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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.

Michael Monroe Taylor, Author

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CONTRIBUTION OF AUTHORS

Dr. Robin Rose assisted with the design and reporting of the experiment. Diane Haase was involved with the experimental design, implementation of the project, help with statistics and editing of this thesis. Douglas Jacobs helped with measuring of electrical conductivity of seedlings and in interpretation of that data.

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CHAPTER 1 - INTRODUCTION AND LITERATURE REVIEW

1.1 Objective

This thesis describes the results of two projects which were established to identify the optimum conditions for subsequent growth and survival of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western larch (*Larix occidentalis* Nutt.) seedlings across a range of plant dates. The current need to quantify success or failure of varying plant dates, especially fall dates, stems from the lack of previous research to pinpoint specific environmental thresholds and physiological variables at the time of planting that influence survival and growth of seedlings after planting.

1.2 Planting date

Winter and early spring are traditionally the favored planting season of foresters in the Pacific Northwest (PNW) due to nursery logistical constraints, high seedling stress resistance, and the fact that weather and soil conditions are favorable for growth after outplanting. However, with the harvest of large parcels of land, the need to extend the operational planting window has increased in the past few decades, resulting in a demand for quantifiable planting guidelines to maintain high survival and productivity under variable environmental conditions.

Fall planting is an alternative that has grown increasingly popular over the past decade. The rationale behind fall planting is that seedlings have dormant shoots but their roots can still actively grow. Advocates of fall planting say that seedlings may be able to establish root-to-soil contact immediately after planting when fall temperatures are ideal for new root growth while longer daylengths and continued photosynthesis increase stored carbohydrates available for root growth in spring (van den Driessche 1987, Major et al. 1994a). This fall root growth may increase seedling access to soil moisture and nutrients in the spring, resulting in increased growth, survival, and competitive ability relative to non-crop vegetation. In addition, fall planting extends the operational planting window, allows access to high elevation sites before winter snows accumulate and block roads, reduces the need for costly long-term storage, and allows managers to maintain planting crews for longer periods of time (Miller 1981, Barber 1989). Although the benefits may be great, the risks are also higher in some areas. Unlike winter- or spring-planted seedlings, those planted in the fall are just entering quiescence and are not as stress resistant (Major et al. 1994b). High temperature and low soil moisture at the time of planting may result in stresses leading to reduced growth or increased mortality.

Soil moisture and temperature at time of planting, the environmental conditions after planting, and the physiological state of the seedlings are the three major factors determining the success or failure of planting date (Crossley 1956, Roy 1957, Walters and Soos 1961, Cleary et al 1978, Adams et al. 1990, Scagel et al. 1990, Grossnickle and Major 1991, Akgul 2004). However, few studies have been published to evaluate this practice and results are conflicting (Kummel 1918, Schopmeyer 1940, Walters and Soos 1961, Sinclair and Boyd 1973, Marion and Alm 1986, Barber 1989, Livingston 2000, Burgess 2003).

In one of the earliest published trials, Kummel (1918) repeated a fall vs. spring planting trial over two years on the same sites with western white pine (*Pinus monticola* Dougl.) seedlings in the Whitman National Forest (Idaho, USA). He found that in the first year (1914-15) spring-planted seedlings had greater survival (86%) than fall-planted seedlings (56%); while the following season (1915-16) fall-planted seedlings had greater survival than spring-planted seedlings (87 and 81%, respectively). Marion and Alm (1986) found that season of planting had no significant effect on fourth-year survival, but that mean annual height growth was greater for spring- vs. fall-planted seedlings of red pine (*Pinus resinosa* Soland). In this study styro-plug containers were planted on a moderately well-drained sandy loam soil in Minnesota, USA. In Northeast Washington, Barber (1989) found that western larch (*Larix occidentalis* Nutt.) seedlings planted in fall (October 1985) were superior to those planted in spring (April 1986) with respect to survival, height growth, and total height. Walters and Soos (1961) found that variability in survival between two planting years (1958 and 1959) and planting dates (April to November) were too variable to draw any firm conclusions or generalizations regarding best dates for planting; however, they emphasized that soil moisture and environmental conditions were the driving forces behind seedling survival.

1.3 Seedling Quality

1.3.1 Morphology

Seedling morphology plays an important role in the success or failure of seedlings planted on different dates. There are a number of physical attributes that influence a seedling's ability to adapt and overcome specific environmental conditions. Simple measurements like height, root collar diameter (RCD), and the shoot:root ratio are often used to predict seedling performance after outplanting. Krumilk and Bergerud (1985) found that morphological differences associated with stocktype in Douglas-fir seedlings were still apparent 21 years after outplanting. The absolute difference between the shortest (1+0) and the tallest (2+0) stocktype increased from 11.1 cm initially to 131 cm after 21 years. Since taller seedlings tend to have a greater leaf area, height can indirectly provide information about the seedling's photosynthetic capacity (Iverson 1984) and transpirational area (Ritchie 1984a). Increased seedling height on productive sites decreases the probability of being overtopped by competing vegetation (Newton et al. 1993); however, large stock is also more susceptible to desiccation on windy sites (Ritchie 1984a). Seedling height must also be balanced with the increased cost of production, transportation, and planting (Arnott and Pendl 1994).

Root collar diameter (RCD) is another common measure of potential performance and is accepted as a better predictor of seedling survival and growth after outplanting than height (Thompson 1985). On five Oregon sites, survival of bareroot 2+0 Douglas-fir seedlings nearly doubled from the smallest (<3 mm) to largest (>5 mm) initial diameter classes and differences persisted in a linear fashion five years after outplanting (Long and Carrier 1993). Rose and Ketchum (2003) reported that Douglas-fir seedlings with larger initial diameters (8-12 mm) outplanted to two Washington sites had 92% greater first-year stem volume and 35% greater stem volume after four years compared to seedlings with smaller initial diameters (5-8 mm).

The shoot:root ratio (measured by volume or dry mass) is commonly used to evaluate the drought avoidance potential of seedlings (Hermann 1964). The ratio is an indicator of water loss potential (transpirational tissue) divided by the absorptive capacity of their roots. Although it is a useful measure of field performance, the type of rooting structure is more important than the volume displaced (Cleary et al 1978). A seedling with more fine roots has a higher absorptive capacity (more rooting area) than a seedling with a large woody rooting structure, suggesting that the seedling with fine roots has a greater ability to uptake water and keep up with a larger above ground transpirational area. Studies show that Douglas-fir 2+0 bareroot seedling survival with larger shoot:root ratio is lower than for those with a lower ratio (Hermann 1964, Lopushinsky and Beebe 1976).

1.3.2 Seedling Physiology

1.3.2.1 Seedling Dormancy

In the PNW, the conventional nursery dormancy induction practice is to decrease irrigation and fertilization in late summer while maintaining natural light conditions. This mimics natural seasonal changes that induce seedlings to enter an environmentally-imposed dormancy. Once this stage of dormancy has been achieved, irrigation and fertilization is resumed at a reduced rate to encourage stem diameter growth, root growth, and to increase whole plant nutrition. If irrigation and nutrition are applied too soon or too frequently after cessation of growth, a second or lammas flush of growth may occur late in the summer or fall which can increase the risk of early frost damage. Douglas-fir seedlings exposed to repeated cycles (11 and 8 cycles for season) of moisture stress at varying intensities had greater survival than those subjected to a less severe moisture stress (van den Driessche 1992).

Another method of dormancy induction is shortened photoperiod. Plants in temperate environments respond to photoperiod as a signal to enter into dormancy. Short photoperiod, or daylength (SD), has been used by northern latitude nurseries for many years to induce dormancy by increasing the amount of inactive phytochrome. As photoperiod is decreased, the amount of active phytochrome decreases due to decreased red light signals. In response, seedlings initiate a terminal bud and increase cold hardiness. Sitka spruce (*Picea sitchensis* (Bong.) Carr.) seedlings that received SD (14-hour night length) compared with a control (natural decreasing day length) had reduced height growth due to early formation of the terminal bud, increased root weight, decreased shoot:root volume ratio, and accelerated cold hardiness acquisition (Hawkins et al. 1996). The use of SD to induce dormancy can be beneficial compared to conventional dormancy induction because irrigation is not reduced. As a result, moisture stress is avoided. On the other hand, the abrupt photoperiod change used in

SD may adversely influence some attributes of seedling morphology and physiology when compared to a gradual photoperiod change (MacDonald and Owens 1993b).

1.3.2.2 Cold Hardiness

Cold hardiness is normally considered a seedling's ability to withstand freezing stress but is also related to overall stress resistance such as stresses associated with lifting, packaging, storing, and outplanting (Ritchie 1989). This measure helps foresters assess seedling quality and gives an estimate of potential survival and establishment after outplanting. The whole-plant freeze test (WPFT) is one common technique used to estimate cold hardiness. In this test, the entire seedling is potted (roots insulated usually with potting media or dry vermiculite) placed in a programmable freezer, and exposed to controlled, sub-freezing temperatures. Freezing temperatures are selected to bracket the LT_{50} (lethal temperature where 50% of the seedlings are killed) and correspond to time of year and accumulated chilling hours. After freezing, seedlings are placed in optimum growing conditions for 6-7 days then assessed for damage to needles, buds, and cambium tissues in order to quantify mortality at a given temperature and estimate the LT_{50}. Results from these tests are used to help managers determine frost protection regimes in nurseries as well as to predict damage to outplanted seedlings from a freeze event.

Cold hardiness is an active seedling response to environmental cues (i.e. photoperiod, temperature, chilling accumulation, etc.) which can allow it to withstand freeze events with little or no damage. The two main types of freezing in plants are intra- and inter-cellular freezing. If ice crystals form between cells it is referred to as intercellular or extracellular but if it occurs within the cell (which is almost always fatal to the tissue) it is referred to as intracellular. Intracellular freezing is generally limited to extreme events when temperatures change rapidly (>10ºC per min); this can happen if seedlings are removed from a greenhouse in winter and placed out-of-doors or after growth has resumed and an extreme frost event occurs. Intercellular freezing is common in temperate climates but can be avoided by a combination of seasonal chemical adaptations and membrane syntheses within the plant. Douglas-fir seedlings with a Dormancy Release Index (DRI) value between 0.25-0.40 had greater height growth after exposure to -15ºC for two hours than seedlings with DRI values ≤ 0.18 (Ritchie 1986). Cold hardiness is also used as an indicator of potential resistance to heat damage. Koppenaal and Colombo (1988) reported that actively growing black spruce (*Picea mariana* (Mill.) B.S.P.) seedlings had an average of 46% stem damage when exposed to 42ºC for 10 min (1ºC /min increase until temperature was reached starting at 25ºC) but dormant seedlings showed no damage when exposed to the same treatment in a controlled environmental test chamber.

Another method for measuring cold hardiness is freeze-induced electrolyte leakage (FIEL), which measures the amount of electrolytes that leak out of cell membranes when they are damaged by freezing. Damage in this case occurs when freezing water within the cell crystallizes and punctures the cell membranes creating “holes” where electrolytes leave to equilibrate with surrounding de-ionized water. These electrolytes are then measured using an electrical conductivity meter and used to estimate the amount of damage in specific plant tissues as a result of freezing (Burr et al. 1990, McKay and Mason 1991, Folk et al 1999). FIEL is calculated by a ratio of the electrical conductivities of the tissue in de-ionized water after exposure to freezing temperature and then again after autoclaving (Folk et al. 1999). FIEL values more than 30% are a general indicator of significant damage (Grossnickle 2000). FIEL measurements are expected to be highest when seedlings are actively growing and lowest when they are dormant due to the plants ability to withstand intracellular freezing.

1.3.2.3 Root growth potential

Root growth potential (RGP) is considered a surrogate indicator of field performance (Scagel et al. 1993, Tinus et al. 2000, Burr et al. 1989). RGP is the ability of tree seedlings to initiate and elongate roots when placed into an environment favorable for root growth (Ritchie 1984b). Seedlings with a high RGP are expected to have high vigor and field growth potential (Ritchie 1984b, McTague and Tinus 1996). RGP is usually determined by counting or weighing (dry weight) new roots greater than 0.5 cm or 1 cm after a specified period of time under optimal conditions (Binder et al. 1990, Landis and Skakel 1988, Grossnickle 2000). Another method is to measure the displacement of roots in a measured solution and calculate the change in volume over time (Burdett 1979). Increasing RGP has been associated with increasing field performance (Ritchie and Dunlap 1980, Ritchie and Tanaka 1990). Omi et al. (1994) found that RGP measurements accounted for 69% of the variation in survival of outplanted ponderosa pine (*Pinus ponderosa* P.&C. Law.) seedlings. Conversely, Scagel et al (1993) found that the variation in seedling mortality and height growth of coastal Douglas-fir under controlled irrigated field conditions was so variable that RGP was not an adequate predictor. Simpson et al (1988) found that interior spruce (*Picea glauca* (Moench) Voss) and lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) seedlings that produced more than 10 new roots > 1 cm in length performed better than seedlings with less than this threshold.

1.3.2.4 Xylem water potential

Plant moisture stress (PMS) is commonly measured by xylem water potential, (Newton and Preest 1988). As water stress increases, xylem water potential becomes more negative (Clark and Hiler 1973). PMS is usually measured early in the morning (i.e. predawn xylem water potential) because plant water potential equilibrates with soil water potential overnight and gives a relative measure of the amount of water in the soil and the seedling's ability to recover from stress. Measurements taken at predawn or mid-day provide information on the degree of stress experienced by seedlings. The amount of stress can be used to gauge the function of other internal processes related to plant hydraulics such as stomatal control, photosynthesis, gas exchange, and uptake and translocation of nutrients (Sun et al. 1995, Loewnstein and Pallardy 1998, Bond and Kavanagh 1999). Stomates are controlled primarily by turgor pressure used to increase or decrease relative concentrations of ions within the guard cells. The opening and closing of these guard cells regulate the internal water potential as well as gas exchange which is pertinent to many metabolic functions like photosynthesis.

Moderate moisture stress (-0.5 to -1.0 MPa) can cause stomata to close thereby reducing photosynthate production for growth while high moisture stress (-1.5 MPa) can damage the entire photosynthetic system (Lopushinsky 1990). Net photosynthesis of Douglas-fir seedlings started to decline at -1.0 MPa and reached zero at -5.39 MPa while transpiration started to decline at a similar level but was still 3% when net photosynthesis was zero (Brix 1979). Height and diameter growth decreased significantly in containerized Douglas-fir seedlings from high to low moisture regimes (65% to 7% soil water content by volume) with the driest regime also having a significant amount of mortality (Khan et al. 1996). While moderate to severe moisture stress may damage seedlings, some level of moisture stress is needed to have adequate budset to increase cold hardiness (Major et al 1994).

1.3.2.5 Foliar Nutrition

The reservoir of seedling nutrients at the time of planting is important for the resumption of terminal growth and the initiation of new roots. Seedling nutrition reflects the amount of fertilization applied in the nursery (van den Driessche, 1983); however, foliar nutrition at the time of planting may not be a useful predictor of overall outplanting performance (van den Driessche 1980). Floistad (2002) found no evidence that excessive nutrient supply (3.3% N in needles) in Norway spruce (*Picea abies* (L.) Karst.) seedlings led to increased autumn frost damage or decreased time to terminal bud break compared to the lower concentration treatment (2.2% N). Shaw et al (1998) found that high levels of foliar nitrogen (71% above low nitrogen treatment) resulted in significantly larger seedlings that allocated more resources to their shoots (34.8 g dry mass) than roots (20.3g) compared to the low nitrogen treatment (9.9 g shoot, 9.4 g root). Though there may be a variable response to nutrient concentrations, seedling nutrition is important for early growth before establishment.

1.4 Planting Environment

1.4.1 Soil moisture

Soil moisture is one of the most important factors influencing survival and growth of seedlings (Hobbs 1992) regardless of plant date. In the PNW, water availability during summer drought months is a primary factor limiting growth of many species (Waring and Franklin 1979). Water plays a vital role in the uptake and translocation of nutrients to and within seedlings. As seedlings transpire, water and nutrients are moved through mass flow and diffusion to the plant roots where they are absorbed. Once absorbed, they translocate either from concentration gradients or evaporative tension to actively transpiring tissues where water is evaporated and nutrients are deposited and used in photosynthesis as well as many other metabolic functions. If soils are unable to pull water through capillary rise from depth faster than seedling uptake, seedlings may undergo water stress, resulting in reduced growth and increased mortality (Helenius et al. 2002). Ideally, soil water potential in the top 25 cm should be greater than 1 bar (< -0.1 MPa) for summer and fall plantings (Cleary et al.

1978, Krumlik et al. 1984). Mortality of white spruce (*Picea glauca* (Moench) Voss) in Alberta, Canada was highest when soil at the time of planting was “powder dry” (Crossley 1956). In an early study on the effects of fall vs. spring planting in the redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) -Douglas-fir region of California, seedling survival was similar between fall and spring plantings as long as soil moisture and weather conditions were “favorable” (Roy 1957). Helenius et al (2002) found that pre-plant drying and post-plant drought resulted in increased mortality, reduced root egress, and reduced height growth in Norway spruce seedlings grown in sphagnum peat plugs (cell volume 85 cm^3) and outplanted into a sandy nursery field.

The availability of water affects seedling growth in a variety of ways. Terminal growth, stem diameter growth, and needle length all increased with increased soil moisture content in 2+0 Douglas-fir seedlings (Haase and Rose 1993). Akgul (2004) observed an increasing relationship between volumetric soil moisture content at the time of planting (September through April of 2000-03) and first-year survival of bareroot slash pine (*Pinus elliottii* Engelm.) seedlings planted in the flatlands of western Louisiana. On the April 2002 plant date, seedling survival averaged across three sites ranged from around 20% when soil moisture was below 8% (volumetric water content) to above 80% when soil moisture was around 20% (volumetric water content). When soil moisture in the root zone (7-9 cm) remained above 13% at the time of planting, survival of bareroot white spruce seedlings was greater than 90% (Sutton 1975). Similarly, when soil moisture dropped from above 13% to 5% in June

1982, survival of bareroot loblolly pine (*Pinus taeda* L.) seedlings planted near Auburn, AL dropped from above 90% to 22% (South and Barnett 1986). Walters and Soos (1961) observed that survival was higher for Douglas-fir and Scots pine (*Pinus sylvestris* L.) seedlings planted August to November when soil moisture was not limiting (precipitation > 25 cm/month) and temperatures were above 6°C. Survival was lower for seedlings planted April to July when soil temperatures were increasing and soil moisture was decreasing (precipitation less than 15 cm/month in April, down to 0 cm/month in July. longest drought lasting 6 weeks).

When seedlings are first outplanted, they may experience "transplant shock" (Mullin 1963, Haase and Rose 1993, Sands 1984) characterized by stunted growth, shortened needles, browning or loss of needles, cessation of growth, or possibly death. Transplant shock results from the stress incurred during the period after planting when roots have not yet established root-to-soil contact and foliage is transpiring, leading to a condition of physiological drought. This condition, when coupled with the onslaught of environmental droughts can lead to reduced growth and increased mortality. Early spring root growth can be an important benefit on hot, dry sites especially in droughty, well-drained soils and may significantly reduce transplant shock. Unlike winter- or spring-planted stock, seedlings planted the previous fall are already established and ready to grow as soon as environmental conditions permit in spring, assuming soil temperatures were adequate in the fall (Barber 1989).

1.4.2 Soil temperature

Soil temperature has a profound effect on seedling development (Balisky and Burton 1997, Domisch et al. 2001, Landhäusser et al. 2001), and this effect varies considerably by plant date. Environmental temperatures control the rate of seedling biochemical functions such as photosynthesis. Below about 5°C, little metabolic activity occurs in conifers because plant organs and enzymes function ineffectively at low temperatures (Cleary et al. 1978). Root growth in Douglas-fir, Pacific silver fir (*Abies amabilis* (Dougl.) Forbes), noble fir (*Abies procera* Rehd.), lodgepole pine, and ponderosa pine seedling transplants began when soil temperature exceeded 5°C and increased rapidly after 10°C, attaining maximum values at 20°C (Vapaavouri et al 1992). Above 20ºC seedling biochemical functions begin to slow and temperatures in excess of 24ºC inhibit the allocation of resources to roots and reduce both shoot and root growth as well (Lopushinsky and Max 1990, Brix 1967). Steinbrenner and Rediske (1964) showed that a high soil temperature treatment (21ºC) had more than twice as much moisture loss from pots as a low soil temperature treatment (10ºC).

Extremely cold soil temperature can cause considerable damage to seedlings. Frost heaving is the upward movement of soil as a result of expansion from ice formation that may partially or fully lift seedlings out of the ground (Cleary et al. 1978). For frost heaving to occur, a specific combination of soil temperature, soil moisture, and soil texture must be present (Spittlehouse and Stathers 1990). Fall-planted seedlings face greater risk of frost heaving especially on sites subject to alternate freezing and thawing cycles (Barber 1989, Orlander et al. 1990). If seedlings are planted at a depth when soil temperatures and moisture are high enough for root growth (to anchor the seedling) this effect may be minimized. Freezing temperatures can also have an influence on root development after outplanting. In a study on black spruce seedlings, long-term effects of freeze damage depended on the amount of live roots left (Bigras 1996). When seedlings lost up to 30% of their living root system survival was 90% or greater; but, when damage increased to 50 and 70%, survival dropped to 45-70% and 20-30%, respectively.

1.4.3 Air temperature

Air temperature throughout the planting season strongly influences many metabolic and physiological processes within seedlings. Plants regulate their internal temperature by means of reradiation of heat after absorbing incident radiation and transpiration. Since water has a high specific heat, and requires a lot of energy to change from the liquid to gas phase, changes in water temperature lag behind changes in air temperature. Therefore plants are able to moderate their internal temperature in a slower, more controlled manner and maintain temperatures that are favorable for photosynthesis and other metabolic processes even when high ambient temperatures might inhibit these processes (Clawson et al 1989). When air temperature increases plants are able to open and close stomatal openings in their leaves allowing for water to evaporate, referred to as evapotranspiration or bioregulated evaporation, creating a suction which draws cooler water through mass movement and diffusion from the soil, to the roots, and into the plant shoots.

Day (2000) found that high temperatures (28, 32, and 36ºC) significantly reduced mean net photosynthesis (5.91a, 5.75a, 3.70b μmol m^{-2} s^{-1}, respectively, letters followed by different letters are considered significantly different at $p<0.05$) and mean stomatal conductance (74.96a, 76.10a, 55.66b mmol m^{-2} s^{-1} respectively) in red spruce (*Picea rubens* Sarg.). Douglas-fir seedlings grown in a growth chamber for four years and exposed to an elevated temperature (average yearly increase of 3.5°C above ambient) had reduced height (359 ± 34 mm) and leaf biomass (20% less) but not stem diameter or woody biomass compared to seedlings grown in a growth chamber under conditions more typical of their current environment (Olszyk et al 1998).

1.4.4 Relative humidity and vapor pressure deficit

Relative humidity (RH) and vapor pressure deficit (VPD) are both measures of moisture content in the atmosphere. RH is the amount of water vapor in the atmosphere divided by the amount of water the air is capable of holding (saturated without condensation) under the same conditions. The amount of water vapor the atmosphere is able to hold approximately doubles for every 11°C increase in air temperature (Anderson 1936), up to a maximum of 100%. Thus the atmosphere at a temperature of 30°C has approximately twice the water holding capacity as the atmosphere at 20°C. It follows that evaporation of water from a given surface will also increase with increases in temperature of air with given content of water vapor, because the air can now hold more water vapor.

The amount of water vapor in the air can strongly influence stomate size and function. A study on Virginia spiderwort (*Tradescantia virginiana* L.) found that plants grown in high RH (90%) environments showed poor control of water loss after being transplanted into a lower RH (55%) environment; some stomates only partly closed or did not close at all in response to desiccation (Nejad and van Meeteren 2005). At 40% RH, the loss of stomatal function of plants grown in high RH resulted in a 112, 139, and 132% increase in the transpiration rate, stomatal conductance, and stomatal aperture when compared to plants grown under moderate RH (55%). In a controlled environment growth chamber study, height growth of ponderosa pine and Douglas-fir seedlings did not differ significantly when grown at low (45%) and high RH (65%) (Steinbrenner and Rediske 1964).

Vapor pressure deficit (VPD) is the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated. When VPD is high, the air has a higher affinity for water and therefore water evaporates more readily from leaves. Stomatal responses to VPD help regulate leaf water potential. The sensitivity of this response is related to changes in whole-plant hydraulics. At high VPD, stomata can be completely closed, stoping photosynthesis (Jarvis 1976).

1.4.5 Precipitation

Precipitation in the PNW occurs predominantly between October and April and ranges from 1000-1500 mm in the Cascades to 4500 mm in the coastal regions. Seedlings must therefore become established before the summer drought period in this region. So most planting is done in the wet winter months when moisture is not limiting. On the other hand, seedlings can also be planted in the late summer or early fall before winter rains have started or just after the first rainfall. Fall planting introduces an element of risk for managers who have to order seedlings and plan for planting during unknown future weather conditions. The timing of precipitation is crucial to fall outplanting success. Akgul (2004) concluded that 97% first-year survival of bareroot slash pine seedlings planted in the flatlands of Alabama was due, in part, to the 100 mm of rain received on the preceding 14 days, with 18 mm falling on the day of planting and the day after. Squllace and Silen (1962) concluded that ponderosa pine trees in western Oregon grew best in areas where annual precipitation fell between September and June. Precipitation late in the summer months before seedlings have entered rest result in seedling susceptibility to second flush, leading to greater potential for increased damage to succulent tissues after early frost.

1.5 Thesis Objectives and Research Approach

The overall objective of this thesis was to understand the effect of outplanting date on the performance of Douglas-fir seedlings in western Oregon and Douglas-fir and western larch seedlings in Eastern Washington. Of particular interest was the potential for planting in the fall when environmental conditions are most likely to be favorable for root growth. The underlying motive for this project was to tie existing research together into one project that captures the various changes in seedling and environment over time.

Secondary objectives of this thesis included (1) evaluate field performance (survival and growth) of seedlings treated with differing dormancy induction treatments at the nursery (Oregon sites, Chapter 2), and (2) assess the effect of tree shelters on performance at high elevation sites (Washington sites, Chapter 3).

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CHAPTER 2 - EFFECT OF PLANT DATE AND NURSERY DORMANCY INDUCTION ON FIELD PERFORMANCE OF DOUGLAS-FIR SEEDLINGS IN WESTERN OREGON

2.1 Abstract

Douglas-fir (*Psudotsuga menziesii* (Mirb.) Franco) seedlings were outplanted on eight dates (every three weeks from mid-August 2005 through mid-January 2006). On each plant date, seedlings from a conventional dormancy (CONV) induction treatment, including moisture and nutrient stress, and a shortened daylength (SD) treatment were outplanted on three western Oregon sites ranging from the moist coastal region (365 m above sea level, 315-355 cm annual precipitation) to the drier valley fringe (275 m above sea level, 100-150 cm annual precipitation). SD treated seedlings initiated primordial development earlier than CONV treated seedlings and tended to have a lower shoot:root ratio due to larger stem diameter and root biomass. On all three sites, seedlings planted on the first three plant dates (August-September) had more root growth shortly after planting and greater seasonal height and stem diameter growth after the first season than those planted on the later 5 dates (October-January). On two of the three sites, seedlings from the CONV dormancy induction treatment grew more in height and stem diameter than SD treated seedlings regardless of planting date. On the wet coastal site seedlings planted on the earliest date (August) grew on average 20 cm more than seedlings planted on the latest date (January) and averaged more than 2 mm in stem diameter growth when measured at the end of the

first growing season. Also on this site seedlings treated with CONV averaged almost 4 cm more in height growth and more than 1 mm in stem diameter growth than seedlings treated with SD.

Soil moisture and temperature were monitored throughout the study period. Soil moisture was above 20% (volumetric water content, soil core method) on all sites at the time of planting and was not deemed a limiting factor when modeled with seedling field performance. However, soil temperature at the time of planting was found to have a significant influence, which is attributed to its effect on early root egress. Seedlings planted into warm soils (>15ºC, first three plant dates) averaged more height growth and stem diameter growth compared with seedlings planted in cooler soils (<15ºC). With the exception of increased mortality for seedlings planted on the first plant date on the driest site, survival was unaffected by plant date or dormancy induction treatment due to adequate soil moisture throughout the planting dates. Although these data are limited to one planting season, fall planting could be a viable alternative to winter planting in PNW coastal areas where soil moisture is adequate.

2.2 Introduction

Winter and early spring are traditionally the favored planting season of foresters in western Oregon due to nursery logistical constraints, high seedling stress resistance, and the fact that weather and soil conditions are favorable for growth after outplanting. On the westside of the Cascade Range, seedlings are commonly planted between December and March so that by spring the newly-planted trees will establish roots and benefit from increasing soil temperature and hours of daylight (Messina 2002). Winter through early spring is also when seedlings are dormant and most resistant to stresses associated with lifting, storage, and planting. In recent years, there has been increasing interest in extending the operational planting window to include fall months.

Success or failure of fall planting is dependent upon both environmental conditions and seedling physiology. The temperature and moisture of the rooting environment is particularly important to seedling establishment. The rationale behind fall planting is that seedling shoots are dormant but the roots are still actively growing. As a result, seedlings may be able to establish root-to-soil contact immediately after planting when warm fall temperatures are ideal for new root growth and daylength is still long enough to allow for continued photosynthesis and greater stored carbohydrates available for root growth in spring (van den Driessche 1987, Major et al. 1994b). This early establishment allows for two cycles of root growth before the first shoot growth the following spring, giving seedlings an established network of roots for uptake of necessary water. Seedlings can then promptly resume growth before summer droughts limit growth. However, as the planting period progresses further into the fall, photoperiod decreases, air and soil temperatures decline, and environmental conditions gradually become less favorable.

Soil moisture and temperature at the time of planting are important to consider when outplanting regardless of season. If soils are too dry, seedlings may be unable to extract water from depths and can suffer increasing moisture stress which may result in reduced growth or mortality (Blake et al. 1979). High temperatures at the time of planting may cause stem damage or fine-root mortality resulting in decreased internal water movement, reduced growth, and increased mortality (Marshall 1986, Stransky 1961). If seedlings are planted too late in the fall or soil moisture and temperature are not favorable for growth, seedlings may have an inadequate period for root establishment which results in a poorly developed root system, lower carbohydrate reserves, and the inability to use water and nutrients for growth promptly the next season compared to spring and early-fall planted seedlings (Adams et al. 1991). There is only a short window between the onset of adequate seedling dormancy at the nursery and the end of the fall planting season when weather conditions preclude planting (Barber 1989) and soil temperatures drop below 5°C for root growth (Lopushinsky and Max 1990).

Seedling physiological condition at outplanting is also vitally important to subsequent field performance. Seedling dormancy status is particularly important not only because it indicates the stress resistance of the seedling but also because it is important for proper growth and survival after outplanting (MacDonald and Owens 1993b, van den Driessche 1990, van den Driessche 1991). Typically, nurseries in western Oregon use moisture stress and reduced fertilizer to induce dormancy. The reduction of water and nutrients is used to mimic natural seasonal changes causing seedlings to enter an environmentally imposed dormancy (Wenny and Dumroese 1992). Once this stage of dormancy has been achieved, fertilization is resumed at a reduced rate to encourage stem diameter growth, root growth, and to increase whole plant nutrition (Lavender and Cleary 1974). The use of shortened photoperiods has been employed by some as an alternative dormancy induction technique either by itself or with mild water or nutrient stress (MacDonald and Owens 2006). This technique has long been used by Canadian nurseries, at higher latitudes, but few studies have evaluated its effectiveness at lower latitudes (Grossnickle et al 1991, Hawkins and Shewan 2000, MacDonald, and Owens 2006). Plants in temperate environments have long been known to respond to shortened photoperiods. As photoperiod is decreased, the amount of active phytochrome decreases and inactive phytochrome increases due to a decreasing amount of red light perceived by cells. In response, seedlings initiate a terminal bud and increase cold hardiness.

2.3 Objectives and hypotheses

2.3.1 Objectives

The objective of this study was to quantify Douglas-fir container seedling performance as influenced by plant date, nursery dormancy induction treatment, and environmental conditions. Specific objectives were as follows:

1. To compare nursery dormancy induction treatments as they affect initial seedling morphology and physiology as well as subsequent growth and survival across several plant dates.
2. To evaluate the effect of plant date on initial seedling morphology and physiology as well as subsequent growth and survival.

3. To determine the relationship between soil moisture and temperature at time of planting on seedling field performance.

2.3.2 Null hypotheses

1. There is no relationship between dormancy induction method and initial seedling morphology and physiology or subsequent growth and survival.
2. There is no relationship between planting date and initial seedling morphology and physiology or subsequent growth and survival.
3. There is no relationship between soil moisture and temperature at time of planting on seedling field performance.

2.4 Materials and methods

2.4.1 Test Sites

Three western Oregon sites were selected across a geographic moisture gradient (coast to valley) to maximize the climatic variability between sites.

2.4.1.1 Pedee Guppy

The driest site, Pedee Guppy, is located on Forest Capital land approximately 55 km from the Oregon coastline (S18, T9S, R6W, Willamette Meridian). The site was logged in the winter of 2005, mechanically piled near landings, and aerial site-prepped with metsulfuron (0.03 l/ac) and glyphosate (2.4 l/ac). The study site has a SE aspect sloping down from an elevation of 275 m. Annual precipitation is 100-150 cm and King's Site index is 105ft at age 50 (King 1966). The previous stand was a well stocked stand of 50-year-old Douglas-fir with a sparse understory of sword fern (*Polystichum munitum* (Kaulfuss) K. Presl), Oregon grape (*Mahonia aquifolium* (Pursh) Nutt.), and salal (*Gaultheria shallon* Pursh).

2.4.1.2 South Red Fir

The moderate moisture site, South Red Fir, is located on Starker Forest land approximately 40 km from the Oregon coast line (SE corner of S7, T11S, R7W, Willamette Meridian). The site was logged in April 2005, mechanically piled in June 2005, and aerially sprayed with glyphosate (1.89 l), sulfometuron (0.12 l) and a surfactant (alkyl phenoxy) with 35.96 liters of water for 37.85 liters of total spray mix per acre on October 25, 2005. The site has a northern aspect sloping down from an elevation of 235 m. The annual precipitation is 150-200 cm and King's Site index is 129 ft at age 50. The original stand composition was predominantly 75-80-year-old Douglas-fir with some scattered hardwoods. The average diameter-at-breast-height (DBH) was 60.7 cm at harvest and the number of trees per acre (TPA) was 60. The trees were widely spaced with a great deal of brush understory composed mainly of vine maple (*Acer circinatum* Pursh) and sword fern.

2.4.1.3 Southern Comfort

The wettest site, Southern Comfort, is located on Forest Capital land approximately 25 km from the Oregon coastline (west half of S8, T9S, R8W, Willamette Meridian). The site was logged in the winter of 2005 and mechanically piled in June 2005, and received no chemical treatment. The site has a west aspect sloping down from an elevation of 365 m. The annual precipitation is 315-355 cm and King's Site index is 125 ft at age 50. The previous stand was a well stocked 55–year-old Douglas-fir stand with some western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and red alder (*Alnus rubra* Bong.) mixed with a sparse understory mainly of sword fern.

2.4.2 Seedlings

Douglas-fir seed was stratified using a hydrogen peroxide (H_2O_2) soak (3% solution) for 30 min followed by immersion in water for 24 hr. After soaking, the seed was placed in cold storage at 1°C for 56 days at the Oregon PRT nursery (Hubbard, OR). Starker Forest seed (seedlot 2005NOT110) was sown on February 23, 2005 in styroblocks (615A, 213 cavities per m^2, 336 ml/cavity, 15.2 cm deep x 6 cm top diameter). Forest Capital seed (seedlot Dallas Low, 2005PNORO) was sown on March 10, 2005 in styroblocks (515A, 284 cavities per m^2, 220 ml/cavity, 12 cm deep x 5.1 cm at top diameter). All seed was sown one to two seeds per cell in 100% peat with no added fertilizer. Seedlings were grown by standard nursery practices until the initiation of dormancy induction treatments.

At each plant date, seedlings were hand lifted and graded according to contract specifications (Starker Forest: 30-50 cm height and a minimum 3.5 mm stem diameter; Forest Capital: 18-45 cm height and a minimum of 3.2 stem diameter). In addition, any seedlings with deformities or undesirable traits were excluded from the study.

2.4.3 Dormancy induction treatments

There were two dormancy induction treatments: short day (SD), sometimes referred to as "blackout" and conventional shutdown (CONV) using moisture/nutrient stress.

Study trees from both treatments were grown under identical water and nutrient regimes until initiation of dormancy treatments at which point seedlings were then randomly chosen out of the operational crop and placed into their respective treatments. Seedlings scheduled for the first three plant dates underwent dormancy induction earlier than those scheduled for the later plant dates. The earlier induction treatments were initiated on June 27, 2005 for both stocktypes and the later induction treatments were initiated on July 19 and 21 for Forest Capital and Starker Forest seedlings, respectively. Seedlings designated for the SD treatment received a 14h nightlength for 21d after being flushed with water twice to remove media nutrients. After 21d they were left in ambient conditions for 7d then put back into 14h nightlength for 7d. The pattern of seven on, seven off was repeated until early September when natural light conditions dropped to 14h nights, which was the nurseries operational regime. Seedlings designated for the CONV treatment remained in ambient light conditions and were flushed with water twice to remove media nutrients then allowed to dry to 65-70% saturation. They were then fertilized with Scotts Peters Conifer Finisher© (4-25-35 + micros) at 50 ppm N and then only irrigated when crop flagging was visible. In both treatments no fertilizer was applied during the shutdown process.

2.4.4 Plant dates

Seedlings were outplanted at three-week intervals from late summer through winter. Dates were selected to encompass thresholds of planting success. At each plant date, protective plastic mesh tubing was installed immediately to protect seedlings from animal browse. The eight planting dates were:

1) August 16, 17 (S. Red Fir planted the first day and the other two sites planted the following day; this was the same for every plant date).

2) September 7, 8

3) September 27, 28

4) October 18, 19

5) November 8, 9

6) November 29, 30

7) December 20, 21

8) January 10, 11

2.4.5 Experimental design

A complete randomized block design was used at each study site. There were five replications (blocks) on Pedee Guppy and S. Red Fir and four replications at S. Comfort. Each block consisted of 16 treatment plots (8 plant dates x 2 dormancy induction treatments). Each treatment plot consisted of 20-25 seedlings planted 3m x 3m, plus an additional 10 interplanted seedlings for excavation to assess root development following planting. A total of 1980 study trees and 800 interplanted seedlings were planted on Pedee Guppy, 1842 study trees and 640 interplanted seedlings were planted on S. Red Fir, and 1479 study trees and 640 interplanted seedlings were planted on S. Comfort.

2.4.6 Data collection

2.4.6.1 Environmental conditions

HOBO microstations (Model # H21-002, Onset Computer Corporation, Bourne, MA) were installed at each of the three sites to monitor environmental conditions throughout the study. Environmental data (rainfall, air temperature 1 m from ground, relative humidity, soil temperature 15 cm depth, and soil moisture at 15 and 20 cm depth) were collected every 6 hr after installation in August 2005.

2.4.6.1.1 Soil moisture

In addition to the HOBO soil moisture probes, two soil samples were collected from each block at each planting date to a depth of 15 cm using a soil core with slide hammer (AMS signature series, American Falls, ID) and a core volume of 101.29 cm^3. Soil samples were placed in sealed plastic baggies and taken to OSU for laboratory determination of percent water by volume in the rooting zone at the time of planting. Soil weight was measured before and after the soil sample was dried in an oven for 48h at 68°C. Volumetric soil water content was then determined using the following formula:

$$\theta = \frac{(m_{wet} - m_{dry}) / 1}{V_b}$$

Where:

θ = volumetric soil water content,

m_{wet} and m_{dry} are the weight of the sample before and after drying in the oven, and

V_b is the volume of the cylinder.

2.4.6.1.2 Vapor pressure deficit

For each plant date, the vapor pressure deficit (VPD) was calculated using the air temperature (T_{air} ºC), dew point temperature (T_{dew} ºC), and % relative humidity (RH) following the procedures of Murray (1967). VPD calculations were as follows:

VPD (saturation vapor pressure deficit) = $e_s - e_a$ (kPa)

Where:

e_s (Saturation vapor pressure) = $\exp \frac{(17.27 * T_{air})}{(T_{air} + 237.3)}$

$$e_a \text{ (Actual vapor pressure)} = \exp \frac{(17.27 * T_{dew})}{(T_{dew} + 326.7)}$$

$$T_{dew} \text{ (dew point temperature °C)} = \frac{237.3\ /}{\{1/(\ln(RH/100)/17.27) + (T_{air} / (237.3 + T_{air}) - 1\ \}}$$

2.4.6.2 Seedling condition at time of planting

2.4.6.2.1 Initial seedling morphology

Three weeks after outplanting, all outplanted seedlings were measured for shoot height (to the nearest cm from groundline to the top of the terminal bud) and stem diameter (to the nearest mm just above groundline). In addition, a subsample of 50 seedlings from each treatment was measured in the lab for height, stem diameter, and biomass (root and shoot volume via water displacement; Burdett 1979).

Parameter	Source	DF
field height, stem diameter, shoot and root volume	replication	4
	plant	7
	treatment	1
	plant*treatment	7

n=25 trees per replication

Parameter	Source	DF
lab height, stem diameter, shoot and root volume	n	49
	plant	7
	treatment	1
	plant*treatment	7

mean of n used

2.4.6.2.2 Cold hardiness

At each plant date, a sample of 60 seedlings from each dormancy induction treatment was measured for whole tree cold hardiness in order to estimate the LT_{50} (lethal temperature to 50% of the seedlings). Seedlings were randomly divided into four groups. Each group was placed into a programmable chest freezer and temperatures were lowered from room temperature to 0°C at 20°C per hour, then decreased to the target temperature at 5°C per hour, held at the target temperature for two hours, then raised back to 0°C at 20°C per hour (Tanaka et al. 1997). The four target temperatures were selected on each date based on the expected ability to bracket the LT_{50} (lower temperatures when seedlings are less hardy, increasing with time). After freezing, seedlings were placed into a greenhouse with adequate moisture, ambient photoperiod, and an average temperature of 20°C. Six days after freezing, damage to foliage, cambium, and buds was evaluated. If the cambium was dead in the mid- to lower section of the main stem or if greater than 50% of the buds were damaged, the seedling was considered nonviable (Tanaka et al. 1997). The LT_{50} was then determined by plotting percent survival against temperature. Assuming a straight line relationship, the LT_{50} is the temperature corresponding to the point where 50% of the seedlings were estimated to have been killed (Tanaka et al. 1997).

Parameter	Source	DF
cold hardiness	n	59
	plant	7
	treatment	1
	plant*treatment	7

mean of n used

In addition to whole tree cold hardiness determination, a sub-sample of 20 seedlings was sent to Dr. Doug Jacobs at Purdue University (Hardwood Tree Improvement and Regeneration Center, West Lafayette, IN) for measurement of freeze-induced electrolyte leakage (FIEL). For each of the treatments, ten 1-cm needle segments were placed into each of 7 20-ml polypropylene vials containing 1 ml of deionized water. Each vial corresponds to one of 7 test temperatures ranging from 2°C to -40°C. This process was repeated 4 times for a total of 28 vials per treatment. The vials were capped and placed in a programmable freezer for approximately 1.5 hours at 2°C, after which the control treatment vials were removed. The freezer temperature was lowered at a rate of 5°C per hr. Once the temperature reached -2°C, the vials were briefly shaken by hand to help nucleate and freeze the water. After 30 minutes, the -2°C treatment was removed. Additional freeze test temperatures were -5, -10, -20, -25, -30, and -40°C. Each temperature was held for 30 min before removing the 16 vials (4 per replication) and lowering to the next temperature. After removal, samples were thawed at room temperature overnight. After thawing, 9 ml of deionized water was added to each vial and they were placed on an orbital shaker (Eberbach Co. Ann Arbor, Michigan) and agitated at 250 rpm for 2 hr. The caps were then removed and electrical conductivity EC of each vial solution was measured with an EC/TDS meter (Mettler Toledo. Columbus, OH). Vials were then autoclaved (Castle Company, Rochester, NY) for 20 min at 121°C to kill the needle tissue completely and allow all electrolytes to leak out. The vials were cooled overnight then agitated on the shaker for 2 hr, and re-measured for EC. The first reading was divided by the second and multiplied by 100 to obtain a relative (%) measure of leakage for each vial.

Parameter	Source	DF
freeze induced electrolyte leakage	replication	3
	plant	7
	treatment	1
	plant*treatment	7

mean of 10 trees per replication

2.4.6.2.3 Root growth potential

At each plant date, subsamples of 20 seedlings were planted in pots (3.8 L) to assess root growth potential (RGP). The pots were placed in a growth room (constant 20°C with 16 h photoperiod) for 21 days after which seedlings were carefully removed from the pots. New roots, greater than 0.5 cm, extruding from the plug were removed, dried, and their weights recorded.

Parameter	Source	DF
root growth potential	replication	4
	plant	7
	treatment	1
	plant*treatment	7

mean of 4 trees per replication

2.4.6.2.4 Foliar nutrition

On four plant dates (1, 2, 5, and 8), a sample of 16 seedlings from each dormancy induction treatment was randomly divided into four groups and severed at the cotyledon scar. The shoots were oven dried for 48 hr at 68°C. After drying, needles were removed from the stems and thoroughly mixed together to form a composite sample for each treatment group. The needles were then sent to A&L Western Agricultural Laboratories (Modesto, CA) and analyzed for both macro and micro nutrient content.

Parameter	Source	DF
foliar nutrition	replication	3
	plant	7
	treatment	1
	plant*treatment	7

mean of 4 trees per replication

2.4.6.2.5 Bud Development

To estimate bud initiation and development in large seedlots, Templeton et al. (1993) found that 20 seedlings could be used reliably if the crop was uniform. MacDonald and Owens (1993b) found that 16 to 24 seedlings were adequate to account for crop and treatment variation. In this study, a random sample of ten seedlings from each dormancy treatment was used since the population at each plant date was relatively small (<300 per plant date) and uniform.

Shoot tips were dissected according to the procedures described by Templeton et al (1993). At each plant date, the terminal bud was excised approximately 2 cm below its base and any needles carefully removed. The excised bud was placed under a dissecting microscope and observed at 10x magnification. Using a hypodermic needle, a small incision was made around the base of the terminal bud below the last bud scale. The end of the hypodermic needle was then inserted into the cut and the bud scales were removed by gently pulling the bud scales away. Any remaining bud scales and excess tissue were carefully peeled away to expose the apical dome and needle primordia. The embryonic shoot was placed in the center of the scope and the number of short columns and the rows were counted then multiplied together to determine the total number of needle primordia (Appendix 1). Buds were preserved in 100% ethyl alcohol and later photographed using a scanning electron microscope.

Parameter	Source	DF
primordia count	n	9
	plant	7
	treatment	1
	plant*treatment	7

mean of 10 trees

2.4.6.3 Seedling field performance

2.4.6.3.1. Growth and Survival

In addition to initial height and stem diameter measurements 3 weeks after outplanting, seedlings were measured again in April 2006 prior to budbreak to determine if fall planting resulted in greater stem diameter growth prior to spring shoot growth. Subsequent analyses showed no differences between the initial measurements and the April measurements. Therefore, the initial measurements were used for all growth calculations. In September 2006, seedlings were measured for first-season height and stem diameter and assessed for percent survival in each plot. Growth was calculated by subtracting initial values.

2.4.6.3.2 Root development

Some of the interplanted seedlings (1-4 seedlings depending on survival) per treatment per replication at each site were carefully excavated three weeks after outplanting, again in April 2006 prior to budbreak, and again in November 2006 after budset. For the first two assessments, all new roots extruding from the plug were counted, removed, and weighed. At the last assessment, a full morphological assessment of height, stem diameter, root volume, and shoot volume was done on the excavated seedlings.

Parameter	Source	DF
field root growth	replication	4
	plant	7
	treatment	1
	plant*treatment	7

mean of 1-4 trees per replication

2.4.6.3.3 Xylem water potential

Predawn xylem water potential was measured every 3 weeks after planting with a pressure chamber (PMS Instruments, Inc., Corvallis, OR) until late-September when water potential leveled out to non-stress levels with the onset of fall precipitation. On each measurement date, two seedlings per treatment per replication on all sites were randomly selected and measured using the methodology developed by Scholander et al (1965) as described by Lopushinsky (1990). A small lateral branch, in the middle of the crown, was cut at a 45° angle from the seedling. The needles within 1 cm of the cut surface were carefully removed and the sample was inserted through a rubber compression ring with the cut end protruding through the lid of the chamber. Chamber pressure was slowly increased with nitrogen gas from a high pressure tank until water was forced back to the cut surface of the sample. The pressure indicated on the gauge at that point was recorded as the water potential for the sample.

Parameter	Source	DF
xylem water potential	replication	4
	plant	7
	treatment	1
	plant*treatment	7

mean of 2 trees per replication

2.5 Statistical analyses

SAS® statistical package (SAS Institute, Inc., Cary, NC, USA) was used for analyses of all data. The Generalized Linear Model (proc GLM), regression analysis (proc mixed) procedures were used for most variables. Covariate analysis was preformed on all growth and ending heights and diameters as a function of initial measurements.

2.5.1 ANOVA

Lab data for each stocktype (515 Forest Capital seedlings and 615 Starker Forest seedlings) were analyzed separately using analysis of variance (Appendix 5). Field data from each site were analyzed separately by ANOVA for a randomized complete block design, with a plant date by dormancy induction treatment factorial (Appendix 5). Sites were analyzed separately for ease of interpretation due to a three way interaction with plant date and treatment. All data were assessed using the procedures described by Sabin and Stafford (1990) to determine the need for transformation and to ensure that all assumptions of the models used were meet. In particular Shapiro-Wilk and Kolmogorov-Smirnov statistics were used to test normality of residuals and Levene's statistic for testing homogeneity of variance. Survival data were assessed using regression (poisson and bionomial regression in context of generalized linear models) as well as ANOVA on transformed and untransformed data. In some cases residuals did not meet the assumption of normality, but the influences on means were assumed robust because given the only slight departure from normality and the power f the Central Limit Theorem. Root growth potential was transformed using the natural log but means were reported after transforming back to the original scale for ease of interpretation. Fisher's Protected Least Significant Differences identified differences among plant dates and treatments ($\alpha \leq 0.05$). Covariance analyses were performed on initial and final height and stem diameter and growth in these dimensions, but no significant covariates were found; all p-values were greater than 0.34 (data not shown). This result most likely is due to the small size distribution of initial measurements compared to the large effect of the treatments.

2.5.2 Modeling

Soil moisture (soil core data) and soil temperature were modeled with first season growth and survival measurements using regression analysis. All three sites were included in this analysis to capture a larger range of environmental conditions and their effects on growth and survival. Significant F-tests were used to determine if the relationships were linear, quadratic, or cubic and the appropriate model was chosen. Soil moisture was found to be a non-significant predictor of seedling growth and survival. Soil moisture did not reach expected summer droughty conditions and therefore was not as limiting as temperature. Soil temperature was the best indicator of seedling field performance and was best represented by quadratic transformation.

2.6 Results

2.6.1 Seedling condition at time of outplanting

2.6.1.1 Initial seedling lab morphology

Measurements in the lab showed seedlings that received the CONV treatment were taller on nearly every plant date as compared to those that received the SD treatment (Tables 2.1 and 2.2). Stem diameter at the time of planting tended to increase over time with few differences between dormancy induction treatments. SD seedlings had significantly larger root volume on most plant dates compared to CONV seedlings whereas shoot volume of CONV seedlings were significantly larger than SD seedlings on most plant dates. As a result, the shoot:root ratio was consistently greater for CONV seedlings than for SD seedlings. It is also important to note that seedlings treated with CONV were still succulent on the first two planting dates and were more susceptible to breaking during the lifting and packing process.

2.6.1.2 Initial seedling lab physiology and nutrition

Cold hardiness increased with plant date (Table 2.1 and 2.2). No statistical tests were conducted because of lack of replication inherent in the test. FIEL indicated increased damage with decreasing temperature on each plant date but was too variable and not a good predictor of cold hardiness (data not shown). RGP was significantly greater for CONV seedlings as compared to SD on several plant dates (Table 2.1 and 2.2). Foliar nutrients changed over time with a general decrease in mobile macronutrient concentrations and an increase in immobile micronutrient concentrations (Table 2.3 and 2.4). Bud primordia count tended to be greater for SD seedlings as compared to CONV seedlings on the earlier plant dates for 515 seedlings outplanted to Pedee Guppy and S. Comfort (Table 2.1, Figure 2.1). For 615 seedlings outplanted on S. Red Fir, primordia count was significantly higher for SD seedlings on the second and fourth plant dates only (Table 2.2). By the fifth plant date (early November), primordia count stabilized above 11 rows. 2.6.2 Environmental Conditions

2.6.2.1 Pedee Guppy

Average daily volumetric soil water content as measured by the HOBO sensors can be seen in Figure 2.2b. Soil moisture ranged from approximately 12-27% from the August to January plant dates. There was little difference between the two depths (10 and 20 cm) from October 2005 to the middle of April 2006. However, from April to October 2006, the moisture content at 10 cm was lower than at 20 cm by about 2%. Average soil moisture at the time of planting as measured by the soil cores increased from August to September then leveled off (Figure 2.2c). Soil moisture decreased from the August to early September plant dates. A small amount of precipitation fell

Table 2.1 Lab measurements of morphology and physiology of seedlings outplanted to the Pedee Guppy and S. Comfort sites (515 stocktype). Within a column, means followed by the same letter are not significantly different at $p<0.05$.

Plant date	Treatment	height (cm)	diameter (mm)	root volume (cm3)	shoot volume (cm3)	shoot / root ratio	root growth potential (g)	cold hardiness LT_{50} (°C)	primordia (row count)
1	short day	24.0 e	3.34 e	7.6 ef	10.4 d	1.39 de	1.08 bc	-2.59	4.9 e
	conventional	34.6 ab	3.42 e	5.6 g	16.3 ab	2.94 ab	1.08 bc	-3.09	0.0 f
2	short day	20.0 f	3.84 cd	9.7 d	9.4 d	1.00 ed	1.06 bc	-2.36	8.8 cd
	conventional	32.6 b	3.58 de	5.7 g	17.8 a	3.21 a	1.95 a	-2.07	5.4 e
3	short day	20.2 f	4.29 b	12.4 bc	10.2 d	0.84 f	0.48 de	-4.70	9.2 c
	conventional	28.5 d	3.72 d	6.1 fg	16.7 ab	2.88 b	1.22 b	-4.00	10.2 bc
4	short day	24.3 e	4.12 bc	9.9 d	10.8 d	1.12 e	0.42 de	-3.20	11.6 ab
	conventional	30.2 cd	4.40 ab	7.1 f	15.5 b	2.20 c	0.40 de	-3.00	7.8 d
5	short day	27.2 d	4.12 bc	11.3 c	13.1 c	1.20 e	0.48 d	-5.17	11.8 ab
	conventional	32.1 bc	4.40 ab	8.1 e	16.1 ab	2.06 c	0.84 c	-4.00	10.2 bc
6	short day	30.3 c	4.24 bc	13.2 b	14.2 bc	1.10 e	0.34 e	-8.67	12.2 a
	conventional	34.7 ab	4.62 a	8.4 e	17.8 a	2.14 c	0.39 de	-6.50	10.8 ab
7	short day	33.8 b	4.00 c	14.8 a	16.2 ab	1.16 e	0.48 de	-12.50	12.0 a
	conventional	32.6 bc	4.17 bc	10.5 cd	16.4 ab	1.58 d	0.31 e	-9.50	12.2 a
8	short day	31.4 c	4.22 bc	10.0 d	14.3 bc	1.45 d	0.52 d	-12.00	11.6 ab
	conventional	36.0 a	4.44 ab	6.8 fg	14.9 bc	2.23 c	0.82 c	-11.53	11.4 ab

Height, diameter, root and shoot volume, and shoot/root ratio n= mean of 40 trees per treatment per plant date

Root growth potential n=mean of 20 trees per treatment per plant date.

Whole plant cold hardiness n=mean of 60 trees per treatment per plant date.

Primordia n=mean of 10 trees per treatment per plant date

Table 2.2 Lab measurements of morphology and physiology of seedlings outplanted to the S. Red Fir site (615 stocktype). Within a column, means followed by the same letter are not significantly different at $p<0.05$.

Plant date	Treatment	height (cm)	diameter (mm)	root volume (cm3)	shoot volume (cm3)	shoot / root ratio	root growth potential (g)	cold hardiness LT_{50} (°C)	primordia (row count)
1	short day	29.7 d	4.17 cd	8.8 d	14.6 d	1.70 e	1.25 b	-3.00	4.4 f
	conventional	32.9 cd	3.70 d	6.0 e	17.9 c	3.07 a	1.22 b	-4.05	1.2 g
2	short day	25.6 e	4.46 c	12.1 bc	13.9 d	1.17 f	1.37 b	-2.00	9.0 d
	conventional	32.4 cd	3.95 d	6.6 e	20.0 bc	3.10 a	2.16 a	-2.50	5.8 e
3	short day	26.3 e	5.05 b	14.9 ab	16.0 cd	1.09 f	0.85 cd	-4.75	9.0 d
	conventional	31.5 d	3.82 d	7.3 de	17.6 c	2.42 c	1.61 ab	-4.50	9.6 cd
4	short day	36.5 b	5.02 b	11.0 c	21.9 b	2.07 d	0.69 cd	-3.86	10.4 c
	conventional	32.5 cd	4.83 b	9.8 cd	20.8 b	2.18 cd	0.63 d	-3.25	9.0 d
5	short day	36.4 b	4.82 b	13.6 b	23.1 ab	1.75 e	1.15 bc	-4.67	11.6 b
	conventional	34.2 c	5.23 ab	10.9 c	20.7 b	1.95 de	0.75 cd	-4.93	10.6 bc
6	short day	37.4 ab	5.20 ab	14.6 ab	24.8 ab	1.74 e	0.60 de	-6.96	12.8 a
	conventional	36.6 b	5.30 ab	14.7 ab	23.9 ab	1.69 e	0.83 cd	-6.17	11.4 bc
7	short day	36.8 b	4.97 b	16.3 a	23.3 ab	1.48 e	0.41 e	-11.67	12.0 ab
	conventional	32.9 cd	4.83 b	15.0 ab	22.0 b	1.48 e	0.46 e	-9.63	11.4 bc
8	short day	39.7 a	5.41 a	9.9 cd	25.4 a	2.71 b	0.87 c	-15.50	12.6 ab
	conventional	37.8 ab	5.29 ab	9.4 cd	23.0 ab	2.46 bc	1.10 bc	-12.00	12.0 ab

Height, diameter, root and shoot volume, and shoot/root ratio n= mean of 40 trees per treatment per plant date

Root growth potential n=mean of 20 trees per treatment per plant date.

Whole plant cold hardiness n=mean of 60 trees per treatment per plant date.

Primordia n=mean of 10 trees per treatment per plant date

Table 2.3 Foliar nutrient concentration for seedlings outplanted on P. Guppy and S. Comfort (515 stocktype). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n= the mean of 16 trees per rep (4) per treatment per plant date

	Macronutrients (%)							Micronutrients (ppm)					
Plant date	N	S	P	K	Mg	Ca	Na	Fe	Al	Mn	B	Cu	Zn
1	2.14 b	0.26 ab	0.52 b	1.63 ab	0.28 ab	0.49 a	0.03 a	143 a	94 a	295 bc	99 b	11 a	59 c
2	2.34 a	0.28 a	0.66 a	1.74 a	0.31 a	0.45 ab	0.03 a	163 a	51 b	389 a	130 a	9 a	85 b
5	1.73 c	0.29a	0.53 b	1.64 ab	0.25 b	0.39 b	0.03 a	141 a	48 b	335 b	125 a	6 b	98 bc
8	1.75 c	0.21 b	0.45 b	1.45 b	0.20 c	0.30 c	0.03 a	152 a	69 ab	277 c	98 b	5 b	111 a
Treatment													
short day	1.87 b	0.29 a	0.37 b	1.45 b	0.26 a	0.43 a	0.03 a	142 a	68 a	334 a	117 a	8 a	102 a
conventional	2.11 a	0.24 b	0.71 a	1.79 a	0.26 a	0.38 a	0.03 a	157 a	63 a	314 a	109 a	8 a	74 b

Table 2.4 Foliar nutrient concentration for seedlings outplanted on S. Red Fir (615 stocktype). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n= the mean of 16 trees per rep (4) per treatment per plant date

	Macronutrients (%)							Micronutrients (ppm)					
Plant date	N[1]	S	P	K[2]	Mg	Ca	Na	Fe	Al	Mn[3]	B[4]	Cu	Zn
1	2.09	0.29 a	0.51 b	1.74	0.26 ab	0.38 a	0.04 a	143 a	51 b	252	126	9 a	60 c
2	1.88	0.29 a	0.63 a	1.95	0.27 a	0.38 a	0.04 a	157 a	56 ab	290	147	9 a	78 b
5	1.68	0.26 a	0.65 a	1.85	0.24 b	0.32 b	0.03 b	151 a	41 c	277	147	6 b	115 a
8	1.77	0.21 b	0.47 b	1.43	0.22 c	0.30 b	0.04 a	170 a	60 a	274	135	6 b	87 b
Treatment													
short day	1.79	0.27 a	0.40 b	1.60	0.23 b	0.34 a	0.03 b	154 a	51 a	273	152	7 b	99 a
conventional	1.93	0.26 a	0.73 a	1.88	0.26 a	0.34 a	0.04 a	157 a	53 a	273	127	8 a	71 b

* Significant interactions are followed by superscript numbers, means are shown for descriptive purposes only

[1] On the first plant date CONV seedlings had significantly higher N content than SD, other are not different

[2] On the fifth and eight plant dates CONV seedlings had significantly higher K content than SD, others are not different

[3] On the fifth plant date CONV seedlings had significantly higher Mn content than SD, others are not different

[4] On the fifth plant date SD was higher than CONV, others are not different

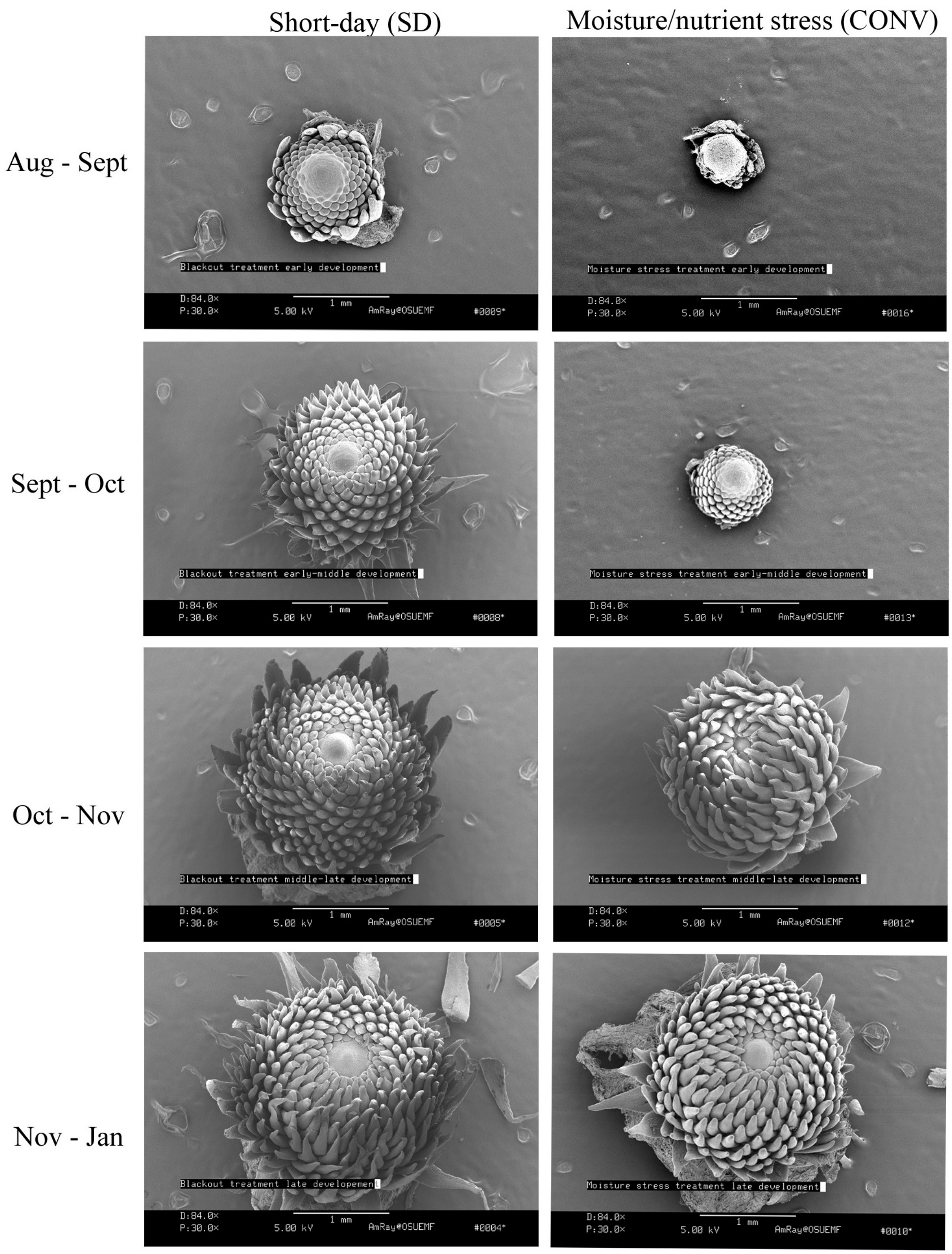

Figure 2.1: Scanning electron microscopy photos of bud development from August 2004 through January 2005 by treatment. Planting dates were grouped together and average size buds were used to illustrate development over time. Stocktypes were grouped because differences between stocktypes were negligible. All photographs were taken at the same zoom so bud size is comparable between photos.

after the second plant date, increasing soil moisture, though soil moisture was still lower than the first planting date.

Average daily soil and air temperatures are shown in Figures 2.2a and 2.3a, respectively. Temperatures decreased from August to March with the exception of an unusual warming trend in December. From March through August, temperatures increased until peaking again in August. Soil temperature did not change as rapidly as air temperature but followed similar trends throughout the study. RH varied greatly from day to day but followed the general seasonal patterns (Figure 2.3b). The RH stayed fairly high on average with a few days of relatively dry conditions (RH < 20%), but for the most part hovered between 50 and 100%. VPD tended to be low (<1 kPa) in the winter months with moderate values in the fall and spring and occasional highs in the summer (Figure 2.3c). On August 25, 2005, 10 days after the first plant date, VPD reached 3.7 kPa. The highest VPD of 5.5 kPa was recorded exactly one year after the start of the study. Monthly precipitation (Figure 2.3d) was low in the summer months and high in the winter months. Total precipitation for the study period was 2200 mm.

2.6.2.2 South Red Fir

Volumetric soil moisture content ranged from 16-29% from August to January 2005 (Figure 2.4b). The two depths (10 and 20 cm) showed little difference from October 2005 to June 2006 but differed by about 2-5% from June to November 2006, when evaporation was high and there was less moisture at the shallower depth. Actual

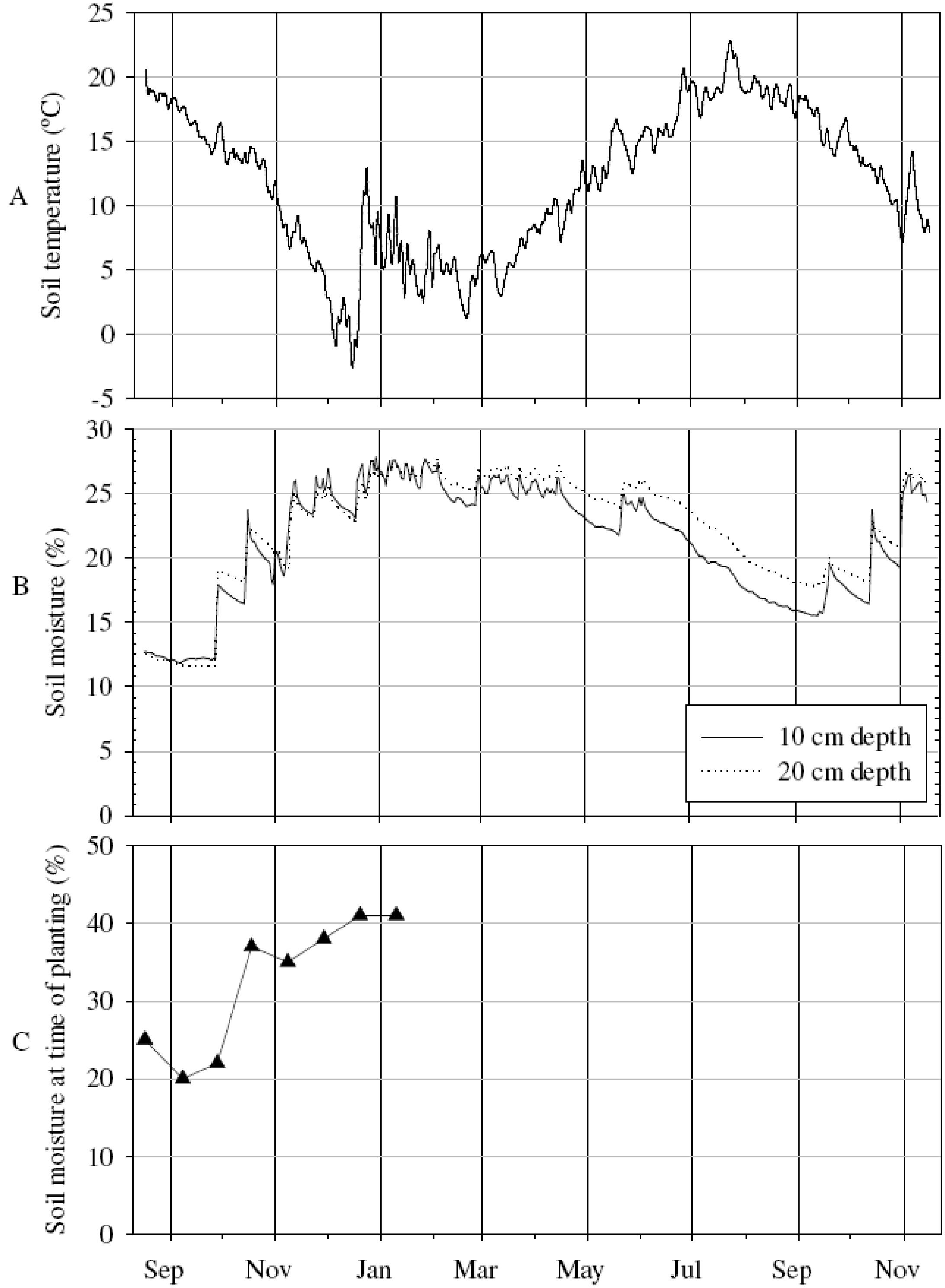

Figure 2.2 Average daily environmental conditions for P. Guppy from August 18 2005 to November 23 2006. (A) soil temperature (B) soil moisture (10 and 20 cm depth) (C) soil core water content at each plant date

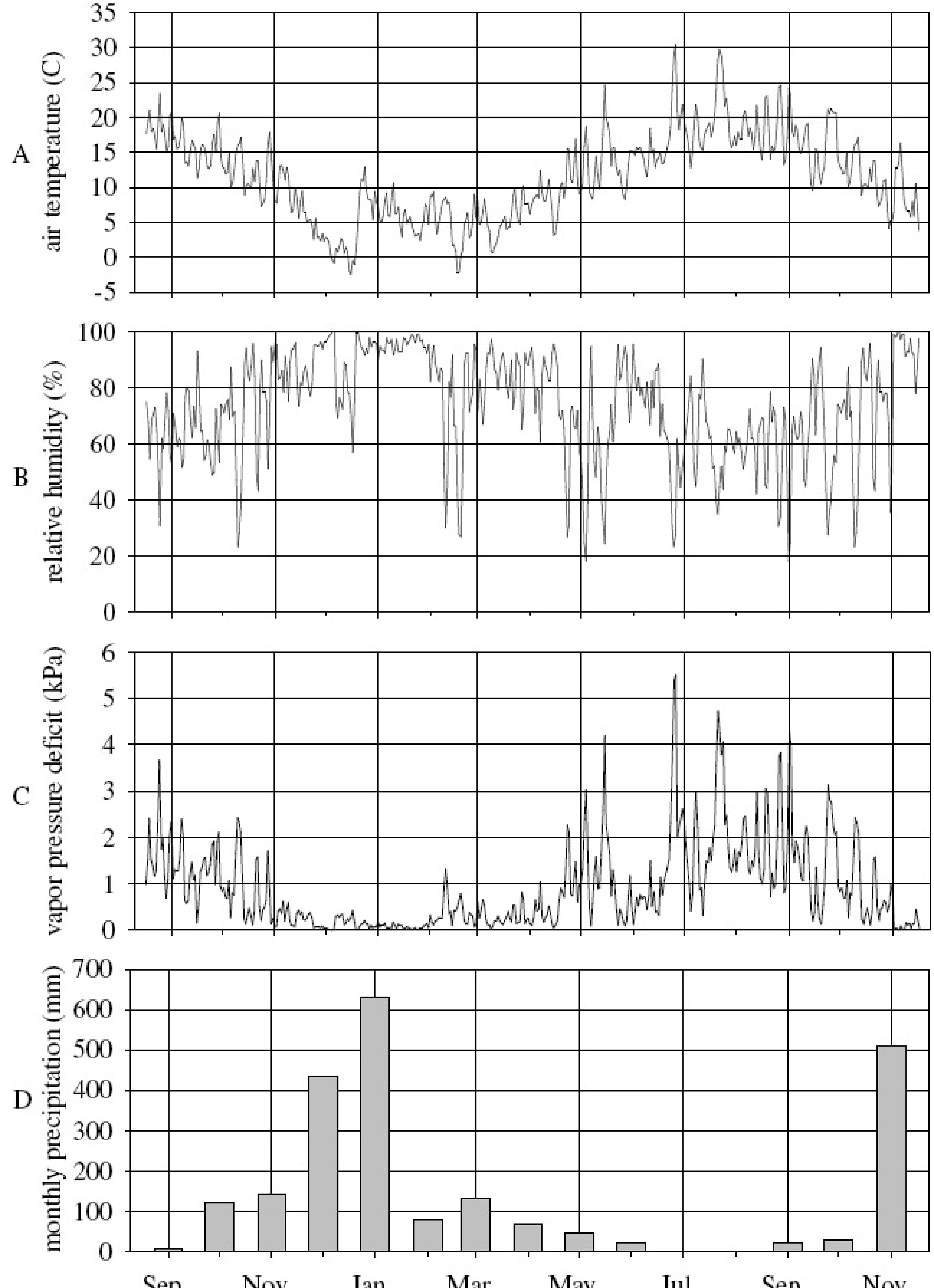

Figure 2.3 Average daily environmental conditions for P. Guppy from August 18 2005 to November 23 2006. (A) air temperature (B) Relative humidity (C) Vapor pressure deficit (D) monthly precipitation

soil moisture remained high (> 32% volumetric water content, soil core) throughout the study on this site (Figure 2.4c).

Average daily soil and air temperature (Figures 2.4a and 2.5a) decreased from August to March, with the exception of an unusual warming trend in December, and then increased again until it peaked in August. Soil temperature remained above root egress minimum (> 5ºC) until mid November. RH remained relatively high but followed seasonal trends with great day to day variability (Figure 2.5b). Average daily VPD remained low (< 1 kPa) from October 2005 to May 2006 and increased with increasing temperatures in the fall and summer months (Figure 2.5c). VPD reached 2.8 kPa two weeks after the initial planting in August 2005. Monthly precipitation (Figure 2.5d) was low in September 2005 but increased from October 2005 to January 2006. There were minimal amounts of precipitation from July to October 2006. The first major rainfall for 2006 did not occur until November when a tropical storm dropped almost 400 mm of rain over a 5-day period. Total precipitation for the 2005-06 study period was 2300 mm. 2.6.2.3 Southern Comfort

Average daily volumetric soil moisture content can be seen in Figure 2.6b. Soil moisture as measured by the HOBO sensors started relatively high compared to the other sites and ranged from 26-33% in 2005 but decreased to 21% in September of 2006. The difference (<3%) between the two depths (10 and 20cm) was similar throughout the study and followed a seasonal pattern. Actual volumetric water content (Figure 2.6c) at the time of planting as determined by the soil cores remained above

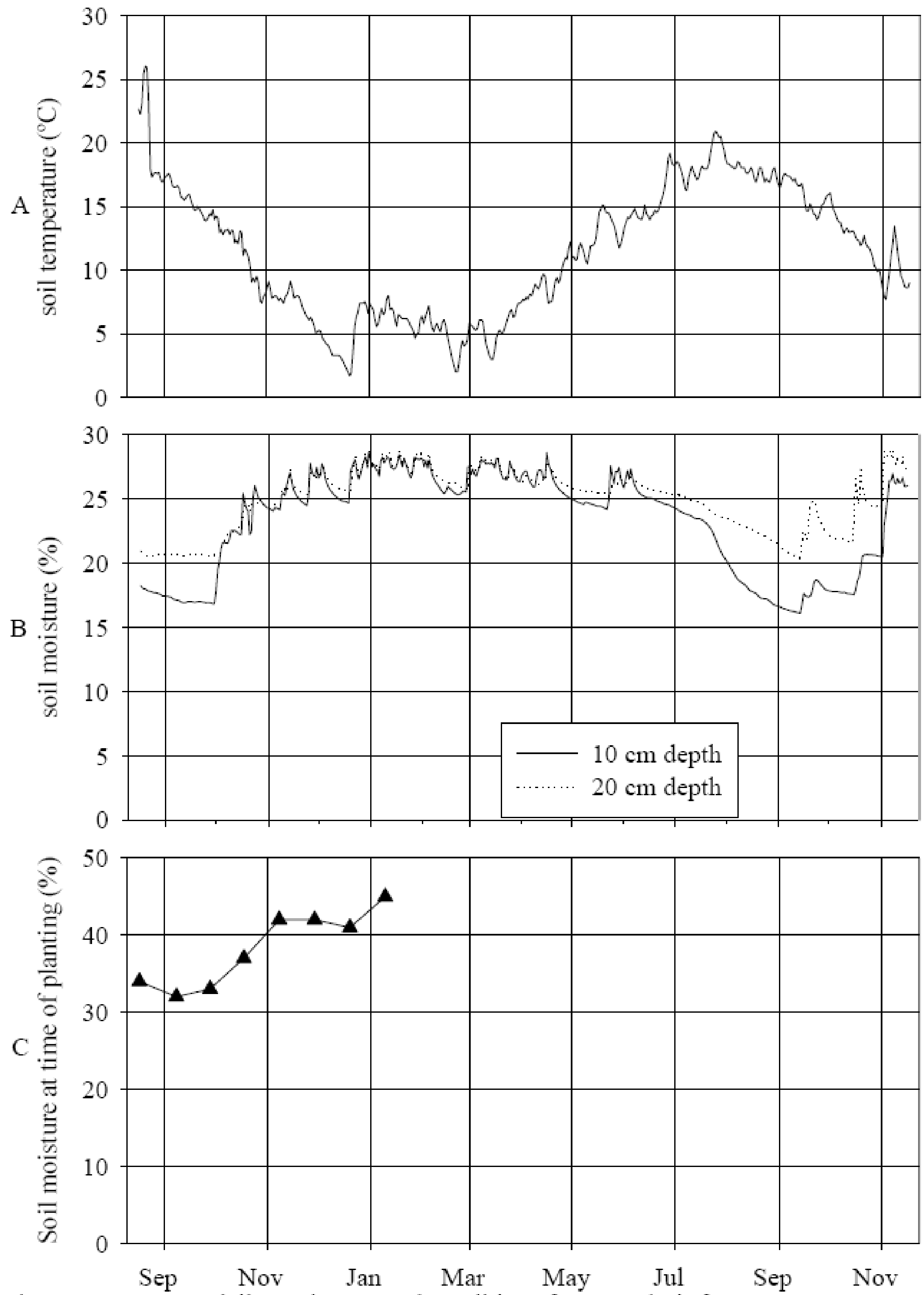

Figure 2.4 Average daily environmental conditions for S. Red Fir from August 18 2005 to November 23 2006. (A) soil temperature (B) soil moisture (10 and 20 cm depth) (C) soil core water content at each plant date

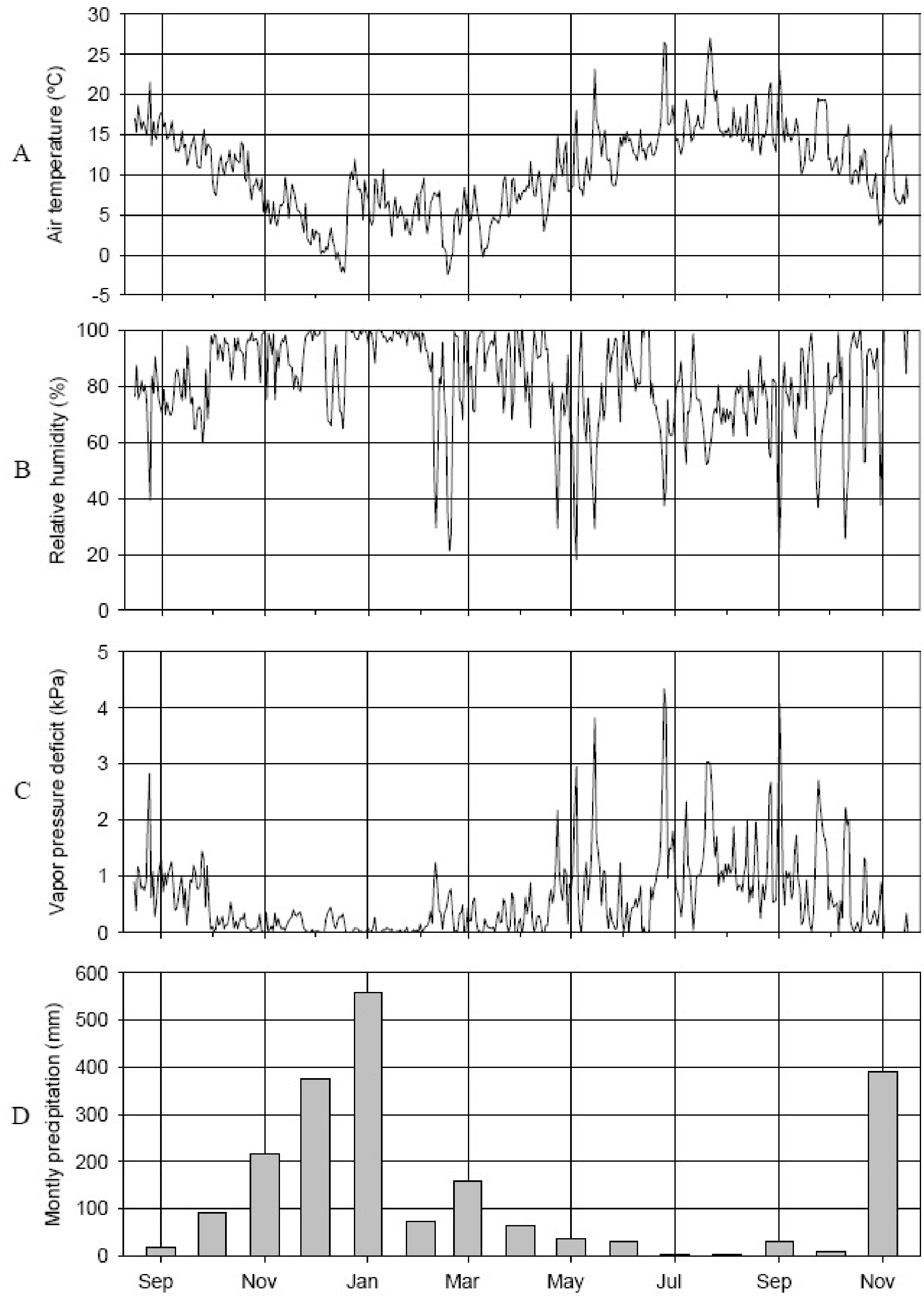

Figure 2.5 Average daily environmental conditions for S. Red Fir from August 18 2005 to November 23 2006. (A) air temperature (B) relative humidity (C) vapor pressure deficit (D) monthly precipitation

37% for all planting dates which decreased stress during establishment due to the site's close proximity to the coast.

Average daily soil and air temperature (Figures 2.6a and 2.7a) decreased from August to March with a short warming period in December. Soil temperature on this site remained above 5ºC allowing for root egress well into the winter (December 2005). Both soil and air temperature increased after March until they peaked in the middle of July, then decreased until November of 2006. RH changed little over time, with slight seasonal increases and decreases, but had variable day to day values (Figure 2.7b). VPD changed with seasonal variations in temperature and relative humidity with more variation from August to October 2005 then from October 2005 to April 2006 (Figure 2.7c). Two weeks after the August 15 plant date, VPD peaked at 2.8 kPa, but with little effect on xylem water potential readings due to high soil moisture content. Monthly precipitation (Figure 2.7d) was over 3200 mm for the 2005-06 study period with, 700 mm falling over a 5 day period in November 2006.

2.6.3 Seedling Field Performance

2.6.3.1 Pedee Guppy

Survival three weeks after planting was 100% for all plant dates (data not shown). However, by April 2006, seedlings planted on the first plant date (August 17) had lower survival (62%) compared to those seedlings planted at later dates (86-100%, Table 2.5). Xylem water potential three weeks after outplanting decreased with plant date but did not differ between dormancy treatments (Table 2.6). Xylem water

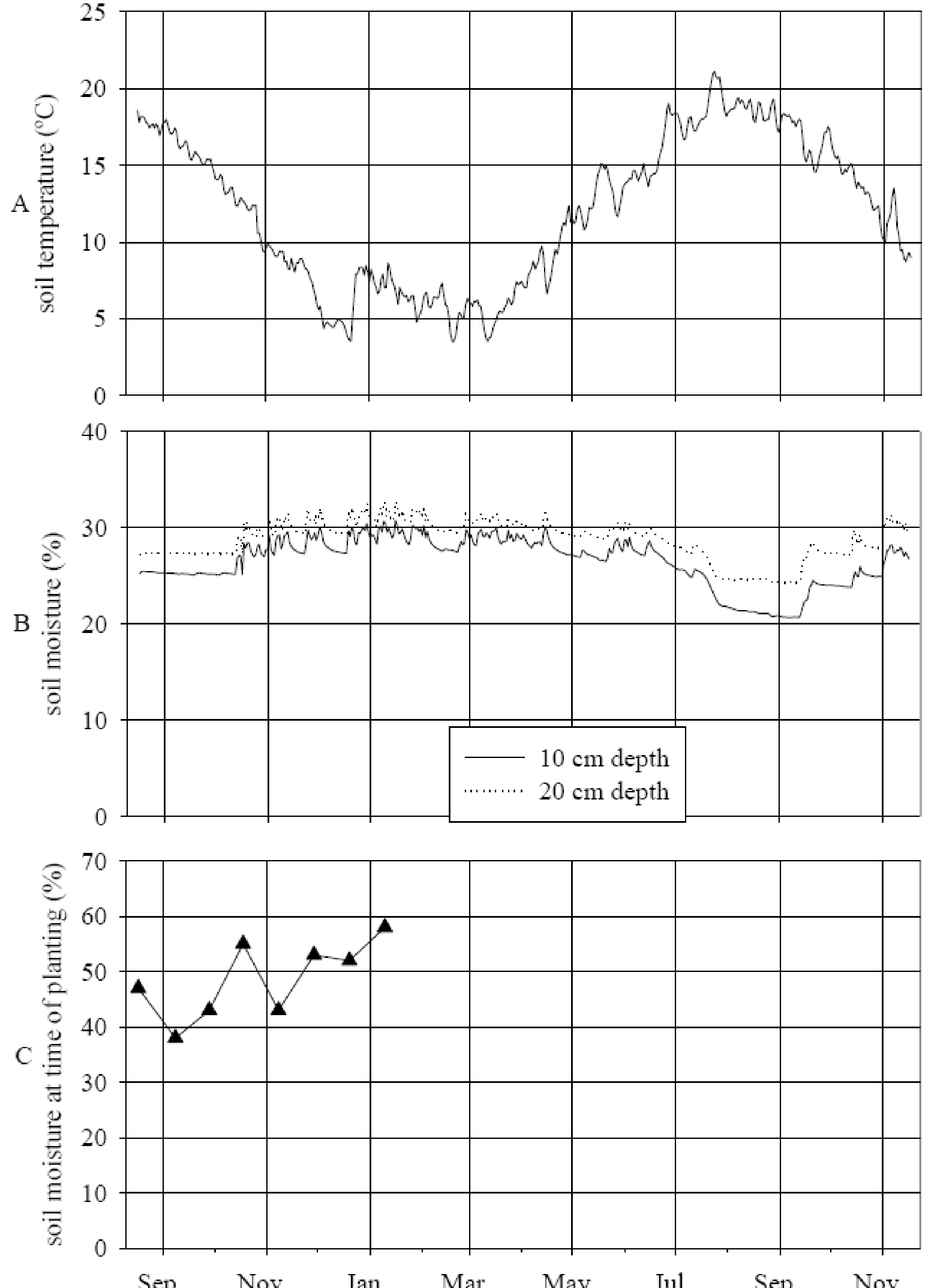

Figure 2.6 Average daily environmental conditions for S. Comfort from August 18 2005 to November 23 2006. (A) soil temperature (B) soil moisture (10 and 20 cm depth) (C) soil core water content at each plant date

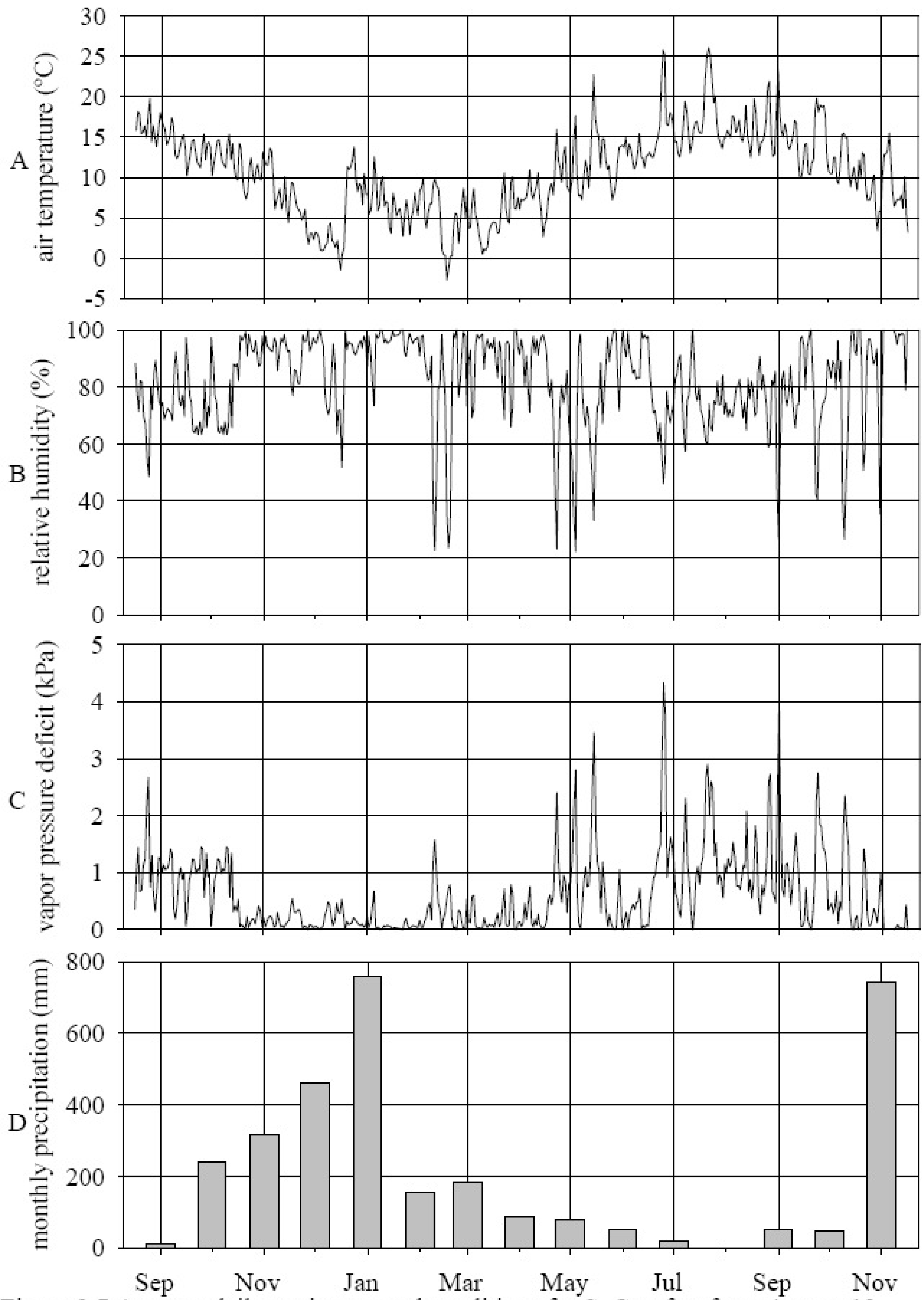

Figure 2.7 Average daily environmental conditions for S. Comfort from August 18 2005 to November 23 2006. (A) air temperature (B) relative humidity (C) vapor pressure deficit (D) monthly precipitation

potential was 35% (-0.7 MPa) higher on the first plant date compared to subsequent plant dates and 25% (-0.5 MPa) higher than measured on the other two sites. Root growth three weeks after planting was greatest for seedlings planted on the third plant date; with 82% (0.4 g) more new root growth than the other plant dates (Table 2.6). In April 2006, field root growth tended to be greatest for those trees planted on the second and third plant dates (Table 2.6). There was no significant difference between the two dormancy treatments for field root growth. After one growing season, both plant date and dormancy induction treatment had a significant effect on seedling growth. Height growth, total height, total stem diameter, and stem diameter growth were significantly greater for seedlings from the CONV dormancy induction treatment as compared to those treated with SD (Figure 2.8, Table 2.5). Seedlings planted on the first three plant dates averaged 38% (8.5 cm) more height growth than seedlings planted on the latter five dates. Similarly, stem diameter growth tended to be greatest for those planted on the first three plant dates compared to later planting dates (Figure 2.8, Table 2.5). At the end of the growing season, data from excavated seedlings showed that CONV seedlings averaged 11 cm taller, 1.3 mm larger in diameter, had 9 cm^3 more root volume, and 25 cm^3 more shoot volume compared to SD seedlings (Table 2.6). Excavated seedlings planted on the first three plant dates tended to be larger than other plant dates, especially those planted on the second planting date (Table 2.6). At the end of the first growing season this difference persisted with 48% survival on the first date compared to 70-90% on the other seven

Table 2.5 Field performance of seedlings planted on P. Guppy (dry, 515). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n=mean of 25 trees per plot per rep with five reps

	height (cm)			stem diameter (mm)			survival (%)	
Plant date	initial[1]	growth '06	total	initial[2]	growth '06	total	April	1st season
1	25.24	20.90 a	45.82 bcd	3.37	4.25 ab	7.73 bc	62 b	48 b
2	27.96	24.33 a	52.36 a	3.74	4.86 a	8.65 a	92 a	75 a
3	27.58	21.69 a	49.11 ab	4.70	3.47 bc	8.20 ab	97 a	83 a
4	27.28	15.19 b	42.45 cd	4.50	2.28 d	6.82 d	93 a	74 a
5	27.68	13.75 b	41.85 d	4.59	2.15 d	6.77 d	98 a	84 a
6	31.42	11.01 b	42.75 cd	4.02	2.85 cd	6.92 d	99 a	82 a
7	32.39	14.40 b	46.93 bc	4.02	3.17 c	7.16 cd	98 a	79 a
8	30.55	14.91 b	45.23 bcd	4.10	2.71 cd	6.81 d	100 a	82 a
Treatment								
short day	25.27	15.64 b	40.90 b	4.11	2.64 b	6.79 b	94 a	76 a
conventional	32.26	18.41 a	50.72 a	4.15	3.79 a	7.98 a	90 a	75 a

[*] Interactions are followed by superscript numbers, means are shown for descriptive purposes only

[1] CONV are greater on all plant dates except plant date 4 and 8 when there was no difference

[2] On plant date 2 SD seedlings are larger, plant date 7 CONV are larger, others are not difference

Table 2.6 Field morphology, field root growth, and seedling stress resistance for seedlings planted on Pedee Guppy (dry, 515). Within a column, means followed by the same letter are not significantly different at $p<0.05$.

	excavated seedling morphology				field root growth		field stress
Plant date	height (cm)	stem diameter (mm)	shoot volume (g)	root volume (g)	3-week (g)	April (g)	xylem water potential (bars)*
1	43.50 b	10.10 ab	68.53 ab	34.26 ab	0.000 b	0.001 b	20 a
2	56.57 a	10.89 a	83.68 a	44.45 a	0.100 b	0.140 a	13 b
3	52.52 ab	10.61 ab	74.78 a	42.32 ab	0.451 a	0.128 ab	5 c
4	47.24 b	9.12 ab	47.56 b	30.32 b	0.075 b	0.052 b	
5	48.48 b	8.83 b	50.68 b	38.07 ab	0.000 b	0.064 b	
6	44.53 b	8.22 b	38.67 b	26.83 b	0.000 b	0.020 b	
7	47.90 b	8.87 b	46.78 b	33.64 ab	0.400 b	0.044 b	
8	44.72 b	9.06 b	45.17 b	30.29 b	0.000 b	0.058 b	
Treatment							
short day	42.52 b	8.71 b	43.10 b	30.33 b	0.077 a	0.062 a	13 a
conventional	54.23 a	10.04 a	68.52 a	39.75 a	0.090 a	0.065 a	12 a

* Xylem water potential was not collected after the third date due to expected low from precipitation

n=2 trees per plot per rep with five reps for all measurements dates (Table 2.5). There was no significant survival difference between dormancy induction treatments.

2.6.3.2 South Red Fir

Survival three weeks after outplanting (data not shown), in April, and after the first growing season was not significantly different by planting date or dormancy treatment (Table 2.7) and remained high due to high soil moisture. Xylem water potential was relatively low on all three dates decreasing with plant date with no treatment effect (Table 2.8). Root development of seedlings excavated three weeks after planting tended to be greatest for those planted on the first four plant dates compared to the later four plant dates; there were no differences between dormancy treatments (Table 2.8). Seedlings excavated in April did not differ by dormancy treatment or plant date (Table 2.8).

After the first growing season, dormancy induction treatments had no significant effect on height, total diameter, diameter growth, or survival on this site (Figure 2.9, Table 2.7). Seedlings planted on the first two plant dates grew on average 43% (11.1 cm) taller than those planted on the third plant date and 70% (18.3 cm) taller than the average of the latter five plant dates. Seedlings planted on the first plant date had greater stem diameter growth than those planted on all other dates (Table 2.7). Seedlings excavated in November 2006 did not show a significant dormancy treatment effect on height, stem diameter or shoot volume; but, SD seedlings averaged 20% (9.4 g) more root volume then CONV seedlings (Table 2.8). In general seedlings

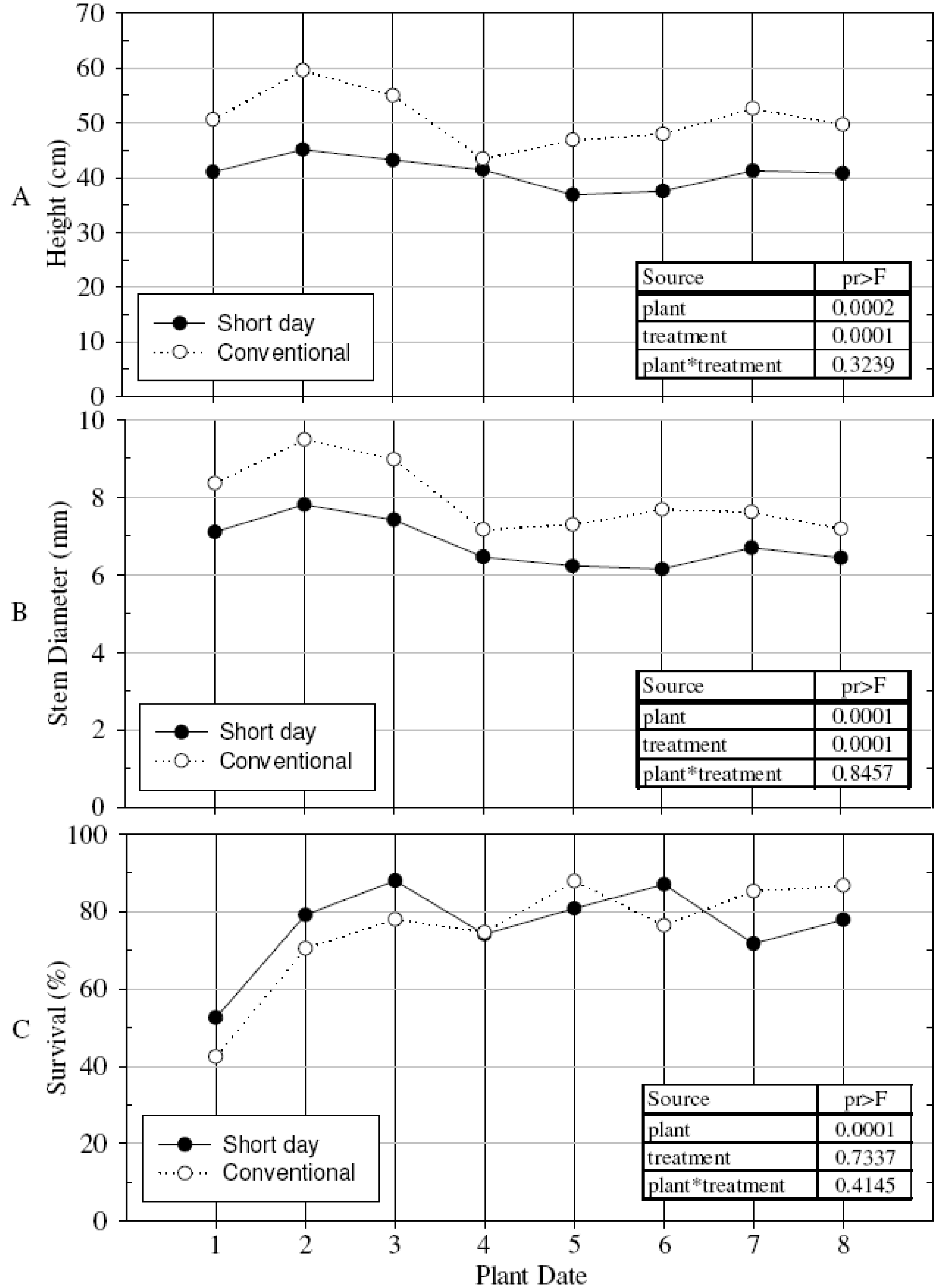

Figure 2.8: P.Guppy - 1st season mean morphological and survival measurements by plant date and treatment. A - height (cm), B - stem diameter (mm), C - survival (%).

Table 2.7 Field performance of seedlings planted on S. Red Fir (mod, 615). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n=mean of 25 trees per plot per rep with five reps

	height (cm)			stem diameter (mm)			survival (%)	
Plant date	initial[1]	growth '06	total[2]	initial	growth '06	total	April	1st season
1	29.02	27.59 a	56.56	3.81 d	6.24 a	10 a	98 a	92 a
2	31.10	24.52 a	55.70	4.89 ab	4.27 b	9.16 b	100 a	96 a
3	30.54	14.94 b	45.56	4.78 b	3.19 c	7.97 c	100 a	92 a
4	39.72	9.37 c	48.95	4.71 b	2.42 cd	7.13 d	99 a	93 a
5	38.93	8.02 c	47.07	4.66 b	2.16 d	6.83 de	100 a	92 a
6	38.25	6.61 c	44.80	4.78 b	1.61 de	6.38 de	99 a	90 a
7	36.58	6.74 c	43.40	4.18 c	2.01 d	6.23 e	100 a	93 a
8	34.99	8.15 c	43.05	5.10 a	1.04 e	6.14 e	100 a	93 a
Treatment								
short day	35.162	13.77 a	48.94	4.75 a	2.91 a	7.59 a	99 a	93 a
conventional	34.617	12.71 a	47.33	4.47 b	2.82 a	7.39 a	99 a	92 a

* Interactions are followed by superscript numbers, means are shown for descriptive purposes only

[1] On plant date 2 and 3 CONV seedlings are larger, plant 4 and 5 SD are larger, others are not different

[2] On plant date 1 CONV are larger, plant date 4 SD are larger, others are not different

Table 2.8 Field morphology, field root growth, and seedling stress resistance for seedlings planted on S. Red Fir (mod, 615). Within a column, means followed by the same letter are not significantly different at $p<0.05$.

	excavated seedling morphology				field root growth		field stress
Plant date	height (cm)	stem diameter (mm)	shoot volume (g)	root volume (g)	3-week (g)	April (g)	xylem water potential (bars)*
1	56.63 b	11.10 b	94.67 b	49.92 ab	0.694 a	0.144 a	12 a
2	68.50 a	13.64 a	137.83 a	64.63 a	0.443 b	0.221 a	8 b
3	53.25 bc	11.27 b	77.81 bc	47.83 bc	0.872 a	0.241 a	5 c
4	53.98 bc	9.41 c	53.79 cd	47.60 bc	0.332 b	0.221 a	
5	50.19 bc	8.96 cd	46.94 d	33.94 bcd	0.000 c	0.202 a	
6	51.33 bc	7.73 d	32.67 d	26.71 d	0.000 c	0.072 a	
7	47.60 c	7.87 cd	33.08 d	32.90 cd	0.043 c	0.071 a	
8	48.44 c	8.12 cd	35.17 d	30.65 d	0.008 c	0.103 a	
Treatment							
short day	54.81 a	9.84 a	68.21 a	46.47 a	0.319 a	0.160 a	8 a
conventional	52.67 a	9.68 a	59.78 a	37.07 b	0.279 a	0.159 a	9 a

* Xylem water potential was collected on the first three dates only.

n=2 trees per plot per rep with five reps for field root growth, excavated seedlings, and xylem water potential planted on the second plant date tended to be largest compared to those planted on the other dates at the end of the first season.

2.6.3.3 Southern Comfort

Seedling survival three weeks after outplanting, in April, and after the first growing season were unaffected by plant date or dormancy induction treatment (Table 2.9). Xylem water potential was relatively low (< -0.7 MPa) for the first three plant dates and did not differ between dormancy induction treatments (Table 2.10). Root development of excavated seedlings three weeks after outplanting did not differ by dormancy induction treatment but tended to be greatest for those planted on the first three plant dates (Table 2.10). Root development in April 2006 did not differ among plant dates or between dormancy induction treatments.

After one growing season, both dormancy induction treatment and plant date had a significant effect on growth but not survival (Figure 2.10, Table 2.9). Height growth and stem diameter growth were significantly greater for seedlings from the CONV dormancy induction treatment than for the SD seedlings. CONV seedlings were 21% taller and 35% larger in stem diameter than SD seedlings. Seedlings planted on the first plant date tended to be tallest compared to those planted on all other dates. Furthermore, those planted on the first two plant dates were 47% (2.2 mm) larger in diameter than those planted on the other six dates. At the end of the growing season, excavated CONV seedlings were 17% (9.45 cm) taller, 19% (1.88 mm) larger in diameter, had 15% (6.24 cm^3) more root volume, and 38% (27.17 cm^3) more shoot

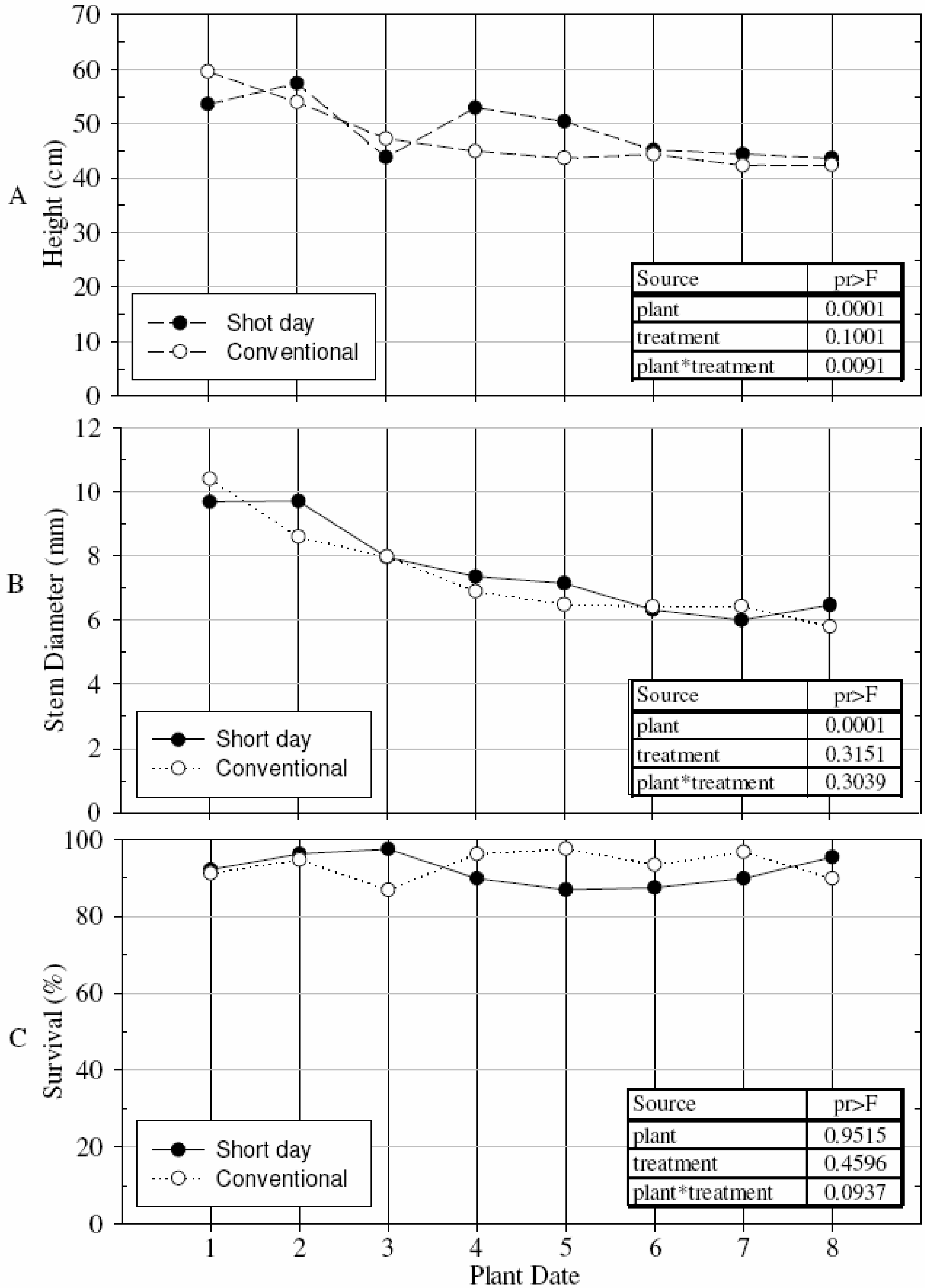

Figure 2.9: S. Red Fir - 1st season mean morphological and survival measurements by plant date and treatment. A - height (cm), B - stem diameter (mm), C - survival (%).

Table 2.9 Field performance of seedlings planted on S. Comfort (high, 515). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n=mean of 25 trees per plot per rep with four reps

	height (cm)			stem diameter (mm)			survival (%)	
Plant date	initial[1]	growth '06	total[1]	initial	growth '06	total[2]	April	1st season
1	25.50	30.35 a	55.79	4.53 a	4.75 a	9.30	96 a	88 a
2	27.49	24.27 b	51.77	3.99 c	4.57 a	8.56	99 a	94 a
3	24.68	21.18 b	45.88	4.77 a	2.75 b	7.52	99 a	97 a
4	26.65	16.54 c	43.22	4.41 ab	2.58 b	7.01	100 a	96 a
5	26.21	13.53 cd	39.86	4.51 ab	2.39 b	6.89	100 a	92 a
6	30.26	10.92 d	41.42	4.13 bc	2.27 b	6.42	100 a	91 a
7	29.74	10.93 d	40.94	3.87 c	2.29 b	6.16	100 a	90 a
8	31.02	10.09 d	41.39	3.99 c	2.49 b	6.48	100 a	96 a
Treatment								
short day	23.72	15.23 b	39.15	4.23 a	2.38 b	6.62	99 a	91 a
conventional	31.66	19.22 a	50.92	4.32 a	3.64 a	7.97	99 a	95 a

* Interactions are followed by superscript numbers, means are shown for descriptive purposes only

[1] On the first six plant dates CONV is taller than SD, others are not different

[2] On plant dates 1 and 5 CONV is larger, others are not different

Table 2.10 Field morphology, field root growth, and moisture stress for seedlings planted on S. Comfort (high, 515). Within a column, means followed by the same letter are not significantly different at $p<0.05$.

	excavated seedling morphology				field root growth		field stress
Plant date	height (cm)	stem diameter (mm)	shoot volume (g)	root volume (g)	3-week (g)	April (g)	xylem water potential (bars)*
1	55.57 ab	11.97 a	101.80 a	44.87 ab	0.551 a	0.529 a	7 a
2	59.09 a	12.29 a	98.32 a	57.60 a	0.239 bc	0.279 a	6 a
3	55.42 ab	10.89 a	77.90 ab	42.75 b	0.365 b	0.286 a	4 b
4	49.79 b	8.36 b	50.27 b	36.48 bc	0.092 cd	0.239 a	
5	47.81 b	8.24 b	51.44 b	34.85 bc	0.000 d	0.162 a	
6	44.75 b	7.59 b	36.54 b	31.17 c	0.000 d	0.142 a	
7	44.10 b	6.85 b	30.75 b	26.33 c	0.000 d	0.096 a	
8	46.29 b	7.46 b	36.58 b	33.21 bc	0.102 cd	0.103 a	
Treatment							
short day	45.41 b	8.09 b	44.57 b	34.61 b	0.172 a	0.242 a	5 a
conventional	54.86 a	9.97 a	71.74 a	40.84 a	0.165 a	0.217 a	6 a

* Xylem water potential was collected on the first three dates only.

n=2 trees per plot per rep with five reps for all measurements volume than SD seedlings (Table 2.10). In general excavated seedlings planted on the first three plant dates tended to be larger than those planted at later dates.

2.6.4 Modeling environmental conditions at time of planting

Regression equations are shown in Table 2.11. The regression equation was derived from environmental conditions from all three sites at the time of planting and first-season seedling growth measurements. Soil moisture was not a significant predictor of growth or survival. This non-significance is reflective of the high volumetric soil moisture (soil core data) throughout the study period with little resulting mortality even for seedlings planted in August. With soil moisture not being the limiting factor, soil temperature had the largest effect on seedling performance because of its influence on fall root egress. The SD treatment shifts the intercept in a negative direction as indicated by the negative parameter estimates. The SD treatment decreased height growth by 1.75 cm and stem diameter growth by 0.8 mm on average across all sites. A limitation of this model is that soil moisture has been shown by numerous studies to be highly influential on seedling growth and survival but was determined to be non-significant in the model statement limiting the usefulness of this model to adequate soil moisture conditions during a particular planting season. In a subsequent study installation conducted the following year on the same site, there was 100% mortality on the August plant date for the driest site demonstrating the high variability from year to year. Another limiting factor of this analysis is that it only

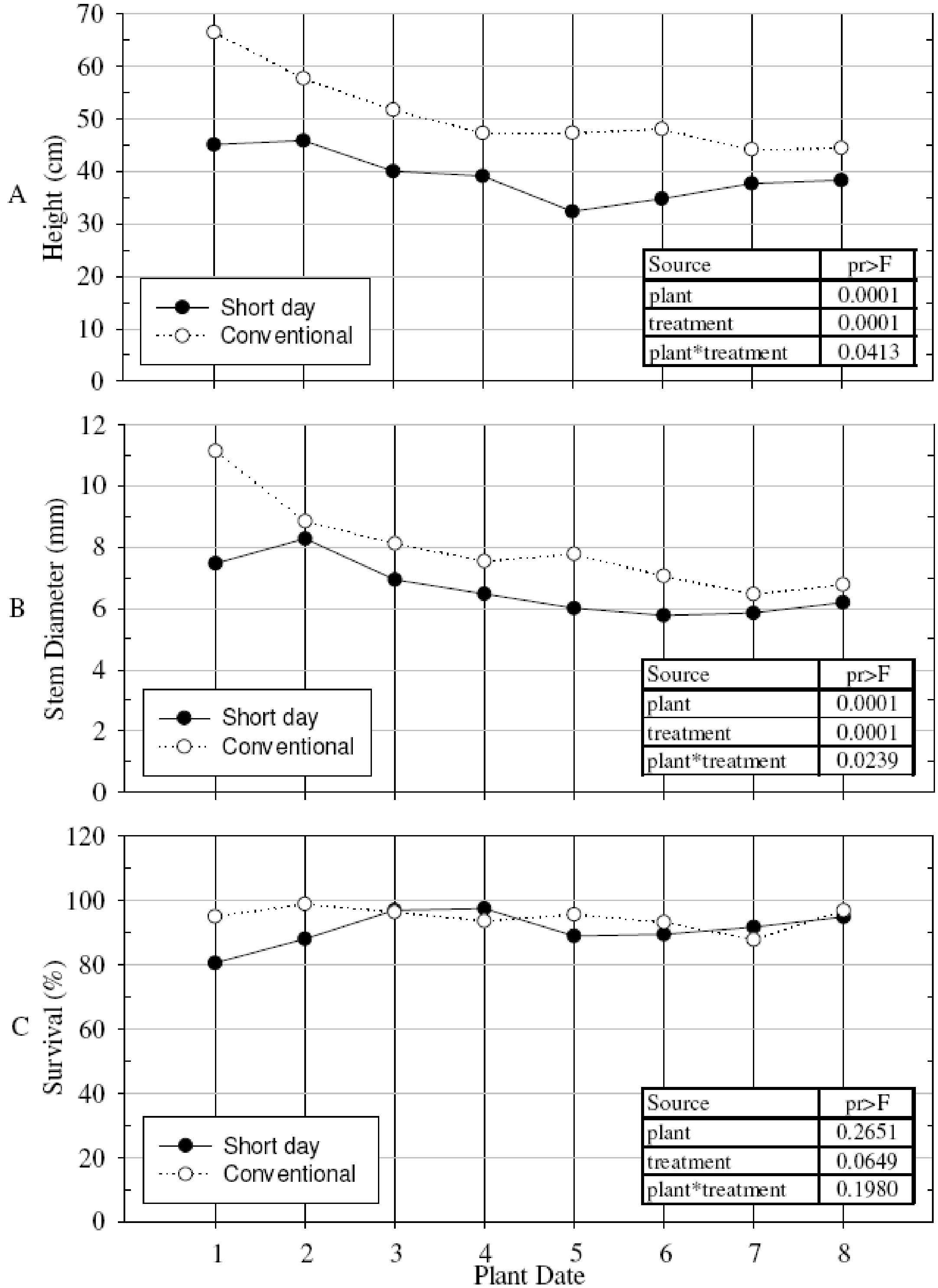

Figure 2.10: S. Comfort - 1st season mean morphological and survival measurements by plant date and treatment. A - height (cm), B - stem diameter (mm), C - survival (%).

Table 2.11 Regression equations for environmental conditions at the time of planting and their effect on seedling field performance during the first growing season. Equations are for predicted growth and survival = intercept + respective dormancy treatment + soil temperature * x1 + soil temperature^2 * x2.

	Intercept	short day	conventional	soil temperature x1 (ºC)	soil temperature^2 x2 (ºC)
height growth	9.34	-1.75	0.00	0.051	0.042
stem diameter growth	0.33	0.08	0.00	-0.023	0.002
1st season survival	0.92	-0.01	0.00	-0.004	n/s

examines environmental data at the time of planting and does not account for subsequent changes in temperature and moisture after planting.

Along with modeling, growth and survival values were graphed relative to soil moisture and soil temperature (Figure 2.11). Height and stem diameter growth show a marked increase when soil temperature at the time is above 15ºC. Seedling survival was reduced by low values of soil moisture at temperature above 15ºC. The high mortality found at high soil temperature and low moisture is attributed to SD treated seedlings; CONV treated seedlings under the same conditions had survival above 80% (Appendix 4). Growth by dormancy induction treatments (grouped by plant dates) can be found in Appendices 2 and 3.

2.7 Discussion

2.7.1 Effect of dormancy induction treatments

2.7.1.1 Seedling condition at time of planting

Dormancy induction treatments had a significant effect on initial morphology and physiology for seedlings outplanted on all three sites. Seedlings treated with CONV dormancy induction and outplanted to the P. Guppy and S. Comfort sites (515 stocktype) were taller, had lower root volume, had greater shoot volumes, and had greater shoot:root ratio than SD treated seedlings on nearly every plant date. This was also seen for seedlings outplanted to the S. Red Fir site (615 stocktype) during the first few plant dates. Similar studies have also noted differences in seedling morphology and physiology due to differing dormancy induction treatments. Black spruce (*Picea*

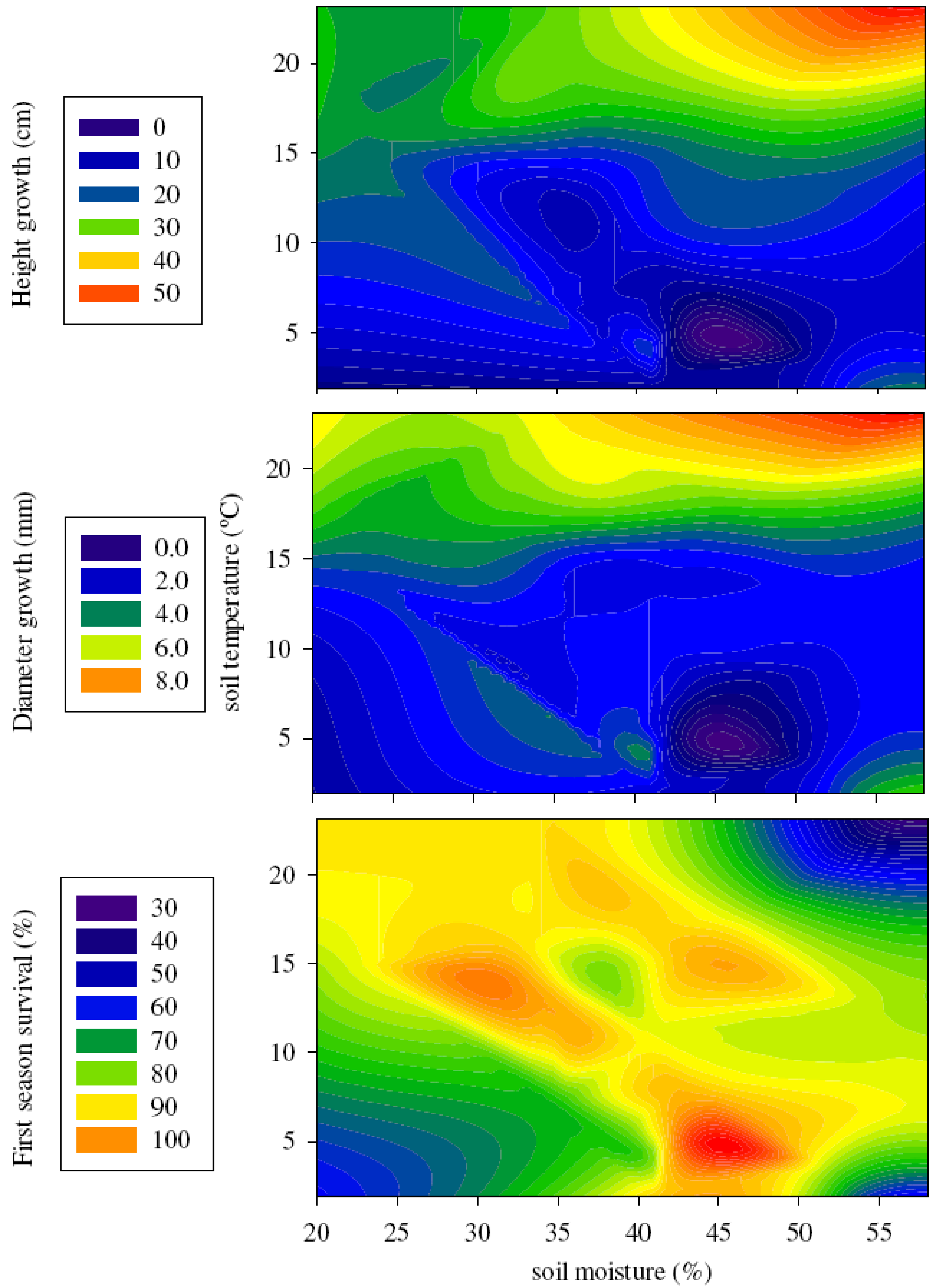

Figure 2.11 Height growth, stem diameter growth, and 1st season survival modeled versus soil moisture and soil temperature at the time of planting across all three sites, combined treatments.

mariana (P. Mill.) B.S.P.) seedlings treated with 12 h nights for 15 days had significantly greater total dry weight (45%) and smaller shoot:root (19%) when compared to seedlings without shortened days (Tan 2007). The use of SD in this study also resulted in shorter more balanced seedlings with lower shoot:root ratios on all eight planting dates. This more abrupt change in photoperiod caused seedlings to cease terminal growth and resume root growth giving SD treated seedlings more rooting mass to support their above ground biomass than seedlings treated with CONV. On the other hand, MacDonald and Owens (2006) reported initial morphological characteristics such as height, diameter, and root and shoot dry weight were not significantly different between seedlings treated with short-day, moisture stress, or a combination of short-day and moisture stress.

In another study, short-day treated western hemlock seedlings initiated a terminal bud sooner than long-day seedlings but moisture stress significantly reduced all morphological characteristics regardless of daylength (O'Reilly et al. 1989). The early initiation of a terminal bud in response to reduced photoperiod is similar to what the current study found; however, a reduction in morphological characteristics for seedlings treated with moisture stress were mixed in relation to the current study. The similarities between these two studies show that shortened photoperiod hastens bud development and reallocation of resources to root and stem development while the difference in height response is most likely due to a species difference. Western hemlock is typically associated with moist, coastal regions where water is not as limiting and may therefore be more affected by moisture stress than Douglas-fir which has adapted to a wider range of environmental conditions.

Similar to the current study, both Tan (2007) and Grossnickle et al. (1991) reported increased initial root volumes for short-day treated seedlings compared to moisture stress treated seedlings. The increased root volume resulted in lower shoot:root ratio which is associated with better drought tolerance in many species (Colombo et al. 2003, Krasowski et al. 1990, Marshall 1986, Helenius et al. 2002). The reduction in root volume for seedlings treated with CONV compared to seedlings treated with SD may be caused by moisture stress-induced root mortality (van Eerden and Gates 1990, and Marshall 1986) but is more commonly associated with resource allocation to roots after terminal bud set (Canham et al. 1996, Domisch et al. 2001). The majority of resources are either dedicated to shoot or root and stem diameter growth so the early bud initiation of seedlings treated with SD would allow a longer period of time for reallocation of resources to the roots compared to seedlings treated with CONV, which initiated terminal buds later.

Although initial root volumes were lower for CONV seedlings, they had greater root growth following planting. Seedlings treated with CONV still had actively growing shoots during the early plant dates and therefore had not yet reallocated resources to their root systems, compared to SD treated seedlings. This may have resulted in faster initiation of new root growth in the field as evidenced by the increase in RGP on the second and third planting date for CONV treated seedlings compared to SD treated seedlings. This may have provided them with a longer period of root establishment in the field compared to seedlings treated with SD that were further along developmentally. In addition, being planted in areas of relative high moisture content allowed for root egress following planting where a drier environment could have stunted root initiation and even resulted in higher mortality due to a higher shoot:root ratio. The repeated exposure to moisture stress may have also decreased transplant shock in CONV treated seedlings compared to SD treated seedlings, because CONV treated seedlings were more conditioned to moisture stress at the time of planting compared to SD treated seedlings, which had minimal moisture stress in the nursery (Seiler and Johnson 1985, Helenius et al. 2002, McDonald and Owens 1993a, van den Driessche 1991a). Kaushal and Aussenac (1989) reported that Corsican pine (*Pinus nigra* Arn. ssp. *laricio* Poiret var. Corsicana) and Cedar of Atlas (*Cedrus atlantica* Manetti) were able to initiate new roots following transplanting at a lower water potential when pre-conditioned using moisture stress in the nursery compared to seedlings that were not pre-conditioned.

Seedlings treated with SD had significantly more needle primordia and larger buds from August until October than seedlings treated with CONV (Tables 2.1 and 2.2, Figure 2.8). O'Reilly et al. (1989) reported similar trends in delayed initiation of western hemlock terminal bud development of moisture stress treated seedlings compared to short-day treated seedlings, but they also reported that moisture stress reduced the final number of needle primordia compared to short-day treatments, which was not true for this study. Douglas-fir terminal buds under the moisture stress dormancy induction regime may have started with fewer needle primordia that were smaller in size, but by November these differences were not evident. The differences between the above study and the current study may be due to the two species adaptations to varying climatic conditions. Western hemlock is less tolerant of moisture stress than Douglas-fir and therefore moisture stress may have had a greater effect on terminal bud development.

Seedlings treated with CONV had higher concentrations of N compared to those treated with SD in spite of nutrient reductions to induce dormancy. The reduction of N for seedlings treated with SD may have been caused by SD treated seedlings having a larger root volume and therefore storing more nutrients below ground compared to seedlings treated with CONV. Increasing concentrations of N have been shown to delay frost hardiness (van den Dreissche 1991) and increase water potential (Margolis and Waring 1986). Although seedlings treated with SD had earlier bud development in the fall, cold hardiness was not different between the two treatments. This was unexpected since seedlings further along developmentally are likely to be more cold hardy than lesser developed seedlings. This differs from the findings of Floistad (2002), where Norway spruce (*Picea abies* (L.) Karst.) seedlings treated with SD had reduced frost damage compared to seedlings treated with longer days. In this case, Norway spruce must adapt to a short, cold growing season, so a reduction in photoperiod may trigger a more abrupt change in physiology and a better ability to survive rapid changes in environmental conditions. In contrast, the seedlings treated with longer days may not have received such an abrupt signal to cease terminal growth and were therefore more susceptible to frost.

2.7.1.2 Seedling growth and survival

The slower dormancy induction of seedlings treated with CONV as evidenced by succulent shoots, higher RGP, and less developed buds, may have increased establishment in favorable conditions for fall planted seedlings. CONV seedlings excavated at the end of the year had greater height, stem diameter, root volume, and shoot volume compared to seedlings treated with SD on the Pedee Guppy and S. Comfort sites. This delay in reallocation of resources until after outplanting may have allowed for rapid root elongation in the new environment instead of root elongation within the cavity. Lavender and Overton (1972) reported similar results with long photoperiods prolonging the free growth phase of Douglas-fir seedlings thereby lengthening the time to terminal bud set and delaying the onset of dormancy. Increased RGP, which has been linked to increased establishment, growth, and survival (Burdett et al. 1983, Simpson and Ritchie 1996, Stone and Benseler 1962, Stone 1955), was 47 and 36% (0.95 g, 515 and 0.80 g, 615 stocktypes, respectively) higher for seedlings treated with CONV on the second plant date compared to seedlings treated with SD. This is similar to results reported by Turner and Mitchell (2003), where RGP decreased in the fall with increasing length of short-day treatment compared to longer photoperiod treatments. Seedlings treated with SD had larger initial root volumes but did not produce as many new roots as seedlings treated with the CONV dormancy induction regime. This is the opposite of conventional thinking; a larger root mass should produce more new roots (Grossnickle and Major 1991, Tan 2007). However, seedlings treated with CONV dormancy induction treatment developed a terminal bud later which may have prolonged the change in resource allocation to the roots (Domisch et al 2001, Duddles 1963) and thereby allowed those seedlings to take advantage of a favorable planting environment compared to seedling that received the SD dormancy induction treatment. Although seedlings from the two dormancy induction treatments may have differed morphologically and physiologically, those differences did not influence survival on any site. Grossnickle et al. (1991) reported similar survival results with both short-day and long-day dormancy treatments maintaining survival between 95 and 97% during the first season.

2.7.2 Effect of plant date and environment

2.7.2.1 Seedling condition at time of planting

Planting date had a significant effect on initial morphology and physiology for seedlings outplanted on all three sites. Seedling morphology differed by planting date and generally increased with time following a typical seasonal increase in height, diameter, root volume, and shoot volume. Seedling physiology varied by planting date but followed normal seedling developmental patterns, although CONV treated seedlings developed later than SD treated seedlings. Root growth potential and seedling cold hardiness decreased with planting date while needle primordial development increased with later planting dates. As seedling dormancy increases, RGP and cold hardiness are both expected to decrease (Ritchie 1984, Ritchie 1986). In general mobile nutrient concentration decreased with later planting dates while immobile nutrient concentration generally increased with plant date as seedlings grew in size and relative concentrations changed.

2.7.2.2 Seedling growth and survival

Seedling growth and survival were significantly influenced by plant date and environmental condition at the time of planting. In general, seedling growth increased while mortality decreased with increasing planting date. The reduced dormancy, higher RGP, and warmer soils for seedlings planted in the fall likely provided a favorable environment for early rooting establishment compared to seedlings planted in the winter. The incomplete bud development and high RGP indicate that seedlings planted in the fall were less dormant than seedlings planted later in the winter and were therefore better able to respond to favorable planting conditions. The early root egress and establishment may have increased future growth.

Soil moisture, which is the most crucial environmental condition for seedling survival and growth, was below the threshold described by Akgul (2004) and South and Barnett (1986) at the Pedee Guppy site on the first plant date where significant mortality occurred. The hottest and driest day of the study period came 9 days after the first plant date with air temperatures of 23, 22, and 20ºC, RH of 30, 36, and 49%, and VPD of 3.6, 2.8, and 2.6 kPa on P. Guppy, S. Red Fir, and S. Comfort respectively. For seedlings planted on P. Guppy, the low soil moisture and high evaporative demand on seedlings likely caused the increased mortality (62% survival) when measured three weeks after planting while the other two sites had high enough soil moisture to recover from this desiccating event and maintained near 100% survival. After the second planting date there was a small amount of precipitation that lowered the temperature, RH, and VPD which may have contributed to the increased survival of seedlings planted on this day and minimized transplant stress. On S. Comfort, 2.8 mm of precipitation came the week after the first planting date while P. Guppy received no precipitation for almost three weeks. During this time, soil moisture at P. Guppy decreased and even with 3.4 mm of precipitation on September 9 (two days after the second plant date) soil moisture was still lower than the first planting date; although the length of time until soil moisture increased was much shorter than for seedlings planted on the first plant date. All subsequent planting dates and the two other sites had sufficient soil moisture as to not significantly increase mortality.

Although soil moisture by October was not limiting, soil temperature cooled to levels below optimum for root egress (Scagel et al 1990). This can be seen best in Figure 2.7 when growth decreased significantly for seedlings that were planted after soil temperature dropped below around 13ºC, after the third planting date. Although there was still root growth until 5ºC, seedling growth was reduced enough to be significantly less than the previous three planting dates.

2.8 Conclusion and recommendations

Planting early in the fall can have serious environmental risks associated with it. The current study period did not result in substantial mortality in the early plant dates since soil moisture was not below a critical level but subsequent years may offer differing results with wider ranges in survival due to varying climatic conditions. If soil moisture and temperature are adequate in the fall, then early establishment may increase field performance compared to seedlings planted in the winter. Fall planting seedlings may be a viable alternative to winter planting if close attention is paid to soil conditions at the time of planting. If soil moisture is too low (<12%), seedling survival may be unacceptably low as was found on the driest site (Pedee Guppy), where only 48% of seedlings planted on the first date survived the first growing season. Soil temperature is also critical. Seedlings planted late in the fall did not differ from those planted in winter because soil temperatures were too low for root egress.

Dormancy induction can also have a significant influence on subsequent seedling performance. In this study, CONV treated seedlings had greater root and shoot growth than SD treated seedlings. This is likely due to a combination of favorable environmental conditions coupled with more active seedlings capable of initiating growth more rapidly. Although this resulted in significant growth increases in this study, it’s important to note that those seedlings were also somewhat succulent during the earliest plant dates and could therefore be susceptible to damage from handling and from early frosts.

This study demonstrates that planting even as early as August in coastal regions may prove to be an important management tool to increase growth during the first growing season. When planting closer to the valley fringe, fall planting tended to become more variable in the early fall dates and unacceptable mortality due to inadequate soil moisture may occur. The NTC is continuing a similar study based on these results to better encompass a wider environmental gradient from which managers can make more informed decisions about the risks and benefits of fall and winter planting. A better understanding of the physiological changes dormancy induction treatments have on seedling performance and survival is also anticipated from these studies.

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CHAPTER 3 - EFFECT OF PLANT DATE AND TREE SHELTERS ON FIELD PERFORMANCE OF DOUGLAS-FIR AND WESTERN LARCH SEEDLINGS ON THE EAST SIDE OF THE CASCADE MOUNTAINS IN WASHINGTON

3.1 Abstract

Reforestation on harsh, high elevation sites near the crest of the Cascade Mountains in Washington can be challenging due to persistent snow pack, extreme climatic variation, and poor water holding properties of volcanic ash soils. The use of tree shelters was investigated with two species [Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western larch (*Larix occidentalis* Nutt.)] on two sites (elevations 1400 m above sea level) across three fall (Sept 20, Oct 4, Oct 25, 2005) and two spring (May 23, June 7, 2006) plant dates. Douglas-fir and western larch seedlings with tree shelters had higher survival (9 and 17% higher respectively) compared to the unsheltered control seedlings after one growing season. Western larch survival was unaffected by plant date. However, Douglas-fir seedlings planted on the first plant date had only 2% survival while those planted on the second and third plant dates had the greatest survival (51%) even though soil moisture for all three fall dates remained below 12%. This is likely due to precipitation which fell shortly after the third plant date increasing soil moisture and survival. At the time of the first planting, soil moisture was below 10% (volumetric water content) on the western larch site and stayed at that level until a few days before the second plant date when a small amount of precipitation almost doubled soil moisture on the following two plant dates.

Seedlings planted on the other two fall dates had greater than 50% survival (after one growing season). Height growth and stem diameter growth averaged 8.3 cm and 1.1 mm respectively for western larch and 4.5 cm and 0.1 mm respectively for Douglas-fir, but growth was unaffected by plant date or tree shelter treatment for both species. Though survival was higher for western larch seedlings with tree shelters, snowpack damage to sheltered seedlings was 28% compared to 3% for the unsheltered control seedlings. On the Douglas-fir site, snow pack damage did not differ between treatments. These results indicate that use of tree shelters may improve survival of Douglas-fir and western larch seedlings planted on a harsh, high-elevation site. These results also demonstrate the importance of soil moisture and the length of time between planting and adequate soil moisture.

3.2 Introduction

High-elevation sites have a short period of favorable planting conditions in the spring followed by a short growing season. This results in several challenges to reforestation managers. Logistically, higher-elevation sites can be difficult to plant in the spring because access to sites may be prevented by a persistent snow pack until late spring or extra expenses must be incurred to gain access earlier (Sinclair and Boyd 1973). Soil moisture at the site may drop to unacceptably low levels by the time sites become accessible naturally (Cleary et al 1978a, Barber 1989, Scagel et al 1990). These sites may be more accessible in fall than in spring, when roads are clear of snow (Krumlik and Bergerud 1985). Even with proper planning the risks of fall planting may outweigh the benefits (Livingston 2000). There are inherent risks in fall planting which require careful consideration of local conditions. Timing and communication with the nursery is crucial to a successful fall planting since there is only a short window when both seedling dormancy and weather conditions are favorable (Barber 1989).

3.2.1 Environmental conditions

High elevation sites are known for extreme climatic variation from one season to the next with short and cool growing seasons resulting in tree growth that is inevitably slower than on low elevation sites. The short window between snowmelt and summer drought conditions provides only a small margin of error between plantation success and failure. The snowpack insulates the ground and young seedlings from constantly changing and potentially deadly temperatures and winds during the winter months but once the snowpack has melted, the seedling environment rapidly changes from wet and cold to hot and dry. Rapid changes in soil moisture, temperature, relative humidity, and solar radiation make plantation establishment more difficult than on lower elevation sites (Scagel et al 1989, Arnott 1975). Severe frosts and a persistent heavy snowpack that can lead to plantation damage or failure (Williams 1966). Soil moisture on these sites comes mainly from melting snow with little precipitation in spring through fall. The dry air also increases evaporative losses and decreases soil moisture even faster, which is the main factor contributing to plantation failure (Brand 1991). Cleary et al. (1978) and Krumlik (1984) suggested acceptable planting conditions for summer and fall planting on the Lillooet Forest District in British Columbia should be as follows: soil temperatures in the top 25 cm of the soil profile is greater than 4°C, soil water potential in the top 25 cm of the soil profile should be greater than -1 bar, air temperature should be less than 18°C, and wind speed should be less than 30 kph.

3.2.2 Tree shelters

The use of tree shelters has been found to increase seedling survival on harsh, high elevation sites (Jacobs 2004). Engelmann spruce (*Picea engelmanni* Parry ex Engelm) seedling survival increased from 58% in non-sheltered trees to greater than 95% using shelters which allowed 21-24% of available photosynthetically active radiation (PAR) to reach the seedlings (Jacobs and Steinbeck 2001). The principal behind tree shelters is to limit the intensity of harmful UV light that may cause damage via desiccation and sun scald to newly planted seedlings. In addition, tree shelters have been shown to increase CO_2, temperature, and relative humidity (Frearson and Weiss 1987, Minter et al. 1992) as well as help shield seedlings from animal browse (Jacobs and Steinbeck 2001). Red oak (*Quercus rubra* L.) seedling relative height growth and survival on a clearcut in southern Michigan was 77 cm with no shelter compared to 130 cm with a shelter, with 90 and 98% survival, in there respective treatments.

Some of the management considerations on the use of tree shelters are the increased cost of purchasing, assembling, and installing them. There are also concerns about yearly maintenance of shelters after winter snow-pack subsides to ensure that the shelters are not restricting growth (Jacobs and Steinbeck 2001). The increased cost may be offset by increased survival which thereby reduces the need to replant at a later date when competing vegetation is more established.

3.3 Objectives and hypotheses

3.3.1 Objectives

The objective of this study was to quantify seedling performance as influenced by plant date, tree shelters, and environmental conditions. Specific objectives were as follows:

1. To determine the effect of tree shelters on Douglas-fir and western larch seedlings growth and survival.
2. To determine the effect of plant date on growth and survival of outplanted Douglas-fir and western larch seedlings.
3. To determine the influence of soil moisture and soil temperature at time of planting on Douglas-fir and western larch seedlings growth and survival.

3.3.2 Null hypotheses

1. Tree shelters are not related to seedling survival or growth.
2. Plant date is not related to seedling survival or growth.
3. Soil moisture and soil temperature at time of planting is not related to seedling survival or growth.

3.4 MATERIALS AND METHODS

3.4.1 Test sites

Sites were selected during the summer of 2005 on the Yakama Nation property on the east side of the Cascade Mountains in Washington. The two sites were chosen to represent different climatic regions and to help meet management objectives of improving establishment of Douglas-fir and western larch.

3.4.1.1 Mt. Adams Lake (western larch site)

Mt. Adams Lake is located in the NW 1/4 of Section 33, T9N, R12W, Willamette Meridian. It was operationally logged and mechanically piled in summer of 2004. The site is relatively flat with a slight southeastern aspect. The annual precipitation is 110-120 cm with the majority as snow in the winter months. The elevation is approximately 1400 m (~ 4600 ft.) with a site index of 53 ft. (50 years) for western larch and around 45 ft (50 years) for lodgepole pine. The previous stand was a mixture of ponderosa pine (*Pinus ponderosa* P. & C. Lawson), Douglas-fir, grand fir (*Abies grandis* (Dougl. Ex D. Don) Lindl.), western larch, and lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) with a sparse understory of grasses and forbs.

3.4.1.2 Pileup (Douglas-fir site)

Pileup is located in the NW 1/4 of Section 12, T9N, R13W, Willamette Meridian. It was operationally logged and mechanically piled in winter of 2003-04. It is on a northern aspect at an elevation of 1400 m. The annual precipitation is 80-90 cm with the majority as snow in the winter months. The site index for western larch is around 45 ft (50 years). The previous stand was a mixture of lodgepole pine, grandfir, western larch, and Douglas-fir with a sparse understory of grasses and forbs.

3.4.2 Seedlings

Douglas-fir and western larch seed were stratified using a hydrogen peroxide (H_2O_2) soak for 24 hours. After soaking, the seed was placed in cold storage for 60 and 30 days for Douglas-fir and western larch, respectively. The same seed lot of Douglas-fir and western larch were used throughout their respective sites to minimize confounding variables. Douglas-fir seed was sown on March 1, 2005 and western larch on May 1, 2005 in styro-10 blocks (364 cavities per m^2, 125 ml per cavity, 11.7 cm deep, 4.2 cm top diameter) at the IFA nursery in Nisqually, WA. Medium was a 70-30 mix of sphagnum peat moss and perlite with Nutricote 16-10-10 (180 day) controlled-release fertilizer incorporated.

Seedlings were operationally grown until being lifted and hand graded in September 2005 using the following criteria for both species: 15 cm height, minimum 3.2 mm stem diameter, acceptable stem form and color, and lack of any other deformities and undesirable traits. Seedlings were placed in cold storage at 2ºC until planting.

3.4.3 Plant dates

There were a total of five plant dates during fall 2005 and spring 2006. The three fall planting dates were selected to capture some mortality due to low moisture content of the soil as well as some less severe weather conditions. The sites were snowed in shortly after the third plant date. The two spring planting dates were chosen to coincide with the earliest access to the site after snowmelt plus an additional date a couple weeks later. Seedlings were planted on the following dates:

1. September 20, 2005
2. October 4, 2005
3. October 25, 2005
4. May 23, 2006
5. June 7, 2006

3.4.4 Tree shelters

At each planting date, a tree shelter (Tree Pro, West Lafeyette, IN) was installed on half the seedlings and the other half were left uncovered. The tree shelters were light in color (permitting penetration of approximately 34% photosynthetically active radiation), approximately 30 cm in height, ranged from 10-15 cm in diameter, and vented to allow some air movement through the shelter. The stakes were made of oak and approximately 2 cm by 4 cm wide and 40 cm tall with one end sharpened. Stakes were pounded into the ground (~10 cm) until they were even with the top of the shelter and attached with plastic ties. In some cases the ground was very rocky and stakes were not always securely placed in the ground. The shelters cost $0.90 each (cost at time of purchase, 2005), plus an additional $0.05 for the stakes (+S&H). No cost analysis was done on the cost of installing or maintaining shelters and shelters were removed at the end of the first season due to vulnerability of shelters to crushing from snowpack. In June 2006, snow damage on sheltered and non-sheltered seedlings was visually assessed for deformed (flattened shelters or seedlings) or damaged shelters or seedlings that would have otherwise killed or severely decreased growth and vigor of the seedling.

3.4.5 Experimental design

All treatments were replicated at each study site in a randomized complete block design. There were five replications (blocks) on both sites for a total of 10 factorial treatment plots (5 plant date x 2 shelter treatments) per block. Treatments were randomly assigned to each plot. Each treatment plot included 20-25 seedlings planted on a 3m x 3m spacing plus an additional 10 interplanted seedlings for excavation to assess root development. There were a total of 1250 western larch study seedlings and 500 interplanted seedlings planted on the Mt. Adams Lake site and 1237 Douglas-fir study trees and 500 interplanted seedlings planted on the Pileup site.

3.4.6 Data collection

3.4.6.1 Environmental conditions

HOBO microstations (Onset Computer Corporation, Bourne, MA) were installed at each site to monitor environmental conditions throughout the study. The weather stations monitored air temperature (1.1 m from ground), relative humidity, soil temperature (15 cm depth), and soil moisture (10 and 20 cm depth). Precipitation was not measured; instead, SNOTEL (Natural Resources Conservation Service, National Water and Climate Center, Portland Oregon) was used which provided snow water equivalent. Environmental data were collected every 6 hr after installation in August 2005. Data from the stations were downloaded at each plant date and at the time of the final measurements in September 2006.

3.4.6.1.1 Soil moisture

In addition to the HOBO soil moisture probes, two soil samples were collected from each block at each planting date to a depth of 15 cm using a soil core with slide hammer (AMS signature series, American Falls, ID) with a core volume of 101.29 cm^3. Soil samples were placed in plastic baggies and taken to OSU for laboratory determination of percent water in the rooting zone at the time of planting. Soil weight was measured before and after the soil sample was dried in an oven for 48 h at 68°C. Volumetric soil water content was then determined using the following formula:

$$\theta = \frac{(m_{wet} - m_{dry}) / 1}{V_b}$$

Where:

θ = volumetric soil water content,

m_{wet} and m_{dry} are the weight of the sample before and after drying in the oven, and

V_b is the volume of the cylinder.

3.4.6.1.2 Vapor pressure deficit

Using the HOBO data, VPD was calculated using the air temperature (ºC), dew point temperature (ºC), and relative humidity (RH, %) following the procedures of Murray (1967). VPD calculations are as follows:

Where:

VPD (saturation vapor pressure deficit) = $e_s - e_a$ (kPa)

$$e_s \text{ (Saturation vapor pressure)} = \exp \frac{(17.27 * T_{air})}{(T_{air} + 237.3)}$$

$$e_a \text{ (Actual vapor pressure)} = \exp \frac{(17.27 * T_{dew})}{(T_{dew} + 326.7)}$$

$$T_{dew} = 237.3 / \{1/ (\ln(RH/100)/17.27) + (T_{air} / (237.3 + T_{air}) - 1 \}$$

RH = relative humidity (%)

T_{air} = Air temperature (C°)

T_{dew} = Dew point temperature (C°)

3.4.6.2 Seedling field performance

All seedlings were measured in June 2006 just after snow melt and prior to bud break. This resulted in a complete data set of field seedling morphology prior to growth and is the initial morphology used for future growth calculations. In September 2006, seedlings were measured for first-season height and stem diameter and assessed for percent survival in each plot.

A sample of interplanted seedlings (1-4 seedlings depending on survival) in each plot at each site was carefully excavated two weeks after outplanting and again in June 2006 prior to budbreak. All new roots extruding from the plug were counted, removed, and weighed.

3.5 Statistical analyses

SAS® statistical package (SAS Institute, Inc., Cary, NC, USA) was used for analyses of all data. The Generalized Linear Model (proc GLM), regression analysis (proc mixed) procedures were used for most response variables. Covariate analysis was performed on all growth responses and ending heights and diameters, with initial measurements as the covariate.

3.5.1 ANOVA

Field data from each site were analyzed separately by ANOVA under a randomized complete block design, with a plant date by tree shelter treatment factorial (Appendix 5). All data were assessed using the procedures described by Sabin and

Stafford (1990) to determine the need for transformation and to ensure that all assumptions of the models were met. In particular, Shapiro-Wilk and Kolmogorov-Smirnov statistics were used to test normality of residuals and Levene's statistic for testing homogeneity of variance. Survival data were assessed using regression (poisson, and bionomial regression in context of generalized linear models) as well as ANOVA on transformed and untransformed data. In some cases residuals from the ANOVA did not meet the tests for normality. In these cases it was assumed that the means on which inferences were based did approximate a normal distribution as would be predicted from the Central Limit Theorem. Fisher's Protected Least Significant Differences identified differences among plant dates and treatments ($\alpha \leq 0.05$). Initial and final height measurements were determined to be significant covariates on Pileup but not Mt. Adams Lake. On Pileup the differences between initial height and final height were small with little influence from plant dates and treatments so the significance is expected. For Mt. Adams Lake all height measurements were not significant therefore they can not be interpreted as significant covariates even though the analysis shows significance.

3.6 Results

3.6.1 Seedling condition at time of outplanting

Initial seedling height and stem diameter, did not differ among plant dates or shelter treatments for either species (Data not shown).

3.6.2 Environmental Conditions

3.6.2.1 Mt. Adams Lake

Soil moisture (as measured by the moisture probe) was 1-3% during the September and October planting dates (Figure 3.1b) and 9-19% using the soil core method (Figure 3.1c). Differences between the two soil moisture measurement methods are attributed to the HOBO's inability to distinguish among soil types; however, relative differences over time are clearly evident. There was little difference between 10 and 20 cm soil depth from September to November 2005 and August to September 2006. From November to August 2005-06, however, soil moisture at 20 cm was 20-40% greater than at the 10 cm depth. Soil moisture peaked in May at the time of the spring plant dates but decreased rapidly by July.

Both soil and air temperatures (Figures 3.1a and 3.2a) decreased from September (first plant date) to October (third plant date). During the first two weeks after the first plant date, high air temperatures were between 11°C and 13°C. By the third plant date air temperature dropped below 2°C where it remained until May 2006. Soil temperatures during the first and second plant dates were between 6°C and 10°C. Soil temperature dropped below 5°C (critical root growth temperature) five days following the third plant date and remained below that until a week before the May plant date. Between October and May, snowpack covered the sensors and temperatures remained relatively constant, within 2°C of freezing. Following snowmelt in May there was a rapid increase in soil and air temperatures, with a peak in July. Average daily RH (Figure 3.2b) increased from fall to winter when it was

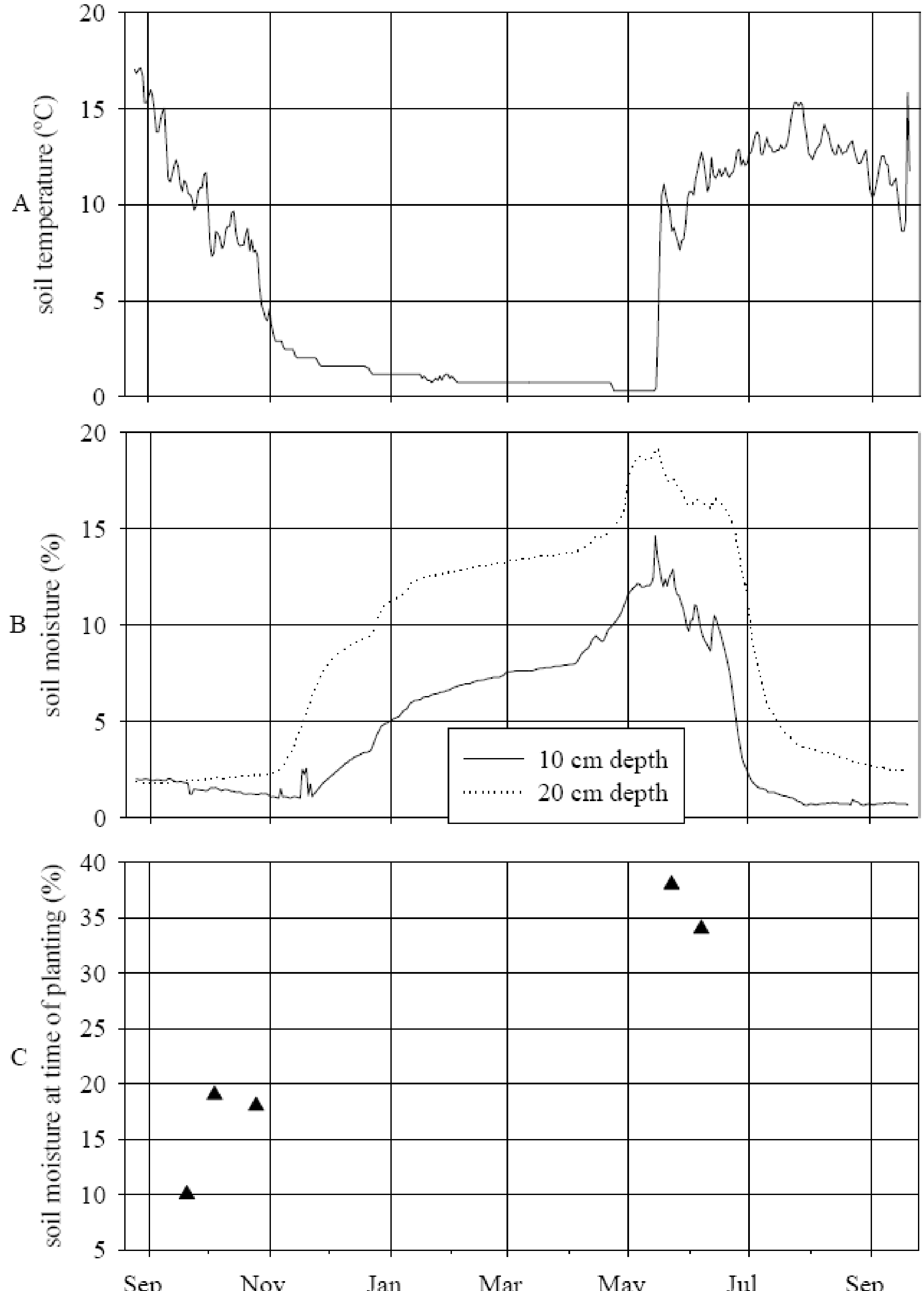

Figure 3.1 Average daily environmental conditions for Mt. Adams Lake from August 18 2005 to September 23 2006. (A) soil temperature (B) soil moisture (10 and 20 cm depth) (C) soil core water content on each plant date

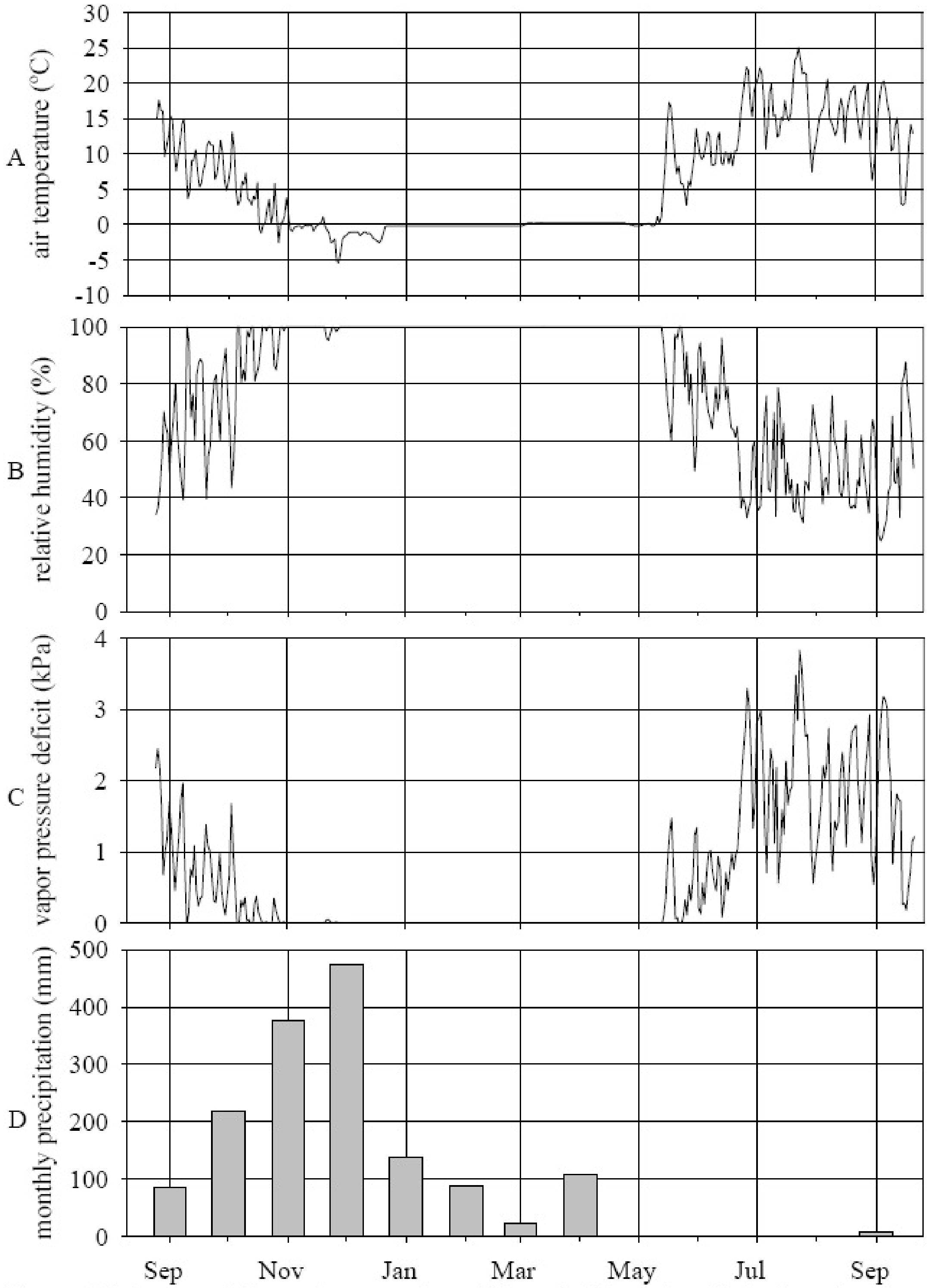

Figure 3.2 Average daily environmental conditions for Mt. Adams Lake from August 18 2005 to September 23 2006. (A) air temperature (B) relative humidity (C) vapor pressure deficit (D) monthly precipitation (data from SNOTEL)

covered by snowpack and remained at near 100% until the snowpack melted in May then slowly decreased until June. On the first plant date, RH was 39% and remained below 60% for the next two days compared to the third planting date when RH was above 80% where it remained for the next five months. Average daily VPD (Figure 3.2c) was near zero in the winter and increased in variability in the spring, summer, and fall. VPD on the first plant date was highest at 1.3 compared to 1.0 and 0.3 on October 4 and 25 plant dates. On the first plant date, VPD remained above 1.0 for the following 3 days. Precipitation (Figure 3.2d) predominantly fell as snowfall from October 29th (four days after the third planting date) to the first part of May when the snow melted (9 days before the fourth plant date).

3.6.2.2 Pileup

Average daily soil moisture content (as measured by the HOBO sensor) ranged from 0-3% during the fall plant dates and 20-22% for the spring plant dates (Figure 3.3b). Soil moisture remained low in the fall until a rain event on October 30 that occurred; 40, 26, and 5 days after the three plant dates respectively. Variation between the two depths (10 and 20 cm depth) was minimal except from January to July when the 20 cm depth was 2-3% higher. Volumetric soil water content, as determined by the soil core method, at the time of planting ranged from 11-12% in the fall and 20-26% in the spring (Figure 3.3c).

Both soil and air temperature (Figures 3.3b and 3.4a) decreased from September (first plant date) to October (third plant date) then increased from May

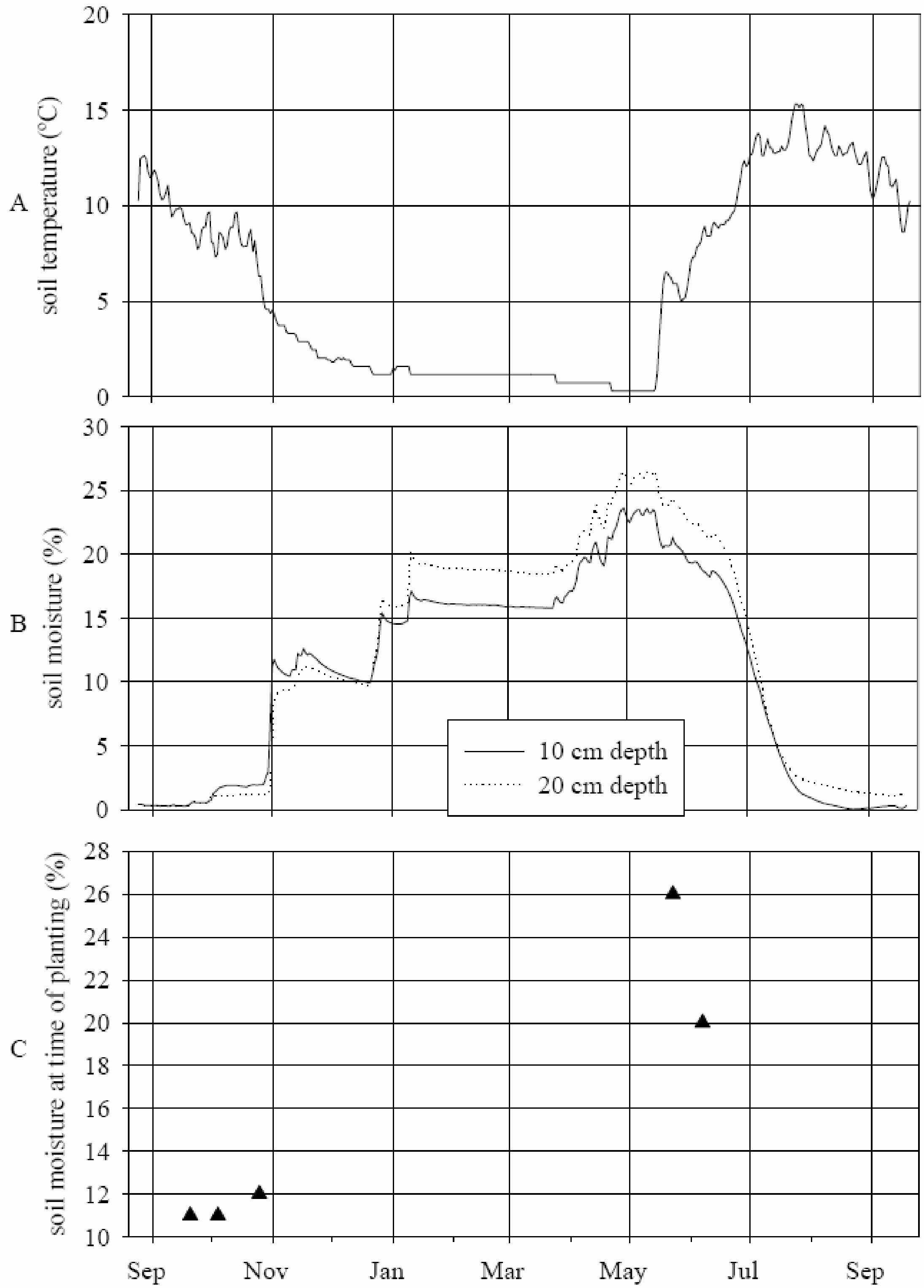

Figure 3.3 Average daily environmental conditions for Pileup from August 18 2005 to September 23 2006. (A) soil temperature (B) soil moisture (10 and 20 cm depth) (C) soil core water content on each plant date

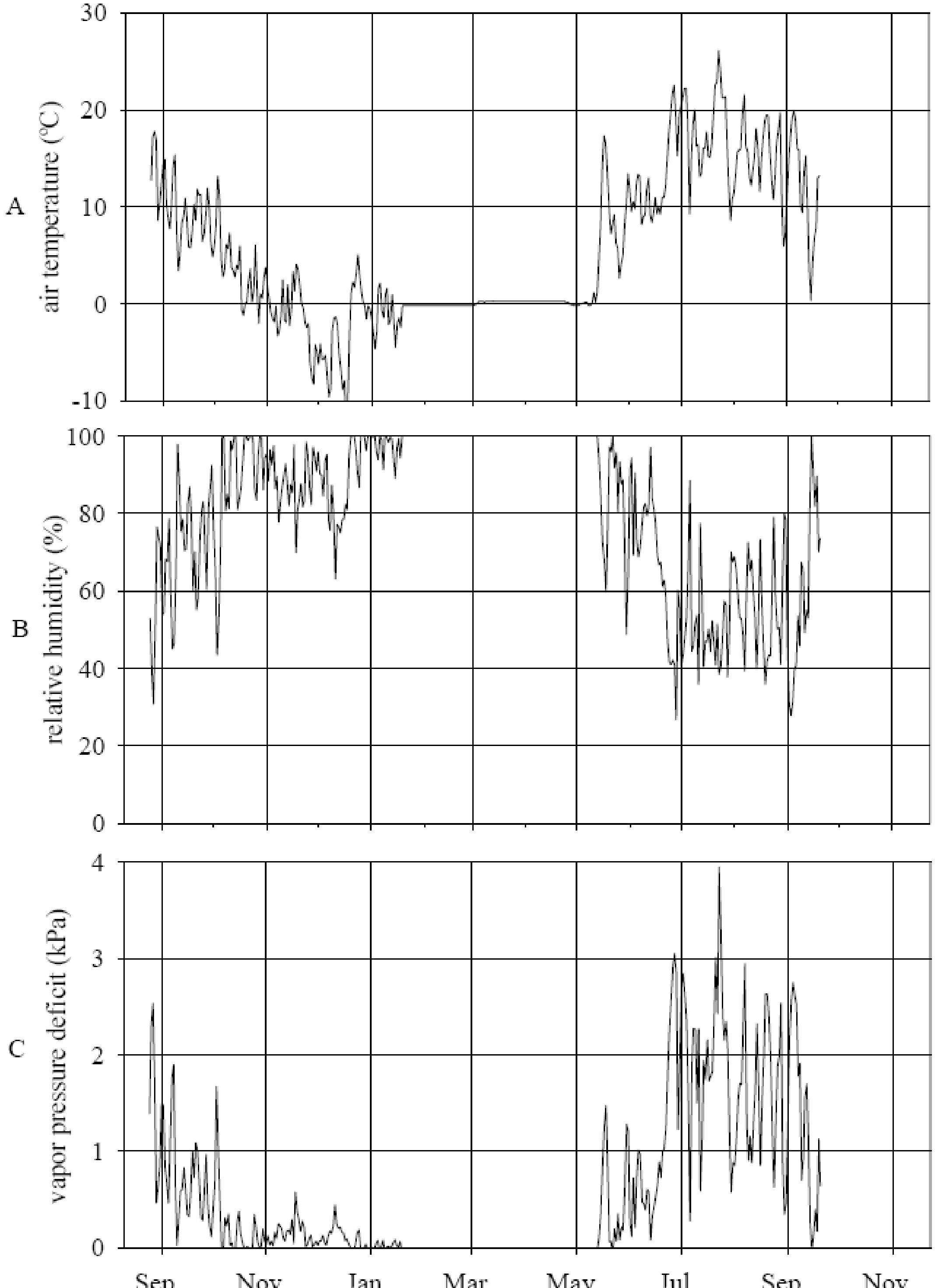

Figure 3.4 Average daily environmental conditions for Pileup from August 18 2005 to September 23 2006. (A) air temperature (B) relative humidity (C) vapor pressure deficit

(fourth plant date) to June (fifth plant date). Air temperature remained above 10°C for the three days following the first plant date but remained below 5°C for 7 months after the two October plant dates. Soil temperature dropped below 5°C (critical root growth temperature) three days after the third plant date and remained below that until 6 days before the May plant date. The air temperature sensor on this site was above the snow pack for a long period of time as seen by the variable winter temperatures compared to the other site. Average daily RH (Figure 3.4b) varied considerably from day-to-day but followed seasonal trends reaching near 100% in the winter under the snowpack. RH remained above 80% for all three plant dates with the exception of two days following the second plant date (maintained above 50%) and three days before and the day of the third plant date (maintained above 50%). Average daily VPD (Figure 3.4c) was 0.7, 1.0, and 0.3 for the first three plant dates respectively, peaking the day before the second plant date at 1.7. After the third plant date VPD remained low until the middle of May. For the fourth plant date VPD was still low (0.2) but slowly increased to the fifth plant date (1.0). VPD increased two weeks after the fifth plant date peaking on July 23 2006, two months after the fourth plant date. Precipitation predominantly fell in the winter as snow (Figure 3.2d).

3.6.3 Seedling Field Performance

3.6.3.1 Mt. Adams Lake (western larch)

Height and stem diameter growth were not significantly affected by plant dates or tree shelters (Table 3.1). Survival, however, was significantly influenced by both

Table 3.1 Field performance of seedlings planted on Mt. Adams Lake (WL). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n=mean of 25 trees per plot per rep with five reps

	height (cm)			stem diameter (mm)		survival (%)		snow damage (%)
Plant date	initial	growth '06	total	growth '06	total	June	1st season	after winter 2005
Sept. 20	20.31 a	7.03 a	27.20 a	0.88 a	4.17 a	91 b	54 a	20 b
Oct. 4	22.08 a	8.47 a	30.56 a	1.15 a	4.67 a	97 a	68 a	26 a
Oct. 25	19.82 a	9.80 a	29.61 a	0.97 a	4.50 a	98 a	74 a	32 a
May 23	21.99 a	8.78 a	30.77 a	1.20 a	4.38 a	100 a	59 a	n/a
June 7	22.24 a	7.45 a	29.69 a	1.03 a	4.08 a	99 a	51 a	n/a
Tree shelter								
without	20.48 a	7.84 a	28.26 a	1.05 a	4.33 a	95 b	53 b	3 a
with	22.10 a	8.77 a	30.87 a	1.04 a	4.39 a	99 a	69 a	28 b

Table 3.2 Field performance of seedlings planted on Pileup (DF). Within a column, means followed by the same letter are not significantly different at $p<0.05$. n=mean of 25 trees per plot per rep with five reps

	height (cm)			stem diameter (mm)		survival (%)		snow damage (%)
Plant date	initial	growth '06	total	growth '06	total	June	1st season	after winter 2005
Sept. 20	26.04 a	3.13 a	29.16 b	1.01 a	3.80 a	9 c	2 c	0 b
Oct. 4	28.19 a	5.58 a	33.77 a	0.83 a	4.35 a	99 a	53 a	13 a
Oct. 25	24.76 a	4.33 a	29.09 b	0.87 a	4.24 a	89 ab	50 a	13 a
May 23	28.50 a	5.06 a	33.56 a	1.07 a	4.10 a	88 b	16 b	n/a
June 7	26.96 a	4.60 a	31.56 ab	0.76 a	4.03 a	86 b	14 bc	n/a
Tree shelter								
without	26.89 a	4.13 a	31.0 a	0.88 a	3.99 a	70 b	23 b	3 a
with	26.89 a	4.94 a	31.8 a	0.94 a	4.22 a	79 a	31 a	7 a

factors. Seedlings with tree shelters had significantly higher survival (69%) than those without tree shelters (53%). Seedlings planted on the first plant date (September 20) had lower survival in June (prior to budbreak) compared to those planted on the other four dates (Table 3.1), though this difference was not evident at the end of the growing season. Snow pack damage to seedlings in the tree shelters was significantly higher (28% damaged) than unsheltered seedlings (Table 3.1).

3.6.3.2 Pileup (Douglas-fir)

Height and stem diameter growth were not affected by plant date or tree shelter although total height for those planted on October 4 and May 23 was tallest (Table 3.2). In June, seedlings with tree shelters had 9% greater survival than those without tree shelters and those planted on October 4 had significantly greater survival than all other dates (except May 23, Table 3.2). After one growing season, survival was 2% for seedlings planted on the first plant date. Those planted on the October dates had greater survival (51%) than the spring plant dates (15%). Seedlings within tree shelters had 8% greater survival after the first season than those without tree shelters (Table 3.2). Snow pack damage to seedlings within tree shelters was 7% compared to 3% in the unsheltered plots but this difference was not statistically significant between the two treatments (Table 3.2).

3.7 Discussion

3.7.1 Effect of tree shelter treatment

The use of tree shelters influenced survival but not growth. Survival was 69 and 53% for sheltered and non-sheltered western larch seedlings, respectively and 31 and 23% for sheltered and non-sheltered Douglas-fir seedlings, respectively (Tables 3.1 and 3.2). Similarly, Jacobs and Steinbeck (2001) reported that light colored (16-24% available PAR) tree shelters increased survival of Engelmann spruce seedlings by 37-41% compared to those without shelters, and also increased height growth and total stem diameter after two years. The same study, 6 years later, reported that unsheltered control seedlings still had lower survival (45%) compared to sheltered seedlings (≥88%, Jacobs 2004). In addition, sheltered seedlings had significantly greater height growth (approximately 7.5 cm more) and the lightest shelter (24% available PAR) had more diameter growth (>1mm) than the unsheltered control regardless of whether the shelters were removed or not after the fourth year (Jacobs 2004). In this study, height and stem diameter were not significantly different for seedlings with tree shelters vs. without (Table 3.1 and 3.2). Burger et al. (1996) found that 2 of 10 tree species outplanted with shelters (122 cm tall, tan Tubex® shelter), had a significant height growth response when compared to non-sheltered controls. Minter et al (1992) reported that sheltered (90-120 cm tall, 8-12 cm diameter shelters; 120 cm were square, 90 cm shape not given) northern red oak seedlings had increased height growth after 3 years but shelters no significant effect on survival.

In the current study, the microclimate effect of shelters may have resulted in increased relative humidity and reduced light levels thereby lowering the evaporative demand and increasing survival of sheltered seedlings compared to the unsheltered controls. Minter et al (1992) reported an increase in carbon dioxide concentration and relative humidity within tree shelters but found no difference in air temperature when compared to unsheltered controls. Carbon dioxide can increase growth in tree shelters (Mayhead and Jones 1991, Peterson et al 1994, Frearson and Weiss 1987, Potter 1988, Swistock et al. 1999). Research shows that levels of carbon dioxide were higher in partially buried shelters and that the level of carbon dioxide decreased from groundline to the top of the shelter (Frearson and Weiss 1987, Mayhead and Jones 1991).The vented shelters used in this study may have resulted in ambient levels of CO_2 and therefore minimized any effect on growth. The vents, however, may have also minimized harmful increases in air temperature. In a study on ventilated versus unventilated shelters, Swistock et al (1999) reported that ventilation consistently reduced inside shelter temperatures by about 2.7ºC. Peterson et al. (1994) reported that height growth of red oak and Norway maple (*Acer platanoides* L.) was greater for seedlings with shelters that did not contain vents compared to seedlings with vented shelters. The use of ventilated shelters in the current study may not have increased growth but a reduction of temperature may have contributed to increased survival. The nonsignificant growth characteristics could also be a function of the severe site and climatic conditions. In harsh climates, growth is secondary to survival. This is evidenced by the average first season height growth being only 4.5 cm for Douglas-fir and 8.3 cm for western larch.

The initial cost of tree shelters is high and is increased even more by the yearly maintenance cost due to high potential for snowpack to crush shelters, as was found in this study. When shelters crush seedlings, they can cause stem damage and deformation which may lead to undesirable stem traits and increased mortality if shelters are not fixed or replaced. In this study, shelters were removed at the end of the season to minimize maintenance costs associated with yearly inspection and correction. Similar studies have reported that shelter removal (after 4 years) had no effect on survival due to acclimation to site environment (Jacobs 2004), while other studies indicate that rigid shelters cause mechanically unstable seedlings (reduced diameter for a given height) that are incapable of standing alone after shelter removal (Burger et al. 1996). Since the shelters were removed after only one growing season and height growth was small, the potential for seedlings to fall over was minimal.

3.7.2 Effect of plant date

Plant date had a significant effect on both total height and survival for Douglas-fir seedlings after one growing season as well as early survival (June 2006) for western larch seedlings. Douglas-fir seedlings planted on October 4 were taller after one growing season than those planted on the other dates. Barber (1989) showed that total height of western larch containerized seedlings was 43% greater for seedlings planted in the fall compared to spring. Unlike the current study sites, environmental conditions in the Barber study (1989) were very favorable with deep, well drained soils derived from weathered basalt instead of shallow volcanic ash as well as soil moisture to a depth of 20-25 cm from fall precipitation (actual amount not measured). Adams et al. (1991) reported that Douglas-fir seedlings planted in mid-August were significantly taller, had larger stem diameters, longer roots and greater total dry weight than seedlings planted from September to November but found few and inconsistent results for western larch seedlings. In the same study, August-planted seedlings had adequate soil moisture due to irrigation to field capacity before planting and high late-summer soil temperatures ideal for prompt root growth and early establishment; but, as the planting season progressed the favorable environmental conditions decreased and limited new growth.

For Douglas-fir seedlings planted on the first three dates, soil moisture stayed constant around 11% but survival varied from 2% on the first planting date to above 50% on the second and third. The generally low survival regardless of plant date can be attributed to the harshness of this site and low water holding capacity of the volcanic ash. The difference between these planting dates may be attributed to the length of time the seedlings planted on the first date were exposed to low soil water content and desiccation. Shortly after the third planting date, soil moisture increased rapidly to above 20% as precipitation increased which likely resulted in greater survival for seedlings planted in October. South and Barnett (1986) reported that survival of loblolly pine (*Pinus taeda* L.) dropped to 22% when soil moisture averaged 5% but when soil moisture increased to 13%, survival increased to over 90%. The low moisture contents in this study and the above study show that soil moisture at the time of planting and shortly after planting are important to seedling survival. Sinclair and Boyd (1973) reported that average first-year survival of Douglas-fir seedlings was greater for spring-planted seedlings as compared to fall-planted seedlings (80 and 60% respectively); soil moisture was 10 to 20% higher in the spring than in the fall. In the present study, all seedlings in this study were lifted and stored at the same time. This long-term storage, without being frozen (2°C), may have interfered with seedling quality for Douglas-fir spring-planting dates (Cannel et al. 1990, Dierauf 1989, Ericsson et al. 1983).

On the western larch site, soil moisture increased shortly after the first plant date from 10 to 19%. Unlike the Douglas-fir site, survival was over 50% for those that were planted on the first plant date. Sinclair and Boyd (1973) found that western larch survival fluctuated during a three-year study but, like the current study, had a similar average between fall- and spring-planted seedlings (34 and 37% respectively). They recommended planting western larch after October 15 to improve survival. The present study supports this conclusion in part since early survival (June 2006) for seedlings planted on September 20 was significantly lower compared to the other planting dates, though this difference disappeared by the end of the growing season.

3.8 Conclusion and recommendations

For establishment of Douglas-fir and western larch seedlings on high elevation sites on the eastern slopes of the Cascades in Washington, the use of tree shelters may increase survival but is unlikely to have an effect on growth. In general, seedlings planted in October had the greatest survival on both sites compared to seedlings planted earlier in the fall or later in spring. The use of tree shelters increased survival of both Douglas-fir and western larch seedlings planted across five dates by 9% and 17%, respectively, but had no statistically detectable impact growth of either species. The increase in survival may be worth the added expense of tree shelters since the cost of replanting can be high. It may also be applicable for small-scale plantings, when seed is scarce, and for high-value seedlots. However, keeping tree shelters in place after the 1st growing season may increase the potential for physical injury from snow damage. The use of vented shelters on harsh sites may help regulate temperatures within the shelters, but added growth benefits of increased microclimate were beyond the scope of this study.

Soil moisture at the time of planting and the length of time seedlings remained in the ground before soil water recharged by precipitation had a profound effect on survival of both species. When volumetric water content was above 15%, then fall-planted western larch seedlings had similar survival to spring-planted seedlings. However, planting Douglas-fir in early fall may not be advised on harsh sites due poor drought tolerance. Fall planting carries more risk than spring planting since a prolonged drought period following planting can adversely affect seedlings. The planting environment of harsh high elevation sites is extremely variable in the fall, but if adequate moisture is available, fall planting may prove to be a viable alternative, especially if persistent snow packs limit access to sites for spring planting. Given that this study covered only one season, further research over multiple years and their variable environmental conditions is needed before making broad inferences about the use of tree shelters or the optimum planting dates. However, the results of this study show that there are potential benefits from fall planting with respect to increased survival on harsh sites.

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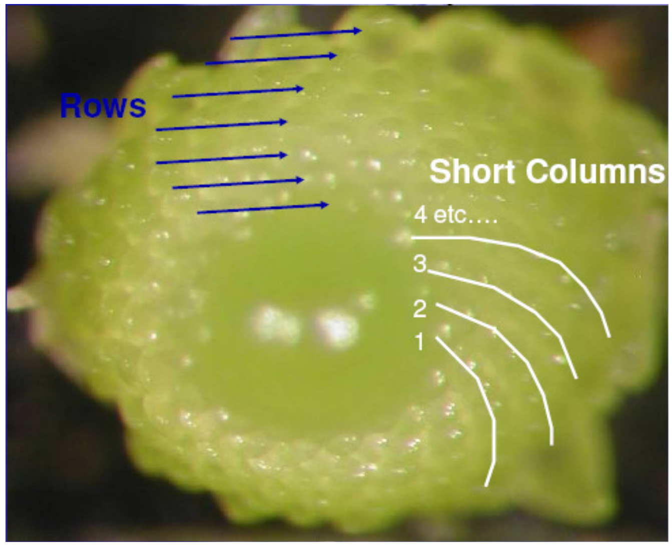
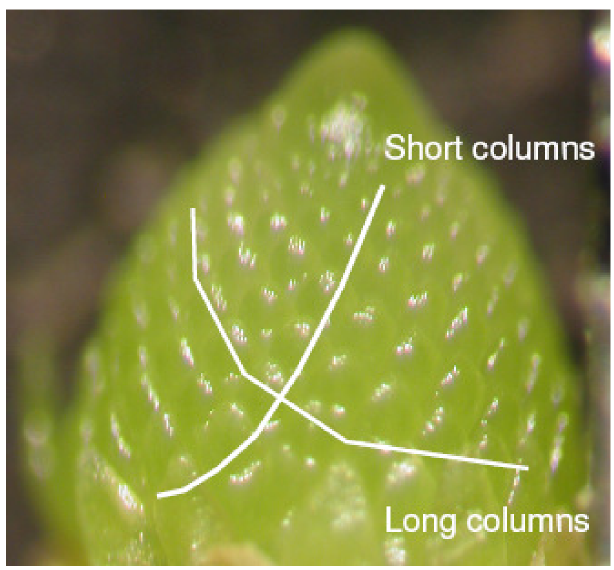
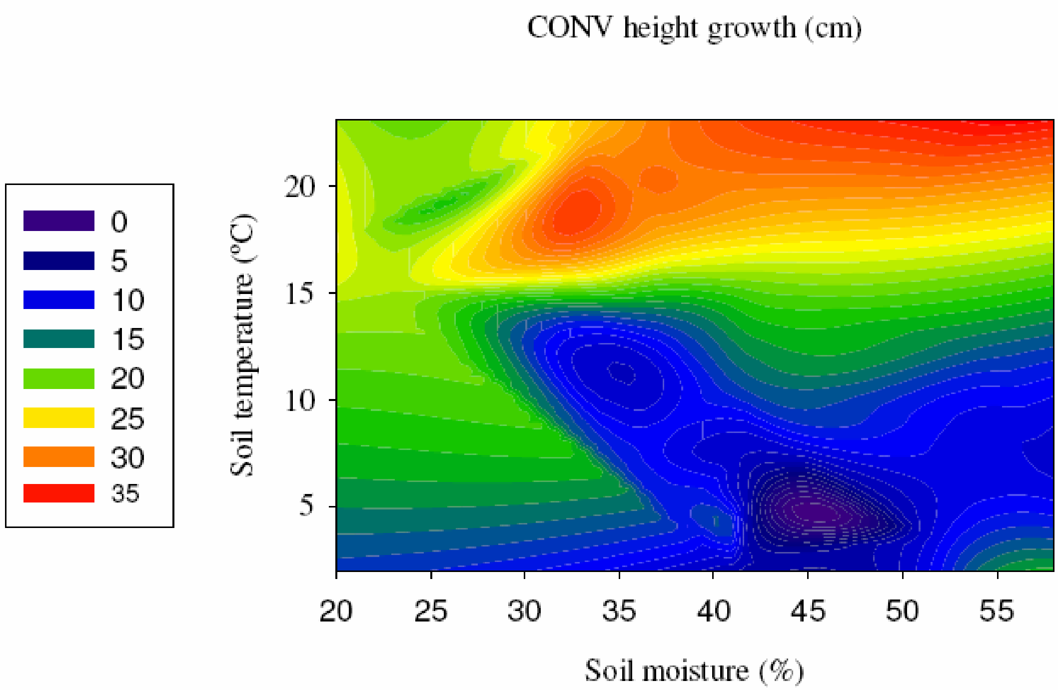
APPENDICES

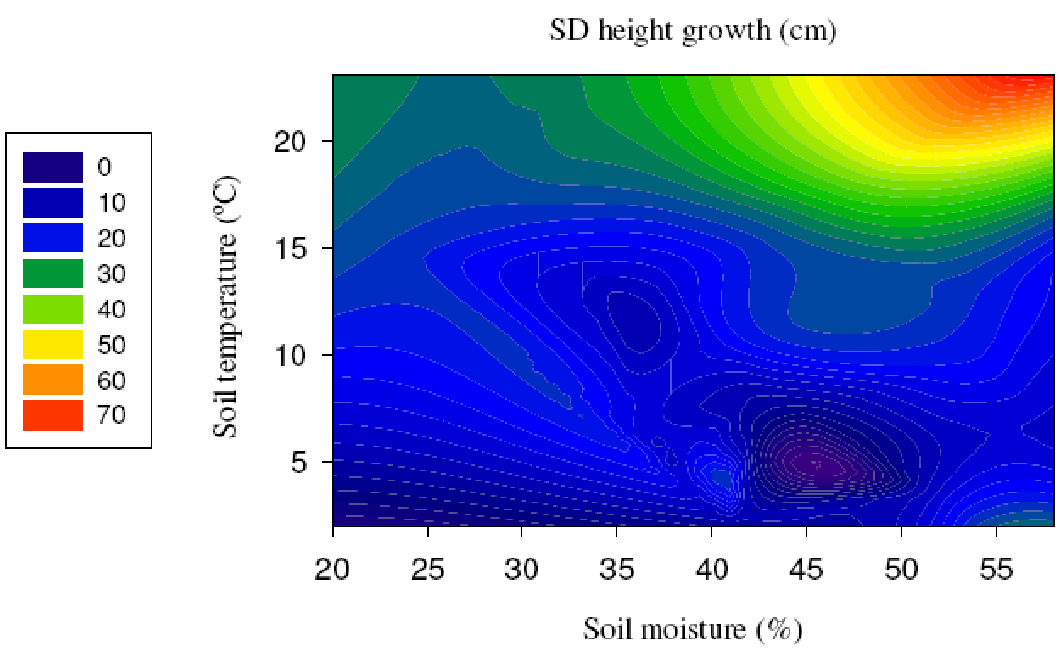




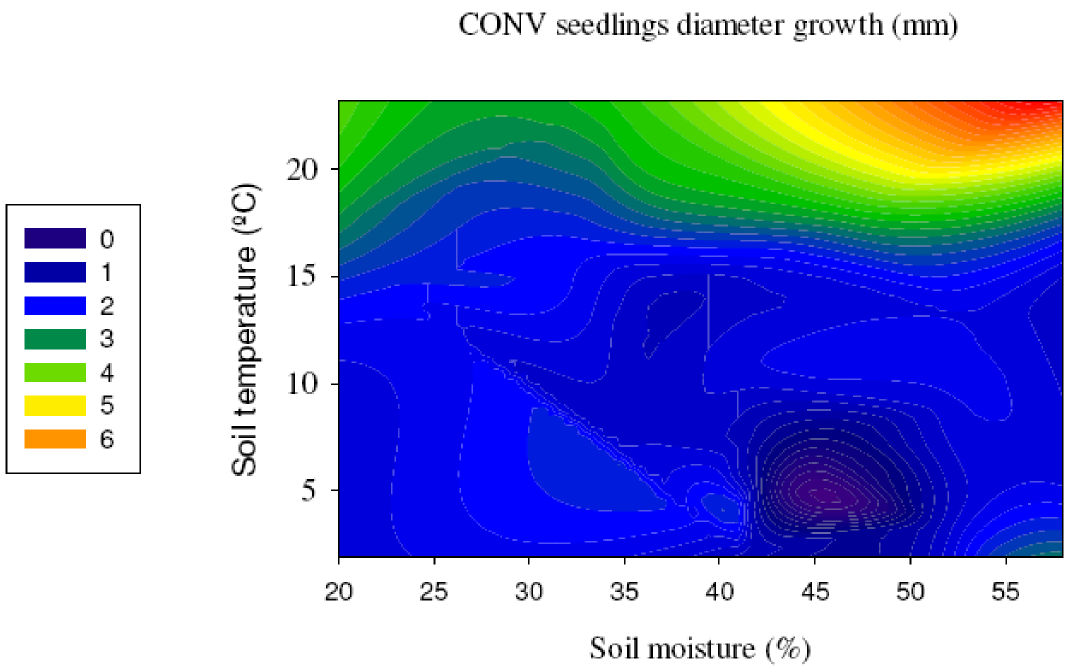
Appendix 1: Counting needle primordia.

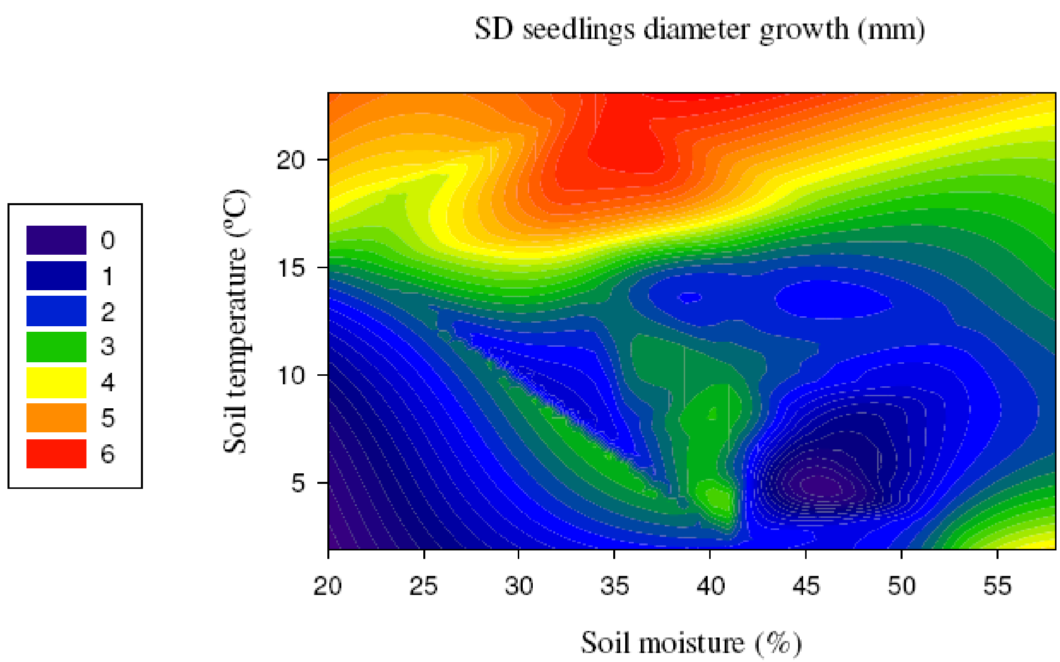
Once the bud has been dissected the number of rows, columns, and an estimate of the total number of primordia can be estimated. When viewing from the top there will be two spirals of primordia descending from the apex towards the base in opposite directions. Count the number of short columns (refer below for better description of short versus long rows) then multiply that number times the number of rows within one short column. The product of those two numbers provides a rough estimate of the total count.



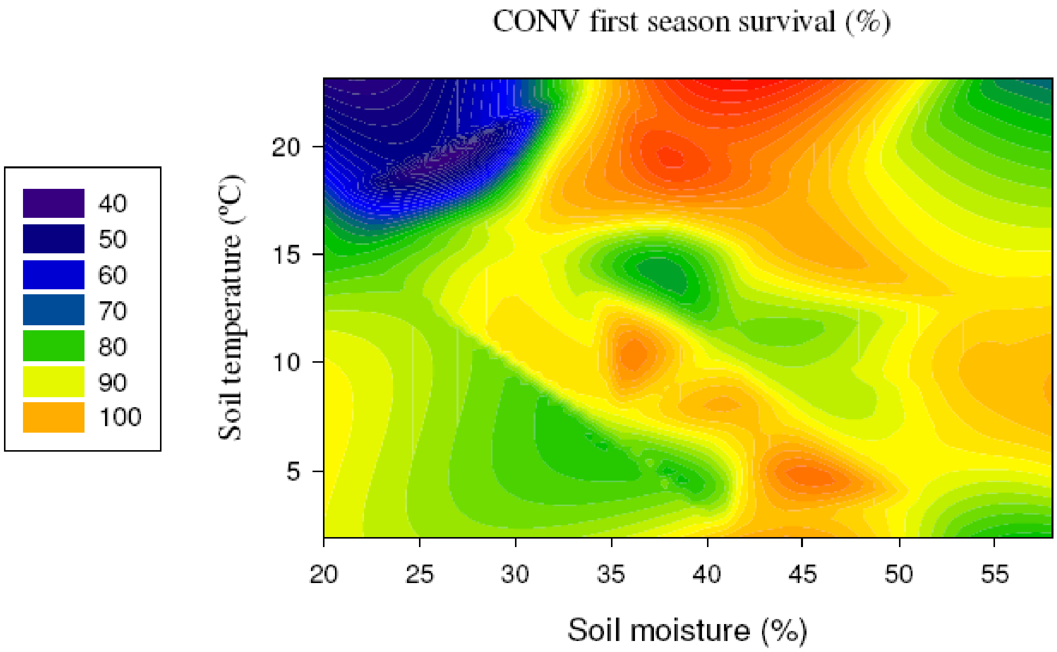


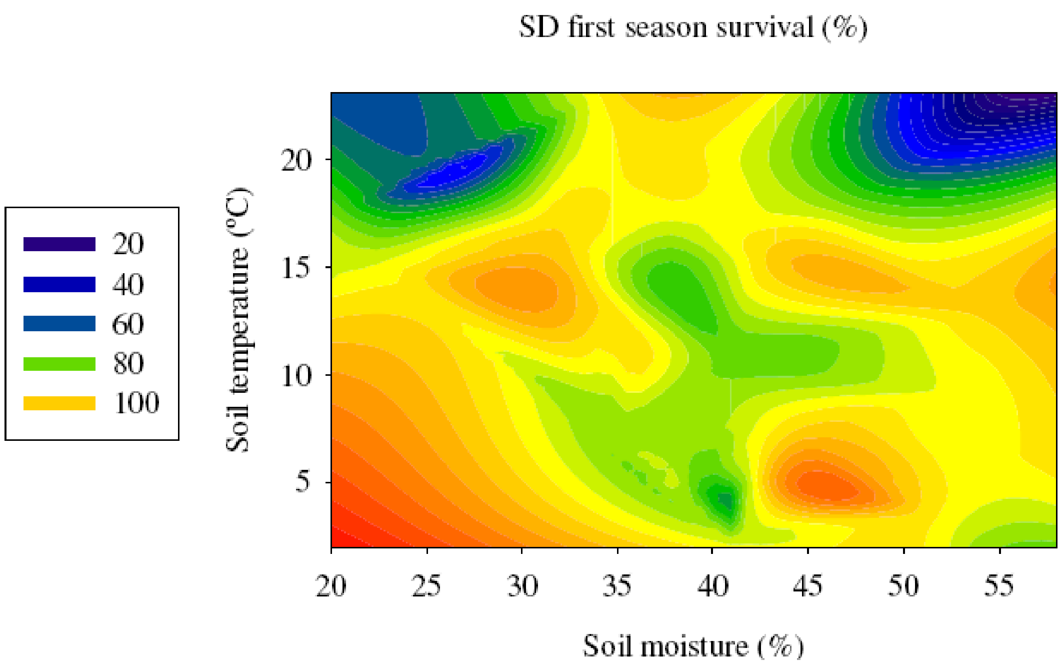
Appendix 2: Modeling environment versus height growth
Height growth by treatment modeled versus soil moisture and soil temperature at the time of planting combined plant date.





Appendix 3: Modeling environment versus stem diameter growth
Stem diameter growth by treatment modeled versus soil moisture and soil temperature at the time of planting with combined plant date.





Appendix 4: Modeling environment versus survival
First season survival by treatment modeled versus soil moisture and soil temperature at the time of planting with combined plant date.

Appendix 5: ANOVA tables

P. Guppy	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
Three week	height	blk	4	17.8249	4.4562	0.74	0.5675
		plant	7	412.3717	58.9102	9.80	0.0001
		treatment	1	976.7210	976.7120	162.52	0.0001
		plant*treatment	7	227.8493	32.5699	5.42	0.0001
	diameter	blk	4	1.5570	0.3893	4.49	0.0031
		plant	7	14.2852	2.0407	23.54	0.0001
		treatment	1	0.0240	0.0240	0.28	0.6006
		plant*treatment	7	1.4498	0.2064	2.38	0.0323
April	survival	blk	4	0.1133	0.0283	2.10	0.0913
		plant	7	1.1120	0.1589	11.80	0.0001
		treatment	1	0.0331	0.0331	2.46	0.1220
		plant*treatment	7	0.0555	0.0079	0.59	0.7621
	xylem water potential	plant	7	908.3333	454.1667	72.59	0.0001
		treatment	1	3.2813	1.0938	0.17	0.9120
		plant*treatment	7	1.2604	1.2604	0.20	0.6592
1st season	height	blk	4	905.1182	226.2795	8.32	0.0001
		plant	7	916.6453	130.9493	4.81	0.0002
		treatment	1	1928.7836	1928.7836	70.91	0.0001
		plant*treatment	7	226.0232	32.2890	1.19	0.3239

P. Guppy	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
1st season	diameter	blk	4	37.9119	9.4780	12.51	0.0001
		plant	7	36.9220	5.2746	6.96	0.0001
		treatment	1	28.1685	28.1648	37.18	0.0001
		plant*treatment	7	2.5430	0.3633	0.48	0.8457
	survival	blk	4	0.5361	0.1340	5.66	0.0006
		plant	7	1.0118	0.1445	6.10	0.0001
		treatment	1	0.0028	0.0028	0.12	0.7337
		plant*treatment	7	0.1722	0.0246	1.04	0.4145
1st season	height growth	blk	4	891.8122	222.9530	8.17	0.0001
		plant	7	1517.7820	216.8260	7.95	0.0001
		treatment	1	153.5719	153.5719	5.63	0.0209
		plant*treatment	7	123.3927	17.6275	0.65	0.7162
	diameter growth	blk	4	41.6618	10.4155	12.82	0.0001
		plant	7	62.3629	8.9090	10.97	0.0001
		treatment	1	26.6210	26.6210	32.78	0.0001
		plant*treatment	7	4.7478	0.6783	0.84	0.5626
	height	blk	4	665.7336	166.4334	2.64	0.0442
1st season excavated		plant	7	1207.6523	172.5218	2.73	0.0171
		treatment	1	2116.7261	2116.7261	33.54	0.0001
		plant*treatment	7	1055.5324	150.7903	2.39	0.0338

P. Guppy	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
	diameter	blk	4	61.6598	15.4149	3.92	0.0074
1st season excavated		plant	7	59.2070	8.4581	2.15	0.0541
		treatment	1	31.9734	31.9734	8.13	0.0062
		plant*treatment	7	26.9054	3.8436	0.98	0.4573
	root volume	blk	4	6013.4152	1503.3538	7.43	0.0001
		plant	7	2532.5424	361.7918	1.79	0.1096
		treatment	1	1870.4003	1870.4003	9.24	0.0037
		plant*treatment	7	995.0733	142.1533	0.70	0.6698
	shoot volume	blk	4	13200.3670	3300.0918	5.81	0.0006
		plant	7	17327.9401	2475.4200	4.36	0.0007
		treatment	1	11440.3001	11440.3001	20.15	0.0001
		plant*treatment	7	5793.6833	827.6690	1.46	0.2031
	shoot:root ratio	blk	4	4.8836	1.2209	6.81	0.0002
		plant	7	3.2241	0.4606	2.57	0.0237
		treatment	1	0.6727	0.6727	3.75	0.0581
		plant*treatment	7	1.8390	0.2627	1.47	0.2001

P. Guppy	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
covariate analysis 1st season	height vs week three height	week three height	1	24.6332	24.6332	0.90	0.3455
		blk	4	899.6564	224.9141	8.26	0.0001
		plant	7	938.8613	134.1230	4.92	0.0002
		treatment	1	344.6129	344.6129	12.65	0.0007
		plant*treatment	7	135.0373	19.2910	0.71	0.6652
covariate analysis 1st season	diameter vs week three diameter	week three diameter	1	0.2136	0.2136	0.28	0.5996
		blk	4	37.9386	9.4846	12.37	0.0001
		plant	7	35.3975	5.0568	6.59	0.0001
		treatment	1	27.7081	27.7081	36.13	0.0001
		plant*treatment	7	2.7557	0.3937	0.51	0.8209

S. Red Fir	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
Three week	height	blk	4	8.9289	2.2322	0.76	0.5552
		plant	7	1216.0741	173.7249	59.18	0.0001
		treatment	1	5.9422	5.9422	2.02	0.1600
		plant*treatment	7	396.5214	56.6459	19.30	0.0001
	diameter	blk	4	0.0266	0.0066	0.09	0.9865
		plant	7	12.1861	1.7409	22.46	0.0001
		treatment	1	1.6106	1.6106	20.78	0.0001
		plant*treatment	7	1.0423	0.1489	1.92	0.0817
April	survival	blk	4	0.0009	0.0002	0.63	0.6410
		plant	7	0.0030	0.0004	1.15	0.3471
		treatment	1	0.0006	0.0006	1.60	0.2106
		plant*treatment	7	0.0023	0.0003	0.89	0.5218
	xylem water potential	plant	7	217.6458	108.8229	80.54	0.0001
		treatment	1	5.1146	1.7049	1.26	0.3189
		plant*treatment	7	5.5104	5.5104	4.08	0.0595
1st season	height	blk	4	486.8270	121.7067	6.59	0.0002
		plant	7	1960.9014	280.1288	15.17	<.0001
		treatment	1	51.5162	51.5162	2.79	0.1001
		plant*treatment	7	387.5594	55.3656	3.00	0.0091

S. Red Fir	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
1st season	diameter	blk	4	20.7445	5.1861	6.59	0.0002
		plant	7	147.5482	21.0783	26.77	0.0001
		treatment	1	0.8081	0.8081	1.03	0.3151
		plant*treatment	7	6.7471	0.9639	1.22	0.3039
	survival	blk	4	0.0269	0.0067	0.94	0.4466
		plant	7	0.0150	0.0021	0.30	0.9515
		treatment	1	0.0040	0.0040	0.55	0.4596
		plant*treatment	7	0.0926	0.0132	1.85	0.0937
1st season	height growth	blk	4	376.8423	94.2106	6.42	0.0002
		plant	7	4902.6967	700.3852	47.71	0.0001
		treatment	1	22.4086	22.4086	1.53	0.2214
		plant*treatment	7	150.0689	21.4384	1.46	0.1988
	diameter growth	blk	4	19.1194	4.7798	5.51	0.0008
		plant	7	197.7697	28.2528	32.56	0.0001
		treatment	1	0.1607	0.1607	0.19	0.6685
		plant*treatment	7	5.6452	0.8065	0.93	0.4907
	height	blk	4	111.6979	37.2326	0.76	0.5209
1st season excavated		plant	7	2485.2431	355.0347	7.27	0.0001
		treatment	1	72.9601	72.9601	1.49	0.2278
		plant*treatment	7	366.9288	52.4184	1.07	0.3956

S. Red Fir	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
	diameter	blk	4	10.7373	3.5791	1.40	0.2565
1st season excavated		plant	7	242.0973	34.5853	13.48	0.0001
		treatment	1	0.4249	0.4249	0.17	0.6859
		plant*treatment	7	19.3283	2.7612	1.08	0.3940
	root volume	blk	4	588.7257	196.2419	0.69	0.5624
		plant	7	9201.7639	1314.5377	4.63	0.0006
		treatment	1	1415.6406	1415.6406	4.98	0.0306
		plant*treatment	7	1597.9983	228.2855	0.80	0.5886
	shoot volume	blk	4	2095.3073	698.4358	0.91	0.4461
		plant	7	77975.2691	11139.3242	14.44	0.0001
		treatment	1	1139.0625	1139.0625	1.48	0.2307
		plant*treatment	7	7134.0556	1019.1508	1.32	0.2627
	shoot:root ratio	blk	4	1.3756	0.4585	2.53	0.0689
		plant	7	8.5918	1.2274	6.78	0.0001
		treatment	1	0.2440	0.2440	1.35	0.2518
		plant*treatment	7	0.5732	0.0819	0.45	0.8635

S. Red Fir	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
covariate analysis 1st season	height vs week three height	week three height	1	24.6332	24.6332	0.90	0.3455
		blk	4	899.6564	224.9141	8.26	0.0001
		plant	7	938.8613	134.1230	4.92	0.0002
		treatment	1	344.6129	344.6129	12.65	0.0007
		plant*treatment	7	135.0373	19.2910	0.71	0.6652
covariate analysis 1st season	diameter vs week three diameter	week three diameter	1	0.2136	0.2136	0.28	0.5996
		blk	4	37.9386	9.4846	12.37	0.0001
		plant	7	35.3975	5.0568	6.59	0.0001
		treatment	1	27.7081	27.7081	36.13	0.0001
		plant*treatment	7	2.7557	0.3937	0.51	0.8209

S. Comfort	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
Three week	height	blk	4	23.1403	7.7134	1.38	0.2619
		plant	7	312.5304	44.6472	7.97	0.0001
		treatment	1	1008.1800	1008.1800	180.01	0.0001
		plant*treatment	7	195.1575	27.8796	4.98	0.0003
	diameter	blk	4	0.0391	0.0130	0.09	0.9676
		plant	7	5.8425	0.8346	5.48	0.0001
		treatment	1	0.1139	0.1139	0.75	0.3919
		plant*treatment	7	0.3501	0.0500	0.33	0.9371
April	survival	blk	4	0.0004	0.0001	0.48	0.6962
		plant	7	0.0134	0.0019	6.74	0.0001
		treatment	1	0.0004	0.0004	1.57	0.2166
		plant*treatment	7	0.0088	0.0013	4.41	0.0008
	xylem water potential	plant	7	53.0625	26.5313	14.88	0.0002
		treatment	1	2.9479	0.9826	0.55	0.6541
		plant*treatment	7	7.5938	7.5938	4.26	0.0546
1st season	height	blk	4	36.0988	12.0329	0.55	0.6494
		plant	7	1878.3759	268.3394	12.31	0.0001
		treatment	1	2213.6304	2213.6304	101.57	0.0001
		plant*treatment	7	354.1626	50.5947	2.32	0.0413

S. Comfort	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
	diameter	blk	4	5.7310	1.9103	2.36	0.0838
		plant	7	69.1572	9.8796	12.22	0.0001
		treatment	1	28.8736	28.8736	35.71	0.0001
		plant*treatment	7	14.7568	2.1081	2.61	0.0239
	survival	blk	4	0.0451	0.0150	2.48	0.0730
		plant	7	0.0558	0.0080	1.32	0.2651
		treatment	1	0.0217	0.0217	3.58	0.0649
		plant*treatment	7	0.0628	0.0090	1.48	0.1980
	height growth	blk	4	3.2731	1.0910	0.07	0.9766
		plant	7	3057.0826	436.7261	27.25	0.0001
		treatment	1	254.1662	254.1662	15.86	0.0002
		plant*treatment	7	207.9276	29.7039	1.85	0.1003
	diameter growth	blk	4	6.1158	2.0386	2.27	0.0927
		plant	7	59.2657	8.4665	9.45	0.0001
		treatment	1	25.4135	25.4135	28.36	0.0001
		plant*treatment	7	12.2982	1.7569	1.96	0.0820
	height	blk	4	197.3063	65.7688	0.95	0.4261
1st season excavated		plant	7	1596.3223	228.0460	3.29	0.0072
		treatment	1	1472.0637	1472.0637	21.23	0.0001
		plant*treatment	7	728.1147	104.0164	1.50	0.1944

S. Comfort	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
	diameter	blk	4	5.4332	1.8111	0.62	0.6044
		plant	7	225.1373	32.1625	11.06	0.0001
		treatment	1	51.9696	51.9696	17.87	0.0001
		plant*treatment	7	7.3822	1.0546	0.36	0.9186
	root volume	blk	4	1894.9370	631.6457	5.68	0.0024
		plant	7	4768.3515	681.1931	6.12	0.0001
		treatment	1	739.8634	739.8634	6.65	0.0136
		plant*treatment	7	1167.5322	166.7903	1.50	0.1947
	shoot volume	blk	4	4668.8572	1556.2857	1.84	0.1555
		plant	7	37612.3094	5373.1871	6.34	0.0001
		treatment	1	11191.8794	11191.8794	13.21	0.0008
		plant*treatment	7	3382.9214	483.2745	0.57	0.7755
	shoot:root ratio	blk	4	1.7924	0.5975	2.05	0.1224
		plant	7	6.4501	0.9214	3.16	0.0092
		treatment	1	2.8205	2.8205	9.66	0.0034
		plant*treatment	7	2.0063	0.2866	0.98	0.4578

S. Comfort	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
covariate analysis 1st season	height vs week three height	week three height	1	24.6332	24.6332	0.90	0.3455
		blk	4	899.6564	224.9141	8.26	0.0001
		plant	7	938.8613	134.1230	4.92	0.0002
		treatment	1	344.6129	344.6129	12.65	0.0007
		plant*treatment	7	135.0373	19.2910	0.71	0.6652
covariate analysis 1st season	diameter vs week three diameter	week three diameter	1	0.2136	0.2136	0.28	0.5996
		blk	4	37.9386	9.4846	12.37	0.0001
		plant	7	35.3975	5.0568	6.59	0.0001
		treatment	1	27.7081	27.7081	36.13	0.0001
		plant*treatment	7	2.7557	0.3937	0.51	0.8209

Stocktype	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
515	Root growth potential	rep	4	0.4832	0.1208	1.68	0.1654
		plant	7	17.3825	2.4832	34.63	0.0001
		treatment	1	1.5374	1.5374	21.44	0.0001
		plant*treatment	7	3.4356	0.4908	6.84	0.0001
	Needle primordia	rep	9	26.6813	2.9646	2.17	0.0276
		plant	7	1448.7938	206.9705	151.67	0.0001
		treatment	1	124.2563	124.2563	91.06	0.0001
		plant*treatment	7	153.7938	21.9705	16.10	0.0001
615	Root growth potential	rep	4	0.3270	0.0818	1.36	0.2592
		plant	7	12.9898	1.8557	30.83	0.0001
		treatment	1	0.4675	0.4675	7.77	0.0071
		plant*treatment	7	1.9997	0.2857	4.75	0.0003
	Needle primordia	rep	9	19.2250	2.1361	1.29	0.2455
		plant	7	1427.2000	203.8857	123.55	0.0001
		treatment	1	72.9000	72.9000	44.18	0.0001
		plant*treatment	7	59.5000	8.5000	5.15	0.0001

Mt. Adams Lake	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
Three week	*height	blk	4	14.9798	3.7449	0.89	0.4816
		plant	4	51.6409	12.9102	3.06	0.0288
		treatment	1	32.7800	32.7800	7.76	0.0085
		plant*treatment	4	7.9616	1.9904	0.47	0.7563
June	survival	blk	4	0.0164	0.0041	2.76	0.0424
		plant	4	0.0456	0.0114	7.68	0.0001
		treatment	1	0.0232	0.0232	15.59	0.0004
		plant*treatment	4	0.0149	0.0037	2.51	0.0588
1st season	*height	blk	4	57.9247	14.4812	1.37	0.2640
		plant	4	80.5321	20.1330	1.90	0.1311
		treatment	1	85.1089	85.1089	8.04	0.0074
		plant*treatment	4	11.2208	2.8052	0.27	0.8984
	*diameter	blk	4	2.7356	0.6839	2.95	0.0330
		plant	4	2.2817	0.5704	2.46	0.0626
		treatment	1	0.0531	0.0531	0.23	0.6349
		plant*treatment	4	0.1720	0.0430	0.19	0.9444
	survival	blk	4	1.5888	0.3972	9.53	0.0001
		plant	4	0.3643	0.0911	2.19	0.0902
		treatment	1	0.3407	0.3407	8.18	0.0070
		plant*treatment	4	0.3765	0.0941	2.26	0.0818

* Model was not significant, ANOVA shown for descriptive purposes only

Mt. Adams Lake	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
	*height growth	blk	4	31.8428	7.9607	1.51	0.2202
		plant	4	48.3696	12.0924	2.29	0.0784
		treatment	1	10.9448	10.9448	2.07	0.1584
		plant*treatment	4	19.6284	4.9071	0.93	0.4574
	*diameter growth	blk	4	1.6960	0.4240	1.98	0.1180
		plant	4	0.6925	0.1731	0.81	0.5274
		treatment	1	0.0020	0.0020	0.01	0.9232
		plant*treatment	4	0.5449	0.1362	0.64	0.6395
	snow damage	blk	4	0.0212	0.0053	0.74	0.5734
		plant	4	0.8663	0.2166	30.02	0.0001
		treatment	1	0.7517	0.7517	104.18	0.0001
		plant*treatment	4	0.5396	0.1349	18.70	0.0001
**covariate analysis 1st season	height	week three height	1	190.1274	190.1274	34.89	0.0001
	vs week three height	blk	4	28.8130	7.2033	1.32	0.2811
		plant	4	53.9116	13.4779	2.47	0.0623
		treatment	1	6.5515	6.5515	1.20	0.2804
		plant*treatment	4	24.8936	6.2234	1.14	0.3529

* Model was not significant, ANOVA shown for descriptive purposes only

** height was not significant therfore is not a significant covariate

Pileup	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
Three week	height	blk	4	14.7895	3.6974	1.13	0.3638
		plant	4	89.2314	22.3078	6.82	0.0007
		treatment	1	0.0005	0.0005	0.00	0.9899
		plant*treatment	4	39.4874	9.8719	3.02	0.0360
June	survival	blk	4	0.0908	0.0227	1.95	0.1246
		plant	4	5.3752	1.3438	115.50	0.0001
		treatment	1	0.0920	0.0920	7.91	0.0081
		plant*treatment	4	0.0717	0.0179	1.54	0.2127
1st season	height	blk	4	31.2009	7.8002	1.14	0.3599
		plant	4	160.7807	40.1952	5.87	0.0017
		treatment	1	4.6530	4.6530	0.68	0.4171
		plant*treatment	4	18.7887	4.6972	0.69	0.6079
	*diameter	blk	4	0.6489	0.1622	1.24	0.3167
		plant	4	0.8846	0.2212	1.70	0.1810
		treatment	1	0.3916	0.3916	3.00	0.0949
		plant*treatment	4	0.9246	0.2312	1.77	0.1645
	survival	blk	4	0.2496	0.0624	3.20	0.0246
		plant	4	2.0865	0.5216	26.77	0.0001
		treatment	1	0.0886	0.0886	4.55	0.0403
		plant*treatment	4	0.0787	0.0197	1.01	0.4163

* Model was not significant, ANOVA shown for descriptive purposes only

Pileup	Parameter	Source	DF	Type III SS	Mean square	F value	pr>F
	height growth	blk	4	26.6516	6.6629	2.84	0.0443
		plant	4	16.1507	4.0377	1.72	0.1751
		treatment	1	4.5534	4.5534	1.94	0.1751
		plant*treatment	4	20.3272	5.0818	2.17	0.1007
	*diameter growth	blk	4	0.4668	0.1167	0.41	0.8009
		plant	4	0.4942	0.1235	0.43	0.7840
		treatment	1	0.0250	0.0250	0.09	0.7696
		plant*treatment	4	0.2134	0.0534	0.19	0.9432
	snow damage	blk	4	0.0435	0.0109	2.76	0.0436
		plant	4	0.2157	0.0539	13.67	0.0001
		treatment	1	0.0149	0.0149	3.77	0.0606
		plant*treatment	4	0.0275	0.0069	1.74	0.1640
covariate analysis 1st season	height vs week three height	week three height	1	120.0423	120.0423	51.82	0.0001
		blk	4	28.4775	7.1194	3.07	0.0345
		plant	4	8.2020	2.0505	0.89	0.4871
		treatment	1	4.5347	4.5347	1.96	0.1740
		plant*treatment	4	23.1771	5.7943	2.50	0.0680

* Model was not significant, ANOVA shown for descriptive purposes only