Effects of mulch, irrigation, and irrigation gel on the establishment of conifer seedlings at Seattle forest restoration sites

Lisa Anne Ciecko

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

Master of Science

University of Washington

2009

Program Authorized to Offer Degree:
School of Forest Resources

University of Washington
Graduate School

This is to certify that I have examined this copy of a master's thesis by

Lisa Anne Ciecko

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Soo-Hyung Kim

Kern Ewing

Robert Edmonds

Date: ______________________________

University of Washington

Abstract

Effects of mulch, irrigation, and irrigation gel on the establishment of conifer seedlings at Seattle forest restoration sites

Lisa Anne Ciecko

Chair of the Supervisory Committee:
Dr. Soo-Hyung Kim
School of Forest Resources

Seattle's forests are rapidly declining as a result of extensive late 19th century logging that replaced conifers with short-lived broad-leaf species. Natural conifer regeneration has been impacted by non-native plant invasions and confounded by decades of a hands-off management approach. In 2005, recognizing the importance of healthy urban greenspace, the City of Seattle partnered with Cascade Land Conservancy to implement the Green Seattle Partnership (GSP), with the primary goal to restore the ecological health of 2,500 acres of forested greenspace by 2025. GSP has seen variable success with reforestation efforts to date. During initial revegetation at Interlaken Park in 2005 and 2006 seedlings mortality rates exceeded 80%. To improve seedling survivorship and promote long-term restoration success, a study was undertaken to better understand the effects of common plant establishment techniques intended to reduce seedling water stress. Drip irrigation, DriWater irrigation gel, and wood chip mulch rings were tested alone and in combination at two field sites. Three native conifer species commonly planted in GSP restoration efforts were used: *Thuja plicata* (THPL), *Tsuga heterophylla* (TSHE), and *Abies grandis* (ABGR). Distinct survivorship differences were observed between experiment sites and can be attributed to tested differences in soil texture; West Duwamish's clay loam soils provided for adequate soil moisture and high survival rates for all species, whereas Interlaken's sandy loam soils provided for poor soil moisture conditions and corresponding high seedling mortality. Treatment influences for this reason were most pronounced at Interlaken, but were species-specific. In the first year, all mulch treatments increased survivorship for THPL and TSHE, while in the second year ABGR was the only species to benefit from all mulch applications. Survivorship findings parallel stem water potential results in the first summer where TSHE was less water stressed when treated with irrigation and mulch, while ABGR and THPL were less stressed with irrigation alone or in combination with mulch. No clear growth or biomass trends were detected. Recommendations are therefore site and species-specific and must consider final restoration site goals.

Table of Contents

List of Figures

Figure Number

List of Tables

Table Number

Acknowledgements

I would like to thank my committee chair and advisor Dr. Soo-Hyung Kim for his guidance throughout my graduate program. This project would not have been possible without his assistance in experimental design and statistical analysis. I will forever be grateful to him for taking me on as a student and teaching me plant science. I would also like to thank my committee members, Dr. Kern Ewing and Dr. Robert Edmonds for their thoughtful feedback and support.

Many thanks are due to the staff at Cascade Land Conservancy, Seattle Parks and Recreation Department, and Seattle Public Utilities for providing research funding and helping to coordinate the experiment. I am especially indebted to Joanna Nelson, Rory Denovan, and Kate Akuyz for their input and assistance throughout the experiment. It has always been important that this experiment improve future Seattle restoration work; their involvement and thoughtfulness has made that a reality. I would also like to recognize Frank Maduzia and his crew for the incredible work in prepping the sites and planting the seedlings, all while complying with experiment design. In the same vein, much thanks to Chris Behrens for his work in designing and installing the drip irrigation system. Thanks to Jim Day and Restoration Logistics for watering in the first year.

This experiment would not have been half as successful had it not been for the support and input of my lab mates in the Ecophysiology Lab. Special thanks to the original crew, Nicole Hackman, Hannah Kinmoth-Shultz, and Jeff Richardson for all their time and input at the start of the project. More thanks to Nate Hough-Snee, Lloyd Nackley, Chessa Gross, Drew Zwiers, and Royce Anderson for reading drafts and providing feedback. Brandon Neahaus and Ben Peterson deserve special thanks for their field assistance. They provided energy, insight, along with good food and good laughs.

Many more thanks to the graduate student community at the Center for Urban Horticulture for keeping it fun, helping with field work, and always being ready and willing to provide feedback. Special thanks to Eva Detweiller-Robinson, Julie Combs, Laura Blume and Mike Hannam for thesis revision and defense presentation feedback.

And finally, I would like to thank my family and friends for their constant support, willingness to talk it out, keep me fed, and keep it real!

This project was made possible by joint funding from Seattle Parks and Recreation Department, Seattle Public Utilities, and Cascade Land Conservancy. Funding of this document does not constitute an endorsement of its content by the Cascade Land Conservancy or the City of Seattle government, its employees, or elected officials.

1.0 INTRODUCTION

1.1 Seattle's Forests

Comprehensive vegetation mapping conducted by the Seattle Urban Nature Project in 2000 captured an alarming trend in Seattle's forests. The assessment found that much of the City's forested lands are dominated by a canopy of deciduous broad-leaf tree species that are reaching the end of their lifespan (Ramsay et al., 2004). Seattle's senior urban forester confirmed that within in the next twenty years the city is in danger of losing 70% of its tree canopy (Weaver, 2005).

Current forest conditions are a result of a century of human influence. Clear-cut logging spurred by European settlement in the late 1800's dramatically reduced conifer forests in the Puget Sound region. Areas that remained undeveloped by settlers were colonized by broadleaf species like *Alnus rubra* (red alder) and *Acer macrophyllum* (big-leaf maple) that survive for up to 100 and 300 years, respectively (Franklin and Dyrness, 1973). Natural conifer regeneration to replace aging pioneer species has been highly confounded by the establishment and spread of non-native invasive plants. These species make up at least 50% of the understory cover on at least half of the City's forested lands, with 456 acres of habitat characterized as deciduous forest being described as "very highly" invaded (Ramsay et al., 2004). Species like *Hedera helix* (English ivy), *Prunus laurocerasus* (cherry laurel), and *Ilex aquifolium* (English holly) effectively out-compete seedlings for space, light, nutrients, and water (Weiner and Vila, 2004; Boersma et al., 2006). *H. helix* and other climbing vines add weight to trees and increase wind-throw, exacerbating the loss of older trees (Swearingen and Diedrich, 2006).

The benefits of a large canopy trees and greenspace in urban areas are far-reaching. Urban forests provide ecosystem services in close proximity to human activities and environmental impacts. Through gas exchange and particulate matter interception, trees improve air quality; one mature tree can capture up to 50 pounds of particulates in a year (Dwyer, 1992). Impermeable surfaces like roads and roofs influence a city's hydrology, but trees can help mitigate the impact by intercepting rainfall, allowing for increased water infiltration and reducing erosion and runoff (Weaver, 2005). Similarly, canopy cover can positively influence temperatures through shading, evaporative cooling, and wind reduction (Codder, 1996; Harris et al., 2004). Other ecological benefits include increased biological diversity, noise buffering, and carbon sequestration. The social and economic benefits of urban greenspace are numerous. Research suggests people living in close proximity to greenspace experience emotional health improvements, more recreational opportunities, and increased real estate values (Dwyer et al., 1992; Wolf, 1998; Harris et al., 2004).

Despite the many positive ecological, social and economic benefits, forest conditions within the city of Seattle have been poorly managed; the assumption for the last century being that forested areas would take care of themselves. Until the mid-1990's little if any budget or staffing resources were allocated for urban forest restoration. A significant shift in management theory now recognizes that human impacts require human involvement (Weaver, 2005).

1.2 Green Seattle Partnership

The city of Seattle partnered with the Cascade Land Conservancy in 2005 to implement the Green Seattle Partnership (GSP) with the primary goal of addressing the ecological health of Seattle's forested public lands. The program uses trained volunteer forests stewards, community members, park staff, and contracted crews to complete restoration on forested lands throughout Seattle. GSP's "treeage" strategy targets restoration sites based on habitat quality, non-native invasive plant cover, and conifer distribution. The 20-year strategic plan published in 2005 outlines the aim to restore 2,500 acres of public forests by 2025, positioning GSP as the nation's largest urban forest restoration program (Weaver, 2005). The GSP model has been adopted by other Puget Sound municipalities, including Kirkland and Tacoma. Large Pacific Northwest cities have also increased efforts to control invasive species and improve greenspace health.

The city of Seattle, private foundations, and donors have provided significant resources for the both the organization and implementation of the GSP program. Unfortunately several key restoration sites, including Interlaken Park, have experienced high conifer seedling mortality (> 80%), threatening the foundation of GSP's efforts to reestablish Seattle's conifer canopy. The program cannot achieve full success if it continues to expend money and human energy only to realize limited tree survivorship. The ecological and social importance of urban forests, combined with the expansion of restoration efforts regionally, and the associated labor and costs, make it especially necessary to understand how we can increase planting success.

1.3 Experiment Objectives

This experiment was initiated in fall 2007 to address the extensive failure of transplanted seedlings at Interlaken Park and to assure the success of future GSP restoration efforts. The objectives of the experiment were as follows:

- To test the influence of three common cultural methods, mulch, drip irrigation, and irrigation gel DriWater on the survivorship and growth of three native conifer species, *Thuja plicata* (western red cedar), *Abies grandis* (grand fir), *and Tsuga heterophylla* (western hemlock)
- To test the influence of the three cultural methods on water stress levels for each species during summer drought conditions
- To characterize environmental conditions, including soil chemical and physical properties, soil moisture levels, slope, and canopy cover found in two parks in Seattle, WA

2.0 BACKGROUND

Addressing seedling mortality in Seattle parks requires understanding the multitude of factors that influence seedling establishment. An expansive body of knowledge on conifers exists, including information on transplant stress, species distribution, drought resistance, and materials and methods available to improve planting success. However, gaps in the research exist that limit its direct application to forest restoration in Seattle. The following review is intended to bring together silviculture, horticulture, and agriculture literature and to understand its relevance in the comparably young field of restoration.

2.1 Transplant Stress

Conifer seedlings planted as part of reforestation efforts experience numerous physiological stressors, known as transplant stress. The process of lifting bareroot seedlings from growing fields, storing in refrigerated lockers, transporting, and then planting them in a new environment creates unavoidable stress, even under the best conditions (Reitveld, 1985). A seedling's long-term success depends heavily on its ability to grow new roots to overcome the root loss and the limited soil-root contact that results from transplanting (Kozlowski and Davies, 1975; Sands, 1984; Grossnickle, 2005).

Internal water status and carbon balance affect a seedlings ability to rapidly regenerate roots. Because seedlings continue respiration and cell maintenance during the period between being lifted from the growing field and transplanted at a new site, carbohydrate reserves are often depleted even before the seedling has reached the planting location (Reitveld, 1989; Grossnickle, 2005). With a small root system and reduced soil contact, a seedling can experience water deficits that trigger stomatal closure and restrict photosynthesis. Low levels of carbohydrate reserves at the time of planting and reduced carbon assimilation after planting can mean that seedlings quickly use up energy and die (Burdett, 1990).

Morphological traits contribute to a seedling's ability to succeed in transplant conditions. Nurseries manipulate seedling morphology through irrigation, fertilization, and planting practices. Bud dormancy can be adjusted to reduce desiccation potential, while increasing root collar diameter can improve seedling vigor. Balancing the root:shoot ratio may help account for shoot water needs once onsite (Ritchie and Dunlap, 1980; Duryea, 1985; Arnott et al., 1988; Burdett, 1990). But quality material appropriate for site-specific conditions is often difficult to find (Maduzia, 2008).

Once transplanted, site conditions play an equally important role in seedling success. Soil physical properties influence water movement and nutrient availability in addition to root penetration, aeration, and soil temperatures (Sutton, 1991). Available soil moisture must be adequate to meet the atmospheric demand for water otherwise seedlings will close stomata to reduce evaporative water loss (Grossnickle, 2005). Without appropriate conditions, seedlings will be unable to access a site's resources, increasing transplant stress (Reitveld, 1989).

2.2 Species Distribution and Site Preferences

This experiment looks at three conifer species native to the Pacific Northwest that are frequently used in greenspace restoration: *Tsuga heterophylla* (TSHE), *Thuja plicata* (THPL), and *Abies grandis* (ABGR). Their respective distribution and growth preferences can inform our understanding of how each species might respond to being planted at Seattle reforestation sites.

Species distribution is often a function of moisture conditions. TSHE occurs from coastal Alaska to northern California, inland along the western and eastern slopes of the Cascade Mountains and in the northern Rocky Mountains (Teskey, 1992b). The Puget Sound basin supports TSHE because of its maritime climate, with moderate temperatures, high annual rainfall, and limited summer precipitation (Franklin and Dyrness, 1988). THPL follows a similar distribution to TSHE and occupies moist sites, including riparian zones and seepage sites in drier climates (Teskey, 1992a). ABGR has a divided distribution; found from coastal British Columbia to northern California and in the interior east of the

Cascades. It is known to grow well in a variety of habitats, from dry sites to riparian areas, but is moisture limited in its southern distribution (Howard et al., 2000). In western Washington, ABGR is primarily a lowland species and occurs sporadically, growing in river valleys and areas with high ground water. In this region it is associated with TSHE, THPL, *Pseudotsuga menziesii* (Douglas-fir), *Picea sitchensis* (Sitka spruce) and deciduous trees like *A. macrophyllum* and *A. rubra* (Burns and Honkala, 1990; Franklin and Dyrness, 1988).

For all three species, partial shade conditions are preferred during the seedling establishment phase. TSHE seedlings are highly tolerant of shade and as such have shallow root growth and no taproot development (Burns and Honkala, 1990). Root penetration and growth rate are better for THPL than that of TSHE, allowing for successful establishment on dry sites. THPL's preference for shade is necessitated by the fact that full sun often causes severe sunburn on the upper foliage of seedlings (Burns and Honkala, 1990). ABGR's initial deep root penetration is thought to make it effective at avoiding drought. Compared to TSHE and THPL on wetter sites, ABGR taproot grows deeper and faster. Heavily shaded conditions limit initial root growth, which can cause stress or mortality when shallow soils dry out, making partial shade preferred on most soil types (Burns and Honkala, 1990).

2.3 Drought Stress

For planted seedlings already experiencing transplant stress, summer drought conditions common in the Pacific Northwest can exacerbate seedling mortality (Livingston and Black, 1986). Although known for rain, Seattle experiences an extended dry period starting in late spring, climaxing in mid-summer, and often lasting through early Autumn, with precipitation uncommon for two to four week periods (NOAA, 1985). The success of Pacific Northwest conifer forests, both in their longevity and the amount of biomass produced, is a result of each tree's ability to adjust to drought conditions. As an example, as much as seventy percent of annual net photosynthesis by established conifers occurs outside of the summer growing season (Waring and Franklin, 1979). Although native conifer species have developed mechanisms to resist drought, transplanted seedlings fall victim to drought stress for many of the same reasons that they are susceptible to transplant stress.

Failure to respond to drought stress can result in the decline of plant processes, including stomatal conductance, CO_2 assimilation, turgor pressure, cell development, and protein synthesis (Hsiao et al., 1976). Such a decline can cause physical injuries, including branch drop, needle senescence, and xylem cavitations. During drought stress, xylem tension can increase to the extent that a conduit breaks, allowing in air and effectively restricting water flow in the plant (Tyree and Sperry, 1988; Lambers et al., 2008).

Each species has a different level of drought resistance and employs different mechanisms to avoid or tolerate drought conditions. Avoidance methods reduce the degree of stress by adjusting physiological functions and morphological features to accommodate limited water availability (Nilsen and Orcutt, 1996). This can include adjusting stomata aperture to reduce water loss. Drought tolerant species, on the other hand, are able to endure restricted moisture conditions, often keeping stomata open longer, allowing for continued photosynthesis and growth (Hinckley et al., 1982). Table 1 compares the drought resistance of Pacific Northwest conifer species, suggesting that ABGR has greater resistance than THPL, which has greater resistance than TSHE.

Table 1. Drought resistance of common Pacific Northwest conifers ranked from high resistance to low resistance. Experiment species are included in bold. Adapted from Hinckley et al. (1982).

Resistance	Species
High	*Quercus garryana*
↓	*Quercus kelloggii*
	Pinus jeffreyi
	Pinus ponderosa
	Libocedrus decurrens
	Pseudotsuga menziesii; Pinus contorta
	Picea engelmannii
	Abies grandis
	Pinus lambertiana; Larix occidentalis
	Abies lasiocarpa; ***Thuja plicata****; Pinus monticola*
	Abies concolor, Picea breweriana
	Chamaecyparis lawsoniana; Abies procera
	Tsuga heterophylla*; Picea sitchensis*
	Abies amabilis
Low	*Abies magnifica; Tsuga mertensiana*

Reforestation efforts with TSHE often see high rates of seedling failure, confirming TSHE's low drought resistance. Livingston and Black (1987) experimented with methods to reduce water stress in TSHE on a clear-cut logging site on Vancouver Island, British Columbia. Low survival even in shaded and irrigated conditions led the authors to conclude that TSHE seedlings lack the stress tolerance mechanisms necessary to deal with drought conditions. In similar research in Oregon's coastal mountain range, Kavanagh and Zaerr (1997) explored newly planted TSHE seedling susceptibility to water stress. As is common in other woody plants, minor branches and needles were sacrificed to reduce leaf area and respond to low water potential conditions. Xylem cavitation events were frequent when water potential declined past - 2.5 MPa, affirming that water stress attributable to the limited root systems of transplanted seedlings quickly causes physical injury that can have lasting effects on TSHE's hydrologic conductivity.

Comparing TSHE and THPL suggests interesting differences in each species physiological response to drought conditions. THPL and TSHE seedlings planted on a clear-cut site in coastal British Columbia responded differently to high vapor pressure deficit (VPD) conditions (Grossnickle, 1993). High VPD levels translates to increased atmospheric water demand and requires plants to access water from their roots or close stomata and reduce carbon assimilation (Nilsen and Orcutt, 1996). As the VPD increased throughout the summer, both species experienced a parallel drop in maximum CO_2 assimilation, but THPL maintained an assimilation rate twice as high as TSHE, indicating an ability to continue photosynthesis at a wider range of water stress conditions. Growth measurements followed similar patterns with THPL maintaining shoot growth while TSHE ceased growing during late summer drought conditions.

Although no research comparing ABGR to TSHE or THPL exists, physiology research provides a picture of ABGR's response to water deficits. Hinckley et al. (1982) confirmed that ABGR relatively high drought resistance is a result of employing both avoidance mechanisms (i.e., stomata closure) and tolerance mechanisms (i.e., maintenance of positive turgor pressures for growth and photosynthesis). However, differences in stomatal reactions to water stress were documented in natural populations of ABGR in the central Oregon Cascades (Zobel, 1974). Populations west of the Cascade crest experienced lower xylem pressure potential than east side populations, indicating that west side populations were less adapted for water stress conditions. Zobel (1974) suggested that this difference is due in part to greater canopy leaf area in western Oregon stands. Lower and higher elevation populations showed equivalent differences in stomatal reaction to water stress, with xylem pressure potential triggering stomatal closure more rapidly at lower elevation sites. The varying response across populations is an important reminder of genotypic differences. Similarly, research on ABGR's limited physiological function in response to wounding during drought conditions reminds us that the species' ability to manage drought can be reduced under the multiple stressors common at restoration sites (Lewinsohn et al., 1993)

2.4 Methods to Reduce Stress

By understanding the physiological response of conifer seedlings to water stress we can better understand the materials and methods needed to improve survivorship at restoration sites. Wood chip mulch, drip irrigation, and irrigation gels have the potential to improve soil moisture conditions, but previous research suggests varied success due to species- and site-specific responses. This is complicated by the variety of available materials and the multitude of application methods. Because of the labor and costs associated with mulch, irrigation, and irrigation gel, it is imperative to understand what influences their effectiveness.

The benefits of using mulch to establish and maintain plantings are recognized across disciplines concerned with plant health. Mulch refers to organic materials (i.e., compost, wood chips, sawdust), inorganic materials (i.e., gravel and lava rock), or plastic materials (i.e., landscape fabric) applied to the soil surface, as opposed to being incorporated into the soil (Chalker-Scott, 2007). The effectiveness of mulch varies widely by material, so the focus here will be organic materials, specifically coarse arborist wood chips, commonly available and used in Seattle forest restoration. Mulch can conserve moisture, suppress weeds, improve long-term soil structure, reduce disease, and increase seedling survivorship (Harris et al., 2004).

Mulch may improve moisture conditions for newly planted seedlings by reducing evaporative water losses, moderating temperatures and limiting weed competition for soil moisture. Harsh temperature and soil moisture conditions in Mexico identified as factors limiting the establishment of *Pinus pseudostrobus* (smooth-bark Mexican pine) were improved in plots mulched with local pine bark, resulting in greater survival and tree height (Blanco-Garcia and Lindig-Cisneros, 2005). Appleton et al. (1990) confirmed that organic mulch over bare ground can buffer temperatures, making fall and winter soil temperatures warmer and decreasing spring and summer extreme temperatures. At a Seattle restoration site, Cahill et al. (2005) saw more weed suppression from wood chip mulch than herbicide application, increasing *Symphocarpus albus* (common snowberry) seedling survivorship and allowing for early reproduction.

Although clear benefits of mulching exist, the variety of materials and application methods strongly impact effectiveness. With Seattle Park Department wood chip mulch sourced from an indeterminate number of tree species and locations, chemical composition, allelopathic effect, and weed contamination are important considerations (Duryea, 1999; Chalker-Scott, 2007). In terms of application methods, shallow mulches (less than 7.6 cm or 3 inches) have been shown to promote weed growth (Kuhns, 1992). Greenly and Rakow (1995) found that while increasing application depth from 7.5 cm to 25 cm (2.95 - 9.84 inches) reduced weed density and improved soil moisture conditions, the deeper mulch created temperature conditions that significantly limited lateral root development and overall tree growth. The diameter of a mulch ring may also be important to growth as suggested by research on deciduous tree regeneration in Belgium that saw a significant correlation between the Relative Growth Rate (RGR) and the diameter of the mulched area surrounding the trees (DeVos, 2002). Both the varied effects of mulch and the fact that no published research exists on the use of mulch in the context of conifer restoration in Seattle forests make this research especially necessary.

Like mulch, irrigation can improve tree establishment on sites where transplanted seedlings would otherwise fail because of difficult conditions like droughty soils (Harris et al., 2004). Irrigation systems are common in maintained landscapes, but become more complicated in the context of restoration. A water source, budget restrictions, and site goals often influence the use of irrigation (Alexander, 2009). Moreover, because its effectiveness is highly dependent on species needs and sites conditions, usefulness varies.

Several experiments substantiate the drawbacks of irrigation use at restoration sites. Irrigation improved survivorship for TSHE seedlings at a logged site on Vancouver Island, British Columbia. Still, mortality rates remained high and findings confirmed that irrigation is only effective in reducing stress if water amounts are adequate for the site conditions (Livingston and Black, 1987). Hau and Corlett (2003) add that the influence of irrigation on seedling survivorship and growth varies dramatically by species. Increases in weed cover instead of desired plant species is a common result of irrigation use at restoration sites. Devine (2007) found that *Quercus garryana* (Oregon white oak) seedlings increased growth in the first year with irrigation, but only when coupled with plastic mulch that limited competition with herbaceous vegetation. Research conducted during restoration of abandoned farmland near Phoenix, AZ found that sprinkler irrigation increased plant cover, but seeded native species only increased to 4% cover, while weed species increased to 50% cover (Banerjee et al., 2006). The cost, logistics, and varied outcomes associated with using an irrigation system in revegetation efforts can be prohibitive, but irrigation remains a key tool to improve plant water relations and increase immediate root develop. Inherently, irrigation should be assessed for use in Seattle urban greenspace restoration.

The challenges associated with irrigation have driven the development of alternative products, including irrigation gels. Although several products exist, most are polyacrylamide hydrogels that are not favored for use in natural systems (Holliman et al., 2003). The product sold by Rainbird under the name DriWater© is a poly cellulose gel made up of 98% water and 2% food grade ingredients, making it environmentally safe. Water becomes available to the target plant when common soil microorganisms decompose the gel. The rate of water release is a factor of the amount of soil the gel is in contact with, as well as existing soil water content and microbial activity as influenced by temperature (DriWater, 2009).

Although DriWater irrigation gel is gaining popularity, very little research exists on its effectiveness. The only published experiment compared the influence of DriWater and tap water on greenhouse grown *Rhododendron indicum* (Satsuki azalea) survivorship (Dellavalle, 1992). Survival was comparable, leading the author to conclude that the DriWater label claims were substantiated. However, had the production goal been rapid growth, the product would have not been appropriate; growth was significantly slower with DriWater treated plants. The DriWater website provides case studies from several municipalities, contractors, and nurseries that imply plantings succeeded because of the use of DriWater. No information on scientific peer-reviewed experiments is provided on the website (DriWater, 2009). Similarly, Harris et al. (2004) suggest that DriWater is being used successfully in landscape projects, but do not offer information on published case studies.

The only case study with comparable site conditions and species was an unpublished experiment that used DriWater cartons at a restoration site on Mercer Island, WA (Stuckey, 2007; Peterson, 2008). Analysis after two growing seasons found that DriWater did not increase survivorship, height, or diameter. Because the cartons were installed in late December at the time of planting and likely released water over a 90 day period when high precipitation is common for the western Washington lowlands, the irrigation gel may have had little effect. Peterson (2008) stated that the use of DriWater during mid-winter was intended to reduce immediate transplant stress, but acknowledged that the choice to install the product at the time of planting was more an issue of budget restrictions and crew availability. Further research on the potential for improving conifer establishment in urban greenspace restoration using DriWater must consider appropriate application dates. Much like mulch and drip irrigation, the irrigation gel DriWater may provide critical soil moisture for transplanted conifer seedlings, but research specific to Seattle greenspace restoration is necessary to validate the cost and labor associated with each method.

3.0 METHODS

3.1 Experiment Locations

The experiment was located at two parks in Seattle, Washington: Interlaken Park on the north slope of Capitol Hill and West Duwamish Greenbelt adjacent to the south Seattle industrial district (Figure 1). Both locations are managed by Seattle Parks and Recreation Department. Previous restoration efforts, space availability, and scheduled invasive plant removal were the main considerations in location choice. Experiment blocks within each park were sited with help from Kate Akyuz, former Seattle Urban Forester, and Joanna Nelson, Green Seattle Partnership Project Manager.

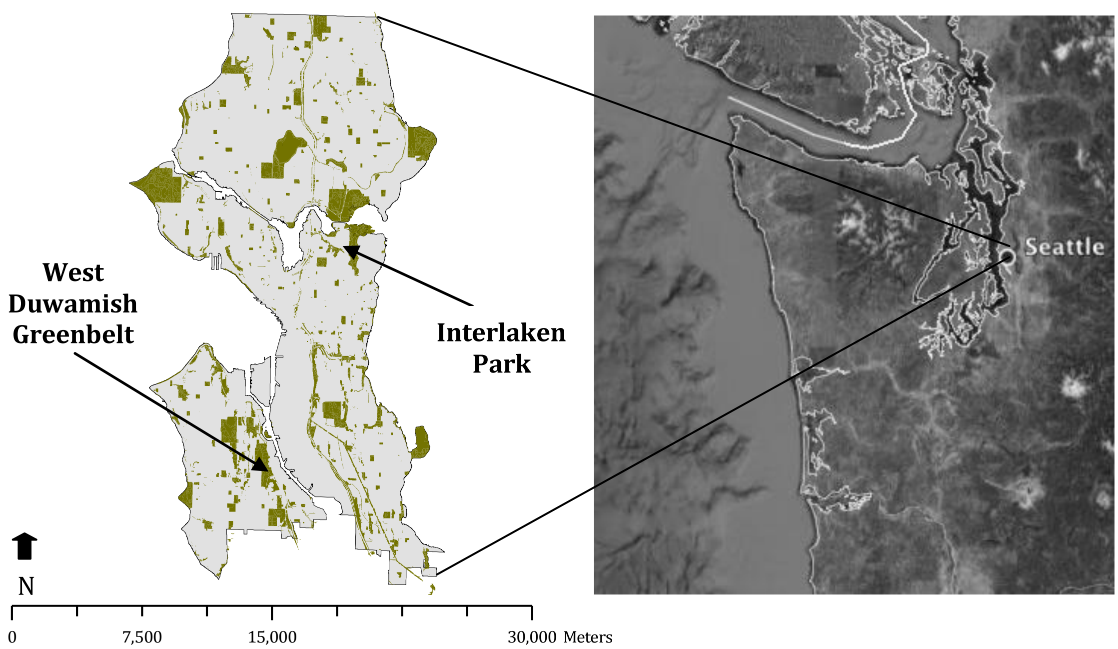

Figure 1. Map of Seattle (left) with Seattle Parks and Recreation property highlighted in green (ArcMap 9.3, ESRI Inc, Redlands, CA) and an image of western Washington State (right) (Google Earth 4.2, Image © 2009 Tele Atlas, Google, Europa Technologies).

Interlaken is a 20.9-hectare (51.7-acre) park that was developed in 1903 as part of the Olmstead Brothers boulevard system (Seattle Parks and Recreation, 2009). Because of the configuration of the park and proximity to neighboring home gardens, it is heavily impacted by a number of non-native and invasive plant species. Common among them are

Prunus laurocerasus (cherry laurel), *Hedera helix* and *H. hibernica* (ivy), *Ilex aquifolium* (English holly), and *Clematis spp.* (Clematis). The area was heavily logged in the late 1800s (McIntosh, 2009). Although there are several areas with large conifers, much of the park is dominated by an aging stand of deciduous trees, including *A. macrophyllum* and *A. rubra*. The Seattle Urban Nature Project (SUNP) Habitat Map (2000) describes the two areas of the park where the experiment blocks are located as being deciduous forest with dominant trees ranging in diameter from 38.1 – 50.8 cm (15 – 20 in)(Seattle Urban Nature Project, 2000a).

West Duwamish Greenbelt is Seattle's largest greenspace, totaling 73.5 hectares (181.6 acres) and stretching south from the West Seattle Bridge along the east slope of West Seattle and White Center, adjacent to the Duwamish River channel and industrial district. The experiment blocks are located where the greenbelt intersects Highland Park Way. The area was logged entirely of its conifer canopy in the early 1900s. Canopy trees at the experiment site include *Populus balsamifera* (black cottonwood) and *A. macrophyllum.* The SUNP (2000b) habitat map describes the site as dominated by deciduous trees 12.7 – 38.1 cm (5 - 15 in) in diameter. The area is very highly impacted by *Hedera spp., Rubus discolor* (Himalayan blackberry), and *I. aquifolium*.

Site preparation, planting, and treatment installation was carried out by restoration contractor Frank Maduzia Jr. and Son, LLC. A contractor was used instead of volunteers to assure consistency in planting and treatment methods. Site preparation occurred during January and February 2008. At West Duwamish Greenbelt, extensive *Hedera spp.* removal was necessary to expose the ground for planting. In each block, *Hedera spp.* were removed completely from the ground and from the base of each tree six feet up and composted in large piles away from the experiment blocks. During this process several large logs were exposed; most were cut into smaller pieces and scattered throughout the experiment blocks to replicate common woody debris conditions. Invasive plant removal at Interlaken Park was less extensive, but included *Hedera spp., C. scoparius, R. discolor, and I. aquifolium.*

3.2 Experiment Design

To account for expected variability between and within each park a split-plot design was used. The split-plot design is an expanded version of the common randomized block design, where an additional factor is applied at the block level (Gotelli and Ellison, 2004). In this case, the parks were the additional factor, creating two sets of multiple blocks – four blocks were located at West Duwamish and three were located at Interlaken. The uneven design was due primarily to space availability. Special attention was given to encompass relatively homogenous conditions within each block, including light levels, soil types, slope gradients, and aspect. Blocks were roughly 1,975 m^2 (6,480 ft^2).

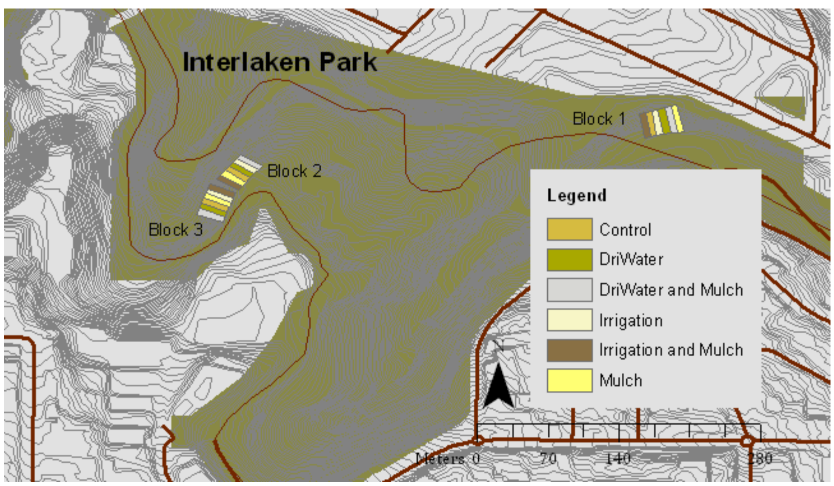

Figure 2. Map of Interlaken Park experiment blocks and treatments plots (ArcMap 9.3).

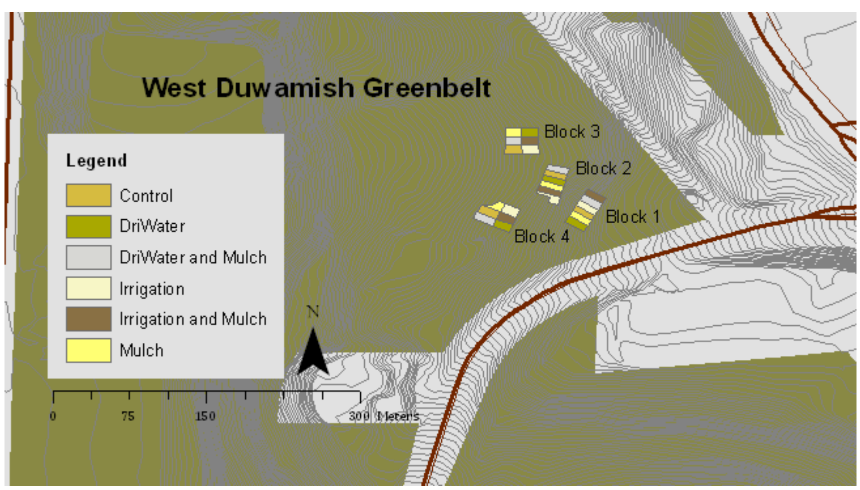

Figure 3. Map of West Duwamish Greenbelt experiment blocks and treatment plots (ArcMap 9.3).

The six experiment treatments were repeated randomly in all seven experiment blocks, totaling 42 treatment plots. The planting treatments were as follows: control (C), mulch (M), mulch and irrigation gel DriWater (MG), mulch and drip irrigation (MI), irrigation gel DriWater only (G), drip irrigation only (I). Three conifer species were used in the experiment: *Thuja plicata* (THPL), *Tsuga heterophylla* (TSHE), and *Abies grandis* (ABGR). Ten seedlings of each species were randomly located within each treatment plot in each experiment block, totaling 1,260 seedlings.

3.3 Materials

3.3.1 Seedlings

Seedlings were purchased from three different locations, with all material for each species from one source and seedling stock type. ABGR were sourced from the Washington State Department of Natural Resources' Webster Forestry Nursery near Olympia, WA. THPL was purchased from Burnt Ridge nursery in Onalaska, WA, while TSHE was sourced from Fourth Corner Nursery in Bellingham, WA. All seedlings were two years old. Both THPL and TSHE were P+1 stock type, meaning they were grown as plugs for the first year and then planted out for a second year in an agricultural field. They were harvested to maintain 20.3 cm (8 in) of roots. ABGR seedlings were field grown for two years and barerooted using a similar process.

Seedlings were installed at West Duwamish Greenbelt and Interlaken Park during the first two weeks of March 2008. The availability of bareroot seedling stock determined the planting dates. Seedlings were kept in cold storage prior to planting and efforts were made to keep plants covered and watered to reduce root desiccation during the two-week installation period. Twenty seedlings per species for each park were randomly selected and evaluated prior to planting. The evaluation focused on root and needle health, as well as signs and symptoms of disease, nutrient deficiencies, and/or mishandling. This assessment was in addition to the destructive samples discussed below.

Each seedling's location within a treatment plot was randomized and planting locations were laid out 1.82 m (6 ft) on center. Native plants were removed from within 31 cm (roughly 1 ft) of the planting locations. At Interlaken, the dense *Polystichum munitum* (sword fern) and *Mahonia nervosa* (dull Oregon grape) understory made it necessary to salvage and replant several dozen plants at an adjacent restoration site. For seedling installation, the contracted crew used a modified slit planting method common in larger-scale reforestation projects. Although this planting method is not appropriate for volunteer use, it can reduce installation time and can be done in a way that reduces j-rooting common with bareroot planting methods (Maduzia, 2008).

3.3.2 Mulch

Coarse arborist wood chip mulch was provided by Seattle Parks and Recreation Department. Specific source and tree type was unknown, but it can be assumed that it is local material that was composted before use. Seedlings in each mulch treatment plot received a 60.96 cm (2 ft) ring of mulch at a depth of 10.16 cm (4 in) at the time of planting. Efforts were made to remove mulch from against the seedling stem. No additional mulch was applied during the experiment.

3.3.3 Drip Irrigation

Drip irrigation materials were purchased by Seattle Parks and Recreation Department. The system was designed by Chris Behrens with assistance from Frank Maduzia and installed during May 2008. The West Duwamish site included a cistern uphill from the experiment blocks, accessed from Riverview Playfield. Interlaken Park had one cistern for blocks two and three and a separate set of irrigation barrels for block one. Each tree receiving the drip irrigation treatment had two emitters positioned on each side of the seedling that provided 7.57 l (2 gallons) of water over the course of two hours on a biweekly schedule. Figure 4 illustrates the position of the irrigation line and drip emitters compared to each seedling. Based on an area 45.72 cm^2 (18 in^2), each seedling received 36 mm (1.42 in) of irrigation per irrigation date.

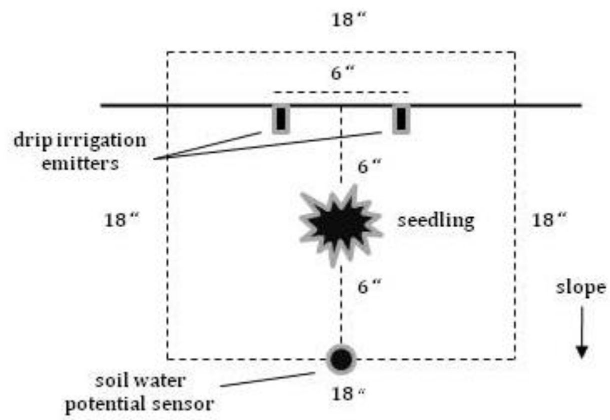

Figure 4. Irrigation line and drip emitter layout for each seedling receiving the drip irrigation treatment, including soil water potential sensor location.

The system was designed so that the amount of water necessary for each block was allowed to drain completely from the cisterns. For this reason, the Restoration Logistics, LLC watering crew filled the tanks on each irrigation date as follows: 1,817 l (480 gallons) for the West Duwamish tank, 908.5 l (240 gallons) for Interlaken blocks 2 & 3 tank, and 454.25 l (120 gallons) for Interlaken block 1. Special attention was given to testing the output for each block because of the differences in slope and seedling spacing from the holding tanks. Findings indicated that there was some variation in water delivered to individual trees, ranging from 4.92 – 7.57 l (1.3 - 2 gallons). Also, filters were installed to reduce potential clogging due to sediment deposition in the water source.

Drip irrigation occurred on a biweekly basis, beginning on June 25, 2008 at both sites and ending on September 11, 2008 at West Duwamish and September 17, 2008 at Interlaken. Due to a miscommunication with the watering contractors, irrigation was applied during opposite weeks at each site starting at the end of July. Drip irrigation was applied regardless of precipitation. No irrigation was applied in the second summer due to budget restrictions.

3.3.4 Irrigation Gel

DriWater gel packs and tubes were purchased from Horizon, Inc. (Bellevue, WA). DriWater is 98% water and 2% cellulose material bound in gel form (DriWater, Inc., Santa Rosa, CA). The product is described as working for 90 days, during which soil microorganisms break down the cellulose material and the bound water is released (DriWater, 2009). DriWater is marketed in several different forms. For this experiment, 7.62 cm (3 in) diameter tubes and gel packs were selected to allow for treatment application during the summer dry season.

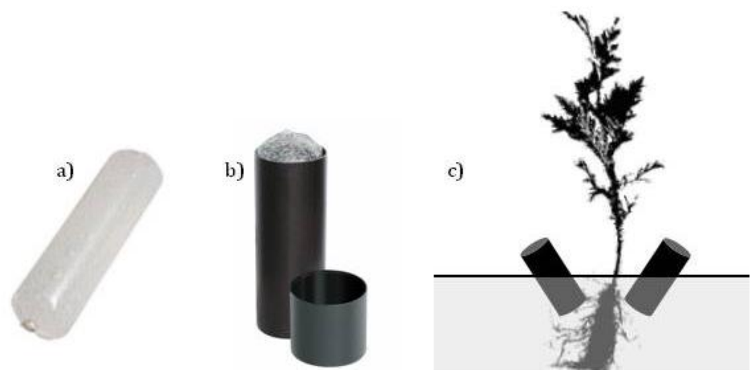

Figure 5. a) DriWater gel pack in plastic package. b) Driwater tube and gel pack product. c) Diagram illustrating DriWater tube installation. Image a and b © DriWater, Inc.

DriWater tubes were installed in designated treatment plots at the same time that seedlings were planted in March 2008. Tubes were dug into the soil 15.24 cm (6 in) from the base of either side of a seedling and angled so that the open bottoms were in the middle of the seedling's rooting zone. The top of the tubes were closed with a removable cap. On June 15 – 16, 2008, the plastic casing on the DriWater gel packs were removed and the gel was inserted in each tube. Because this experiment aims to understand the effectiveness of each material under common restoration project constraints, no water was applied to the tubes when the gel packs were opened as recommended in the product directions (DriWater, 2009). Instead, it was expected that June rains would create adequate soil moisture conditions. Although tubes remained in the ground for the duration of the experiment, gel was not reapplied during the second summer due to budget restrictions.

3.4 Measurements

3.4.1 Soil Physical and Chemical Conditions

Several measurements of soil chemical and physical properties were made at the beginning of the experiment. Organic matter and soil nutrients were determined for each treatment plot within each block. Five samples were collected randomly for each of the 42 treatment plots from a depth of 10.6 – 20.32 cm (4 – 8 in) to capture soil conditions in the rooting zone. They were then mixed together and dried on butcher paper for one week and a 237 ml (1 cup) sample was selected for testing. Samples were analyzed by the UMASS Plant and Soil Testing Laboratory (University of Massachusetts West Experiment Station, Amherst, MA). The analysis provided data on extractable nutrients, pH, extractable heavy metals, cation exchange capacity, percent base saturation, and percent organic matter. For the N analysis, samples were taken from block 1 and 2 at Interlaken and block 1 and 2 at West Duwamish. Several samples were collected throughout an experiment block, mixed together, and air dried for one week. A 237 ml (1 cup) subsample from each block was sent for analysis, providing N concentrations for sampled blocks.

Soil texture was assessed in September 2008 for each treatment plot within each block. Using a ribbon test analysis (Thein, 1979), a handful of soil from a depth of 10.6 – 20.32 cm (4 – 8 in) was collected from each plot. To confirm field test findings, an additional soil texture analysis was conducted on a sample of soil from each block using a hydrometer (Soil Testing Laboratory at South Dakota State University, Brookings, SD). Bulk density soil samples were collected using a soil core with six interior rings (AMS Inc, American Falls, ID). One sample was collected from a depth of 2.54 - 17.78 cm (1 - 7 in) at the same point along the slope of each treatment plot within each block, totaling 42 samples. Of the six ring sample, the bottom and top ring were cut off, leaving a sample with consistent volume. Samples were dried for 48 hours at 75 °C (167 °F) in a drying oven at the University of Washington Botanic Garden's Douglas Research Conservatory. Dry weight in grams was taken for each sample and divided by the volume in cm^3 to provide an estimate of each plots soil bulk density.

3.4.2 Soil Moisture Conditions

Soil water potential was measured in each treatment plot using a Watermark Soil Moisture Sensor and a Watermark Digital Meter (Spectrum Technologies, Inc., Plainfield, IL). The sensors measure water potential in kilopascals (kPa), with 0 being saturated and -200 being dry. One sensor was installed 15.24 cm (6 in) down slope from the base of a seedling and planted between 15.24 and 20.32 cm (6 - 8 in) deep in the rooting zone. Each treatment plot had one sensor, totaling 24 sensors at West Duwamish Greenbelt and 18 sensors at Interlaken Park. Installation occurred at the time of planting so as to not disturb root development. Sensors were checked weekly during the first summer season, biweekly during the second summer season, and once monthly during fall, winter, and spring of both years.

3.4.3 Temperature

Air temperature was monitored throughout the experiment using UA-001-08 HOBO Temperature/Alarm Pendant Data Loggers (Onset Computer Corporation, Bourne, MA). One logger was installed in each experiment block, attached to a tree near the center of the block and positioned on the north side of the tree roughly 1.82 meters (6 feet) from the ground. The logger was housed in a foam cup with holes to reduce exposure to direct sunlight.

3.4.4 Slope

Slope was measured for each treatment plot for all blocks using a handheld clinometer (Suunto Corporation, Vaanta, Finland). With one person positioned at the base of the slope and a second positioned at the top holding a 1.82 m (6 ft) pole, slope was determined by reading the clinometer.

3.4.5 Canopy

Canopy openness was measured for each treatment plot in all seven experiment blocks. Hemispherical photos were taken using a Nikon CoolPix 4500 with a Nikon FC-E8 fisheye lens on a tripod (Nikon Instruments Inc., Melville, NY). The photography process followed directions provided by Richardson (2008). Efforts were made to take images when the sky was overcast. Images were taken during leaf on and leaf off periods. Photos were analyzed using the Gap Light Analyzer V. 2.0 program (Simon Fraser University, Burnabay, B.C., Canada), which provides an estimate of percent openness.

3.4.6 Seedling Survivorship

An assessment of seedling health was completed twice during the experiment in October 2008 and August 2009. Plants were classified as dead, poor, and healthy using the following guidelines: dead seedlings had complete needle dieback and a brown cambium, poor seedlings had at least 20% needle dieback, and healthy seedlings had less than 20% needle dieback. Seedlings classified as healthy and poor were included in the total count of alive seedlings, which was divided by total seedlings planted to determine survivorship per treatment per block for each site.

3.4.7 Seedling Growth

Height and diameter were measured five times over the course of the experiment on a sub-sample of trees. Five seedlings per species per plot were selected at random, totaling 90 seedlings per block and 630 seedlings for both experiment sites on each measurement date. Initial measurements were taken in March 2008 during the two weeks after the seedlings were installed. Additional measurements were taken in August 2008, November 2008, March 2009, and August 2009.

Height measurements were made using a tape measure and recorded to the closest quarter centimeter. Because TSHE seedlings often exhibit a drooping leader, height was measured by extending the dominant stem and measuring to the tip.

Diameter measurements were taken 2 cm (0.79 in) above the root crown using a digital caliper (Absolute Digimatic Caliper, Mitutoyo Corporation, Japan) and recorded in mm to the tenths place. Because seedling stems are not perfectly circular, special efforts were made to capture the diameter at the same position for each measurement by positioning the caliper perpendicular to the slope.

3.4.8 Stem Water Potential

On July 30 – 31, 2008 and again on the same dates in 2009, stem water potential was assessed using the Scholander Pressure Chamber Model 1000 (PMS Instruments Company, Albany, OR). Measurements were made on one randomly selected seedling of each species in each treatment plot. When a reading was unable to be made before reaching -3.0 MPa, a second seedling was selected randomly to be tested. A 10 cm (3.93 in) branch sample was taken from an upper side branch of the selected seedling. Data collection occurred during pre-dawn hours to assure the seedlings were not transpiring while photosynthesizing. The stem water potential measurement process followed directions provided by Cleary, et al. (2007).

3.4.9 Biomass

For each species, twenty trees were destructively sampled during March 2008 as part of initial planting efforts. Seedlings were measured for height and diameter (as described above) before being divided at the root crown into root and shoot components. Samples were dried at 75 °C (167 °F) in a drying oven at the University of Washington Botanic Garden's Douglas Research Conservatory for 48 hours or until no weight difference was recorded. Dry weight of root and shoot components were recorded in grams to the tenths place using a digital scale (Ohaus Adventurer SL, Ohaus Corporation, Pine Brook, NJ).

At the end of the experiment, three seedlings per treatment plot for each species were destructively sampled for shoot biomass. Accurate root biomass samples were difficult to obtain due to soil conditions and existing vegetation, so no root measurements were made at the end of the experiment. Due to extensive dieback at Interlaken, collecting three samples was not possible for every plot. Shoot samples were dried in the oven at 75 °C (167 °F) in a drying oven at the University of Washington Botanic Garden's Douglas Research Conservatory for 48 hours and weighed using a digital scale (Ohaus Adventurer SL, Ohaus Corporation, Pine Brook, NJ).

3.5 Data Management and Statistical Analysis

All data were stored and managed in Excel version 11.3.7 (Microsoft Corporation, 2004, Redmond, WA). Statistical analysis was conducted using R version 2.8.1 (R Development Core Team, 2008, Vienna, Austria). Figures were created in SigmaPlot version 9.0 (Systat Softwar Incorporated, San Jose, CA).

Before statistical analysis was completed, data were assessed for normality using Quantile-Quantile Plots ("qqplot" function) and the Shapiro-Wilks Test ("shapiro.test" function) in R. Statistical analysis was then conducted to compare variation of mulch treatments, water treatments, and their interaction using Analysis of Variance model ("aov" function) in R. Dependent variables included seedling survival after the first and second summer seasons, seedling height and diameter after two growing seasons, stem water potential during the first and second summer, and final biomass. Species were analyzed separately for all outcomes, as were annual measurements. Specific information on how results were calculated and used in R is included in Results (Section 4.0) for each measurement.

After a significant difference ($p < 0.05$) between experiment locations was determined for each measurement, sites were analyzed separately to better understand the effect of treatments on the site-specific experience of seedlings. Because of the highly significant difference between experiment locations, blocks were included as fixed effects. Tukey's Honestly Significantly Different Test ("TukeyHSD" function) was utilized to compare between treatments. Variance is presented as standard error of measurement means by plot. Results were considered significant at $\alpha = 0.05$, but p values are included for $\alpha = 0.10$.

4.0 RESULTS

4.1 Soil Physical and Chemical Conditions

Some soil physical and chemical properties differed between West Duwamish and Interlaken, while others were equivalent. Selective results for each site are provided in Table 2 and Table 3 and include information for each block, as well as a site averages. The most defining difference between sites is soil texture, with Interlaken having loamy sand/sandy loam soils and West Duwamish having clay/clay loam soils. Although higher at West Duwamish, organic matter and cation exchange capacity (CEC) were sufficient at both sites. Soil pH levels ranged from 5.4 to 6.8 for both sites. Although not substantially different, pH for West Duwamish blocks 1 and 2 and Interlaken block 1 were in the range considered to be too alkaline for conifer plantings (UMASS Soil and Plant Tissue Testing Lab, 2009). Soil nutrients levels were similar across sites, with low phosphorous levels and high levels of potassium, calcium, and magnesium. All micronutrients levels (not listed) were normal.

Table 2. Interlaken Park soil chemical and physical analysis results.

Soil Property	Block 1	Block 2	Block 3	Site Average	Standard Deviation
Soil pH	6.40	5.40	5.70	5.83	±0.51
Nitrogen (%)	0.29	0.22	NA	0.25	±0.06
Phosphorus (μg/g)	8	4	3	5	±2.65
Nitrate (μg/g)	11	7	6	80	±2.65
Potassium (μg/g)	212	153	139	168	±38.74
Calcium (μg/g)	1776	987	1264	1342.33	±400.29
Magnesium (μg/g)	234	157	216	202.33	±40.28
Organic Matter (%)	8.40	5.50	5.40	6.43	±0.08
Cation Exchange Capacity (MEQ/100g)	15.1	12.40	11.90	13.3	±1.72
Bulk Density (g/cm^3)	0.94	0.87	1.07	0.96	±0.18
Texture	loamy sand	loamy sand	sandy loam	loamy sand/sandy loam	NA

Table 3. West Duwamish Greenbelt soil chemical and physical analysis results.

Soil Property	Block 1	Block 2	Block 3	Block 4	Site Average	Standard Deviation
Soil pH	6.80	6.40	5.80	5.50	6.13	±0.59
Nitrogen (%)	0.27	0.34	NA	NA	0.31	±0.09
Nitrate (μg/g)	12	1	12	10	8.75	±5.25
Phosphorus (μg/g)	3	4	4	5	4	±0.82
Potassium (μg/g)	419	481	290	392	395.50	±79.59
Calcium (μg/g)	2076	1905	1414	1539	1733.50	±309.10
Magnesium (μg/g)	538	593	394	472	499.25	±85.85
Organic Matter (%)	7.20	8.00	5.50	7.00	6.93%	±0.01
Cation Exchange Capacity (MEQ/100g)	17.90	20.90	18.50	24.70	20.50	±3.06
Bulk Density (g/cm^3)	1.02	1.09	1.18	1.02	1.08	±0.14
Soil Texture	clay loam	clay loam	silty clay laom	clay/clay loam	clay/clay loam	NA

4.2 Soil Moisture Conditions

Site soil water potential, regional precipitation, and irrigation estimates are presented in Figure 6 A and B for West Duwamish and Interlaken, respectively. Soil moisture data collected for each treatment plot are presented here as an average for each treatment type at each site. Precipitation data were sourced from the closest National Oceanic and Atmospheric Administration (NOAA) weather station; the Sea-Tac Airport weather station is located 9.7 miles south of the West Duwamish experiment site and the Sand Point weather station is located 5 miles northeast of the Interlaken site (NOAA National Climatic Data Center, 2009).

Dry soil conditions occurred at both sites during the summers of 2008 and 2009. Interlaken soils were drier even though precipitation and irrigation conditions were similar at West Duwamish. Despite this discrepancy, clear trends existed at both sites for plots that received mulch (mulch alone, mulch + irrigation, and mulch + irrigation gel) at the time of seedling installation. Mulched plots consistently had higher soil water potential during summer seasons; differences between mulched and un-mulched plots were accentuated during the summer of 2009.

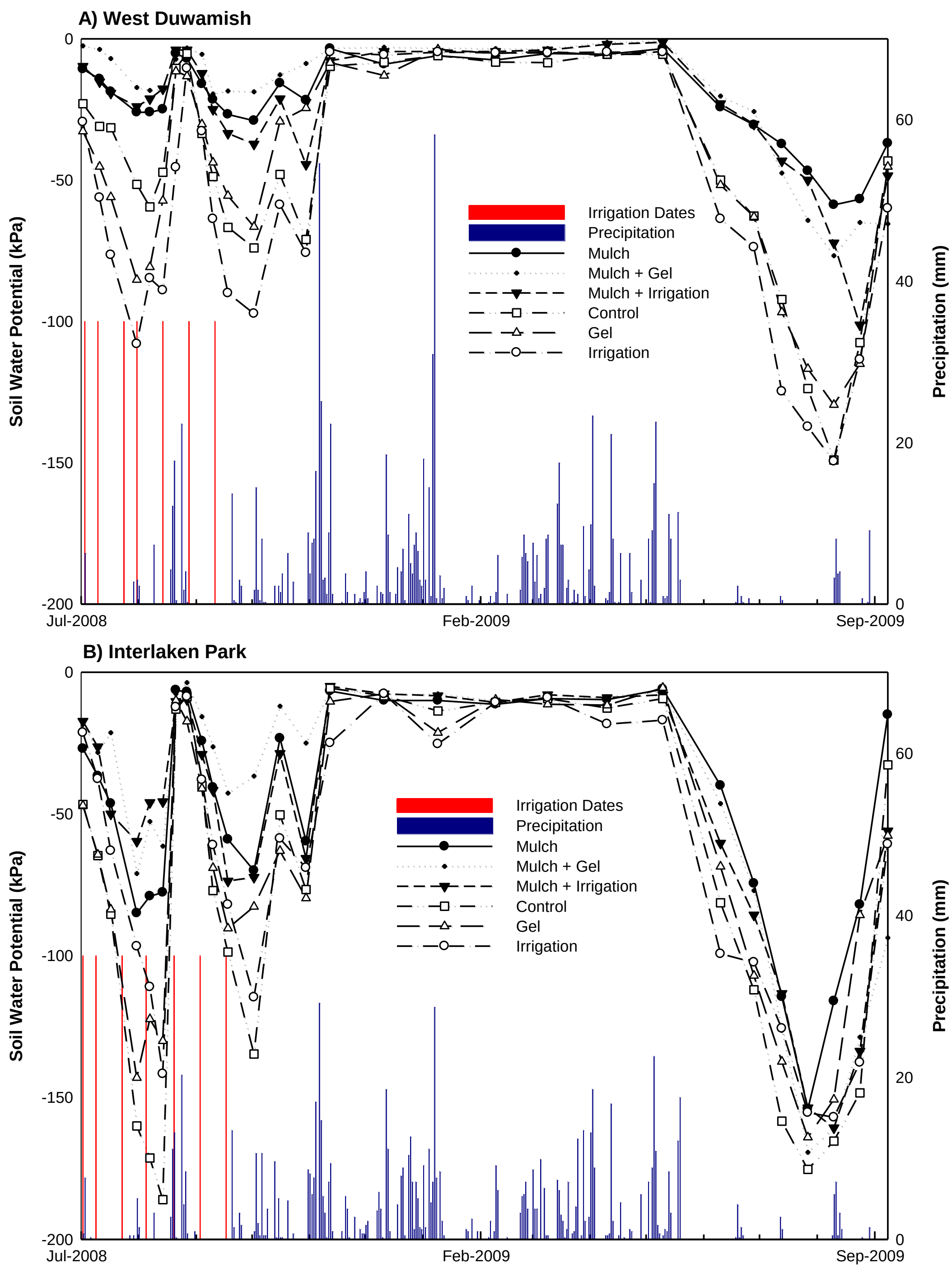

Figure 6. Moisture conditions from June 2008 to September 2009 at West Duwamish Greenbelt (A) and Interlaken Park (B), including irrigation (mm), regional precipitation (mm), and soil water potential (kPa) by treatment type with 0 being saturated and -200 being dry.

4.3 Temperature

No temperature differences were observed between parks. Both sites saw the highest recorded temperature during unseasonably warm weather on May 17, 2008 with 31.84 °C (89.31 °F) and 31.95 °C (89.51 °F) at Interlaken and West Duwamish, respectively (Figure 7). Temperatures reached as low as -8.71 °C (16.32 °F) at Interlaken and -7.39 °C (18.69 °F) at West Duwamish on December 20, 2008 during a sustained winter storm. An extended period of heat occurred during late July 2009, but was not captured by the onsite temperature loggers due to limited memory. Record highs were recorded at both the Sand Point and Sea-Tac Airport weather stations on July 29, 2009 when temperatures reached 40.56 °C (105.01 °F) and 39.44 °C (102.99 °F), respectively (NOAA, 2009b).

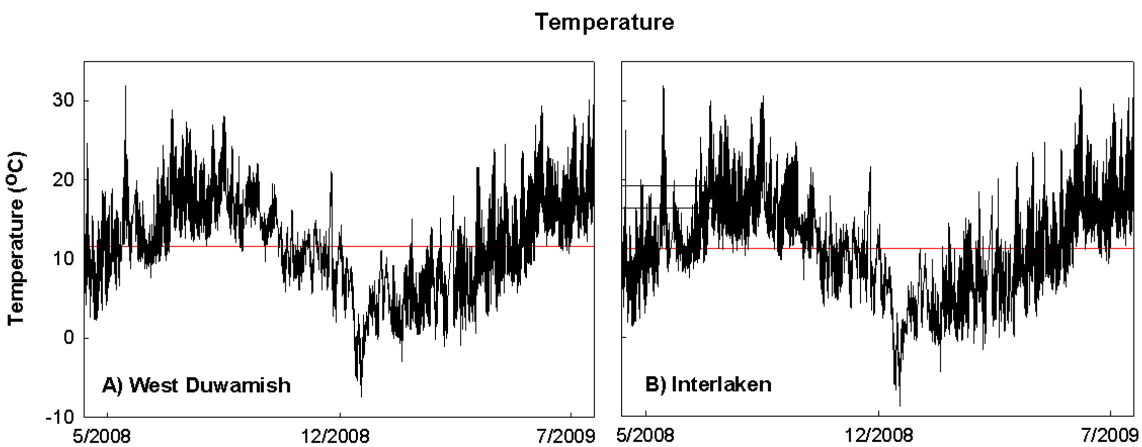

Figure 7. Average air temperature (°C) for A) West Duwamish Greenbelt and B) Interlaken Park from April 2008 through July 2009. Red lines indicates mean temperatures.

4.4 Slope

Percent slope varied between and within each park. Slope was averaged from three measurements taken in each block. The steepest conditions were found in Interlaken blocks 2 and 3, where the slope reached 76 %. West Duwamish blocks 3 and 4 had the gentlest slope conditions.

Table 4. Average percent slope for each experiment block at Interlaken Park and West Duwamish Greenbelt.

Site	Block	Slope (%)
Interlaken Park	1	30.3
	2	64.3
	3	76.0
West Duwamish Greenbelt	1	38.3
	2	25.0
	3	19.3
	4	17.3

4.5 Canopy

Differences in canopy openness were observed between blocks as well as between sites. Block canopy openness is the average of the six plot canopy values. Interlaken canopy for each block ranged from 5.59% to 14.21% openness, while West Duwamish block canopy ranged from 12.12 to 15.79% openness (Figure 8). Although not included in the figure below, differences were observed from plot to plot in West Duwamish blocks 1 and 2. As an example, in West Duwamish block 2 plot 3 had 9.07% openness, while plot 6 had 20.29% openness.

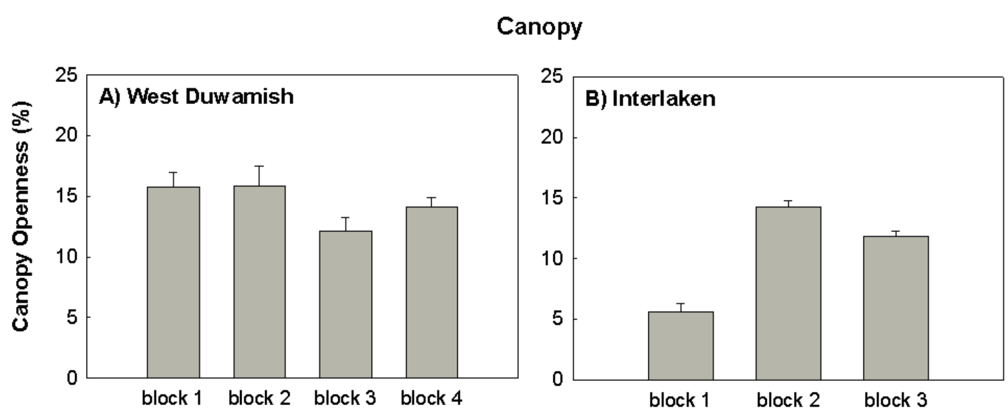

Figure 8. Canopy openness (%) for A) West Duwamish Greenbelt and B) Interlaken Park by experiment block. Bars represent standard error calculated from plot measurements averaged for each block.

4.6 Seedling Survivorship

4.6.1 First Year Survivorship

First year survivorship was significantly different between experiment locations for all species ($p < 0.0001$). Overall survival for TSHE was 96% at West Duwamish compared to 26% at Interlaken. THPL had slightly better overall survival at Interlaken with 62%, but the lowest at West Duwamish compared to other species, with 93%. ABGR had the highest overall survival: 99% at West Duwamish and 71% at Interlaken.

Treatments influenced survivorship at Interlaken Park, but had limited influence at West Duwamish (Figure 9). Seedling survivorship increased at Interlaken with the presence of mulch treatments (including mulch, mulch + irrigation, and mulch + gel) for TSHE ($p = 0.046$) and THPL ($p = 0.020$). For THPL, water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) also increased survivorship at Interlaken, although not significantly ($p = 0.077$). Tukey's HSD test suggested irrigation and mulch increased survivorship for THPL seedling more than control plots at Interlaken ($p = 0.049$). THPL was the only species at West Duwamish to benefit from treatment. A significant interaction effect for all water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) and all mulch treatments (mulch alone, mulch + gel, mulch + irrigation) existed for THPL at West Duwamish ($p = 0.034$). Statistical analysis suggested that seedlings treated with mulch + gel survived more than seedlings that received mulch + irrigation ($p = 0.042$).

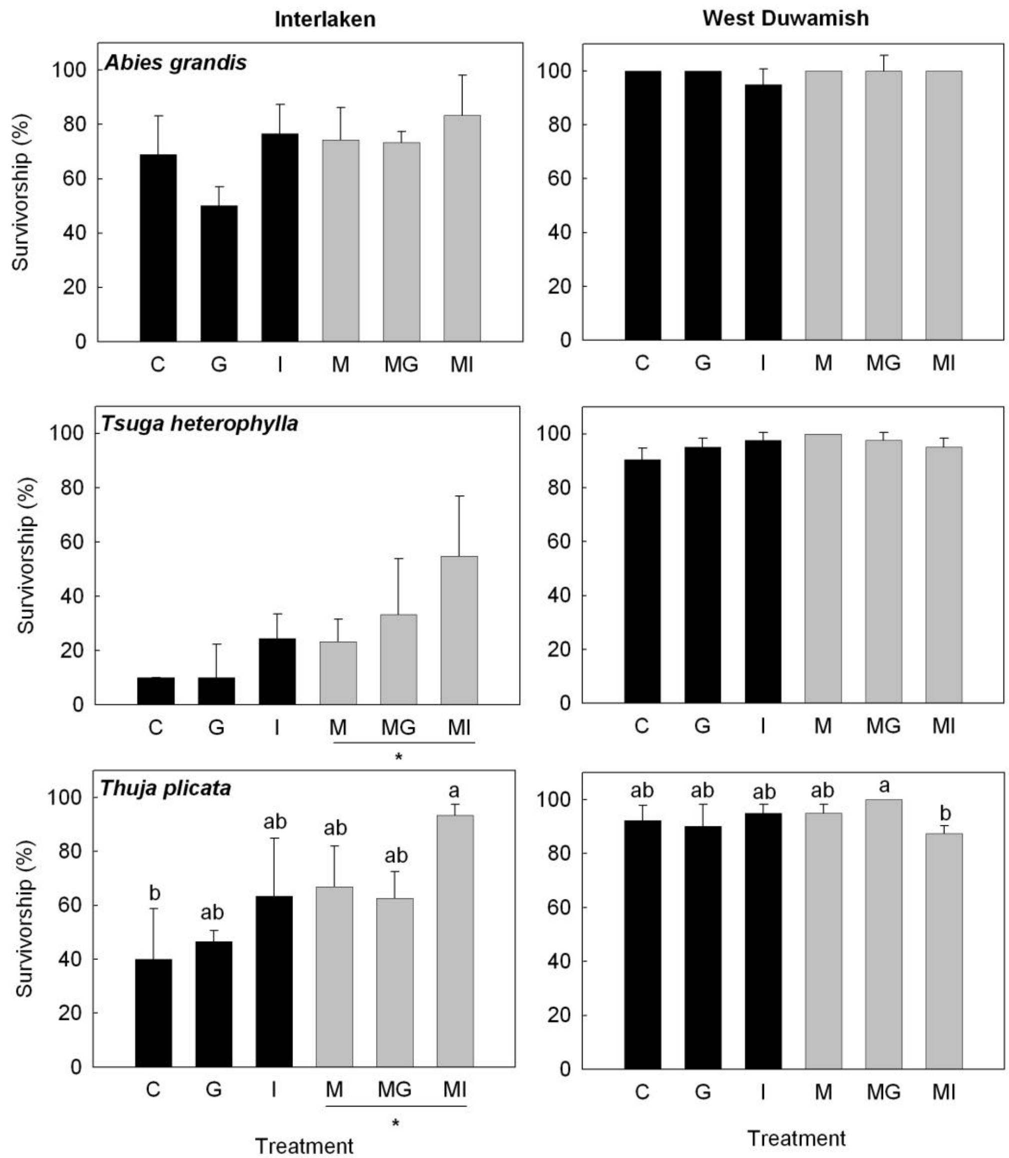

Figure 9. First year survivorship by site and species. Site differences were significant for all species. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Vertical bars with the same letter are not significantly different (α = 0.05) according to Tukey's HSD test for mean comparisons. Error bars represent standard error. Treatment codes: C = control: I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel.

4.6.2 Second Year Survivorship

After two summer seasons, survivorship trends between parks stayed consistent, with West Duwamish Greenbelt maintaining significantly higher survivorship than Interlaken Park for all species ($p < 0.0001$). Overall survivorship for TSHE declined to 21% at Interlaken, but remained similar at West Duwamish with 94% survival. ABGR had 96% survival at West Duwamish averaged over all treatments and 48% survival at Interlaken. THPL had the best overall survivorship at Interlaken with 52%, but declined to 91% at West Duwamish.

Treatment applications that occurred in the first year had lasting effects on survivorship. ABGR experienced significantly higher survivorship after the second summer in plots at Interlaken that originally received mulch (mulch alone, mulch + gel, mulch + irrigation) ($p = 0.022$). THPL followed similar trends ($p = 0.062$). Again in the second year there was a significant interaction of all water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) and all mulch treatments (mulch alone, mulch + gel, mulch + irrigation) for THPL at West Duwamish ($p = 0.034$). Tukey's Honestly Significantly Different Test found mulch + gel increased survivorship over mulch + irrigation ($p = 0.026$).

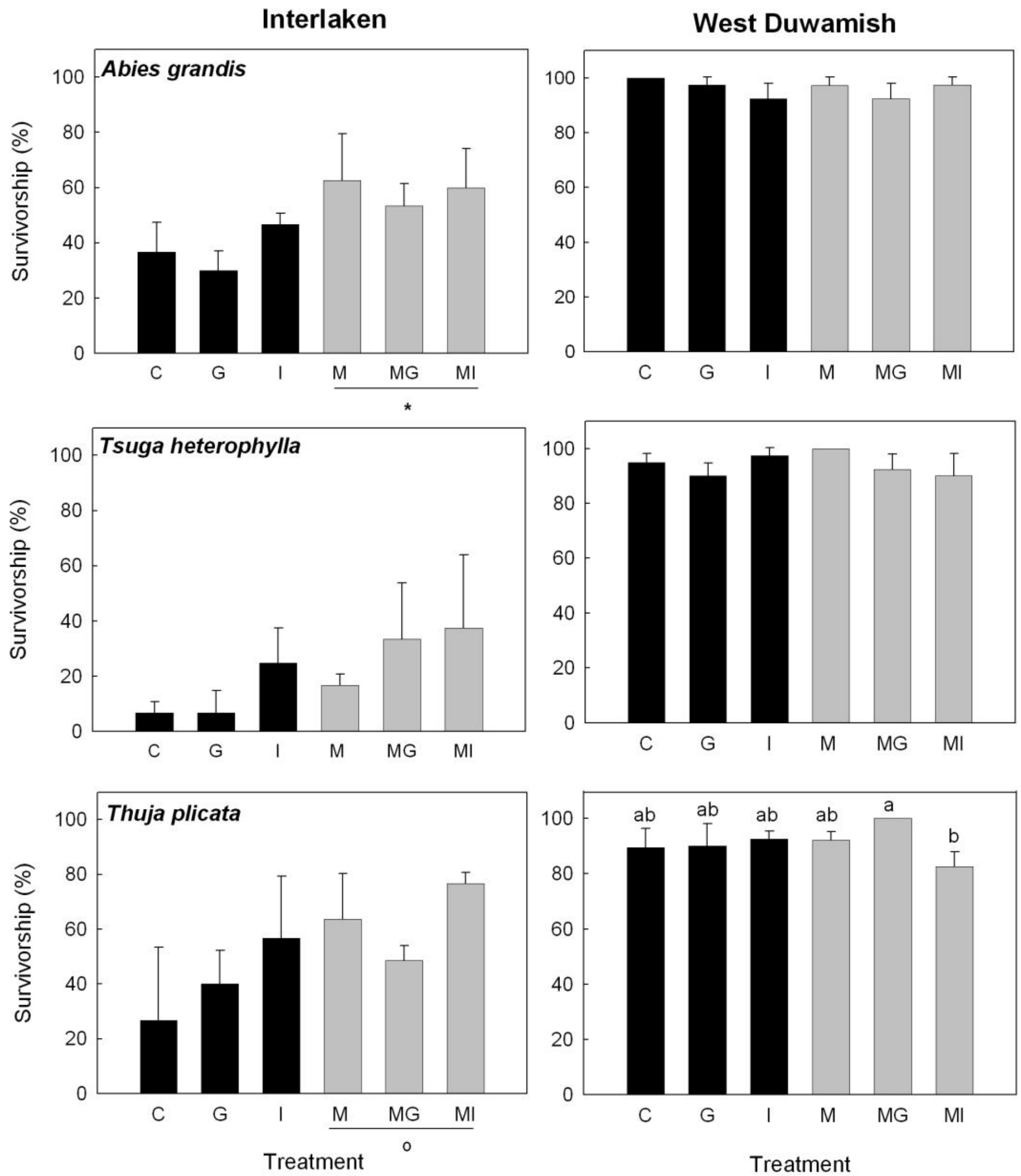

Figure 10. Second year survivorship by species and site. Survivorship by site was highly significant for all species. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Vertical bars with the same letter are not significantly different (α = 0.05) according to Tukey's HSD test for mean comparisons. Error bars represent standard error. Treatment codes: C = control; I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel.

4.7 Seedling Growth

4.7.1 Diameter

As has been the trend with other measurements, final diameter was significantly different for each site for all species ($p < 0.0001$). Significant differences in diameter between blocks were found for ABGR at both sites: Interlaken blocks 3 and 2 ($p = 0.006$) and blocks 2 and 1 ($p = 0.048$); West Duwamish blocks 4 and 1 ($p = 0.007$) and blocks 4 and 2 ($p = 0.026$). THPL diameter was also different between blocks 3 and 2 at Interlaken ($p = 0.045$). The presence of drip irrigation (including irrigation alone and mulch + irrigation) increased diameter size for ABGR at Interlaken ($p = 0.036$) and West Duwamish ($p = 0.086$). Statistical analysis did not show a significant difference between drip irrigation treatment types. No treatment effects were observed for THPL or TSHE.

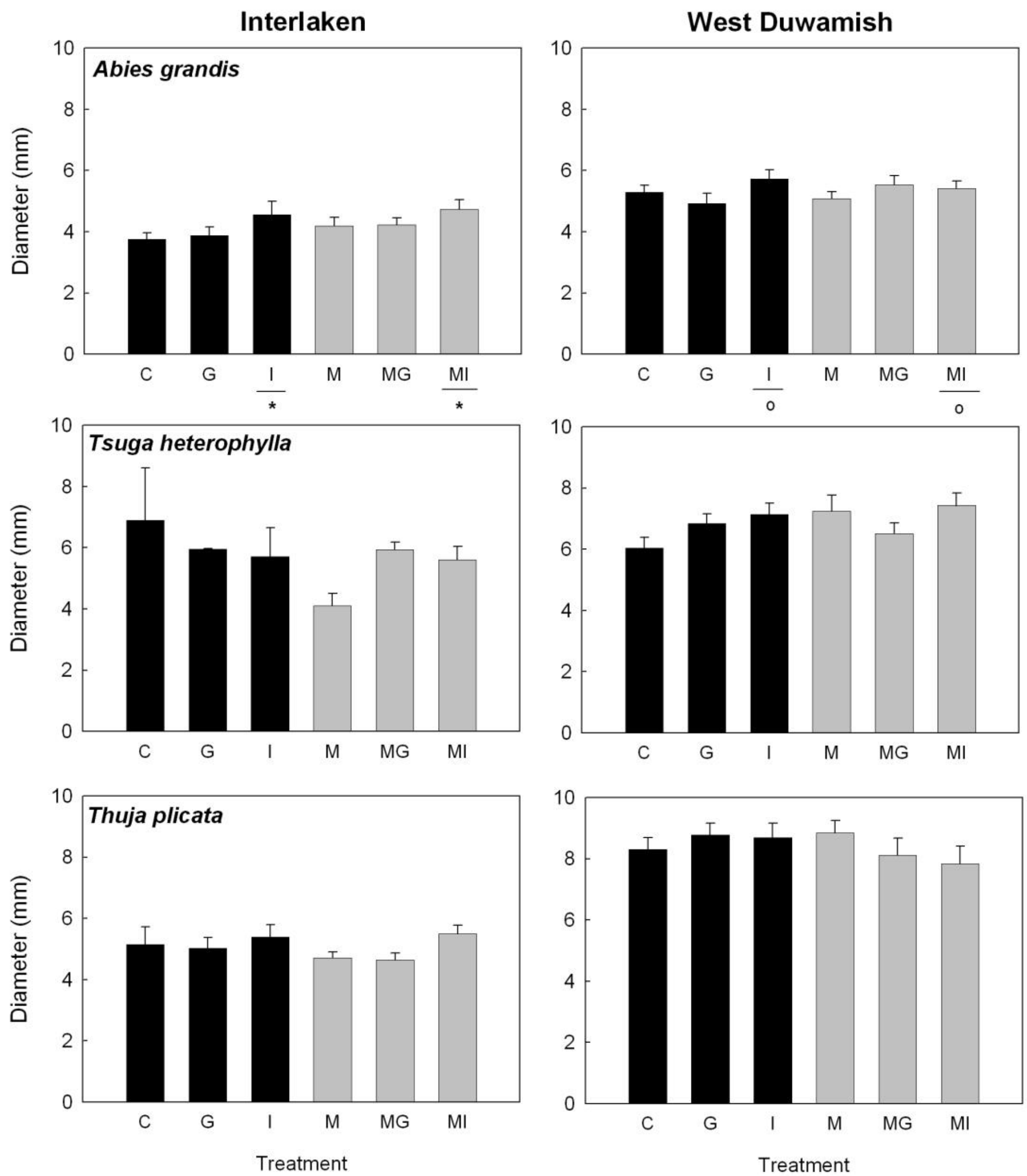

Figure 11. Final stem diameter (mm) for each species at each park in August 2009. Final stem diameter was significantly different between sites for all species. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Error bars represent standard error. Treatment codes: C = control; I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel.

4.7.2 Height

Height followed similar patterns between sites, with all species having significant site differences ($p < 0.0001$). Significant differences in height between blocks at Interlaken were found for TSHE (blocks 3 and 1 p = 0.03) and for ABGR (blocks 2 and 1 p = 0.026, blocks 3 and 2 p = 0.033). Blocks 4 and 1 were significantly different for ABGR at West Duwamish (p = 0.012).

Treatment influenced final height at both sites. For TSHE at Interlaken there was a significant interaction of all water and all mulch treatments (p = 0.046) and the presence of the water (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) increased height (p = 0.046). Tukey's HSD test suggested that mulch + gel increased height over mulch alone (p = 0.017) and that control plots had significantly better height for TSHE compared to plots that received mulch (p = 0.02). This may be misleading because high mortality at Interlaken meant that there were only two TSHE seedlings left in all control plots at Interlaken, making the average less robust than for the twenty seedlings measured and averaged at West Duwamish. For ABGR at Interlaken, the presence of water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) increased survival (p = 0.012). Tukey's HSD found no significant differences between treatments. For THPL at Interlaken water treatments increased height (p = 0.027), although no specific treatment influenced height more than the others. At West Duwamish mulch (mulch alone, mulch + gel, mulch + irrigation) increased height for TSHE (0.009), with mulch alone having the most influence (p = 0.014). For ABGR at West Duwamish all water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) increased height, although not significantly (0.091).

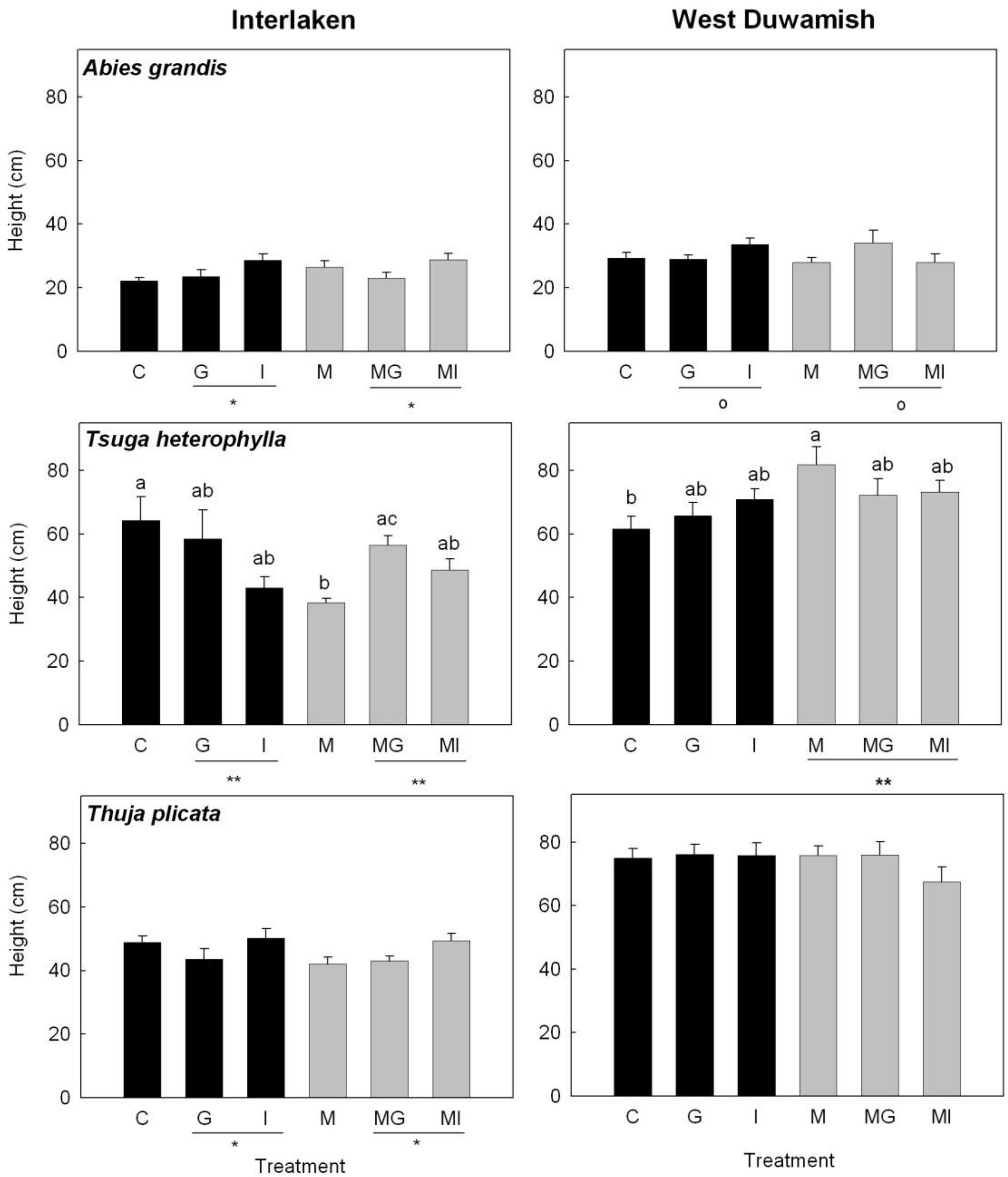

Figure 12. Final shoot height (cm) for each species at each park in August 2009. Final stem height was significantly different between sites for all species. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Vertical bars with the same letter are not significantly different (α = 0.05) according to Tukey's HSD test for mean comparisons. Error bars represent standard error. Treatment codes: C = control; I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel.

4.8 Stem Water Potential

4.8.1 First Year Stem Water Potential

Following survivorship trends stem water potential (SWP) was significantly lower at Interlaken than at West Duwamish for each species ($p < 0.0001$) in late July 2008. Treatments influenced SWP at Interlaken, but no differences were observed between treatments at West Duwamish. For TSHE seedlings at Interlaken, water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) increased SWP ($p = 0.027$). Tukey's HSD suggested that mulch + irrigation seedlings experienced higher SWP than control treatments ($p = 0.031$). Seedling SWP improved for ABGR at Interlaken with the presence of mulch (mulch alone, mulch + gel, mulch + irrigation) ($p = 0.046$) or water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) ($p = 0.004$). Specifically, irrigation alone ($p = 0.025$) and mulch + irrigation ($p = 0.005$) increased SWP. THPL SWP improved at Interlaken with the presence of water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) ($p = 0.002$) and with the presence of mulch (mulch alone, mulch + irrigation, and mulch + gel), although not significantly ($p = 0.071$). Tukey's HSD test suggested mulch + irrigation ($p = 0.014$) and irrigation alone ($p = 0.009$) had better SWP than the control treatment. Irrigation + mulch was found to improve SWP more than the irrigation gel at Interlaken for THPL ($p = 0.032$).

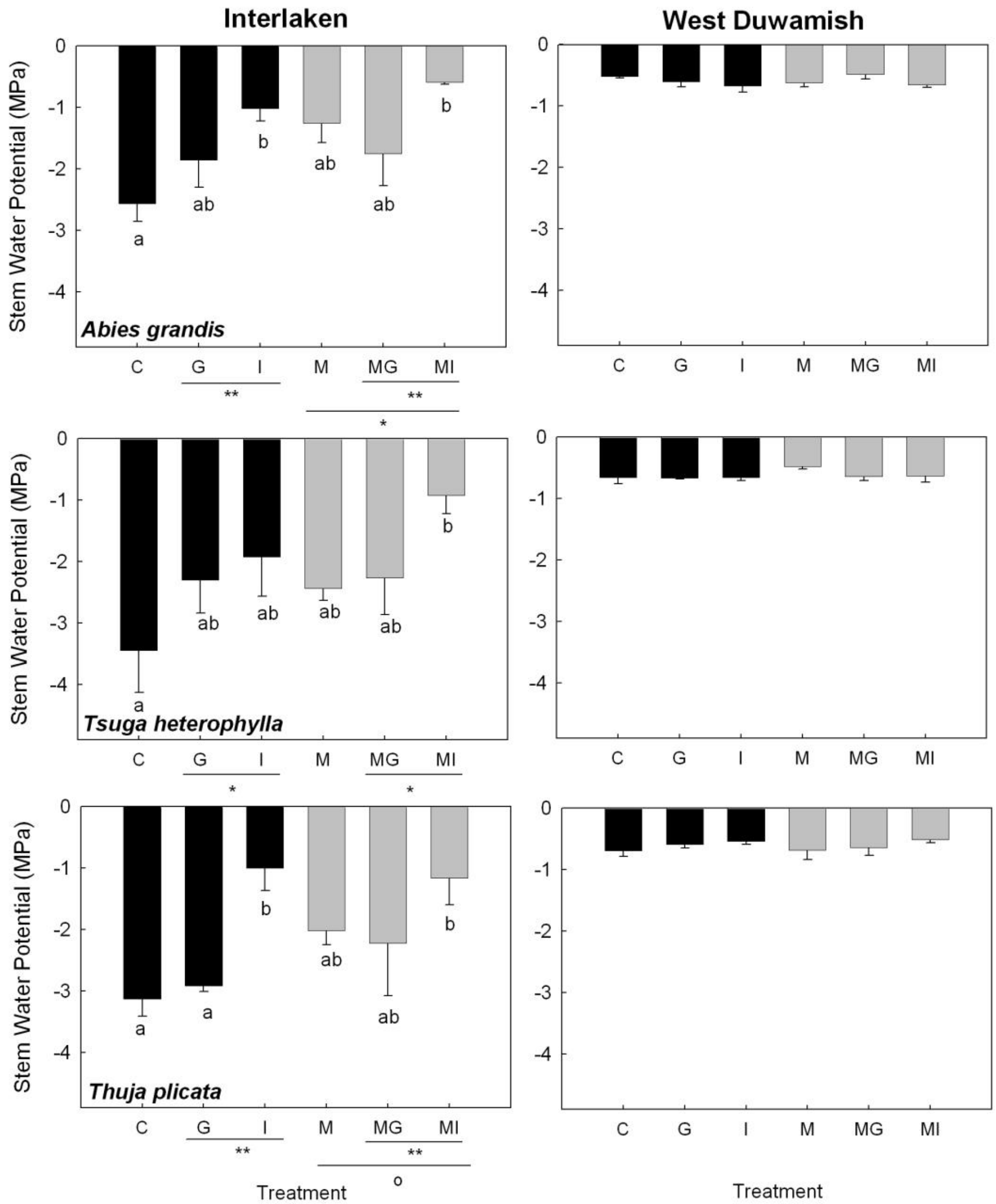

Figure 13. First summer stem water potential for each species at each park measured on July 30-31, 2008 pre-dawn. Lower stem water potential indicates less water available for use by the plant. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Vertical bars with the same letter are not significantly different (α = 0.05) according to Tukey's HSD test for mean comparisons. Error bars represent standard error. Treatment codes: C = control; I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel. Error bars represent standard error.

4.8.2 Second Year Plant Water Status

In the second summer season, plants were more stressed overall, but Interlaken still had significantly worse SWP levels for all species compared to West Duwamish ($p < 0.0001$). For TSHE seedlings at Interlaken that received water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) SWP improved, but not significantly ($p = 0.086$). No treatment differences were found for THPL at Interlaken. However, highly significant effects were observed at West Duwamish for treatments plots receiving mulch (mulch, mulch + gel, mulch + irrigation) ($p = 0.0009$). Seedlings that received mulch ($p = 0.020$), mulch + irrigation ($p = 0.092$), and mulch + gel ($p =0.034$) had significantly better water status than control seedlings. No treatment effects were observed for ABGR at either site.

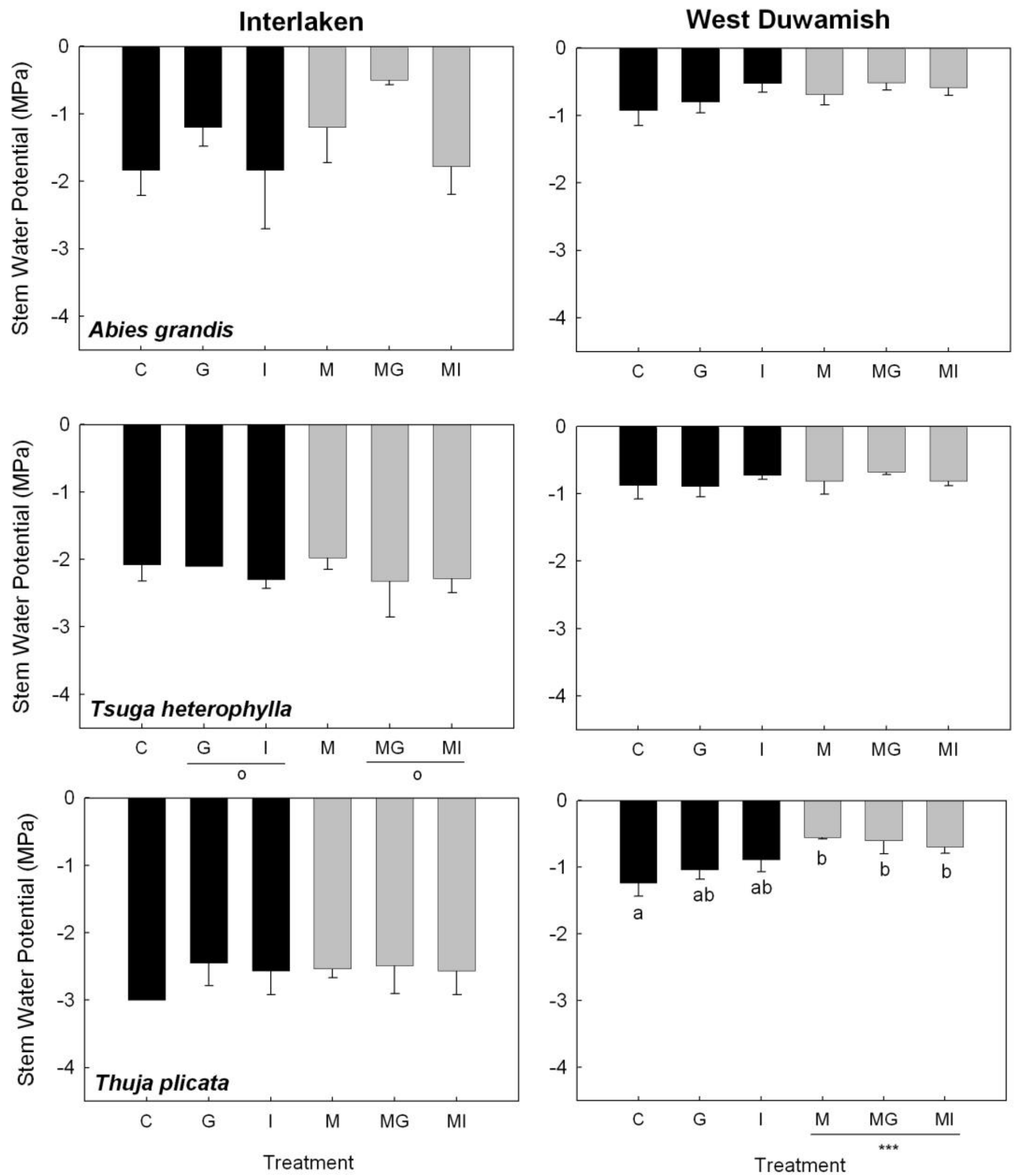

Figure 14. Second summer stem water potential for each species at each park measured on July 30- 31, 2008 pre-dawn. Lower stem water potential indicates less water available for use by the plant. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Vertical bars with the same letter are not significantly different (α = 0.05) according to Tukey's HSD test for mean comparisons. Error bars represent standard error. Treatment codes: C = control; I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel. Error bars represent standard error.

4.9 Biomass

4.9.1 Initial Biomass

Root:shoot (R:S) ratios for each species at the time of planting suggest uneven biomass distribution. ABGR seedlings had an average R:S of 0.61, while TSHE had 0.62 and THPL had 0.41. Figure 15 represents the average dry weight (g) of root and shoot components for each species.

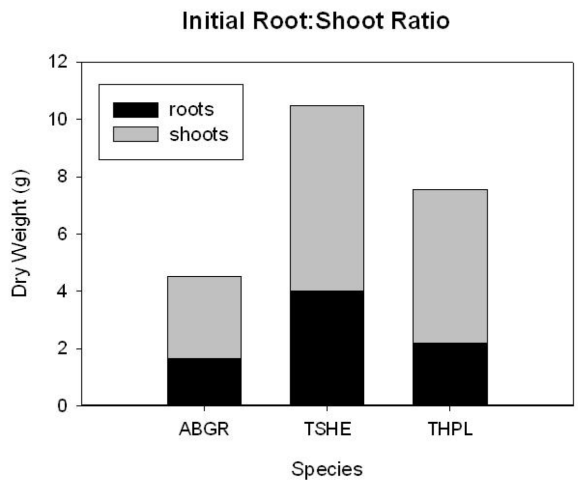

Figure 15. Initial root and shoot dry weight (g) for each species from a random destructive sample of seedlings at the time of planting.

4.9.2 Final Above-Ground Biomass

Final above-ground biomass illustrates seedling productivity by treatment and experiment location. Again, differences between sites were significant for all three species ($p < 0.0001$). Block differences were found at Interlaken for TSHE (blocks 3 and 2 $p = 0.021$). For ABGR, water treatments (drip irrigation, mulch + irrigation, irrigation gel, and mulch + gel) increased biomass, but not significantly ($p = 0.084$). Treatments had no influence on final aboveground biomass for TSHE or THPL at both experiment sites.

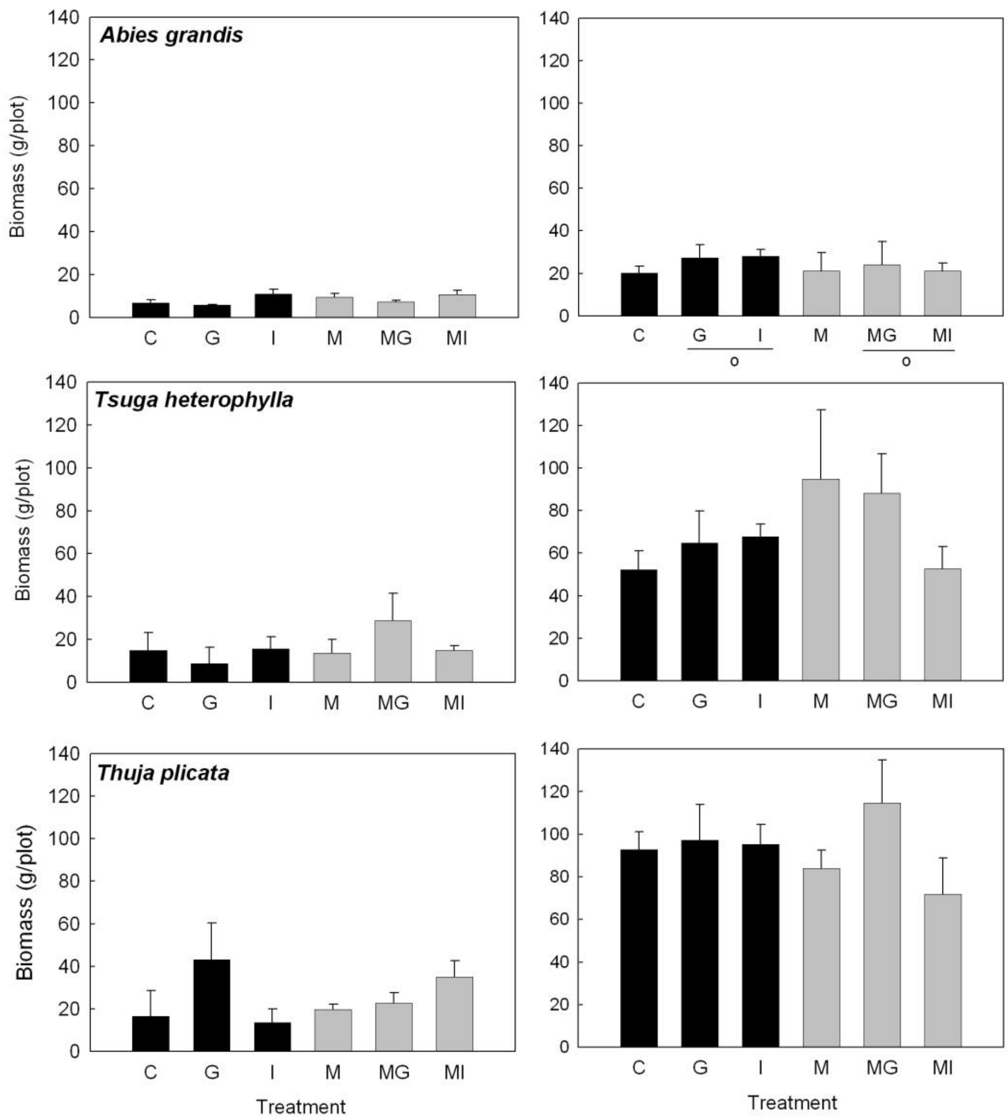

Figure 16. Final above ground plot biomass (g) by treatment for each species at each park. Experiment sites had significantly different above ground biomass regardless of treatment for all species. ANOVA significance values: α=0.1 (°), 0.05 (*), 0.01 (**), 0.001 (***). Treatment codes: C = control; I = drip irrigation; G = irrigation gel; M = mulch; MI = mulch and drip irrigation; MG = mulch and irrigation gel.

5.0 DISCUSSION

This experiment set out to understand how to improve conifer restoration in Seattle, WA. By testing the influence of drip irrigation and irrigation gel alone and in combination with coarse arborist wood chip mulch for three native conifer species, we can propose methods to meet restoration goals. Moreover, measuring environmental conditions over the course of the experiment provided an important understanding of a transplanted seedling's initial experience at two forested Seattle parks, affirming the impact of summer drought conditions and the need for treatments to improve available soil moisture. Important trends across and between parks emerged, as did treatment effects for each species.

5.1 Survivorship Differences

Experiment results captured survivorship extremes common at GSP restoration sites. West Duwamish maintained high survivorship for the duration of the experiment, while very few seedlings survived two growing seasons at Interlaken. Planting treatments did not appear to influence the survivorship at West Duwamish, suggesting seedlings will thrive without the addition of mulch, drip irrigation, or irrigation gel. However, at Interlaken mulch treatments were an important addition; TSHE and THPL were able to stay alive because of the application of all mulch treatments (mulch alone, mulch + drip irrigation, mulch + gel). In the second year at Interlaken, mulch improved survivorship for ABGR and THPL, but not TSHE. The extreme survivorship differences between parks beg the question of what site specific conditions influenced survivorship.

5.2 Soil Influences

The significant differences in survivorship at Interlaken and West Duwamish can be attributed in large part to the differences in physical soil properties, particularly texture, classified by the distribution of sand, silt, and clay particles. West Duwamish was found to have clay/clay loam soil texture (Table 3), while Interlaken soils were consistently loamy sand/sandy loam texture (Table 2). Texture influences water holding capacity, water movement, nutrient availability, root penetration, and soil structure (Sutton, 1991). Clay soils like at West Duwamish are made of fine soil particles and as such have more surface area, increasing water and nutrient holding capacities. Sandy soils typical at Interlaken have coarse soil particles and large pores that increase aeration and water penetration, but often limit a soil's capacity to hold on to nutrients and water (Kohnke and Franzmeier, 1995).

Because they swell and shrink depending on water content, clay and organic matter influence the formation of aggregates and the maintenance of pore space, improving the structure of the soil (Sutton, 1991). Although clay soils are known for poor drainage, West Duwamish's clay texture and high organic content suggest good aggregation and porosity, positively influencing water movement and root penetration. Observations of Interlaken soils, often found sloughing away even with limited disturbance support the idea that the park's soil suffers from a lack of structure.

Soil moisture results bolster the claim that each site's soil texture influenced water holding capacity and in turn determined seedling survivorship (Bhattacharjee et al., 2008). Although each site experienced similar precipitation and irrigation, Interlaken soils were consistently drier than West Duwamish during the summer season. With soil moisture reaching close to -175 kPa (on a scale of 0 to -200 kPa with -200 being driest) in 2009 (Figure 6), it is clear that seedlings at Interlaken had very little water during summer months to move beyond transplant stress and begin rapid growth (Reitveld, 1991; Grossnickle, 2005).

In addition to the water necessary to support plant function, available soil moisture has far-reaching impacts on soil properties. Sutton (1991) writes, "Of the many factors that influence root growth and root function, soil water is of particular importance since it acts on growth and function both directly and indirectly through its influence on other factors such as nutrition, aeration, mechanical impedance, and soil temperature". Although macro- and micro-nutrient levels were sufficient at both sites, drier soil conditions at Interlaken may have decreased nutrient access and restricted growth.

Planting treatments influenced soil moisture conditions at each site, paralleling survivorship trends. During the 2008 summer season, all mulch treatments improved soil moisture conditions. These findings uphold claims that mulch improves soil moisture conditions (Appleton et al., 1990; Greenly and Rakow, 1996; Chalker-Scott, 2007). At West Duwamish in 2009, the trend was accentuated, with all mulch plots showing moister soils than plots that did not receive mulch at the time of planting (Figure 6). This is understandable since drip irrigation and irrigation gels were not applied in the second year. But the same was not true for Interlaken, suggesting that soils were too dry to benefit from mulch's influence on evaporative water loss.

It should be noted that the effect of the irrigation gel and drip irrigation treatments on soil moisture levels may not be well represented in the results. Both treatments were positioned to the right and left of a seedling while the soil moisture sensors were centered 15.24 cm (6 in) in front of a seedling. It is possible that the sensors did not pick up the effect of these treatments on soil moisture.

5.3 Physiological Responses

The relationship of seedling survivorship, soil texture, and available soil moisture conditions is captured by pre-dawn stem water potential. With less available soil moisture, seedlings at Interlaken were susceptible to more extreme water stress, matching mortality over time. All three species respond differently to reduced stem water potential (Nilsen and Orcutt, 1996) and so findings must be interpreted according to each species' known response, as shown in Table 5.

Table 5. Physiological responses to reduced stem water potential. Numbers represent stem water potential (MPa) during pre-dawn conditions. Adapted from PMS Instruments (2008) and Hinckley et al. (1982).

Tsuga heterophylla	***Thuja plicata***	***Abies grandis***	**Physiological responses**
-0.5 MPa	-0.7 MPa	-1.0 MPa	Growth not limited by water, supply adequate, seedling maintains maximum shoot growth
-1.0 MPa	-1.0 MPa	-1.2 MPa	Slight to moderate shoot growth reductions. Stress limits phloem transport, leaf expansion, and diameter growth, but is highly variable depending on environmental conditions
-1.5 MPa	-2.0 MPa	-2.4 MPa	Stress response initiated, i.e. vegetative growth limited, flowering stimulated. Stomata close, shoot growth stops, overall growth rate declines

ABGR is considered to be more tolerant to water deficits than TSHE or THPL (Hinkley et al., 1982). This was true at both sites in both years. In 2008, stem water potential was roughly -0.5 MPa for all treatments at West Duwamish, suggesting that the water supply was adequate for the species to maintain all functions. In 2009, during the height of the summer drought and during the highest temperatures recorded during the duration of the experiment, ABGR still maintained stem water potential around -1.0 MPa at West Duwamish. Conversely, Interlaken ABGR seedlings were impacted by drought conditions in both years. Control plots in the first year had an average of -2.5 MPa stem water potential, suggesting stress responses were triggered. Although no treatment effects were observed in the second year, mulch alone and mulch with drip irrigation improved stem water potential in the first summer.

Similarly, TSHE stem water potential in the first year followed survivorship trends closely, with drip irrigation and mulch significantly improving seedling water status and survivorship at Interlaken. No treatment effect was observed in the second year at Interlaken; all treatment types saw stem water potentials between -2.0 and -2.5 MPa, suggesting that all seedlings at Interlaken were extremely stressed in the second year. TSHE's extremely high mortality rate at Interlaken (79% overall) may be attributed to its higher susceptibility to xylem cavitation, effectively cutting off water flow in the xylem conduits (Kavanaugh and Zaerr, 1997). West Duwamish seedlings had slightly lower water potential in the second year than was experienced in the first year, but both years had low stress levels (ranging between -0.5 and -1.0 MPa), matching overall survivorship trends.

Of the three species, THPL had the lowest stem water potential, and like previous research, survivorship results suggest that THPL was able to tolerate low stem water conditions (Grossnickle, 1993). Potentials reached below -3.0 MPa in both years for seedlings in control plots at Interlaken and around -1.75 MPa in control plots in the second year at West Duwamish. Drip irrigation and mulch significantly improved stem water potential at Interlaken in 2008, while all mulch treatments increased stem water potential at West Duwamish in 2009, suggesting that mulch improved soil moisture conditions and in the long term, improved seedling physiological function.

5.4 Morphological Responses

Diameter, height, and biomass data confirm that Interlaken seedlings were unable to move beyond transplant stress and summer drought conditions to begin rapid growth. At the end of the experiment, many of the Interlaken seedlings were close to the same small size as when the experiment began. As has been the pattern, diameter, height, and biomass were significantly different between parks. Small height gains were made by seedlings that received water treatments (drip irrigation, irrigation gel, mulch + irrigation, and mulch + gel) at Interlaken. The presence of drip irrigation (irrigation alone and mulch + irrigation) increased diameter size for ABGR at Interlaken and West Duwamish. The clearest influence came from West Duwamish, where the presence of mulch increased height for TSHE, with mulch alone having the most influence. This is opposed to previous research that suggests wood chip mulch can influence available soil nitrogen and may inhibit growth (Kraus, 1988; Hallsby, 1995).

Biomass measurements taken at the beginning of the experiment on destructively sampled seedlings provide an interesting look at seedling morphology at the time of planting. Root:shoot (R:S) ratios suggest that seedlings from each species had significantly more shoots than roots (Figure 15). This is important because a seedling's root system must be able to absorb adequate water to support respiration and evaporative water loss from shoots (Grossnickle, 2005; Rose and Hasse, 2005). Root loss from injury and desiccation during the transplanting process (Reitveld, 1989), combined with transplant stress and droughty summer soil conditions to influence seedling survivorship.

Part of the issue in understanding morphological responses to each treatment comes from the bias introduced as seedling mortality increased. With very few remaining seedlings in some treatments at Interlaken, sample size was reduced. For example, TSHE at Interlaken treated as controls appear to have grown taller compared to seedlings in plots that received mulch alone. With two relatively large seedlings remaining out of the original thirty planted at Interlaken, mean height is highly skewed. This data must be examined with a close eye to survivorship results.

5.5 Other Factors Affecting Seedling Success

Existing canopy cover reduces light intensity and during summer drought conditions can reduce site temperatures and transpirational water loss (Hobbs, 1983). The three species selected for this research were chosen in part because of their tolerance of shaded conditions during the establishment phase. In contrast, observations at the more open West Duwamish experiment blocks (Figure 8) suggest that given adequate soil moisture conditions seedlings grew more in plots with more available light.

Canopy cover was the only measurement of other vegetation within this experiment. With both sites being under closed canopies, we can infer that large trees and shrubs existed in each block and may have competed for nutrients, light, and soil moisture. Although understory species were removed from within one foot of the experimental seedlings, competition was likely. At Interlaken, the extensive distribution of *Polystichum munitum* (sword fern) meant that within months of transplanting, seedlings were being over topped by fern fronds, strongly reducing light availability and exacerbating already droughty summer soils. Because of the extent of invasive plants, particularly *Hedera helix* (English ivy), at West Duwamish much of the ground cover and shrub layer was removed from the experiment blocks, leaving mostly bare ground and canopy trees. Soil water availability decreases as plant cover increases (Grossnickle, 2005) and so although canopy openness was similar between sites (Figure 8), shrub and ground cover likely influenced seedling water relations at Interlaken. Previous silviculture research suggests that controlling other vegetation on site can increase conifer seedling survivorship and growth, an important consideration for future urban forest restoration (Gjerstad et al., 1984; Balneaves, 1987; Rose and Ketchum, 2002).

Available soil moisture may have been further impacted by steep slope conditions in blocks 2 and 3 in Interlaken Park. Figure 17 compares percent slope and survivorship rates for each block at each park. The graph suggests that slope did not directly influence survivorship. Interlaken block 1 had gentler slope conditions comparable to all West Duwamish blocks, but seedling's still experienced high mortality.

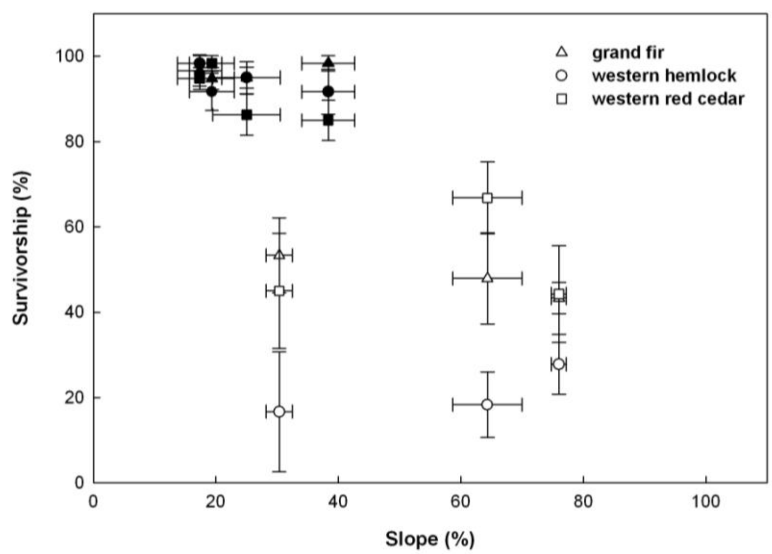

Figure 17. Average block survivorship by average block slope for each species at Interlaken (open symbols) and West Duwamish (closed symbols).

A final consideration of what influenced seedling success is the amount of water provided by the drip irrigation and DriWater irrigation gel treatments. The irrigation system delivered an estimated 7.57 liters (2 gallons) over two hours on a biweekly schedule to each seedling receiving drip irrigation or irrigation + mulch treatments. This amount and application interval may not be appropriate for sandy soils; commonly, less water more frequently is recommended for sandy soils (Harris et al., 2004). Considering that the two research sites fell on opposite ends of the soil texture spectrum, it is difficult to understand if in more moderate soil texture conditions we would have seen a more clear benefit of irrigation. This issue is amplified for DriWater irrigation gel, which only released an estimated 0.927 liters (0.245 gallons) of water from each tube for the entire summer. It may well be that this is too little water to sustain a seedling during summer drought conditions, but it is hard to say whether different site conditions would have shown a more positive influence of DriWater on survival or growth.

6.0 Conclusion

This experiment was developed to better understand common planting methods to reduce water stress and improve conifer seedling survivorship at Green Seattle Partnership restoration sites. Important site, species, and treatment findings are as follows:

- Distinct survivorship differences were observed between experiment sites and can be related to tested differences in soil texture; West Duwamish's clay loam soils provided for adequate soil moisture and high survival rates for all species, whereas Interlaken's sandy loam soils provided for poor soil moisture conditions and corresponding high seedling mortality, with ABGR, THPL, and TSHE experiencing the least to most mortality, respectively.
- West Duwamish findings suggest that GSP restoration sites that have similar environmental conditions, particularly soil texture conditions, will not require additional mulch, drip irrigation, or irrigation gel at the time of planting to assure high survival rates.
- Treatment influences were most pronounced at Interlaken because of poor soil moisture conditions. In the first year, all mulch treatments increased survivorship for THPL and TSHE, while ABGR was the only species to benefit from all mulch applications during the second year.
- Stem water potential results paralleled survivorship findings in the first year. At Interlaken, TSHE was less water stressed when treated with irrigation and mulch, while ABGR and THPL were less stressed with irrigation alone or in combination with mulch.
- The close to complete failure of TSHE at Interlaken suggests that the species may not be suitable for restoration plantings at the park. That said, restoration practices can be adjusted to match our findings at Interlaken by increasing the number of trees transplanted, always using mulch and irrigation, and altering survival expectations.

Seattle's alarming decline in forest canopy trees cannot be adequately addressed if conifer seedlings planted as part of the Green Seattle Partnership experience mortality rates as high as have occurred at Interlaken Park. This experiment captured important information about common planting methods, allowing for more objective application decisions that will save money, time and labor. Maybe more importantly, this research provides an unparalleled understanding of soil physical conditions and soil moisture conditions common at Seattle park restoration sites. These conditions are foundational to seedling establishment and as such, must be considered more as restoration planning and implementation continues. Recommendations for future restoration efforts and research include:

- Train forest steward volunteers and other project planners in methods to test soil texture (i.e. ribbon test, jar test).
- Develop a GIS database that captures soil texture information for individual restoration sites.
- Implement decision making tools that incorporate soil texture as an indicator of site soil moisture conditions and uses texture findings to inform irrigation and mulch application decisions.
- Use mulch rings to reduce summer water stress and increase seedling survivorship at sites with limited summer soil moisture.
- Where soils are primarily sand, use irrigation in combination with mulch and consider using less water during more frequent applications.
- Consider methods to reduce competition from existing native vegetation on sites where vegetation density may reduce available soil moisture, nutrients, and available light.
- Seek out conifer seedling stock types that are appropriate for droughty soil conditions.
- Use appropriate species for soil moisture conditions. Consider using more drought tolerant species at sites with droughty soils.
- Adjust planting density and seedling numbers to account for high mortality at sites where soil moisture is limited.

Literature Cited

Alexander, B., Sound Native Plants. Personal Communication. 24 July 2009.

Appelton, B.L., J.F. Derr, and B.B. Ross. (1990). The effect of various landscape weed control measures on the soil moisture and temperature, and tree root growth. *Journal of Arboriculture* 16(10): 264 – 268.

Arnott, J. T., B.G. Dunsworth, and C. O'Reilly. (1988). Effect of nursery culture on morphological and physiological development of western hemlock seedlings. In: *Proceedings, Combined Meeting of the Western Forest Nursery Associatio,: Western Forest Nursery Council, Forest Nursery Association of British Columbia, and Intermountain Forest Nursery Association,* August 8 – 11, 1988, Vernon, British Columbia, RM-167: 38 - 44.

Balneaves, J.M. (1987). Growth response of radiate pine to area of herbaceous weed control. In: *Proceedings of the 40th New Zealand Weed and Pest Control Conference,* August 11 – 13, 1987, Nelson, New Zealand: 49 - 51

Banerjee, M.J.G., J. Vanda, and E.P. Glenn. (2006). Native plant regeneration on abandoned desert farmland: effects of irrigation, soil preparation and amendments on seedling establishment. *Restoration Ecology* 14(3): 339 - 349.

Bhattacharjee, J., J.P. Taylor, Jr., L.M. Smith, and L.E. Spence. (2008). The importance of soil characteristics in determining survival of first-year cottonwood seedlings in altered riparian habitats. *Restoration Ecology* 16(4): 563 – 571.

Blanco-Garcia, A. and R. Lindig-Cisneros (2005). Incorporating restoration in sustainable forestry management: using pine-bark mulch to improve native species establishment on tephra deposits. *Restoration Ecology* 13(4): 6.

Boersma, P.D., S.H. Riechard, and A.N. Van Buren (editors). (2006). Invasive Species in the Pacific Northwest. *University of Washington Press*, Seattle, WA.

Burns, R.M., and B.H. Honkala. (1990). Silvics of North America: 1 Conifers. Washington D.C.: U.S. Department of Agriculture, Forest Service.

Cahill, A., Chalker-Scott, L., and K. Ewing. (2005). Wood-chip mulch improves woody plant survival and establishment at no-maintenance restoration site (Washington). *Ecological Restoration* 23(3): 212-213.

Chalker-Scott, L. (2007). Impact of mulches on landscape plants and the environment - a review. *Journal of Environmental Horticulture* 25(4): 239 - 249.

Cleary, B., J. Zaerr, J. Hamel. (2007). Guidelines for measuring plant moisture stress with a pressure chamber. http://pmsinstrument.com/tutorials/Guidelines%20Booklet.pdf. Accessed 15 August 2008.

Cochard, H. (1992). Vulnerability of several conifers to air embolism. *Tree Physiology* 11: 73-83.

Coder, K.D. (1996). Identified Benefits of Community Trees and Forests. *University of Georgia Cooperative Extension Service, Forest Resources Publication*: FOR96-39.

Crawley, M.J. (2007). *The R Book*. Wiley: Silwood Park, UK.

Dellavalle, N.B. (1992). Efficacy test of driWater: a slow water release substrate. *Communications in Soil Science and Plant Analysis* 23(17 - 20): 6.

Devine, W.D.H., A. Constance, and L.P. Lathrop. (2007). Post-Planting Treatments Increase Growth of Oregon White Oak (*Quercus garryana* Dougl. ex Hook.) Seedlings. *Restoration Ecolog*y 15(2): 11.

DriWater, Inc. DriWater: Specifications - 3" Tube & Gel Pac. http://www.driwater.com/productuse/how/pro_tube/tube.pdf. Accessed on 11 January 2008.

DriWater, Inc. http://www.driwater.com. Accessed 11 January 2008.

Duryea, M.L., R.J. English, and L.A. Hermansen. (1999). A comparison of landscape mulches: chemical, allelopathic, and decomposition properties. *Journal of Arboriculture* 25(2): 88 - 96

Dwyer, J.F., E.G. McPherson, H.W. Schroeder, R.A. Rowntree. (1992). Assessing the benefits and costs of the urban forest. *Journal of Arboriculture 18*(5): 227 - 234.

Ewing, K. (2002). Effects of initial site treatments on early growth and three-year survival of Idaho fescue. *Restoration Ecology* 10(2): 7.

Franklin, J.F. and C.T. Dyrness. (1988). *Natural Vegetation of Oregon and Washington*. Oregon State University Press: Corvallis, OR.

Gjerstad, D.H., L.R. Nelson, J.H. Dukes, Jr., and W.A. Retzlaff. (1984). Growth response and physiology of tree seedlings as affected by weed control. In: *Seedlings physiology and reforestation success: Proceedings of the Physiology Working Group Technical Session, Society of American Foresters National Convention,* Portland, OR, October 16- 20, 1983. Forestry Sciences, The Hague: 179 - 224

Greenly, K.M. and D.A. Rakow. (1995). The effect of wood mulch type and depth on weed and tree growth and certain soil parameters. *Journal of Arboriculture* 21(5): 225 - 232.

Grossnickle, S. C. (1993). Shoot water relations and gas exchange of western hemlock and western red cedar seedlings during establishment on a reforestation site. *Trees - Structure and Function* 7(3): 148 - 155.

Grossnickle, S. C. (2005). Importance of root growth in overcoming planting stress. *New Forests* 30 (2/3): 273 - 294.

Hallsby, G. (1995). Field performance of outplanted Norway spruce: effects of organic matter amendments and site preparation. *Canadian Journal of Forest Research* 25(8): 1356-1367.

Hau, B.C.H. and R.T. Corlett. (2003). Factors affecting the early survival and growth of native tree seedlings planted on a degraded hillside grassland in Hong, Kong, China *Restoration Ecology* 11(4): 483 - 488.

Hinckley, T.M., R.O. Teskey, R.H. Waring, Y. Morikawa. (1982). The water relations of true firs. In: *Proceedings of the Biology and Management of True Fir in the Pacific Northwest Symposium*. College of Forest Resources, University of Washington, Seattle, WA, USA.

Hobbs, S.D. (1973). The influence of species and stocktype selection on stand establishment: An ecophysiological perspective. In: *Seedlings physiology and reforestation success: Proceedings of the Physiology Working Group Technical Session, Society of American Foresters National Convention,* Portland, OR, October 16- 20, 1983. Forestry Sciences, The Hague: 179 - 224

Holliman, P.J., J.A. Clark, J.C Williamson, and D.L. Jones. (2005). Model and field studies of the degradation of cross-linked polyacrylamide gels used during the revegetaion of slate waste. *Science of the Total Environment* 336(1/3): 13 – 24.

Howard, J.L., and K.C. Aleksoff. (2000) Abies grandis. In: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/. Accessed 7 March 2009

Hsiao, T.C. (1973). Plant responses to water stress. *Annual Review of Plant Physiology* 24: 519-570

Jones, H.G. (2007). Monitoring plant and soil water status: established and novel methods revisited and their relevance to studies of drought tolerance. *Journal of Experimental Botany* 58(2): 119-130

Lambers, H., F.S. Chapin, and T.L. Pons. (2008). *Plant Physiological Ecology.* New York: Springer

Kavanagh, K.L. and J.B Zaerr. (1997). Xylem cavitation and loss of hydraulic conductance in Western Hemlock following planting. *Tree Physiology* 17: 59-63.

Kohnke, H., and D.P. Franzmeier. (1995). *Soil Science Simplified*. Prospect Heights, III: Waveland Press.

Kozlowski, T.T., and W.J. Davies. (1975). Control of water balance in transplanted trees. *Journal of Arboriculture* 1(1): 1-10.

Krasowski, M.J. and Owens, J.N. (1991). Growth and morphology of western red cedar seedlings as affected by photoperiod and moisture stress. *Canadian Journal of Forest Research* 21: 340-352.

Kraus, H. (1998). Effects of mulch on soil moisture and growth of desert willow *HortTechnology* 8(4): 588-590.

Kuhns, L.J. (1992). Efficacy and phytotoxicity of three landscape herbicides with and without a light mulch. *Proceedings of the Northeastern Weed Science Society* 46: 85 - 89

Lewinsohn, E., M. Gijzen, R.M Muzika, K. Barton, and R. Croteau. (1993). Oleoresinosis in grand fir (*Abies grandis*) saplings and mature trees: modulation of wound response by light and water stress. *Plant Physiology* 101(3): 1021-1028.

Livingston, N.J. and T.A. Black. (1987). Water stress and survival of three species of conifer seedings planted on a high elevation south-facing clear-cut. *Canadian Journal of Forest Research* 17: 1115-1123.

Maduzia, F., Frank Maduzia Jr. and Son, LLC. Personal Communication. 21 February 2008.

McIntosh, P. 2009. Seattle Parks and Recreation: Interlaken Park and Boulevard. *Sherwood Park History Files*. http://www.seattle.gov/parks/history/InterlakenPK.pdf. Accessed 4 October 2009.

Nilsson, U. and G. Orlander. (1996). Effects of regeneration methods on drought damage to newly planted Norway spruce seedlings. *Canadian Journal of Forest Research* 25: 790-802.

NOAA National Climatic Data Center (2009). http://www.ncdc.noaa.gov/oa/ncdc.html. Accessed 13 October 2009

NOAA. (1985). Climate Narratives of the States: Washington. http://www.wrcc.dri.edu/narratives/WASHINGTON.htm. Accessed 5 November 2009.

NOAA. (2009a). National Weather Service Forecast Office Seattle, WA. http://www.weather.gov/climate/local_data.php?wfo=sew. Accessed 26 October 2009.

NOAA. (2009b). National Weather Service Forecast Office Seattle, WA. http://www.wrh.noaa.gov/climate/monthdisp.php?stn=KSEW&year=2009&mon=7&wfo=sew. Accessed 22 November 2009.

Peterson, B. (2008). Conifer transplant survival in urban forests. MS Thesis. University of Washington, Seattle, WA.

PMS Instruments Company. (2008) PMS Guidelines for Selected Conifers. http://pmsinstrument.com/PMS-Conifer.pdf. Accessed 15 August 2008.

Ramsay, M., N. Salisbury, and S. Surbey. (2004). A citywide survey of habitats on public lands in Seattle: a tool for urban restoration planning and ecological monitoring. *Proceedings of 16th International Conference of the Society for Ecological Restoration*, *August 24-26, 2004 Victoria, Canada*

Reitveld, W.J. (1989). Transplanting stress in bareroot conifer seedlings: its development and progression to establishment. *Northern Journal of Applied Forestry* 6(3): 99 – 107.

Richardson, J. (2008). Estimating leaf area index from multiple return, small-footprint aerial LiDAR at Washington Park Arboretum. MS Thesis. University of Washington, Seattle, WA

Ritchie, G.A. and J.R. Dunlap. (1980). Root growth potential: its development and expression in forest tree seedlings. *New Zealand Journal of Forest Science* 10: 218

Rose, R. and D.L. Haase. (2005). Root and shoot allometry of bareroot and container Douglas-fir seedlings. *New Forests* 30: 215-233.

Rose, R. and J.S. Ketchum. (2002). Interaction of vegetation control and fertilization on conifer species across the Pacific Northwest. *Canadian Journal of Forest Research* 32: 136 - 152

Sands, R. (1984). Transplanting stress in radiata pine. *Australia Forest Resources* 14: 67 – 72.

Seattle Parks and Recreation (2009) Interlaken Park. http://www.cityofseattle.net/parks/park_detail.asp?id=3023. Accessed 4 October 2009.

Seattle Urban Nature Project. (2000a). Publication 25: Volunteer Park, Eastlake, Montlake & Vicinity Habitat Map. http://www.seattleurbannature.org/Resources/CEmaps/ce-25.html. Accessed 12 May 2009.

Seattle Urban Nature Project. (2000b). Publication 42: South Seattle Community College & Vicinity Map. http://www.seattleurbannature.org/Resources/SWmaps/sw-42.html. Accessed 12 May 2009.

UMASS Soil and Plant Tissue Testing Lab. (2009). Soil Analysis Report for Needeleaf Evergreens. http://www.umass.edu/plsoils/soiltest/interp1.htm. Accessed 9 November 2009.

Stuckey, A. (2007). Effects of planting techniques on Pacific Northwest native conifers in urban forested open-spaces. MEH Thesis. University of Washington, Seattle, WA

Sutton, R.F. (1991). Soil properties and root development in forest trees: a review. Forestry Canada, Sault Ste., Marie, ON.

Swearingen, J.M. and S. Diedrich. (2006) Plant Conservation Alliance's Alien Plant Working Group: *Hedera helix* Fact Sheet. http://www.nps.gov/plants/alien/fact/hehe1.htm. Accessed 9 November 2009.

Tesky, J.L. (1992a). Thuja plicata. In: Fire Effects Information System, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/. Accessed 7 March 2009

Tesky, J.L. (1992b). Tsuga heterophylla. In: Fire Effects Information System, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/. Accessed 7 March 2009

Thien, S.J. (1979). A flow diagram for teaching texture by feel analysis. *Journal of Agronomic Education* 8: 54-55.

Tyree, M.T. and J.S. Sperry. (1988). Do woody plants operate near the point of catastrophic xylem dysfunction caused by dynamic water stress? *Plant Physiology* 88: 574-580.

Waring, R.H. and J.F. Franklin. (1979). Evergreen Coniferous Forests of the Pacific Northwest. *Science* 204: 1380-1386.

Weaver, E. ed. (2005). 20 Year Strategic Plan. www.greenseattle.org/files/gsp-20yrplan5-1-06.pdf/view. Accessed 12 September 2007

Weiner, J. and M. Vila. (2004). Are invasive species better competitors than native plant species? – evidence from pairwise experiments. *Oikos*, 105(2): 229 – 238.

Wolf, K. (1998). Fact Sheet #1: Urban Nature Benefits: Psycho-Social Dimension of People and Plants. Center for Urban Horticulture, University of Washington, Seattle, WA

Zar, J.H. (2008). Biostatical Analysis*. Prentice Hall,* Indianapolis, IN.

Zobel, D.B. (1974). Local variation in integrating *Abies Grandis-A. concolor* populations in the central Oregon Cascades. II. Stomatal reaction to moisture stress. *Botanical Gazette* 135(3): 200-210.

Appendix A: Experiment Photos

Figure 18 A) West Duwamish block 1 prior to invasive plant removal. B) Interlaken block 2 prior to invasive plant removal and native plant relocation. C) Contractor installing seedlings in Interlaken block 1. D) Interlaken block 1 after seedling installation, mulch application, and DriWater tube installation. E) West Duwamish block 4 after invasive plant removal prior to seedling installation, with planting locations flagged according to species. F) TSHE seedling at Interlaken block 2 after planting in March 2008 G) THPL seedling with DriWater tubes and gel packs prior to installation on June 15, 2008. H) Drip irrigation hose and emitters adjacent to TSHE at West Duwamish block 4. I) ABGR with needle dieback at Interlaken during summer 2009.

Appendix B: Analysis of Variance Tables

Table 6. ANOVA table for survivorship of each species in the first year at each site

Site	Species	Factor	Df	Sum Sq	Mean Sq	F Value	P Value
Interlaken	TSHE	block	2	0.05021	0.02511	0.5819	5.77E-01
		water	2	0.17288	0.08644	2.0034	0.18548
		mulch	1	0.22445	0.22445	5.2022	0.04572
		water:mulch	2	0.0219	0.01095	0.2538	0.7807
		residuals	10	0.43146	0.04315		
West Duwamish	TSHE	block	3	0.007383	0.002461	0.8406	0.4926
		water	2	0.000533	0.000267	0.0911	0.9134
		mulch	1	0.006017	0.006017	2.055	0.1722
		water:mulch	2	0.014533	0.007267	2.482	0.1172
		residuals	15	0.043917	0.002928		
Interlaken	ABGR	block	2	0.0741	0.03705	1.6692	0.2369
		water	2	0.101233	0.050617	2.2804	0.1528
		mulch	1	0.063606	0.063606	2.8655	0.1214
		water:mulch	2	0.029544	0.014772	0.6655	0.5354
		residuals	10	0.221967	0.221967		
West Duwamish	ABGR	block	3	0.005	0.001667	1	0.4199
		water	2	0.003333	0.001667	1	0.3911
		mulch	1	0.001667	0.001667	1	0.3332
		water:mulch	2	0.003333	0.001667	1	0.3911
		residuals	15	0.025	0.001667		
Interlaken	THPL	block	2	0.11963	0.05982	1.6992	0.2316
		water	2	0.23563	0.11782	3.3467	0.07714
		mulch	1	0.26645	0.26645	7.5689	0.02044
		water:mulch	2	0.0163	0.00815	0.2315	0.79747
		residuals	10	0.35203	0.0352		
West Duwamish	THPL	block	3	0.073679	0.02456	8.7931	0.001323
		water	2	0.005758	0.002879	1.0308	0.380649
		mulch	1	0.001837	0.001837	0.6579	0.429991
		water:mulch	2	0.030925	0.015462	5.5361	0.015826
		residuals	15	0.041896	0.002793		

Table 7. ANOVA table for survivorship of each species in the first year at each site

Site	Species	Factor	Df	Sum Sq	Mean Sq	F Value	P Value
Interlaken	TSHE	block	2	0.04218	0.02109	0.4169	0.670
		water	2	0.11284	0.05642	1.1155	0.3653
		mulch	1	0.12169	0.12169	2.4058	0.1519
		water:mulch	2	0.02404	0.01202	0.2377	0.7928
		residuals	10	0.50582	0.05058		
West Duwamish	TSHE	block	3	0.018333	0.006111	0.8594	0.4834
		water	2	0.015833	0.007917	1.1133	0.3542
		mulch	1	2.93E-31	2.93E-31	4.12E-29	1
		water:mulch	2	0.0175	0.00875	1.2305	0.32
		residuals	15	0.106667	0.007111		
Interlaken	ABGR	block	2	0.030044	0.015022	0.5643	0.58588
		water	2	0.042711	0.021356	0.8022	0.47522
		mulch	1	0.196356	0.196356	7.3756	0.02172
		water:mulch	2	0.013378	0.006689	0.2513	0.78259
		residuals	10	0.266222	0.266222		
West Duwamish	ABGR	block	3	0.004846	0.001615	0.3264	0.8063
		water	2	0.007008	0.003504	0.7081	0.5083
		mulch	1	0.000504	0.000504	0.1019	0.754
		water:mulch	2	0.011008	0.005504	1.1123	0.3545
		residuals	15	0.074229	0.004949		
Interlaken	THPL	block	2	0.19668	0.09834	2.0133	0.18418
		water	2	0.19234	0.09617	1.9689	0.19012
		mulch	1	0.21561	0.21561	4.414	0.06198
		water:mulch	2	0.06101	0.03051	0.6245	0.55516
		residuals	10	0.48846	0.48845		
West Duwamish	THPL	block	3	0.075712	0.025237	5.2826	0.01097
		water	2	0.022575	0.011288	2.3626	0.12824
		mulch	1	0.000504	0.000504	0.1055	0.74978
		water:mulch	2	0.041008	0.020504	4.2918	0.03358
		residuals	15	0.071662	0.004777		