7.10	14.30	80.00	7.49
16-30	0.70	20.50	76.00	7.81
30+	0.80	3.80	70.00	7.91

Table A.2. Average exchangeable cation and effective cation exchange capacity (CEC) of three different soil depths for selected polygons at the plantation location. Soil analysis was conducted by the MFLNRO soils lab in Victoria, BC (Terpsma 2016).

Soil Depth (cm)	Al	Ca	Fe	K	Mg	Mn	Na	CEC
	(Cmol+/kg)							
0-15	0.006	11.87	<0.001	0.56	2.24	0.002	0.008	14.68
16-30	0.006	8.82	<0.001	0.23	2.25	<0.001	0.015	11.32
30+	0.004	5.83	<0.001	0.32	2.01	<0.001	0.076	8.24

Table A.3. Percentage of ground coverage of each vegetation species recorded at the field site over the entire studied location (Terpsma 2016).

Vegetation Species	% of coverage over entire landscape
Artemisia tridentata	22.95
Bromus tectorum	18.37
Achnatherum occidentale	10.72
Opuntia fragilis	6.82
Dry moss	3.27
Agropyron cristatum	2.42
Chrysothamnus viscidiflorus	2.27
Populus balsamifera	2.25
Centaurea maculosa	0.45
Salix spp.	0.43
Pinus ponderosae	0.28
Amelanchier alnifolia	0.11
Juniperus communis	0.11
Other grasses	10.92
Bareground soil	18.62

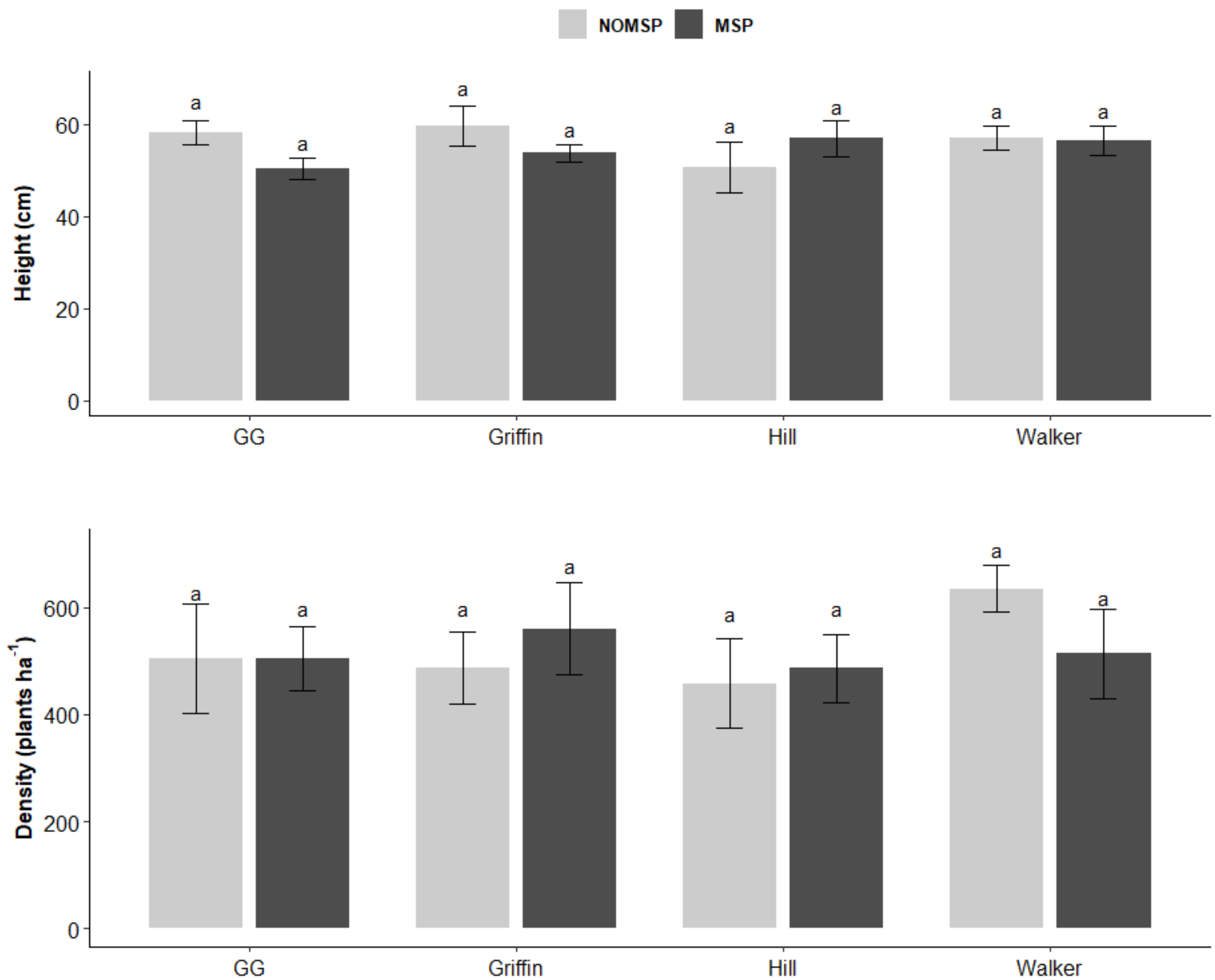


Figure A.4. Average post-planting height and density of *Artemisia tridentata* growing in each plot. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

APPENDIX B. PLANTATION ESTABLISHMENT

Table B.1. Project Budget

Category	Description	Cost
Irrigation	Submains, laterals, fittings	$ 33,500.00
Irrigation	Emitters	$ 5,911.00
Irrigation	Main line	$ 5,900.00
Irrigation	HDPE return line	$ 5,450.00
Irrigation	Poly Tank	$ 2,693.00
Pump	HDPE Drive Pipe	$ 6,540.00
Pump	5 Glockemann ram pumps	$ 11,812.00
Site prep	72.5 hours @$75/hour	$ 5,440.00
Subtotal		$ 77,246.00

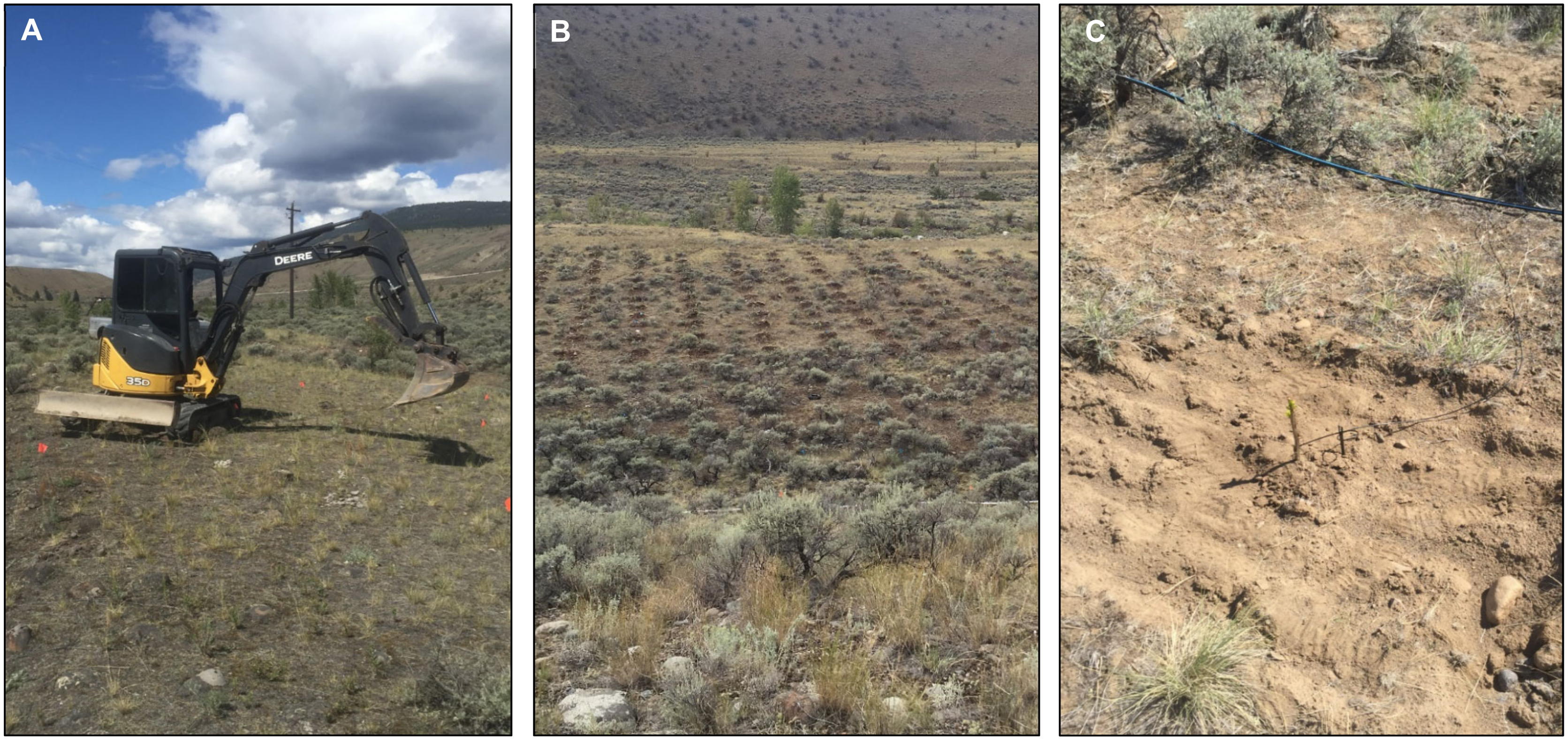


Figure B.1. A) Image of John Deere 35D rubber-track excavator preparing to create an MSP establishment treatment area with the teeth of a rock bucket in block J1 of the poplar plantation on May 16, 2016. B) Image of block G1 of the poplar plantation after completion of the May 2016 MSP treatment and before the July 2016 planting of poplar clones. C) July 2016 image of a recently planted cutting of the Green Giant poplar clone in an approximately 100 cm x 100 cm x 15 cm MSP establishment treatment area in block G1 of the poplar plantation. In the background of the image is a lateral irrigation line made up of 1.27 cm outside diameter polyethylene tubing, feeding into a capillary tube-style emitter of dimensions 0.6 mm internal diameter by 3.35 mm outside diameter.

Figure B.2. A) Image of a 53 cm total height cutting of the Green Giant poplar clone with approximately one month of growth after the July 2016 planting date. The cutting was planted by hand in a NOMSP treatment area in Block J1 of the poplar plantation. B) Image of an example of a Green Giant poplar clone basal diameter measurement at 3 cm with a digital caliper after the end of the 2017 growing season. The cutting was planted by hand in a NOMSP treatment area in Block H2 of the poplar plantation.

APPENDIX C. SURVIVAL AND INITIAL GROWTH OF FOUR POPLAR CLONES

Table C.1. Identity, parentage and section, diameter, height and percent survival of the poplar clones used in the study. Measurements were from June 2016 to November 2017 and standard errors are given in parentheses. Different letters indicate significant differences (p<0.05) between treatments.

Clone	Genus	Female parent species/hybrid	Male parent species/hybrid	Section	Treatment	Diameter 2016 (mm)	Diameter range 2016 (mm)	Height 2016 (cm)	Height range 2016 (cm)	Survival 2016-2017 (%)
Green Giant	*Populus*	*deltoides*	*x petrowskyana (P. laurifolia x P. nigra)*	(Aigeiros x (Tacamahaca x Aigeiros)) x (Tacamahaca x Aigeiros)	NOMSP	14.2 (0.3)ab	12.4-16.3	23.7 (1.1)ab	16.9-27.5	54ab
					MSP	14.5 (0.3)a	12.9-16.4	21.5 (1.1)b	14.4-25.2	68a
Griffin	*Populus*	*deltoides*	*x petrowskyana (P. laurifolia x P. nigra)*	(Aigeiros x (Tacamahaca x Aigeiros)) x (Tacamahaca x Aigeiros)	NOMSP	9.3 (0.2)e	8.6-10.3	24.8 (0.5)a	22.7-27.6	22c
					MSP	9.4 (0.3)e	8.1-10.8	23.0 (0.7)ab	18.9-26.0	41bc
Hill	*Populus*	*deltoides*	*x petrowskyana (P. laurifolia x P. nigra)*	(Aigeiros x (Tacamahaca x Aigeiros)) x (Tacamahaca x Aigeiros)	NOMSP	11.9 (0.3)d	10.4-13.6	22.9 (0.6)ab	19.4-26.0	41bc
					MSP	12.3 (0.4)cd	10.6-14.4	21.9 (0.7)ab	18.4-26.3	56ab
Walker	*Populus*	*deltoides*	*x petrowskyana (P. laurifolia x P. nigra)*	(Aigeiros x (Tacamahaca x Aigeiros)) x (Tacamahaca x Aigeiros)	NOMSP	12.9 (0.4)bcd	11.7-15.6	24.7 (0.4)a	23.2-26.9	44b
					MSP	13.3 (0.4)abc	10.5-16.3	22.5 (0.4)ab	20.6-24.1	59ab

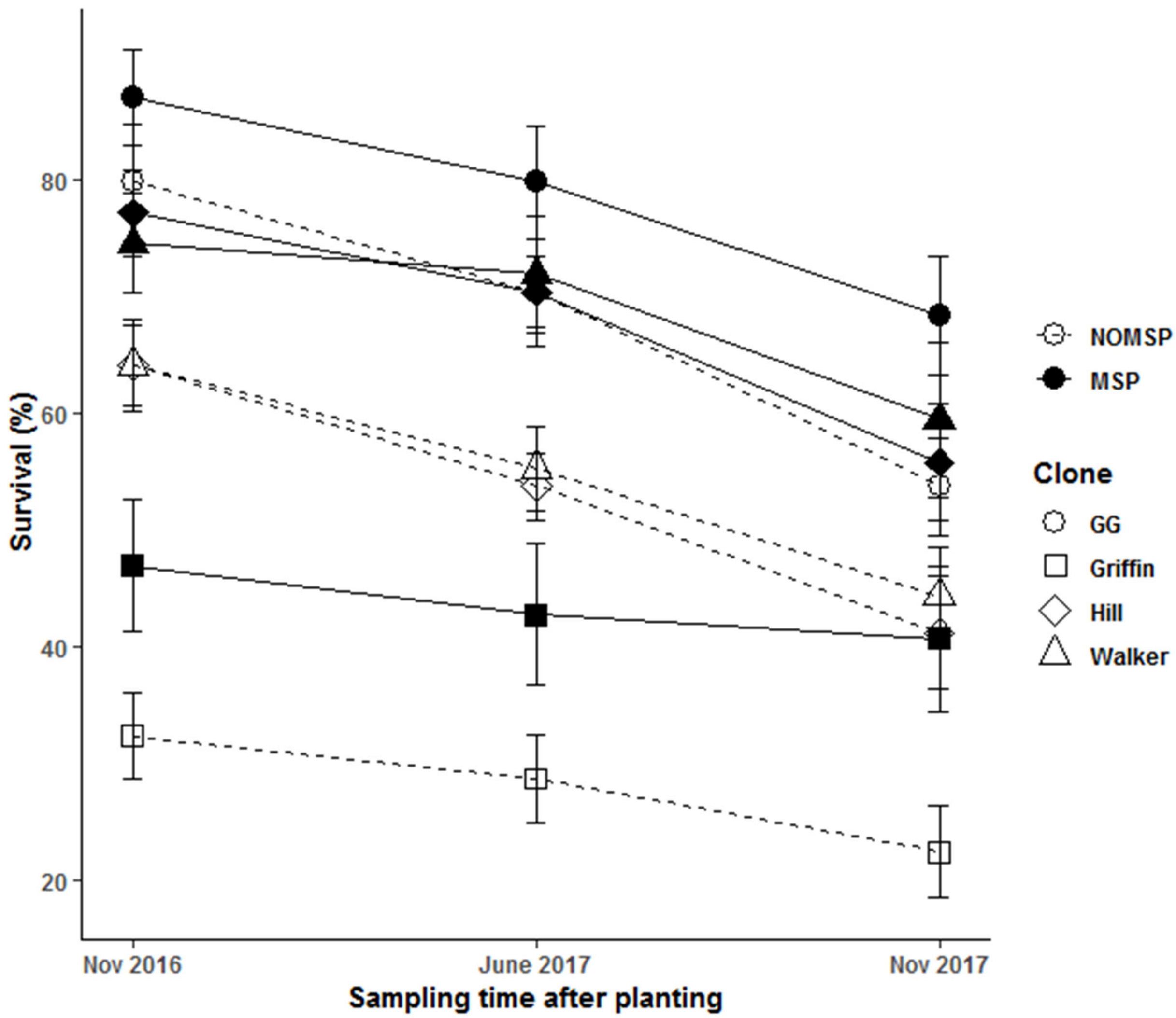


Figure C.1.Tree survival (%) as determined after the first year following planting and at the beginning and end of the second growing season. For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different clones and line types represent standard error.

Table C.2. Total tree survival, diameter, height and volume index across the two plantation establishment treatments for the four clones during each sampling period. Standard errors are given in parentheses. Different lowercase letters indicate significant differences among establishment systems for a given clone and sampling period (p<0.05).

		Clone			
Establishment system	**Variable**	**Green Giant**	**Griffin**	**Hill**	**Walker**
NOMSP	Survival (%)				
	Nov 2016	79.7 (4.93)ab	32.3 (3.68)c	64.1 (3.45)b	64.1 (3.93)b
	Jun 2017	70.3 (4.56)abc	28.7 (3.81)e	53.7 (2.93)cd	55.2 (3.60)bcd
	Nov 2017	53.7 (4.18)ab	22.4 (3.88)c	41.2 (4.83)bc	44.3 (4.25)b
	Diameter (mm)				
	Nov 2016	14.2 (0.33)ab	9.3 (0.17)e	11.9 (0.32)d	12.9 (0.35)bcd
	Nov 2017	15.6 (0.37)a	12.2 (0.63)bc	14.0 (0.50)ab	15.1 (0.48)a
	Height (cm)				
	Nov 2016	41.8 (1.21)a	36.4 (1.22)a	41.0 (1.20)a	41.2 (1.46)a
	Nov 2017	44.3 (2.01)abc	38.4 (2.46)c	48.1 (1.75)a	44.9 (2.11)abc
	Volume Index (dm^3)				
	Nov 2016	0.10 (0.006)a	0.05 (0.005)cd	0.08 (0.005)abc	0.10 (0.009)ab
	Nov 2017	0.12 (0.009)a	0.06 (0.011)bc	0.11 (0.012)ab	0.12 (0.01)a
MSP	Survival (%)				
	Nov 2016	87 (4.10)a	46.9 (5.68)c	77.1 (3.72)ab	74.1 (4.25)ab
	Jun 2017	79.7 (4.87)a	42.7 (6.05)de	70.3 (2.99)abc	71.9 (5.01)ab
	Nov 2017	68.3 (5.07)a	40.6 (6.22)bc	55.8 (5.01)ab	59.4 (6.68)ab
	Diameter (mm)				
	Nov 2016	14.5 (0.27)a	9.4 (0.25)e	12.3 (0.36)cd	13.3 (0.43)abc
	Nov 2017	15.3 (0.35)a	11.8 (0.38)c	14.0 (0.29)ab	15.4 (0.51)a
	Height (cm)				
	Nov 2016	40.0 (1.64)a	36.6 (1.10)a	40.1 (1.30)a	38.5 (1.51)a
	Nov 2017	43.0 (1.67)abc	39.1 (1.54)bc	47.2 (1.5)ab	42.5 (2.17)abc
	Volume Index (dm^3)				
	Nov 2016	0.10 (0.006)ab	0.05 (0.003)d	0.07 (0.004)abc	0.10 (0.008)ab
	Nov 2017	0.11 (0.008)a	0.06 (0.006)c	0.10 (0.005)abc	0.11 (0.01)a

Table C.3. Equations, p's and R^2's, for regressions of diameter versus survival, height increment and volume increment of NOMSP and MSP treatments with blocking factor.

Establishment System	x	y	Equation	p	R^2
NOMSP	2016 Diameter (mm)	Survival (%)			
		Nov 2016	-43.5+8.3x	**<0.001**	0.65
		Jun 2017	-32.4+7.4x	**<0.001**	0.65
		Nov 2017	-19.3+5.8x	**<0.001**	0.58
	2016 Diameter (mm)	Height Increment (cm)			
		Nov 2016	-11.4+2.0x	**<0.001**	0.74
		Nov 2017	-2.0+0.4x	0.07	0.23
	2016 Diameter (mm)	Volume Index Increment (dm^3)			
		Nov 2016	0.04+0.007x	**<0.001**	0.59
		Nov 2017	0.006+0.001x	0.41	0.13
MSP	2016 Diameter (mm)	Survival (%)			
		Nov 2016	-11.7+7.3x	**<0.001**	0.64
		June 2017	-3.9+6.7x	**<0.001**	0.62
		Nov 2017	-9.5+5.2x	**<0.001**	0.60
	2016 Diameter (mm)	Height Increment (cm)			
		Nov 2016	-7.4+1.8x	**<0.001**	0.66
		Nov 2017	-0.8+0.4x	**0.01**	0.33
	2016 Diameter (mm)	Volume Index Increment (dm^3)			
		Nov 2016	0.04+0.006x	**<0.001**	0.63
		Nov 2017	0.005+0.001x	0.06	0.25

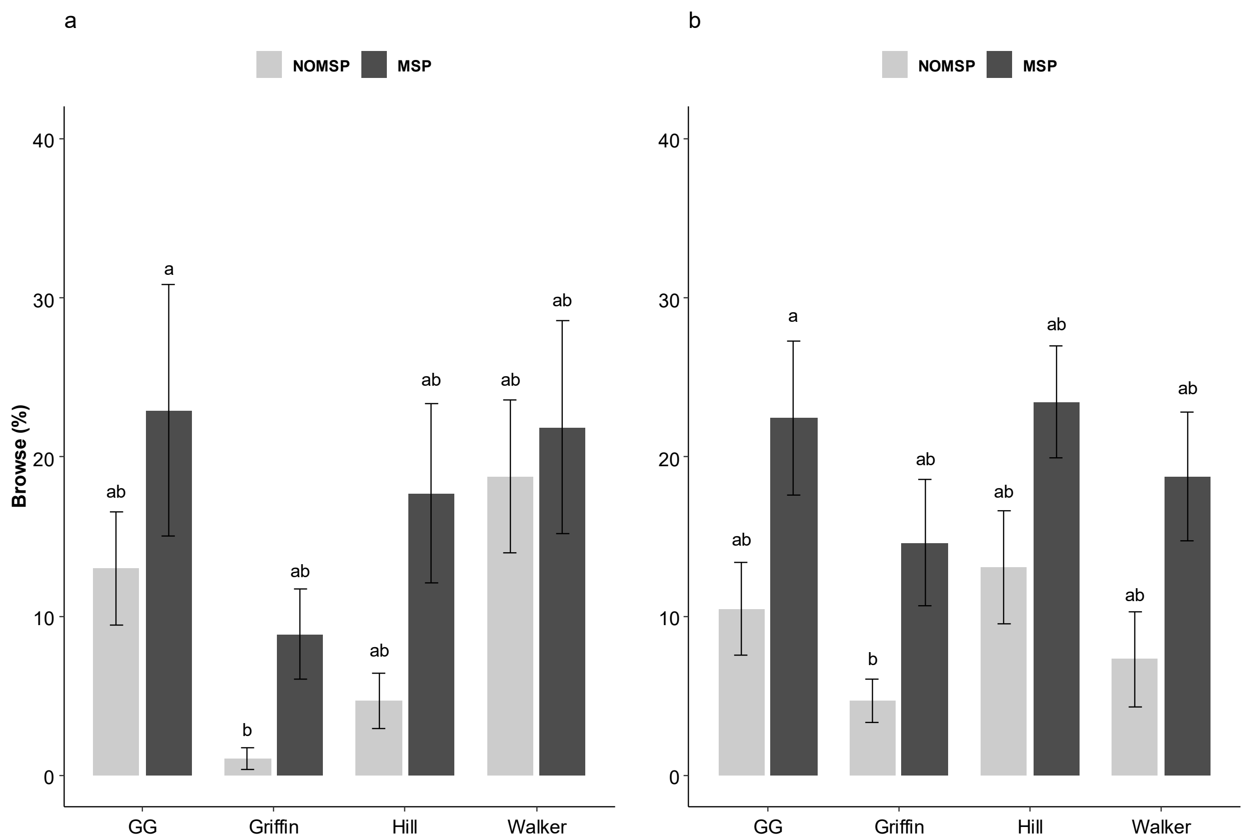


Figure C.2. Frequency (%) of browse over (a) the winter of 2016 and (b) 2017 growing season by deer for each clone and in the different establishment systems. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

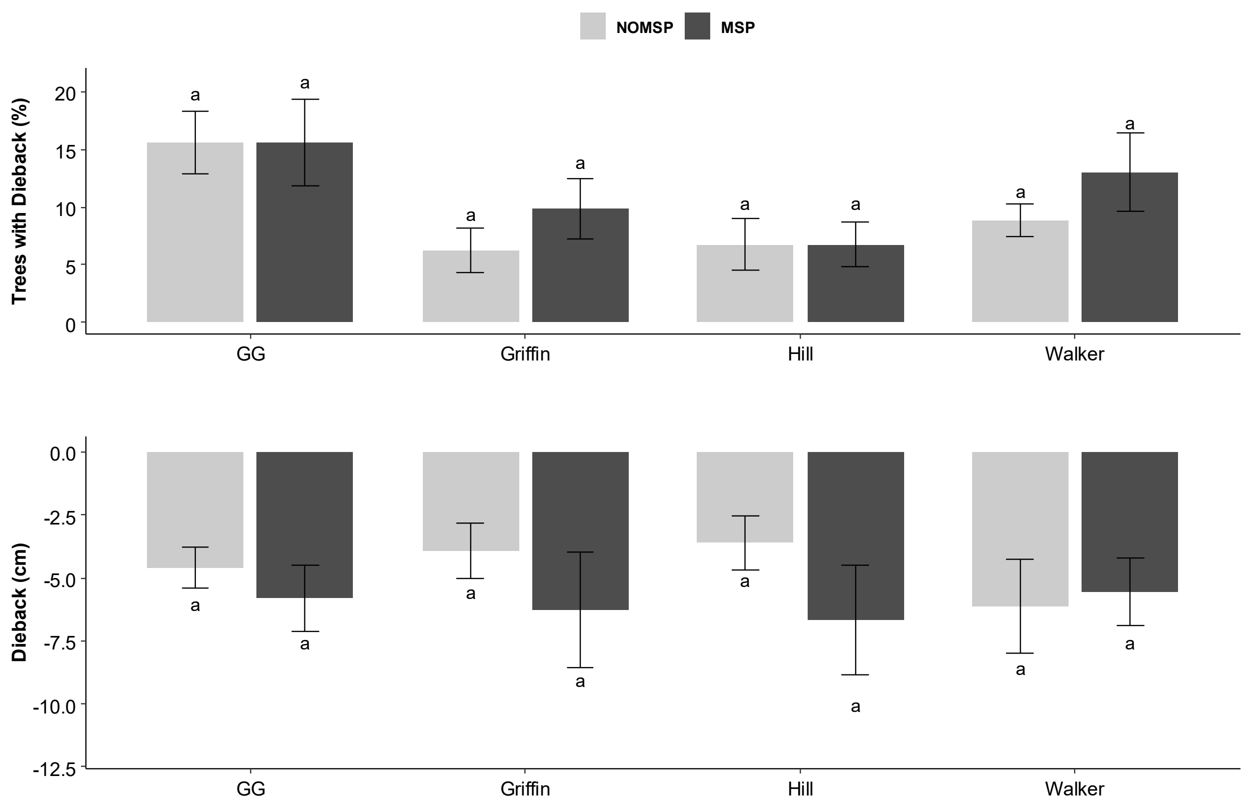


Figure C.3. Frequency (%) and amount (cm) of damage to poplar trees from browse by deer and/or winter dieback for each clone and the different establishment systems for the time between 2016 and 2017 samplings. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.

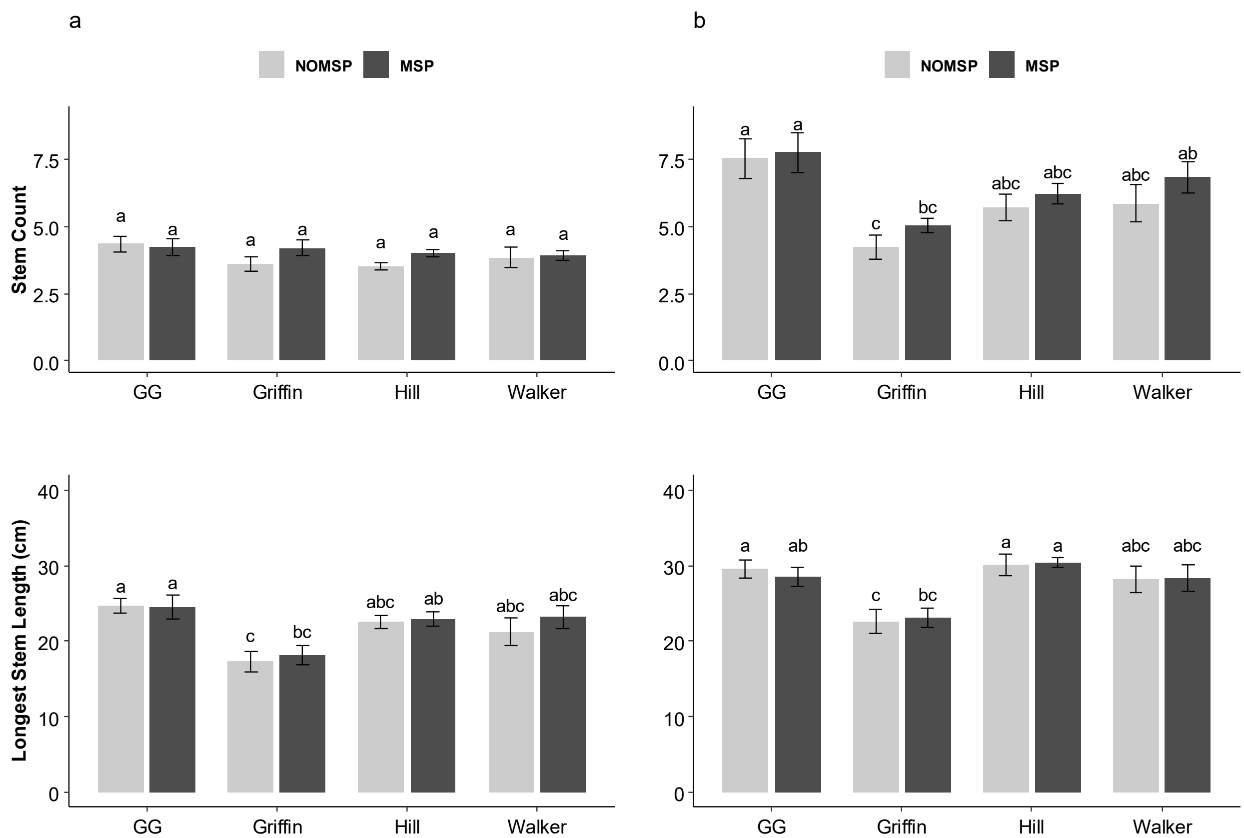


Figure C.4. Mean canopy architecture in the form of stem count and length of longest stem (cm) as determined after the (2016) first year following planting (a) and at the end of the (2017) second growing season (b). For each treatment and clone, each value is the mean of 12 plots. Symbols represent different clones and line types represent different establishment systems. Different lowercase letters indicate differences among treatments for each clone (p-value <0.05). Error bars represent standard error.