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Early in the establishment of Pacific Northwest conifer plantations, herbaceous weeds often decrease seedling growth through competition for soil moisture during the dry summer months. Critical period studies have reported that reductions in competitive weed cover are necessary during the initial years of establishment to avoid reductions in seedling growth. Six herbicide treatment regimes commonly applied over the first two years of plantation establishment were studied in a randomized block design to understand Douglas-fir seedling growth response. First season results demonstrate that seedling growth was improved when competing vegetation cover was reduced through the regimes examined. Volume growth increased from 5 cm^3 in the untreated control to greater than 20 cm^3 when total weed cover was reduced below 10%. Multiple vegetation surveys within a single season revealed that reductions in total vegetation cover were associated with the treatments and tracked distinct changes to the species composition of the weed communities that remained in these plots. Soil moisture and xylem water potential were intensively measured and demonstrated that

the vegetation management regimes utilized in this study improved growing conditions. While all herbicide regimes in the experiment increased seedling growth relative to the untreated control, the incorporation of a site preparation spray and a spring release was the most effective treatment. This regime had a profound impact on seedling growth, vegetation cover, soil moisture, and xylem water potential during the initial season of the critical period.

EVALUATING THE EFFECTIVENESS OF COMMONLY USED HERBACEOUS WEED CONTROL REGIMES IN A PACIFIC NORTHWEST CONIFER PLANTATION

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Eric J. Dinger, Author

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CONTRIBUTION OF AUTHORS

Robin Rose assisted with the design and reporting of the experiment. Lee Rosner was involved with the experimental design and implementation of the project. Douglas Maguire, Manuela Huso, Lisa Ganio, and Jennifer Kling provided statistical assistance.

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CHAPTER 1

1.0 LITERATURE REVIEW

1.1 An Overview of Vegetation Management

Plants seek light, nutrients, and water in quantities necessary for survival, growth, and reproduction (Shadbolt and Holm 1956). Intense competition for any of these resources often results in a decrease in the potential growth of a desired crop species (Cousens 1987). Agricultural researchers were the first to analyze this phenomenon and have carefully chronicled the negative interaction between many varieties of crops and the plant communities, usually deemed weeds due to their undesirability, that develop in field settings (Brimhall et al. 1965; Buchanan and Burns 1970; Shadbolt and Holm 1956).

From the mid 1950s to the early 1970s, agricultural researchers quantified the impact of competition on vegetable crop yield. Results from this research demonstrated that crops such as onions, carrots, sugar beets, and cotton had significant yield losses when weed species were present (Buchanan and Burns 1970, Brimhall et al. 1965, Shadbolt and Holm 1956). This early research clearly demonstrated the need for weed control and hypothesized that there must be a specific timeframe when a reduction in the amount of weed cover is necessary, so that crop growth is maximized while minimizing the cost per unit of yield increase. Nieto et al. (1968) tested the growth of corn subjected to varying amounts of time under weed free and weed infested situations. Their results illustrated the critical period concept by defining the specific amount of time that weeds must be controlled in order to maximize corn yield

(Nieto et al. 1968). This concept, developed through further research, (Balandier et al. 2006) identified the weeks when weed control was necessary for maximizing growth in a variety of crop species and has become a standard operational practice for annual crop production (Zimdahl 1988).

Forest managers in the Pacific Northwest (PNW) were keenly aware of the need to quickly establish plantations (Miller et al. 1991; Petersen and Newton 1985) in order to protect assets and meet legal reforestation requirements set forth by state law in the early 1970s (ODF 2003; WADNR 2006). Herbicide trials demonstrated that seedling growth, much like food crops, benefited from reductions in weed cover. Increases in height, diameter, and stem volume were found when competing vegetation was controlled for the initial years of plantation establishment (Cole and Newton 1988; Cole et al. 1989; Creighton et al. 1987; Newton and Preest 1988). Similar to the agricultural literature, this work led researchers to believe there was a specific timeframe when weed control was crucial, with the key exception that this critical period may occur over a number of successive years rather than within a single season.

It was not until Robert Wagner's work in the mid-1990s that the critical period concept appeared in forestry literature (Wagner et al. 1996). The primary component of critical period analysis was the understanding of seedling growth in relation to weed free and weed infested situations over the course of several years (Rosner and Rose 2006; Wagner et al. 1996). By studying this interaction with different species of trees, response curves were developed that demonstrated the years when vegetation must be controlled in order to avoid reductions in growth (Wagner 2000; Wagner et al. 1996).

The critical period concept spawned a series of studies specific to Pacific Northwest conifer plantations with the similar goal of creating the most efficient seedling growth through the establishment period. Expanding areas of weed control (Cole and Newton 1987; Rose and Rosner 2005), fertilizer-vegetation management interactions (Rose and Ketchum 2002), comparisons of vegetation management regimes (Balandier et al. 2006; Richardson 1993), and the interaction of seedling size and weed control (Long and Carrier 1993; Rose and Ketchum 2003) have been studied. Each of these studies identified specific components that must be considered in order to achieve forest regeneration objectives. Common to all of them was the recognition that significant negative impacts on seedling growth can be avoided when weed cover is reduced through the use of herbicides.

1.2 Vegetation Community Development

Logging in the Pacific Northwest is currently one of the major sources of disturbance to forest ecosystems in the region (Walstad et al. 1987). The removal of the conifer overstory, or a significant portion of it, allows more sunlight to reach the ground and temporarily decreases the demand for soil moisture (Chen et al. 1995; Gray et al. 2002). Soil disturbance occurring through harvesting operations can expose bare mineral soil, turn over large portions of the seed bank, and create adequate conditions for seed germination and plant development (Dyrness 1973; Halpern 1989). Plant species are capable of invading recently harvested areas from a variety of sources including the existing seed bank, on-site vegetative reserves, or seed rain (Chen 2004; Dyrness 1973; Halpern 1989; Walstad et al. 1987). Once present on a site, the growing conditions enable many plant species to grow rapidly, capture site resources, and compete with desired crop trees (Chen 2004; Dyrness 1973; Halpern 1989).

Development of this weed community is largely determined by three general mechanisms of succession; facilitation, tolerance, or inhibition (Connell and Slatyer 1977). Facilitation occurs as one species prepares the site for a second in a series of events which commonly occurs (but is not limited to) areas experiencing primary succession (Connell and Slatyer 1977). Plants that exploit different niches within a particular disturbed site exhibit tolerance when they coexist with little competitive overlap due to specific life history traits (Connell and Slatyer 1977). Inhibition is the mark of competition where certain species are better equipped to utilize current site resources and secondary species grow under lower resource availability or must invade after the dominant species have senesced (Connell and Slatyer 1977).

Inhibition is the mechanism that forest managers are most interested in preventing during plantation establishment. Silvicultural treatments are prescribed to channel site resources into the desired seedlings by reductions in the cover of potentially inhibiting weed species. Herbicides are chemicals that disrupt normal plant functions and cause severe physiologic impairment and/or death (William 1994). They are used to reduce weed cover so that the desired seedling species are given a temporary competitive advantage and are commonly applied in a sequence of years to ensure that seedlings have optimum growing conditions through the critical period of plantation establishment. A list of commonly used herbicides as part of sivicultural prescriptions in the PNW has been compiled and is provided in Appendix 1.

Weed control through the use of herbicides has been tested in a variety of forestry situations for the purpose of releasing seedlings from competition (Walstad and Kuch 1987). Incremental reductions in the amount of competition around crop trees have been shown to create progressive increases in height, ground line diameter, and volume growth, as well as decreases in height to diameter ratio (Newton and Preest 1988; Petersen and Newton 1985; Petersen et al. 1988; Rose et al. 1999; Rosner and Rose 2006). The impact on seedling growth was cumulative as those seedlings receiving less control continually lagged behind those growing under more weed free situations. Currently, research is needed that compares specific herbicide treatment regimes employed by forest managers in the PNW with regard to their effectiveness at reducing weed cover and increasing seedling growth.

1.3 Vegetation Community Composition

Vegetation management research has principally focused on reducing the total amount of weed cover (usually below 20%) to levels that promote seedling growth (Wagner 1989). In order to assess the effectiveness of the treatments employed in the experiments, sampling of the vegetation community has typically occurred once during the mid-summer (Cain 1991; Freedman et al. 1993; Newton and Preest 1988; Petersen et al. 1988; Roberts et al. 2005; Rose et al. 1999; Sullivan et al. 1998). Multiple vegetation surveys within a single year that are designed to document the development of the vegetation community at the species level are surprisingly lacking in the literature. Without repeated vegetation surveys, the rebound of the vegetation community during the first year after logging disturbance would be difficult to capture. The seasonal development of this early seral community would provide a basis for understanding the change in competitive growing conditions created during the growing seasons of the critical period. Zutter et al. (1986) was one of the few to complete multiple surveys for the assessment of total cover. His findings demonstrated a major difference in how the herbaceous and woody above-ground biomass responded to disturbance and the use of herbicides. The herbaceous component was found to be the primary contributor to the depletion of soil moisture and increase in the physiological stress on planted pines in the southeast for the initial two years of plantation establishment (Zutter et al. 1986).

Generally, the herbaceous component of the weed community is the first to rebound after a disturbance with the woody portion of the community slightly slower to respond (Chen 2004; Halpern 1989; Rose et al. 1999; Zutter et al. 1986). Studies in the PNW have shown that herbaceous vegetation invading a site is a major competitor for the first few years and that woody vegetation is slower to develop but has much longer-lasting effects (Newton and Preest 1988; O'Dea et al. 1994; Rose et al. 1999; Rose and Rosner 2005). Forestry studies in the southeastern United States have found similar trends with loblolly and slash pine plantations (Cain 1991; Lauer et al. 1993; Miller et al. 1991).

The development of this early herbaceous vegetation community directly impacts seedlings in the sensitive time immediately following planting (Cole and Newton 1987, Rose et al. 1998, Newton and Preest 1988). Their rapid occupancy of the site is primarily due to the fact that many of these herbaceous weeds are capable of disseminating large amounts of seed, exhibit minimal germination requirements, and are known for possessing rapid growth rates (Balandier et al. 2006; Radosevich and Holt 1984). These weeds establish themselves and extend their roots in the upper soil horizons where they directly compete with seedlings for site resources (Sands and Nambiar 1984).

Herbicides have been shown to affect the species composition of the vegetation community and can dramatically alter the species capable of growing in treatment plots (Boateng et al. 2000; Boyd et al. 1995; Freedman et al. 1993). Research has suggested that certain treatment regimes reduced a particularly dominant species, opened germination sites, and changed growing conditions such that the community composition shifted toward species with different life history traits (Boyd et al. 1995; Freedman et al. 1993; Halpern 1989). This shift has the potential to create a site that is dominated by weed species that may be much more undesirable than the species already present. There is anecdotal evidence among researchers and field foresters in the PNW that specific treatment regimes (or the chemicals included in the prescriptions) can shift the composition of the weed community. Research is needed to rigorously test how treatment regimes alter the composition of the weed communities in response to herbicide use.

1.4 Soil Moisture

Depending on parent material, development, and textural makeup, soil has a specific ability to hold and release moisture. The amount of water that can be held by a specific soil type against the force of gravity is defined as field capacity and is a direct function of the complex matrix of sand, silt, and clay particles, pore spaces, and organic matter (Brady and Weil 2002). While nutrients and/or light can be limiting resources in many ecosystems, soil moisture takes prime importance in areas with a pronounced summer drought (Brady and Weil 2002; Newton and Preest 1988; Petersen et al. 1988; Powers and Reynolds 1999; Zutter et al. 1986). The PNW is dominated by a Mediterranean climate which is known for having cool wet winters followed by summer months with high air temperatures, low relative humidity, and usually less than 10 cm of precipitation (UW 2007). During this summer drought, soil at field capacity becomes a moisture reserve that enables plant growth in the absence of further moisture input from precipitation during the growing season.

Seedlings have the ability to exploit only a small portion of the upper soil horizons during the first years of plantation establishment. Their limited root systems prevent them from accessing soil moisture reserves found in deeper horizons and/or through a more extensive area (Czarnomski et al. 2005; Sands and Nambiar 1984). Competition for moisture between weeds and seedlings occurs where their root zones overlap (depending on the weed species and seedling stocktype), typically the uppermost 10 to 20 cm. Premature depletion of soil moisture in this zone causes seedlings to experience severely desiccating conditions as they respire, photosynthesize, and grow (Nambiar and Sands 1993).

Reducing the weed cover on a site has large impacts on seedling growth response by increasing the amount of soil moisture available (Bassett 1964; Creighton et al. 1987; Newton and Preest 1988; Pessin 1938; Petersen et al. 1988; Powers and

Reynolds 1999; Roberts et al. 2005; Sands and Nambiar 1984; Stransky 1961). Reducing the competing vegetation through the use of herbicides reserves soil moisture that can be used later in the growing season, thereby lengthening the effective growing season and increasing total growth (Harrington and Tappeiner 1991; Nambiar and Sands 1993; Newton and Preest 1988). While these studies utilized herbicide treatments to reduce weed cover and improve soil moisture conditions, the herbicide applications were not designed to test regimes similar to those employed operationally in PNW conifer plantations. In one study, soil moisture depletion was tested utilizing (Roberts et al. 2005) herbicide treatments that were not intended to mimic operational regimes and soil moisture was measured at six irregular intervals in year two and biweekly in year three. Zutter et al. (1986) recommended that regular intensive measurements of soil moisture depletion in response to specific regimes will be needed to provide an understanding of growth mechanisms during this early integral portion of the critical period.

1.4.1 Soil Moisture Sensor Calibration

Gypsum blocks, soil cores, neutron probes, and electronic sensors have all been used to calculate volumetric soil moisture in forestry situations. Each method has advantages and drawbacks depending on the needs of the researcher and the conditions on the site. Electronic sensors have been shown to provide quick, accurate, and relatively inexpensive readings of volumetric soil moisture (Czarnomski et al. 2005). These sensors calculate volumetric soil moisture by relying on the dielectric constant of water and require calibration to the specific soil type on the study site in order to ensure accuracy (Czarnomski et al. 2005).

Water influences the rate at which an electrical signal will travel through the soil due to its higher dielectric constant relative to mineral soil and pore space (Topp et al. 1980). Both the Hydrosense TDR and ECH2O soil moisture probes use time domain reflectometry to measure volumetric soil moisture (Czarnomski et al. 2005). These instruments estimate the volumetric soil moisture based on the change in the electrical signal developed by the probe (Czarnomski et al. 2005; Dean et al. 1987; Topp and Davis 1985; Topp et al. 1980). The Hydrosense TDR probe propagates a signal along two parallel rods and measures the capacitance of the soil to predict this dielectric constant (Topp et al. 1980). The ECH2O soil moisture probe measures the amount of time it takes to charge a capacitor (the probe itself) that is in the soil (Czarnomski et al. 2005). Regardless of measurement technique, a standard equation specific to each probe type is used to calculate the volumetric soil moisture based on the signal developed from a "general" soil. Higher electrical conductivity or a soil that has a different sand-silt-clay content than the "general" soil type can result in inaccurate readings, necessitating the development of equations that calibrate these probes to the specific soil type on the study site (Czarnomski et al. 2005; Dean et al. 1987; Topp and Davis 1985).

1.5 Plant Moisture Stress

Plants depend upon a continuous supply of water from the soil matrix to living tissues (Glerum and Pierpoint 1968). Moisture stress develops when water becomes limiting in the continuum that exists between the soil, plant, and atmosphere (Nambiar and Sands 1993; Newton and Preest 1988). A long dry PNW summer, competition from other plants, or a combination of the two can deplete soil moisture resulting in an increasing level of tension on a seedling's water column on both daily and seasonal time scales (Gates 1991; Ritchie and Landis 2005). Recovery from normal diurnal stresses typically occurs at night when plants are capable of reducing water column tension through extraction of soil moisture in the absence of rapid losses that occur during daytime gas exchange (Kozlowski 1958). Night recovery is limited however as summer drought continues without soil recharge, so desiccating conditions and/or heavy competition will gradually widen the gap between the moisture needed and moisture remaining in the soil matrix. If this stress is severe enough, it can cause a build-up of tension resulting in stomatal closure, an adaptation that preserves the integrity of the water column. Stomatal closure decreases daily photosynthesis, photosynthetic efficiency, growth, and can eventually lead to cavitation and plant death (Bond and Kavanagh 1999; Brix 1979; Kozlowski 1958; Kramer and Kozlowski 1979).

Xylem water potential, a direct measurement of plant moisture stress, is often assessed using a pressure chamber that was developed by Scholander et al. in the 1960s (Scholander et al. 1965). The device uses nitrogen gas to measure the amount of pressure (reported in negative megapascals, -MPa) required to force water in the xylem tissue out the cut end of a leaf or small branch sample taken from a plant. The amount of pressure required to accomplish this is equivalent to the amount of tension the water column was originally under (Waring and Cleary 1966). Bond and

Kavanaugh (1999) studied the effect of moisture stress on the stomatal behavior of Douglas-fir and found that stomatal conductance was greatly reduced as moisture stress increased beyond -1.0 MPa (Bond and Kavanagh 1999). By measuring photosynthetic rates with an infrared CO_2 gas analyzer in conjunction with plant moisture stress, Brix (1979) found that Douglas-fir has the ability to maintain nearly 100% photosynthetic efficiency down to -1.0 MPa of xylem water potential. Decreasing xylem water potential beyond this point continually drops net photosynthetic activity until it reaches approximately 20% of its maximum at -2.2 MPa (Brix 1979).

Heavy competition from weed species can cause premature depletion of soil moisture that triggers a general slowing of seedling metabolic processes through a decrease in xylem water potential and inhibition of photosynthesis. If this occurs early in the growing season, there is a longer period of time that seedlings are exposed to these low xylem water potentials during the summer months. The cumulative effect of lower soil moisture and lower xylem water potentials over extended periods causes reductions in seedling growth (Harrington and Tappeiner 1991; Nambiar and Sands 1993; Newton and Preest 1988; Petersen et al. 1988). The use of herbicides during the critical period is designed to increase the amount of water available for tree seedlings and enable them to maximize growth potential.

Due to the determinant growth habit of Douglas-fir, the potential leaf area is dependent on the bud that was formed the previous year (Tappeiner et al. 1987). If that bud is formed under conditions of severe moisture stress due to competition, it will be much smaller (i.e. less leaf primordia) with less stored carbohydrates to utilize the following spring. Height growth as well as lateral crown expansion can be greatly impacted by buds formed under these conditions. By controlling vegetation and maintaining higher soil moisture reserves later in the growing season, seedlings are capable of producing larger buds with more leaf primordia for the next year's spring growth (Harrington and Tappeiner 1991; Tappeiner et al. 1987).

Unlike height, radial growth is not determinate and will continue to accrue through the mid to late summer as long as the soil moisture and xylem water potentials remain high enough to allow seedlings to photosynthesize (Harrington and Tappeiner 1991; Kramer and Kozlowski 1979). If growing conditions are improved, particularly late in the season, the cumulative effect would increase the radial growth of seedlings and change the morphology of the tree by decreasing the height to diameter ratio (Harrington and Tappeiner 1991). This shift toward lower height to diameter ratios indicates seedlings that are more vigorous and capable of resisting environmental or competitive stresses through the early period of stand establishment (Cole and Newton 1987; Rose et al. 1999).

Cleary (1971) remarked that it was particularly important to know when seedlings reached low xylem water potential levels in order to understand at what point in the season growth was ceasing due to adverse conditions. Xylem water potential measurements have been used to demonstrate how reductions in competitive weed cover can alleviate the stresses imposed on seedlings (Newton and Preest 1988; Petersen et al. 1988; Sands and Nambiar 1984). Predawn and/or midday xylem water potential measurements are commonly taken on a monthly basis. Xylem water potential has not been measured frequently enough during the first two seasons of plantation establishment to understand the onset and duration of moisture stress in the context of specific vegetation management regimes.

1.6 Vegetation Management Research Needs

Critical period studies have identified the years when weed control is needed to minimize reductions in seedling growth but there is little published research assessing regime efficacy with respect to the level of control achieved. Reductions in early herbaceous weed cover immediately after treatment application has not been documented in a sufficiently intensive manner to quantify the seasonal development of this plant community. Herbicide application is designed to increase soil moisture availability and improve growing conditions to achieve an effectively longer growing season. Regular and frequent measurements of soil moisture and xylem water potential are required to understand how alternative treatment regimes improve moisture conditions and influence seedling growth.

The current challenge in vegetation management research is to develop more efficient methods of herbicide application that achieve maximum seedling growth with the least amount of money, equipment, and personnel. This study was undertaken to provide information on mechanisms by which specific treatment regimes improve growth so that inferences can be extended to a wide range of control options. The results will produce information that will assist forest managers in predicting seedling growth responses to treatments and in making sound silvicultural decisions during the critical period of conifer plantation establishment.

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CHAPTER 2

2.0 EVALUATING THE EFFECTIVENESS OF COMMONLY USED HERBACEOUS WEED CONTROL REGIMES IN A PACIFIC NORTHWEST CONIFER PLANTATION

2.1 Introduction

Harvesting merchantable trees causes disturbance to the forest canopy and floor changing the growing conditions, as well as the structure and composition of the remaining vegetation community. Felling trees, yarding logs, and preparing the site for regeneration create light, temperature, and moisture conditions that promote the colonization of the site by vascular plants other than the desired crop tree species (Balandier et al. 2006; Chen 2004; Dyrness 1973; Halpern 1989). These plants are considered weeds from the standpoint of tree establishment and growth (Radosevich and Holt 1984) and are capable of capitalizing on disturbed conditions by rapidly establishing themselves, persisting for long periods of time, and directly competing with tree seedlings for limited site resources (Balandier et al. 2006; Halpern 1989; Walstad and Kuch 1987).

While competition for nutrients and light can occur between weeds and tree seedlings, it is principally soil moisture that is the key limiting resource in locations with a pronounced summer drought period (Cole and Newton 1987; Nambiar and Sands 1993; Newton and Preest 1988; Powers and Reynolds 1999; Stransky 1961; Zutter et al. 1986). The Pacific Northwest (PNW) is dominated by a Mediterranean climate where the majority of the precipitation is received during the fall, winter, and spring (UW 2007). The summer months are typically dry, therefore plant growth occurring during this time is limited to the moisture held in the soil matrix. Heavy competition from herbaceous weeds during these months can cause a premature depletion of soil moisture and a general decrease in the xylem water potential of planted seedlings (Creighton et al. 1987; Nambiar and Sands 1993; Newton and Preest 1988; Petersen et al. 1988; Rose et al. 1999; Zutter et al. 1986). Early herbaceous vegetation control can improve seedling growth (Balandier et al. 2006; Lauer et al. 1993; Rose and Rosner 2005; Zutter et al. 1986), increase soil moisture availability (Petersen et al. 1988; Powers and Reynolds 1999; Zutter et al. 1986), and increase seedling xylem water potential (Cleary 1971; Nambiar and Sands 1993; Newton and Preest 1988; Petersen et al. 1988).

The critical period concept states that weed control for a specific number of years during plantation establishment will minimize reductions in seedling growth (Rose et al. 1999; Wagner 2000; Wagner et al. 1996). Herbicides designed to kill and/or severely impair plants (Ahrens 1994) are often applied to competing vegetation and encourage vigorous seedling growth. These chemicals are an important management tool for temporarily reducing the amount of weed cover and allowing seedlings to capture site resources and maximize early growth. The herbicidal effects of these chemicals are not permanent because they are regularly bound up in the soil or degraded by microorganisms (Ahrens 1994). Treated areas are rapidly reinvaded by weeds, necessitating follow-up applications of herbicides until seedlings have improved their competitive ability, are beyond the critical period, and become dominant on the site (Balandier et al. 2006).

Forest managers in the PNW utilize herbicide regimes that consist of a site specific combination of a fall site preparation spray and spring release applications during successive years as needed (Balandier et al. 2006; Lauer et al. 1993). The goal of these regimes is to maximize seedling growth and vigor through the critical period while minimizing the amount of herbicides applied (Wagner 2000). Herbicide application is a costly endeavor and requires most forest managers to balance the financial pressure to minimize costs with the need to successfully establish a plantation.

The current challenge before forest managers and the scientific community is to understand the intricate mechanisms driving Douglas-fir seedling growth responses to weed control practices common to PNW plantations. In a general sense, specific herbicide treatments affect soil moisture, xylem water potential, and seedling growth through the early part of the critical period, primarily by changing the amount and/or composition of early seral vegetation. However, many of these links have not been formally tested and very few have been quantified. The objectives of this study were to: (1) evaluate the effectiveness of six herbaceous weed control regimes for increasing seedling growth, (2) chronicle the changes in the weed community resulting from herbicide use, and (3) intensively measure soil moisture and xylem water potential to link treatments to competing vegetation development, soil moisture availability, seedling water stress, and growth.

2.2 Materials and Methods

2.2.1 Site Description

The study site is located five miles southwest of Oakville, WA (46^{o} 49’15” N and 123^{o} 16’ 34”) on land managed by the Washington Department of Natural Resources (WDNR). The elevation is 135 meters (440 feet) and slopes to the west at 5 to 20%. Soils were derived from non-carbonate sedimentary bedrock and classified as part of the Centralia series fine-loamy, mixed, mesic Xeric Palehumults (Campbell 2007; WDNR 2006c). This part of Washington is dominated by a Mediterranean climate with cool moist winters and warm dry summers. According to 30-year average climate data, Oakville receives 145 cm (57.35 inches) of precipitation annually with only 17 cm (6.5 inches) falling from June 1st to September 30th (UW 2007). WDNR stand inventory information reveals that the site has a mean site index of 41 meters (135 feet) at 50 years (WDNR 2006b). The previous stand on the 25.9 hectare (64 acre) unit had 144.1 MBF harvested in the spring of 2005 with a cable yarding system (WDNR 2006a). The majority of the volume was concentrated in a few large Douglas-fir trees (3.2 trees per hectare) and many red alder (462 trees per hectare) (WDNR 2006b).

2.2.2 Experimental Design

Six treatment regimes were examined by means of a randomized complete block design with each treatment replicated four times on 24.4 x 24.4 meter plots (80 x 80 feet). Treatments were randomly assigned to the plots in September 2005 (see Appendix 2 for a site map). A perimeter fence was constructed to eliminate the potential for ungulate browse damage. It is recognized that fencing may shift the weed community toward species that are more palatable to ungulates in the area but the impact of uneven browse on measurement trees was deemed to be a greater risk.

2.2.3 Seedlings

The bareroot 1+1 Douglas-fir seedlings used in the study were grown at Webster Nursery (WDNR) in Olympia, Washington, from improved seed in the central breeding zone. Grading criteria were established in order to minimize seedling variability and maximize the potential for vigorous seedlings (Long and Carrier 1993). On October 24, 2005, prior to lifting and sorting at the nursery, height and caliper measurements were taken on a random sample of 300 seedlings in the beds. Descriptive statistics were calculated on this morphology data and grading criteria were selected from this information. Seedlings were to be between 35 to 55 cm in height and 7 to 9 mm in diameter (see Appendix 3 for details). The site was planted on February 25, 2006 with 1,536 seedlings in a 3.05 x 3.05 meter (10 x 10 foot) grid which allowed 36 measurement trees (864 total) to be surrounded by a buffer row of seedlings (672 total) inside every plot.

2.2.4 Treatments

Herbicides were chosen for the treatment regimes based on information from local field foresters and matched to the weed community on site. Regimes were designed to be applied over the course of the first two years of plantation establishment. The results reported here are from the first year only, so treatments 2 and 3 as well as 5 and 6 are identical. The differences between these treatment regimes will occur in year two (Table 1).

Table 1. Description of the six herbicide treatment regimes.

Treatment	Description	
Year 1/Year 2	Year 1	Year 2
1. -/-	No Control	No Control
2. F/-	Fall Site Prep	No Control
3. F/S	Fall Site Prep	Spring Release
4. FS/S	Fall Site Prep and Spring Release	Spring Release
5. FSG/S	Fall Site Prep, Spring Release, Glyphosate Release	Spring Release
6. FSG/SG	Fall Site Prep, Spring Release, Glyphosate Release	Spring Release, Glyphosate Release

First-year herbicide applications were completed on three separate occasions (see Table 2). The fall site preparation spray was completed on September 20, 2005 with a broadcast application of Chopper® (imazapyr, (+/-)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid, isopropylamine salt at 2.3 liters/hectare), Accord® Concentrate (glyphosate, N-(phosphonomethyl)glycine, isopropylamine salt at 3.5 liters/hectare), Hasten® (ethylated corn, canola, soybean oil and non-ionic surfactant blend at 9.4 liters/hectare), and Syl-Tac® (organo silicone non-ionic and ethylated seed oil surfactant at 292.2 milliliters/hectare). On April 12, 2006, the spring release treatment was a broadcast spray of Atrazine 90 WSP (atrazine, 6-chloro-N-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine at 4.9 kilograms/hectare) and Transline® (clopyralid, 3,6-dichloro-2-pyridinecarboxylic acid, monoethanolamine salt at 0.58 milliliters/hectare). At the same time, plots receiving the spring release treatment were also spot sprayed for woody vegetation control with Garlon 4® (triclopyr, [(3, 5, 6-trichloro-2-pyridinyl) Oxy] acetitic acid at 20% solution) and basal oil (petroleum oil at 80% solution). A follow-up release treatment of Accord® (glyphosate, N-(phosphonomethyl)glycine, isopropylamine salt at 2% solution) was spot sprayed on weeds in treatments 5 and 6 on June 20, 2006. On the same date, stump sprouting species (*Acer macrophyllum* and *Alnus rubra*) in all plots were cut and treated with a 75% solution of Accord®.

Table 2. Herbicides applied for the treatment regimes.

Fall Site Preparation (F)		Spring Release (S)		Glyphosate (G)	
Date	September 20, 2005	Date	April 12, 2006	Date	June 20, 2006
Herbicides Applied	Rate	Herbicides Applied	Rate	Herbicides Applied	Rate
Chopper	2.3 l/ha	Atrazine 90 WSP	4.9 kg/ha	Accord Concentrate	2%
Accord Concentrate	3.5 l/ha	Transline	584.1 ml/ha	Accord Concentrate	75%
Hasten	9.4 l/ha	Garlon 4	20%		
Syl-Tac	292.2 ml/ha	Basal oil	80%		
Volume: 224.6 liters solution/ha		Volume: 187.2 liters solution/ha		Volume: 79.6 liters total (spot spray)	
		(Garlon 4 spot spray - stumps)		(75% solution - stumps)	

2.2.5 Environmental Data

A Hobo Microstation (Model # H21-002, Onset Computer Corporation, Bourne, MA) was installed to collect on-site weather data every three hours throughout the course of the experiment. Due to the site's consistent aspect, it was assumed that the environmental conditions were homogeneous. Four environmental sensors from Onset Computer Corporation (Bourne, MA) were connected to the microstation including a relative humidity/air temperature gauge (Model # S-THA-M002), tipping bucket rain gauge (Model # S-RGA-M002), a wind speed indicator (Model # S-WSA-M003), and a solar radiation meter (Photosynthetically Active Radiation) (Model # S-LIA-M003).

2.2.6 Growth

On March 24, 2006 initial height (to the nearest cm) and caliper (to the nearest 0.1 cm) measurements were taken on all measurement seedlings. Seedling height and caliper were measured again on October 15, 2006, to determine seasonal growth which was calculated as the difference between the initial and end of season measurements. Seedling survivorship was calculated using the formula (100*(live/dead). Volume (cm^3) was calculated using the standard formula for the volume of a cone ($V= (\pi d^2 h)/12$) where *d* is the diameter (caliper) and *h* is the height. Crown radius was measured on October 16, 2006 and was determined by taking the average of two measurements. The first measurement was taken with a meter stick placed perpendicular to the stem along the longest lateral branch. Then the meter stick was rotated 90^o clockwise for a second measurement. Height to diameter ratio (HDR) was calculated by dividing seedling height by diameter.

2.2.7 Vegetation

Seven permanent one meter radius vegetation survey sub-plots were established within each treatment plot to measure the weed community response to the various treatment regimes. Six of these subplots were located using a stratified random approach in the fall of 2005. Each treatment plot was divided into six equal areas and one subplot location was randomly assigned within each strata. The seventh was a tree-centered plot established in the spring of 2006 and was randomly selected with the guideline that it could not overlap any of the other sub-plots. The 168 sub-plot locations were permanently marked with rebar and high visibility plastic caps.

The vegetation community was assessed in all sub-plots on September 8, 2005, March 30, 2006, June 5, 2006, and July 19, 2006. The September, March, and June surveys were completed prior to herbicide application and the July survey was at the approximate peak of the growing season. Total percent weed cover as well as percent cover by species were visually determined. In order to divide the sub-plots into equal areas, a cross with four one-meter pieces of PVC (polyvinyl chloride) pipe was constructed. Cover from logging slash, separated into <7 cm and >7 cm categories, was recorded during the September vegetation survey. Hitchcock and Cronquist (2001) and Pojar and MacKinnon (2004) were used as references for plant identification.

These two references were also used to compile information about growth habit, origin, and lifespan of each plant that was identified to the species level. The information was then merged with the data collected from the four vegetation surveys. During the vegetation surveys, some plants were immature and could not be positively identified to species. In these cases, the plants were included in the survey at the family or genus level. Plants that were present only as cotyledons and could not be reliably identified at the time of survey were designated as an “unknown forb.” All plant growth habits were noted, as was lifespan where applicable (for example, perennial woody plants like *Ribes* spp.). Other plants for which this information could not be accurately ascertained were not included in the specific analysis of origin and lifespan.

2.2.8 Soil Moisture

Volumetic soil moisture was measured using three different methods, a Hydrosense TDR soil moisture probe with 20 cm prongs (Model # CS-620 Spectrum Technologies, Plainsfield, IL), an array of 24-ECH2O 20cm soil moisture sensors (MorphH2O Water Management, Ogden, UT), and soil cores taken with an AMS core sampler with a slide hammer and 5.1 cm x 5.1 cm removable sleeves (AMS Inc., American Falls, ID). The units of measure for all three methods are presented as the volume of water per volume of soil (m^3 H_20/m^3 soil) (Brady and Weil 2002). Utilizing all three methods allowed checks between the two different electronic sensor types in case of failure and provide information that could be used to calibrate the electronic probes to volumetric soil moisture values found with the soil cores.

The Hydrosense TDR probe was used to make point estimates of soil moisture on a biweekly basis. Bare mineral soil on a random azimuth was exposed just outside each of the vegetation sub-plots for probe insertion and measurement. In this manner, 168 soil moisture measurements were taken on each of the 12 measurement dates from May 5 to October 16, 2006. One ECH2O sensor was installed vertically in each of the

24 treatment plots using an insertion tool produced by MorphH2O Water Management (Ogden, UT). Sensor locations were randomly chosen but were placed greater than one meter from a seedling and outside all vegetation sub-plots. Two Hobo Microstation data loggers (Model #H21-002, Onset Computer Corporation, Bourne, MA) were programmed to take measurements of volumetric soil moisture twice daily. Four ECH2O “smartsensors” (Model # S-SMA-M003, Onset Computer Corporation, Bourne, MA) were attached to each logger. The remaining 16 sensors (Model # EC-20) provided point estimates of soil moisture using an ECH2O check handheld sampler to take measurements on the same days as the Hydrosense TDR. The 24 ECH2O soil moisture sensors were installed by March 28, 2006.

Twelve soil cores were taken on each of the soil moisture measurement dates from June 6 to October 16, 2006 (120 total). A small hole was excavated in a random location inside each of the six treatment plots occurring in two different blocks (outside all vegetation sub-plots). The cores were taken horizontally at 10 cm depth on the undisturbed cut face. Cores were labeled and placed immediately in a resealable plastic bag. At a laboratory facility in Corvallis, Oregon, the soil was removed from the sleeve and the sample was weighed, dried for 48 hours at 41^{o}C (105^{o}F), and reweighed. Bulk density (mass of dry soil/volume of soil in the sample) and volumetric soil moisture ((mass of soil water/mass of dry soil in the sample) * bulk density) were calculated from this information.

Two soil pits 0.75 m wide x 1.5 m long x 1.5 m deep were dug by hand on the site outside all measurement plots. Soil horizons were compared with the data found through the online Washington state soil survey to ground truth the information (NRCS 2007). Rooting zone depth observed in the soil pits was determined to be less than 50 cm with the majority of the roots occurring in the top 35 cm. Careful excavation of 19 weed species growing near the upper soil pit revealed that their rooting depth was indeed less than 25 cm (unpublished data). Tree roots were an exception to this trend as they often continued throughout the soil profile to depths greater than 1.5 m. On October 16, 2006 equal amounts of soil were taken from the A and A/B horizons in both the pits and thoroughly mixed by common horizon to provide composite samples for soil chemistry analysis. Samples were immediately placed in a Styrofoam cooler with dry ice and transported to the Central Analytical Laboratory at Oregon State University for analysis. The soil chemistry data are provided in Table 3.

2.2.9 Sensor Calibration

Regression analysis (Proc REG in SAS version 9.1, Cary, NC) was used to develop equations that calibrated the Hydrosense TDR and ECH2O probe data with the information resulting from the biweekly soil cores. A portion of the larger Hydrosense TDR and ECH2O soil moisture datasets were used as the basis for the calibration equations. Volumetric soil moisture (m^3 H_2O/m^3 soil) values from the same plot on the same date were compared. Sensor values were used as the independent variable (x) and the volumetric soil moisture values from the soil cores were used as the dependent (y) values. Cubic, quadratic, and linear equations were examined for both sensor types and only parameters that were significant at the

Table 3. Soil chemistry information by soil horizon for the Centralia series.

Horizon	Depth	pH	NO_3 #	NH_4 #	Min. N #	P #	K #	Ca *	Mg *	Na *	CEC *
O	0-5cm	~	~	~	~	~	~	~	~	~	~
A	5-25cm	5.2	7.4	3.9	20.0	5.5	180	1.0	0.3	0.1	15.9
A/B	25-45cm	5.3	4.0	2.3	9.1	1.5	154	1.7	0.5	0.1	12.3

Footnote: # denotes parts per million and * indicates milliequivalents per 100 grams.

$\alpha = 0.05$ level were included in the final model. A quadratic equation was selected for the Hydrosense TDR calibration and a linear equation was chosen for the ECH2O. See Table 4 for the equations and the adjusted R^2 associated with the models.

2.2.10 Xylem Water Potential

Xylem water potential measurements are reported in negative megapascals (-MPa). A reference to decreasing xylem water potential means that seedlings in a treatment plot were moving from a high potential for water movement to a lower potential for water movement (for example: -0.4 MPa down to -1.5 MPa). The opposite situation is referred to as an increase in xylem water potential.

Measurements were taken with two Model 600 pressure chambers (PMS Instrument Company, Albany, Oregon) biweekly from May 5 to October 16, 2006, on the same 12 sampling dates that soil moisture was measured. Two seedlings were randomly selected from every plot and sampled at both the predawn and midday periods. Predawn measurements were taken between the hours of 0400 and 0600 while midday moisture stress was measured from 1200 to 1400. At each measurement, a 6 to 8 cm sample was cut from the terminal end of a branch growing in the middle third of the seedling and placed in a labeled black film canister. Analysis was completed immediately after all samples were collected. After seedlings were sampled on a measurement date, they were not sampled again in order to minimize damage to the seedlings.

Table 4. Calibration equations for Hydrosense TDR and ECH2O soil moisture probes.

Probe Type	n	Calibration Equation	adj R^2
Hydrosense TDR	120	$y= 0.06824 + 2.11875(x) - 3.20772(x^2)$	0.6674
ECH2O	120	$y= 0.17820 + 0.98403(x)$	0.4954

Footnote: x variable is the sensor value (Hydrosense TDR or ECH2O) and y variable is the soil core value.

2.3 Statistical Approach

The data collected from the experiment were analyzed as a randomized complete block design using Statistical Analysis Software version 9.1 (SAS Institute Inc. Cary, NC). ANOVA model assumptions of normality, linearity, and constant variance were examined on the residuals for each variable analyzed and no transformations of the data were required.

2.3.1 Growth Analysis

Analysis of variance general linear models (Proc GLM in SAS code) were used to test hypotheses concerning treatment effects on survival, growth (height, ground line diameter, and volume), as well as year one crown radius and height to diameter ratio. Comparisons among treatment means for growth were tested using Fisher's protected least significant difference t-tests. The initial measurements of height and caliper made on March 24, 2006 as well as the initial height to diameter ratio were analyzed for statistical differences at the start of the experiment.

2.3.2 Vegetation Community Analysis

Across the four survey dates, 102 different plant taxa were found on the site. This number included those plants identified to the family, genus, or species level. Additionally, two categories of slash (<7 cm and >7 cm), logs, stumps, and total vegetation cover values were also recorded which brought the total number to 107. In order to provide a common foundation for comparisons across the various treatments, a dataset was created (using Microsoft Access) that had the entire list of 107 attached to each of the vegetation sub-plots (144 sub-plots for the September 2005 survey and 168 sub-plots for the surveys in 2006). The four vegetation surveys were then merged individually (using a proc merge statement in SAS) to this common list creating four master datasets. Cover values specific to each survey were inserted in the merging process ("if then" statement in SAS). If a species was present in a sub-plot, the associated cover value was inserted based on that particular species. If there was no cover value because that species did not appear in that survey, a zero was inserted by the program.

Statistical analysis for treatment effects was completed individually for each survey date using treatment plot means for total vegetative cover. Analysis of variance (Proc GLM) and Fisher's protected least significant difference t-tests were used to test total weed cover response to herbicide use.

Analysis of the vegetation community composition was completed by comparing species autecology information on the four survey dates. The basis for these comparisons was developed through a two stage process. First, the mean weed cover percentage for each of the 102 plant taxa occurring on the site was calculated by treatment (means for total weed cover, the two slash categories, logs, and stumps were not included). Each mean was the average of the 28 times (7 sub-plots replicated 4 times) that a particular species could occur in each treatment (except for the September 2005 survey which had only 24 – 6 sub-plots replicated 4 times). Second, the 102 plant taxa cover means for a treatment regime on each survey date were summed based on common growth habits (forb, shrub, tree, etc.), species origin (native or introduced), or the duration of weed lifespan (annual, biennial, and perennial). The relative composition shift of the weed community in each treatment was shown through these cover values for the particular attributes and the calculation of ratios by survey for species origin (native divided by introduced) and duration of lifespan (perennial divided by the sum of annual and biennial).

2.3.3 Soil Moisture Analysis

A single volumetric soil moisture value by sensor type was developed for each treatment plot on all of the twelve sample dates. Means were calculated from the seven measurements taken in each plot with the Hydrosense TDR probe. The sixteen ECH2O probes provided single point estimates of volumetric soil moisture that were combined with the information from the ECH2O "smartsensors" to create a single ECH2O composite dataset. The twice daily measurements taken with each ECH2O "smartsensor" were averaged to form a daily volumetric soil moisture value for the eight plots in which they were deployed. Only data from the ECH2O "smartsensors" that occurred on the twelve sampling dates was included in the composite ECH2O dataset.

Treatment plot means for both sensor types were calibrated using the formulas resulting from regression analysis (Table 4). Analysis on the cumulative level of soil moisture was developed by summing the calibrated volumetric soil moisture values (based on sensor type) by plot across the twelve measurement dates to form a single value for each of the 24 plots. For example, block 1 plot 1 had 12 calibrated Hydrosense TDR volumetric soil moisture means across the measurement period (0.35, 0.34, 0.39, 0.35, 0.22, 0.18, 0.22, 0.20, 0.17, 0.17, 0.18, 0.25 m^3 H_20/m^3 soil) that when summed, produced a value of 3.0 m^3 H_20/m^3 soil. Analysis of variance, using Proc GLM and Fisher's protected least significant difference t-tests, were used to test for differences among the cumulative treatment plot means for both sensor types. Standard errors were calculated by treatment over the replications.

2.3.4 Xylem Water Potential Analysis

Treatment plot means for predawn and midday xylem water potential were calculated from the two samples taken on a particular date and time. These means were then summed by treatment plot across the twelve measurement dates forming the basic datasets used in the cumulative analysis. Analysis was completed separately on the cumulative predawn and midday xylem water potential values. The data were analyzed using ANOVA procedures (Proc GLM) to determine treatment effects and Fisher's protected least significant difference t-tests to understand treatment differences. Again, standard errors were calculated by treatment over the replications.

2.3.5 Treatment Effectiveness

Orthogonal contrasts were designed to assess statistical differences among specific preplanned treatment comparisons by partitioning the treatment sums of squares into the various component parts. Increases in growth parameters, cumulative level of soil moisture, and cumulative xylem water potential were analyzed using the same set of five orthogonal contrasts (Table 5). Contrast one tested for a general herbicide effect by comparing the no-action control with all other treatments receiving at least one application of herbicides. Contrast two compares the site prep only treatments (2 and 3) with the more intense treatments (4, 5, and 6). Contrast three compares treatment 4 which received a site prep and spring release application with treatments 5 and 6 which had an additional glyphosate follow-up spray.

Table 5. Preplanned orthogonal contrasts testing specific treatment comparisons.

		Treatment					
		1	2	3	4	5	6
Contrast		-/-	F/-	F/S	FS/S	FSG/S	FSG/SG
1	herbicide effect	5	-1	-1	-1	-1	-1
2	site prep vs trts 4, 5, 6	0	-3	-3	2	2	2
3	trt 4 vs trt 5 and 6	0	0	0	-2	1	1
4	diff between trt 2 and 3	0	-1	1	0	0	0
5	diff between trt 5 and 6	0	0	0	0	1	-1

Contrasts four and five were designed to test for a significant difference between treatments that were similar in the first year of the study (2/3 and 5/6).

2.4 Results

2.4.1 Weather

The summer drought period began around June 15, 2006 after relatively normal spring precipitation (UW 2007). For the next 92 days (until September 15), the site received 11.8 mm of precipitation, had an average maximum air temperature of 24°C, and an average minimum relative humidity of 46% (Figure 1). The average maximum photosynthetically active radiation (PAR) during this period was 696 watts/m^2. By comparison, from November 15, 2006, to January 15, 2007, the site received 175 watts/m^2.

2.4.2 Seedling Growth

There were no differences among the treatments for height, caliper, and height to diameter ratio at the beginning of the experiment among the treatments (p-values 0.2619, 0.2681, 0.7915 respectively, Appendix 4). Seedlings were within the selection criteria ranging from 41 to 43 cm in height, 0.7 to 0.75 cm in caliper, and HDR was 59 or 60 (Appendix 4). Mean seedling survivorship did not differ among the treatment regimes (p-value 0.2240, Table 6) and was 98.7% across the site (Table 7).

Height growth of the seedlings was affected by the treatments (p-value 0.0085) as of October 16, 2006. Height growth ranged from 15.1 cm in the control to 19.9 cm in treatment 6 which was a range of 4.8 cm representing a 24% increase over the control. Seedling crown radius was affected by the treatment regimes (p-value

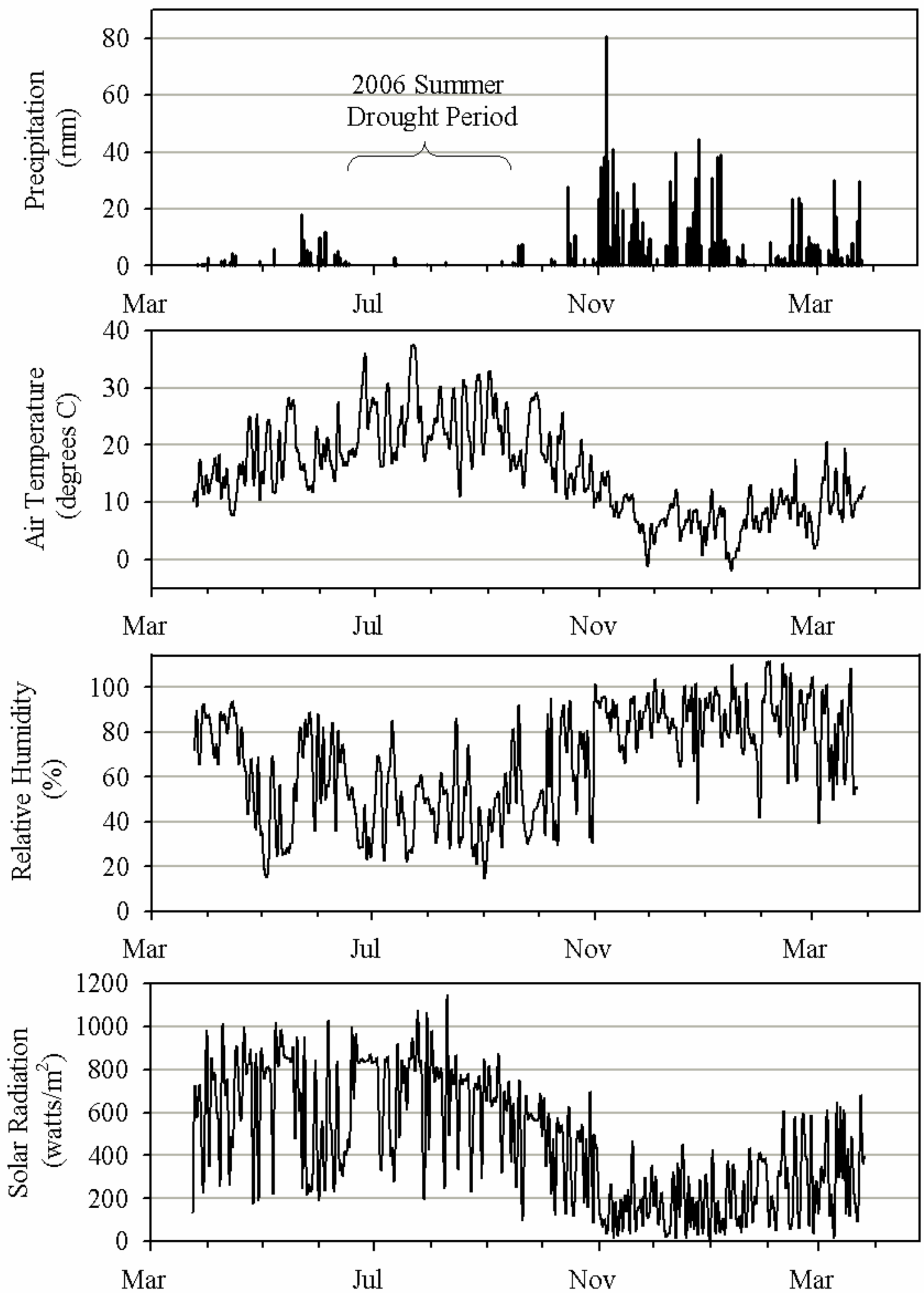

Figure 1: Study site weather from March 28, 2006 to March 26, 2007.

Table 6. Analysis of variance table for treatment effects on first year survival, growth (height, ground line diameter, and volume), as well as crown radius and height to diameter ratio.

Parameter	Source	DF	Sums of squares	Mean square	F value	Pr>F	
Survival	block	3	0.9645	0.3215	0.12	0.9457	
	treatment	5	20.8976	4.1795	1.59	0.2240	
Height	block	3	5.6879	1.8960	0.37	0.7790	
	treatment	5	122.9894	24.5979	4.74	0.0085	*
Ground line diameter	block	3	0.0552	0.0184	1.46	0.2651	
	treatment	5	0.5936	0.1187	9.43	0.0003	*
Volume	block	3	107.4171	35.8057	1.33	0.3008	
	treatment	5	985.5862	197.1172	7.34	0.0012	*
Crown Radius	block	3	17.2972	5.7657	3.06	0.0607	
	treatment	5	33.5257	6.7051	3.56	0.0255	*
Height to Diameter Ratio	block	3	154.7267	51.5756	1.65	0.2197	
	treatment	5	1126.8063	225.3613	7.22	0.0013	*

Footnote: * indicates significance at $\alpha = 0.05$.

Table 7. Treatment effects after the first growing season on mean survival (SVL), seedling height growth (HT), ground line diameter growth (GLD), and volume growth (VOL) as well as crown radius (CR), and height to diameter ratio (HDR). Values within a column that have different letters are different at α=0.05. Standard errors are in parentheses.

Treatment	SVL (%)		HT (cm)		GLD (cm)		VOL (cm^3)		CR (cm)		HDR	
1. -/-	97.2 b	(0.01)	15.1 b	(0.48)	0.10 d	(0.01)	4.95 c	(0.33)	16.1 c	(0.28)	70 a	(1.10)
2. F/-	98.6 ab	(0.01)	13.7 b	(0.67)	0.19 cd	(0.01)	6.83 c	(0.42)	17.8 bc	(0.34)	63 ab	(0.99)
3. F/S	100.0 a	(0.00)	17.1 ab	(0.61)	0.29 bc	(0.02)	10.72 bc	(0.67)	17.7 bc	(0.31)	60 b	(0.96)
4. FS/S	99.3 ab	(0.01)	16.2 b	(0.79)	0.46 ab	(0.02)	17.13 ab	(0.98)	18.0 abc	(0.32)	51 c	(0.88)
5. FSG/S	97.9 ab	(0.01)	19.7 a	(0.93)	0.48 a	(0.03)	21.24 a	(1.46)	19.0 ab	(0.36)	55 bc	(1.22)
6. FSG/SG	99.3 ab	(0.01)	19.9 a	(0.98)	0.52 a	(0.02)	20.43 a	(1.11)	19.9 a	(0.36)	51 c	(0.87)

0.0255). Crown radius increased from 16.1 cm in the control to 19.9 cm in treatment 6. This range represented a 19% increase over the crown radius found in the control treatment. A second flush of growth, known as lammas growth, occurred in mid-July. On July 27, 2006 a survey was conducted to document this event and record whether or not each measurement tree (all 864) exhibited lammas growth. Statistical analysis of the results show a moderate treatment effect (p-value 0.0564, Table 8) with an increasing trend toward more seedlings producing lammas growth as treatment regimes intensified (Table 9).

Caliper growth was affected by the treatment regimes (p-value 0.0003). The control treatment averaged 0.1 cm of caliper growth while the site prep only treatments grew between 0.2 and 0.3 cm, a 50 to 66% increase in growth over the control. Treatments 4, 5, and 6 did not differ from one another and grew approximately 0.5 cm in caliper. When compared to the control, this was an 80% increase in caliper growth.

Treatment regimes resulted in volume growth differences (p-value 0.0012). Volume growth in the control treatment was 4.95 cm^3. The site prep only treatments (2 and 3) showed volume increases of 6.8 to 10.7 cm^3, respectively. When compared to the control, this was a 28% to 54% increase in volume growth. Treatment 4 showed a 71% gain over the control with a mean volume growth of 17.1 cm^3. There was no difference between treatments 5 and 6 which showed an 80% increase over the control with a 20.8 cm^3 mean volume growth response.

Table 8. Analysis of variance table for treatment effects on the total occurrence of lammas growth on July 27, 2006.

Parameter	Source	DF	Sums of squares	Mean square	F value	Pr>F
Lammas	block	3	100.125	33.375	1.36	0.2919
	treatment	5	341.375	68.275	2.79	0.0564

Table 9. Mean number of seedlings with lammas growth on July 27, 2006. Values within the column that have different letters are different at the α=0.05 level. Standard errors are in parentheses.

Treatment	Lammas Growth	
1. -/-	17 c	(1.65)
2. F/-	19 bc	(3.34)
3. F/S	24 abc	(2.90)
4. FS/S	25 ab	(1.87)
5. FSG/S	27 a	(2.02)
6. FSG/SG	27 a	(3.01)

Treatment regimes also affected the HDR of the seedlings (p-value 0.0013) with an inversely proportional relationship between the intensity of herbicide application and the HDR response. The control had a HDR of 70 while the site prep only treatments (2 and 3) responded with a mean ratio of 61.5, a 12% decrease. Treatments 4, 5, and 6 were not different from one another and had a mean HDR of 52, which was an improvement of 25% over the control.

2.4.3 Vegetation Community Development

The four vegetation survey dates captured weed community development over a ten month period of time (Figure 2). The initial September 2005 survey represented the vegetation community that existed approximately six months after the cessation of logging activities. Treatment regimes reduced the total cover values found on the March, June, and July survey dates in reference to the control (Table 10). The survey completed in March captures the weed community present after winter die-back and/or the fall site prep herbicide application (and before the April treatment). Spring development of the weed community in response to the treatments was shown with the data from the June survey. Persistent drought conditions and a lack of summer rains in the summer of 2006 made the date of the July survey the peak of the growing season for the weed community.

On September 8, 2005, there were no differences in the total weed cover measurements across the experiment (p-value 0.2118, Table 10). The difference in the mean cover observed between treatments 2 and 3 was due to the distribution of yarding corridors across the site (see map Appendix 2). There were no treatment effects on slash level for either size class, ranging from 20 to 30% cover for slash <7

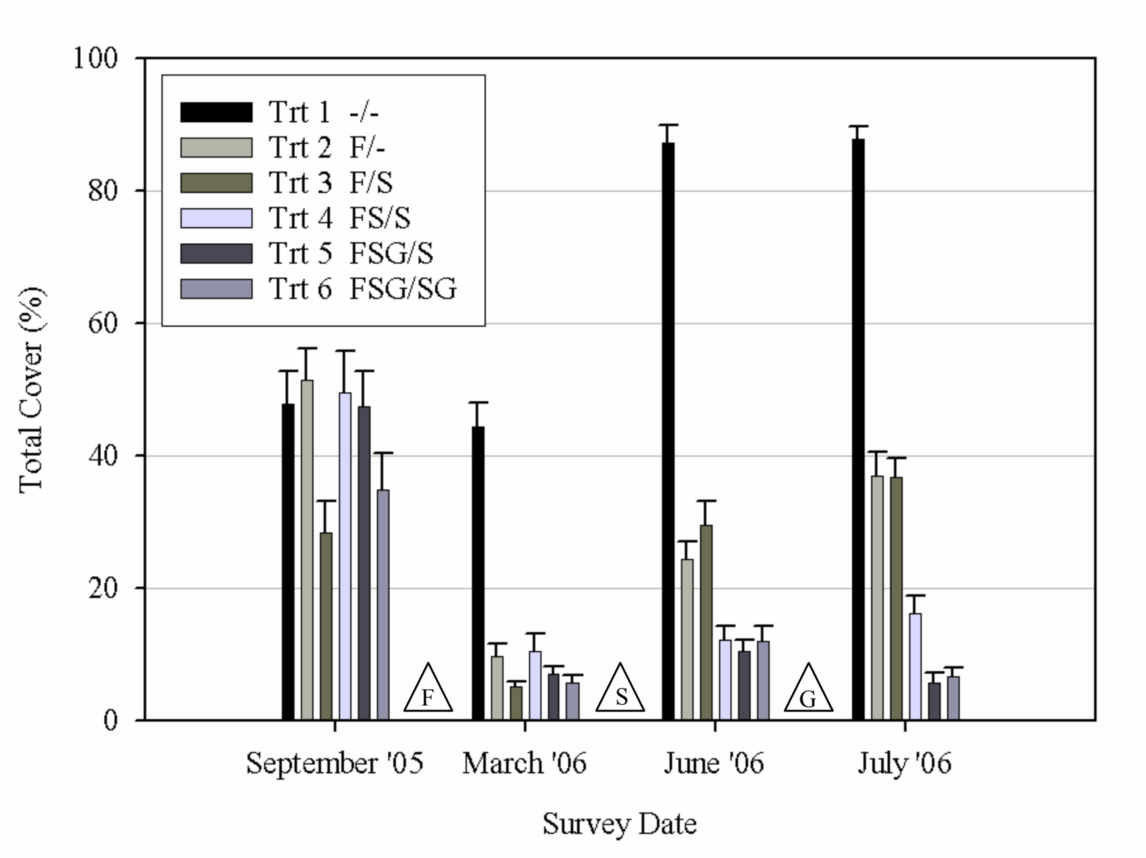

Figure 2: Mean total cover per treatment across four survey dates. Triangles represent the approximate time when herbicides were applied to plots receiving that specific treatment. They are marked with the letter corresponding to that treatment (F=Fall, S=Spring, G=Glyphosate).

Table 10. Analysis of variance table for treatment effects on total vegetation cover by survey date.

Survey	Source	DF	Sums of squares	Mean square	F value	Pr>F	
September 2005	block	3	281.7639	93.9213	0.4400	0.7270	
	treatment	5	1737.8611	347.5722	1.6300	0.2118	
March 2006	block	3	137.9626	45.9875	0.9800	0.4275	
	treatment	5	4601.7313	920.3463	19.6600	<.0001	*
June 2006	block	3	45.6352	15.2117	0.1700	0.9140	
	treatment	5	17315.1369	3463.0274	39.0300	<.0001	*
July 2006	block	3	85.2270	28.4090	0.6300	0.6056	
	treatment	5	18950.8512	3790.1702	84.3300	<.0001	*

Footnote: * indicates significance at $\alpha = 0.05$.

Table 11. Mean total vegetation cover by treatment across the four survey dates. Values within columns that have different letters are different at α=0.05. Standard errors are in parentheses.

Treatment	September '05		March '06		June '06		July '06	
1. -/-	47.75 ab	(5.04)	44.36 a	(3.66)	87.25 a	(2.69)	87.82 a	(1.86)
2. F/-	51.38 a	(4.90)	9.64 b	(1.91)	24.36 bc	(2.62)	36.89 b	(3.67)
3. F/S	28.33 b	(4.89)	5.04 b	(0.85)	29.4 6b	(3.64)	36.86 b	(2.77)
4. FS/S	49.54 ab	(6.21)	10.46 b	(2.62)	12.25 c	(2.01)	16.25 c	(2.56)
5. FSG/S	47.33 ab	(5.46)	6.96 b	(1.31)	10.00 c	(1.73)	5.79 d	(1.44)
6. FSG/SG	34.92 ab	(5.37)	5.75 b	(1.17)	12.00 c	(2.31)	6.71 cd	(1.29)

cm and approximately 7 to 12% cover from slash >7 cm (p-value 0.0632 and 0.1478 respectively, see Appendix 4). The fall site prep herbicide application was very effective at reducing vegetative cover as evidenced by the treatment effect shown from the March survey results (Table 10). Spring growth occurring from March 30 to June 5, 2006, was heavy in the control as well as treatments receiving only a fall site prep spray (Table 11). During this period of time weed cover in the control nearly doubled while treatments 2 and 3 showed an increase of 2.5 to 5.8 times, respectively. The weed community in treatments 4, 5, and 6, which had been treated with Atrazine and Transline®, did not demonstrate the same growth and produced less than 15% cover.

On July 19th, the final vegetation survey revealed that treatment regimes had resulted in mean total covers that were approximately 50% reductions with each successively more intensive herbicide application (Figure 2 or Table 11). The control treatment had nearly 90% weed cover. Applying only a fall site prep application resulted in approximately 40% cover. Adding a spring release herbicide application brought weed cover to around 20%. Following up with a directed glyphosate treatment in June brought the weed cover below 10%.

2.4.4 Vegetation Community Composition

Treatment regimes not only changed the amount of cover but also the composition of the weed communities that remained over the course of the 2006 growing season. In reference to the untreated control, herbicides affected the weed communities occurring in treatment plots through distinct changes in the species capable of growing under their influence. A complete list of species on the site as well as their autecological information is located in Appendix 5. The number of species for the various categories has been included in each of these tables to show how the 102 plants found on the site were separated into these component parts.

At the beginning of the experiment (September 2005 survey), the study site had a wide variety of species, representing a range of growth forms and was predominantly composed of native perennials (Tables 12, 13, and 14). Growth forms like vine/shrubs (*Rubus* spp.), ferns, forbs, and shrubs were abundant at this time. Survey results from March and June demonstrate the rebound of the weed community in response to the treatments applied. As the growth of weed species developed from early spring to the July peak, the proportions of growth habits, origin, and lifespan duration of the weeds changed in response to the herbicide treatments.

At the height of the growing season in July, the control treatment was still dominated by a native perennial weed community with a variety of growth habits. The fall site prep only treatment shifted the weed community toward annual/biennial introduced forbs. Species lifespan shifted as the relationship between perennial to annual/biennial decreased from 5:1 to a 1:1 ratio (Table 14). The fall site prep also changed the ratio of native to introduced species from greater than 10:1 to a 2:1 relationship (Table 13). Adding a spring release herbicide application pushed the weed community back to a native perennial mix. There were much lower cover values associated with the intensity of these herbicide applications but the most dominant species were vine/shrubs (*Rubus ursinus*), fern (*Polystichum munitum*), and various forb species. A follow-up directed application of glyphosate further reduced the total amount of cover in treatments 5 and 6 but resulted in a similar community

Table 12. Mean weed species cover by treatment and growth form across the four vegetation survey dates.

			Treatments					
			1	2	3	4	5	6
Date	Growth Form	# Species	-/-	F/-	F/S	FS/S	FSG/S	FSG/SG
September 2005	Forb	70	7.1	11.3	7.5	11.3	8.1	13.8
	Fern	3	12.3	13.7	8.9	12.5	10.7	8.0
	Grass	5	1.4	3.0	0.7	1.9	2.3	2.2
	Shrub	9	4.8	14.6	2.3	7.6	4.2	2.8
	Shrub/Tree	2	0.0	0.0	0.0	0.0	0.0	0.0
	Tree	8	3.2	5.7	3.0	7.0	6.8	5.3
	Vine/Shrub	5	25.3	11.4	11.4	22.0	24.0	12.3
March 2006	Forb	70	18.4	2.6	3.3	3.9	3.2	2.9
	Fern	3	9.3	8.3	3.8	8.1	5.4	4.5
	Grass	5	1.1	0.3	0.0	0.3	0.3	0.3
	Shrub	9	3.4	0.5	0.2	0.5	0.1	0.1
	Shrub/Tree	2	0.0	0.0	0.0	0.1	0.0	0.1
	Tree	8	1.6	0.4	0.5	0.5	0.7	0.4
	Vine/Shrub	5	12.6	0.3	0.3	0.3	0.4	0.5
June 2006	Forb	70	36.7	12.2	25.4	4.6	2.8	3.0
	Fern	3	21.2	7.2	3.6	5.2	5.3	4.9
	Grass	5	3.5	1.2	0.8	0.3	0.2	0.4
	Shrub	9	4.0	1.2	0.2	0.9	0.3	0.0
	Shrub/Tree	2	0.1	0.4	0.6	0.3	0.3	0.4
	Tree	8	6.4	2.4	1.8	0.6	1.0	0.9
	Vine/Shrub	5	32.5	2.3	1.2	2.5	2.4	3.5
July 2006	Forb	70	17.1	26.0	27.9	4.7	1.3	1.9
	Fern	3	23.9	5.2	3.1	4.8	2.5	3.4
	Grass	5	2.9	1.0	0.9	0.4	0.1	0.1
	Shrub	9	3.9	0.7	0.6	0.6	0.2	0.0
	Shrub/Tree	2	0.1	0.4	1.0	0.8	0.1	0.4
	Tree	8	9.4	4.0	5.0	0.9	1.1	0.7
	Vine/Shrub	5	55.6	4.9	3.6	6.5	2.1	1.8

Footnote: The percentage of cover for each weed species was averaged across a treatment creating a list of 102 means. Those means were then summed based on similar growth forms. For example, in September 2005, the five species of plants classified as vine/shrubs had individual mean cover percentages that collectively were responsible for 25.3% of the vegetative cover found in the control treatments.

Table 13. Mean weed species cover by treatment and origin across the four vegetation survey dates, along with the ratio of native to introduced cover.

			Treatment					
			1	2	3	4	5	6
Date	Origin	# Species	-/-	F/-	F/S	FS/S	FSG/S	FSG/SG
September 2005	Introduced	25	1.7	1.7	4.4	3.5	1.3	4.0
	Native	52	49.3	53.5	28.0	54.8	51.5	35.8
		Ratio	29.6	31.3	6.4	15.5	39.8	9.0
March 2006	Introduced	25	1.8	0.3	0.4	0.3	0.2	0.3
	Native	52	39.9	10.8	6.3	11.7	8.2	7.0
		Ratio	21.9	37.8	16.0	41.0	38.3	24.5
June 2006	Introduced	25	6.5	5.0	4.3	0.1	0.2	0.2
	Native	52	91.8	20.1	27.9	13.6	11.5	12.1
		Ratio	14.1	4.0	6.5	95.2	64.6	56.7
July 2006	Introduced	25	9.1	18.0	12.6	0.4	0.1	0.3
	Native	52	99.7	21.6	27.3	17.6	7.1	7.6
		Ratio	10.9	1.2	2.2	41.2	66.0	30.6

Footnote: The percentage of cover for each weed species was averaged across a treatment creating a list of 102 means. Those means were then summed based on similar origins (introduced or native). For example, in September 2005, there were 52 species of plants classified as natives and had individual mean cover percentages that collectively were responsible for 49.3% of the vegetative cover found in the control treatment.

Table 14. Mean weed species cover by treatment and lifespan across the four vegetation survey dates, along with the ratio of annual to the biennial/perennial cover.

			Treatment					
			1	2	3	4	5	6
Date	Duration	# Species	-/-	F/-	F/S	FS/S	FSG/S	FSG/SG
September 2005	Annual	16	1.4	1.5	2.1	3.0	1.4	3.1
	Biennial	2	0.3	0.5	1.5	0.8	0.3	0.8
	Perennial	58	49.3	53.3	28.8	54.6	51.0	35.8
		Ratio	29.6	27.8	7.9	14.2	29.9	9.1
March 2006	Annual	16	9.5	1.0	1.4	1.2	1.0	1.0
	Biennial	2	0.4	0.0	0.1	0.1	0.0	0.1
	Perennial	58	31.7	10.0	5.2	10.5	7.3	6.1
		Ratio	3.2	9.6	3.6	8.4	7.1	5.9
June 2006	Annual	16	16.7	8.9	19.5	3.1	1.2	1.0
	Biennial	2	0.6	0.3	0.3	0.0	0.0	0.0
	Perennial	58	81.0	15.9	12.3	10.6	10.5	11.4
		Ratio	4.7	1.7	0.6	3.4	8.6	11.4
July 2006	Annual	16	5.9	19.7	18.0	2.7	0.3	0.5
	Biennial	2	1.1	0.6	0.5	0.0	0.0	0.0
	Perennial	58	101.9	19.2	21.5	15.4	6.9	7.4
		Ratio	14.5	0.9	1.2	5.7	21.4	14.8

Footnote: The percentage of cover for each weed species was averaged across a treatment creating a list of 102 means. Those means were then summed based on lifespan duration (annual, biennial, perennial). For example, in September 2005, there were 58 species of plants classified as perennials and had individual mean cover percentages that collectively were responsible for 49.3% of the vegetative cover found in the control treatment.

composition as that seen in treatment 4. One observable difference between the fall site prep with a spring release and those receiving an additional glyphosate application was the lower relative abundance of annual species in response to the latter (Table 14).

2.4.5 Soil Moisture

Over the course of the measurement period (May 5 to October 16, 2006), herbicide treatments increased the cumulative level of soil moisture as measured by the Hydrosense TDR and ECH2O probes (p-values <0.0001 and 0.0104, respectively, Table 15). The control had the lowest cumulative level of soil moisture found in the study at 3.2 to 3.3 m^3 H_2O/m^3 soil (see Table 16). Applying a fall site prep treatment increased cumulative soil moisture to 3.5 to 3.7 m^3 H_2O/m^3 soil, which is a 3 to 11% gain over the control. The fall site prep and spring release application (treatment 4) increased the cumulative soil moisture 19 to 20% over the control with values ranging between 4.1 and 4.3 m^3 H_2O/m^3 soil. When compared to the control, treatments 5 and 6 improved cumulative soil moisture by 17 to 23% with increases from 4.0 to 4.3 m^3 H_2O/m^3 soil. There was no difference between treatments that received the same herbicide applications in the first year of the study (2/3 and 5/6). Bulk density was not different among the treatments, ranging from 1.10 to 1.15 grams/cm^3 (p-value 0.4596, see Appendix 4).

Although the inferred values of volumetric soil moisture are different between the two types of probes, both demonstrated similar trends across the measurement period (Hydrosense TDR Figure 3 and ECH2O Figure 4). Volumetric soil moisture was near field capacity (> 0.34 m^3 H_2O/m^3 soil for both sensor types) on the site until just after the measurements on June 20, 2006. After this date, volumetric soil moisture

Table 15. Analysis of variance table for treatment effects on the cumulative level of soil moisture (Hydrosense and ECH2O) and both predawn and midday xylem water potential.

Parameter	Source	DF	Sums of squares	Mean square	F value	Pr>F	
Hydrosense TDR	block	3	0.0522	0.0174	0.8600	0.4841	
	treatment	5	3.6937	0.7387	36.3900	<0.0001	*
ECH2O	block	3	0.1623	0.0541	0.3500	0.7876	
	treatment	5	3.4548	0.6910	4.5100	0.0104	*
Predawn	block	3	1.3748	0.4583	2.0600	0.1488	
	treatment	5	51.3802	10.2760	46.1700	<.0001	*
Midday	block	3	27.2234	9.0745	32.9100	<.0001	*
	treatment	5	32.5673	6.5135	23.6300	<.0001	*

Footnote: * indicates significance at $\alpha = 0.05$.

Table 16. Treatment means for the cumulative levels of soil moisture (m^3 H_2O/m^3 soil) with Hydrosense and ECH2O probes, as well as both predawn and midday xylem water potential (-MPa). Values within columns that have different letters are different at α=0.05. Standard errors are calculated by treatment over replications and are in parentheses.

Treatment	Hydrosense TDR		ECH2O		Predawn		Midday	
1. -/-	3.2 d	(0.08)	3.3 c	(0.23)	-9.1 d	(0.21)	-18.9 d	(0.34)
2. F/-	3.7 c	(0.02)	3.5 bc	(0.20)	-7.4 c	(0.33)	-18.3 cd	(0.65)
3. F/S	3.5 c	(0.06)	3.6 bc	(0.22)	-6.4 b	(0.18)	-17.8 c	(0.67)
4. FS/S	4.1 b	(0.11)	4.3 a	(0.14)	-5.0 a	(0.13)	-16.7 b	(0.80)
5. FSG/S	4.2 ab	(0.06)	4.0 ab	(0.15)	-5.1 a	(0.30)	-15.8 a	(0.63)
6. FSG/SG	4.3 a	(0.06)	4.3 a	(0.15)	-5.3 a	(0.33)	-16.0 ab	(0.77)

Footnote: The Hydrosense TDR and ECH2O cumulative level of soil moisture are calculated by summing the 12 mean values of volumetric soil moisture by plot.

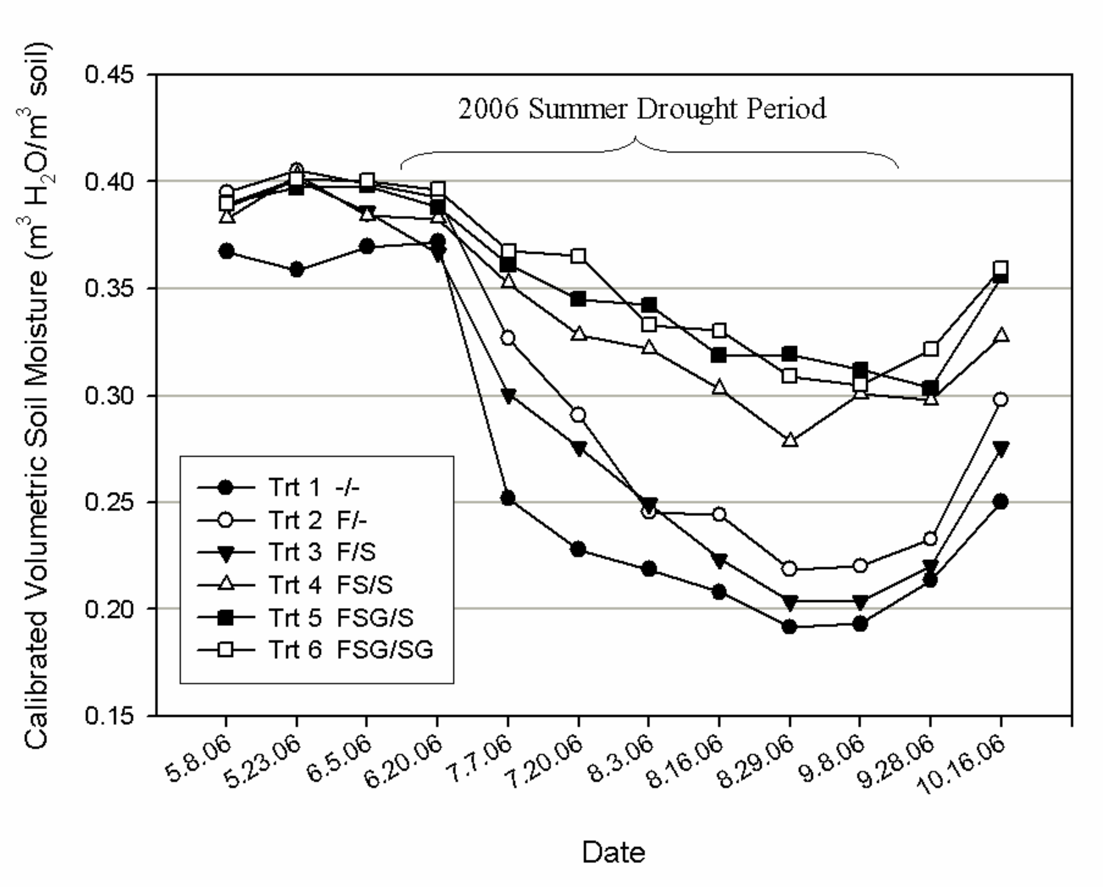

Figure 3: Calibrated volumetric soil moisture by treatment regime using a Hydrosense TDR sensor with 20cm prongs.

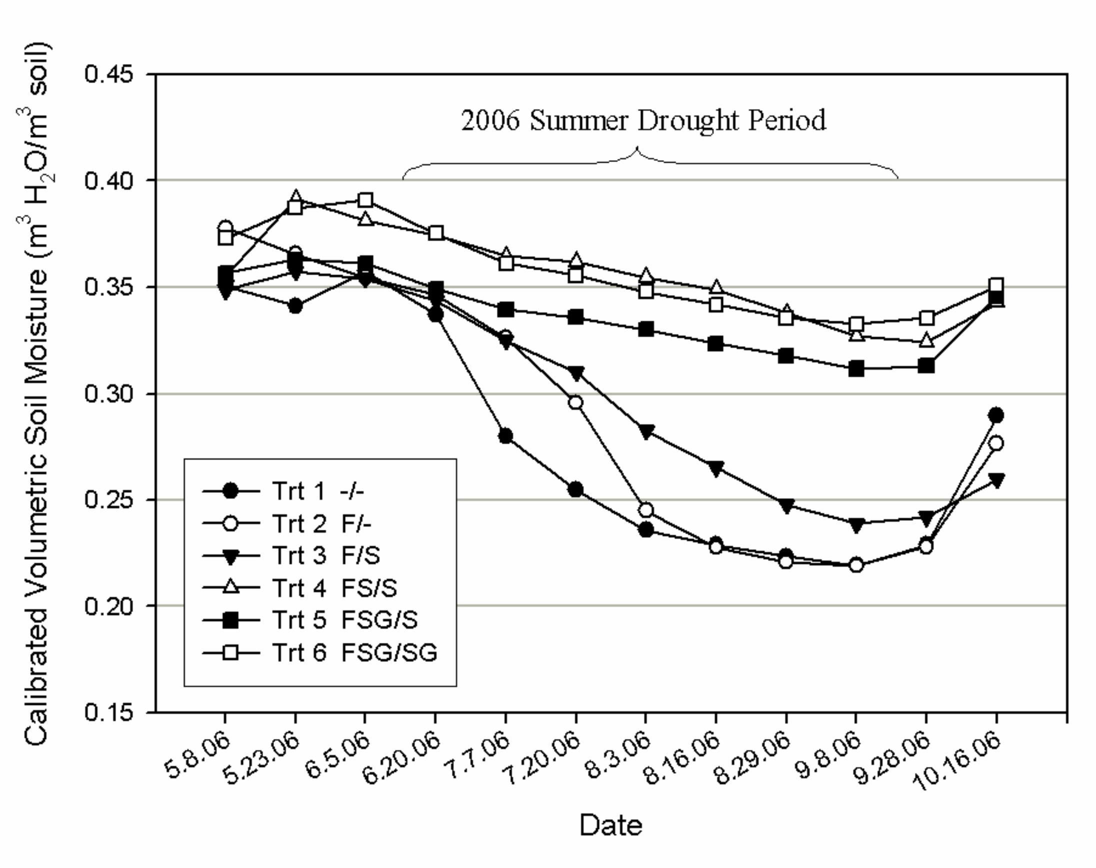

Figure 4: Calibrated volumetric soil moisture by treatment regime using 20cm ECH2O sensors.

was affected by the treatment regimes as shown by the rates of depletion. Both sensor types demonstrated a rapid depletion of volumetric soil moisture in the control treatment during the two week period from June 20 to July 7, 2006. While the rate of depletion slowed after this point in time, the control treatment continued to drop until reaching the lowest values observed in the study on September 8, 2006 (Hydrosense TDR 0.19 m^3 H_2O/m^3 soil and ECH2O 0.22 m^3 H_2O/m^3 soil). Volumetric soil moisture depletion in the fall site prep only treatments (2 and 3) dropped at noticeably slower rates than the control. On August 3, 2006, the fall site prep only treatments came to similarly low levels of volumetric soil moisture as those seen in the control (Hydrosense TDR <0.26 m^3 H_2O/m^3 soil and ECH2O <0.28 m^3 H_2O/m^3 soil). Treatments 4, 5, and 6 retained high levels of volumetric soil moisture (never dropping below 0.28 m^3 H_2O/m^3 soil with the Hydrosense TDR probe and 0.31 m^3 H_2O/m^3 soil ECH2O) across the measurement period. Depletion rates among these three treatments were a nearly consistent 0.01 to 0.03 m^3 H_2O/m^3 soil from June 20 to September 8, 2006. Rains returned to the site on September 15 (Figure 1) and began to replace soil moisture in the upper profiles as observed in the Figures 3 and 4.

2.4.6 Xylem Water Potential - Predawn

Seedling cumulative predawn xylem water potential was different among the treatment means (p-value <0.0001, Table 15). The control treatment had the lowest cumulative predawn xylem water potential at -9.1 MPa (Table 16). Treatments 2 and 3 were statistically different from one another and experienced -7.4 MPa and -6.4 MPa xylem water potential across the season, respectively. This is a 22 to 42% increase in cumulative water potential when compared to the control. Treatments 4, 5, and 6 were not statistically different from one another and resulted in a mean cumulative predawn xylem water potential of -5.1 MPa. This was an improvement of 77% over the potentials observed in the control treatment.

Early season predawn measurements occurring from May 8 to July 7, 2006 demonstrated high xylem water potentials (Figure 5). After the measurement on July 7, xylem water potential decreased differently among the treatment regimes. The control treatment showed the sharpest decline in potential. Seedlings in treatments 4, 5, and 6 never dropped below -0.7 MPa and collectively demonstrated the highest predawn xylem water potentials across the season observed in the study. The lowest potentials in all the treatments occurred on September 8 and were steadily increasing over the last two measurement dates as rains returned to the site in mid-September.

2.4.7 Xylem Water Potential - Midday

Cumulative midday xylem water potential was different among the treatment means (p-value <0.0001, Table 15). Blocking had an effect on the cumulative midday xylem water potentials, most likely due to slope position (p-value <0.0001). The control had the lowest cumulative midday xylem water potential at -18.9 MPa (see Table 16). The site prep only treatments (2 and 3) resulted in cumulative xylem water potentials ranging from -18.3 to -17.8 MPa, respectively, an improvement of 3 to 6% over the control. The site prep and spring release treatment improved midday potential by 13% with an increase in cumulative xylem water potential of -16.7 MPa. Applying an additional glyphosate treatment increased the cumulative midday xylem water potential between -15.8 to -16.0 MPa which is an average improvement of 19% when compared to the control.

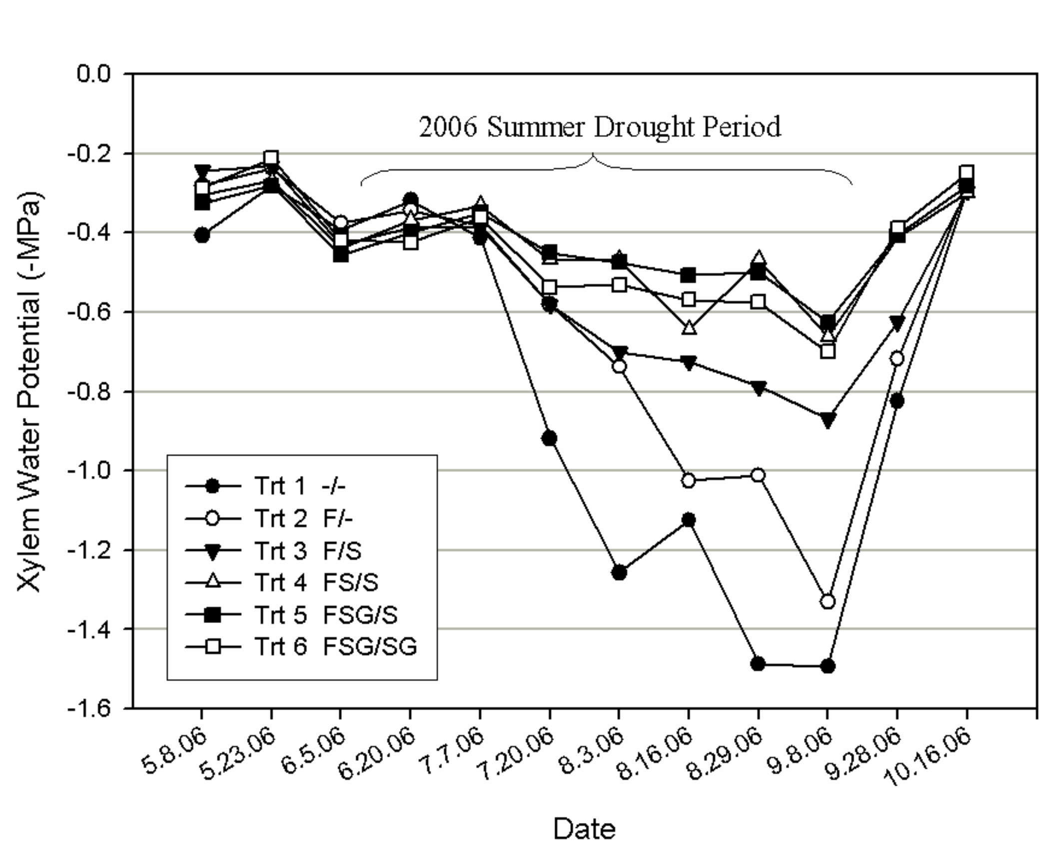

Figure 5: Seasonal development of predawn xylem water potential by treatment regime.

Generally, there was an increase in midday xylem water potential as the herbicide treatments became more intense (Figure 6). Midday measurements did not begin to differentiate among the treatments until July 20. At this point, xylem water potentials in the control began to decrease and reached the lowest values found in the study, nearly -2.5 MPa on August 29. Treatments 2 and 3 also reached their lowest xylem water potential values on August 29, nearly -2.2 and -1.9 MPa, respectively. Treatments 4, 5, and 6 did not drop below -1.7 MPa at any point in the season and represented the highest midday xylem water potentials found in the study. Precipitation returning to the site in mid-September alleviated these stresses dramatically and by mid-October xylem water potential values were at or near the levels experienced in the spring.

2.4.8 Treatment Effectiveness

Orthogonal contrast analysis explored the differences that occurred among specific preplanned treatment comparisons. The structure of the contrasts provided an understanding of the marginal improvements resulting from the effect that the treatment regimes had on seedling growth, cumulative soil moisture, and cumulative xylem water potential. The effectiveness of the treatments at improving growth or the moisture conditions was demonstrated through the observation of statistical differences among the set of five contrasts.

All five growth parameters analyzed were affected by the range of treatment regimes employed in the study. A general herbicide effect on height growth tested by comparing the control with all other treatments was not significant (p-value 0.0990, Table 17). However, height growth increases caused by additional applications of

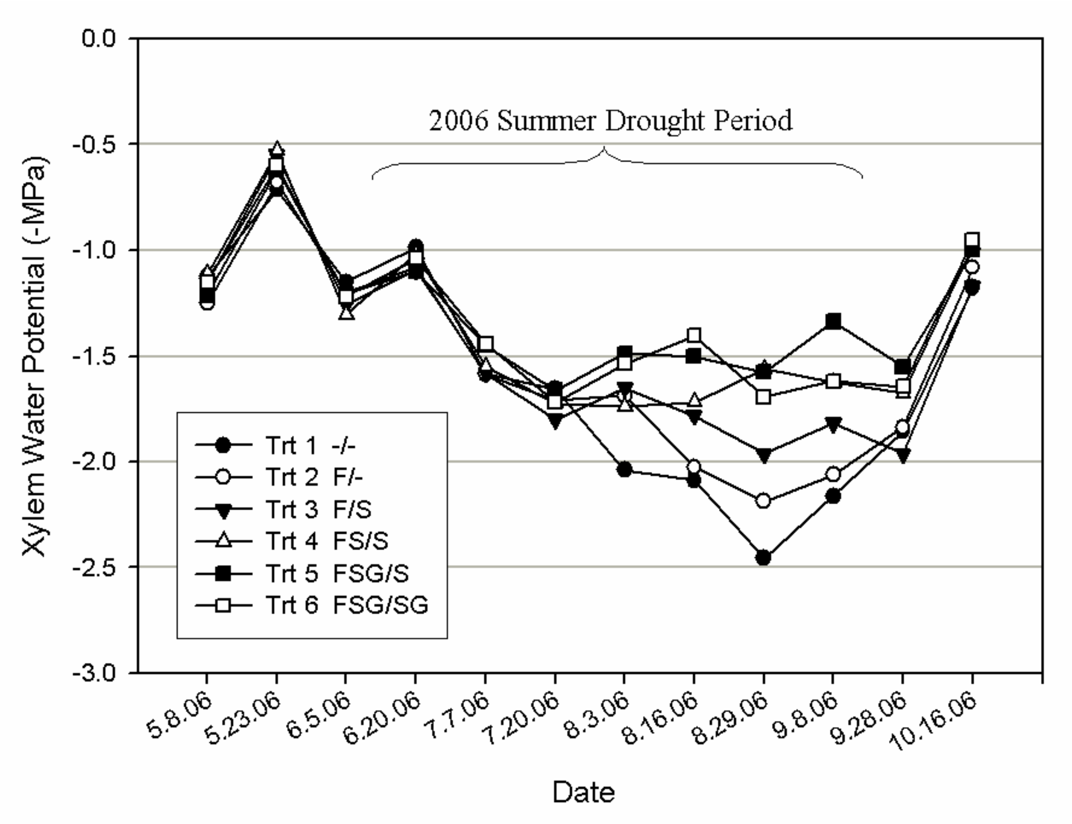

Figure 6: Seasonal development of midday xylem water potential by treatment regime.

Table 17. Probability of greater F-statistics for specific treatment comparisons of first year seedling growth.

Characteristic	Comparison	DF	Contrast SS	F value	Pr > F	
Height Growth	herbicide effect	1	16.0538	3.09	0.0990	
	site prep vs trts 4, 5, 6	1	48.7435	9.39	0.0079	*
	trt 4 vs trt 5 and 6	1	34.6935	6.69	0.0207	*
	diff between trt 2 and 3	1	23.4205	4.51	0.0507	*
	diff between trt 5 and 6	1	0.0781	0.02	0.9040	
Caliper Growth	herbicide effect	1	0.2721	13.20	0.0003	*
	site prep vs trts 4, 5, 6	1	0.2923	20.95	0.0002	*
	trt 4 vs trt 5 and 6	1	0.0053	1.36	0.5266	
	diff between trt 2 and 3	1	0.0215	1.13	0.2109	
	diff between trt 5 and 6	1	0.0024	0.05	0.6686	
Volume Growth	herbicide effect	1	354.6320	21.61	0.0024	*
	site prep vs trts 4, 5, 6	1	562.7450	23.21	0.0004	*
	trt 4 vs trt 5 and 6	1	36.6210	0.42	0.2611	
	diff between trt 2 and 3	1	30.2759	1.71	0.3051	
	diff between trt 5 and 6	1	1.3123	0.19	0.8280	
Crown Radius	herbicide effect	1	19.1123	10.14	0.0062	*
	site prep vs trts 4, 5, 6	2	7.5979	4.03	0.0631	
	trt 4 vs trt 5 and 6	3	5.2333	2.78	0.1164	
	diff between trt 2 and 3	4	0.0223	0.01	0.9149	
	diff between trt 5 and 6	5	1.5599	0.83	0.3774	
HDR	herbicide effect	1	680.0786	21.79	0.0003	*
	site prep vs trts 4, 5, 6	1	406.0322	13.01	0.0026	*
	trt 4 vs trt 5 and 6	1	10.5521	0.34	0.5696	
	diff between trt 2 and 3	1	10.2025	0.33	0.5760	
	diff between trt 5 and 6	1	19.9409	0.64	0.4366	

Footnote: * indicates significance at $\alpha = 0.05$.

herbicides over that of a site prep only treatment were significant (p-value 0.0079). There was also a difference between the height growth observed in treatment 4 and that found in treatments 5 and 6, which had an application of glyphosate (p-value 0.0207). Caliper and volume growth were increased by the use of herbicides in the study (p-values 0.0003 and 0.0024, respectively). The intensity of treatments 4, 5, and 6 had a significant effect on caliper and volume growth when compared to the growth observed in the site prep only treatments (p-values 0.0002 and 0.0004). Adding a follow-up application of glyphosate did not create an increase in the caliper and volume growth when compared to the growth resulting from a fall site prep and spring release treatment (p- values 0.5266 and 0.2611). Comparisons between similar treatments in year one (2/3 and 5/6) yielded no differences in height, caliper, or volume growth.

The increasing crown radius observed across the full range of treatment regimes indicated a herbicide effect (p-value 0.0062, Table 17). No other comparisons were found to be significant toward the increase in crown radius. The height to diameter ratio was affected by the use of herbicides when compared to the control (p-value 0.0003). There was also a difference between HDR in the site prep only treatments verses treatments that received more intense applications of herbicides (treatments 4, 5, and 6) (p-value 0.0026). An additional application of glyphosate did not reduce HDR and there was no difference between treatments that were similar in year one of the study.

The cumulative level of soil moisture was affected by the use of herbicides as measured with both sensor types (p-values Hydrosense TDR <0.0001 and ECH2O 0.0156, Table 18). There was also a difference between the soil moisture observed in the site prep only treatments and those treatments (4, 5, and 6) receiving additional applications of herbicides (p-values Hydrosense TDR <0.0001 and ECH2O 0.0019). The Hydrosense TDR probe showed a moderate difference between treatment 4 and those receiving an additional application of glyphosate (p-value 0.0433). The ECH2O probe did not show a difference in the same comparison (p-value 0.6909). No differences were found between the soil moisture as observed with both sensor types in treatments that were similar in year one of the study (2/3 and 5/6).

There was an increase in predawn cumulative xylem water potential from the herbicide regimes (Table 18). There was a herbicide effect (p-value <0.0001) over the untreated control. Predawn potentials were increased by using herbicide regimes that were more intense than a site prep only treatment (p-value <0.0001). Although they received the same herbicide treatment regime in the first year of the study, there was a difference between treatments 2 and 3 (p-value 0.0105). There was not an increase in predawn cumulative xylem water potential resulting from the additional application of glyphosate over that observed in treatment 4 or between treatments 5 and 6 (p-value 0.5398).

Midday cumulative xylem water potential increased through the application of herbicides (p-value <0.0001, Table 18). Midday potentials also were increased by the intensity of treatments 4, 5, and 6 when compared to that observed in the site prep

Table 18. Probability of greater F-statistics for specific treatment comparisons of the cumulative level of volumetric soil moisture (Hydrosense and ECH2O probes), as well as cumulative predawn and midday xylem water potential.

Characteristic	Comparison	DF	Contrast SS	Mean S	F value	Pr > F	
Hydrosense TDR	herbicide effect	1	1.7489	1.7489	86.1500	<.0001	*
	site prep vs trts 4, 5, 6	1	1.7802	1.7802	87.6900	<.0001	*
	trt 4 vs trt 5 and 6	1	0.0989	0.0989	4.8700	0.0433	*
	diff between trt 2 and 3	1	0.0613	0.0613	3.0200	0.1029	
	diff between trt 5 and 6	1	0.0045	0.0045	0.2200	0.6460	
ECH2O	herbicide effect	1	1.1401	1.1401	7.4400	0.0156	*
	site prep vs trts 4, 5, 6	1	2.1574	2.1574	14.0800	0.0019	*
	trt 4 vs trt 5 and 6	1	0.0252	0.0252	0.1600	0.6909	
	diff between trt 2 and 3	1	0.0172	0.0172	0.1100	0.7422	
	diff between trt 5 and 6	1	0.1148	0.1148	0.7500	0.4003	
Predawn	herbicide effect	1	34.9380	34.9380	156.9900	<0.0001	*
	site prep vs trts 4, 5, 6	1	14.3521	14.3521	64.4900	<0.0001	*
	trt 4 vs trt 5 and 6	1	0.0876	0.0876	0.3900	0.5398	
	diff between trt 2 and 3	1	1.9013	1.9013	8.5400	0.0105	*
	diff between trt 5 and 6	1	0.1013	0.1013	0.4500	0.5103	
Midday	herbicide effect	1	13.6519	13.6519	49.5200	<0.0001	*
	site prep vs trts 4, 5, 6	1	16.8375	16.8375	61.0700	<0.0001	*
	trt 4 vs trt 5 and 6	1	1.5251	1.5251	5.5300	0.0328	*
	diff between trt 2 and 3	1	0.5000	0.5000	1.8100	0.1981	
	diff between trt 5 and 6	1	0.0528	0.0528	0.1900	0.6679	

Footnote: * indicates significance at $\alpha = 0.05$.

only treatments (p-value <0.0001). Adding a follow-up application of glyphosate increased midday cumulative xylem water potential over treatment 4 (p-value 0.0328). Differences were not found between treatments that were similar in the first year of the study.

2.5 Discussion

2.5.1 Seedling Growth

Considering the intensity of the summer drought and the stresses observed through the xylem water potential measurements, seedling survival in the experiment was remarkably high. Wagner et al. (1989) found that ponderosa pine seedling survival could remain high in the presence of heavy competition. Others have noted a similar trend in a variety of conifer tree species including Douglas-fir (Newton and Preest 1988; Nambiar and Sands 1993; Miller et al. 1991). This study utilized several methods that have also proven to encourage high rates of survival including good cultural practices at the forest nursery (Duryea and Landis, 1984), seedling grading criteria that select for larger calipers (Long and Carrier, 1993; Rose and Ketchum 2003), and careful management of an experienced planting crew (Rose 1992).

Unlike survivorship, seedling caliper and volume growth is reduced in the presence of competitive weed cover during the critical period of plantation establishment (Wagner 1989, Rose et al. 1999, Rosner and Rose 2006; Newton and Preest 1988; Petersen et al. 1988). The caliper and volume growth resulting from the treatments employed in this study are in strong support of this generalization. Reductions in weed cover improved growing conditions (as measured by the soil moisture and xylem water potential), enabling seedlings to accrue more caliper and volume growth over the course of the summer. The site prep only treatment reduced competitive weed cover to approximately 40% and thereby increased soil moisture, xylem water potential, and seedling caliper and volume growth. However, these treatments did not improve conditions for the entire season and growth of seedlings in these plots was still limited by soil moisture depletion. Applying a spring release application further reduced the weed community to less than 20% throughout the season, minimizing soil water use by competing vegetation and allowing seedlings in treatments 4, 5, and 6 to maximize caliper and volume growth.

Due to the determinate habit of Douglas-fir (Kramer and Kozlowski 1979), the height and crown radius growth observed during the 2006 season occurred from buds developed under the homogenous and well-supplied conditions of the nursery in 2005. It is believed that the slight differences in height growth and crown radius at the end of the first season were mostly due to the occurrence of a second flush of growth which occurred in mid-July. This second flush, known as lammas growth or lammas shoot, is defined as free growth that occurs after predetermined growth has ceased (Roth and Newton 1996). Roth and Newton (1996) reported that Douglas-fir could produce significant growth gains through a lammas flush if herbicide regimes reduced competing vegetation enabling this response to occur while soil moisture conditions are appropriate during the mid-summer. It is also important to recognize that strong lammas growth in older seedlings can lead to stem deformation and poor growth form so this may not be a response to encourage.

The site received almost 4 mm of rain on July 12 and 13 which coupled with the soil moisture conditions observed in the treatments (Figures 3 and 4) could have initiated lammas growth. The growing conditions as reported by the soil moisture and xylem water potential measurements for the remainder of the season would either encourage the extension and development of this initial flush (treatments 4, 5, and 6) or suppress it due to the high level of moisture depletion (treatments 1, 2, and 3).

First season results from this study support the findings that specific weed control regimes can improve the vigor of planted seedlings (Cole and Newton 1987; Rose et al. 1999). When compared to a no-action control, utilizing a site prep only treatment reduced the HDR, an index of vigor, thereby increasing the likelihood of establishment success (see Table 7). Seedlings in these plots were still limited by site resource depletions to the extent that a spring release treatment reduced competition, further improving HDR. The conditions created by treatments 4, 5, and 6 allowed seedlings to maximize growth potential producing seedlings that are more vigorous (Rose et al. 1999). Decreasing HDR early in plantation establishment could set seedlings up for the continuation of rapid growth for a period of time after herbicide applications have ceased. This may serve to lengthen herbicide effectiveness beyond the chemical's persistence on the site and shorten the amount of time associated with the critical period of plantation establishment.

2.5.2 Vegetation

Research by Wagner and Radosevich (1991), Rose and Rosner (2005), Zutter et al. (1986), and Miller et al. (1991) illustrate the strong development of the herbaceous component of the weed community after vegetation management in the

PNW and Southeastern US. Results from this study further support the premise that on certain sites herbaceous weed species can rapidly invade and dominate during the first season of plantation establishment.

Incorporating repeated sampling of permanent plots with four surveys tracked the development of the weed community in response to herbicide application and distinct seasonal changes. Intensive vegetation surveys established the coarse-scale effectiveness of the treatments by monitoring total cover of competing species (Figure 2) but also demonstrated responses in species composition by growth form (Table 12), origin (Table 13), and lifespan (Table 14). The vegetation responses were further refined with Figures 7, 8, 9, and 10 by showing the ten most common species on the site and their general season of growth. DIFO (*Dicentra formosa* (Andr.) Walp.) and MOSI (*Montia siberica* (L.) Howell) grew rapidly in the early spring, reached their peak by the survey in mid-June (Figure 9), and were senescing by mid-July (Figure 10). RUUR (*Rubus ursinus* Cham. & Schlecht.) and SESY (*Senecio sylvaticus* L.) on the other hand, demonstrated their most prolific growth during the period of time from June (Figure 9) to July (Figure 10). This information along with soil moisture and xylem water potential, provides an understanding of when certain species most actively use site resources, impact the growth of crop trees, and provides some insight into herbicide efficacy.

Applying a fall site prep herbicide application comprised of Chopper® and Accord® reduced the vegetation occurring in these plots and increased seedling growth. Imazapyr, the active ingredient in Chopper®, controls a large spectrum of

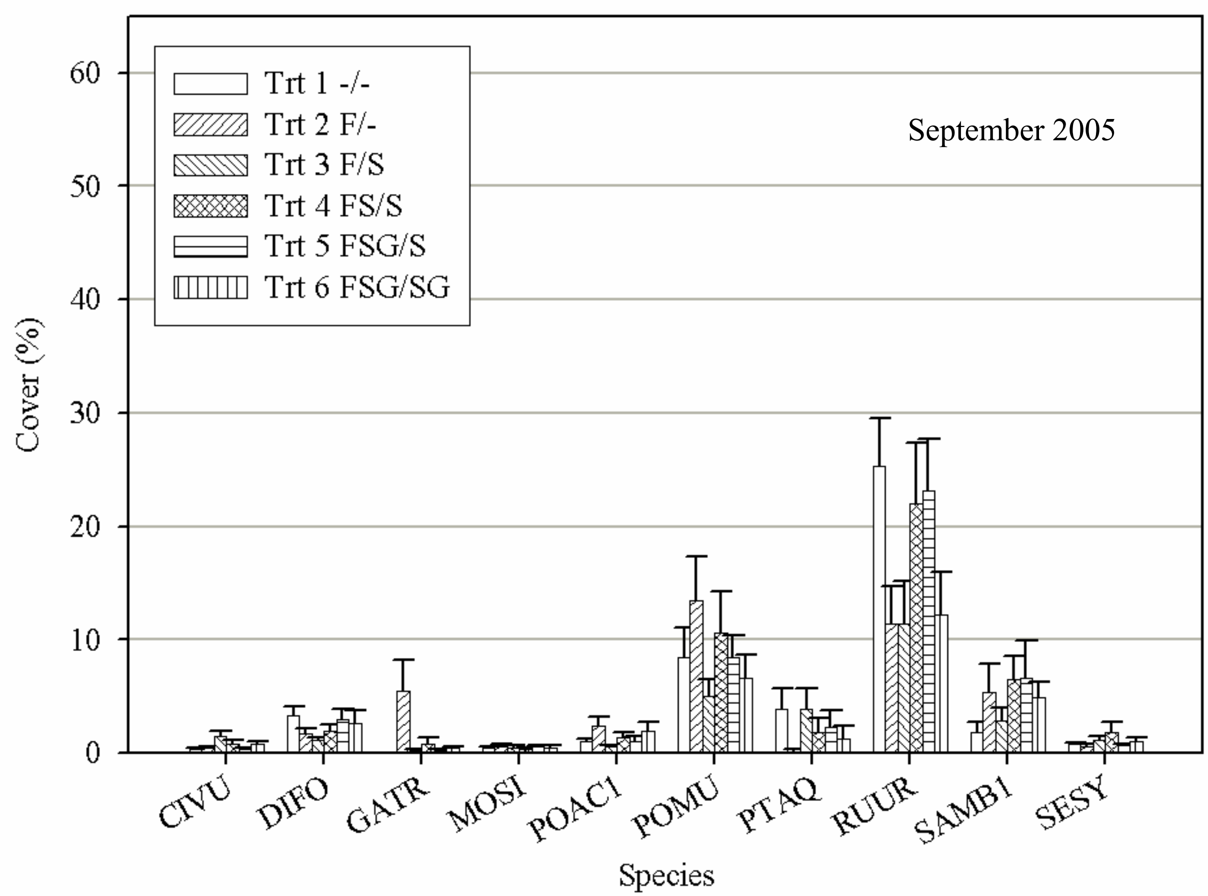

Figure 7: Percent cover of the 10 most common species in September 2005.
CIVU (*Cirsium vulgare* (Savi) Tenore); DIFO (*Dicentra formosa* (Andr.) Walp.); GATR (*Galium triflorum* Michx.); MOSI (*Montia sibirica* (L.) Howell); POAC1 (Poaceae spp.); POMU (*Polystichum munitum* (Kaulf.) Presl); PREM (*Prunus emarginata* (Dougl.) Walp.); PTAQ (*Pteridium aquilinum* (L.) Kuhn.); RUAC (*Rumex acetosella* L.); RUUR (*Rubus ursinus* Cham. & Schlecht.); SAMB1 (*Sambucus* spp. L.); SESY (*Senecio sylvaticus* L.)

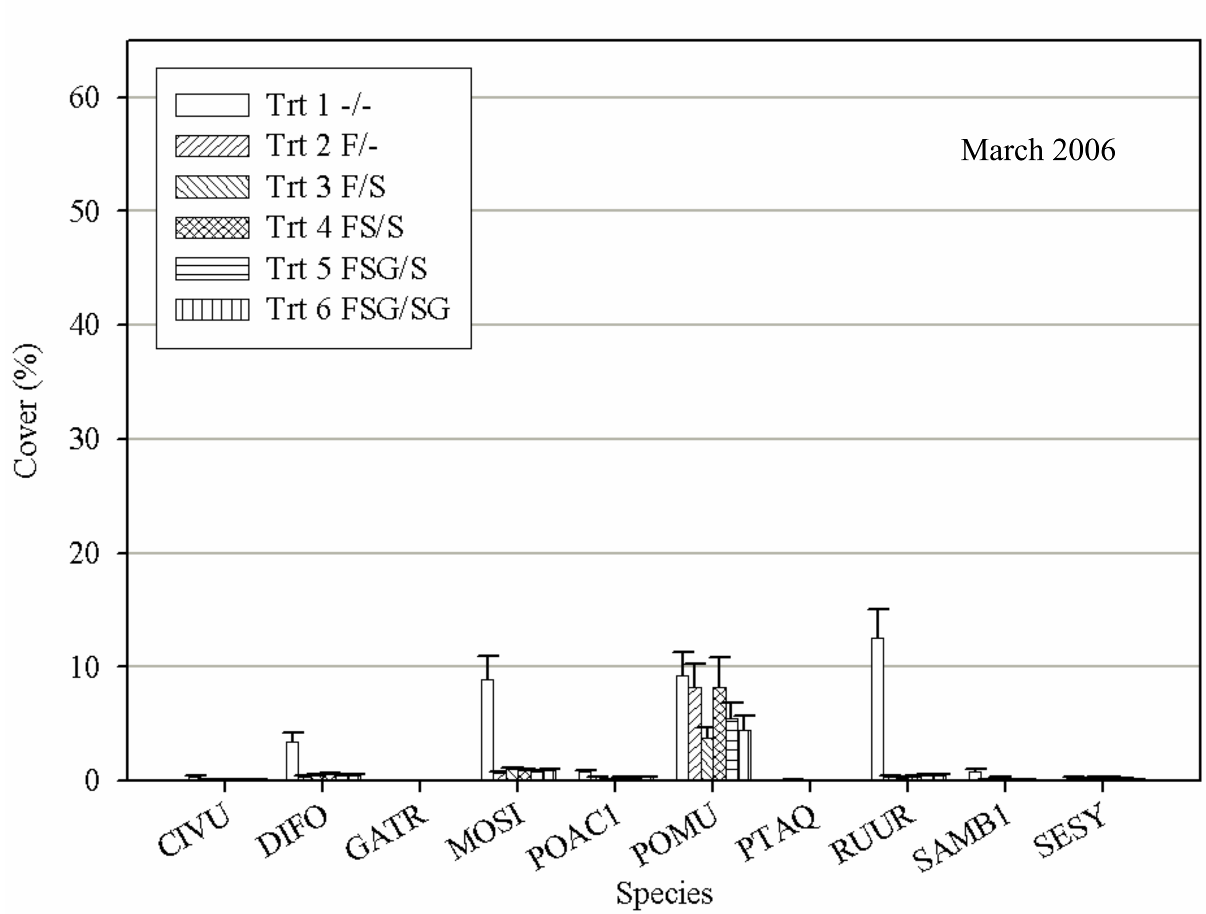

Figure 8: Percent cover of the 10 most common species in March 2006.
CIVU (*Cirsium vulgare* (Savi) Tenore); DIFO (*Dicentra formosa* (Andr.) Walp.); GATR (*Galium triflorum* Michx.); MOSI (*Montia sibirica* (L.) Howell); POAC1 (Poaceae spp.); POMU (*Polystichum munitum* (Kaulf.) Presl); PREM (*Prunus emarginata* (Dougl.) Walp.); PTAQ (*Pteridium aquilinum* (L.) Kuhn.); RUAC (*Rumex acetosella* L.); RUUR (*Rubus ursinus* Cham. & Schlecht.); SAMB1 (*Sambucus* spp. L.); SESY (*Senecio sylvaticus* L.)

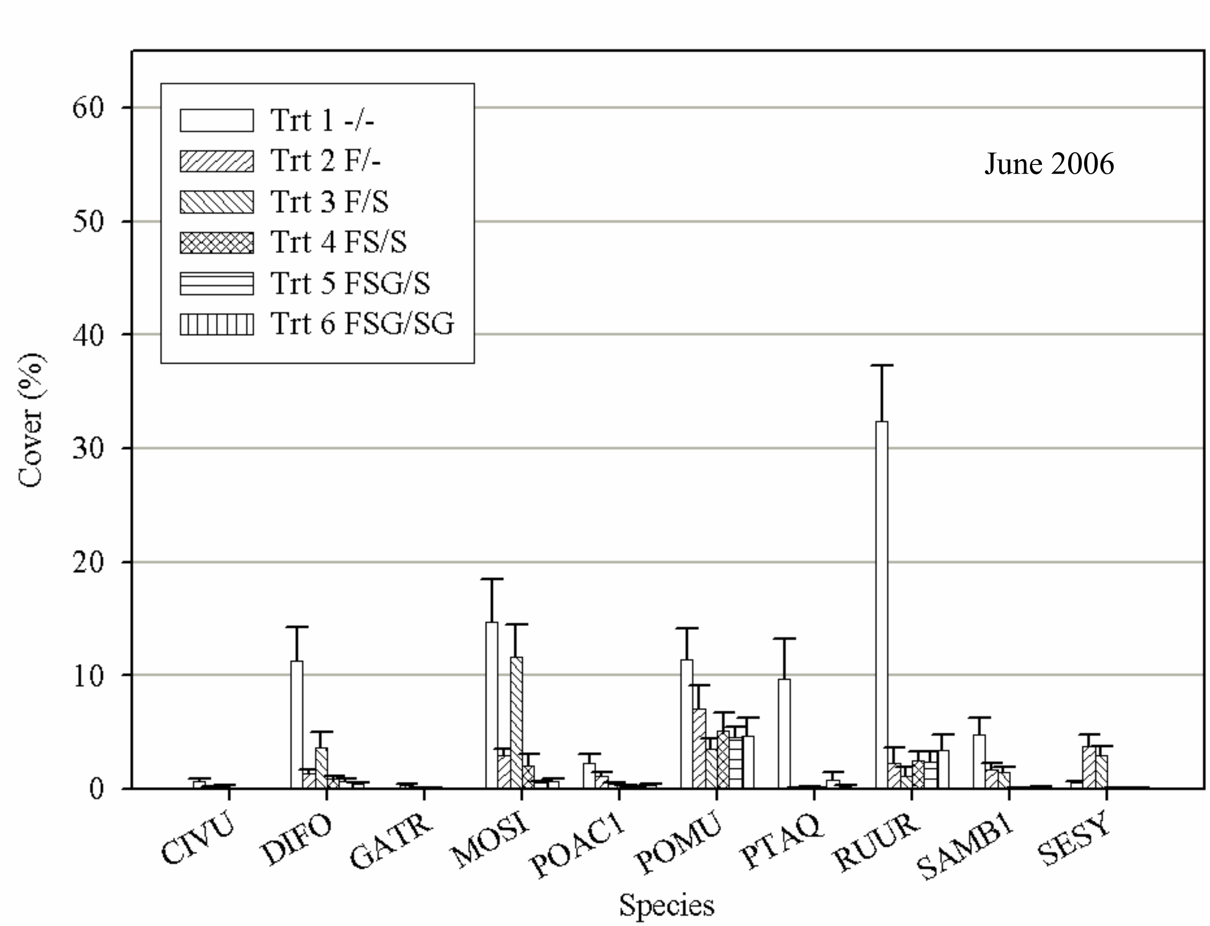

Figure 9: Percent cover of the 10 most common species in June 2006.
CIVU (*Cirsium vulgare* (Savi) Tenore); DIFO (*Dicentra formosa* (Andr.) Walp.); GATR (*Galium triflorum* Michx.); MOSI (*Montia sibirica* (L.) Howell); POAC1 (Poaceae spp.); POMU (*Polystichum munitum* (Kaulf.) Presl); PREM (*Prunus emarginata* (Dougl.) Walp.); PTAQ (*Pteridium aquilinum* (L.) Kuhn.); RUAC (*Rumex acetosella* L.); RUUR (*Rubus ursinus* Cham. & Schlecht.); SAMB1 (*Sambucus* spp. L.); SESY (*Senecio sylvaticus* L.)

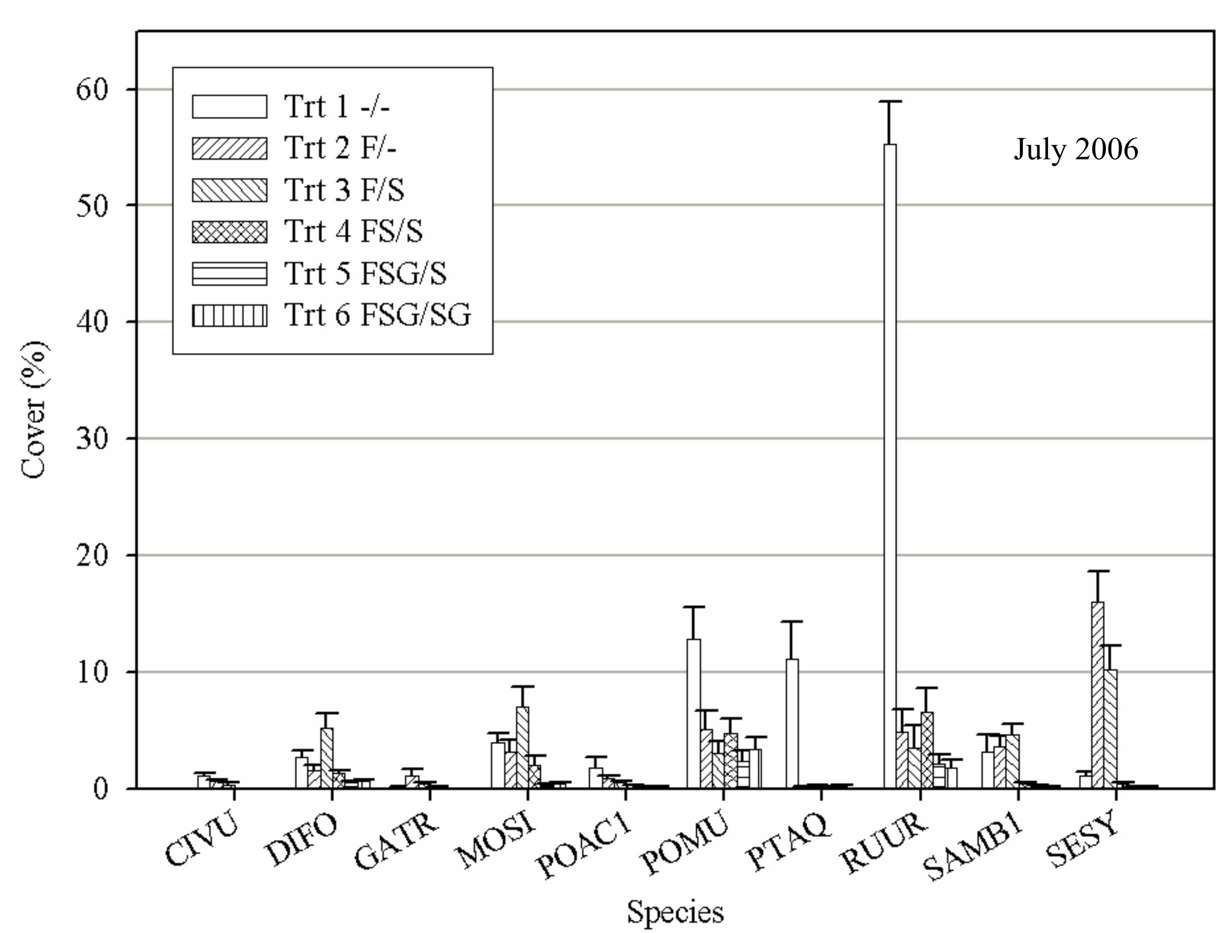

Figure 10: Percent cover of the 10 most common species in July 2006.
CIVU (*Cirsium vulgare* (Savi) Tenore); DIFO (*Dicentra formosa* (Andr.) Walp.); GATR (*Galium triflorum* Michx.); MOSI (*Montia sibirica* (L.) Howell); POAC1 (Poaceae spp.); POMU (*Polystichum munitum* (Kaulf.) Presl); PREM (*Prunus emarginata* (Dougl.) Walp.); PTAQ (*Pteridium aquilinum* (L.) Kuhn.); RUAC (*Rumex acetosella* L.); RUUR (*Rubus ursinus* Cham. & Schlecht.); SAMB1 (*Sambucus* spp. L.); SESY (*Senecio sylvaticus* L.)

weed species through broadcast application of the chemical which is absorbed by the foliage or the roots (William 1994; Ahrens 1994). This chemical is soil persistent and can provide control for up to six months (Ahrens 1994). Glyphosate, the activeingredient in Accord®, is broadcast applied, absorbed by the foliage, and exhibits almost no soil persistence due to binding on soil particles upon contact (Ahrens 1994).

Reducing the native vegetation through the application of these chemicals changed the composition of the weed community in plots receiving treatments 2 and 3. Several studies in North America have reported changes in weed community composition as a result of herbicide usage (Boateng et al. 2000; Boyd et al. 1995; Freedman et al. 1993; Sullivan et al. 1998). Herbicide application shifted the dominance of the vegetation toward species adept at germinating and growing under more open conditions. The introduction of a secondary disturbance after logging initiated this kind of shift (Boyd et al. 1995; Freedman et al. 1993). Presumably, the application of imazapyr and glyphosate in the fall site prep treatment had little or no effect on the weed growth occurring in the spring of 2006, more than 6 months after the chemical was applied.

Plots receiving only a fall site prep had a burst of growth from the introduced annual, *Senecio sylvaticus* L.. This species is known for having up to 8,500 small windborne seeds per plant capable of germinating when warm moist spring conditions occur (West 1968). The bare or relatively uncovered soils in treatments 2 and 3 coupled with the plant's rapid growth rates and a lack of competition from the native community (West 1968, Halpern 1989, Dyrness 1973, Radosevich and Holt 1984) allowed it to colonize and utilize site resources that would otherwise be available to Douglas-fir seedlings in these plots. This study can not provide information on the competitive mechanisms of *Senecio sylvaticus* L., but the rate of soil moisture decline from mid-June to mid-July when its abundance is high relative to other species in these treatment plots (Figures 9 and 10) suggest that it is a major consumer of soil moisture. Further research in the area of soil moisture and other resource use by weeds is needed. An in-depth knowledge of highly competitive weed species could create more precise herbicide prescriptions that improve herbicide effectiveness and produce larger growth gains earlier in plantation establishment.

Incorporating a follow-up spring release further reduced the weed cover in treatments 4, 5, and 6. The two chemicals employed in this spring release, Atrazine and Transline® (chemical name clopyralid), are known to prevent weed growth through foliage and/or root uptake (William 1994; Ahrens 1994). Both of these chemicals are moderately adsorbed in the soil and have half lives of 40 to 60 days (Ahrens 1994). Applying these chemicals in April would immediately reduce competing species in the plots, and chemical persistence through the spring would help to minimize the weed growth occurring after germination. Again, similar soil properties would degrade the effectiveness of the chemical but their application had reduced the weed community long enough for adequate germination and growing conditions to pass as the summer drought continued. These plots were then left relatively devoid of competing vegetation throughout the summer because the introduced annual component was minimized, shifting the species composition back to native perennials.

2.5.3 Soil Moisture and Xylem Water Potential

While forestry literature has documented that soil moisture and xylem water potential decline relative to increasing amounts of vegetation (Nambiar and Sands 1993; Newton and Preest 1988; Miller et al. 1991; Petersen et al. 1988; Powers and Reynolds 1999; Zutter et al. 1986), a study has not been found that provides detailed information for the initial season of plantation establishment with the treatment regimes used in this research. Zutter (1986) in his study of loblolly pine establishment remarked that intense measurements of soil moisture would be required to understand how specific vegetation management regimes affect growing conditions. Cleary (1971) noted that frequent and regular measurements of xylem water potential are required to observe the onset of seasonal stress, the intensity of that stress, and the length of time seedlings are under these conditions. The biweekly measurements reported here demonstrate how soil moisture and xylem water potential are affected by treatment regimes aimed at improving the growing conditions around planted Douglas-fir seedlings (Figures 3, 4, 5, and 6).

Harrington and Tappiener (1991) stated that through reductions in competing vegetation, it is possible to actually lengthen productive growing time by freeing limiting resources for use later in the season. The control treatment represents taking a "hands-off" approach to vegetation management. After the precipitous drop in volumetric soil moisture from June 20 to July 7, seedlings in these plots were exposed to low levels of volumetric soil moisture for greater than 90 days until the return of fall rains in late September (Figures 3 and 4). Reducing the cover to approximately 40% through a fall site prep freed soil moisture for growth later in the season but only for a limited time. From August 3 to September 28, a period of 56 days, volumetric soil moisture was near the levels observed in the control treatment. Treatments 4, 5 and 6 had total cover values that were less than 20% and showed a slower rate of soil moisture depletion across the growing season, but never reached the dry conditions of treatments 1, 2, and 3.

These periods of decreased soil moisture in plots with high amounts of weed cover may have reduced productive growing time to a few hours each day during the early morning. Brix (1979) studied photosynthesis with a CO_2 gas analyzer in conjunction with xylem water potential and found that Douglas-fir seedlings maintained nearly 100% photosynthetic efficiency when xylem water potential was above -1.0 MPa. Decreasing xylem water potential below this level steadily inhibited photosynthesis. By comparing the rates of gas exchange under these decreasing levels of xylem water potential with those observed under well watered conditions, the concept of net photosynthetic efficiency in the presence of limiting water supply was developed (Brix 1979). Extrapolating these results, it becomes possible to illustrate how vegetation control regimes may be able to increase daily photosynthetic efficiency.

On August 29, 2006, seedlings in the control treatment plots had predawn xylem water potentials of -1.5 MPa (Figure 5). These seedlings started the day at approximately 70% photosynthetic efficiency and by noon had dropped to around 20%

when the xylem water potential reached -2.5 MPa (Figure 6). By comparison, seedlings in treatment 4 on the same day began at -0.6 MPa and by midday had reached approximately -1.5 MPa, a decrease from 100% efficiency at dawn to around 60% by noon. If this trend of night recovery persisted throughout the season, seedlings in plots receiving treatments 4, 5, and 6 were able to extract enough soil moisture overnight allowing them to achieve near 100% photosynthetic efficiency by dawn and maintain higher levels of efficiency for a longer period each day.

This increase in daily efficiency helps to explain the growth gains associated with herbicide control during the first season of the critical period. Over the course of the 2006 summer growing season, the cumulative effect of night recovery and daytime efficiency would lead to increased production of photosynthate and the significantly larger growth gains observed in treatments 4, 5, and 6. The opposite could be said of seedlings in treatments 1, 2, and 3 which spent considerable portions of the summer months in plots with low soil moisture and low xylem water potential, reducing photosynthetic efficiency and subsequent growth.

Figure 11 is a schematic diagram representing the concept of how daily and cumulative season-wide efficiency of Douglas-fir seedlings may produce dramatic growth gains. The vertical bars in the graphic depict the amount of growth occurring from reductions in vegetative cover associated with the various treatment regimes employed in this study. The arrows represent productivity on both a daily and season time scale. Arrow width indicates the relative amount of productive growing time among seedlings in treatment plots on a daily resolution, while the length of the arrows provides an understanding of growth duration through the season.

In the spring, seedlings had the capacity to be relatively productive as they are growing in an environment with high amounts of soil moisture and high xylem water potentials. Productivity began to decline when soil moisture became limiting due to the summer drought and moisture depletion by weeds. The various treatment regimes utilized in the experiment manipulated the amount of competitive weed cover and created soil moisture conditions that dramatically changed the level of daily seedling productivity. The cumulative effect of daily efficiency translated into large season-wide differences as seedlings were capable of maintaining higher amounts of productivity for a longer period of time into the season. The dashed line in the schematic follows the general pattern of seedling growth observed in this study and is similar to the growth response curve under weed infested situations identified with the critical period concept (Wagner 2000). A reverse sigmoid curve was selected as it more accurately represents the relationship indicated by the dramatic improvement in seedling growth when weed cover was reduced below 20%. When this dashed line is combined with the productivity resulting from reductions in weed cover, the schematic provides a conceptual understanding of how seedling growth is affected during the first season of plantation establishment and the stage is set for growth through the remainder of the critical period.

Figures 3, 4, 5, and 6 demonstrate another point of interest, i.e., the noticeable lag in the decrease of xylem water potential behind the depletion in soil moisture.

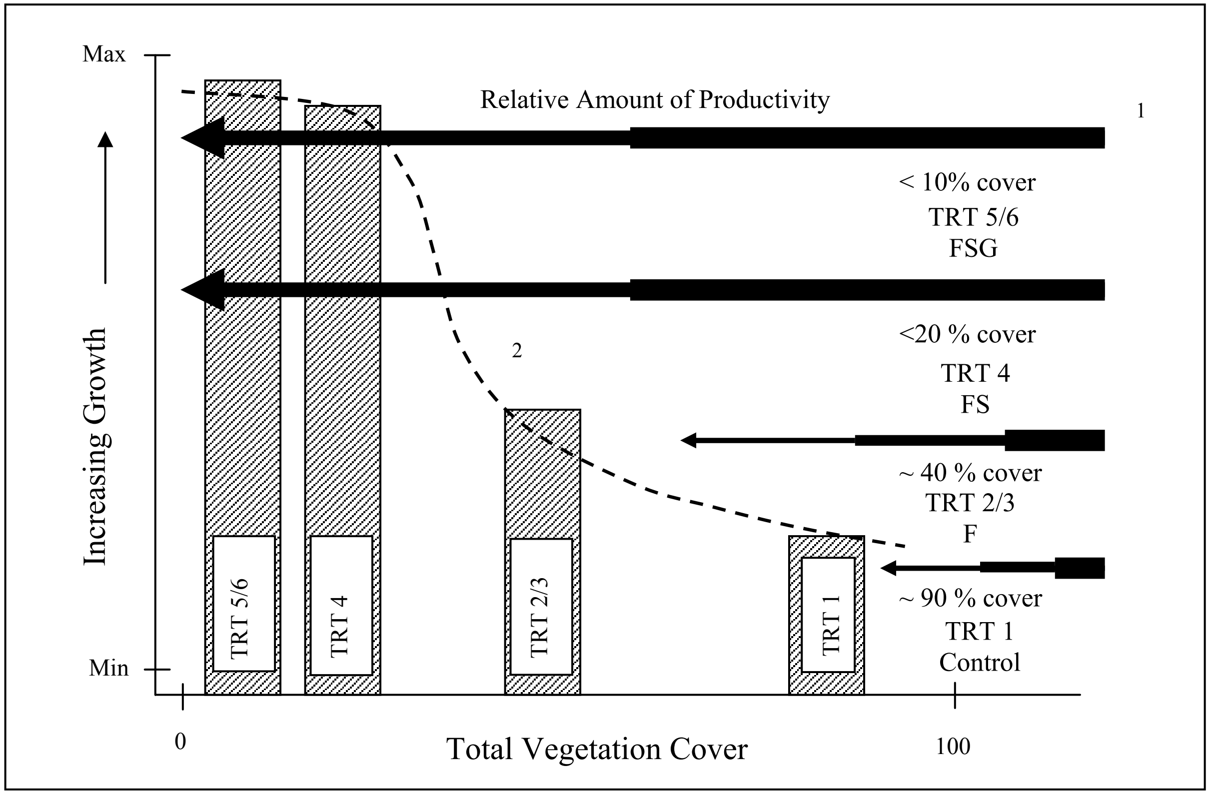

Figure 11: Schematic diagram of the cumulative effect of increased productivity on seedling growth through reductions in cover resulting from specific herbicide treatments during the first season of plantation establishment.

Footnote:
[1] Arrow width indicates the relative amount of daily productivity while the length of the arrow represents productivity on a seasonal scale.
[2] Dashed line follows the general pattern of first year seedling growth in response to daily and seasonal productivity.

Even though soil moisture began to differentiate among the treatments in late June/early July, xylem water potential (both predawn and midday) did not behave in a similar fashion. It was not until volumetric soil moisture reached a certain level that xylem water potentials began to decrease at different rates among the treatment regimes. Havranek and Benecke (1978) found that soil moisture had to drop below a specific threshold (25% with the soils in their study) for three conifer species to show decreasing xylem water potentials that impacted physiologic processes. Thomas (1970) reported that the xylem water potential of 13- to 28-year-old Douglas-fir trees growing on a variety of Oregon coast range sites did not decrease until soil water potential reached a tension specific to the soil type. Harms (1969) found a similar trend with southern pine species. It appears that the Douglas-fir seedlings in this study were able to extract the soil moisture necessary to maintain relatively high xylem water potentials until volumetric soil moisture decreased beyond a certain level. After this point, particularly in the control and the fall site prep only treatments, overnight recovery was limited and seedling xylem water potential began to decrease based on the soil moisture conditions created by these treatment regimes.

2.5.4 Treatment Effectiveness

It is important to note that there is a comparison being made by the structure of the orthogonal contrasts that is not directly tested but is decidedly informative. A significant difference in contrast two infers that treatments 4, 5, and 6 were responsible for the difference in the particular response in question when compared to the site prep only treatments. Contrast three tests for a statistical difference between treatment 4 and 5/6, an insignificant difference here means that the added glyphosate treatment did not improve conditions more than those achieved through the site prep with a spring release. When this situation occurs, the regime responsible for the largest gain for the parameter in question is treatment 4, a fall site prep with a spring release.

Compared to the control, any application of herbicides reduced competing vegetation and improved seedling growth; however, results from this research demonstrate that there is a treatment that is more effective at producing that growth. Treatment 4 was responsible for the greatest amount of caliper and volume growth, the largest decrease in HDR, and the dramatic increase in soil moisture and predawn xylem water potential. Reducing cover below 20% through the implementation of a site prep and spring release application maintained conditions that maximized seedling growth during the first year of plantation establishment.

Applying only a site prep treatment improved the growth of seedlings but it did not provide conditions that enabled seedlings to achieve their maximum potential. The additional application of glyphosate in mid-June improved conditions over treatment 4, which minimally impacted height growth, soil moisture, and midday xylem water potential. While treatments 5 and 6 improved conditions, the difficulty associated with applying glyphosate at that time of year and the slight amount of gains associated with the regime would make it challenging to justify this treatment in an operational forestry context. However, this treatment was not without merit as it provides an indication of the growth potential possible when the maximum amount of vegetation control is achieved.

2.6 Conclusions and Management Implications

Forest managers are continually searching for the most cost-effective means of producing the greatest amount of seedling growth early in stand establishment. Herbicide treatment effectiveness is a prime concern when budgets and personnel resources are limited. In order to meet this challenge, there is a need to find treatments that maximize growth early in the critical period in an effort to shorten the length of time when control is needed. The objectives of this study were to evaluate six weed treatment regimes for their effectiveness at increasing seedling growth, to chronicle changes to the weed community, and to intensively measure soil moisture and xylem water potential. It is evident that the treatment regimes employed in this study had a profound effect on first year seedling growth. Each successive reduction in competitive cover resulting from the progressively more intense herbicide regimes incrementally improved seedling performance. Herbicide use reduced the total cover and introduced a disturbance that had the potential to shift species composition of the weed community. Growing conditions were dramatically improved, as indicated by increases in soil moisture and seedling xylem water potential, having a profound effect on productivity. The improvement of growing conditions created a more efficient photosynthetic process for a longer period of time each day that translated into a season-wide cumulative effect of increased seedling growth. Incorporating a fall site prep and a spring release application was most efficient at producing the greatest increase in seedling growth through significant improvements in soil moisture and seedling xylem water potential. Herbicide regimes which reduce weed cover below

20% have the potential to lengthen daily and seasonal growing time through increased soil moisture and seedling xylem water potential. This encouraged the maximum growth of Douglas-fir seedlings during the initial season and may hasten seedlings through the critical period of establishment.

In 2007, the second season of herbicide regimes will begin. Vegetation sub-plots will be assessed in a similar fashion as the previous year and soil moisture and xylem water potential measurements will continue on a biweekly basis throughout the growing season. Results from this second year should continue to assist forest managers with information needed in the selection of herbicide regimes designed to successfully establish Douglas-fir plantations with maximal vigor.

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Appendices

Appendix 1: Common herbicides used in vegetation management regimes of the Pacific Northwest.

Sivlicultural Rx	Trade Name	Common Name	Form
Site Preparation	Oust®	sulfometuron methyl	dispersible granules
(prior to planting)	Accord®	glyphosate	water soluable liquid
	Escort®	metsulfuron methyl	dry flowable
	Chopper®	isopropylamine salt of imazapyr	emulsifiable concentrate
	Velpar L or DF®	hexazinone	water dispersible liquid/dry flowable
	Garlon®	triclopyr	low volatile ester
	MSO®	modified vegetable oil	liquid
Spring Release	Oust®	sulfometuron methyl	dispersible granules
(after planting)	Transline®	clopyralid	liquid concentrate
	Velpar L or DF®	hexazinone	water dispersible liquid
	Atrazine 90 WSP	atrazine	water soluble packets
Stump Treatment	Garlon®	triclopyr	low volatile ester
(year 2 - 5)	Accord®	glyphosate	water soluable liquid
	Chopper®	isopropylamine salt of imazapyr	emulsifiable concentrate

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1. Ahrens, W.H., and Edwards, M.T. 1994. Herbicide handbook. Weed Science Society of America, Champaign, IL. 352 pp.
2. William, R.D. et al. 1994. Pacific Northwest weed control handbook. Oregon State University Press, Corvallis. 344 pp.
3. Vegetation Management Research Cooperative, unpublished data.

Appendix 1: Common herbicides used in vegetation management regimes of the Pacific Northwest (Continued).

Trade Name	Application Rate	Timing	Target
Oust®	140 - 280 ml/ha	Aug to Sept	multiple
Accord®	0.75 - 1.5% of spray vol	(after harvesting	multiple
Escort®	140 ml/ha	and before planting)	weed and brush control (primarily rubus)
Chopper®	1.7 - 3.4 l/ha		multiple (primarily brush)
Velpar L or DF®	4.7 - 14.0 l/ha		herbaceous weeds, thistles, and brush
Garlon®	2.3 - 18.7 l/ha		woody and broadleaf weed species
MSO®	~		adjuvent

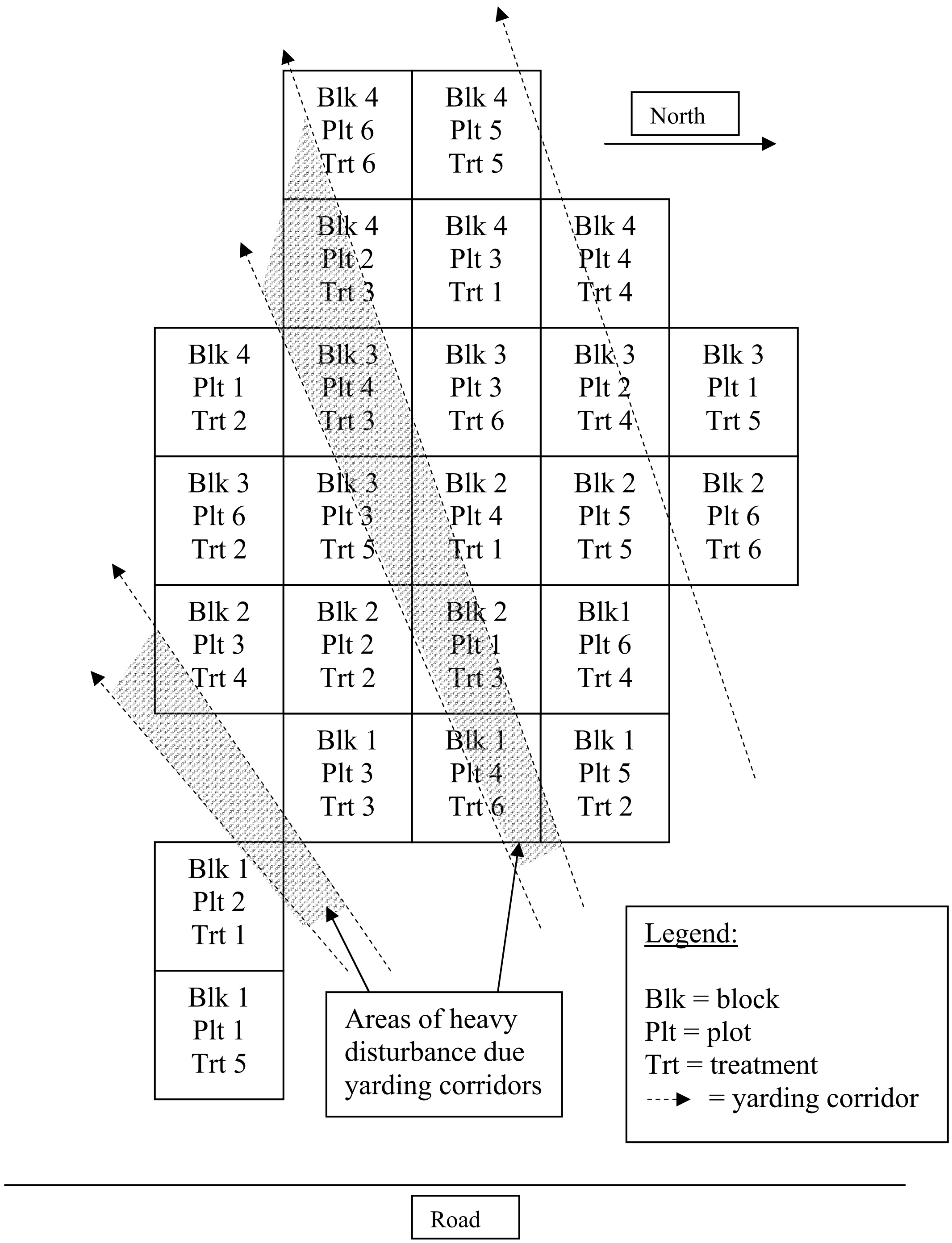
Oust®	140 - 280 ml/ha	March to April	preemergent
Transline®	403 - 813 ml/ha	(prior to bud break)	primarily grass, herbaceous, and thistles
Velpar L or DF®	11.6 - 14.0 l/ha		herbaceous weeds, thistles, and brush
Atrazine 90 WSP	2.5 - 40.9 kg/ha		broadleaf and grass weeds

Garlon®	20 - 30% of spray vol	April to June	stump sprouting species
Accord®	40-100% of spray vol	(need leaf area)	
Chopper®	560 - 1122 ml/ha		

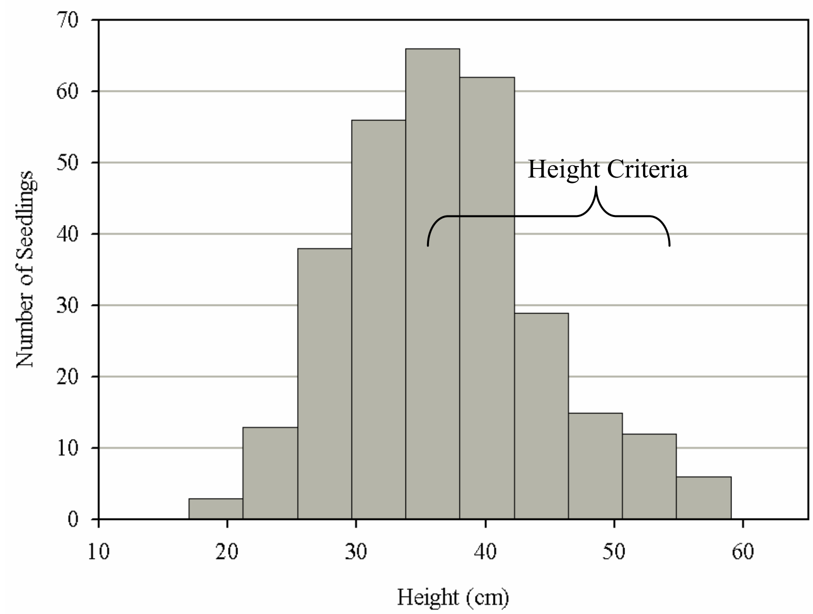
References:

1. Ahrens, W.H., and Edwards, M.T. 1994. Herbicide handbook. Weed Science Society of America, Champaign, IL. 352 pp.
2. William, R.D. et al. 1994. Pacific Northwest weed control handbook. Oregon State University Press, Corvallis. 344 pp.
3. Vegetation Management Research Cooperative, unpublished data.

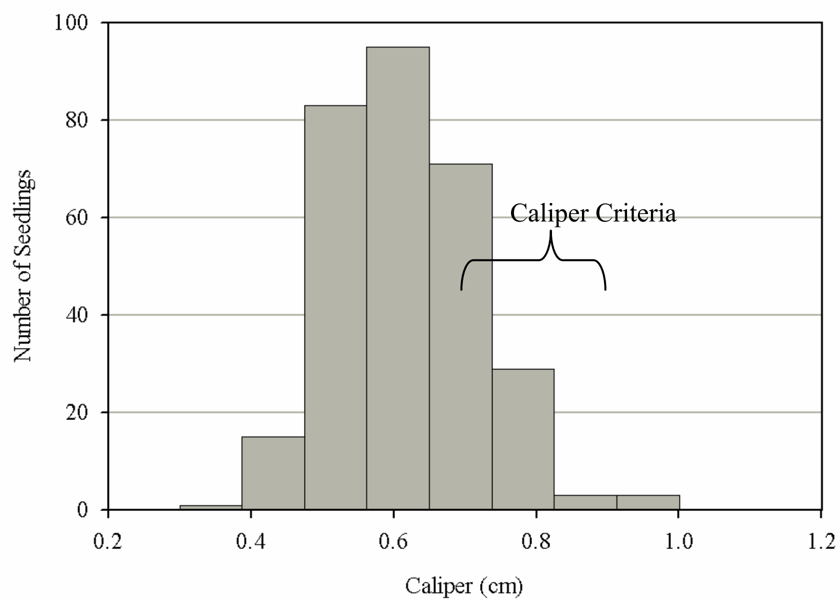
Appendix 2: Site map



Appendix 3: Seedling Grading Criteria



Height
Min: 17 cm
Max: 59 cm
Mean: 36.6 cm
St Dev: 7.65 cm
n= 300



Caliper
Min: 0.3 cm
Max: 1.0 cm
Mean: 0.61 cm
St Dev: 0.12 cm
n= 300

Appendix 4: Analysis of variance table for additional factors that could have impacted seedling growth

Parameter	Source	DF	Type III SS	Mean square	F value	Pr>F
Initial Height	Block	3	22.4407	7.4802	3.13	0.0570
	Treatment	5	17.3794	3.4759	1.46	0.2619
Initial Caliper	Block	3	0.0013	0.0004	0.41	0.7476
	Treatment	5	0.0076	0.0015	1.44	0.2681
Initial HDR	Block	3	21.1608	7.0536	3.08	0.0596
	Treatment	5	5.4036	1.0807	0.47	0.7915
Slash >7 cm	Block	3	236.0139	78.6713	3.01	0.0632
	Treatment	5	86.6481	17.3296	0.66	0.6570
Slash <7 cm	Block	3	598.7130	199.5710	2.07	0.1478
	Treatment	5	286.4583	57.2917	0.59	0.7057
Soil Bulk Density	Block	3	0.0170	0.0057	2.09	0.1441
	Treatment	5	0.0133	0.0027	0.98	0.4596

Appendix 4: Treatment means for additional factors that could have impacted seedling growth including initial seedling measurements (height HT 0, caliper Cal 0, height to diameter ratio HDR 0), % cover of slash less than 7 cm (<7 cm), % cover of slash greater than 7 cm (>7 cm), and soil bulk density (BD g/cc). Values within columns that have different letters are different at the α=0.05 level. Standard errors are in parentheses. (Continued).

Treatment	Ht 0 (cm)	Cal 0 (cm)	HDR 0	<7 cm	>7 cm	BD (g/cc)
1. -/-	43.3 a (0.52)	0.75 a (0.01)	59 a (0.86)	20.1 a (3.01)	10.0 a (1.75)	1.15 a (0.03)
2. F/-	41.8 a (0.53)	0.71 a (0.01)	60 a (0.95)	23.2 a (4.27)	6.8 a (1.83)	1.13 a (0.01)
3. F/S	41.1 a (0.49)	0.70 a (0.01)	60 a (0.92)	22.4 a (3.65)	12.2 a (3.21)	1.10 a (0.02)
4. FS/S	42.2 a (0.50)	0.72 a (0.01)	59 a (0.79)	30.2 a (5.61)	8.4 a (2.10)	1.11 a (0.02)
5. FSG/S	43.4 a (0.54)	0.74 a (0.01)	59 a (0.80)	25.8 a (4.58)	12.0 a (2.13)	1.10 a (0.05)
6. FSG/SG	41.6 a (0.48)	0.70 a (0.01)	60 a (0.90)	20.4 a (4.37)	10.2 a (3.52)	1.15 a (0.02)

Appendix 5: Plant species summary information (scientific name, family, origin, lifespan duration, and growth habit) for plants recorded in the vegetation surveys.

Scientific Name	Family	Origin	Lifespan	Habit
Acer macrophyllum	Aceraceae	Native	Perennial	Tree
Adenocaulon bicolor	Asteraceae	Native	Perennial	Forb
Alnus rubra	Betulaceae	Native	Perennial	Tree
Anaphalis margaritacea	Asteraceae	Native	Perennial	Forb
Astragalus canadensis	Fabaceae	Native	Perennial	Forb
Aster spp.	Asteraceae	.	.	Forb
Athyrium filix-femina	Polypodiaceae	Native	Perennial	Fern
Berberis nervosa	Berberidaceae	Native	Perennial	Shrub
Campanula spp.	Campanulaceae	Native	Perennial/An	Forb
Cardimine nuttallii	Brassicaceae	Native	Perennial	Forb
Cardimine oligosperma	Brassicaceae	Native	Annual/Bi	Forb
Caryophyllaceae spp.	Caryophyllaceae	.	.	Forb
Centaurea umbellatum	Asteraceae	Introduced	Annual	Forb
Chrysanthemum leucanthemum	Asteraceae	Introduced	Perennial	Forb
Circaea alpina	Onagraceae	Native	Perennial	Forb
Cirsium arvense	Asteraceae	Introduced	Perennial	Forb
Cirsium vulgare	Asteraceae	Introduced	Biennial	Forb
Conyaza canadensis	Asteraceae	Native	Annual	Forb
Corylus cornuta	Betulaceae	Native	Perennial	Tree
Crepis capillaris	Asteraceae	Introduced	Annual	Forb
Cyperaceae spp.	Cyperaceae	.	.	Grass
Dicentra formosa	Fumariaceae	Native	Perennial	Forb
Digitalis purpurea	Scrophulariaceae	Introduced	Biennial	Forb
Epilobium angustifolium	Onagraceae	Native	Annual	Forb
Epilobium spp.	Onagraceae	.	.	Forb
Epilobium paniculatum	Onagraceae	Native	Annual	Forb
Erechtites minima	Asteraceae	Introduced	Annual	Forb
Fabaceae spp. #1	Fabaceae	.	.	Forb
Fabaceae spp. #2	Fabaceae	.	.	Forb
Galium aparine	Rubiaceae	Native	Annual	Forb
Galium parisiense	Rubiaceae	Introduced	Annual	Forb
Gaultheria shallon	Ericaceae	Native	Perennial	Shrub
Galium spp.	Rubiaceae	.	.	Forb
Galium triflorum	Rubiaceae	Native	Perennial	Forb
Geranium molle	Geraniaceae	Introduced	Annual	Forb
Gnaphalium spp.	Asteraceae	.	.	Forb
Hieracium albiflorum	Asteraceae	Native	Perennial	Forb

Appendix 5: Plant species summary information (scientific name, family, origin, lifespan duration, and growth habit) for plants recorded in the vegetation surveys. (Continued).

Scientific Name	**Family**	**Origin**	**Lifespan**	**Habit**
Holcus lanatus	Poaceae	Introduced	Perennial	Grass
Hypericum perforatum	Hypericaceae	Introduced	Perennial	Forb
Hypochaeris radicata	Asteraceae	Introduced	Perennial	Forb
Hydrophyllum tenuipes	Hydrophyllaceae	Native	Perennial	Forb
Juncus spp.	Juncaceae	.	.	Grass
Lactuca muralis	Asteraceae	Introduced	Annual	Forb
Liliaceae spp.	Liliaceae	.	.	Forb
Lonicera ciliosa	Caprifoliaceae	Native	Perennial	Vine/Shrub
Lotus spp	Fabaceae	Native	Perennial	Forb
Luzula campestris	Juncaceae	Native	Perennial	Grass
Montia sibirica	Portulacaceae	Native	Annual	Forb
Nemophila parviflora	Hydrophyllaceae	Native	Annual	Forb
Oemleria cerasiformis	Rosaceae	Native	Perennial	Tree
Osmorhiza chilensis	Brassicaceae	Native	Annual	Forb
Phacelia nemoralis	Hydrophyllaceae	Native	Perennial	Forb
Poaceae spp.	Poaceae	.	.	Grass
Polystichum munitum	Polypodiaceae	Native	Perennial	Fern
Prunus emarginata	Rosaceae	Native	Perennial	Shrub/Tree
Pseudotsuga menziesii	Pinaceae	Native	Perennial	Tree
Pteridium aquilinum	Polypodiaceae	Native	Perennial	Fern
Ranunculus uncinatus	Ranunculaceae	Native	Perennial	Forb
Rhamnus purshiana	Rhamnaceae	Native	Perennial	Shrub/Tree
Ribes spp.	Rosaceae	Native	Perennial	Shrub
Rosa spp.	Rosaceae	.	Perennial	Shrub
Rumex acetosella	Polygonaceae	Introduced	Perennial	Forb
Rumex crispus	Polygonaceae	Introduced	Perennial	Forb
Rubus discolor	Rosaceae	Introduced	Perennial	Vine/Shrub
Rubus laciniatus	Rosaceae	Introduced	Perennial	Vine/Shrub
Rubus leucodermis	Rosaceae	Introduced	Perennial	Vine/Shrub
Rubus parviflorus	Rosaceae	Native	Perennial	Shrub
Rubus procerus	Rosaceae	Introduced	Perennial	Shrub
Rubus spectabilis	Rosaceae	Native	Perennial	Shrub
Rubus ursinus	Rosaceae	Native	Perennial	Vine/Shrub
Salix spp.	Salicaceae	.	Perennial	Tree
Sambucus spp.	Caprifoliaceae	Native	Perennial	Tree
Sambucus racemosa	Caprifoliaceae	Native	Perennial	Tree

Appendix 5: Plant species summary information (scientific name, family, origin, lifespan duration, and growth habit) for plants recorded in the vegetation surveys. (Continued).

Scientific Name	Family	Origin	Lifespan	Habit
Saxifragaceae spp.	Saxifragaceae	.	.	Forb
Senecio jacobaea	Asteraceae	Introduced	Perennial	Forb
Senecio sylvaticus	Asteraceae	Introduced	Annual	Forb
Senecio vulgaris	Asteraceae	Introduced	Annual	Forb
Smilacina spp.	Liliaceae	Native	Perennial	Forb
Smilacina racemosa	Liliaceae	Native	Perennial	Forb
Smilacina stellata	Liliaceae	Native	Perennial	Forb
Sonchus spp. #1	Asteraceae	.	.	Forb
Sonchus spp. #2	Asteraceae	.	.	Forb
Stachys rigida	Lamiaceae	Native	Perennial	Forb
Stellaria spp.	Caryophyllaceae	.	.	Forb
Symphoricarpos albus	Caprifoliaceae	Native	Perennial	Shrub
Thalictrum occidentale	Ranunculaceae	Native	Perennial	Forb
Trifolium dubium	Fabaceae	Introduced	Annual	Forb
Trifolium spp. #1	Fabaceae	.	.	Forb
Trifolium spp. #2	Fabaceae	.	.	Forb
Trifolium pratense	Fabaceae	Introduced	Perennial	Forb
Trifolium repens	Fabaceae	Introduced	Perennial	Forb
Trillium ovatum	Liliaceae	Native	Perennial	Forb
Unknown forb spp. #1	.	.	.	Forb
Unknown forb spp. #2	.	.	.	Forb
Unknown forb spp. #3	.	.	.	Forb
Urtica dioica	Urticaceae	Native	Perennial	Forb
Vancouveria hexandra	Berberidaceae	Native	Perennial	Forb
Vaccinium parviflorum	Ericaceae	Native	Perennial	Shrub
Vicia spp.	Fabaceae	.	.	Forb
Viola glabella	Violaceae	Native	Perennial	Forb
Vicia hirsuta	Fabaceae	Native	Annual/Pe	Forb
Viola spp.	Violaceae	.	.	Forb