The Growth Of Styroblock, Chemical And Mechanical Root Pruned Lodgepole Pine Seedlings In Interior British Columbia

Dev Khurana

B.Sc. University of Northern B.C., 2001

Thesis Submitted In Partial Fulfilment Of

The Requirements For the Degree Of

Masters of Science

In

Natural Resources And Environmental Studies

(Forestry)

The University Of Northern British Columbia

April 2007

Library and Archives
Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-60834-0
Our file Notre référence
ISBN: 978-0-494-60834-0

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

1. Introduction

In northern coniferous forests of British Columbia (BC) where clear cut harvesting is commonly practiced, natural regeneration proves inadequate to meet Free-to-Grow stocking guidelines due to the unpredictably long duration of re-establishment (Eastham and Jull, 1999). Foresters, therefore, make use of preferred species of nursery-grown containerized seedlings to re-stock cut blocks, to ensure spacing uniformity and timely growth of preferred species (Delong et al., 1997, Wright et al., 1998).

While planted nursery stocks come in various sizes, all are, to some degree, root-bound by the containers in which they are grown (Balisky et al., 1995). Once planted, rooting patterns have shown to be inferior from naturally germinated seedlings (Halter et al., 1993). In an attempt to improve container deficiencies, root-pruning methods have been recommended (Wenny et al., 1988; Winter and Low, 1990; Krasowski and Owens, 2000; Jones et al., 2002; Rune, 2003). Since the long-term success of a planted tree is strongly determined by its ability to establish a well-developed root system (Eis, 1978), this research has focused on evaluating the early rooting establishment in planted lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) - BC's most commonly planted species (B.C. MOF, 2005).

Evaluation of root development in planted seedlings needs careful attention, which considers the tremendous efforts and costs, involved. Root growth is influenced by three main factors: the inherent attributes of the microsite (soil and site conditions), the nursery effect of the stock type, and planting technique. In this thesis, considering that root development is critical to seedling establishment and growth, the hypothesis being tested, is that root pruning a containerized seedling improves its rooting development compared to the conventional non-pruned containerized Styroblock stock (PSB). We compared various types of root pruning including several mechanically knife-pruned methods (RP) as well as chemical root-pruning (PCT). Root growth parameters were measured and analysed after 21 days from a nursery bed and after one field-growing season on two contrasting soil conditions.

1.1. Objectives

The primary objective of the thesis was to compare one-year growth parameters of lodgepole pine seedlings planted as conventional Styroblock stock type (PSB) with conventional chemical treatment (PCT) and several mechanical (or knife) root pruning (RP) treatments. The response of seedlings to different pruning treatments was assessed in two contrasting site conditions at Red Rock and Aleza Lake sites.

2. Review of Literature

2.1. Reforestation and the Artificial Plantation

The trend in scale of reforestation has dropped over the recent years from 253 million seedlings planted in the 1994-95 period (Barlette, 1996), 232 million in the 1997-98 period, to 170 million in the 2004-05 period (BC MOF, 1996). However, it may again be on the rise with the increases in rate of harvest as a result of salvaging from the pine bark beetle epidemic. In the 2005-2006 year period, 197,600 ha were cut. While harvesting method has remained stable at about 90% clear-cutting over the last decade (the remainder being selection harvest systems), the size of the cuts has dropped since the late 1980's from an average of 45.5 ha to 26.6 ha (Barlette, 1996; Gov. of BC, 2000).

With objectives of sustainability, reforestation standards exist as Free-to-Grow stocking guidelines to ensure that harvested areas meet density targets for regeneration, with a minimum height requirement within a set timeline and be relatively free of vegetative competition. Foresters comply with the Free-To-Grow legislation requirements after clear-cutting using artificially planted nursery stock. This provides the greatest management control of regeneration at predictable densities of preferred species in a timely fashion. Once a plantation meets the standards of Free–To-Grow by successfully reaching its growth requirements, foresters are removed of any further liability securing a fixed allowable cut without penalties from non-sufficiently stocked back-log of previously harvested areas. Thus legislation and economics has created a ubiquitous management strategy in BC that has streamlined forests for clear-cut harvesting methods with artificially planted regeneration.

In order to ensure plantation success, foresters manage with broad based silviculture treatments at the resolution of the site unit that are several hectares in scale. Some of the generalized silviculture activities that are carried out on these site units include: site preparation, chemical brushing and herbicide, manual brushing, fertilization, pruning and spacing (BC MOF, 2005). The cost of reforestation is a big driver for the BC economy. A yearly cost of $150 million is spent in efforts to cover costs of reforestation (Gov. of BC, 1990).

Relying on natural regeneration with clear-cutting as a harvesting method poses a risk in achieving regeneration guidelines. Natural regeneration is arguably unreliable because of a limited availability in seed-bed substrates mostly the result of winter harvesting. Also, there has been a great reduction in the use of prescribed fires (Barlette, 1996). Additionally clear-cutting methods reduce the availability of seed of preferred species (Eastham and Jull, 1999).

Over the last quarter century, the BC landscape has seen an alteration of a great portion of our mature forest into a mosaic of disturbance patches of uniform size, shape, height, and species. In this way BC forest resources are scheduled to achieve sustainable timber as forecasted in the Timber Supply Analysis (B.C. MOF, 1996). Certainly the current regeneration regulations are hardly ecologically based. Uniformity of even density plantations does not mimic the natural regenerating progression of disturbed stands nor do they mimic any natural disturbance type. As such there is minimal variation to the reforestation management strategy regardless of the forest ecosystem or disturbance regime (BC MOF, 1998). Of the 183 million seedlings planted in the 2005/06 period, most commonly planted species were 9% Douglas fir (*Pseudotsuga* *menziesii* var *glauca)*, 30% hybrid spruce (*Picea glauca* Voss. *x engelmanii* Perry) and 48% lodgepole pine. (*Pinus contorta* Dougl. var. *latifolia* Engelm.) (BC MOF, 2005). About, 96% of the seedlings planted are of containerized stock type, the remaining 4% being that of a bareroot type (BC MOF, 1998).

2.2. Natural Seedling Root Development

Roots act to anchor and support the tree, for storage of energy reserves such as carbohydrate, and an instrument to sequester available soil water and nutrients (Kozlowski, 1997). Initially root development is influenced by genetic control and by environmental conditions in which the seedling is grown (Horton, 1958; Eis, 1978). Genetics control the radical (primordial root) to develop from the germinated seed. This primordial root establishes vertically as cells divide longitudinally in the root cap. The root penetrates downward and a tap-root is developed. The first branches are primary lateral roots that emerge progressively down the tap from the root collar at the soil surface. Like the tap-root, primary lateral roots develop with rapid rates of growth and longer durations of meristematic activity (Puhe, 2003). Primary lateral roots structurally anchor the tree to the soil and serve as conduits of nutrient transfer from finer 'feeding' roots proliferating extensively in the soil environment. Secondary roots may also emerge from the tap and primary laterals. These are smaller in diameter than primary roots and non-structural.

As roots enlarge with growth rings, termed secondary growth, the pattern of the structural root system becomes established. Root growth is described as compensatory, that is, roots grow rates differ according to soil condition (Kozlowski, 1997; Krasowski et al., 1999). For example, enhanced root growth is commonly found in areas where soil structure, temperature, bulk density, root penetration, nutrients, and moisture provide a favourable environment for growth (Sutton, 1980). However, the development mechanisms of a natural mature root system have yet to be fully understood. Main structural roots of a root system likely develop in the early stages of tree development (Martisson, 1986); yet, trees have the capacity to change over its lifetime with death and replacement (Preston, 1942). In northern forests of central BC where soils are cool and humid, root development is more intensified near the soil surface. This includes roots of all sizes ranging from structural roots to small mycorrhizal feeder roots (Preston, 1942; Heineman et al., 1999; Puhe, 2003). Surface soils tend to be warmer, more aerobic, less dense, and more enriched with nutrients than sub-surface horizons (Eis, 1978). Essentially, the root system grows expansively as well as prolifically to encompass sufficient soil volumes to endure the variability of climate as well as out-compete others within the stand. In all species, root systems of dominant trees have consistently better-developed root systems with more branches, more symmetry and greater root to shoot ratio than root systems of other trees (Eis, 1978).

Among species, root morphology varies due to genetic differences. Within a species, root systems vary mostly due to soil environmental conditions giving rise to characteristic root systems that are predisposed to a certain range of soil conditions (Eis, 1978; Strong and Roi, 1983). Rooting development strategy varies across a large range of soil edaphic conditions as in the case for lodgepole pine (*Pinus contorta Dougl. var. latifolia Engelm.*) In well-drained soil conditions, lodgepole pine is often tap-rooted usually displaying a whorl containing 3 to 11 primary lateral roots (Eis, 1978; Horton, 1958). Alternatively, but less frequently, a heart root system develops in the absence of a taproot, where primary roots develops sinkers roots oriented vertically to form a characteristic heart shape root system (Fig. 2.1). In poorly drained and compact soils, a supporting tap root system is abandoned for a shallow spreading root plate system (Horton, 1958; USDA, 1990). Strong and Roi (1983), in their study of root development of Jack pine in boreal environments, observed the ratio of biomass allocation of lateral structural roots to vertical tap roots to be 0.60 and 0.95 for well and poorly drained sites, respectively. The behaviour of natural rooting systems has been well studied and serves as the standard to which planting stock types are compared (Halter et al., 1993, Preisig et al., 1979).

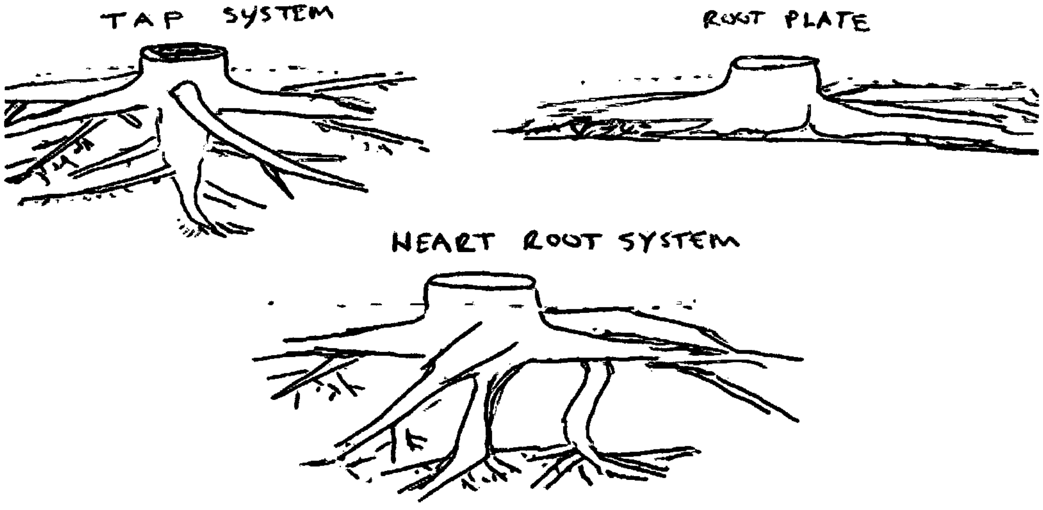


Figure 2.1. Characteristic forms of root systems in northern conifer species.

2.3 Achieving a Quality Planted Seedling

Nursery-grown seedlings must remain vigorous through the process of transportation, handling and planting in order to achieve high success of survival. Nursery production of seedling root systems must be free from deformities to allow the development of primary coarse structural roots characteristic of its species. Planting method must avoid developmental deformities. While the plug must remain snug, planting method should not compact the soil or rooted plug either vertically or horizontally. Primary lateral roots must be able to develop symmetrically to capitalize on available soil volumes and maintain the stems stability.

To increase survival rate of planted seedlings, forest management activities should not impede the existing productive capacity of the site. To provide optimum growth, harvesting practices and site preparation treatments should avoid degrading the productive capacity of site. For economic and commercial reasons, a planted tree should be established with low economic investment and should exist with minimum impact to the ecology of natural forest system. A planted tree should not replace existing healthy preferred or acceptable naturally regenerated seedlings. Reduction of existing healthy preferred residual trees with harvesting and site preparation should be avoided.

2.4 Evolution of the planted seedling: the Styroblock - PSB.

Early tree plantations were reforested with bareroot stock that were established in nursery beds and with roots mechanically pruned to restrict the extent of root growth in favour of a bushier root system. After one or to two years in field beds at the nursery, bareroot stocks were excavated, packaged into boxes, and transported to the site for plantation. With mechanization in the late 1970's, seedlings switched to being grown in green houses on trays of varying sized seedling containers filled with peat and vermiculite. Container grown seedlings achieve greater economic efficiency, with greater product reliability in increased quantities with little differences to growth performances of bareroot stocks (Becker et al., 1987; Burdette et al., 1984).

Today, in BC and in the rest of Canada, seedlings are almost universally container grown (Barlette, 1996) and are commonly referred to as Styroblock seedlings. Their rooting pattern has been well characterized by Balisky et al. (1995). Plug Styrofoam Block (PSB) seedling is grown in styrofoam trays with ribbed dimensional cavities. The cost of PSB seedlings varies with size of the growth cavity or the number of seedlings in a given tray. The walls of the container limit and bind root development in the cavity over their first growing season. Vertical ribs were introduced to the containers to reduce the incidence of root spiral, a deformity caused when primary lateral root preferentially grow horizontally in intertwining spirals around the container. With ribbed cavities, roots typically deflect downward along the walls of the plug and coalesce at the bottom where they are air pruned at the cavity water drain hole. When lifted from the tray cavity, containerized seedlings are easily handled with its rooted plug neatly amassed and intertwined with branching roots that coalesce at the bottom of the plug.

Salonius et al. (2000) found a rather weak correlation (R^2= 0.50) between initial root density (mg root/ container volume cm^3) in the plug and root growth in a one-year field trial for black spruce. Height growth showed a negative relationship to initial root density (R^2= -0.46) perhaps due to root bind. Initial plug root density was correlated (R^2= 0.90) to its soil to space ratio (the seedling container volume relative to the density per tray). Thus, reduced root bind within the plug as a result of growing seedlings at higher densities can explain almost half of the increased root growth after one year of planting in the field. When planted, seedlings with the lesser-developed root systems grew proportionately more and consequently explored more initial soil volume than seedlings with well-developed root systems. Providing stem height and vigour can be maintained, a threshold of crowding of nursery seedling is considered beneficial to their field rooting performance.

Initial root biomass of containerized seedlings did not reflect the function of root growth in a water conductivity experiment by Krasowski and Caputa (2005). Individuals with increased initial root biomass for a given containerized plug volume neither reliably explained the ability of roots to absorb nor to conduct water. Such evidence helps support the theory that excessive root density plug and associated root bind can reduce the ability of a seedling to maximize its root development when planted in the field.

Results presented at the Symposium on the Root Form of Planted Trees (Van Eerden, 1978) demonstrated that both nursery and planting techniques causes a certain degree of root deformation. The potential for root deformation is species specific. The pine genus has been identified as species more prone to deformation (Van Eerden, 1978; Halter et al. 1993). Containerized PSB roots have been demonstrated to restrict lateral development and radial symmetry due to their initial confinement within the container. Once planted, root egress occurs mostly from a portion of the coalesced roots at the bottom of the plug often in one or two directions (Wenny et al., 1988; Heineman, 1991; Balisky and Burton, 1997; Krasowski and Owens, 2000). Van Eerden (1978) observed that the restriction of lateral root development was higher in lodgepole pine than hybrid spruce or Douglas fir, and that trajectory of its root egress was in the direction of their initial orientation. In later research, Van Eerden (1981) argues that deformed root systems of planted trees can overcome their initial deficiencies and eventually acquire a more normal rooting habit. In the long term, it is possible that the root architecture of a planted seedling may develop adventitiously from the stem (Coutts et al., 1990). However, this phenomenon is species specific, and is strongly observed in certain genera like spruce but not pine.

Indeed the root growth and form of nursery seedlings remain markedly different than those that geminated naturally. Fig. 2.2 demonstrates growth differences between planted and natural stock with the structural roots of the planted tree is different in number, size, and location. Robert (2004) showed comprehensive differences in root morphology between planted juvenile lodgepole pine and naturals. Planted stock showed much greater root deformities than natural germinates. Some roots have the ability to graft to reduce abnormalities such as tangling (Van Eerden, 1981; Halter et al., 1993, Wass and Smith, 1994). Severe root deformities have been shown to impede the translocation of sugars through the phloem (the inner bark) exhibiting growth exaggerations above the constriction described as root balling (Hay and Woods, 1978).

Figure 2.2. Comparison of excavated 3-year old pine seedling near 70 Mile House. Left, natural germinant; Right, PSB 3-13 seedling showing dead needles from previous year's growth due to stresses imposed during establishment.

In favourable microsites, roots of planted trees emerged from the plug in abundance of 50 – 120 roots (Balisky and Burton, 1997). As trees mature, the numbers reduce to 3-10 dominant structural roots (Eis, 1978). Root deformities, caused by abnormal root growth in the container, create impediments and restrictions to growth. Deformities are described as kinks (abrupt changes in direction) and braids (root strangulation causing constrictions in growth of vascular and cork cambium growth). Fig. 2.3, below, shows two cases of 6-year-old pine. The left shows stem curvature and bilateral root symmetry, likely the result of the shovel blade compacting soils in two planes at the time of planting. The right shows a compacted plug as a result of improper planting technique. Note the lack of structural primary roots and also the diameter difference between structural primary roots and secondary roots.

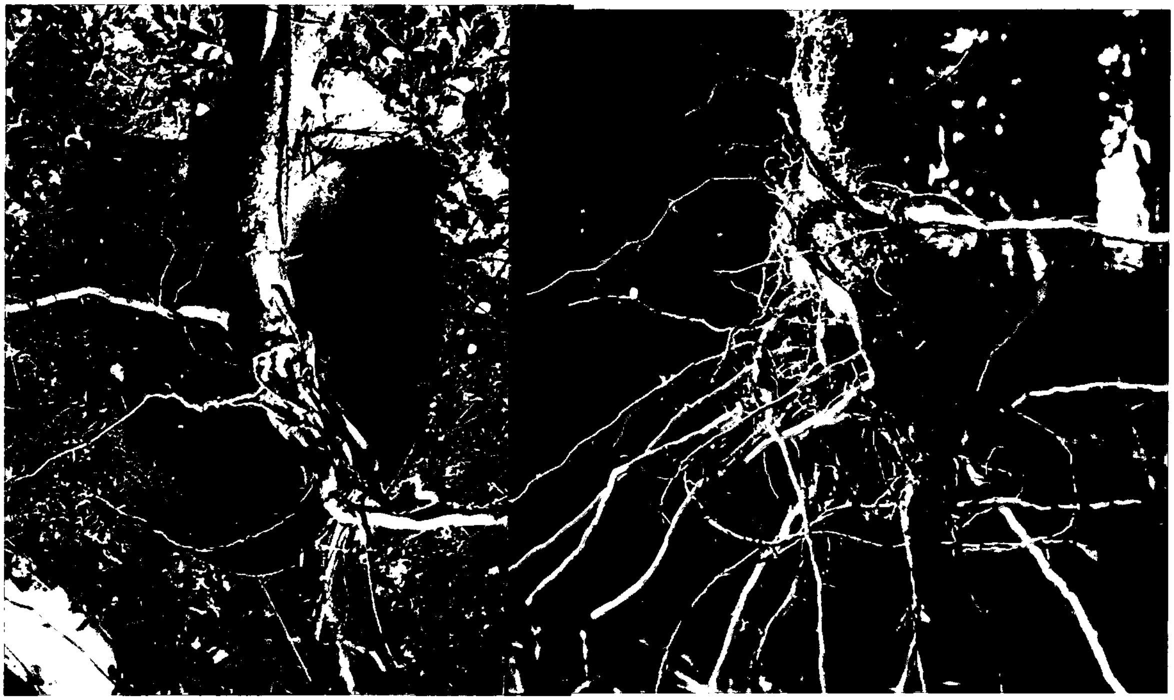


Figure 2.3. Six-year-old Pine seedlings showing poor rooting development – 70 Mile House.

For most studies, observations are limited to short term growth indices such as survival and height growth. Height measurements do not allow for the evaluation of sub-soil root development that may ultimately affect long-term development of the seedling. Reduced numbers of large primary roots, reduced root symmetry, and root deformation may lead to stem deformities such as curvature (eventually leading to compression wood undermining wood quality) (Krasowski, 2003). Studying long-term growth may also address seedling resilience to unfavourable environmental conditions such as stochastic events of wind, snow, and drought.

2.5. Root Pruning as an Alternative

Seedlings are grown in Styroblock (PSB) because of cost efficiency and high success rates of tree establishment. Many advances in handling and processing PSB stocks include several alternatives such as root pruning techniques. Current forms of root pruning include air holes through the sides of the container called air pruned blocks (Rune, 2003), mechanical (knife) pruning as in Vapo technology (Krasowski and Owens, 2000) and chemical root pruning (PCT) where copper oxychloride is painted on the wall of the Styroblock (Jones et al., 2002). The principal aim of root pruning treatment is to retard the growth of lateral primary roots as they approach the walls of the container. This avoids forcing root growth in a downward trajectory and subsequently avoids having roots entangle with each other. Unfortunately, root pruned stocks are less commonly used due to various limitations and lack of short-term enhancement of height growth performance. With air-block stock, growing trays are costly and require high maintenance because of susceptibility to drought and in many cases show higher rates of nursery mortality. PCT stock has slightly higher costs due to the tray's shorter life span and disposal issues associated with the toxic metal paint (Jones et al., 2002).

Results from many studies on the performance of various types of seedlings, showed varied growth improvements. Often measured in the short term, the implications of root pruning are hard to evaluate. Evidence from Burdette et al. (1983), Wenny et al., (1988), Krasowski (2003), Krasowski and Owens (2000), Jones et al. (2002) and Rune (2003) suggest that root pruning increases root development in the upper portions of the rooted plug but the effect of root pruning is not conclusive with respect to height growth or survival. Burdette et al. (1983) reported that when an applied chemical paint was added to the wall of the lodgepole pine container as compared with the non-pruned control, height growth increased in the 4-year measurements.

With mechanical root pruning, a nursery practice used to localize root growth in bare root seedlings, seedlings exhibited adventitiously budded root primordia within the vascular cambium as a physiological response to injuries sustained during pruning (Sutton, 1980). Box pruning, a systematic mechanical root pruning method where roots are repeatedly pruned to reduce the space constriction in a containerized plug, produces a burst of increased growth despite initial low root to shoot ratios for both pine and spruce species (Krasowski and Owen, 2000; Krasowski, 2003). Once knife pruned, cut primary lateral roots develop new large diameter tips. Experiments with repeated mechanical pruning systems such as box pruning showed high total water flux (Krasowski and Owens, 2000), less crooked stems (Krasowski, 2003), and larger initial starch reserves (Edgren, 1975). However, the high cost of repeated mechanical pruning prohibits its general use in the forest industry. A single root pruning of PSB stock may be a compromise to achieve a similar effect.

Presently, a discrepancy exists in the prescribed use of stock types for pine reforestation between licensee tenured blocks and by the BC Timber Sales (BCTS) blocks. Licensees favour PSB stock while BCTS prefers the PCT stock types due to the improvements in root morphology (Bob Merrell, MOF administrator for coastal nurseries, and Mike Theliz, Manager of PRT Nursery, Red Rock, personal communication). Well-developed root system in the long-term may correlate with juvenile height growth, and fits with the vision of sustainable forest management. The law, if not the licensee, must promote long-term benefits of a planted tree.

2.6. Rationale for Knife Pruning

Many root-pruning studies were developed to improve the cultural practice of reforestation using bare root seedlings. Blake (1983) found a lack of physiologic responses to root pruning treatments of 0, 25, 50 and 75% removal of the initial root volume. No differences either in transpiration rates, drought resistance, or stomatal resistance could be detected between pruned and non-pruned seedlings after a 6-week period for planted white spruce. Paterson and Maki (1994) examined the effects after a six-year field performance trial on Jack pine between bare root and root-pruned seedlings (25, 50 and 75% removal) on disk trenched sandy loam in Ontario. After the first year, survival was greatly reduced to 60% in the 75% pruning treatment as compared to 83-87% survival in the other treatments. Of those who survived, heights of seedlings in the control treatment were 10 – 13 cm taller than seedling heights in 50 and 75% pruning treatments.

With PSB stock, Bigras (1998) showed that after a two-year trial on black spruce, 0, 20, 40 60 and 80% root removal treatments did not show significant difference in seedling survival. Growth index such as height showed 3% gain with 20% removal and declined by 1, 3 and 13% in the 40, 60 and 80% pruning treatments, respectively. Diameter growth showed a negative trend throughout the treatment regime with 1, 4, 8, and 19% reductions in diameter, respectively for the 0, 20, 40 60 and 80% treatments.

In a two-year study on bare root beech (*Fagus sylvatica* L.), Anderson (2001) compared root growth after coarse roots (> 2 mm) and fine root (< 2 mm) removal in addition to root cuts at 7, 13, and 19 cm to the 25 cm-long control seedlings. Anderson

(2001) reported that beech trees were sensitive to the loss of roots irrespective of environmental conditions. Mortality was high with treatment of > 50% removal, regardless of applied irrigation. Also evident was top shoot die back with root pruning. Fine root removal treatment showed pronounced declines in growth and survival regardless of site condition. Fine roots, it seems, are of greater immediate necessity to establishment than large roots. Personal observations by the author have shown that of the transplanted wildlings (natural geminated seedlings) for horticultural purposes, pine species and deciduous trees such as birch and aspen are of greater sensitivity to root pruning as compared with other conifers like spruce and Douglas fir.

Winter and Low (1990) compared PCT, mechanically pruned and uncut PSB 3-13 stocks of lodgepole pine in interior BC. Mechanical pruning (MP) treatments removed 1, 3 and 5 cm from the bottom of the plug. After 5 years, the 3 cm cut showed small height growth improvements; where as, height growth and survival was reduced in the 5-cm removal treatment. No differences were observed in height with the PCT treatment. In all pruning treatments, mechanical and chemical, root growth symmetry was greatly improved in radial direction of primary roots. After 5 years, PSB seedlings were mostly bilaterally symmetric. Root balling, the result of root deformity and subsequent swelling, showed greatest reduction in PCT stock but was unaffected in MP treatments.

The aforementioned experiments suggest that root-pruning of coniferous seedlings slightly improves the growth of trees up to a certain point and then likely reduces growth and survival beyond that. The studies also suggest that rooted plug can tolerate a considerable amount of root pruning to correct the larger root deformities and allow for their proliferation into greater soil volumes.

A series of cuts to the rooted plug may stimulate root growth in a variety of ways: promote adventitious primary roots to develop in the buried stem, support greater surface lateral development, reduce root entanglement, promote greater radial symmetry and engage greater initial soil volumes. Since soil conditions vary, a pruning regime may be found that would benefit seedling root development specifically for certain soil types. Regardless of method, two assumptions must be made: first, knife pruning must be blind to the specific locations of roots within the plug in order to keep it operational, and second, root pruning must be facilitated in manner that rooted plugs can be handled such that it can be planted without falling apart.

2.7. Effect of Microsite on Seedling Development

Site preparation techniques such as mounding, trenching, prescribed burning, and herbicide treatments have been reported to improve the growth and survival of planted seedlings (Jones et al., 2002; Heineman et al., 1999; Bednesti FRDA II, 1992; Patterson and Maki, 1994). An alternative to site preparation, which is being increasingly practiced, is duff or straight planting where seedlings are directly planted into the forest floor horizons. This method has proven to be favourable to seedling growth under certain soil and vegetative conditions (Heineman, 1998; Balisky and Burton, 1997). Duff planting minimizes site preparation costs and reduces risk of soil compaction associated with heavy machinery. Unlike site prepared ground, duff planting necessitates the planting of cut block soon after harvesting while competing vegetation is at a minimum. Duff planting necessitates that the tree planter be more aware of specific planting requirements like microsite, species, and spacing selection as well as the identification natural tree seedlings.

While stock type has shown relatively minor effects on growth and survival, variations in soil environmental conditions strongly influence the development of planted seedlings (Balisky and Burton, 1997; Jones et al., 2002). Root growth morphology is strongly altered by the conditions in which the tree grows as seen in Fig. 2.4. While growth rate and pattern of root development are species specific (Eis, 1978), growth parameters are also dependent on the microsite conditions, including soil and environment (Eis, 1970; Heinemann, 1991; Delong et al., 1997). Patterson and Maki (1994) suggested that the selection of an appropriate microsite has greater influence on growth than planting method in Jack pine seedlings grown in a trenched sandy soil. Wass and Smith (1994) demonstrated that 59 % of 6-year old Douglas fir seedlings had roots conforming to the shape of the planting shovel while areas with compacted soils showed obvious root restrictions in vertical development. Delong et al. (1997) found that decomposed logs, mounds and exposed mineral substrates in boreal Alberta were better for establishment than shovel screefs and undisturbed humus (surface organic) seedbeds.

Heineman (1991), in a study of planting method for two-year old PSB 4-15 interior spruce stock on a cool hygric site with thick forest floors, found differences in the form of root systems across microsite treatments but failed to show height growth differences among treatments after two years. Trees grown in woody substrates had fewer roots but these were elongate and shallow with few branches. Microsites that were very wet or imperfectly drained, particularly found in screefed mineral spots had few roots egress out of the bottom of the plug favouring only surface roots showing any sign of coarse root differentiation. Where mineral soils were better draining, root egress was described as bushy, with abundant branching and steeply ascending roots. The development of seedlings planted into the 20-cm thick F and H organic horizon was intermediate between the well-drain mineral soil and the wood microsite types. Narukawa and Yamamoto (2003) demonstrated the adaptability of roots in *Abies* seedling that were naturally germinated and stratified by soil type to decayed wood and mineral forest floor substrates. Strong patterns in rooting morphology were observed in the different substrates. Egress of planted seedling roots that are adaptable to soil condition is seen as desirable to the quality of plant tree species as they will likely have greater survival, be more tolerant of stresses, and show better stem form.

Figure 2.4. Excavated planted spruce seedlings on the same cut block from Aleza Lake after one growing season from different microsites: well draining sand, poorly draining clay, wet but well draining woody debris.

Van Den Driessche (1987) showed that new root growth of transplanted seedlings is primarily composed of photosynthate since time of planting. If light is inadequate, some reserves may be utilized but the amount of new growth appears dependent on photosynthesis. Root morphogenesis is determined by soil properties such as bulk density, pore size and distribution, soil strength, moisture content, oxygen availability, temperature, fertility, acid toxicity, reaction, and soil depth (Sutton, 1980). Growth of shoot relative to root decreases with declining amounts of available water, nutrients, oxygen and temperature (Fitter and Hay, 1987).

In cool northern forests where moisture is not limited, microsites with higher average daily temperatures produce seedlings with lower shoot to root ratios (Heineman, 1991). In a one-year pine trial on high elevation forests in interior BC, Balisky and Burton (1997) observed that cool microsites (10-13 °C) resulted in decreased root counts and reduced stem heights as compared to warmer sites (18-25 °C). PSB stock had poor lateral performance characterized by the dominant root egress at the bottom of the plug regardless of microsite types. Furthermore, in colder ecosystems it was suggested that bottom root development, typical of the PSB seedling, was a handicap, since root growth is directed into the colder soil horizons where they likely increase their susceptibility to over-winter injury (Krasowski et al., 1996). In a hydroponics study (Vapavuori et al., 1992), low root temperatures (5 and 8 °C) decreased or inhibited the initiation and elongation of European Norway spruce and Scots pine roots.

During waterlogged periods, higher proportion of fine root biomass of grand fir was more dead than alive despite its greater tolerance than Norway spruce to anoxic conditions at greater vertical depth (Xu et al., 1997). Under dry soil conditions, root systems of young Scots pine and Norway spruce ceased to grow at moisture content lower than –1.5 MPa. However, root growth resumed and even increased within 6 days of re-wetting. Root elongation was higher in lateral direction than vertical orientations with rates equivalent to 4.8 and 12.3 mm per day for spruce and pine, respectively (Bartsh, 1987).

With a better understanding of the effects of microsite conditions on seedling establishment and tree root growth, foresters can make more effective harvest prescriptions and site preparation techniques. In addition, tree planters can make better selection of microsites and implement appropriate planting techniques to ensure high rates of seedling survival and development. With respect to root pruning, microsite or soil type will likely show growth interactions supporting greater results from the treatment in distinct soil conditions. Because root pruning reduces root densities, it may be seen as detrimental on the drier sites. But as root pruning alters the distribution of roots with greater distribution of roots through the plug, greater improvements in root development may be realized in soils that are wetter and colder in condition.

3. Experimental Methods

3.1 Site Descriptions

3.1.1 Red Rock

The Red Rock site is located at PRT nursery field beds (53°45'48" N, 122°42'05" W) roughly 30 km south of Prince George. Perched on a terrace 58 meters above the Fraser River at an elevation ~ 617 masl (Table 3.1), site topography is uniformly flat. Soils were derived from a bed of periglacial deltaic sand bed that sits with conformity above clayey glaciolacustrine sediments (Tipper, 1971). Pedogenesis was dominated by anthropogenic influence from repeated ploughing, and resulted to a well-developed 35-cm thick plough layer (Ap) (Fig. 3.1).

Soil profiles at Red Rock were divided into three strata: Upper (0-10cm), Middle (10-20cm) and Lower (20-30cm), for the characterization of soil properties. Bulk density (D_b) was determined using undisturbed core method (Blake and Hartage, 1986). A sample core volume of 491 cm^3 (9.7 cm diameter and 6.65 cm long depth) was used. Bulk densities in 6 randomly positioned replicates ranged from 1.53 to 1.64 g/cm^3 in Upper, 1.35 to 1.48 g/cm^3 in the Middle, and 1.55 to 1.68 g/cm^3 in the Lower strata (Appendix A). Being a ploughed site, the Upper and Lower strata have significantly higher D_b than the Middle stratum. Drainage is rapid at the Red Rock site due to its sandy texture. The site has submesic moisture regime based on ecosystem site description guidelines (Gov. of B.C., 1988). Submesic soil class has soil water content regulated by precipitation rather than seepage. Moist for only brief periods of time following precipitation, water percolation is rapid in relation to its supply. Aeration was confirmed up to a depth of 75 cm based on three soil pits across the site in the wet October period.

Soil at 15 cm depth was uniform across the entire site as single grain structure and loose consistence.

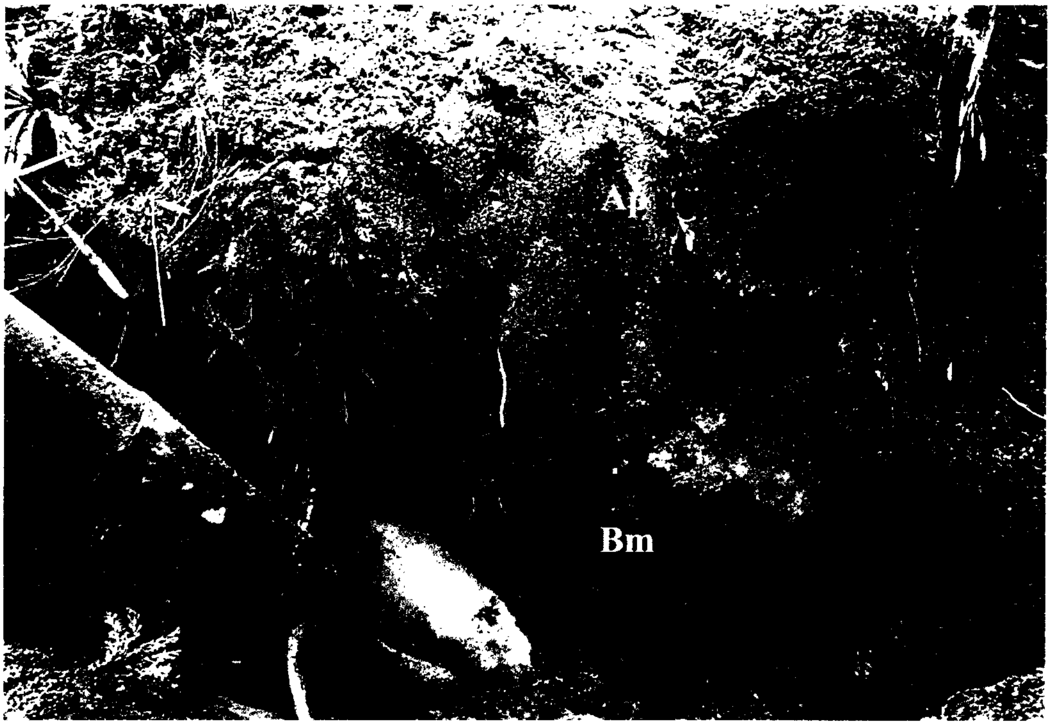


Figure 3.1. Red Rock soil profile to a depth of 60cm has sandy texture, strong granular structure, and loose consistence; a ploughed horizon (Ap) is evident from surface to the middle of the picture.

Climate at Red Rock, based on records from a Prince George weather station (STP, data 1971-2000: 579 masl, located 13 km to the north on the west bank of the Fraser River) is relatively mild and dry. Mean annual temperature is around 5 °C with a mean annual precipitation of 550 mm. Spring months of March and April have the least mean monthly precipitation of 26 mm and 30 mm, respectively. Mid summers months of June and July receive the highest mean monthly precipitation at 53 mm and 56 mm, respectively. The growing season from May to September receives an average of 260 mm of precipitation and 14.5 °C mean temperature.

3.1.2 Aleza Lake

The Aleza lake site is located at the Aleza Lake Research Forest (54°01'57"N, 122°08'52" W) at km 47.5 on the Bear Forest Service Road ~ 40 km east of Prince George. The cut block sits at ~ 710 masl. The surrounding terrain is flat, punctuated with sphagnum bogs and the occasional dissected creek. Aleza Lake parent material consists of a thick glaciolacustrine mantle of sediments originating from periglacial lake Prince George developed at the time of deglaciation of the Cordilleran ice cap. Within the sub-aqueous kame deltaic environment, minor topographic relief reveals a mosaic of soil textures from well drained sands to poorly drained clay (Tipper, 1971).

Within the experimental area of the Aleza Lake site, textures ranged from silt loam to clay. Typical of forest soils, bulk density (D_b) at the Aleza Lake site increased with soil depth within the 30 cm soil profile (n=15) and ranged from 0.36 to 0.87 g/cm^3 in the Upper (0-10cm), 0.97 to 1.27 g/cm^3 in the Middle (10-20cm), and 1.00 to 1.47 g/cm^3 in the Lower (20-30cm) strata (Appendix A). Aeration depth measurements using the iron rod method (Carnell and Anderson, 1986) revealed that median summer aeration depth was 39.5 cm (n=12) in August 2005 (Appendix B). Fall rains reduced median aeration depth to 26.5 cm (n= 106) (Appendix C). Thickness of forest floors at Aleza Lake ranged from 1 to 12 cm with mean value of 5.3 cm (SD = 2.2 cm, n=101) (Appendix C). Thicker forest floors measured at the Aleza Lake site were associated with decayed wood materials and upturned root wads where topsoil accumulated in discrete volumes. The Aleza Lake soil typically demonstrated a mull humus form with a characteristic Ah horizon (Greens et al., 1993). Earthworms were evident but not prevalent.

Based on site aeration and moisture content, soil moisture regime at the Aleza Lake site ranged from hygric to subhydric (Gov. of BC, 1988). Puddles were evident with heavy fall precipitation within the recently logged area. Anaerobic soil conditions associated with poor water infiltration produced mottles in the mineral soil (Fig. 3.2). Permanently saturated soils were observed on microsites exhibiting gley soil conditions. Additional description of physical and chemical characteristics of soils at Aleza Lake can be found in Arocena and Sanborn (1999).

Figure 3.2. Aleza Lake soil profile characterized by hygric moisture regime, fine textures, shallow rooting, mull humus form (Ah) and mottled horizons (Luvisolic Btg) (mottles not visible on photo).

Soil structure was described at the 15 cm depth from excavated cores, showing various characteristics ranging from massive structure with a characteristic anaerobic sulphurous smell; weakly developed blocky structure with gleying within peds and mottlings on the ped surface (Fig. 3.3); granular structure and friable consistence with clay enrichment and mottling at depth (Fig. 3.4), and granular structure and loose consistency with mottling (Fig. 3.5).

Figure 3.3. An example of soil at Aleza Lake site with mottled, large, weak sub-angular blocky structure and firm consistency (mottles not visible on photo).

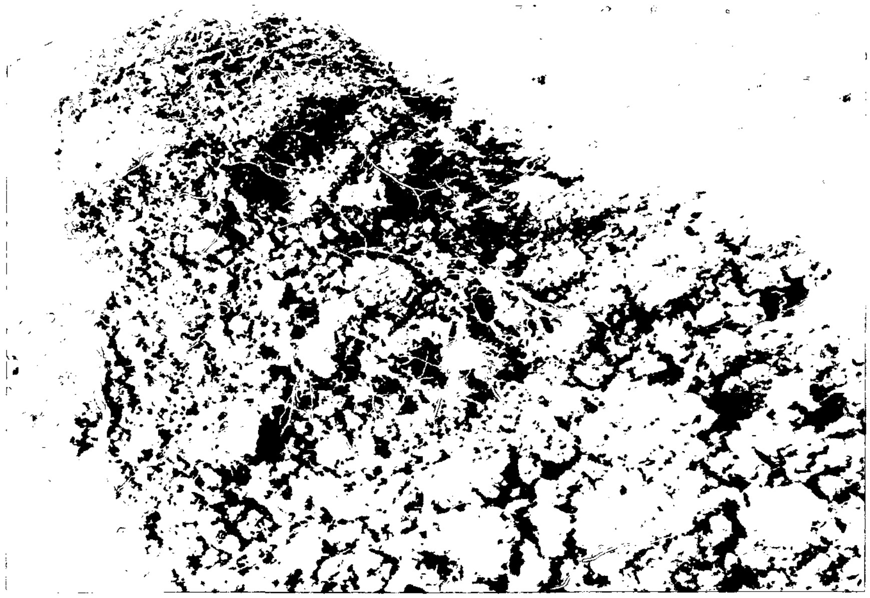


Figure 3.4. An example of soil at Aleza Lake site with moderate to strong, granular and friable consistency.

Figure 3.5. An example of soil at Aleza Lake site with strong granular structure and loose consistency.

Vegetation at the Aleza Lake site showed considerable variety. Hybrid spruce (*Picea glauca x engelmannii*), subalpine fir (*Abies lasiocarpa)* and paper birch (*Betula papyrifera)* existed throughout the study area while isolated Douglas fir (*Pseuotsuga menziesii var. glauca)* dominated the canopy where site drainage was rapid. Western hemlock (*Tsuga heterophylla)*, commonly found in the eastern part of the Rocky Mountain trench were infrequently scattered, black spruce (*Picea mariana*) and lodgepole pine (*Pinus contorta var laifolia)* graded into the forest community in the clayey and wet areas. Devils club *(Oplopanax horridus)*, raspberry *(Rubus idaeus*), lady fern (*Athyrium filix-femina*) and red stem moss *(Pleurozium schreberi*) dominated the zonal sub-canopy while rushes (*Juncaceae*), coltsfoot (*Pedasites sp.*) and sphagnum moss (*Sphagnum sp.*) were found in the wetter areas.

The biogeoclimatic zone for Aleza Lake is Wet Cool Sub-Boreal Spruce (SBS wk1) characterized by relatively severe and snowy winters with short, cool and moist growing seasons. Mean annual precipitation is high for the sub boreal plateau at 930 mm with 374 falling as snow; snow packs average ~ 1 m. The growing season from May to September averages 336 mm of precipitation. The mean annual temperature is ~ 3 °C but recently this average is closer to 4 °C as recorded from1941-1970 and from 1998-2003 at the Aleza Lake Weather Station.

A feller-buncher and grapple skidder harvested the cut block in the winter of 2003/2004. Typical of contemporary harvesting systems, a modest retention of non-utilizable species was retained. Slash, treetops, branches, and discards of non-merchantable logs were piled and burned. The block was left fallow for a year after harvest and planted in the following May 2005.

3.1.3 Site Summary

Table 3.1 Selected site characteristics of the study areas

Site Characteristic	Red Rock	Aleza Lake
Elevation (masl)	617	710
Annual Precipitation (mm)	550	930
Texture	Sand	Silt Loam to Clay
Drainage	Rapidly well	Poor
Moisture Regime (0-8)	Submesic (3)	Hygric to Subhydric (6-7)
Median Aeration Depth	Greater than 75cm	Summer: 39.5cm / Fall: 26.5cm
Forest Floor	None (Ap layer)	Mull 5.3 ± 2.2cm
Soil Structure and Consistency	Single Grain, Loose	Granular to Blocky, Friable to Hard

3.2. Site Soil Moisture Characteristics

Seasonal fluctuations of moisture content were determined with intermittent sampling. Due to the constraints of access to the Aleza Lake site, measurements were limited to three sampling times. Moisture was calculated from a composite of 16 samples collected using core method (Gardner, 1986). A 2 cm x 30 cm soil core was inserted into ground at designated site markers to capture site uniformity with successive measurements. Soil samples were divided into the Upper (0-10cm) and Lower (20-30cm) strata of the collected cores. Soils were weighed initially then re-weighed oven dried at 100 °C. Moisture content (MC) of a given soil stratum was derived as:

$$\text{MC (\%)} = ((\text{mass wet soil} - \text{mass dry soil}) / \text{mass dry soil}) * 100 \qquad (1)$$

Volumetric moisture allows comparison across soils of different bulk density and was calculated as:

$$\text{Vol. MC (\%)} = \text{MC (\%)} * \text{Mean Stratum Bulk Density} \qquad (2)$$

A one-time fall profile volumetric moisture determination was done to determine site variability within the 30-cm moisture profile. Here, the entire 30-cm core was collected within 5 cm of trees selected for excavation. Profile Volumetric Moisture was determined by calculating the MC (%) as described above, in seasonal moisture, multiplied by the site average profile bulk density (Appendix A).

3.3 Stock Types

This study used genetically improved class 'A' lodgepole pine seed (lot number 60297). Operationally, the seed-lot is suited for elevation range between 700 to 1200 meters covering a wide range of the interior of British Columbia (from the Kootenay region to Smithers). The following stocks were provided by PRT and Peltons Nursery for use in the study: PSB 4-15b, 2 boxes - 540 seedlings; PCT 4-10, 1 box - 270 seedlings; PCT 5-12, 1 box - 105 seedlings. Seedling stocks are coded as follows: PCT - **P**lug **C**hemically **T**reated conventional containerized stock, and PSB - **P**lug **S**tyro**B**lock, the conventional non-treated Styrofoam container stock (Table 3.2). The numbers associated with stock type refer to the ~ dimensions of the seedling root cavity (e.g., 4-10 = 4cm diameter and 10 cm long plug). Due to the limited supply of the seedlot at the time of the experiment, two sizes of PCT stock, 5-12 and 4-10, were used to compare against PSB 4-15 control (Fig. 3.6).

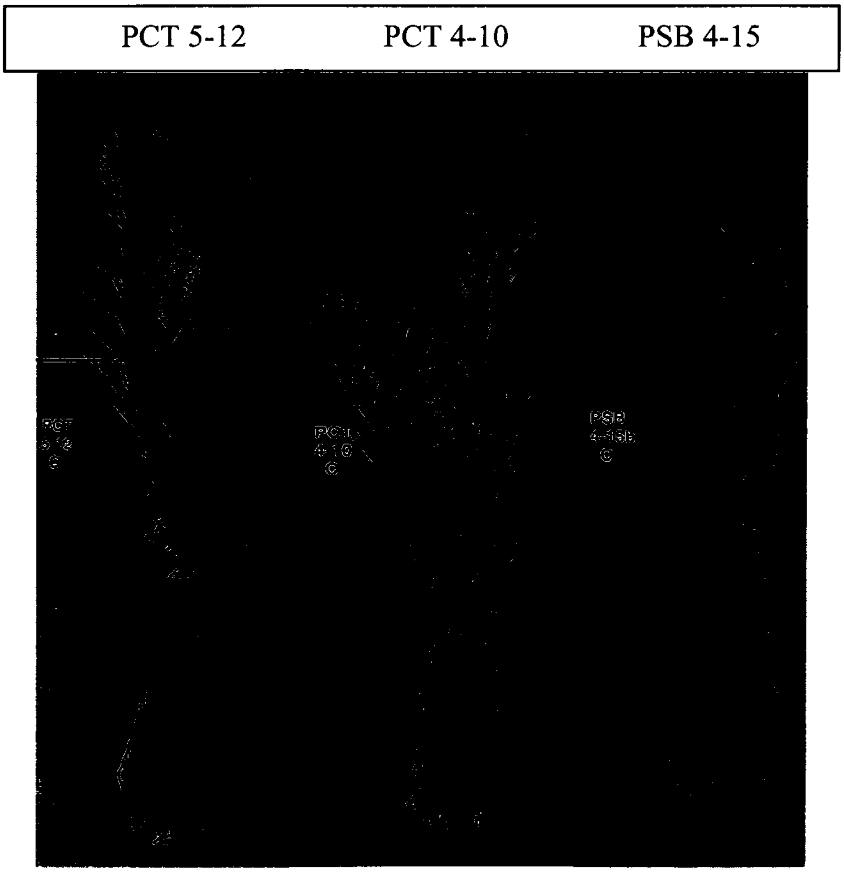


Figure 3.6. Root and shoot differences in the stock types used in the study. Some of the initial differences include the following: size differences in root and shoot.

Table 3.2 Stock dimensions (n=45) and growing conditions (B.C. Ministry of Forests, 1998) and estimated cost per tree (PRT Nursery sources).

Stock type	Cavity Vol. (ml)	Initial Height (SE) (cm)	Initial Diameter (SE) (cm)	Tree Density (#/m^2)	Est. Cost ($)
PCT 5-12	2	20.9 (0.35)	3.86 (0.07)	280	0.400
PCT 4-10	8	25.2 (0.32)	3.69 (0.05)	527	0.225
PSB 4-15	9	15.8 (0.35)	3.01 (0.05)	527	0.22

3.4 Stock Sorting and Pruning

All seedlings were shipped to the Enhanced Forestry Lab at the University of Northern BC (EFL-UNBC) in May 2005. The PCT 5-12 and PSB 4-15 were in excellent condition, however, many PCT 4-10 showed signs of detritus fungi on their lower foliage associated with the stress of thaw during shipment. Once received, seedlings were kept at 4 °C in a walk-in cooler for sorting and seedling preparation. Seedling sizes in various stocks varied extensively. Removing the outliers according to height, diameter, and root density minimized variations in sizes among seedling populations. For the PSB 4-15 and subsequent knife pruning treatments, stock was first divided into five piles of 45 seedlings then bagged and randomly selected for knife root pruning treatments. All seedlings were colour-coded using plastic strap to identify the imposed treatment throughout the duration of the experiment.

Mechanical knife pruning was conducted only to the PSB 4-15 stock with the use of a fillet knife and a plastic tube template with pre-established slits inserted for each treatment type (Fig. 3.7). Treatments were thus unbiased to specific root location with each tree receiving similar severity and location of knife cuts. Fig. 3.8 demonstrated washed replicates for each of the root pruning treatments prior to planting.

Figure 3.7. Mechanical root pruning to PSB 4-15 stock. Materials used: A) fillet knife, B) plastic tube pruning template, and C) colour-coded identification straps.

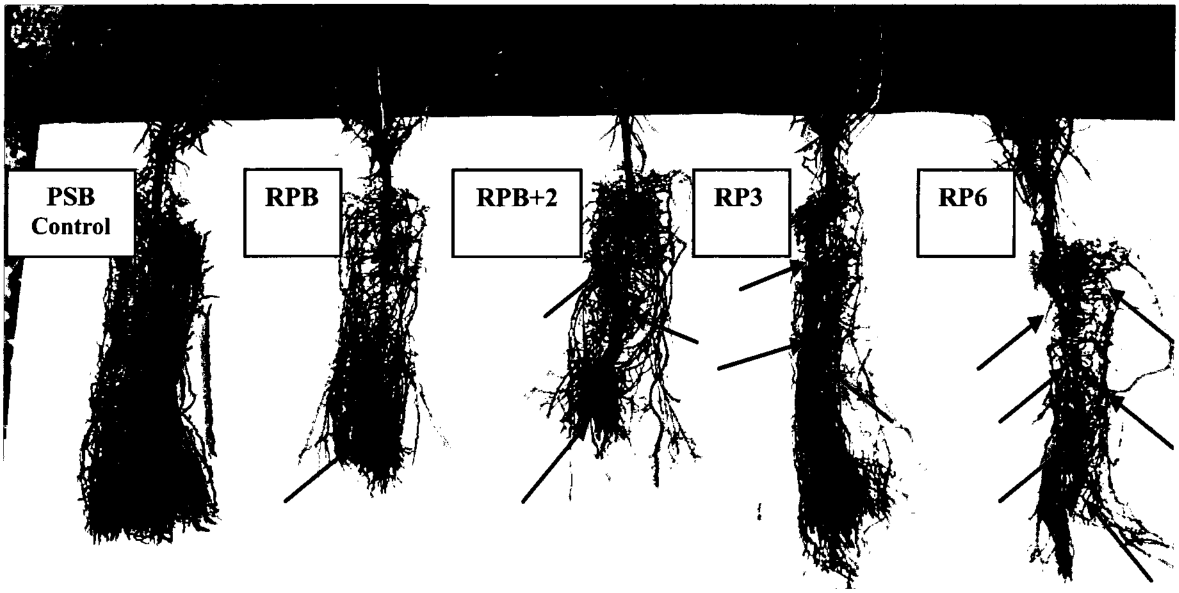


Figure 3.8. Mechanical root-pruning treatments for PSB 4-15 stock. Arrows point to cut locations. PSB 4-15 – control (uncut); RPB – bottom 2 cm cut; RPB+2 – bottom 2 cm and two perpendicular cuts at 4 and 8 cm down the plug; RP3 – three tangential cuts, 1 cm deep and 2 cm long, at 3, 6 and 9 cm at 120 ° from each other; RP6 – six tangential cuts, 1 cm deep and 2 cm long, at 2, 4, 6, 8, 10 and 12 cm at 90 ° from each other.

Table 3.3. Seedling stock types tested and root pruning treatments.

Stock	Treatment	Action
PCT 5-12	Chemically Pruned	Container with copper based paint
PCT 4-10	Chemically Pruned	Container with copper based paint
PSB 4-15	Control group	No action – control group
	RPB	Knife Pruned: Bottom 2cm cut off (removes most root tips).
	RPB+2	Knife Pruned: Bottom 2cm cut and two 2cm wide perpendicular cuts through the entire plug, at 4 and 8 cm down the plug (removes most root tips and cut some structural roots and fine roots)
	RP3	Knife Pruned: Three tangential cuts, 1 cm deep and 2 cm long, at 3, 6 and 9cm down the long axis of the plug; progressively 120 degrees from each other spiralling down the plug (removes structural roots and fine roots mostly to upper plug).
	RP6	Knife Pruned: Six tangential cuts, 1 cm deep and 2 cm long, at 2, 4, 6, 8, 10 and 12 cm down the long axis of the plug, 90 degrees progressively from each other in a spiral (removes many structural and fine roots).

3.5. Planting and Brushing

On May 11 and 12, 2005, seedling trials were established at the Red Rock and Aleza Lake sites, respectively. A total of 25 replicates for each stock type and treatment were planted at each site. Seedlings were planted by the author to minimize any planting bias. The experimental design had treatment replicates planted in an alternating series of blocks (rows) so that each treatment had equal representation across a possible site change. At either site, seedlings were planted in blocks of 5-7 replicates per treatment with inter-tree spacing variable to select for best microsite (1 metre minimum spacing). Microsites selected at Aleza Lake consisted of raised forest floor spots away from excessive decayed wood, brush, roots, and stumps. Typical of duff planting technique, only coarse forest litter and harvesting debris were removed at each planting spot.

Planting was done typical of industrial forest operations. Seedlings were inserted by the rooted plug into the ground buried 1-2 cm past the root collar. With the hard soils at Aleza Lake, the planting shovel was used to chop the soil several times in preparation of planting as well as when pressing the soil around the newly planted seedling. This effort helped break up compacted soil associated with opening the hole in the hard clay. Trees were given a light tug to ensure a snug fit. Both sites were brushed on occasion to reduce but not remove the effect of vegetative competition. This was done with hand pulling and hand pruning three times over the growing season.

3.6. Initial Biomass Measurement - Shoot Mass, Root Mass, Shoot to Root Ratio

Ten seedlings for each treatment were selected. Each was hand washed with water using a spray gun to remove the peat from the plug for the determination of biomass. Samples were inspected to remove debris and cut roots. Seedlings were severed at the root collar to separate root mass from shoot. Roots and shoots were placed separately in paper bags and oven dried for three days at 70 °C. Biomass of shoot and root was weighed using a digital scale with accuracy of 0.01 grams. Shoot to root ratio was calculated from the results of biomass measurements according to the following:

$$\text{Shoot to Root mass fraction} = \text{shoot mass (g)} / \text{root mass (g)} \tag{3}$$

3.7. Field Root Growth Capacity Test

After 21 growing days, 10 seedlings of each stock treatment, at the Red Rock site were used for the Field - Root Growth Capacity test (Field-RGC). A Field-RGC is similar to the industry practices where RGC is determined under controlled conditions in a growth chamber. RGC test is used as an industry standard to provide a comparative assessment of the vigour of the initial growth of a given stock (Ritchie and Dunlap, 1980; Burdette et al., 1983).

The standard variable in RGC test is Total Root Count determined as number of roots whose length > 1.0 cm. All roots counted were partitioned to plug location as Side and Bottom growth development.

3.8 One-Year Pine Tree Measurements

3.8.1 Survival

In early September 2005, seedlings were assessed for tree vigour as Good, Poor and Dead. Parameters used to assess vigour were to account for: general stem deformities such as a fork, frost or insect damage, excessive vegetative competition, moose hoof compaction, and browse. Poor and Dead individuals were removed from the measurement sample population. A Good tree had minimal degree of deformities, while a Poor seedling had obvious growth impairments.

3.8.2 Relative Growth Height (RGH) and Diameter (RGD)

Initial Height (Hi) and Diameter (Di) were measured soon after planting on May 11-12, 2005. Height and Diameter were measured initially after planting.

Height was measured to the nearest 0.5 cm from the ground to the tip of the terminal bud. A digital calliper was used to obtain an accuracy of 0.2 mm in measurements taken for diameter just above the forest floor. In September 2005, after cessation of leader growth and bud set, seedlings were re-measured for final Height (Hf) and Diameter (Df). For growth calculations, relative growth was used to correct against differences in Hi and Di across sites and treatments at the time of planting. The relative growth was calculated as follows:

$$\text{Relative Growth Height (RGH)} = \ln(\mathrm{Hf}) - \ln(\mathrm{Hi}) \quad (4)$$

$$\text{Relative Growth Diameter (RGD)} = \ln(\mathrm{Df}) - \ln(\mathrm{Di}) \quad (5)$$

3.8.3 Mid-Leader Needle Length

Mid-leader needle length of the current year's growth was measured as an indicator of tree vigour and site quality. Mid-leader needle length was used as an indirect measure of growth associated with potential growth shock associated with root pruning and poor root establishment (Burdette et al., 1984). Needle length was calculated from the mean length of three pairs of needles from the mid leader of the current year's growth to the nearest 0.1 cm.

3.8.4 Root System Excavation Method

Sixteen trees from each treatment were randomly selected for excavation to investigate the growth of root systems from the entire sample population minus the trees found to be poor conditions. At Red Rock site, seedlings were excavated to a depth of 50 cm, within a 40 cm radius around the tree, using spade shovels. Prying and agitating then fractured the soil column and the tree root system was easily recovered.

At Aleza Lake site, the cohesive nature of clayey soils required the use of a large steel core (10 cm radius, 25 cm long) to excavate the seedlings. The seedling was cut at root collar and the steel core was fitted around tree and pounded into ground using the 10-kg slide hammer. A shovel was used to excavate the soil core with the root system intact. Samples were stored in bags and taken to laboratory for assessment of soil structure and root development (Fig. 3.9).

Figure 3.9. Steel core apparatus (left) and a soil core with root system (red tag) (right) at the Aleza Lake site.

3.8.5 Root Symmetry

Each excavated seedling was washed with water to remove soil and peat materials prior to assessment of planting deformities in the root system. Symmetry was assessed from the radial development of the root system in each quadrant around the root collar. A discrete interval scale from 1 - 4 as shown in Fig. 3.10 was used in the assessment.

Unidirectional - 1 Bilateral symmetry – 2 Three quadrants of growth -3

Figure 3.10. Root symmetry classes used in the assessment of root growth. 1 - one direction usually straight down; 2- bilateral growth usually in opposite direction; 3- lacks growth in one direction; 4- balanced growth in all direction (picture not shown).

3.8.6 Total and Large Root Counts

Root abundance was divided into Total Root Count (TRC) and Large Root Count (LRC). For each category, counts were partitioned according to location of egress from the plug as follows (Fig. 3.11): Top (upper 3 cm), Middle (rooting area between Top and Bottom), and Bottom (bottom 2cm). Total root count included all but the following: senesced roots and roots < 5 cm. Large roots were characterized as those that have secondary growth characteristics: yellowish in colour with sloughing of the brownish outer cortex and thicker diameter. Only top ten largest roots were counted although some replicates had < 10 large roots and others >10.

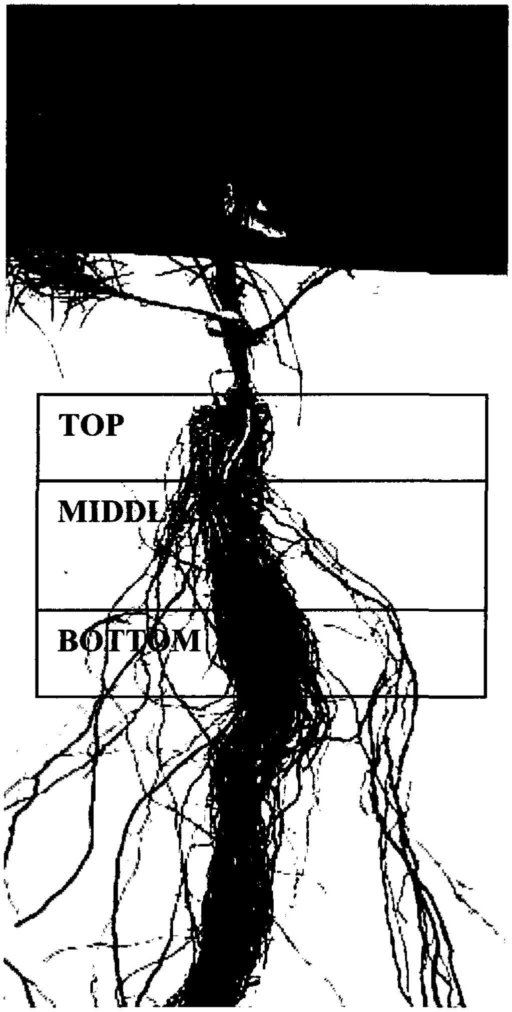


Figure 3.11. Tree root system showing Top, Middle and Bottom plug locations.

3.8.7 Large Root Deformity

Large root deformity was assessed from the ten largest roots selected. The degree of root deformity was grouped as Braided, Kinked or Direct (Fig. 3.12). Braided roots have twisted primary roots prior to growth trajectory while Kinked roots exhibit kinks or points of obvious weakness. Direct roots showed no recognizable deformities or intertwining and are considered free to establish as structural primary roots without the likelihood of deformity. Direct roots included those that have deflected downward along the wall of the plug and may include some degree of lateral deflection such as a bend (a sharp bend however, would be considered a kink).

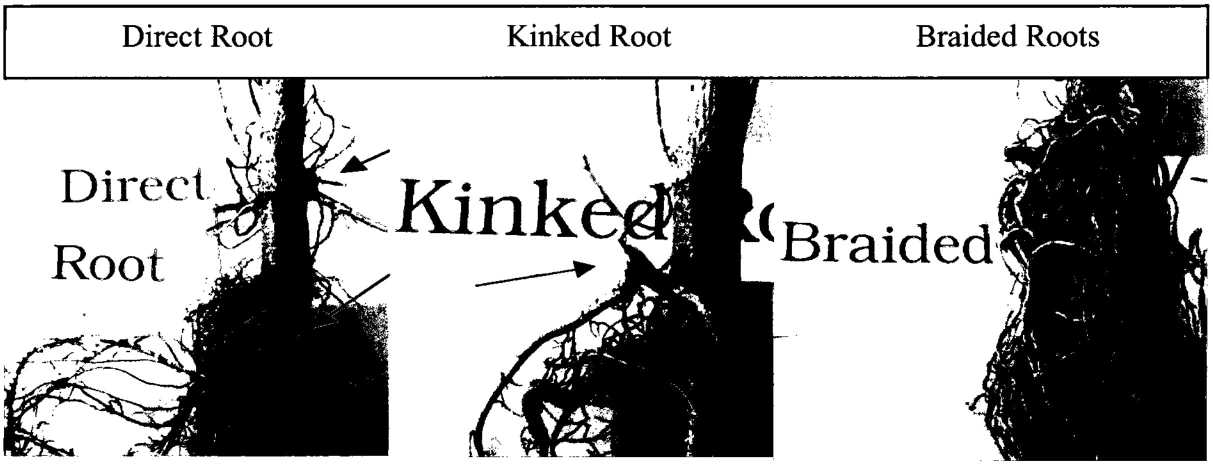

Direct Root Kinked Root Braided Roots

Figure 3.12. Pictorial examples of root deformity classes.

3.8.8 Taproot Development

Taproot development was evaluated as binary nominal classes of Yes or No. In the Yes category, taproot displayed a large primary root with characteristic secondary growth similar to criteria for large root count (Section 3.8.6). The No category had taproot without differentiated secondary growth.

3.9 Statistical Analysis

A 2-way ANOVA (analysis of variance) using SYSTAT (version 11, 2004) was used to compare means between site and treatment for root counts and tree measurements at P-value < 0.05. Tests for normal distribution and similarity of variance were conducted prior to ANOVA with Box Cox transformations used on variables where distribution was not normal and/or variances not equal (Box and Cox, 1964). Post hoc Bonferroni pair wise comparisons were used to compare treatments. A Logistic Regression Model was used for the discrete variable of taproot development (yes, no) and an Extended Logistic Model was used for the 4-class scale of symmetry. Logistic Models were conducted using SAS version 9.1.3 (SAS Institute).

4. Results

ANOVA and logistic regression tables are presented in Appendix E.

4.1 Site Volumetric Moisture Content

Average monthly precipitation normals (1975-2000) for Prince George weather station (Airport) indicated that the 2005 growing season started with the month of April being 64% drier than normal, but by mid summer, July was 145% wetter than average. Over the growing season, volumetric moisture content (VMC) of the Lower stratum (20-30cm) at Aleza Lake demonstrated a 9% variation between 39% VMC (mid-summer) and 48% VMC (mid-fall). A 13% seasonal variation was observed at Red Rock varying from 14%–27% VMC (Figs. 4.1 and 4.2) during the same period. At Aleza Lake, VMC of the Upper and Lower strata differed only slightly (Fig. 4.1). At Red Rock, however, Upper soil stratum typically retained less moisture than Lower stratum (Fig. 4.2).

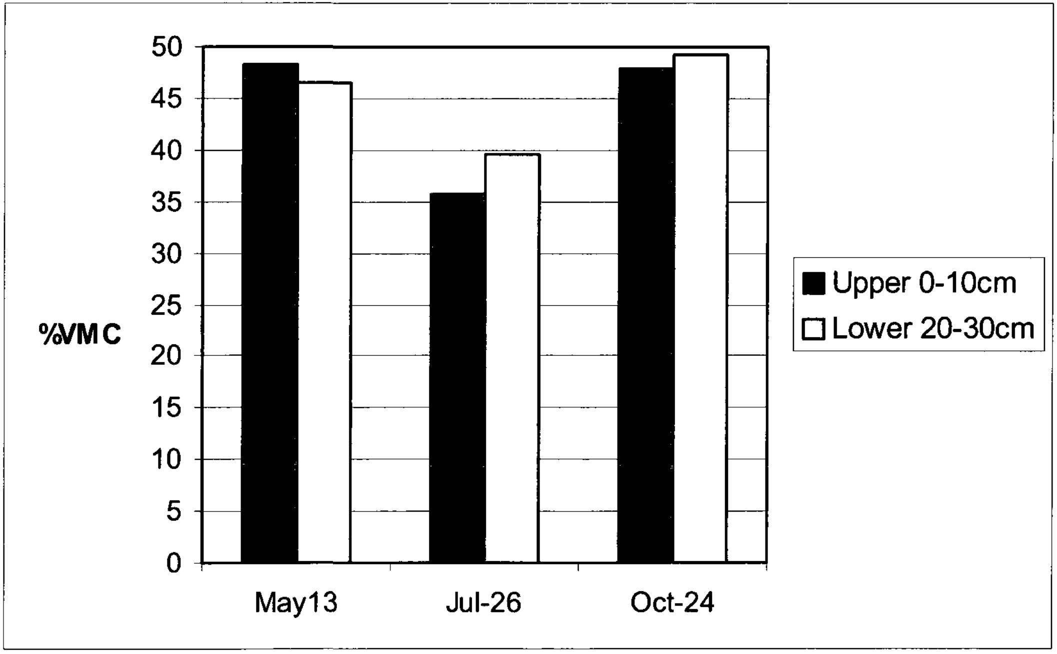


Figure 4.1. Site Volumetric Moisture Content from a composite of 16 cores at fixed locations for Upper and Lower strata at Aleza Lake site during the 2005-growing season.

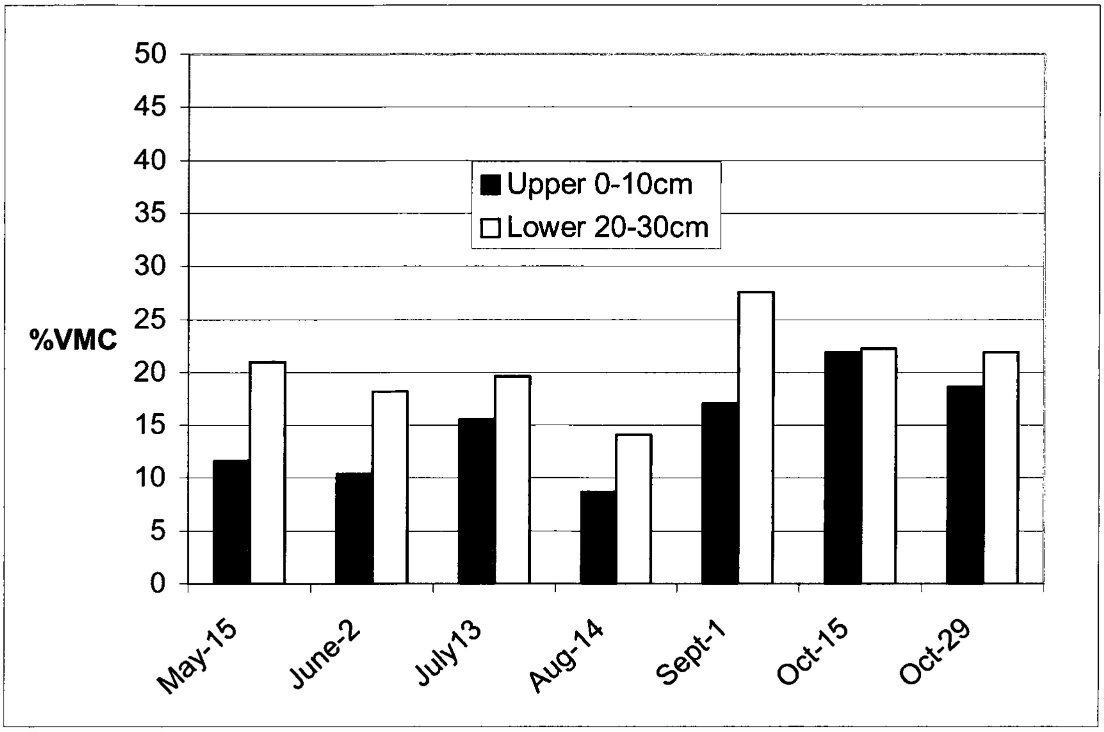


Figure 4.2. Site Volumetric Moisture Content from a composite of 16 cores at fixed spots for Upper and Lower strata at Red Rock site during the 2005-growing season.

A one-time fall volumetric soil moisture was measured as a baseline of inherent site variation (Figs. 4.3 and 4.4). Aleza Lake's wetter clayey forest soil showed random site variation with a mean volumetric moisture content and standard error of 47 % ± 0.80 (Fig 4.4), while Red Rock's ploughed sandy field had a more uniform variation and lower mean moisture content of 21 % ± 0.39 (Fig. 4.3).

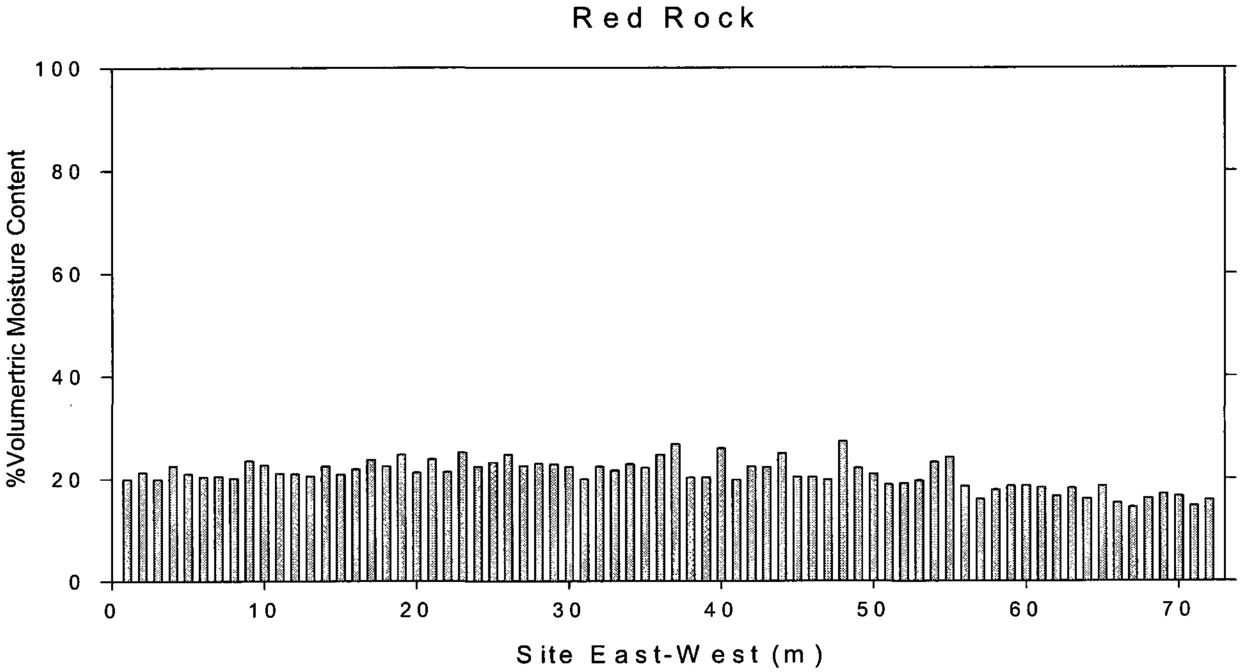


Figure 4.3 Red Rock one-time measurements of fall volumetric soil moisture content (%) in 30-cm soil cores across site from West to East, on October 15, 2005 (n=72).

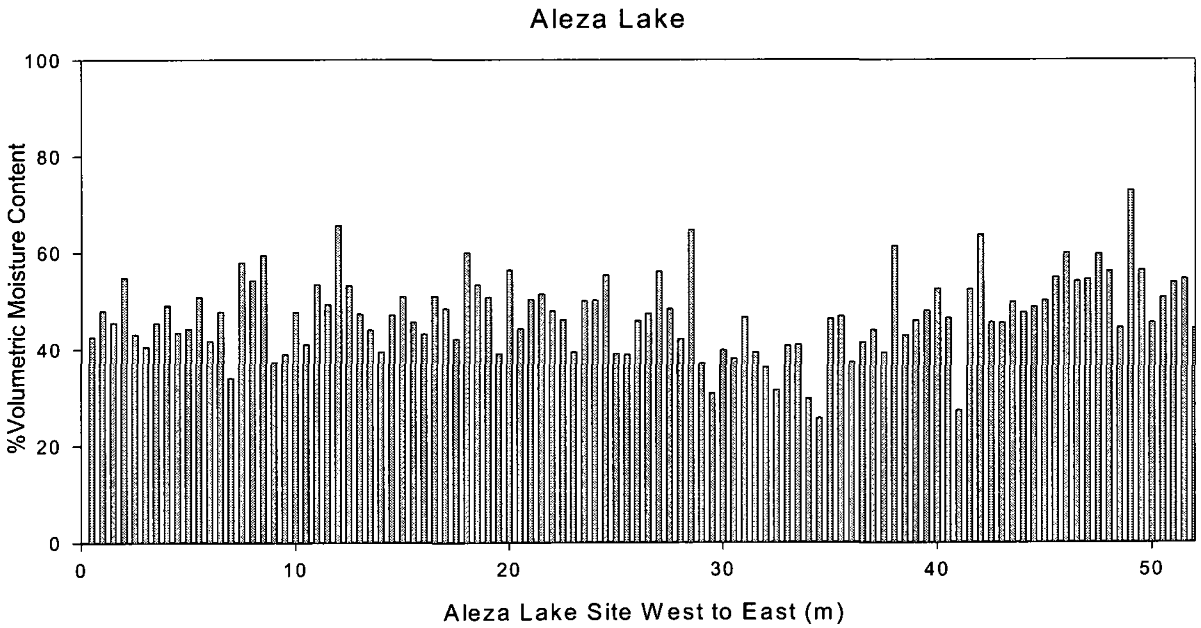


Figure 4.4 Aleza Lake one-time measurements of fall volumetric soil moisture content (%) from 30-cm soil cores across site from West to East, on October 19, 2005 (n = 104).

4.2 Seedling Initial Biomass

A large range in initial root and shoot mass was tested owing to large variation within and among the different stock sizes and knife prune treatments. Ten replicates were tested for each of the 7 treatments. Mean initial root mass (± SE) ranged from 0.52g ± 0.037/seedling for the RP6 treatment to 1.60g ± 0.103/seedling for the PCT 5-12 treatment. Initial shoot mass ranged from 1.40g ± 0.10/seedling for PSB 4-15 and all subsequent knife pruned RP treatments to 4.10g ± 0.285/seedling for the PCT 5-12 treatment.

As compared with the PSB 4-15 control group, knife-pruning treatments (RPB – RP6) demonstrated a negative mean root mass trend as a consequence of the increasing severity and frequency of cuts (Appendix C). With the PCT and PSB seedlings, there showed distinct mean initial root mass differences reflecting the different container sizes with PCT 5-12 > PSB 4-15 > PCT 4-10. Initial shoot mass differences were established as PCT 5-12 > PCT 4-10 > PSB 4-15 (Appendix C).

Shoot to root ratios showed that the PCT 4-10 treatment had the greatest amount of shoot compared to its small root while the PSB 4-15 had the greatest amount of root relative to a smaller shoot. The larger PCT 5-12 stock had shoot to root ratios in the middle of this range (Fig. 4.5). Among knife pruning treatments all but the RPB pruning treatment (RPB+2, RP3, RP6) were associated with higher shoot to root ratios compared to the uncut PSB 4-15 control matching the shoot to root ratio of the PCT 512 treatment.

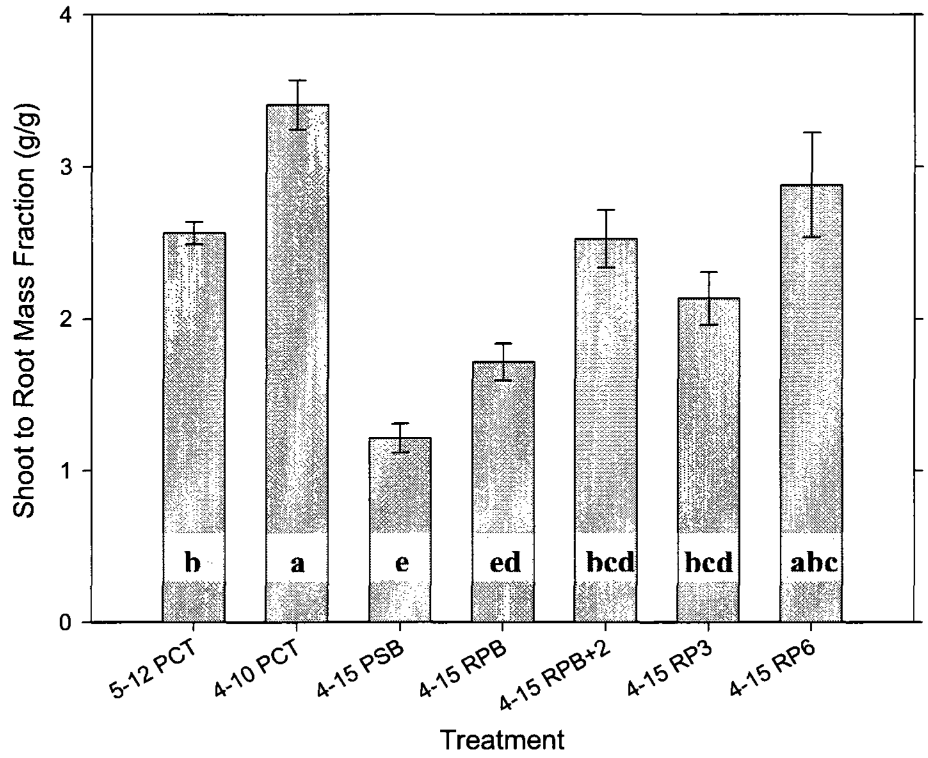


Figure 4.5. Mean and standard error for initial shoot to root ratios for stock type and post knife-pruning treatments, (n = 10). Treatment means with same letter are not significantly different (P>0.05).

4.3 Roots Cut in Plug as a Consequence of Knife Pruning

Observed in RPB+2, RP3 and RP6 treatments was increasing numbers of large roots cut in the upper and mid plug with an increasing frequency and severity of lateral cutting (Fig. 4.6). While the RPB, bottom cut treatment, had large roots pruned, these only occurred at the bottom of the plug.

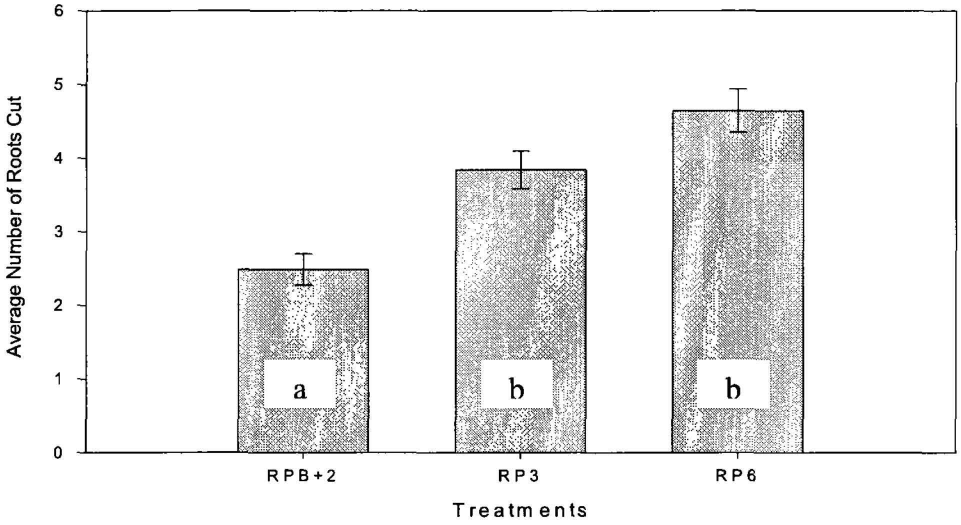


Figure 4.6. Mean and standard error estimate of large roots cut within upper plug as a result of each knife-prune treatment. Treatment means with same letter are not significantly different (P>0.05).

Also the frequency of tap-roots cut in the upper plug varied depending upon the method and severity of lateral cuts in knife-pruning treatments (Fig. 4.7). The RPB+2 treatment with two deep cuts showed a similar effect as 6 more shallow tangential cuts.

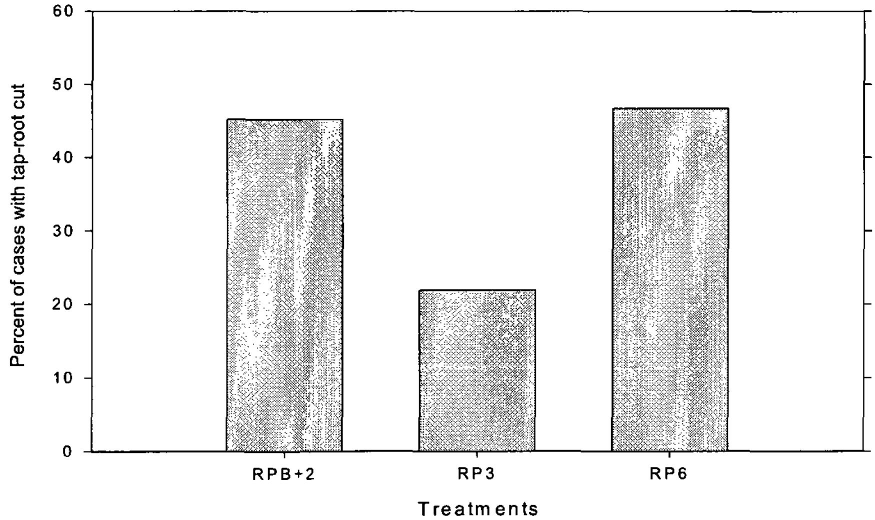


Figure 4.7. Incidence of tap-root cutting in the upper plug region in knife-pruning treatment (both site combined).

4.4 Seedling Performance After One Growing Season: Aleza Lake and Red Rock

4.4.1 Survival and Sample Size

Prior to root excavations in September 2005, all seedlings in treatment populations (N) at each site were surveyed for vigour and survival (Table 4.2). After one growing season, survival was 100% except for the PCT 4-10 stock. This stock also had shown pre-treatment signs of stress evident as detritus needle fungi from extended thaw period as a result of shipping. Seedlings with damage or growth impediments were classed as poor vigour. These were a consequence of excessive vegetative competition, brushing injury, hoof press and rabbit browse.

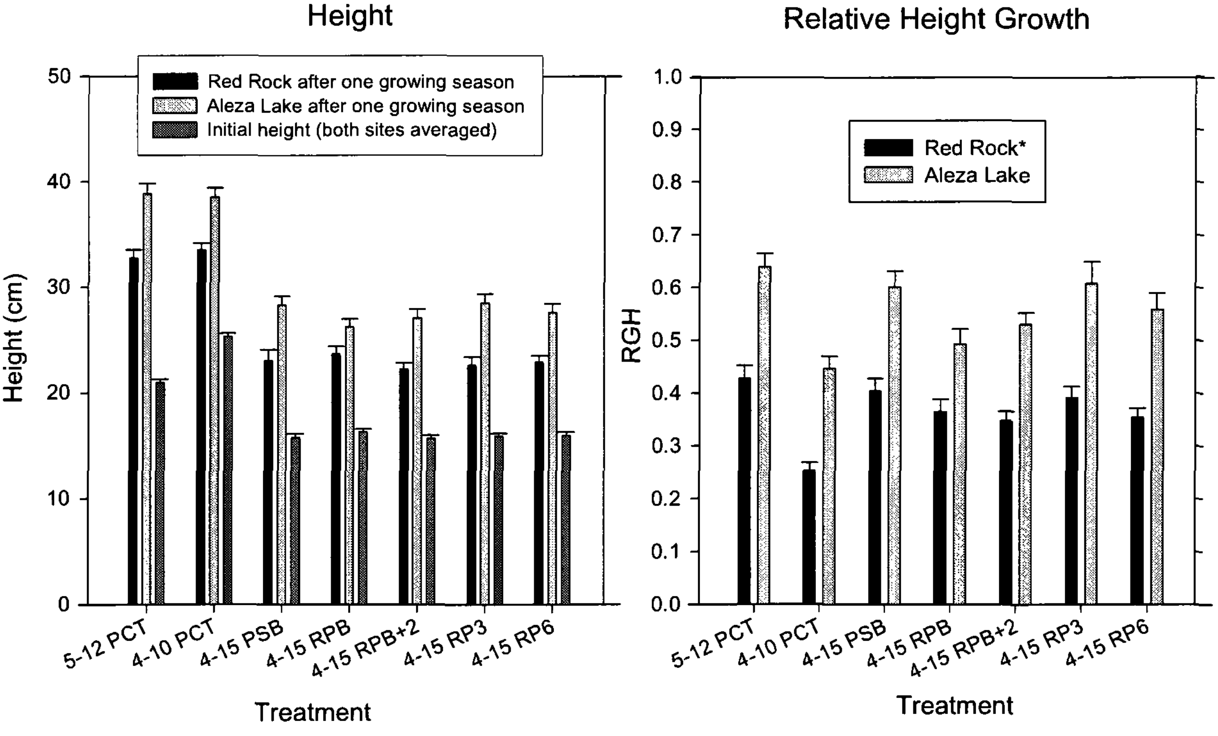
From the initial sample populations of 25 replicates per stock and treatment, only trees with good vigour were selected for stem measurements (Table 4.2). From these, 16 trees were randomly selected for root measurements. Unfortunately occasional damage occurred to Aleza Lake samples reducing some of root sample sizes (n) producing an unbalanced design.

Table 4.2 Initial numbers of seedlings (N) showing degree of vigour, survival and randomly chosen root sample size (n) at study both sites after one growing season. AL=Aleza Lake, RR=Red Rock.

Treatment	Site	N	Lost	Dead	Poor	Good	n	Site	N	Dead	Poor	Good	n
PCT 5-12	AL	25	1	0	0	24	14	RR	25	0	0	25	16
PCT 4-10	AL	25	0	1	2	22	16	RR	25	4	4	17	16
PSB 4-15	AL	25	2	0	0	23	16	RR	25	0	0	25	16
RP1 4-15	AL	25	0	0	1	24	15	RR	25	0	1	24	16
RP2 4-15	AL	25	0	0	7	18	15	RR	25	0	1	24	16
RP3 4-15	AL	25	0	0	5	20	16	RR	25	0	2	23	16
Rp6 4-15	AL	25	0	0	7	18	14	RR	25	0	2	23	16

4.4.2 Relative Growth - Height, and Diameter

Relative Growth Height (RGH) (Fig. 4.8) and diameter (not shown) were significantly different for site ($P<0.01$) and treatment ($P<0.01$). Seedlings at the Aleza Lake site had greater relative growth in height and diameter than seedlings at Red Rock. Among the treatments, the initial tallest of tested stock, the PCT 4-10, were the only treatment to show significantly lower relative growth (Fig 4.8.A). This occurred against only the PCT 5-12 and PSB 4-15 ($P<0.01$), at both sites. After the first year's growth, RGH values among knife-pruning treatments (RP) were not significantly different ($P>0.05$) than the non-pruned PSB 4-15 control.



(A) (B)

Figure 4.8. (A) Comparison of mean and standard error between initial height (cm) (both sites averaged with no significant differences) and final height after one field-growing season; and (B) mean and standard error for Relative Growth Height after one-growing season at Aleza Lake and Red Rock sites (* indicates significant site differences $P<0.05$).

4.4.3 Mid-Leader Needle Length

A 2-way ANOVA of needle length detected significant differences for site ($P<0.01$) and treatment ($P<0.01$) (results not shown). Seedlings at Aleza Lake had longer (9.5cm) mid-leader needles than Red Rock (7.7cm). Among treatments the PCT 4-10 seedlings produced shorter needles than all other treatments consistently at both AL and RR sites. No interaction effects between site and treatments were observed.

4.4.4 Root Symmetry

No site differences and strong treatment differences were observed in a 2-factor extended logistic regression for seedlings response in root growth symmetry. Three benchmark treatments: **PCT 4-10**, **PSB 4-15** and **RP6 4-15** were use to compare the odds ratio estimates against all the other treatments with 95% confidence. Frequency distribution of Root Symmetry classes shows how root-pruning treatments, both chemical and mechanical significantly improved root symmetry over the un-pruned control PSB 4-15 (Fig. 4.9). Comparing root symmetry classes against base-line treatments, the PSB 4-15 and RPB treatment were least symmetric, while the rest of the pruned treatments (RPB+2, RP3, PCT 4-10, PCT 5-15) proved not different. Odds ratio comparisons showed:

PCT 4-10, PCT 5-12, RPB, RPB+2, RP3, RP6 > **PSB 4-15**

PCT 5-12, RPB+2, RP3, RP6 = **PCT 4-10** > PSB 4-15, RPB

PCT 4-10, PCT 5-12, RPB+2, RP3 = **RP6** > PSB 4-15, RPB

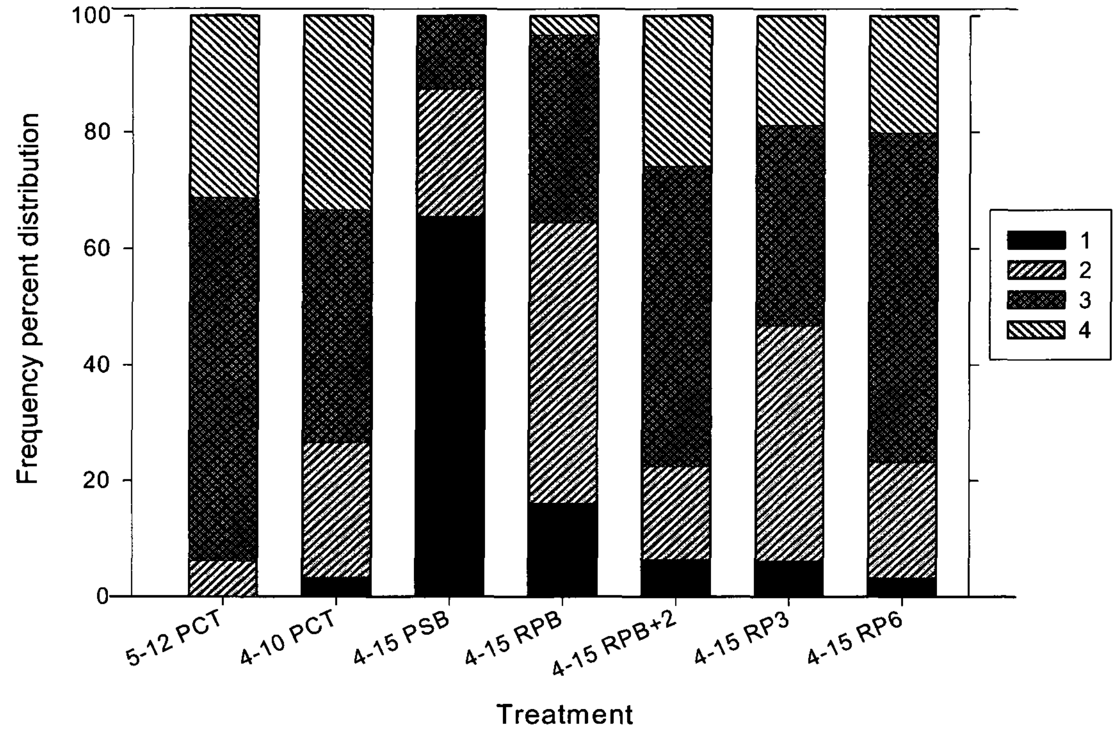


Figure 4.9. Percent frequency distribution of root symmetry classes among treatments after one- growth year (data pooled among non-statistically different sites).

4.4.5 Root counts after 21 days: Red Rock Field Root Growth Capacity Test

A one-way analysis of variance (ANOVA) showed significant treatment differences in root counts after 21 days. The largest stock type (PCT 5-12) produced the greatest root numbers over any other treatments tested (Fig. 4.10). While the PCT 4-10 and PSB 4-15 had similar Total Root Counts, the PSB 4-15 control demonstrated the lowest average proportion of side root development. Plugs whose bottoms were severed in knife pruning treatments (RPB and RPB+2) had significantly lower proportions of bottom roots developing after 21 days ($P<0.05$). RP3 and RP6 knife pruning treatments also demonstrated reduced mean total root counts but transformed means were not statistically different to the uncut PSB 4-15 control.

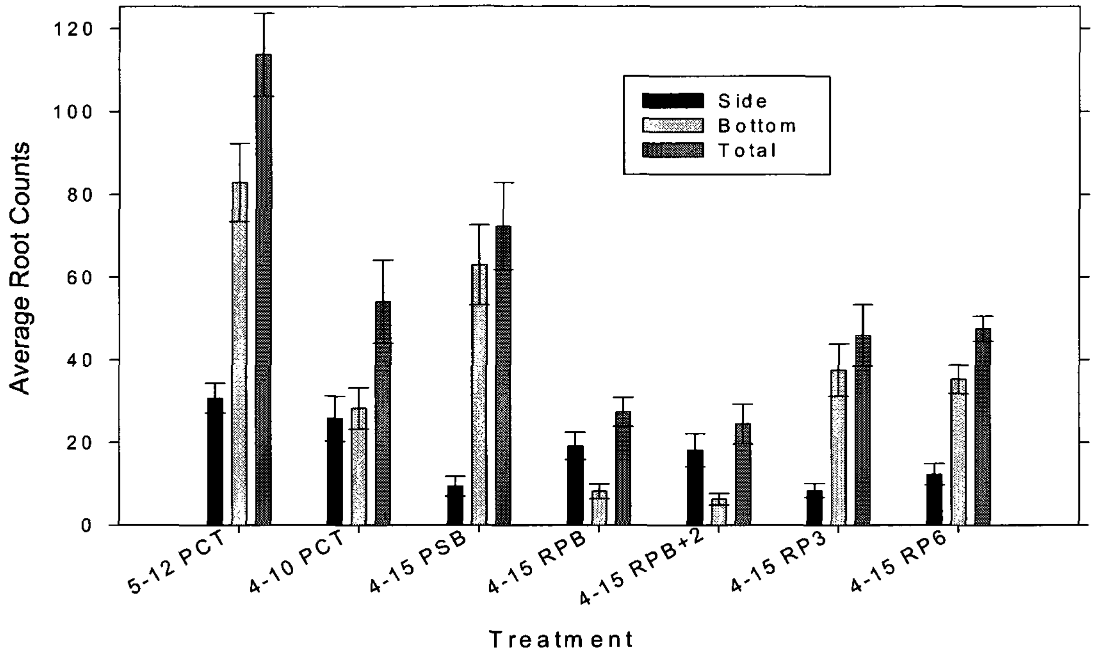


Figure 4.10. Mean and standard error for total, side and bottom root counts > 1 cm at Red Rock site (n = 10) for the 21 day test.

4.4.6 Root Counts After One-Field Growing Season: Aleza Lake and Red Rock

Significant site (P<0.01) and treatment (P<0.01) differences in root counts were observed after one growing season. Aleza Lake site produced significant albeit minor increased counts compared to Red Rock (Fig. 4.11). Similar to the Total Root Count (TRC) treatment trend after a 21-day growth period, the larger sized PCT 5-12 plugs produced significantly more roots than any other treatment. Both bottom plug removal treatments, RPB and RPB+2, showed reduced counts for both sites as compared to the uncut control (P<0.01).

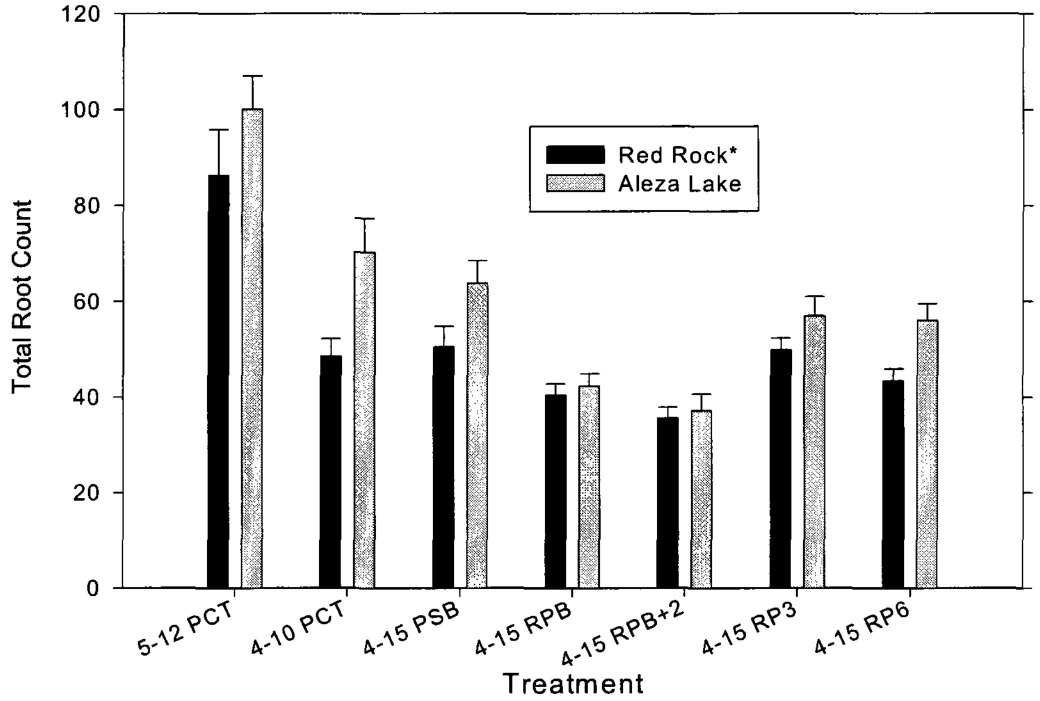
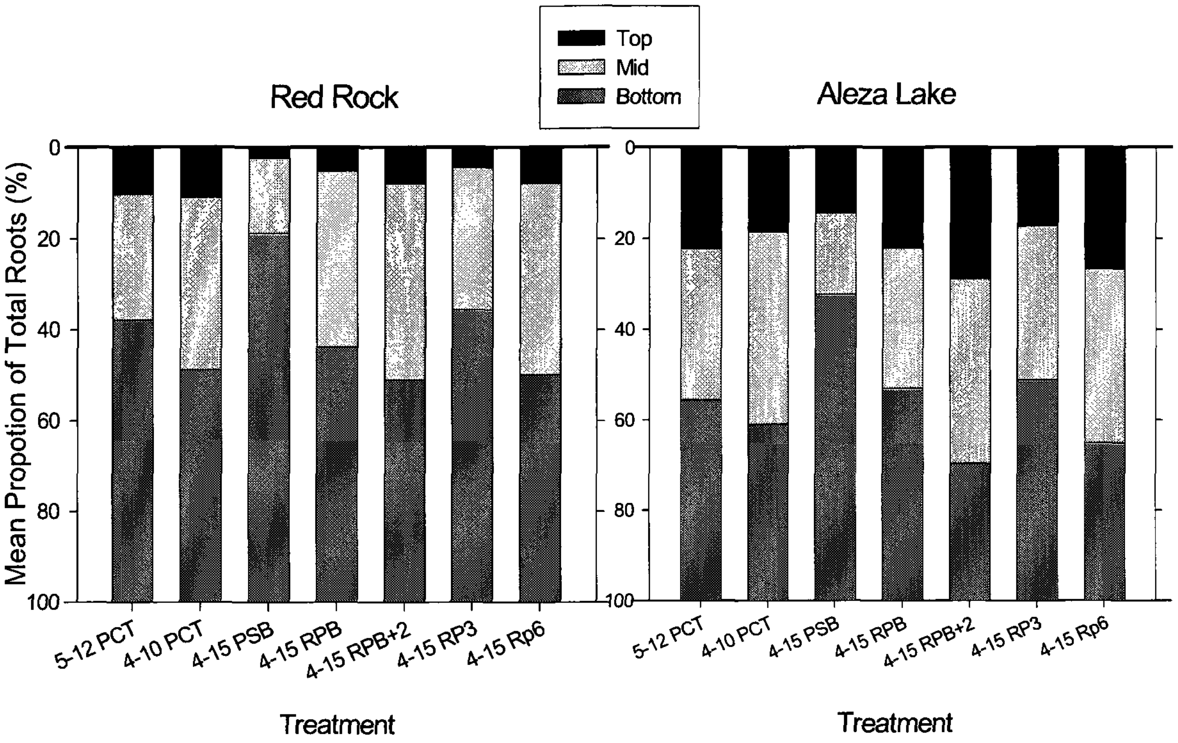


Figure 4.11. Mean and standard error for total roots counted after one growing season at Aleza Lake and Red Rock sites. (* indicates significant site differences).

Since stock size showed a positive influence on total root numbers, root counts were partitioned according to relative contribution to plug location: top, middle and bottom (Fig 4.12). Top root growth was proportionately greater at Aleza Lake relative to Red Rock ($P<0.01$), while bottom root growth was proportionately greater at Red Rock relative to Aleza Lake ($P<0.01$). The proportional contribution of mid plug roots showed no site differences.

Among treatments, the PSB 4-15 was the most restricted to bottom root growth regardless of site. As compared to the non-pruned PSB 4-15, knife pruning significantly increased the proportion of middle roots and reduced the proportions of bottom roots, while top root showed mean differences consistent with both sites but these were not significant.



(A) (B)

Figure 4.12. Mean proportion of total roots counted partitioned to top middle and bottom plug location at sites:(A) Red Rock and (B) Aleza Lake.

4.4.7 Large Root Counts

Large root counts (LRC) showed site and treatment differences ($P<0.01$) (Fig 4.13). At Red Rock, typically seedling root systems had more than 10 LRC, while at Aleza Lake most root systems had less than 10 LRC. Site x Treatment interaction was also significant ($P<0.05$). Reduced large root counts were observed in the control PSB 4-15, particularly at the Aleza Lake site. Relative to the uncut PSB 4-15, lateral-cutting methods in the knife prune treatments, RPB+2, RP3 and RP6, showed increases in LRC.

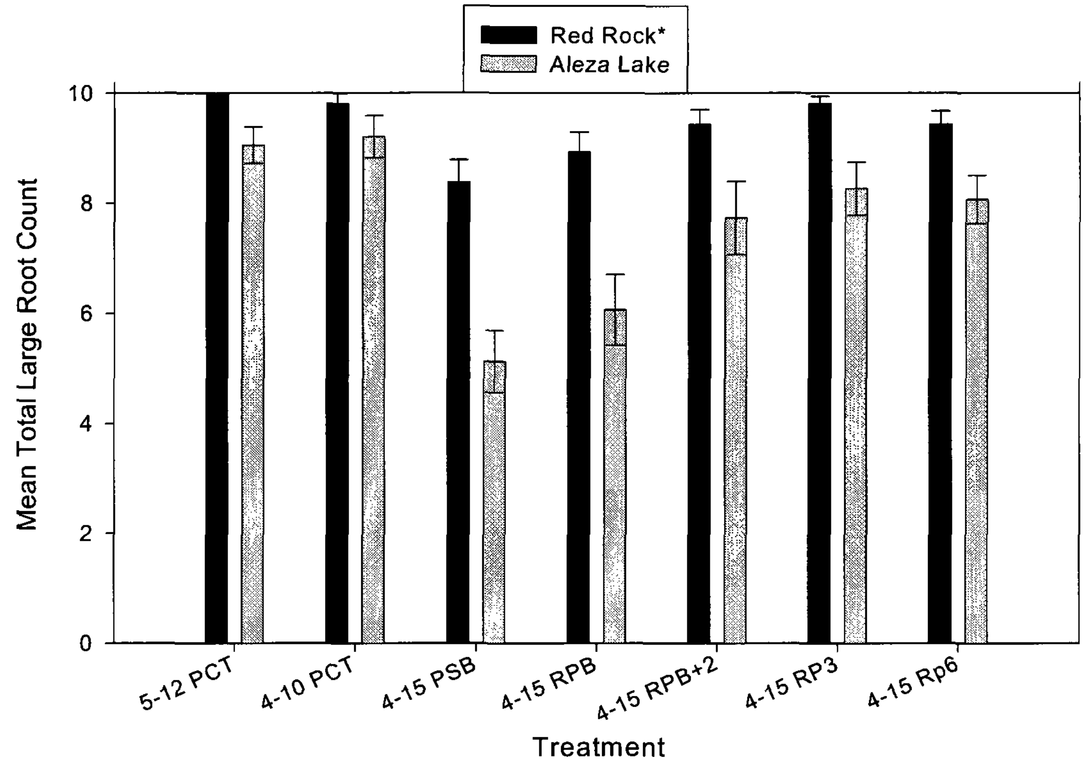
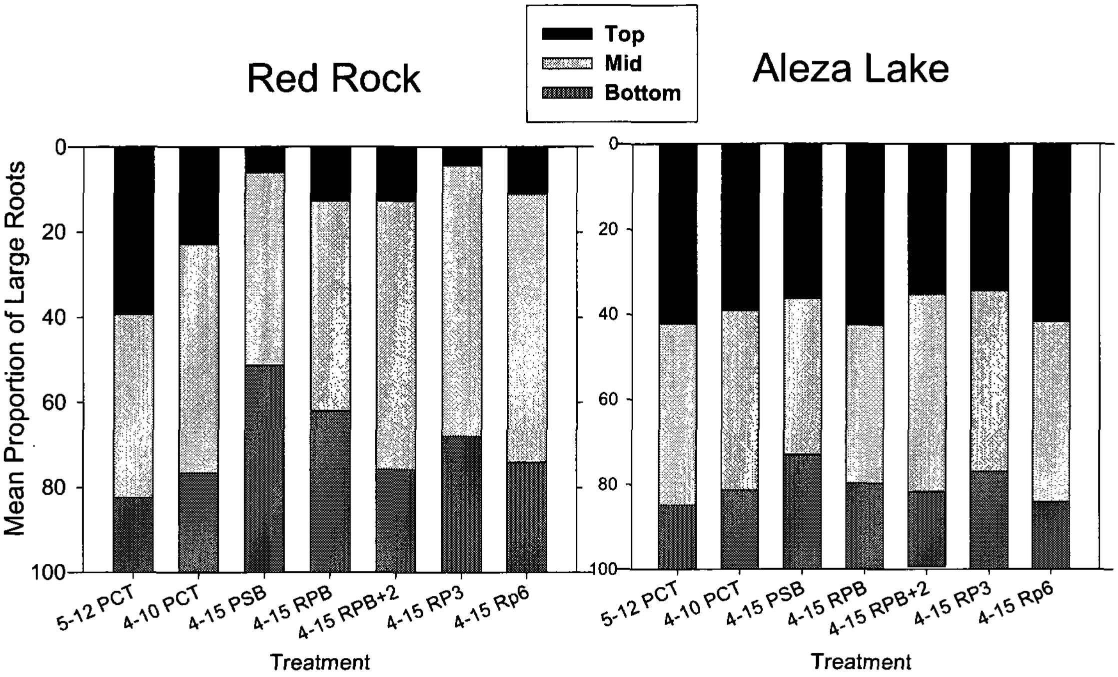


Figure 4.13. Mean total large roots counted and standard error (up to a cut off of 10) after one growing season at Aleza Lake and Red Rock sites. (* indicates significant site differences).

When large root counts were partitioned to relative contribution, according to plug location, sites influenced root location preferences as: middle > bottom > top for Red Rock and top = middle > bottom at Aleza Lake (Fig 4.14). Compared to total roots, large roots were more frequently developed in the top and middle plug locations, rather than from the bottom. Among treatments, the chemically pruned stock showed relatively low variation in root partitioning between sites, where as the PSB 4-15 and knife pruning treatments demonstrated site adaptation.



(A) (B)

Figure 4.14. Mean proportion of large roots partitioned to top, middle and bottom plug location after the first growing season at sites: (A) Red Rock (n=15) and (B) Aleza Lake.

4.4.8 Root Deformity Among Large Roots Counted

The mean percentage (and standard error) of non-deformed Direct Large Roots (DLR) at Aleza Lake was 48 % ± 2.7, significantly higher than the DLR at Red Rock at 37 % ± 2.6. The effect of treatment was also detected in DLR. The PSB 4-15 control and RPB treatment had the lowest DLR values tested while the PCT group had the highest mean proportions of DLR (Fig. 4.15). As compared with the control PSB 4-15, knife pruning with lateral pruning treatments increased mean DLR approaching values comparable to the chemically pruned PCT 4-10.

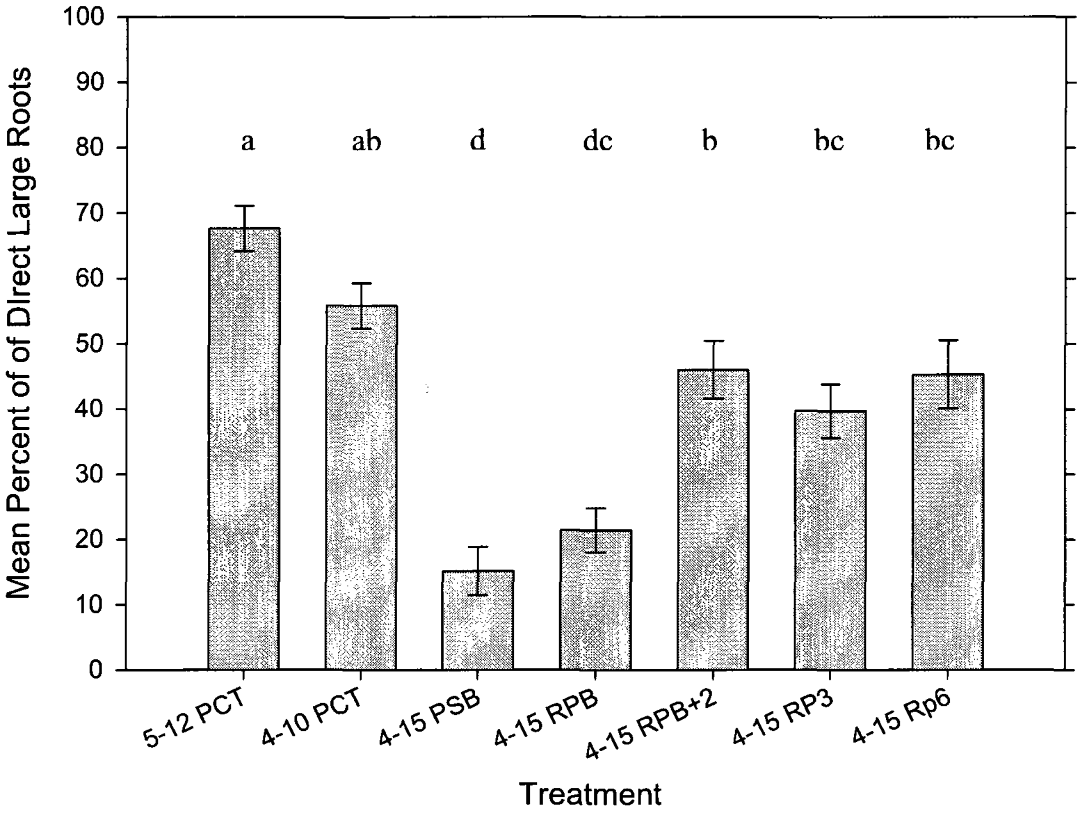


Figure 4.15. Treatment mean and standard error for the proportion of direct large roots after one-year for both sites combined. Means with same letter are not significantly different ($P > 0.05$). Sites were significantly different ($P < 0.05$).

4.4.9 Tap-Root Development

Tap-root development showed a poor trend as compared to the rest of the measured variables. Among sites and treatments, the population with secondary tap-root growth occurred 55% of the time. Analysis using logistic regression of tap-root development after one growing season was analysed for two factors: site and treatment. No site difference was observed (Fig. 4.16). Occasional treatment differences were detected when three bench-mark treatments: **PCT 4-10**, the **PSB 4-15** and the **RP6 4-15** were used to compare against all the other treatments with 95% confidence. In all cases when comparisons were analysed, the RP6 and RPB+2 showed significant increases in tap-rooting; all other treatments showed no difference.

RP6, RPB+2 > **PSB 4-15** = PCT 4-10, PCT5-15, RPB, RP3
RP6, RPB+2 > **PCT 4-10** = PSB 4-15, PCT5-12, RPB, RP3
RPB, RPB+2, RP3, PCT 5-12 = **RP6** > PCT 4-10, PSB 4-15

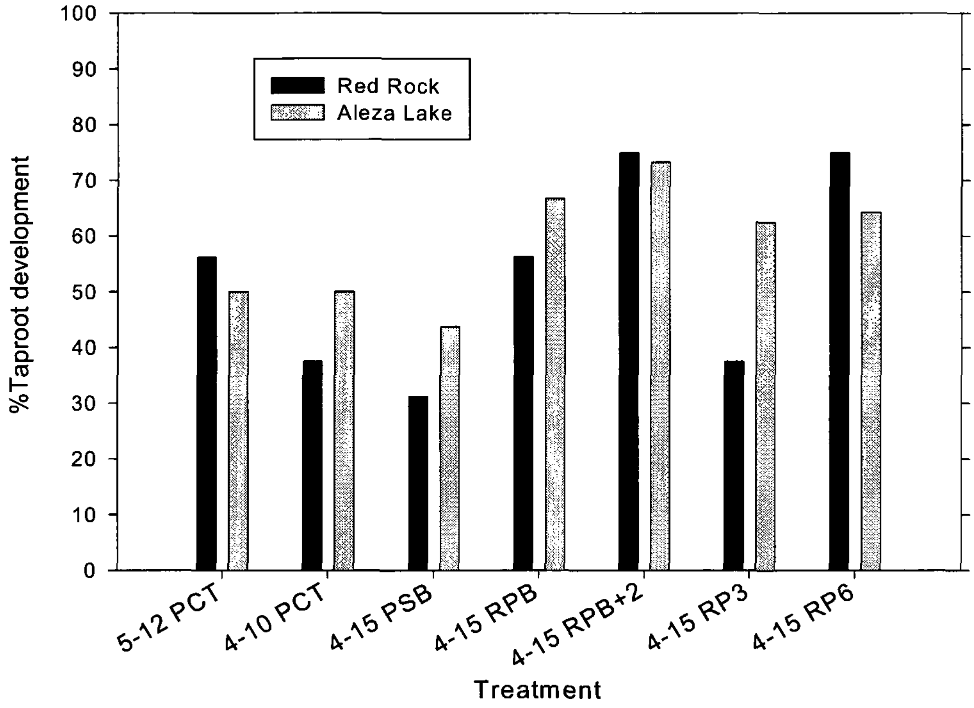


Figure 4.16. Percentage of treatment population with detected secondary growth in tap-root after one-year growth for Red Rock and Aleza lake sites.

5. Discussion

5.1 Site Differences and its influence on Seedling Growth and Development

Many of the measured growth variables demonstrated significant site differences, an indication of contrasting productivity in the two sites studied (Narukawa and Yamamoto, 2003; Jones et al., 2002; Balisky and Burton, 1997; Heinemann, 1991; Becker et al., 1987). Improved seedling height and diameter growth at Aleza Lake is likely the result of higher moisture and nutrient availability. Also root growth parameters, including the extent and location of root egress, were strongly dependent on soil type give rise to characteristic rooting patterns (Narukawa and Yamamoto, 2003; Eis, 1970).

For example, in dry soils, seedlings need to establish their root systems rapidly at the cost of height growth developing high root to shoot ratios (Preston, 1942). Enhanced root differentiation in dry soils explains why Red Rock seedlings had greater large root counts over total roots counted. Low water availability in Red Rocks upper 10 cm explains why roots were restricted in development in the uppermost plug (Fig. 4.14). Seedling root trajectories were oblique to steeply descending. Limited water retention capacity in the upper soil strata can be explained by the absence of a forest floor in addition to sites dominated by sandy texture (Fig. 4.1). Forest floors also buffer the evaporative demand, reflecting and insulating mineral soil from solar radiation (Heineman, 1998). Finally, observations made during seedling excavation, the extent of roots of some individuals exceeded 100 cm in lateral and 50 cm in vertical direction.

In contrast to Red Rock, the dominant root growth at Aleza Lake was in the upper and middle sections of the plugs where rooting trajectories were observed to be horizontal to oblique. Enhanced rooting at the soil surface is, in part, the result of poor soil drainage causing water saturation and anaerobic soil conditions. This restricts the development of roots with closer to the soil surface (Xu et al., 1997). Also, surface soils have higher nutrient availability because of the humus-rich forest floor (Brady and Weil, 1996).

Red Rock showed increased proportion of deformed large roots because there were a greater proportion of these to emerge out of the bottom of the plug. Increased deformity in the bottom of the plug is likely the effect of the container. As roots are deflected from their outward trajectory down the long axis of the container wall, they are more likely to interact with each other and braid (Balisky et al., 1995). Braided roots are prone to root balling, the subsequent disproportionate swelling of the plug (Winter and Low, 1990). Root balling occurs when root deformities are severe enough to impede the translocation of sugars within the phloem and concentrate an exaggeration of growth above root constrictions (Hay and Woods, 1978).

5.2 Field Root Growth Capacity at the Red Rock site

Root growth capacity (RGC) after 21-days was shown to be a useful tool for a rapid assessment of stock vigour and the potential rooting locations for PSB and PCT seedlings. Low total root counts in the bottom cut knife pruning treatments: RPB and RPB+2 might indicate poor stock performance (B.C. MOF, 1998), this claim however, was not reflected in decreased height growth needle length after one growing season under the tested site moisture regimes. A longer time frame is required in interpreting the results if height is impeded by pruning method or extent.

Reduced initial root counts may not be as important to seedling survival or growth as is the ability to develop non-deformed primary roots in the optimum soil conditions. For example, naturally germinated seedlings have far fewer roots than planted stock, however, these are of primary root types situated typically near the surface soil, well developed, expanding and branching extensively into the soil environment (Eis 1978, Horton 1958). Also, rooting development may not establish exclusively from pre-existing root tips within the plug. Adventitious roots emerge gradually and can be responsible for much of the structural roots as found in planted spruce seedlings (Heineman et al., 1999; Coutts et al., 1990). In the knife-pruned treatments, many adventitious roots emerged from the "wounds" resulting from knife pruning cuts. These roots likely developed after a lag time required for the "wounds" to heal. Considering the rooting delay, knife-pruning may compromise planted trees only in the driest of sites or seasons found in the BC interior.

Finally, the RGC test is limited in its application to assess the performance of out-planted stock considering the characteristic rooting patterns of seedlings planted under contrasting soils. For example, in very wet or cold soils, where rooting is limited with soil depth, stock types, like the PSB with its aggressive bottom plug growth, may perform sub-optimally with fewer root counts closer to the soil surface.

5.3 Comparison of Root Growth and Development Between Stock Types

The initial biomass ratio of the non-pruned PSB 4-15, with the lowest initial shoot to root ratio, proved to be a poor predictor of seedling performance with no differences in height growth detected after one year. In terms of root growth morphology, more important than initial root biomass is the initial root arrangement, which, in the case of the PSB 4-15 stock was mostly limited to bottom of the plug development. This style of growth, similar to a showerhead, showed the poorest development in root symmetry and greatest incidence of large root deformity. Dominant bottom root development, found in PSB 4-15 stock, agrees with the results of Heineman (1991), and Balisky and Burton (1997). PSB stock are, therefore, less likely to adapt to sites where rooting is best developed in surface soils. Examples of sites unfavorable to root development in surface soils include cut-blocks in central interior of BC where sites have cool soil temperatures (Balisky and Burton, 1997), reduced aeration, poor drainage (Heineman, 1991), scalped soils and increased soil density (Wass and Smith, 1994). Speculation exists whether root development where restricted to the bottom of the plug and deeper in the soil, as observed in the PSB 4-15 stock, particularly in the longer stock sizes, are more likely to be susceptible to stressful environmental episodes. PSB stock with greater bottom root development may be more responsive to site preparation designed to ameliorate soil conditions to achieving more vigorous establishment growth (Bedford and Sutton, 2000).

The PSB 4-15 stock scored lowest in large root tallies and showed the highest incidence of deformed large roots at both sites. Reduced number of large root counts in the PSB 4-15 stock could be due to their excessive root deformation leading to root balling and reduced distal growth. Reduced root symmetry in the PSB 4-15 stock is similar to the findings from a 5-year lodgepole pine trial by Winter and Low (1990). This suggests that developmental symmetry is a phenomenon that may have longer-term implications to tree growth. Since root tips grow in the direction of their initial orientation (Puhe, 2003), reduced root symmetry occurs because most of the root tips are typically pointed downward at the bottom of the plug. Greater root symmetry of large roots may show for greater resilience from mechanical forces that act on a stem as from wind, competing vegetation, snow press and from frost wedging during soil freeze-thaw events. Forces acting on the stem lead to curvature (Coutts et al., 1999). Higher incidences in stem curvature in PSB stock of lodgepole pine has been reported by Krasowski (2003). Stem curvature can lead to the development of compression wood detrimental to wood structural properties (Rune and Warensjö, 2002).

Compromised root growth demonstrated as reduced root symmetry, reduced large root counts and high incidence of large root deformity suggests that PSB seedlings has difficulty recovering from their containerized 'root-bound' conditions. Salonius et al. (2000) demonstrated in black spruce PSB seedlings that increased growing space led to higher photosynthate allocation to root over shoot and resulted in increased root density due to continuous root branching within the plug and the development of mature suberized root systems. However, Salonius et al. (2000) found that these over-developed plugs had poorer field growth performance as compared with seedlings grown at limited spacing with low root densities and more juvenile root systems. Norgren (1996) explained that as a colonizer species of disturbed soils, lodgepole pine have fast rates of root growth, particularly in fine root production, suggesting shorter cultivation times for container stock to avoid subsequent root deformation and root instability.

5.4. Root Growth and Development Among Root Pruning Treatments

Root pruned seedlings consistently produced superior root growth (e.g., balanced symmetry, low large root deformity, higher development of large root) relative to the non-pruned control seedlings. In addition, chemically pruned PCT (5-12 and 4-10) stock had greater incidence of top and mid plug development similar to the findings of Jones et al. (2002). When out-planted, the initiation of the dormant primary roots is again favoured as is demonstrated by increased incidence of large root counts (Fig. 4.13) and with more even root distribution throughout the plug (Fig. 4.14).

Cases of seedling mortality, reduced relative height growth, and shorter needle length, were observed only in the PCT 4-10 stock at both sites. This was likely caused by the stock's poor condition as a result of shipping stress. Mortality was greater at the Red Rock site suggesting it was exacerbated by low available moisture. However it is unlikely that the rooting pattern of this PCT 4-10 stock would change too drastically in response to the different soil types. Thus the relative growth if not the absolute in measured root parameters for this stock is still likely to be valid.

Growth results among the knife pruned treatments showed resilience to losses in initial root biomass with no reductions to stem growth after the first field-growing season. Based on the observed roots counts after 21 days, knife pruning treatments with lateral cuts showed better results than bottom plug removal cuts because the former did not significantly depress total roots counts in their early establishment. In addition to retaining a greater numbers of initial root tips, lateral pruning methods dispersed roots to a greater distribution throughout the plug. New adventitious roots grew in more outward directions created from the "wounds" left behind by cuts of the knife. Knife cuts to the mid-plug reduced the propensity of root braids reducing root deformity. While knife-pruning methods, RPB+2, RP3 and RP6, were statistically equivalent (Symmetry, Large Root Count, and Direct Large Roots) to chemical root pruning, the latter had root systems that still appeared more natural with a more consistent rooting pattern, reduced large root bending and inter-root constrictions within the plug.

It remains unclear if knife pruning stimulates tap-root development in early seedling development. Only two of three lateral cutting treatments showed statistically significant increases in tap-root development. When the replicates base from both sites were pooled and tap rooting was compared by seedlings that did not have their tap-roots cut (94 cases from PSB 4-15, PCT 4-10 and PCT 5-12), only 49% showed tap-rooting with secondary growth; this compared to 63% with tap-roots showing secondary development in those replicates that had their tap-root knife pruned in the lower plug (47 cases of knife prune bottom cut treatments: RPB and RPB+2); and 71% showing tap-root development from the 35 cases when lateral pruning severed the tap-root in the upper plug (RPB+2, RP3 and RP6). Since development for lodgepole pine is considered a tap-root dominant species particularly in well draining conditions (Eis, 1970), a study design that properly examines tap-root development with root pruning is warranted considering the beneficial attributes of tap roots dominance to tree rigidity and anchorage (Coutts et al., 1999).

In this study, knife-pruning methods tested fell below the critical maximum when growth and survival was compromised. It suggests that the PSB containerized seedling has considerable resilience to root system manipulation. Since knife pruning reduced the incidence of root deformities in the PSB 4-15 plug, in theory, continued knife pruning should improve root growth parameters further. A critical maximum point should exist however, where continued pruning would begin to show declines in stem growth (height, diameter, and needle) and survival. Indeed detection of growth loss will be more clearly evident by the second growing season. For example Bigras (1998) began to observe declines in growth performance of containerized black spruce at 40% biomass removal in her bottom plug removal technique. She also observed greater growth losses to diameter than height with 19% and 13% growth loss respectively in her maximum 80% biomass removal treatment. In another experiment, 50% destruction of the root system by root freezing Jack pine seedlings showed losses to height growth (Bigras and Margolis, 1997).

A root-pruning maximum should also exist as treatments interact with the effect of soil condition. For example, the harsher Red Rock site would likely tolerate less pruning than Aleza Lake before growth losses and mortality is realized. In this experiment, the most severe knife pruning treatment, RP6, removed on average 60% of the original root biomass, increasing the average shoot/root biomass fraction from 1.21 in the control PSB 4-15 to 2.88. In future, pruning treatments should encompass a shoot mass/root mass of up to 5 for sites in the BC interior. This will cover a greater pruning range and provided better understanding of the consequences of the higher levels of pruning treatments.

Significant height growth differences between sites but not among pruning treatments agrees with the findings of Winter and Low (1990) and Jones et al. (2002) supporting the theory that site has a greater effect on seedling growth than stock types or pruning treatments. Certainly, a longer study period of study, say four years, would provide better information on seedling growth differences among treatments because growth differences can manifest over a longer period of time as was observed by Burdette et al. (1983).

6. Conclusions and Management Implications

- **Root pruning treatments improved root growth**

Chemical and knife pruning treatments produced superior root growth (e.g., balanced symmetry, low large root deformity, higher development of large root) relative to the non-pruned PSB 4-15 lodgepole pine seedlings, grown on two contrasting sites in the interior of British Columbia. After one growing season, PCT and knife pruned seedlings had at least 90% of their roots develop in at least three directions compared to <30 % in uncut control (PSB). Root pruning increased the distribution of total roots throughout the plug, increased the proportion of large roots, as well as reduced the incidence of large root deformities. Among these aforementioned variables, chemical pruning treatments consistently exhibited better results than the knife pruning methods. The incidence of increased tap root development, however, may have increased with lateral cutting methods with knife pruning. Indeed more research is required to properly determine the long-term implications of root pruning on rooting development. The evidence presented here, however, suggests that benefits of root pruning showed consistency across the contrasting site conditions supporting its operational feasibility.

- **PCT stock offers improved rooting development**

Improved root development and the readily available PCT treated seedlings in commercial quantities makes PCT the preferred stock type over the PSB for reforestation in northern British Columbia. The effectiveness of PCT, however, has shown to be species limited but pine species such as lodgepole, white, and ponderosa as well as the

Douglas fir species have shown positive benefits (Krasowski, 2003; Wenny et al., 1988; Burdette et al., 1983). Interior spruce species has shown little effect (Krasowski and Owens, 2000). Due to species limitations and some environmental issues with the use of heavy metal paint, alternatives in methods of root pruning should still be encouraged.

- **Lateral rather than bottom cutting methods were favoured in knife pruned seedlings**

Lateral cutting was seen as more favourable than bottom cutting in terms of stimulating root growth because it retains some of the active root tips at the bottom of the plug and lead to higher initial root counts. Lateral cutting methods also improves the total root distribution, produces more balanced root symmetry, has higher large root counts and possibly increases tap root development. The intention for lateral pruning should be to cut progressively down the plug to untangle and redistribute large roots. Sufficient fine feeding roots should be retained for effective acquisition of immediate moisture and nutrition. Operationally, knife pruning could be performed with a tool attached to the bags of a tree planter where seedlings are pruned just prior to planting. Alternatively, knife pruning could be mechanically done at the nursery before packaging and cold storage.

- **Knife pruned stock must be handled with care**

Knife pruned seedlings should be handled with extra care because pruning treatments effectively reduce root density. Reduced root density renders seedlings susceptible to plug disintegrations with excessive handling. Operationally this may require innovations such as maintaining trees in a frozen state during planting as suggested by Kooistra and Bakker (2005).

- **Seedling size and chemical pruning method**

Growth parameters (e.g., height) of PCT 4-10 seedlings were better than other stock sizes used in the thesis. After four months growth the PCT 4-10 were comparable in root growth and height but not diameter when compared with the PCT 5-12. In comparison to the PSB 4-15, the PCT 4-10 seedlings were taller and larger in diameter with improved root development and root development than PSB 4-15 seedlings.

Presently, reforestation at the Aleza Lake Research Forest uses the PSB 4-15B seedling. A stock type change to PCT 4-10 is warranted to improve root development at a marginal additional cost. Also worth noting, the PCT 4-10 seedling was found to be much more efficient to plant than the 5-12 or the 4-15 stock size due to their smaller plug size. The 5-12 trees are awkward, requiring a big hole to accomodate the large plug while the 4-15 seedlings are very long, making them more difficult to plant without vertically compressing the plug or shutting the hole sufficiently without producing air pockets in heavy Aleza lake clay.

- **Soil conditions influenced root growth**

Site conditions such as soil properties significantly altered root size, abundance, distribution, trajectory and percentage of rooting deformities of lodgepole pine seedlings after the one growing season. The low volumetric water retention capacity in Red Rock site restricted root development in the uppermost 10-cm of the plug. In contrast, the dominant root growth at Aleza Lake was in the upper as well as in the middle sections of the plug where water is still available. The differential root development in two contrasting sites highlights the importance of soil properties to root growth. Other results imply the influence of soils on seedling performance and on management decisions such as harvesting method, site preparation, stock size selection and planting method, species and microsite selection.

- **Suggestions for future study**

The results of one-year experiment provided a short-term benefits of root pruning and identified areas that need to be addressed to understand the implications of pruning treatments, soil conditions and stock types to the long-term seedling growth and development. For example does root bind in PSB stocks have long-term implications to seedling growth? Are the beneficial effects of root pruning species dependent? Will root pruning improve seedling resilience to episodes of stress like climate, vegetation or snow? There is a need for long-term experiments addressing root development in various altitude-related seasonal temperature changes, growing substrates (mineral or organic), vegetative competition, species, microsite, stock type, and planting techniques.

- **Possible changes in the legislation**

The results from this thesis have shown that pruning improved the rooting development of chemical and knife pruned seedlings of lodgepole pine. Although the results in this thesis are short-term, if longer-term benefits of root pruning can be shown to improve rooting development against a PSB stock, across species, stock sizes, and soil conditions in a predictable and consistent outcome, it should be required by legislation. With the principal reforestation objective of industrial forestry is to achieve free-growing stocking standards, there exists no incentives to root prune since there is no confirmed height growth or survival advantage. Should legislation be put in place that makes this treatment mandatory, such a rule would be similar to the regulation that requires that foresters to use due diligence to obtain the best possible seed (class 'A' seed is preferred) available to a prescribed cut block.

Literature Cited

Anderson, L. 2001. Survival and growth of *Fagus sylvatica* seedlings root-pruned prior to transplanting under competitive conditions. Scandinavian Journal of Forest Research 16: 318-323.

Arocena, J. M. and Sanborn, P. 1999. Mineralogy and genesis of selected soils and their implications for forest management in central and northeastern British Columbia. Canadian Journal of Soil Science 572-592.

B.C. Ministry of Forests, 1993. Guidelines for the tree species selection and stocking standards for B.C. Victoria: Government of British Columbia.

B.C. Ministry of Forests, 1996. Timber supply analysis. Victoria: Government of B.C, and Ministry of Environment Land and Parks.

B.C. Ministry of Forests, 1998. Provincial Seedling Stock Type Selection and Ordering Guidelines. Victoria: Government of British Columbia.

B.C. Ministry of Forests, 2005. Annual Report. Victoria: Government of British Columbia, National Library of Canada.

Balisky, A. C., Salonius, P., Walli, C., Brinkman, D., 1995. Seedling roots and forest floor: Misplaced and neglected aspects of British Columbia's reforestation effort. Forestry Chronicle 71: 59 – 65.

Balisky, A. C. and Burton, P. J., 1997. Planted conifer seedling growth under two soil thermal regimes in high-elevation forest openings in the interior of British Columbia. 1997, New Forests 14: 63-82.

Barlette, K. J., 1996. Just the Facts - A Review of silviculture and other forestry statistics. FRDA 11, Victoria B.C., Government of British Columbia and Government of Canada.

Bartsh, N. 1987. Responses of root systems of young *Pinus sylvestris* and *Picea abies* plants to water deficits and soil acidity. Canadian Journal of Forest Research 17: 805-811.

Becker, C.A., Mroz, G.D., Fuller, L.G., 1987. The effects of plant moisture stress on red pine (*Pinus resinosa*) seedling growth and establishment. Canadian Journal of Forest Research 17: 813-820.

Bedford, L., Sutton, R.F., 2000. Site Preparation for establishing lodgepole pine in sub-boreal zone of interior British Columbia: The Bednesti trial, 10-year results. Forest Ecology and Management 126 (2000) 227-238

Bednesti, FRDA II, 1992. Testing the Biological Effectiveness of Mechanical Site Preparation Equipment. Victoria, Government of British Columbia.

Blake, G.R., Hartage K.H., 1986. Bulk density. In: Klute A., ed. Methods of soil analysis. Part 1, 2nd ed Madison, WI: ASA, 1986:364-366 Agron. Monogr. 9.

Blake, T.J., 1983. Transplanting shock in white spruce: effect of cold-storage and r,oot pruning on water relation and stomatal conditioning. Physiologia Plantarum 57: 210-216.

Bigras, F. J. 1998. Field performance of containerized black spruce seedlings with root system damaged by freezing or pruning. New Forests 15: Jan. 1998.

Bigras, F.J. and Margolis, H.A. 1997. Shoot to root sensitivity of containerized black spruce, white spruce and jack pine seedlings to late freezing. New forest 13: May 1997

Box, G. E. P. and Cox, D. R. , 1964. An analysis of transformations. Journal of Royal Statistical Society, Series B, vol. 26, pp. 211--246.

Brady, N. C. and Weil, R.R., 1996. The Nature and Properties of Soils (Eleventh Edition). New Jersey: Prentice-Hall Inc.

Burdette, A. N., Herring, L. J., Thompson, C. F. 1984. Early growth of planted spruce. Canadian Journal of Forest Research 14:644-651.

Burdette, A.N., Simpson, D. G., Thompson, C.F., 1983. Root development and plantation establishment success. Plant and Soil 71: 103-110.

Burdette, A. N., 1978. Control of morphogenesis for improved mechanical stability in container-grown lodgepole pine. Canadian Journal of Forest Research 8: 483 – 486.

Carnell, R., and Anderson, M. A., 1986. A technique for extensive field measurement of soil anaerobism by rusting of steel rods. Forestry 59: 129-140.

Coutts, M. P., Nielsen, C.C.N., and Nicoll, B.C., 1999. The development of symmetry, rigidity and anchorage in the structural root system of conifers. Plant and Soil 217: 1-15, 1999.

Coutts, M. P., Walker, C., and Burnand, A. C., 1990. Effects of establishment method on root form of lodgepole pine and Sitka spruce and on the production of adventitious roots. Forestry Vol. 63 No. 2.

Delong, H. B., Lieffers, V. J., and Blenis, P. V., 1997. Microsite effects on first year survival of white spruce in aspen-dominated boreal mixed woods. Canadian Journal of Forest Research 27: 1452-1457.

Eastham, A. M., and Jull, M., 1999. Factors affecting regeneration of *Abies lasiocarpa* and *Picea engelmainnii* in subalpine silviculture systems trial. Canadian Journal of Forest Research. 29:1847-1855.

Edgren, J.W. 1975. Wrenching-Recent developments in an old technique. USDA

Eis, S. 1978. Natural root forms of western conifers. Symposium on root form of planted trees. Ministry of Forest/ Canadian Forest Service joint report No. 8, pages: 23-28.

Eis, S. 1970. Root growth relationships of juvenile white spruce, alpine fir and lodgepole pine on three soils in the interior of British Columbia. Canadian Forest Service, Publication: 1276.

Fitter, A. and Hay, R., 1987. Environmental Physiology of Plants, San Diego Press

Gardner, W. 1986. Water content. P. 493-544, in In. Klute et al. (eds) Methods of soil analysis Part 1 Physical and mineralogical Agronomy Monograph no. 9 2nd ed, Soil Science Society America, Inc., Madison

Government of British Columbia, 2000. Just the Facts - A Review of silviculture and other forestry statistics, Victoria: Government of British Columbia, Government of Canada.

Government of British Columbia, 1990. Regenerating British Columbia's Forests. Vancouver: University of British Columbia Press.

Government of British Columbia, 1988. Field manual for describing terrestrial ecosystems. Land Management Handbook #25, Ministry of Forest, Ministry of Lands and Parks, Victoria.

Greens, R.N., Trowbridge, R.L., Klinka, K.,1993. Towards a taxonomic classification of Humus Forms. Forest Sicence, Monograph 29, Society of American Foresters.

Halter, M. R., Chanway, C. P., Harper, G. T., 1993. Growth reduction and root deformation of containerized lodgepole pine saplings 11 years after planting. Forest Ecosystem and Management 56 : 131 – 146,

Hay, R.L. and Woods, F. W., 1978. Carbohydrate relationships in root systems of planted loblolly pine seedlings. In Proceedings of the root forum of planted trees symposium; 1978 May 16-19, B.C. Ministry of Forest Service/ Canada Forestry Joint Report No. 8 ; p 73-84.

Heineman, J., Bedford L., and Sword D., 1999. Root system development of 12-year old white spruce on a mounded subhygric-mesic site in Northern Interior B.C. Forest Ecosystem Management 123: 167-177.

Heineman, J. 1998. Forest Floor Planting: A discussion of issues as they relate to site limiting factors. Forest Site Management: Silviculture Note 16, BC Ministry of Forest.

Heineman, J. 1991. Master's Thesis Dissertation: Growth of Interior Spruce seedlings on forest floor materials. University of British Columbia.

Horton, K., W., 1958. Rooting habits of lodgepole pine. Dept of Northern Affairs and Natural resources Technical note. No. 67.

Jones, M.D., Kiiskila, S. and Flanagan, A., 2002. Field performance of pine stock types: Two-year results of a trial on interior lodgepole pine seedlings grown in Styroblocks, Copperblocks, or AirBlocks. B.C. Journal of Ecosystems and Management Vol. 2 #1.

Kooistra, C. M., Bakker, J.D., 2005. Frozen-stored conifer container stock can be outplanted without thawing. Native Plants Fall 2005, 267-278.

Kozlowski, T.T., 1997. Physiology of woody plants. San Diego: Academic press.

Krasowski, M. J. and Caputa, A., 2005. Relationships between the root system size and its hydraulic properties in white spruce seedlings, New Forest May 6 2005.

Krasowski, M. J., 2003. Root system modifications by nursery culture reflect on post-planting growth and development of coniferous seedlings. The Forestry Chronicle, 79: 882-891.

Krasowski, M. J., and Owens, J. N., 2000. Morphological and physiological attributes of root systems and seedling growth in three *Picea glauca* reforested stock. Canadian Journal of Forest Research 30: 1669-1681.

Krasowski, M. J., Owens, J.N. Tackaberry, L.E., and Massicotte, H.B., 1999. Above- and below-ground growth of white spruce seedlings with roots divided into different substrates. Plant Soil 217:131-143.

Krasowski, M. J., Letchford, T., Caputa, A., Bergerud, W.A., and Ott, P.K., 1996. The susceptibility of white spruce to overwinter injury and their post-injury field responses, New Forest May 1996: 261-278.

Martisson, O., 1986. Taproot formation and early root/shoot ratio of *Pinus Contorta* and *Pinus Sylvestris.* Scandinavian Journal of Forest Research 1 (2): 233-242.

Norgren, O., 1996. Growth Analysis of Scots pine and lodgepole pine seedlings. Forest Ecology and Management 86 (1996) 15-26.

Narukawa,Y. and Yamamoto, S., 2003. Development of conifer seedling roots on soil and fallen logs in boreal and subalpine coniferous forests of Japan. Forest Ecology and Management 175 (2003) 131-139.

Paterson, J. M., and Maki, D. S., 1994. Effect of initial seedling morphology and planting practices on field performance of jack pine 6 years after planting. Forest Research Report No. 130.

Preisig, C. L., Carlson, W.C., Promnitz, L.C., 1979. Comparative root systems morphologies of seeded-in-place, bareroot, and containerized Douglas-fir seedlings after outplanting. Canadian Journal of Forest Research 9: 399 – 405.

Preston, R.J., 1942. Growth and development of root systems of juvenile lodgepole pine. Ecological monographs 12: 449-468.

Puhe, J., 2003. Growth and development of the root system of Norway spruce (*Picea abies*) in forest stands- a review. Forest Ecology and Management 175: 235-273.

Ritchie, G. A. and Dunlap, J. R., 1980. Root Growth Potential: its development and expression in forest tree seedlings. New Zealand Journal of Forest Science 10, 218-248.

Robert, J. A. 2004. Effects of root deformation on growth and susceptibility of lodgepole pine to attack by the warren root collar weevil. M.Sc. Thesis, UNBC.

Rune, G. 2003. Slits in container wall improve root structure and stem straightness of outplanted scots pine seedlings. Silva Fennica 37(3): 333-342.

Rune, G. and Warensjö, 2002. Compression wood in Scots pine. Scandinavian Journal of Forest Research 17 (2002).

Salonius, P., Beaton, K., Roze, B., 2000. Effects of cell size and spacing on root density and field performance of container-reared black spruce. Canadian Forest Service Information Report M-X- 208E.

Strong, W. L. and Roi, G. H., 1983. Root-system morphology of common boreal forest trees in Alberta, Canada. Canadian Journal of Forest Research 13: 1164-1173.

Sutton, R., F., 1980. Root System Morphogenisis. New Zealand Journal of Forest Sciences 10:264-92.

Tipper, H.W., 1971. Glacial geomorphology and Pleistocene history of central British Columbia. Bulletin 196, Geological Survey of Canada, Department of Energy, Mines and Resources, Ottawa, ON.

USDA 1990. Silvics of North America – Vol. 1: Conifers. USDA Agriculture Handbook 654.

Van Den Driessche, R.,1987. Importance of current photosynthate to new growth in planted conifer seedlings. Canadian Journal of Forest Research 17: 776-781.

Van Eerden, E., 1981. Root form of planted trees, Symposium on root form of planted trees. In Proceedings of the root forum of planted trees symposium; 1981 May, B.C. Ministry of Forest Service/ Canada Forestry Joint Report ; p: 401-406.

Van Eerden, E., 1978, Roots of planted trees in Central B.C. Symposium on root form of planted trees. In Proceedings of the root forum of planted trees symposium; 1978 May 16-19, B.C. Ministry of Forest Service/ Canada Forestry Joint Report No. 8; p: 23-28.

Vapavuori, E.M., Rikala, R., Ryyppo, A., 1992. Effects of root temperature on growth and photosynthesis in conifer seedlings during shoot elongation. Tree Physiology 10: 217-230.

Wass, E. F., and Smith R. B., 1994. Impacts of soil disturbance on root systems of Douglas-fir and logdepole pine seedlings. Canadian Forest Service Information report.

Wenny, D.L., Liu, Y., Dumroese, R.K., Osborne H.L., 1988. First year field growth of chemically root pruned containerized seedlings. New Forests 2: 112, 118.

Winter, R. and Low, S., 1990. Manual and chemical root pruning of lodgepole pine PSB 2-11 stock. Ministry of Forest Silviculture Branch Interim Report. Victoria: Province of British Columbia.

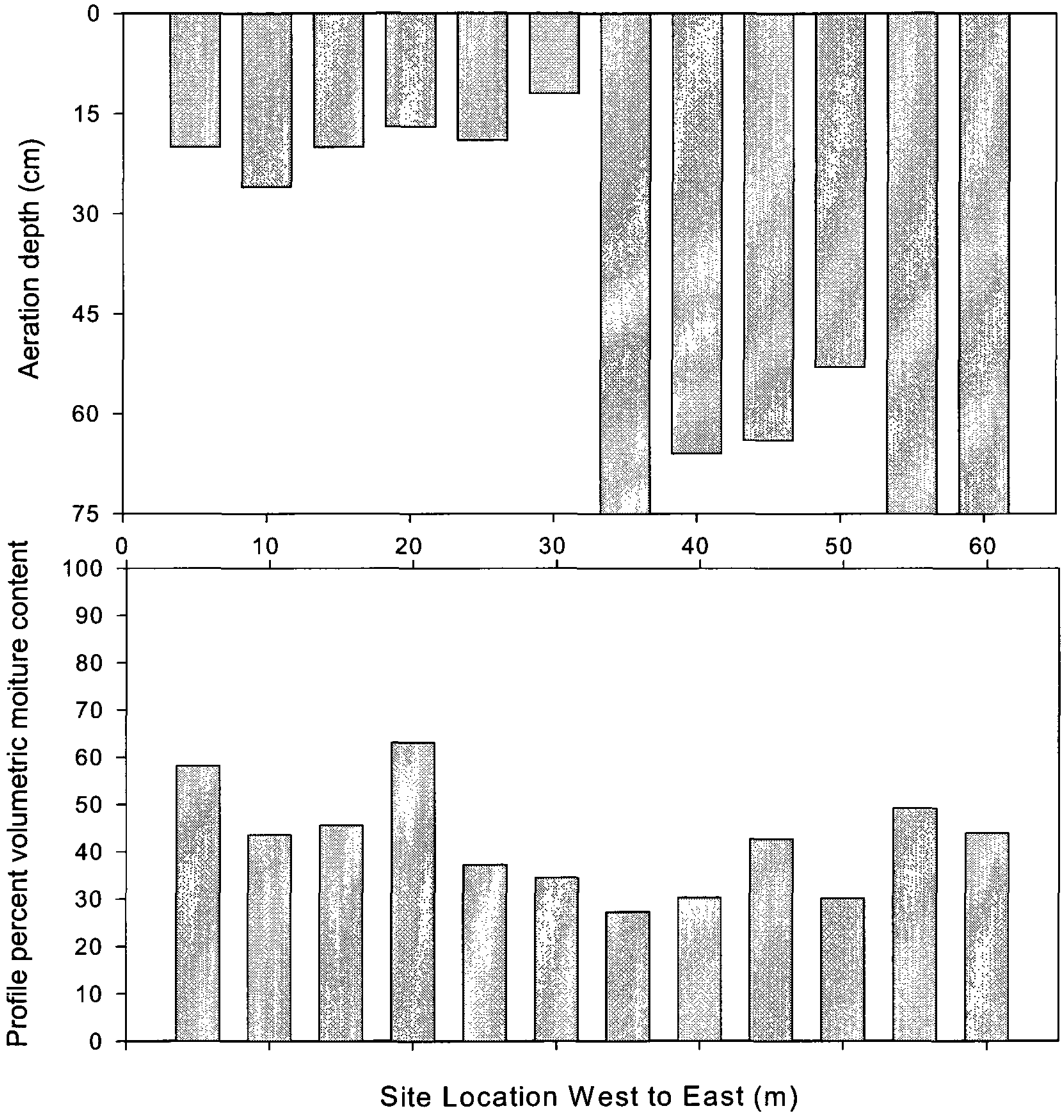
Wright, E. F., Coates, K. D., and Bartemucci P., 1998. Regeneration from seed of six tree species in the interior cedar-hemlock forests of B.C. as affected by substrate and gap position. Canadian Journal of Forest Research. 28: 1352-1364.

Xu, Y., Rohrig E., and Folster H. 1997. Reaction of root systems of grand fir (*Abies grandis* Lindl.) and Norway spruce (*Picea abiea* Karst.) to seasonal waterlogging. Forest Ecology and Management 93: 9-19.

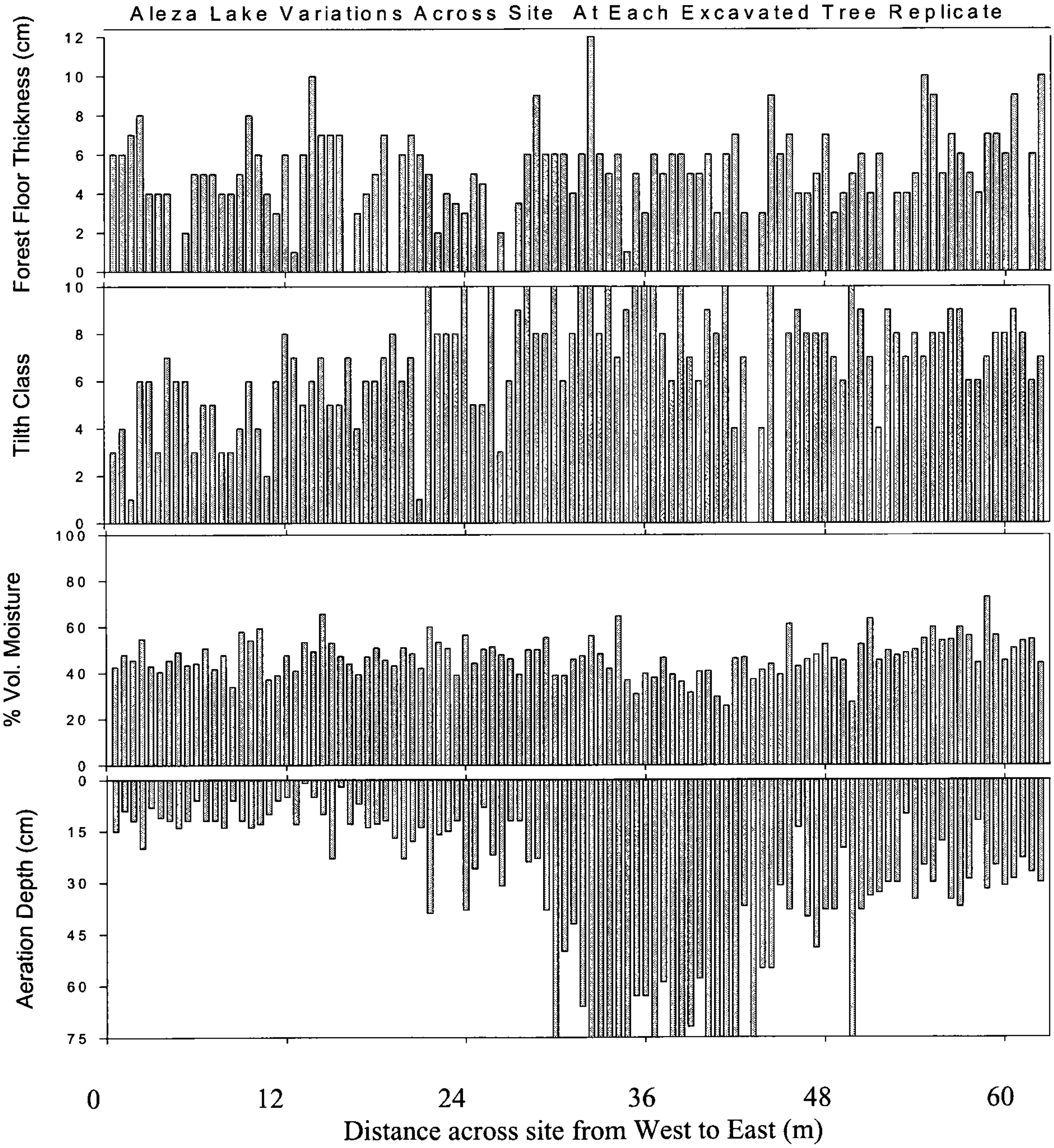
Appendix A. Mean and (standard deviation) of soil bulk density (g cm^{-3}) at various strata in Aleza Lake (n = 15) and Red Rock sites (n = 6).

Strata	Aleza Lake	Red Rock
Upper (0-10cm)	0.70 (0.130)	1.58 (0.042)
Middle (10-20cm)	1.08 (0.095)	1.41 (0.050)
Lower (20-30cm)	1.24 (0.163)	1.60 (0.038)

Appendix B. Aleza Lake Summer Aeration (Aug.5- Sept 5, 2005) for 12 observations across 60 m site (West –East) and the corresponding volumetric moisture contents on Sept 5, 2005

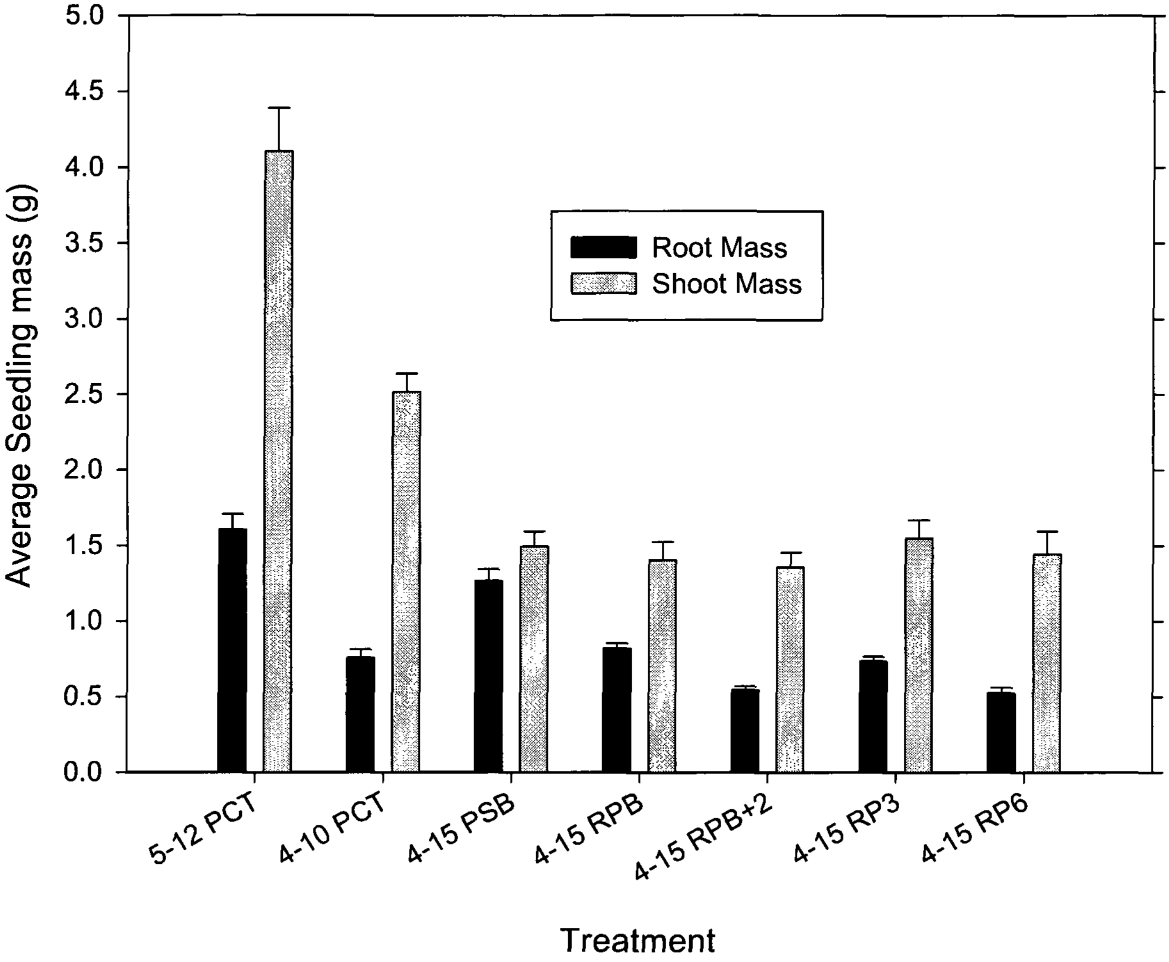


Appendix C. Forest floor thickness, soil tilth class*, volumetric moisture content and aeration depth measured at Aleza Lake on Oct 20, 2006. Measurements were from 105 randomly chosen trees planted in 10m rows (North to South) across 65m site (East to West): Zero represent missed observation



*Soil Tilth Class = Structure class + Consistence class

Appendix D. Mean and standard error for initial root and shoot biomass (g) for stock type and knife pruning treatments (n = 10) .



APPENDIX E. Anova and Logistic Regression Tables For Data Analyzed in Chapter 4.

Dependent Var: Shoot to Root Biomass Ratio N: 7
Multiple R: 0.815 Squared multiple R: 0.664
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
TREATMENT	7.286	6	1.214	20.708	< 0.001
Error	3.695	63	0.059		

Dependent Var: Number of Laterals Cut in Upper Plug N: 90
Multiple R: 0.544 Squared multiple R: 0.296
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
TREATMENT	70.792	2	35.396	18.290	< 0.001
Error	168.364	87	1.935		

Dependent Var: Relative Growth Height N: 310
Multiple R: 0.689 Squared multiple R: 0.475
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	2.575	1	2.575	192.061	< 0.001
TREATMENT	0.969	6	0.162	12.051	< 0.001
SITE*TREATMENT	0.058	6	0.010	0.724	0.631
Error	3.969	296	0.013		

Dependent Var: Relative Growth Diameter N: 310
Multiple R: 0.510 Squared multiple R: 0.260
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	2.838	1	2.838	70.857	< 0.001
TREATMENT	0.671	6	0.112	2.792	0.012
SITE*TREATMENT	0.227	6	0.038	0.943	0.465
Error	11.856	296	0.040		

Dependent Var: AVENEEDLE Length N: 310
Multiple R: 0.485 Squared multiple R: 0.235
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	235.655	1	235.655	66.381	< 0.001
TREATMENT	70.020	6	11.670	3.287	0.004
SITE*TREATMENT	1.007	6	0.168	0.047	1.000
Error	1050.814	296	3.550		

```
Response Variable              Symmetry
     Number of Response Levels     4
     Model                         cumulative logit
     N= 218
                    Response Profile
            Value           Sym      Frequency
              1              1           32
              2              2           55
              3              3           90
              4              4           41
                                                   Odds Ratio Estimates
                                                 Point          95% Wald
            Effect                               Estimate      Confidence Limits
            Site        AL vs RR                   1.441       0.867       2.397
            Stock_Type  PSB 4-15 vs PCT4-10       52.567      17.350     159.266
            Stock_Type  PCT 5-12 vs PCT4-10        0.627       0.243       1.619
            Stock_Type  RP1 4-15 vs PCT4-10        6.928       2.602      18.446
            Stock_Type  RP2 4-15 vs PCT4-10        1.147       0.443       2.971
            Stock_Type  RP3 4-15 vs PCT4-10        2.589       0.995       6.741
            Stock_Type  RP6 4-15 vs PCT4-10        1.418       0.547       3.676
            Stock_Type  PCT 4-10 vs PSB4-15        0.019       0.006       0.058
            Stock_Type  PCT 5-12 vs PSB4-15        0.012       0.004       0.036
            Stock_Type  RP1 4-15 vs PSB4-15        0.132       0.048       0.362
            Stock_Type  RP2 4-15 vs PSB4-15        0.022       0.007       0.065
            Stock_Type  RP3 4-15 vs PSB4-15        0.049       0.017       0.142
            Stock_Type  RP6 4-15 vs PSB4-15        0.027       0.009       0.080
            Stock_Type  PSB 4-15 vs RP6 4-15      37.075      12.508     109.897
            Stock_Type  PCT 4-10 vs RP6 4-15       0.705       0.272       1.828
            Stock_Type  PCT 5-12 vs RP6 4-15       0.442       0.172       1.138
            Stock_Type  RP1 4-15 vs RP6 4-15       4.887       1.875      12.736
            Stock_Type  RP2 4-15 vs RP6 4-15       0.809       0.315       2.077
            Stock_Type  RP3 4-15 vs RP6 4-15       1.826       0.713       4.677
```

Dependent Var: RGC TOTAL ROOT Number (after 21 days)   N: 70
Multiple R: 0.775   Squared multiple R: 0.601
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
TREATMENT	55735.086	6	9289.181	15.785	< 0.001
Error	37074.400	63	588.483		

Dep Var: TOTAL ROOT COUNT After One Growing Season N: 218
Multiple R: 0.713 Squared multiple R: 0.509
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	1.637	1	1.637	18.578	< 0.001
TREATMENT	16.309	6	2.718	30.850	< 0.001
SITE*TREATMENT	0.699	6	0.116	1.322	0.249
Error	17.973	204	0.088		

Dep.Var: TOP/TOTAL TOTAL ROOT COUNT After One Growing Season
N: 218 Multiple R: 0.718 Squared multiple R: 0.516
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	11304.515	1	11304.515	168.609	< 0.001
TREATMENT	2456.771	6	409.462	6.107	< 0.001
SITE*TREATMENT	1006.702	6	167.784	2.503	0.023
Error	13677.303	204	67.046		

Dep Var: BOTTOM/TOTAL Fraction of TOTAL ROOT COUNT N: 218
Multiple R: 0.732 Squared multiple R: 0.535
Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	11541.296	1	11541.296	73.076	< 0.001
TREATMENT	25690.704	6	4281.784	27.111	< 0.001
SITE*TREATMENT	499.089	6	83.181	0.527	0.788
Error	32218.673	204	157.935		

Dep Var: TOTAL Large Roots (up to 10)   N: 217   Multiple R: 0.671   Squared multiple R: 0.450

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	166.362	1	166.362	66.191	< 0.001
TREATMENT	204.667	6	34.111	13.572	< 0.001
SITE*TREATMENT	44.341	6	7.390	2.940	0.009
Error	510.211	203	2.513		

Dep Var: TOP/TOTAL LARGE ROOT COUNT   N: 217

Multiple R: 0.637   Squared multiple R: 0.405

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	29196.080	1	29196.080	91.497	< 0.001
TREATMENT	9682.899	6	1613.817	5.058	< 0.001
SITE*TREATMENT	5201.014	6	866.836	2.717	0.015
Error	64775.624	203	319.092		

Dep Var: MID/TOTAL LARGE ROOT COUNT   N: 217

Multiple R: 0.422   Squared multiple R: 0.178

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	9121.698	1	9121.698	22.611	< 0.001
TREATMENT	5911.774	6	985.296	2.442	0.027
SITE*TREATMENT	2500.962	6	416.827	1.033	0.405
Error	81893.551	203	403.417		

Dep Var: BOTTOM/TOTAL LARGE ROOT COUNT   N: 217   Multiple R: 0.437   Squared multiple R: 0.191

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	5785.378	1	5785.378	15.388	< 0.001
TREATMENT	9909.823	6	1651.637	4.393	< 0.001
SITE*TREATMENT	2297.706	6	382.951	1.019	0.414
Error	76323.204	203	375.976		

Dep Var: DIRECT ROOT COUNT/TOTAL LARGE ROOT COUNT   N: 218

Multiple R: 0.642   Squared multiple R: 0.412

Analysis of Variance

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
SITE	101.691	1	101.691	5.812	0.017
TREATMENT	2372.183	6	395.364	22.595	< 0.001
SITE*TREATMENT	40.404	6	6.734	0.385	0.888
Error	3569.551	204	17.498		

```
Response Variable      TAP ROOT DEVELOPMENT
           Number of Response Levels     2
           Model   Binary logit        N=  218
                     Response Profile
           Ordered                         Total
           Value          tap        Frequency
              1             0              97
              2             1             121
                       Odds Ratio Estimates
                                             Point          95% Wald
            Effect                          Estimate      Confidence Limits
            Site       AL vs RR               0.774        0.444       1.348
            Stock_Type PSB4-15 vs PCT4-10     1.287        0.464       3.565
            Stock_Type PCT 5-12 vs PCT4-10    0.679        0.249       1.854
            Stock_Type RP1 4-15 vs PCT4-10    0.484        0.174       1.346
            Stock_Type RP2 4-15 vs PCT4-10    0.266        0.090       0.785
            Stock_Type RP3 4-15 vs PCT4-10    0.819        0.298       2.250
            Stock_Type RP6 4-15 vs PCT4-10    0.313        0.108       0.904
            Stock_Type PCT4-10 vs RP6 4-15    3.197        1.106       9.243
            Stock_Type PSB4-15 vs RP6 4-15    4.113        1.428      11.846
            Stock_Type PCT 5-12 vs RP6 4-15    2.172        0.765       6.164
            Stock_Type RP1 4-15 vs RP6 4-15    1.546        0.535       4.472
            Stock_Type RP2 4-15 vs RP6 4-15    0.850        0.277       2.603
            Stock_Type RP3 4-15 vs RP6 4-15    2.617        0.916       7.477
            Stock_Type PCT 4-10 vs PSB4-15    0.777        0.281       2.153
            Stock_Type PCT 5-12 vs PSB4-15    0.528        0.194       1.434
            Stock_Type RP1 4-15 vs PSB4-15    0.376        0.136       1.042
            Stock_Type RP2 4-15 vs PSB4-15    0.207        0.070       0.608
            Stock_Type RP3 4-15 vs PSB4-15    0.636        0.233       1.740
```