CONDITIONING WHITE SPRUCE (*PICEA GLAUCA* (MOENCH) VOSS) TRANSPLANTS FOR OVERWINTER STORAGE BY ROOT PRUNING AND WRENCHING

by
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A Thesis Submitted in Partial Fulfillment
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ABSTRACT

Buse, L.J. 1987. Conditioning white spruce (*Picea glauca* (Moench) Voss) transplants for overwinter storage by root pruning and wrenching. M. Sc. F. Thesis, School of Forestry, Thunder Bay, Ont. Major Advisor: Prof. R. J. Day

KEYWORDS: White spruce, *Picea glauca*, root pruning, root wrenching, root conditioning, bareroot nursery practice, overwinter frozen storage, root growth potential, shoot growth potential, potassium fertilizer.

Problems associated with the establishment and early growth of outplanted white spruce (*Picea glauca* (Moench) Voss) led to research on conditioning white spruce transplants for overwinter frozen storage by root pruning and wrenching. The objectives of the research were: 1) to use root pruning and wrenching treatments in conjunction with potassium fertilizer treatments during the final year in the nursery to modify the morphology and physiology of white spruce transplants, 2) to monitor the effects of the treatments on the shoot and root growth response of the stock during overwinter frozen storage, and 3) to monitor the performance of both overwinter frozen stored and spring lifted stock, which had been subjected to root pruning and wrenching treatments, after outplanting.

In 1984, 2+1 white spruce transplants were root pruned in three phenological stages: 1) pre-flush, 2) mid-flush and 3) post-flush, followed by root wrenching at 28-day intervals. Additional potassium fertilizer was applied at three levels (0 kg/ha, 100 kg/ha and 200 kg/ha). In 1985, 2+1 white spruce transplants were root pruned early in the season followed by 1) wrenching at 21-day intervals or 2) wrenching periodically to coincide with periods of peak root growth. Additional potassium fertilizer was applied at two levels (0 kg/ha and 75 kg/ha). In both years, 25 transplants per variate were monitored throughout the season for height and root collar diameter growth. At the end of the season, these samples were assessed for morphological quality. Bud samples were collected to assess the effects of wrenching on primordia development. Samples of the stock were fall lifted and placed into overwinter frozen storage at -2^{o}C. Batches of stock were removed from the freezer at one month intervals during the winter and assessed for time to bud break and root growth potential after 21-days in the growth chamber. Fall lifted and overwinter stored stock was outplanted simultaneously with spring lifted stock from the same experiments. The outplanted stock was assessed for root growth potential after 21 days, survival and growth after the first and second year for the 1984 root conditioning trial and the first year for the 1985 trial. Plant moisture stress was monitored for the first three weeks after outplanting.

Root conditioning modified the morphology of the stock in both years by reducing height and root collar diameter and inducing the development of a more compact fibrous root system. Early season root pruning followed by wrenching at regular intervals throughout the growing season was most effective in modifying the morphology of the stock. Root growth patterns during overwinter frozen storage were different in the two years, with a mid-season peak occurring the first year and a gradual decline occurring through the winter in the second year. Shoot growth response was similar in both years. Survival was excellent but growth was poor for the 1985 outplant. Survival and growth wre excellent for the 1986 outplant. Differences between the two years can be attributed to differences in climate and handling practices rather than the treatments. The results indicate that root conditioning does not confer any significant advantage to stock outplanted in wet years and that additional potassium fertilizer does not increase survival through storage or after outplanting.

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INTRODUCTION

Successful reforestation depends to a great extent on the production and establishment of large numbers of high quality forest tree seedlings. The low survival and slow growth of both bareroot and container stock during the early years after outplanting and the high costs associated with planting trees are currently of considerable concern in Ontario (von Althen 1985). In spite of this, planting of bareroot seedlings and transplants remains the most widely used method of regeneration because it is the most dependable and efficient. The increasing importance of artificial regeneration in Ontario's forest industry is apparent from recent statistics, which indicate that black spruce (*Picea mariana* Mill. B.S.P.) seedling production tripled and that of jack pine (*Pinus banksiana* Lamb.) doubled in the five year period from 1979-1984. During the same time, the amount of white spruce (*Picea glauca* (Moench) Voss) nursery stock produced remained relatively constant at 16-18 million per year (O.M.N.R. 1986).

Historically, white spruce has been an important species in the Canadian forest industry because of its widespread distribution and usefulness for both pulpwood and lumber (Stiell 1976). White spruce is found sporadically in the Boreal mixedwood of Ontario, usually in conjunction with aspen (*Populus tremuloides* Michx.). Once it becomes established, white spruce grows rapidly and recent work has suggested that it may outproduce aspen on certain sites (Bell 1985). To date, more white spruce has been planted in Ontario than any other species (Blake 1983). In the Thunder Bay district alone, five million bareroot white spruce were planted between 1979 and 1984 (Kenny 1985).

The lack of increase in white spruce seedling production relative to that of jack pine and black spruce is due to specific problems associated with establishing and growing it in plantations. White spruce is considered to be one of the more difficult species to establish (Burdett *et. al.* 1984) because of its tendency to go into 'planting check', which is a period of very slow growth after outplanting (Mullin 1963a), and its susceptibility to late spring frosts (Vyse 1981). Both planting check and frost damage can have a negative impact on the success of plantations owing to their inhibitive effect on survival and growth after outplanting. The key to improving the successful establishment of white spruce plantations lies in overcoming planting check and reducing frost damage during the first five to ten years after outplanting.

Planting check is related to the physiological state of the seedlings at the time of lifting and planting (Burgar and Lyon 1968). Early spring lifting has been the most successful method of establishing white spruce in the past; but increasingly, nursery stock in Ontario is being fall lifted and overwinter stored to facilitate the handling of larger numbers of trees at the nurseries. Stock planted from storage has been shown to be less frost susceptible since its growth is delayed by one to three weeks (Brown 1971). However, other problems have been encountered after outplanting overwinter stored white spruce nursery stock. Survival and growth after outplanting have been quite variable, especially in dry years or on dry sites. Jorgenson and Stanek (1962) obtained positive results with white spruce stored in uncontrolled conditions, whereas Mullin (1966) indicated poor survival and growth of frozen stored white spruce relative to fresh lifted stock. Mullin and Forcier (1976) found that frozen stored white spruce seedlings showed poor survival and growth when compared with spring lifted stock. More recently, Day and Harvey (1984a,b) indicate that fresh lifted stock survives and grows better than frozen stored stock but that proper conditioning treatments and planting times can result in reasonable results with the latter as well. Despite these variable results, the amount of stock being cold stored by Ontario nurseries is increasing steadily (Thieman 1985, pers. comm.), making research on improving white spruce survival and growth after cold storage necessary.

Physiological damage in storage may be contributing to poor survival and growth after outplanting. This may result from a lack of cold hardiness when the stock is placed in storage, a build up of toxic substances in the storage containers or lack of conditioning through temperature, light, humidity and daylength fluctuations in storage. Since potassium deficiency has been shown to increase the susceptibility of seedlings to frost damage (Mengel and Kirkby 1978), potassium fertilization has been suggested as a potential means of increasing frost hardiness. The literature on this subject is inconclusive (Pellet and Carter 1981), but potassium fertilization may be a means of improving the survival of overwinter stored stock after outplanting.

Burdett *et. al.* (1984) state that since water stress is the major limiting factor for white spruce bareroot stock the first year after outplanting, planting check can be reduced or prevented by using stock with high root growth potential and physiological adaptations for drought resistance. Exposure to moderate stress in the nursery is thought to make seedlings more resistant to future stresses (Levitt 1980a), such as those encountered during lifting, handling, planting and the critical establishment period. Measures aimed at hardening seedlings before they are lifted may increase their resistance to storage (Navratil 1973). Root pruning (undercutting with a sharp blade) and wrenching (drawing a blunt, angled blade beneath the roots) at intervals during the final year in the nursery cut off the fine root tips and subject the stock to moisture stress. These conditioning treatments have been shown to improve the establishment and growth of many species after outplanting (Rook 1969, Chavasse 1978). For example, with Douglas-fir (*Pseudotsuga menzieseii* (Mirb.) Franco) and Monterey pine (*Pinus radiata* D. Don), root conditioning treatments resulted in seedlings with low shoot/root ratios and many fine absorbing roots. These characteristics, together with high root growth potential, are the most important for successful seedling establishment and growth on stressful sites (Hobbs 1984).

The survival and growth of outplanted seedlings are functions of vigour, growth rate and resistance to environmental stresses. Cultural treatments applied at the nursery are probably more effective than at any other stage in the growth of the tree because growth responses in seedlings are more elastic (Brown 1984). By understanding the physiology of seedling growth and how it is affected by environmental influences, nursery cultural practices can be used to modify seedling quality for improved survival and growth after outplanting. Harvey (1984) is the only researcher to date to investigate the effect of root pruning and wrenching white spruce transplants in the nursery on their morphological and physiological characteristics. He showed that root conditioning improved the morphology of 2+2 white spruce transplants, increased the abundance of fine absorbing roots and caused a threefold increase in root growth after outplanting. His study indicated no difference in survival or growth of wrenched versus unwrenched stock the first year after outplanting which he attributed to a moist growing season.

This study attempts to modify Harvey's (1984) treatments to improve the physiological response of the stock to conditioning and to determine if root conditioning is an appropriate method of preparing white spruce to withstand the stresses of overwinter frozen storage and outplanting. The hypothesis was that the survival and growth of overwinter stored white spruce stock could be improved by root pruning and wrenching during the final year on the nursery. The objectives of the research were as follows:

1) To assess the effects of root conditioning (root pruning followed by root wrenching) on the morphological and physiological quality of rising 2+2 white spruce transplant stock during the final year on the nursery.

2) To evaluate the shoot and root growth response of both root conditioned and non-conditioned 2+2 white spruce transplants entering dormancy and after dormancy release during six months in overwinter storage at - 2^{o}C.

3) To field test and monitor the performance of both root conditioned and non-conditioned 2+2 white spruce transplant stock that were overwinter stored at - 2^{o}C with identical stock that was overwintered in the nursery beds and spring lifted.

4) To evaluate the effect of potassium fertilization on the survival and growth of overwinter stored white spruce transplants after outplanting.

LITERATURE REVIEW

ROOT PRUNING AND WRENCHING

Terminology

Root pruning and wrenching, also defined as root conditioning (Sutton and Tinus 1983), consist of root pruning in the spring and root wrenching at one or more times during the final growing season before the stock is shipped. The terminology for these procedures has been thoroughly reviewed by Harvey (1984) and will not be repeated here except to define how the terms are used in this paper. Root pruning is used synonymously with undercutting and refers to horizontal pruning only. A single sharp blade is drawn through the nursery bed at a depth of 5-10 cm to sever the tap root and other long vertical roots of the stock. Root wrenching refers to a series of stressing treatments where a dull, angled blade is pulled through the nursery bed at a depth of 10-15 cm to break the fine root tips of the stock and loosen and aerate the soil.

Purpose of Root Pruning and Wrenching

Root pruning has been a conventional nursery treatment since the early part of this century. Root pruning was introduced in the United States to increase the root fibrosity of pines and eliminate costly transplanting (Hastings 1923). Experiments with root pruning were expanded from fall treatments to spring and summer prunings in an attempt to increase the number of plantable seedlings (Huberman 1940). Spring pruning of seedling stock became standard practice to control height growth in southern pines which were being held until the following spring (Clifford 1956, Eide and Grimm 1958). In New Zealand in the 1960's, root pruning was considered standard nursery practice and was used to condition seedlings to withstand transplanting stress (Gingerich and Hertel 1962, Sweet and Rook 1972).

Table 1 summarizes the information available on pruning and wrenching treatments applied in the nursery bed and their effects. Note that in Australia and New Zealand root pruning is only done in conjunction with root wrenching. All of the early studies in Canada and the United States deal exclusively with root pruning. Root wrenching was not tried in North America until the 1960's.

Root wrenching was adopted to solve different problems in various climatic regions. In the warm temperate regions of Australia and New Zealand, the emphasis has been on increasing the resistance of planting stock to drought after outplanting. In these countries, the stock does not become dormant before transplanting, thus seedlings must be conditioned by cultural methods that will induce shoot dormancy (Donald and Simpson 1985). In the pacific northwest of Canada and the United States, the major problem is increasing the dormancy of stock for lifting and storage. Large amounts of rain and relatively mild temperatures reduce the rate of dormancy induction and result in non-dormant stock being lifted for overwinter storage. In this region, wrenching is used to stress the stock, encourage budset and prepare it for storage and/or planting. It is interesting to note that van den Driessche (1983)

Table 1. A summary of the information available in the English literature on root pruning and wrenching treatments applied in the nursery bed.

Region	Species	Type	Author	Date	Density (m2)	Pruning	Depth (cm)	Wrenching	Depth (cm)	Effect in Nursery HT	RCD	TDW	RDW	S/R	After Outplanting Survival Time	Survival Response	Growth Time	Growth Response	
Australia and New Zealand	Monterey Pine *	1-0	Goudie	1935	-	-	-	Manual	10	R	R	-	-	-	-	-	-	-	
	Monterey Pine	1-0	Rook	1971	-	Early summer	5-8	Weekly, biweekly monthly	10	R	R	R	R	R	-	-	-	-	
	Monterey Pine	1-0	Sweet and Rook	1972	300	Midsummer	7.5-10	Biweekly	10	Increase root growth rate					-	-	-	-	
	Monterey Pine	1-0	van Dorsser and Rook	1972	-	Midsummer	8	Frequency dep. on site	10	R	R	-	-	R	2	I - 30%	2	I - 52%	
	Monterey Pine	1-0	Benson and Shepherd	1977	-	-	-	Manually-2X,5X 20-28 wks frm sow	13	R	R	R	NE	I	2	NE	5	NE	
	Monterey Pine	1-0	Namblar et.al.	1979	-	Midsummer	15	Manually-24,27,30 weeks after sowing	15	-	-	-	-	-	Increased root growth in cold soil, decreased water stress				
	Caribbean Pine	1-0	Bacon and Bachelard	1976	-	-	-	weekly, monthly	15	R	-	-	-	R	-	-	-	-	
United States	-	-	Hastings	1923	-	Fall	10-15	-	-	Replace transplanting					-	-	-	-	Southern pines
	Shortleaf pine Jack pine	2-1 2-1	Janouche	1927	- -	Beg. of 2-0 year	20-25	-	-	R	R	-	-	-	1	NE	-	-	Southern pines
	Longleaf pine Shortleaf, Slash	1-0	Huberman	1940	390 430	June, July, Aug same	10-15	-	-	Increase plantable % -	- -	- -	- -	- -	- -	- -	- -	- -	Southern pines
	Austrian pine	3-0	Gingerich and Hertel	1962	-	Early spring	-	-	-	-	-	R	NE	R	-	-	-	-	Southern pines
	Longleaf pine Slash, Loblolly	1-0	Shoulders	1963	-	Various	10-15	-	-	NE NE	NE NE	- -	- -	- -	1 1	I - 40% I - 20%	- -	- -	Southern pines
	Loblolly pine Douglas-fir	1-0 2-0	Tanaka et. al.	1976	- 377	August April	15 15	biweekly 4X	15 15	NE NE	R NE	R NE	NE I	R R	1 1	I - 30% I - 15%	1 1	NE NE	Pacific Northwest
	Douglas-fir	2-0	Koon and O'Dell	1977	62	-	-	biweekly, monthly	15,20	R	R	R	R	R	1	I - 25%	-	-	Pacific Northwest
	Douglas-fir	2-0	Duryea and Lavender	1982	260-700	April	15	single (July) biweekly	15 15	R R	NE R	NE R	NE NE	R R	1 3	NE NE	1 3	NE R	Pacific Northwest
	Douglas-fir	2-0	Stein	1984	-	April	15	August	18	NE	NE	NE	NE	NE	5	NE	5	NE	Pacific Northwest
Canada	Douglas-fir	2-0	van den Driessche	1983	179-195	-	-	Aug-Sept., weekly early, mid, late, all	20-25 20-25	R R	- -	- R	- I	R R	1 2	NE I - <7%	1 2	R - 16% V	Pacific Northwest
	Jack pine	2-0	Burgar	1965	-	May	10-15	-	-	-	-	-	-	-	1	NE	1	NE	
	Red pine	3-0 3-0 2-0 3-0	Bunting and McLeod	1984a 1984b 1984c	- - - -	April May April April	10-15 7.5-10 10-15 10-15	early,3 week,6 week control,1X,3 wk,6 wk as above control,3 week,6 week	10-15 7.5-10 10-15 10-15	NE R NE R	NE R R R	R R - R	- - - -	- R - R	1 1 1 1	I - 25% NE NE I - 20%	3 2 2 1	NE I NE R	
	White spruce	2-2	Mullin	1957	-	Machine, hand	various	-	-	-	-	-	-	-	1	NE	-	NE	
	White spruce	3-0	Mullin	1966	-	Post-flush	5-10	-	-	R	NE	NE	NE	NE	5	I - 8%	5	NE	
	White spruce	2+2	Harvey	1984	-	May	8-10	3 week intervals	12	R	R	R	NE	R	1	NE	1	NE	

LEGEND
- I Increased
- R Reduced
- NE No effect
- V Varied

* A glossary of botanical names is given in Appendix 4.

reports root wrenching was done for a number of years in British Columbia without knowing what effect it was having on the performance of the stock after outplanting.

In Ontario, research on the effects of root pruning was initiated in the early 1950's at Midhurst Nursery (Mullin 1957). Single prunings were done by hand and machine at various times throughout the summer to determine the effects on both nursery growth and outplanting survival. Machine pruning was shown to result in the best seedling morphology whereas moderate hand pruning gave the best survival after outplanting. Mullin (1966) defined the purposes of root pruning as follows: 1) to develop a sturdier seedling, 2) to develop a more compact and fibrous root system, 3) to reduce top growth in the nursery and, 4) to increase field survival. It was also thought that root pruning might act as an alternative to transplanting. This had recently been demonstrated with Austrian pine (*Pinus nigra* Arn.) resulting in the advantages of lower costs and less bed space requirements (Gingerich and Hertel 1962).

The timing of root pruning and wrenching treatments during the season are rarely justified in the literature in relation to seedling growth patterns. In Ontario, root pruning is not a conventional nursery cultural treatment but if used it is done in the spring and may be followed by wrenching at regular intervals throughout the growing season. Some trends in the effectiveness of root conditioning at various times have evolved from experience. Late season wrenching (wrenching after shoot elongation) does not affect height growth in determinate species (those which have pre-formed primordia in a terminal bud) (eg. Stein 1984). Frequent wrenching treatments throughout the growing season are more effective for reducing growth (Duryea and Lavender 1982) and in some cases, increasing survival (Bunting and McLeod 1984 a and c) than single or few treatments. Table 1 shows that many different treatments have been attempted with variable results. Ideally, root pruning and wrenching treatments should be applied to compliment the root growth patterns of the stock. Studies with white spruce have shown that root growth in the nursery peaks in late May followed by a reduction in growth during shoot elongation in June. Subsequent pulses of root growth occur in mid-July and late August (Mullin 1963b, Day *et. al.* 1976). Root wrenching should be most effective if carried out just before these pulses of root growth (Bunting 1985). The rising 2+2 year is an ideal one for conditioning white spruce stock by root pruning and wrenching because the root area index increases approximately three times over that in the 2+1 year (Sadreika 1968).

The depth of conditioning treatments also varies from study to study. Root pruning depths range from 5 - 25 cm and wrenching depths range from 7.5 - 25 cm. Again, little justification is found in the literature regarding depth, but shallow treatments seem to have a more pronounced effect on seedling morphology (van Dorsser and Rook 1972). In British Columbia, the standard depth for conditioning treatments is 20 cm (Donald and Simpson 1985). By New Zealand standards this is too deep to be considered effective, but different species and soil conditions require appropriate changes in technique. Thus, it is necessary to do trials before implementing a major program of root conditioning at any nursery.

Root pruning and wrenching treatments in the nursery bed have many advantages over root trimming, the term designated by Sutton and Tinus (1983) to mean root pruning at lifting time. The latter involves removing a large portion of fine roots resulting in a high shoot/root ratio and thus an imbalanced tree at planting time (Eis and Long 1972). Columbo (1981) found that root trimming of white spruce seedlings, which were subsequently overwinter frozen stored, decreased root growth rate, increased shoot moisture stress and decreased photosynthetic efficiency after outplanting. This may not pose a problem on moist, fertile soils but on dry sites can cause mortality and planting check (Sutton 1967). Root pruning and wrenching, on the other hand, control root length and encourage the development of a compact fibrous root system with many roots ready to grow when planted.

Response in the Nursery

Seedling Morphology

Biologically, morphology refers to the form or structure of an object but in the study of seedlings it is commonly used to refer to characteristics, such as height and root collar diameter, that can be observed or measured (Ritchie 1984, Duryea 1984). Root pruning and wrenching treatments have been shown to have a fairly consistent effect on the morphological characteristics of species such as Monterey pine. Studies in New Zealand showed that root conditioning inhibited shoot growth, increased lateral and tertiary root production and decreased shoot/root ratios (van Dorrser and Rook 1972, Chavasse 1980). Thus, a sturdier tree with a more compact fibrous root system was obtained. Similar results were achieved in the U.S. and Canada with Douglas-fir (Koon and O'Dell 1977, van den Driessche 1983), caribbean pine (*Pinus caribbaea* Mor. var. *hondurensis*) (Bacon and Bachelard 1978), red pine (*Pinus resinosa* Ait.) (Bunting and McLeod 1984 b, c) and white spruce (Harvey 1984).

Van den Driessche (1983) and Stein (1984) agree that late summer wrenching is most likely to increase survival without affecting height growth. This is true for determinate species because the current years shoot growth has almost ceased. For example, Tanaka *et. al.* (1976) and Bunting (1984a) found that wrenching did not affect height growth but in both cases wrenching treatments were not initiated until late July, when elongation was almost complete. Root pruning and wrenching during the period of bud formation can affect the following years height growth by reducing the number of primordia formed in the resting bud of determinate species. Harvey (1984) found that root conditioning reduced the number of primordia in the terminal buds of white spruce by an average of 16.5 percent.

The frequency of treatments has a significant effect on the results obtained from root conditioning. Duryea and Lavender (1982) found that while a single wrench causes a slight reduction in height growth and root collar diameter, multiple wrenchings result in greater reductions. Similar results were obtained by Benson and Shepherd (1977) and Bunting and McLeod (1984b).

A reduction in root collar diameter is a fairly consistent and notable effect of root conditioning. Root collar diameter is indicative of a seedling's sturdiness and reserves (Burdett 1983) and is one of the few morphological characteristics that correlates well with outplanting survival (van den Driessche 1982). Thus, a reduction in root collar diameter is not desirable. Bunting (1985) suggests that this reduction in root collar may be offset by growing seedlings to be wrenched at lower bed densities, although this is not apparent in Table 1. Koon and O'Dell (1977) had very low bed densities but still had a significant reduction in root collar size.

Many of the above authors (eg. van Dorsser and Rook 1972, van den Driessche 1983) suggest that the changes in morphological quality improve seedling resistance to water stress after outplanting because the fibrous root system can more effectively meet the demands of the smaller shoot. Increasing the fine root proportion gives stock the ability to function over a wider range of soil moisture potentials, because the roots exploit a larger volume of soil and allow the stock to maintain shoot elongation when soil moisture is restricted (Clarke 1975).

Seedling Physiology

Physiological quality includes such attributes as water relations, root growth potential, nutrient relations, frost hardiness and stress resistance (Ritchie 1984). Increasing emphasis is being placed on these aspects of seedling quality because they are more indicative of growth potential after outplanting than morphological quality. Thus, the objective of recent root conditioning research has been less oriented toward the modification of morphological characteristics and has focussed more on the physiological quality of the stock. The stressing caused by wrenching treatments is mainly related to the reduction in water absorption caused by a temporary decrease in the number of absorbing roots. This is confirmed by the lower water potentials found in recently wrenched stock at the nursery (Duryea and Lavender 1982, van den Driessche 1983). Seedling physiology is mainly altered through the effects of this stressing on photosynthesis, stomatal functioning and assimilate partitioning. For example, root pruning of young Monterey pine seedlings in controlled conditions was shown to increase stomatal resistance and decrease photosynthesis for a number of days following treatment. The high stomatal resistance was maintained long after the seedlings had recovered their leaf water potentials and photosynthetic capacities, suggesting that the seedlings would be more able to maintain a positive water balance after outplanting (Stupendick and Shepherd 1980).

Immediately after wrenching, shoot/root ratios are larger in wrenched than unwrenched stock (Stein 1984). After wrenching, the stock is subject to stress both because many of the fine absorbing roots have been removed and because an imbalance has been created between roots and shoots. When the top/root ratio is increased by removing part of the root system, compensatory growth occurs. Severe root wrenching is followed by translocation of large amounts of hormones and carbohydrates to the roots so that sufficient root growth occurs to restore the original balance (Kramer and Kozlowski 1979).

During this time the amount of substances allocated to the shoot are decreased, resulting in the characteristic reduction in height growth associated with wrenching. Zabkiewicz (1979) found that in Monterey pine seedlings, starch levels in the roots were substantially increased one day after wrenching, peaked nine days after wrenching and then reverted to normal by three weeks after wrenching had occurred. Presumably, repeated wrenchings would maintain high translocation of carbohydrates to the roots throughout the growing season. Rook (1969,1971) showed that wrenched trees shunted a greater proportion of photosynthate to the roots, maintained a higher concentration of sugars and starches especially in the roots and maintained higher leaf turgidity when under moisture stress. Root conditioning has also been shown to affect growth regulator levels in the plant. Using the *Avena* L. coleoptile bioassay, Sweet and Rook (1972) found that root conditioned Monterey pine seedlings had lower levels of inhibitor compounds per unit root weight and higher relative root growth rates than unconditioned controls. All of these physiological changes, which manifest themselves in the characteristic morphological changes associated with wrenching, aid in improving survival on droughty sites and reducing transplanting shock.

Root Growth Potential

Root growth potential (RGP) is defined as "the ability of a tree seedling to initiate and elongate roots when placed into an environment favorable for root growth" (Ritchie 1985). RGP is related to species, seedlot, family, cultural practices, physiological condition at time of lifting, time in storage, soil temperature after planting and soil moisture availability (Sutton 1980a, Ritchie 1985). For example, black spruce and jack pine have inherently higher RGP than white spruce when evaluated under similar conditions (Day and Harvey 1983, 1984a and b). High RGP enables rapid establishment after outplanting and wrenching has been shown to increase RGP. The minimum amount of root elongation and total root number thought to be required for the successful establishment of white spruce are 35 cm and 35 respectively (Day and Harvey 1984a).

Most of the variability in root growth in the field is due to RGP of the stock, soil temperature and available moisture. Variations in RGP are also affected by endogenous factors in the stock (Thompson and Timmis 1978). Next to seedling and soil moisture content, RGP is the most important characteristic for seedling survival after outplanting (van Dorsser and Rook 1972, Tanaka *et. al.* 1976, Bacon and Bachelard 1977, Sutton 1979) and has been found to predict survival and growth independently of morphological characteristics for white spruce (McMinn 1980, Burdett et al. 1983). RGP is especially important on dry sites, since much of the root system of conventional nursery stock is lost during the lifting and grading processes, leaving mainly older, suberized roots which do not absorb water as efficiently as new fine roots (Thompson and Timmis 1978).

The development of adventitious roots may be a major mechanism for the replacement of root systems which have been unbalanced by an injury or stress, such as is caused by pruning and wrenching.

Mechanical wounding causes a localized burst of cell division activity and causes a change in the growth pattern so that new cells cover the wound (Galston and Davies 1970). Sutton (1980b) states that root regeneration can occur in three ways: 1) if only the extreme root tip is removed, a new growing point forms directly at the wound surface, 2) if more is cut off, regeneration is only partial with new growing centres formed in the outer part of the root, and 3) if a large portion of the root is removed, true regeneration does not occur, rather adventitious roots form from the callus tissue. Adventitious roots are especially important in the development of root sytems of many species of planted trees. Adventitious roots normally arise from from the main stem but can also arise from root tissue after injury. They can be from preformed root primordia or induced primordia in tissue which had not formed roots during normal development (Sutton 1980b).

The removal of the root apex often causes an increase both in the elongation rate of existing roots and the initiation of new lateral roots. The distance behind the apex that branching is inhibited depends on growth rate and species (McCully 1975). Root growth and branching are probably controlled by plant growth regulators such as cytokinins and auxins. Cytokinins increase cell division rates and are required for lateral root initiation. Auxins are required for root primordium initiation and for lateral root initiation in excised roots (Phillips 1971). Since cytokinins are produced in root tips, wrenching may affect the concentration of these growth regulators. When the root tips are removed, the relative concentration of auxin in the tissues should increase causing more root initiation. The new root tips grow and produce more cytokinins causing increased lateral root initiation. The end result is higher RGP. Bacon and Bachelard (1978) induced a ten fold increase in the RGP of caribbean pine by root wrenching. Harvey (1984) attained a three fold increase in the RGP of white spruce after outplanting through root pruning and wrenching treatments. If the effects of root conditioning on the physiological characteristics of the stock were better understood, these treatments could prove useful in modifying the RGP peaks of certain species to better suit lifting and planting schedules.

Nutrient Uptake

Root conditioning may also affect seedling quality by changing the nutrient uptake pattern. Very few studies have dealt with this topic. Benson and Shepherd (1977) indicate that as the severity (that is, frequency and shallowness) of wrenching increases, the nitrogen and phosphorous levels in the shoot tissues of Monterey pine decline. Van den Driessche (1983) and Donald and Simspon (1985) found that wrenching affected potassium and phosphorous uptake more than nitrogen uptake. Shallow conditioning (10 cm depth) has been shown to reduce the nitrogen, phosphorous and potassium content in the needles of white spruce seedlings by 4, 19 and 18% respectively compared to standard conditioning (20 cm depth) (Donald and Simpson 1985). All summer and early summer wrenching increased the needle content of nitrogen in Douglas-fir seedlings by 5 and 10% respectively, whereas late summer wrenching decreased it by 10%. Needle phosphorous was decreased by all wrenching treatments but most by late summer (19%) and all summer (25%) wrenching. All summer wrenching reduced the needle potassium content 13% compared to non-wrenched Douglas-fir seedlings, whereas late summer wrenching reduced needle potassium by only 6%.

These effects on nutrient uptake may be explained through the effects of wrenching on seedling growth rate and water stress. Plants with depressed growth rates have been shown to take up less nutrients and their ability to translocate those absorbed to the shoot is impaired (Mengel and Kirkby 1978). Ion uptake and translocation of nutrients which are absorbed are also decreased by water stress. However, water stress induced ion deficiency can be prevented by adequate fertilization before subjecting the plant to stress (Levitt 1980b). Experiments with maize have shown that fertilization with potassium decreases the effect of water stress on nutrient uptake. High levels of potassium fertilizer have been shown to increase root formation in agricultural plants (Shuurman 1969), which would result in decreased water stress, but there is no evidence in the literature that this applies to tree seedlings. There is however, some indication that excess potassium is detrimental to roots (Donald 1983).

Fertilization during the final year on the nursery is used to increase the nutrient reserves of the stock for better growth after outplanting. Supplementary fertilization in the nursery may be necessary to compensate for the effects of wrenching on nutrient uptake.

Stress Resistance

Stress has been defined as an excess or deficiency of any factor necessary for growth and the presence of unnecessary factors such as disease (Timmis 1980). It may be merely inhibitory or severely injurious depending on the level of stress experienced by the plant. Stress resistance is a plant's ability to continue growth in a non-optimal environment (Timmis 1980). This may be either through avoidance of the harmful agent or tolerance of it (Levitt 1972). Moderate stresses in the nursery have often been found to be beneficial in increasing the seedling's resistance to stresses encountered during lifting, handling, planting and establishment (Levitt 1980a, Zaerr *et. al.* 1980). Intermittant moderate stress thus results in adaptation to a particular stress or type of stress and eventually results in a degree of resistance in the plant. However, the physiological processes involved in stress resistance are not well understood (Ritchie 1984). Root pruning and wrenching which provide intermittant water stressing should increase the ability of tree seedlings to withstand water stress during handling and after outplanting resulting in better survival.

Performance After Outplanting

In general, root conditioning results in smaller, sturdier stock with more compact fibrous root systems. The effect of root conditioning on growth and survival after outplanting varies from a reduction to an increase in both survival and growth. For example, results of outplanting trials with Douglas-fir indicate 25% higher survival rates for wrenched seedlings as compared to controls (Koon and

O'Dell 1977). Tanaka *et. al.* (1976) also indicate 15 and 30% better survival for root conditioned Douglas-fir and loblolly pine (*Pinus taeda* L.) seedlings respectively, with greater differences occurring between the treatments on southern exposures and dry sites. Root pruning in combination with wrenching, has been shown to increase the survival of overwinter stored red pine seedlings 20-30% after outplanting (Bunting and McLeod 1984a,c). On the other hand, Duryea and Lavender (1982) found that root wrenching Douglas-fir during the second growing season did not improve either survival or the seedlings ability to withstand dry conditions.

Mullin (1966) showed that root pruned white spruce seedlings had less terminal growth the first year after outplanting but that after 3-5 years the root pruned seedlings showed a faster rate of growth. This same trend has been shown for red pine (Bunting and McLeod 1984a,b). The reduction in height growth of the wrenched stock in the nursery persisted the first year in the field, but once established top growth equalled or surpassed that of the controls. Bunting (1985) relates this to the superior root system of the wrenched stock. Others have found no difference in the growth of wrenched versus unwrenched seedlings after outplanting (Tanaka *et. al.* 1976, Benson and Shepherd 1977). Duryea and Lavender (1982) found that the growth of wrenched Douglas-fir seedlings was reduced for up to three years after outplanting.

The variable results in the trials discussed above can be attributed in part to differences in species used, treatments applied and environmental conditions during treatment and after outplanting. For example, Donald and Simpson (1985) pruned and wrenched white spruce at three different nurseries in the same year and got fairly consistent results where the same methods were used. However, the results presented in Table 1 show that this is not always the case. Environmental conditions are difficult to control in bareroot nurseries and their effects are hard to document. However, variations in environmental conditions play a significant role in treatment effectiveness. The purpose of conditioning seedlings is to prepare them to survive the extremes which can occur after outplanting but this should not be at the cost of growth in an average year. Thus, it is important to test seemingly optimum treatments more than once to ensure their effects are reproduceable over the normal range of environmental conditions.

Water Relations

Eighty to ninety percent of the variation in tree growth can be attributed to water stress (Zahner 1968) making the water relations of the soil at time of outplanting are very important for establishment and growth. A reduction of 15-20% in the water content of the plant results in cessation of growth, but one as small as 1-2% can cause physiological and morphological changes in the plant (Joly 1985). For example, Zahner (1968) found that water stress during flushing resulted in smaller leaves spaced closer together on the shoot. Water stress also regulates the number of primordia formed within the developing bud (van den Driessche 1978). Buxton *et. al.* (1985) found that shoot growth was reduced by 50% and transpiration rates declined to less than half of control values in 21-22 week old containerized white spruce seedlings subjected to an osmotic stress of -0.4 mPa. Both shoot and root elongation ceased at stresses of -1.6 mPa.

Water absorption is controlled by the rate of water loss from the plant, the extent and efficiency of the root system and the water potential and hydraulic conductivity of the soil (McDonald 1984). Both water deficiencies and surpluses influence the formation and activity of root systems. In wet soil, roots comprise a lower percentage of the total plant weight than in dry soil (Lyr and Hoffman 1967). In dry soil, the quantity of water entering the plant is closely related to the amount of root per unit volume of soil with available water, so an extensive root sytem is necessary to provide the shoot with water and nutrients (Russel 1977). Characteristics known to improve seedling performance on dry sites are high RGP, a fibrous root system with numerous growing tips, large root collar diameters, short tops and shoot-root ratios of two or less (Hennessey and Dougherty 1984, Hobbs 1984).

Plant moisture stress (negative water potential) consists of gravitational, frictional, solute and matrix potentials and changes with atmospheric energy demand, soil moisture supply and the ability of roots to absorb water (Day and Walsh 1980). The degree of water stress in a seedling can be measured using a pressure chamber which indicates the additive effects of gravitational and frictional potential within the plant. Solute and matrix potentials are generally ignored because they are negligible or constant (Cleary and Zaerr 1980). Plant moisture stress measurements indicate the amount of stress a seedling is under at the time of measurement, but do not indicate how much stress the seedling can withstand. For example, seedlings just out of frozen storage are metabolically inactive and thus have a high tolerance to stress, but the same seedlings will be damaged at much lower levels of water stress later in the spring when they are actively growing (Columbo 1985).

The amount of stress a seedling can withstand at various stages of development can be estimated from pressure-volume curves. These curves are used to predict the responses of seedlings to water stress and to evaluate the effects of cultural treatments on the physiological condition of the stock (Hennessey and Dougherty 1984). They are derived from the reciprocal of plant moisture stress over percent water loss measurements taken from seedling shoots over a period of time. From the curves, the osmotic potential at full turgor and the osmotic potential at zero turgor can be estimated. Decreasing osmotic potential represents the effects of dissolved solutes in the cell sap and thus decreases water potential. It is best to determine both osmotic and turgor potential when studying water relations since these are directly involved in responses to stress. This is not easily achieved because osmotic potential varies with seasonal changes in seedling physiology and short term changes in solute concentration and turgor pressure cannot be measured directly.

Physiological drought resistance is thought to be initiated in the nursery by cultural treatments such as wrenching, watering and fertilization regimes (Kandiko *et. al.* 1980). Hennessy and Dougherty (1984) found that moderately water stressed loblolly pine seedlings (rewatered when predawn water potentials fell below -0.8 mPa) showed an osmotic adjustment. That is, an accumulation of solutes occurred in the cells, changing their water potential and giving the seedlings the capacity for increased turgor maintenance over a wider range of water potentials. Kandiko *et. al.* (1980) found that in western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) seedlings, moderate water stress (-1.0 mPa) resulted in more negative values of osmotic potential at full turgor and at plasmolysis indicating an adaptation to drought conditions. It is thought that osmotic adjustment may allow cell elongation, stomatal opening, photosynthesis and root growth to occur during water deficits which would normally negatively affect these processes (Kramer 1983). Such adjustments in osmotic potential should also occur through water stress imposed by wrenching but this has not been documented in the literature.

Very little emphasis is placed on seedling resistance to excess water since the major problem in plantations seems to be lack of water after outplanting. Excess water is detrimental to survival and growth of stock after outplanting mainly because it causes reduced oxygen levels in the soil. In a study of comparative water relations of Norway spruce (*Picea abies* (L.) Karst), Scots pine (*Pinus sylvestris* L.), aspen and birch (*Betula verrucosa* Ehrh.) under controlled conditions, spruce was found to be most sensitive to both wet and dry conditions in terms of root development, net assimilation rate and transpiration (Jarvis and Jarvis 1963). Even at 10% oxygen in the soil, which is considered adequate for most species (Wilde et al. 1972), spruce showed 30% less root growth than in air (Jarvis and Jarvis 1963). Another laboratory study, comparing the effects of various oxygen levels in the rooting medium on the survival and growth of jack pine, black spruce and white spruce, found white spruce to be most sensitive to low oxygen levels (Zinkan *et. al.* 1974). Saturated soils reduce water uptake through oxygen deficiency which induces the same type of physiological stress as is experienced during drought (Hobbs 1984). The damage incurred depends on the age of the plant, its dormancy status and prior adaptations to flooding. The question is, do treatments such as wrenching, which are applied to increase stress resistance and induce drought tolerance also increase resistance to flooding?

Harvey (1984) found no increase in the survival of wrenched white spruce transplants in a moist year. Bunting (1985) found that wrenching conferred no benefit to red pine seedlings in a wet year. Other authors have obtained much greater increases in the survival of wrenched seedlings on dry sites than on moister sites (Tanaka *et. al.* 1976, Koon and O'Dell 1977). This would suggest that adaptation for drought does not confer any additional benefits to stock in normal years or on moderate sites, but neither is it detrimental to the seedling's ability to survive and grow under these conditions.

Soil Temperature

Soil temperature is another major factor controlling the survival and growth of tree seedlings after planting, probably through its effect on root growth. Grossnickle and Blake (1985) found that white spruce seedlings grown at soil temperatures of 10°C experienced more water stress than those grown at 22°C because of a greater physical resistance to the flow of water through the soil-plant-atmosphere continuum and slower root regeneration. Nambiar *et. al.* (1979) found that soil temperature affected initiation, elongation, branching, thickness, weight and morphology of new roots in Monterey pine. However, seedlings can be conditioned to grow roots at low temperatures. Root wrenching in the nursery stimulated new root growth at low temperatures (5-10°C), but at temperatures closer to the optimum for root growth (15-20°C) unwrenched trees had higher numbers of roots and more root elongation. Plants growing at higher temperatures recovered from initial water stresses better because of faster root growth (Nambiar *et. al.* 1979). Hennessey and Dougherty (1984) found that moderately water stressed (rewatered when pre-dawn water potentials reached -0.8mPa) loblolly pine seedlings regenerated three times as many roots as non-stressed (rewatered when pre-dawn water potentials reached -0.3 mPa) seedlings at day/night temperatures as low as 9° and 7°C respectively. Thus, wrenched stock should be more able to function at the lower extremes of soil temperature than unwrenched stock.

COLD STORAGE

Overwinter cold storage is the storing of cold tolerant, hardened nursery stock at temperatures close to 0°C from fall lifting until spring. Overwinter frozen storage normally involves holding the stock at -2°C for the winter months. It may also include a warm up period of two to four weeks at +2°C in the spring to condition the stock for planting. This is in contrast to spring storage which involves lifting stock early in the spring and storing it at +2°C until planting time. This maintains the stock in resting condition and delays flushing, allowing extension of the planting season.

Interest in overwinter frozen storage of nursery stock has increased in recent years for a number of reasons. Fall lifting and overwinter storage reduce the spring work load at the nursery, ensure that the trees are ready for shipping when they are needed in the field, allow handling of a greater number of trees, reduce losses from wind dessication and frost heaving and ensure that nursery beds can be cultivated as early as possible in the spring (Brown 1971, Hocking and Nyland 1971, Sutton 1982). In addition to these operational advantages, overwinter frozen storage can be used as a means of manipulating the physiological quality of the stock. For example, the stock can be held in an inactive state until it is needed, allowing extension of the planting season (Mullin 1966, Sutton 1982). Frozen storage (below 0°C) is used rather than cold storage (above 0°C) to control mold and reduce respiration.

Stock lifted early in the spring performs better than that lifted later in the season, but operational difficulties often prevent lifting at the optimum time (Sutton 1982). Consequently, fall lifting and overwinter storage has become fairly routine practice in Ontario. A 1972 survey of 128 Canadian and U.S. tree nurseries revealed that 44% used some type of overwinter storage. Only 2% of this was at temperatures below freezing, 84% was in the 1° - 14°C range (Hocking 1972). Since then the amount of stock stored has increased greatly. For example, 30% of the stock produced at the Thunder Bay Forest Station is currently stored and 50% will be stored by the fall of 1987 (Phillion 1986, pers. comm.).

The first cold storage trials recorded in Ontario were undertaken in the early 1940's at Orono nursery. Tests with species commonly grown in the province, including pine, spruce, larch and cedar, were done at temperatures ranging from -18° to +14°C, under a number of storage conditions (Leslie 1945). The best results were obtained by storing stock in enclosed crates at temperatures of 0°C or slightly less under high humidity.

By 1966, cold storage was considered to be common practice at Ontario nurseries (Mullin 1966). Until recently, further trials have involved mainly spring lifting combined with storage as a means of extending the planting season. During this time the variables affecting the success of storage were recognized as being species, stock type, time of lifting, length of storage and humidity and temperature during storage. The data on how or why these factors affect performance after planting is minimal and variable but an attempt will be made to summarize the available information.

Variables Affecting the Success of Cold Storage

Various species react differently to storage; for example, some success has been documented with spruce (Jorgenson and Stanek 1962, Harvey 1984, Day 1985) whereas pine and larch generally show poor survival and growth after storage (Mullin 1966, Bunting 1980). Stock type and morphological quality also have an effect. Transplants have been shown to survive storage better than seedlings of similar age (Mullin 1966, Williams and Rambo 1967) and stock with large root collar diameters generally survives storage better than that with small root collar diameters (Bunting 1975).

Nursery stock can be held in cold storage successfully for up to 6 months depending on the species. For example, Jorgenson and Stanek (1962) reported good survival and growth for white spruce held in storage for 6 months. Deffenbacher and Wright (1954) obtained 100% survival in the first year with ponderosa pine and noble fir (*Abies procera* Rehd.) that had been stored for a full year but this is unusual. Most species, except for the southern pines, can be stored successfully from 4 to 7 months (Hocking 1972). The normal period of overwinter frozen storage in Ontario is 6 to 8 months.

Moisture retention during storage is critical to survival. Survival after storage has been shown to be zero if seedlings go below 30% moisture content, but can be up to 90% if moisture content remains above 80% (Hocking and Nyland 1971, Navratil 1973). Initially, stock was placed in storage with the roots protected but the tops exposed to the air, resulting in the death of all seedlings stored at temperatures below freezing and most of the seedlings stored above freezing because of dessication. Later, experiments comparing bales, burlap and plastic as storage containers were undertaken (Bunting 1970, Hocking and Ward 1972), which resulted in the use of poly-lined kraft bags or plastic bags lining waxed kraft boxes to protect the stock from dessication and physical damage during storage and handling. The latter system is presently used in Ontario nurseries.

Optimum temperatures for storage are not yet established but they may vary with species (Sutton 1982). Temperature is an important factor in storage since in combination with humidity it controls the rate of change of stock condition. Low temperatures control mold and reduce respiration of carbohydrate reserves (Hellmers 1963, van den Driessche 1979). By reducing respiration, a potentially harmful build-up of gases, such as ethylene, in the storage containers is also minimized (Navratil 1973, Barnett 1983). Bunting (1970) indicated that white spruce stored at -3°C survived better than stock stored at +1.5°C. However, others have obtained 97% survival with spring lifted seedlings but only 72% survival with frozen stored white spruce stock (Hocking and Ward 1972). This is hard to explain merely through the effects of temperature or moisture since the seedlings left in the field are also essentially frozen under the snow and are subjected to dessicating winds in the spring when the snow is melting.

Lifting time can be a very important factor in the success of overwinter frozen storage. If the stock is lifted too early in the season it will not survive storage because of inadequate reserves or inadequate hardening, among other things. Many authors state that physiological hardening is required for the successful storage of coniferous stock (Blake *et. al.* 1979, Burdett 1983, Lavender 1984), but the precise characteristics of an 'adequately hardened seedling' have yet to be defined. It is apparent that some hardening process occurs in the stock making it more resistant to storage conditions since stock lifted later in the fall survives storage better than that lifted before October 1st under the same storage conditions. This may be attributable to less rapid depletion of carbohydrates in storage; for example, Hocking and Ward (1972) found that white spruce stock lifted at the end of October showed less rapid depletion of starch than stock lifted in mid-October. The reason for this is not clear. It is likely that survival of overwinter storage is related to the dormancy status and winter hardiness of the stock (Racey 1985).

There has been much controversy over the terms 'dormancy' and 'hardening' in recent years. The classical and most frequently cited definition of dormancy is that of Doorenboos (1953) which states that a plant is dormant when "a tissue predisposed to elongate does not do so when exposed to favorable environmental conditions". This definition is lacking in that it specifies neither physiological nor morphological criteria. Buds assumed dormant by visual inspection may be morphologically and physiologically active. For example, primordia initiation continues in the fall after elongation is complete and buds are fully developed externally (Owens *et. al.* 1977). A more recent definition of dormancy and related processes proposed by Lang *et. al.* (1985) helps to clarify the terminology. They define dormancy as being "no visible growth of any structure containing a meristem". Dormancy is divided into three distinct categories: 1) eco-dormancy, which relates to environmentally imposed dormancy such as would be induced by water stress, 2) ecto-dormancy, which is imposed by physiological factors outside the affected structure, for example a photoperiodic response, and 3) endo-dormancy, which is regulated by physiological factors inside the affected structure, for example chilling responses. The first two are reversible upon removal of the factor limiting growth but the third type of dormancy can only be broken by satisfying the physiological requirement. Whether dormancy is environmental or physiological, dormant plants are thought to be more resistant to stresses such as cold storage.

Frost hardiness is important to the survival and growth of seedlings after storage for a number of reasons. If seedlings are not frost hardy when lifted, they will not survive overwinter storage or they will be weakened and thus more susceptible to environmental stresses (Navratil 1973). Frost damaged trees are more likely to die after outplanting (Duryea and McClain 1984). Frost hardiness is a component of cold hardiness and is defined as the ability of plant cells to withstand freezing temperatures without suffering irreversible physical damage (Lavender 1984). The development of frost hardiness is a process which has been shown to include changes in cell membranes and protoplasm to allow movement of water to extracellular ice crystals and to resist the effects of dessication (Levitt 1980a). It is thought that frost hardiness can only develop if the seedling has adequate carbohydrate reserves and active growth has ceased (Lavender 1985). Hardiness seems to be closely related to the cessation of growth processes in the plant rather than its dormancy status. Weather conditions may play a role in inducing frost hardiness. For example, for Douglas-fir in the Pacific Northwest, growth cessation requires warm dry days and nights. Short, mild days and mild nights initiate hardening. In general, drought is a major factor in growth cessation of western conifers, whereas photoperiod is crucial for eastern and central North American conifers (Herman *et. al.* 1972). In white spruce, cessation of shoot growth and initiation of hardiness is mainly a photoperiodic response although temperature and moisture can have an effect (Owens *et. al.* 1977, Glerum 1982). Hardiness is further increased by cool short days and cool nights which cause changes in sugars and proteins in the cells which in turn aid freezing resistance. Maximum hardening is induced by cool days and freezing nights which cause binding of water enabling the plant to resist dehydration (Weiser 1970). However, these need to occur in sequence for hardiness to develop properly.

Frost hardiness can be modified through cultural practices such as reducing irrigation near the end of the growing season to induce moisture stress, as is routinely done in container nurseries to induce budset and initiate hardening of the foliage, changing fertilization practices or root wrenching (Duryea and McClain 1984). These measures cause maturing or hardening of the stock and increase its resistance to storage (Navratil 1973).

Effects of Cold Storage on Seedling Physiology

The effect of cold storage on survival and growth after outplanting is determined largely by the factors discussed above. Cold storage affects the physiological quality of the seedling in the following ways. It has been found to delay flushing of the buds in the spring (Jorgenson and Stanek 1962). Once outplanted, trees from storage take two to three weeks to break bud (Brown 1971) and the number of actively growing seedlings has been shown to lag behind spring lifted stock for up to ten weeks (Nyland 1974). This lag may reduce growth in the first few years after outplanting especially if it means the trees are trying to elongate in July when soil water is limiting. However, Nyland (1974) indicates that the delay in flushing does not affect height growth in the first year. The delay may be beneficial in that it allows the stock to avoid frost damage after outplanting. Jorgenson and Stanek (1962) found that stored white spruce seedlings were more resistant to spring frosts than spring lifted seedlings. In addition, a functioning root system can be established before excessive water demands are made by the growing shoot. Alternatively, it may be argued that the root system develops in response to signals (such as growth regulators) from the shoot so that late flushing would inhibit establishment.

The reason for delayed flushing may be high abscisic acid levels induced by water stress caused by cold storage (Glerum and Lavender 1980). It may also be a result of lack of exposure to increasing temperatures experienced in the field, which are necessary to initiate growth within the bud in the early spring. However, Harvey (1984) evaluated the response of seedlings to overwinter storage in coolers (dark, constant temperature) versus polyhouse (natural light, moderated fluctuating temperatures) and the nursery bed (natural light, fluctuating temperatures). The progression of bud flushing during the winter months was not affected by the various storage treatments but field stock had significantly lower numbers of buds flushed after 28 days in the growth chamber. No difference was found between the cooler and the polyhouse treatments. It would appear that storage location was not the decisive factor in bud development.

Cold storage has been shown to affect the stomatal mechanism of the stock, thereby altering water relations after outplanting (Blake 1983). Blake found transplanting shock, as indicated by changes in water potential, diffusive resistance and transpiration, to be minimal in frozen stored stock. He proposed that freezer stored stock was better adapted to survive outplanting due to a greater degree of dormancy (of the shoot) when planted, lower transpiration and diffusive resistances and the abscence of reduction in stomatal aperture following planting. He postulates that cold storage may condition the stomata to reduce water loss when water is limiting without reducing stomatal aperture. Thus, the photosynthetic potential of the seedling would not be impaired when moisture was adequate.

More recently, Grossnickle and Blake (1985) found that cold storage disrupts the stomatal mechanism. Stomata of white spruce seedlings from frozen storage did not respond as rapidly to light as those of actively growing seedlings and the stomata did not close fully, especially on mature foliage resulting in initially greater water stress. They found that 18 to 20 days were required for acclimation of stomatal response after removing seedlings from storage. The mechanism by which cold storage affects stomatal response is unknown but may be due to an increase in abscisic acid levels induced by drought stress (Glerum and Lavender 1980).

Cold storage also affects the RGP of seedlings. Ritchie and Dunlap (1980) found that the effects of storage on RGP depended on lifting date, duration and species. The patterns of RGP are related to bud dormancy and chilling requirements. For example, if stock is put into overwinter storage during deep dormancy, its chilling requirements will continue to be satisfied. Harvey's study confirmed this for white spruce. RGP increases until the chilling requirement is fulfilled then decreases after dormancy release occurs. Donald and Simpson (1985) found that 7 to 8 months of storage increased the RGP of white spruce root conditioned at a 20 cm depth at three nurseries in British Columbia. However, it decreased the RGP of stock conditioned at a 10 cm depth, especially if it had been fertilized. Harvey (1984) found that storage did not affect the RGP of white spruce transplants when these were compared with spring lifted stock.

POTASSIUM FERTILIZATION

Optimum Rates

Optimum needle potassium contents for white spruce have been determined to be in the range of 0.7-1.1% of dry weight (Tamm 1964). Levels of potassium producing the highest shoot dry weights in 16 and 26 week old white spruce seedlings grown under greenhouse conditions were shown to be from 11 kg/ha to 45 kg/ha with older seedlings requiring higher rates of fertilizer. These levels resulted in needle potassium contents of 0.7% (Swan 1971). An earlier study showed that as the level of potassium fertilizer applied to white spruce seedlings, grown under greenhouse conditions, increased from 0 kg/ha through 7.5 and 17.5 to 175 kg/ha, potassium content of the seedlings on a percent dry weight basis increased from 0.2% to 0.3%, 1.2% and 1.6% respectively (Swan 1960). Potassium applied to 2-0 white spruce in the nursery at a rate of 27 kg/ha of elemental potassium resulted in needle potassium contents ranging from 0.8 to 1.5% at different times throughout the growing season (Armson 1960). Potassium content as a percent of dry weight was found to decrease over the growing season.

The amount of fertilizer applied to raise the potassium content of the foliage depends to a great extent on the clay content and minerals present in the soil (Mengel and Kirkby 1978). Additional potassium fertilizer (that which is applied over and above routine nursery fertilization rates) has been applied at levels from 120 kg/ha to 400 kg/ha in recent nursery trials in the Pacific Northwest. Van den Driessche (1983) obtained foliage potassium contents of 0.72%, 0.79% and 0.86% in Douglas-fir seedlings fertilized with 0 kg/ha, 120 kg/ha and 240 kg/ha additional potassium respectively. Donald and Simpson (1985) report foliage potassium contents of 0.55%, 0.60% and 0.59% in white spruce seedlings fertilized with additional potassium at rates of 0 kg/ha, 200 kg/ha and 400 kg/ha respectively. The lack of increase in potassium content at the 400 kg/ha level, indicates that this level is far beyond the optimal for white spruce growing at bed densities of 200 seedlings/m^2.

Effect on Cold Hardiness

Potassium fertilization is thought to be a potential way of increasing frost hardiness but the literature on this subject is inconclusive. A review of the literature summarizing the effect of fertility on the ability of plants to tolerate cold temperatures included three studies which showed increasing tolerance as a result of increasing levels of potassium (Aldhous 1972, Kopitke 1941, Benzian 1966), two which showed no effect (Benzian *et. al.* 1974, Christersson 1975) and one which showed a negative effect (O'Carrol 1973). Potassium deficiency, which occurs at potassium levels of 0.3% of foliage dry weight (Tamm 1964), has been shown to increase the susceptibility of seedlings to frost damage (Mengel and Kirkby 1978). Late season top dressings of potassium, which accumulate in seedlings, were shown to eliminate frost damage to Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Benzian 1966). Increases in the potassium content of Scots pine seedlings, from 0.3 to 1.6% of dry matter, have been shown to increase survival after a severe winter (Christersson 1973). Although the same author found no correlation between frost hardiness development and the potassium content of the seedlings, potassium fertilization was shown to have more effect on cold hardiness development in conditioned (seedlings subjected to three weeks of short days and cold temperatures) than unconditioned seedlings. A 20 to 25% higher potassium content was found in the shoots of conditioned seedlings caused by movement of potassium from root to shoots. This is thought to be a defensive mechanism against winter drying. Potassium moderates stomatal control and thereby decreases transpiration, resulting in reduced water loss and thus would help the plant to avoid winter drying (Mengel and Kirkby 1978).

On the other hand, Christersson (1975) found no relationship between survival under greenhouse conditions after exposure to low temperatures (0^{o} to $-30^{o}C$) and the potassium content of Scots pine seedlings. However, the difference in the potassium content of the needles between fertilized unfertilized seedlings was only 0.2%. Oldencamp *et. al.* (1969) found that fertilization of Douglas-fir with nitrogen and potassium before lifting for overwinter frozen storage had no influence on subsequent survival.

Some of the discrepancies between these studies are a result of varying application procedures and rates, types of stress applied and assessment of damage (Pellett and Carter 1981). When one nutrient is supplied in very large amounts it can result in deficiencies in other nutrients creating an imbalance which could reduce hardiness (van den Driessche 1983, Glerum 1985). For example, imbalances in the potassium to nitrogen ratio reduced cold hardiness development of container seedlings (Timmis 1974). The ratio of potassium to nitrogen for optimum cold hardiness was suggested to be 0.6. Navratil (1973) found that high nitrogen content especially when combined with low potassium content reduced the resistance of stock in cold storage to deterioration. Tests of cold hardiness often involve laboratory tests using single temperatures rather than a range and abrupt temperature changes rather than the gradient which would be experienced in the field, giving inapplicable results. Assessment of damage is often visual and thus subjective. In addition, the test are often done on tissue samples rather than whole plants so evaluation of growth and survival afterwards is difficult.

In general, higher than necessary fertilization with any fertilizer singly or in combination decreases hardiness (Pellet and Carter 1981, van den Driessche 1983). Fertilizer levels promoting optimum growth are best for cold acclimation since many nutrients are involved in the metabolic changes of the hardening process (Alden and Herman 1971, Glerum 1985) and higher than necessary fertilizer rates can result in root damage, thereby reducing growth (Donald and Simpson 1985).

Effect on Plant Water Status

Whether or not potassium increases cold hardiness, it is required for outplanting success since it aids in regulating plant water status (Fisher and Mexal 1984). It is known that potassium increases cell permeability and increases the soluble carbohydrate content of cells (Levitt 1956). Potassium accumulation in the xylem decreases water potential and thus increases water uptake. It also aids in lowering water loss by controlling the transpiration rate (Mengel and Kirkby 1978). Low potassium levels may result in loss of stomatal control during the critical period after outplanting. Greenhouse experiments with Sitka spruce indicated that nutrient status had little effect on the transpiration rate of dormant trees but that potassium fertilization significantly decreased transpiration in actively growing seedlings (Bradbury and Malcolm 1977). Christersson (1973) also found that high potassium levels decreased the transpiration rate in Scots pine seedlings. A reduction in transpiration and an increase in water use efficiency is important for newly planted trees during the period of establishment especially if the vapour saturation deficits are high. Christersson (1976) found that the effect of potassium on increasing seedling survival was not through decreasing the transpiration rate since needle potassium levels of 0.8 and 1.4% increased the transpiration rate of Norway spruce seedlings from 550 to 800 mg/g/h, but rather by raising the dessication tolerance of the cytoplasm. Although the mechanisms are not yet clearly understood, potassium is important in increasing the survival of outplanted seedlings on dry sites.

METHODS

Three experiments were carried out to examine the effects of root pruning and wrenching on white spruce transplants. The root pruning and wrenching trials were carried out at the Thunder Bay Forest Station (48° 22' N. Lat., 89° 22' W. Long.), the growth chamber experiments were carried out in the greenhouse at Lakehead University in Thunder Bay, Ontario and the outplanting trials were located near Great Lakes Forest Products Camp 45, 120 km north of Thunder Bay, (1985 - 49° 12' N. Lat., 89° 11' W. Long., 1986 - 49° 13' N. Lat., 89° 12' W. Long.). As two sets of experiments were carried out in two different years, each year will be dealt with separately even though some of the methodology may be the same.

1984-85 EXPERIMENTS

Root Pruning and Wrenching Trial

In May 1984, a split-plot design with four root culture treatments and three potassium fertilizer treatments replicated four times was set out on Compartment 10 of the Thunder Bay Forest Station after the rising 2+2 transplants (seed source 3424000)[1] were checked and found to have sufficient vertical root development to permit early season root pruning at a depth of 7-10 cm. The plot layout is shown in Figure 1. The four root culture treatments were randomly assigned to beds in the compartment with each treatment being repeated four times. The length of the beds was determined by pacing and each bed was divided into tenths. Three tenths in each bed were selected at random to receive the potassium fertilizer treatments. Thus, 4 x 4 x 3 = 48 plots were established with each plot representing an experimental unit. The beds on either side of irrigation pipes were excluded from the experiment because of limited tractor access.

The four root conditioning treatments consisted of:

1) a control, which received no root pruning or wrenching treatments,

2) pre-bud burst root pruning followed by wrenching at twenty-eight day intervals,

3) mid-shoot elongation root pruning followed by wrenching at twenty-eight day intervals, and

4) post-shoot elongation root pruning followed by wrenching at twenty-eight day intervals.

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[1] Refers to Site Region (34 = Thunder Bay Area), District (24 = Manitouwadge), Area (000).

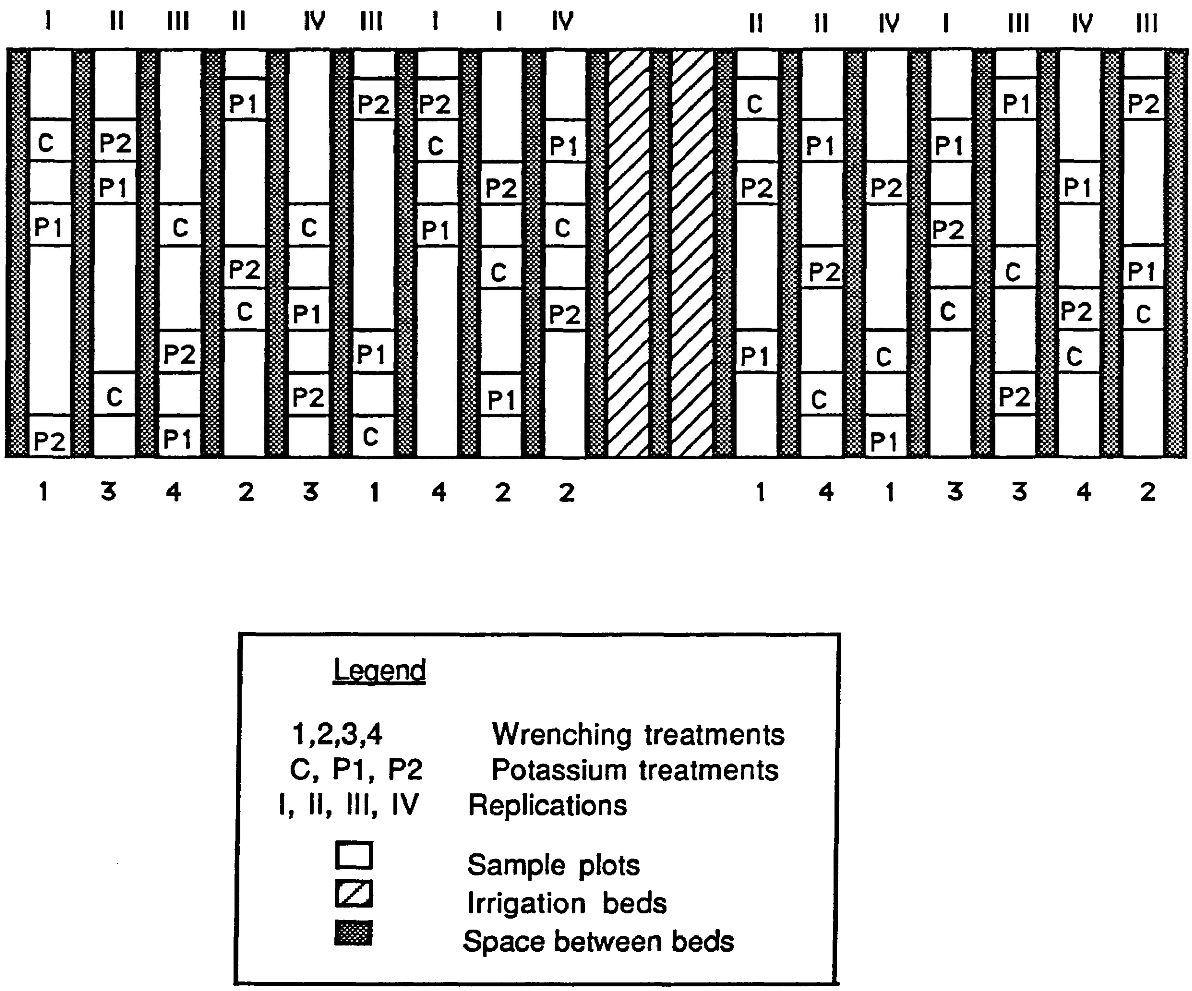


Figure 1. Layout of the 1984 root conditioning trial on compartment 10 of the Thunder Bay Forest Station.

Each treatment was pruned once and wrenched three times during the growing season, except treatment 4, which was wrenched twice.

The three potassium treatments consisted of:

1) a control, 0.0 kg/ha potassium sulphate,

2) 100.0 kg elemental potassium applied in the form of fertilizer grade potassium sulphate at a rate of 25 kg/ha at four monthly intervals from July 14 - October 14, 1984, and

3) 200.0 kg/ha elemental potassium applied as in level 1 but at rates of 50 kg/ha each time.

A schedule of treatments is given in Figure 2. Apart from these treatments, all beds received the standard cultural treatments used at this nursery. This included irrigating to field capacity when the soil moisture tension reached -5.0 bars, applying herbicides, fungicides and insecticides as needed and applying fertilizer top dressings at levels recommended by Glendon Hall (Univ. of Toronto) based on soil samples (Phillion, 1985). Total fertilizer applied by the nursery in 1984 was 50 kg/ha elemental nitrogen, 21 kg/ha elemental phosphorous and 11 kg/ha elemental potassium (Phillion 1986, pers. comm.).

The root pruning was carried out using a single, sharp horizontal blade mounted on a double-acting hydraulic system beneath one of the Thunder Bay Forest Station's tractors. The root pruning was done at a depth of 7.5 to 10 cm to sever the roots close to the root collar without reducing the stability of the stock. The root wrenching was carried out with a single blunt blade on the same hydraulic system at a depth of 12 to 15 cm but angled from front to rear at 35^o to raise the stock, temporarily loosen the soil and break the long fine roots without causing excessive damage to the root system. Figure 3 shows the blade positioning during the root pruning and wrenching treatments and their respective effects on the root systems and soil in the nursery beds.

Potassium fertilizer treatments were applied by hand, sprinkling pre-measured amounts of fertilizer as evenly as possible across the plots.

On each of the plots, 25 transplants were marked at the root collar with white latex paint and tagged for identification. Height growth, defined as the distance from the base of the previous year's growth node to the tip of the growing shoot, and root collar diameter of the tagged trees were monitored before pruning and in early July. These trees were fall-lifted and assessed for height growth, root collar diameter, bud diameter (measured with calipers at the widest point), top dry weight, shoot dry weight, root dry weight and top/root ratio. The data were checked for normality using RANKIT plots, then were checked for homogeneity using Bartlett's F test and analyzed by a split-plot analysis of variance (ANOVA) using the SPSS package on the VAX 11/780 computer. Tukey's honestly significant

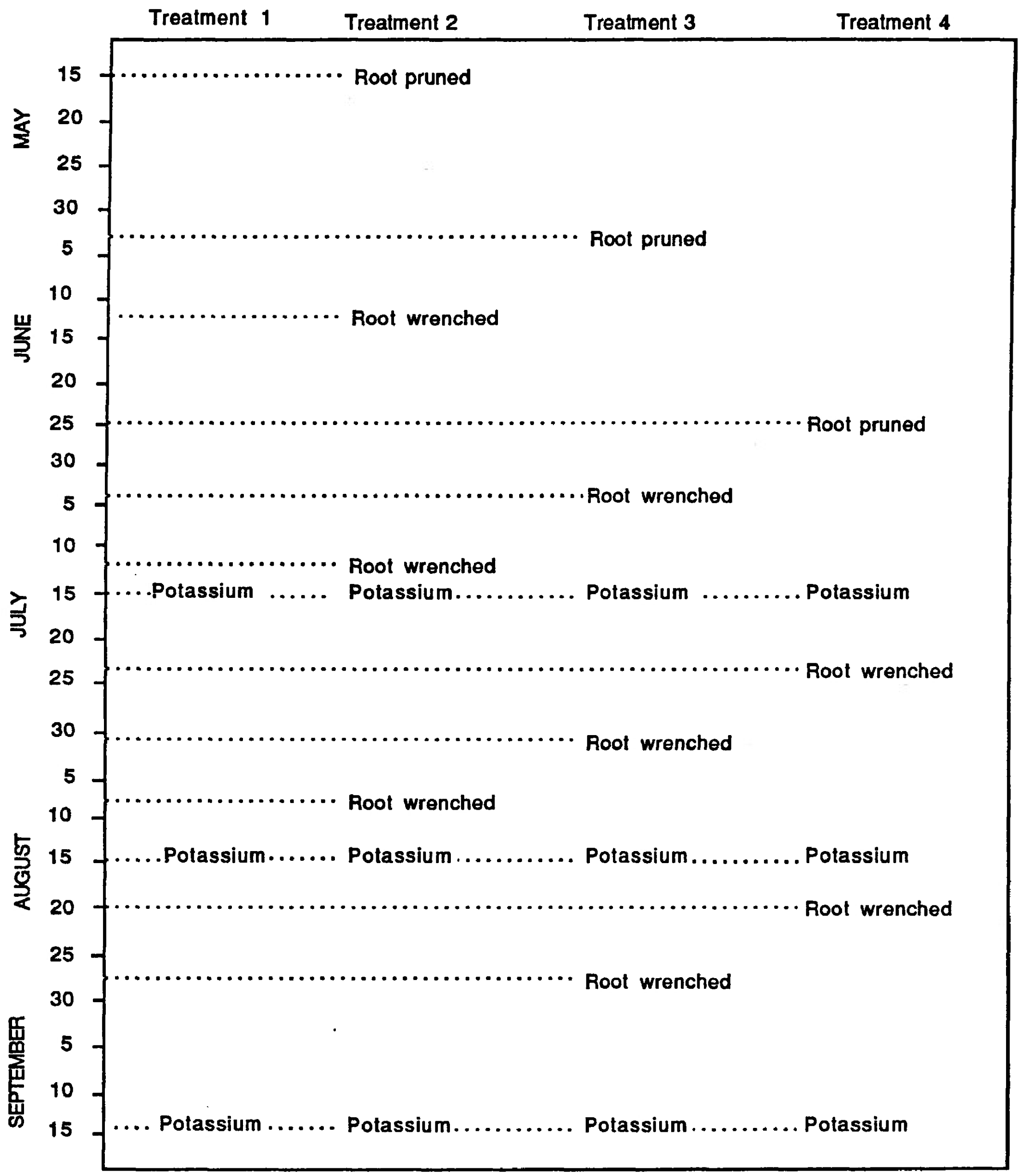


Figure 2: Schedule of treatments applied to 2+2 white spruce transplants in 1984.

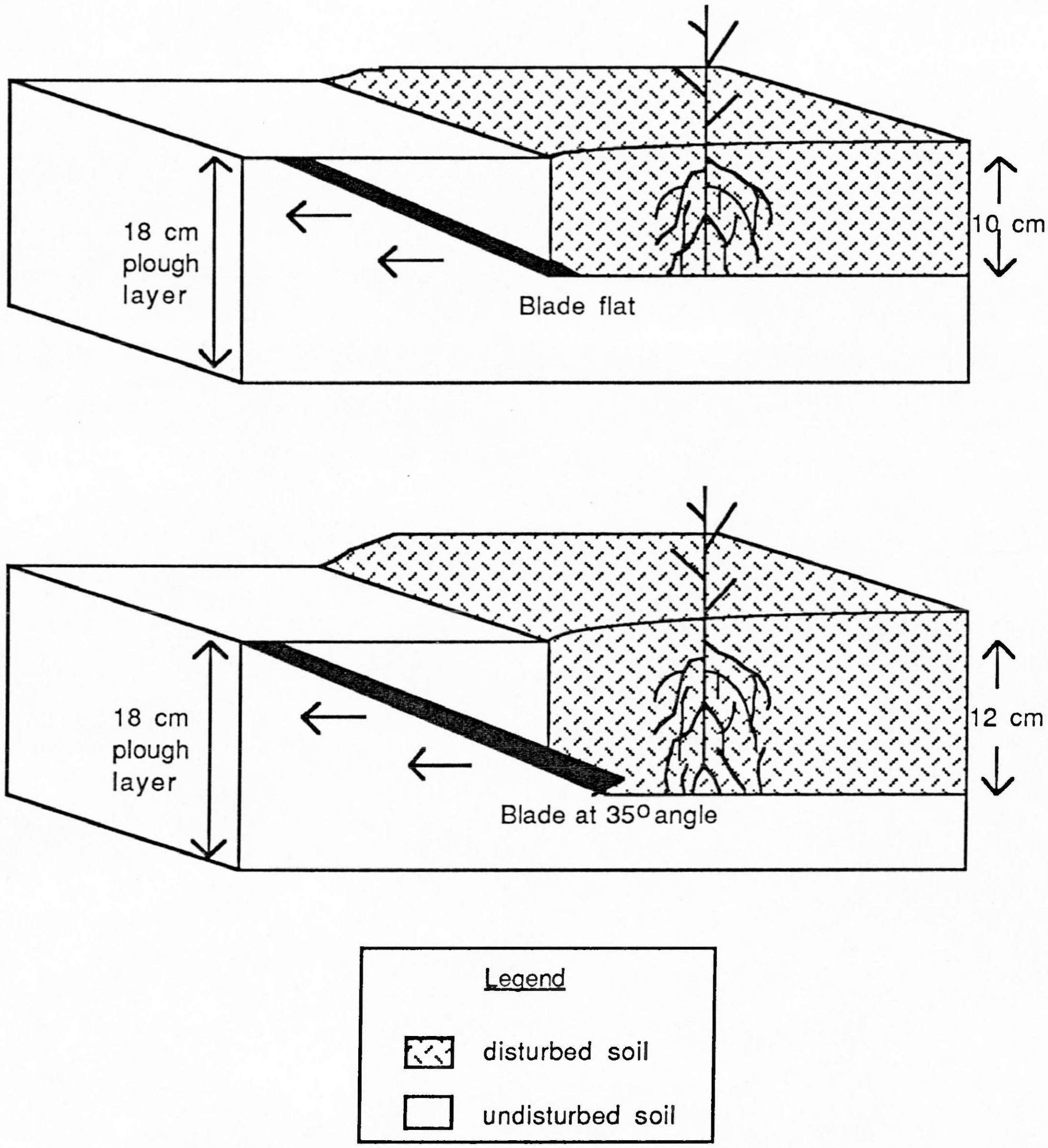


Figure 3. Profile of nursery bed showing position of blade during root pruning (top) and wrenching (bottom) and their effects on seedling roots and soil.

difference (HSD) was used to determine the significance of differences between individual treatments (Steele and Torrie 1980). The expected mean squares (EMS) table is given in Appendix 1 (Table 1A) (Steele and Torrie 1980).

On October 17th, root boards were used to visually compare the root development of the four treatments. These boards consist of plywood with nails every 2 cm in offset rows and are used to observe depth and distribution of roots. Trenches one metre wide were dug across one bed of each of the wrenching treatments so that the root boards could be inserted. The boards were removed, carefully washed free of soil and examined for depth and fibrosity of roots.

On November 1st, the stock to be overwinter stored was lifted using an Egedal seedling lifter with shaking action. Unfortunately, the soil froze as the day went on so that only three replicates of each treatment could be lifted. The trees were bundled in groups of ten and the roots were pruned to 23 cm in accordance with standard nursery procedures. The stock was then packed in plastic lined kraft boxes in lots of 200 and placed in the freezers at - 2°C + or - 1°C.

The mean and standard deviation method of estimating stock quality, developed by Day (1980), was used to establish the morphological quality of seedlings from the control and pre-bud flush wrenching treatments relative to northern Ontario standards.

On November 29th, 1984, buds of ten seedlings per variate were collected by clipping the distal five cm of the terminal shoot of random trees in the treatment plots to determine whether wrenching had affected bud development. These were immediately fixed by putting them in plastic bottles containing McClintock's fixative (25% glacial acetic acid, 75% ethanol). The number of primordia in the buds was determined using the methods documented by Pollard (1974) as follows. Older seedlings have mixed phyllotaxis so this was determined first, then the primordia in three of the parastichies (spiral rows of primodia) were counted and the average was multiplied by the number of clockwise parastiches to obtain the average number of primordia. The data were analyzed by ANOVA after checking for normality using RANKIT plots and homogeneity with Bartlett's F test. The EMS table is given in Appendix 1 (Table 1B) (Steele and Torrie 1980).

Growth Potential Tests During Overwinter Storage

RGP and bud flushing tests were done throughout the period of overwinter cold storage to monitor changes in the physiological quality of the stock as the winter progressed. Not all of the treatments could be included in the growth chamber tests because of lack of space. The control and pre-bud flush pruning treatments were chosen because they showed the largest contrast in morphological characteristics and it was assumed they would show the effects of root conditioning most effectively. The potassium treatments were not included in these tests.

From December 1984 to March 1985, at monthly intervals, 10 seedlings from each of the three replicates of wrenching treatments 1 and 2 with no additional potassium were removed from the freezers and taken to the University greenhouse where they were placed in a cooler at +2°C for 24 hours to thaw. The roots were carefully washed. Height, taken as the distance from the root collar to the tip of the terminal bud, root collar diameter, root area index, and length of and number of buds on the terminal whorl were measured. Ten transplants from each variate were selected randomly and potted, three per 20.5 cm diameter pot. The pots were filled to a 17 cm depth with a 2:1 peat:vermiculite mixture. They were then placed in a growth chamber for 21 days. The growth chamber was programmed to provide a 16 hour day with an eight hour night at 25°C and 20°C, respectively. Humidity was maintained between 60 and 80%. Every three to five days the stock was watered and the pots were re-randomized to reduce edge effects in the chamber. Every five days the number of buds on the terminal whorl of each seedling with bud scales opening and the number of buds flushed were counted and recorded to determine the time to bud break. After 21 days, the stock was unpotted, the roots carefully washed and height growth and root area index were determined. The number of new roots (RN) were counted and their elongation was measured and placed in the following classes: small (<0.5 cm), medium (0.5-1.0 cm) and long (>1.0 cm). The February test ran for 25 days.

The experimental design for the physiological tests was a blocked factorial consisting of 4 test dates for the buds, five for the roots (blocks) with two wrenching treatments replicated three times. The data were checked for normality and homogeneity as above. Non-homogeneity in three response variables had to be corrected using a square root transformation. All data were subsequently analyzed by ANOVA. The EMS tables are given in Appendix 1 (Tables 1F and 1G). Significant differences were determined using Student-Newman-Keuls (S-N-K) tests (Steele and Torrie 1980).

The time to new root initiation for wrenched versus unwrenched stock was determined by placing ten seedlings from each treatment in a root mist chamber, described in detail by Harvey (1984), coincidentally with the growth chamber trials. These trees were monitored at three day intervals and the number of trees with new roots was determined. The time to new root initiation was not analyzed statistically because of the small sample size. In addition, ten seedlings from each treatment were tested for plant moisture stress (PMS) the day the stock was potted using the methods documented by Day and Walsh (1980).

Outplanting Trial

In the spring of 1985 an outplanting trial was established to assess the effects of the root conditioning and potassium fertilizer treatments on the outplanting performance of the overwinter frozen stored and spring lifted stock. The site was located adjacent to Stucco Lake near Great Lakes

Forest Products Camp 45 (Appendix 2, Figure 2A).

The planting site, which originally supported a balsam fir (*Abies balsamea* (L.) Michx.), white birch (*Betula papyrifera* Marsh.) and white spruce mixture, had been burned over in a 1980 wildfire then was site prepared with barrels and chains through standing, burned timber in 1984. As a result slash loading was heavy with little advance growth apparent. The area was a gentle southeast facing slope with sandy loam soil and scattered surface rock. Competition was heavy, consisting mainly of raspberry (*Rubus ideaus* L.), fireweed (*Epilobium angustifolium* L.), wild rose (*Rosa* sp.), speckled alder (*Alnus* sp.) and some aspen.

On April 26th, the temperature of the coolers at the Thunder Bay forest station were increased from -2^{o}C to +2^{o}C, to allow for a conditioning period of about three weeks before planting. During this time samples of the stock were removed from the cooler for an hour, measured for height, root collar diameter and bud diameter, tagged and returned to the cooler.

On May 16th, the spring lifted stock was removed from the nursery compartment and heeled in at the Lakehead University nursery for measuring and tagging. They were not packed in boxes and cold stored prior to outplanting as many of them had swollen buds or were beginning to flush. It was felt they would be damaged by such handling. On May 22nd, this stock was taken from the heeling beds, packed in boxes and taken with the frozen stored stock to the outplanting site where it was heeled in. On May 23rd, 24th and 25th, the stock was planted in a randomized complete block design consisting of 3 blocks, 2 lifting times, 4 root conditioning treatments and three potassium treatments each with 60 trees per plot. A map showing the layout of the plots is given in Appendix 2 (Figure 2B). The trees were planted using the L-slit method at approximately one metre spacing to allow trees for destructive sampling in the fall while retaining the Ontario Ministry of Natural Resources' desired spacing of 2 x 2 m. At the same time, stock from root conditioning Treatments 1 and 2 were both planted in the field, and potted and placed in the growth chambers at the University for 21-day RGP trials. In addition to height, root collar diameter and bud diameter, the root area index of these trees was measured prior to planting. Analysis of the RGP tests was by ANOVA after square root transformation of some of the response variables to correct non-homogeneity (EMS Table 1J, Appendix 1) (Anderson and McLean 1974). Significant differences were assessed by S-N-K tests.

A separate trial consisting of ten trees from each of the variates was planted at the Lakehead University nursery on Oliver Road the day after the field plant ended to determine if wrenching decreased PMS after outplanting. The trial was established at the University rather than at the outplanting site to provide easy access for pre-dawn measurements. After the initial 3 weeks, the trial was ended due to excess rain. Time constraints prevented all seedlings from each variate being measured at each sample time, but at least ten seedlings from each treatment were assessed between 5:30 and 8:00 a.m. This trial was not analyzed statistically because sample size was insufficient.

During growth chamber trials conducted in the winter months, it became apparent that the seedlings were infested with spruce budworm (*Christoneura fumiferana* Clemens). Spraying was necessary to reduce losses of experimental material. On May 28th, the spring lifted stock was sprayed for budworm using Malathion (0,0-dimethyl phosphorodithioate of diethyl mercapto-succinate) at a rate of 10 ml per 5.5 l in a Chapin compressed air sprayer. On June 13th, only those trees with signs of damage were sprayed again and on July 4th the frozen stored stock was sprayed. The difference in time of spraying was a result of the three to five week delay in flushing of the frozen stored stock.

In July, the trees were assessed to determine height growth, basal caliper and condition code. Basal caliper was used due to difficulty in relocating the root collar in the field. The condition codes were subjective values from zero to five , developed by Day and Harvey (1983, 1984a and b), to indicate the health of the tree. Zero indicates a healthy seedling and five describes a seedling which is 100% brown or defoliated with dead inner bark. Full details of the coding system are given in Appendix 3. In September, twenty trees per plot were excavated to determine final bud diameter, root area index, terminal dry weight (terminal dry weight was taken as the weight of the current year's terminal growth), shoot dry weight and root dry weight. The trees were measured, cut up, put in bags and dried for 48 hours at 70^{o}C.

Twenty-seven of the remaining live trees per plot were demarkated at random with seedling pins as permanent samples for measurement in 1986 and 1987. In 1986, these trees were assessed for survival, height growth, root collar diameter, condition code and bud diameter in mid-August. The data were summarized by calculating means and standard deviations, to determine if the samples were statistically sound and to become familiar with any trends. The data were then checked for normality using RANKIT plots and for homogeneity using Bartlett's F test. Significant differences were determined by ANOVA (EMS Table 1K, Appendix 1), then Tukey's HSD was used to determine where the differences were. Note that a true estimate of experimental error was not available so the four and three-way interactions were used to test the main effects and two-way interactions.

1985-1986 EXPERIMENTS

Root Pruning and Wrenching Trial

In May 1985, a split-plot design with three root culture treatments and two potassium treatments was set out in four blocks on Compartment 85 of the Thunder Bay Forest Station in 2+2 transplants (seed source 3424027), using the same criteria and procedures as in 1984. Blocks were used rather than replications to remove the initial variation in seedling morphology across the compartment. The plot layout is shown Figure 4.

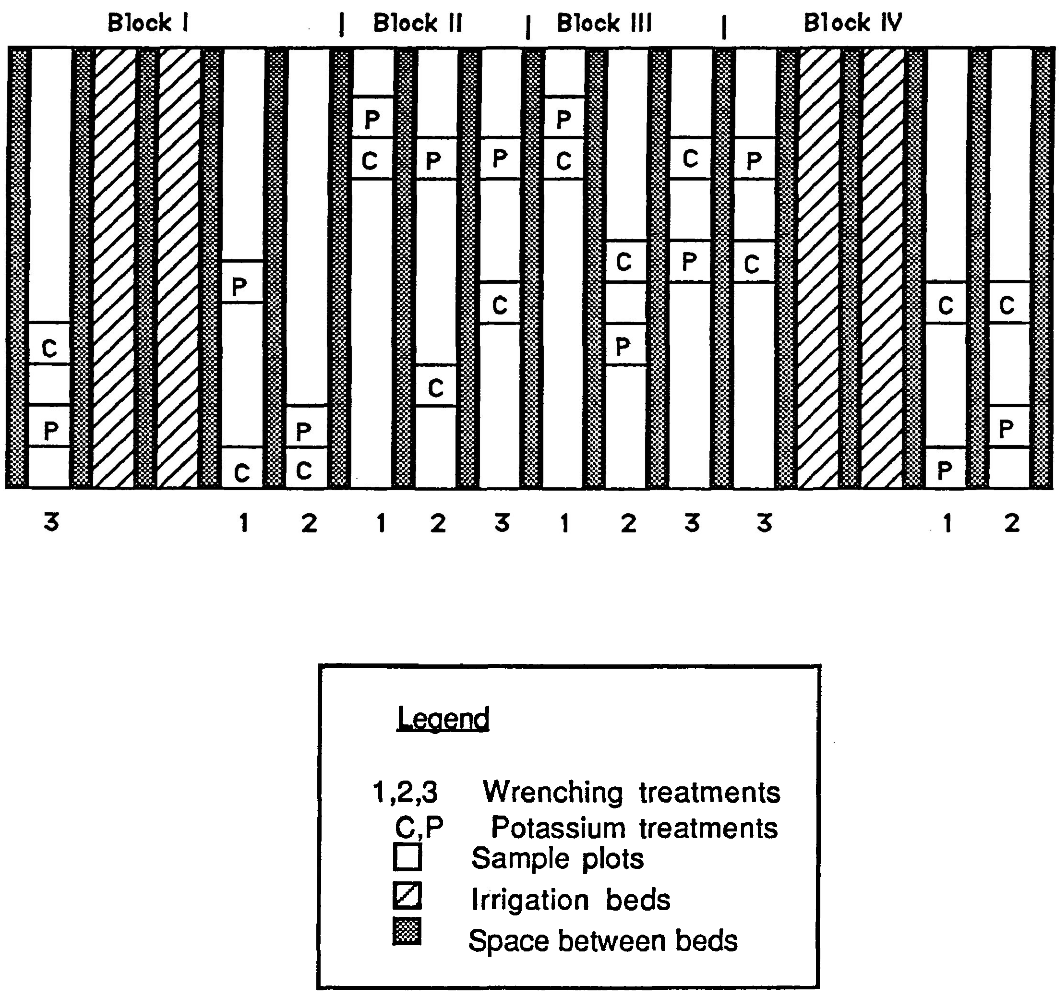


Figure 4. Layout of the 1985 root conditioning trial on compartment 85 of the Thunder Bay Forest Station.

The three root conditioning treatments consisted of:

1) control, to which no root pruning or wrenching treatments were applied,

2) early season root pruning followed by wrenching at 21-day intervals, and

3) early season root pruning followed by wrenching in accordance with periods of root growth.

Treatment 2 was wrenched four times after pruning while Treatment 3 was wrenched twice.

The two potassium treatments consisted of:

1) control, 0.0 kg/ha potassium sulphate, and

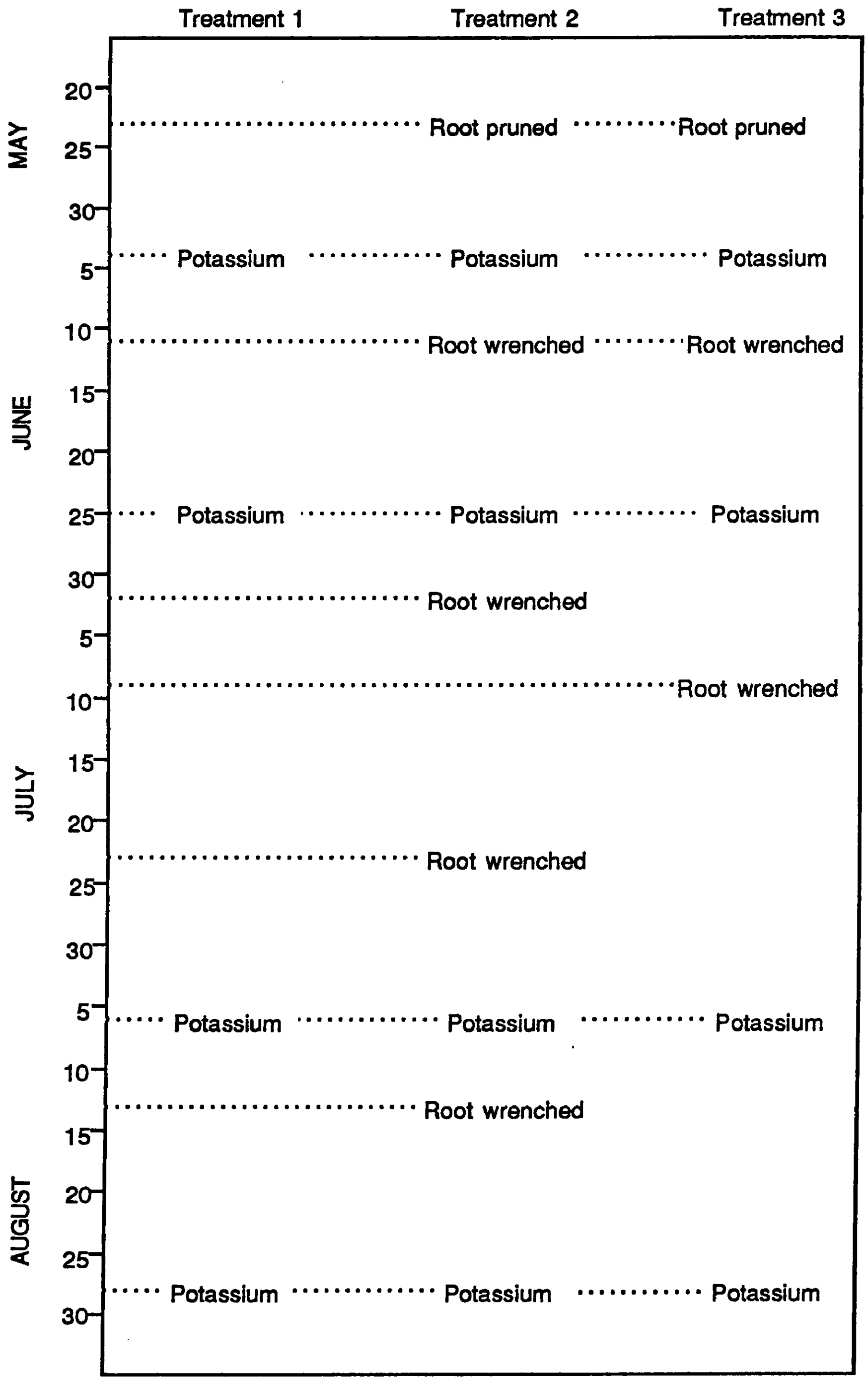
2) 75.0 kg/ha level elemental potassium applied as potassium sulphate at five times throughout the summer.

A schedule of treatments is shown in Figure 5. The routine applications of fertilizer used by the nursery were 120 kg/ha elemental nitrogen, 49 kg/ha elemental phosphorous and 55 kg/ha elemental potassium (Phillion 1986, pers. comm.).

The methods used for root pruning and wrenching were the same in 1984 and 1985. Height growth and root collar diameter were monitored on a permanent sample of 25 transplants per variate at three week intervals throughout the summer. This stock was lifted and assessed for bud diameter, root area index, root dry weight, terminal dry weight and shoot dry weight at the end of the season. The data were summarized by calculating means and standard deviations, to determine if the samples were statistically sound and to become familiar with any trends. The data were checked for normality using RANKIT plots and for homogeneity using Bartlett's F test. Significant differences were determined by ANOVA, then Tukey's HSD was used to determine where the differences lay. The EMS table is given in Appendix 1 (Table 1C) (Anderson and McLean 1974).

The bulk density and moisture content of the soil was monitored at weekly intervals throughout June and July to determine the effects of wrenching on soil moisture and aeration. Five samples per bed were determined to be adequate for bulk density sampling using Freese's sample size estimation formula (Freese 1962). The samples were collected by hand using 50 cc bulk density samplers, transferred to plastic bags and taken to the University where they were immediately weighed and dryed at 105^{o}C for 24 hours. These data were analyzed by ANOVA after testing for normality and homogeneity. The EMS table is shown in Appendix 1 (Table 1E).

An attempt was made to follow bud development of the wrenched trees through the summer. Samples were taken from ten trees per variate on July 16th, August 13th and September 9th to determine when wrenching affects the number of primordia formed in the buds. However, the study had to be abandoned due to the following technical difficulties. Early in the season it is very difficult to



<u>Figure 5:</u> Schedule of treatments applied to 2+2 white spruce transplants in 1985.

distinguish bud scales from primordia. In other studies this has been circumvented by using a known average number of bud scales for a particular group of trees, removing these and treating the remainder as primordia (Macdonald 1985, pers. comm.). However, the expected number of bud scales in this study was not known and wrenching could have affected this as well as the number of primordia. Thus, only a sample taken September 9th, 1985 was assessed for number of primordia using the same methods as in 1984. These data were analyzed by ANOVA after checking for normality and homogeneity (EMS Table 1D, Appendix 1) (Anderson and McLean 1974).

The stock was lifted October 22nd, 23rd and 24th, graded, bundled into groups of 10, packed into poly-lined kraft boxes and placed in frozen storage at -2°C + or -1°C. This year the roots were not trimmed before packing since the nursery staff did not pack the seedlings. The mean and standard deviation method was once again used to determine the morphological quality of the stock in relation to northern Ontario standards.

Growth Potential Tests During Overwinter Storage

From November 1985 to March 1986, RGP and bud flushing studies were carried out as in 1984, except that all three root conditioning treatments were included in each test. Again the potassium treatments were not included in these trials. Instead of monitoring bud swell and flushing every five days, bud flushing only was monitored every three days. Analysis was the same as in 1984-85 (EMS Tables 1H and 1I) (Anderson and McLean 1974). PMS was not determined owing to a request by the Thunder Bay Forest Station to minimize the number of trees used.

Outplanting Trial

In 1986, an outplanting trial was established to assess the effects of the root conditioning and potassium fertilizer treatments on the outplanting performance of the overwinter frozen stored and spring lifted stock. The site was located adjacent to Snake Lake near Great Lakes Forest Products Camp 45 (Appendix 2, Figure 2A). It originally supported an aspen, white birch, balsam fir and white spruce mixture. It was cut in 1983 with a Koehring shortwood harvester then site prepared in the fall of 1984 using a crawler tractor and Young's teeth spaced at approximately 2 m. The site contained heavy slash with patches of residuals and little advance growth. The planting area was located on a northeast facing slope on loamy sand. The competition on the site was fairly heavy consisting mainly of *Carix* spp., raspberry (*Rubus ideaus* L.) and shrubs such as speckled alder, aspen and hazelnut (*Corylus* spp.).

On April 14th, the coolers were turned up to +2°C. The spring lifted trees were lifted from the nursery beds on April 17^{th} using an Egedal lifter, packed in boxes and placed in the coolers. All of the stock was moved to the Lakehead University cooler, which was at +2°C, on May 1^{st} so it could be measured and tagged. The stock was planted in a randomized complete block design using the L-slit method on May 13^{th}, 14^{th} and 15^{th}. The trees were planted 25 to a plot at 2 x 2 m spacing. The experimental design was a blocked factorial with two lifting times, three wrenching treatments and two potassium treatments planted in four blocks. A map showing the layout of the plots is given in Appendix 2 (Figure 2C). Simultaneously, five trees from each wrenching treatment were planted in the field and five were potted and placed in the growth chambers at the University for 21-day RGP tests (EMS Table 1L, Appendix 1). In addition, five trees per variate were planted adjacent to Block 1 at the outplanting site for PMS measurements. They were monitored between 7:30 and 8:30 a.m. for the first three weeks after outplanting. At the end of August, these trees were destructively sampled to determine differences in root dry weight and terminal dry weight between the treatments. Top dry weight and root/shoot ratio could not be determined as branches had been removed to test PMS.

At the beginning of July and the end of August, the permanent sample trees were assessed to determine height growth, basal caliper, and condition code. In addition, bud diameters were included with the August measurements. The data were summarized by calculating means and standard deviations, to determine if the samples were statistically sound and to become familiar with any trends. The data were checked for normality using RANKIT plots and for homogeneity using Bartlett's F test. Significant differences were determined by ANOVA (EMS Table 1M), Appendix 1), then Tukey's HSD was used to determine where the differences lay.

In June, transplants from each of the six treatment combinations of both the frozen and spring lifted stock were used to establish pressure volume curves. Initially the operational method suggested by Columbo (1985) was used. Thirty seedlings from each treatment combination were cut at the root collar and the tops were placed in buckets in 5 cm of water. After 24 hours, a branch from the terminal whorl of each top was cut, prepared for the pressure chamber, weighed and allowed to dry for a period of time such that PMS readings could be obtained at five minute intervals from the branches with each being used only once. After oven drying the branches at 90°C for 24 hours, they were reweighed and a curve of reciprocal plant moisture stress over percent water loss was plotted using the scattergram program of the SPSS package on the VAX 11/780 computer. This method produced a very unsatisfactory curve at the upper end so the method was modified to allow measurement of plant moisture stress at one minute intervals for the first twenty minutes, then at five minute intervals thereafter.

A sample pressure-volume curve is shown in Figure 6. The osmotic potential at full turgor (Point A) of the stock in each treatment was estimated by extrapolating the linear portion of the curve to the ordinate axis. The wilting point or osmotic potential at zero turgor (Point B) of the stock in each treatment was estimated by extrapolating a horizontal line from the inflection point of the curve to the ordinate axis. The zero turgor point is the point beyond which no growth can occur (Timmis 1980).

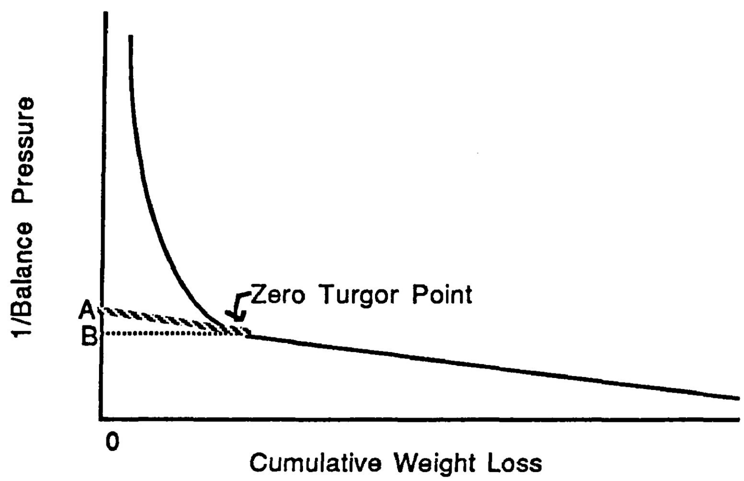


Figure 6. A sample pressure-volume curve. Point A gives an estimate of osmotic potential at full turgor and point B gives an estimate of osmotic potential at zero turgor. (Adapted from Ritchie 1984)

SOILS AND CLIMATE STUDY

Since climate is one of the uncontrollable factors that can be very important in determining the outcome of field studies, the water relations for the two years at the nursery and on the two sites during the respective growing seasons were compared using the Thornthwaite climatic water balance (Thornthwaite and Mather 1957). This procedure provides a means of evaluating soil moisture either on a monthly or daily basis. Air temperature and precipitation values are converted into potential evapotranspiration. The rate of evapotranspiration is calculated in relation to the water holding capacity of the soil. Soil water deficits and surpluses are calculated relative to the depth, bulk density and water holding capacity of the soil as well as the latitude of the site.

Monthly water balances for the 1984 and 1985 years were run using weather data from the Thunder Bay airport (Environ. Can. 1986) and soil data from the nursery, in conjunction with the THORNM fortran program on the VAX 11/780 computer, to evaluate the occurrence of moisture deficits during the two years in which the root conditioning trials were done.

In early July of 1986, soil samples for soil moisture retention curves were collected from both field sites. Three samples were collected from each block at random. They included the soil to a depth of 25 cm after the duff had been scraped away. The samples were air-dried, texture determination was carried out using the hydrometer method and percent organic matter was estimated by ignition. Soil moisture retention curves were run according to the procedures outlined in the operating instructions for the ceramic plate extractor (Soil Moisture Equipment Corp., undated). The pressures used were 1/10, 1/3, 1, 3 and 15 bars. Bulk samples were considered adequate since undisturbed samples are only necessary in structured soils, which the soils of northern Ontario generally are not (Thrower and Schmidt 1985).

Climatic records for both sites were obtained from the Ministry of Natural Resources fire weather station at Camp 45, approximately 1 km from the 1986 site and 3 km from the 1985 site. These data were used in conjunction with the THORND fortran program available on the VAX 11/780 computer to determine the daily water balances for the outplanting sites. The necessary bulk density and depth information was obtained as follows. Average depth was determined by digging ten soil pits at random locations across the site to bedrock or the water table. An estimate of the bulk density was obtained using 50 cc hand samplers. Fifteen samples were collected at random from the site. Freese's sample size estimation formula indicated that eight samples adequately estimated the bulk density to within 10%.

Monthly water balances were first run for 1983-1986 using weather data from the atmospheric environment service at the Thunder Bay airport, since year-round data were not available anywhere near the site. Soil water storage in April, estimated using the water holding capacity of the respective outplanting site, was used as an estimate of the soil storage at the beginning of the season for the daily water balances. In both years the soil was determined to be fully saturated at the beginning of the growing season. Daily water balances were then run for the sites from May 1st - August 31st for both the rooting zone (taken as 25 cm) and the average depth of the soil profile at each site.

RESULTS

ROOT PRUNING AND WRENCHING TRIALS

1984 Results

The 1984 root conditioning trial results will be discussed in two parts: 1) the effect of root conditioning and 2) the effect of potassium fertilizer on the morphology of the 2+2 white spruce transplants.

Mórphological Quality

Root conditioning during the summer affected many of the commonly measured morphological parameters of the stock (Table 2). Initial heights and root collar diameters (RCD) were measured a week before the treatments were applied rather than at the beginning of the season, so initial measurements are not given for Treatment 4 (pruned post-flush) in Table 2 because growth was well advanced at the time of measurement. Root conditioning significantly reduced the height growth and RCDs of the transplants in Treatments 2 (pruned pre-flush) and 3 (pruned in mid-flush). The root area indices (RAI's) of stock from Treatments 2 and 4 were greater than those of Treatments 1 (control) and 3. Tukey's HSD tests on year end measurements indicated that Treatments 2 and 3 significantly decreased final seedling dry weight, top dry weight, shoot dry weight, and root dry weight as compared with Treatments 1 and 4. Root pruning and wrenching had a greater effect on the shoot growth than the root growth of the stock. Top dry weight was reduced 24%, terminal shoot dry weight was reduced 32% but root dry weight was only reduced 13% when the average of Treatments 2 and 3 were compared with Treatment 1. The top/root ratio was significantly lower for Treatment 2 and significantly higher for Treatment 1 than for the other treatments.

Table 2. Means and significance of difference for initial and final morphological characteristics of white spruce transplants from the 1984 root conditioning trial.

Treatment	Initial Height (cm)	Final Height (cm)	Initial RCD (mm)	Final RCD (mm)	RAI (cm^2)	TDW (g)	RDW (g)	T/R Ratio	Bud Diam. (mm)	# of Primordia
1) Control	13.8a*	27.6a	3.6a	6.3a	63b	4.4a	1.5a	3.0a	3.4a	434a
2) Pre-flush	13.5a	23.4b	3.1a	5.5b	74a	3.2b	1.3b	2.4c	2.7c	338bc
3) Mid-flush	13.8a	24.6b	3.3a	5.6b	65b	3.3b	1.2b	2.7b	2.8c	330c
4) Post-flush	-	28.0a	-	6.2a	78a	4.1a	1.5a	2.6b	2.9b	357b

* Values in columns followed by different letters are significantly different at the 95% level of confidence.

In the fall of 1984, there were significant differences in the number of primordia in the terminal buds between treatments. Results of Tukey's tests indicated that buds of stock from Treatment 1 had developed significantly more primordia than those of any other treatment. The stock in this treatment also had the largest bud diameters. Treatment 4 developed more primordia than Treatment 3, but there were no significant differences in the number of primordia in the terminal buds between Treatments 2 and 4 nor between Treatments 2 and 3, despite the significantly larger mean bud diameter of Treatment 4.

The differences between the size classes of the fall lifted stock are shown in Table 3. Treatment 1 stock was balanced while all other treatments had short tops relative to root system size.

Table 3. The size classes of fall lifted 2+2 white spruce transplants subjected to root conditioning treatments in 1984, according to northern Ontario nursery stock standards (Day 1980).

Treatment	Size Class Ht RCD RAI	Type	Comments
1) Control	MBM - MBN - MBN	Ht=RCD=RAI	Stock normal, balanced
2) Pre-flush	MBL - LBN - MAN	Ht=RCD<RAI	Roots adequate, top short and sturdy
3) Mid-flush	HCM - LBN - HBM	Ht<RCD=RAI	Roots adequate, top short and sturdy
4) Post-flush	MBN - MBL - MAN	Ht=RCD<RAI	Roots adequate, top short and sturdy

Root sampling with root boards in the beds of the root conditioning trial showed that there was considerable difference in depth of root development between the treatments. Control stock had roots right to the bottom of the plow layer (25 cm), whereas the roots of wrenched stock generally only penetrated to a depth of 18 cm but had much more lateral root development and many more fine roots.

Potassium Fertilization

Potassium fertilization had a small but significant effect on bud diameter and RAI in the fall of 1984 (Table 4). The 200 kg/ha rate of potassium fertilizer caused a significant increase in bud diameter when averaged over all the root conditioning treatments. The 100 kg/ha rate of potassium fertilizer had a negative effect on RAI as compared with the control (0.0 kg/ha) and the 200 kg/ha rate of potassium fertilizer.

Table 4. Effect of potassium fertilizer on the morphological characteristics of 2+2 white spruce transplants from the 1984 root conditioning trial.

Treatment kg/ha	Initial Height (cm)	Final Height (cm)	Initial RCD (mm)	Final RCD (mm)	RAI (cm^2)	TDW (g)	RDW (g)	T/R Ratio	Bud Diam. (mm)	# of Primordia
0.0	12.4	26.1	3.8	5.8	75a	3.6	1.4	2.6	2.9b	364
100.0	12.0	26.0	3.6	5.9	65b	3.6	1.4	2.7	2.8b	367
200.0	12.3	26.0	3.7	6.0	72a	4.0	1.4	2.8	3.1a	363

* Values in columns followed by the different letters are significantly different at the 95% level of confidence.

1985 Results

The 1985 root conditioning trial results will be discussed in three parts: 1) the effect of root conditioning, 2) the effect of potassium fertilization on the morphology of the 2+2 white spruce transplants, and 3) the effect of the root conditioning treatments on soil characteristics.

Morphological Quality

Root conditioning during the summer had a moderate effect on the morphology of the 2+2 white spruce stock in 1985 (Table 5) when compared with 1984. Tukey's tests showed that root

Table 5. Means and significance of difference for initial and final morphological characteristics of white spruce transplants from the 1985 root conditioning trial.

Treatment	Initial Height (cm)	Final Height (cm)	Initial RCD (mm)	Final RCD (mm)	RAI (cm^2)	TDW (g)	RDW (g)	T/R Ratio	Bud Diam. (mm)	# of Primordia
1) Control	12.5a	23.3a	3.2a	6.4a	86a	7.3a	2.9a	2.7a	4.0a	293a
2) 21-Day	11.4a	18.3b	3.1a	5.5b	96a	5.3b	2.6a	2.2b	3.5b	284a
3) Periodic	11.6a	19.5b	3.1a	5.7b	78a	5.8b	2.5a	2.5ab	3.6b	-

* Values in columns followed by different letters are significantly different at the 95% level of confidence (except 85 ratio - 90% level).

conditioning significantly reduced the height growth and RCD of the stock. Year end measurements indicated there were no significant differences in mean root dry weight or RAI between the three treatments but top dry weight was reduced by root conditioning. Stock from Treatment 1 had significantly higher total top dry weights and higher terminal shoot dry weights than that from

Treatments 2 or 3. The shoot dry weights of stock from Treatment 1 were not significantly different from those of Treatment 3 but were higher than those from Treatment 2. For all but Treatment 2, which had a mean total top dry weight of 5.3 g, the mean total top dry weight of the stock was larger than the average of 5.4 g for northern Ontario nursery stock (Day 1980). Once again, the root pruning and wrenching treatments had more effect on the shoots than the roots of the stock. Top dry weight was reduced by 25% and terminal shoot dry weight was reduced by 42% when the average of Treatments 2 and 3 were compared with Treatment 1, whereas root dry weight was only reduced by 12% which was not significant. The mean top/root ratio of Treatment 2 was significantly smaller than that of Treatment 1 at the 90% level of confidence.

Figure 7 shows that root conditioning began to affect the height growth of seedlings in mid-June, and reduced its rate until the end of the growing season. The height growth of Treatment 2 (pruned pre-flush and wrenched every 21-days) was reduced more than that of Treatment 3 (pruned pre-flush and wrenched periodically), but the difference was not significant at the 95% level of confidence. Although the height growth of the Treatment 1 (control) stock also slowed down as the season progressed, the reduction was not as pronounced. Treatment 1 stock was significantly taller than stock from either of the root conditioning treatments at all sample times after May.

The RCD growth of the stock in all three root conditioning treatments over the season is given in Figure 8. RCD decreased slightly in all treatments in May, then increased after mid-June. The difference in RCD between the treatments was not significant until mid-July.

Examination of the number of primordia contained in the buds at the end of the season, showed no significant difference between the treatments although the bud diameters of stock from Treatment 1 were significantly larger than those of Treatment 2 stock. There were no significant differences between the bud diameters of Treatments 1 and 3 nor Treatments 2 and 3 (Table 5).

The size classes of the fall lifted stock are shown in Table 6. In general, the morphological characteristics of the stock from all three treatments were good but no great differences were apparent between the treatments. Comparing these with the treatments in 1984 indicates that the control stock was shorter in height this year but had larger root systems.

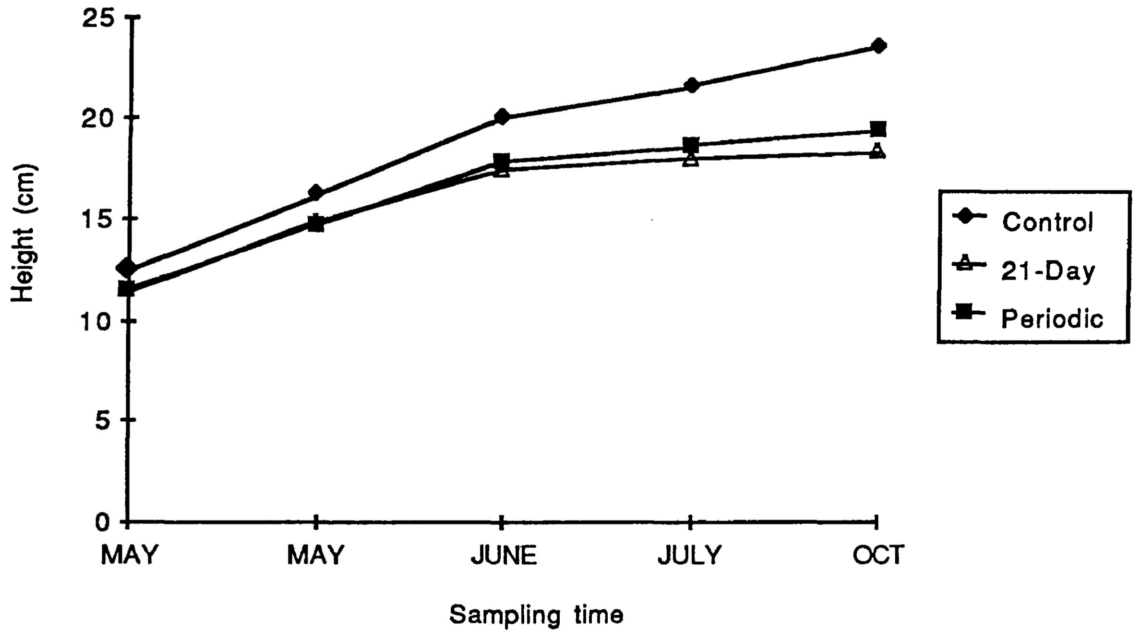


Figure 7. Cumulative height growth curve for control and root conditioned 2+2 white spruce transplants on the Thunder Bay Forest Station in 1985.

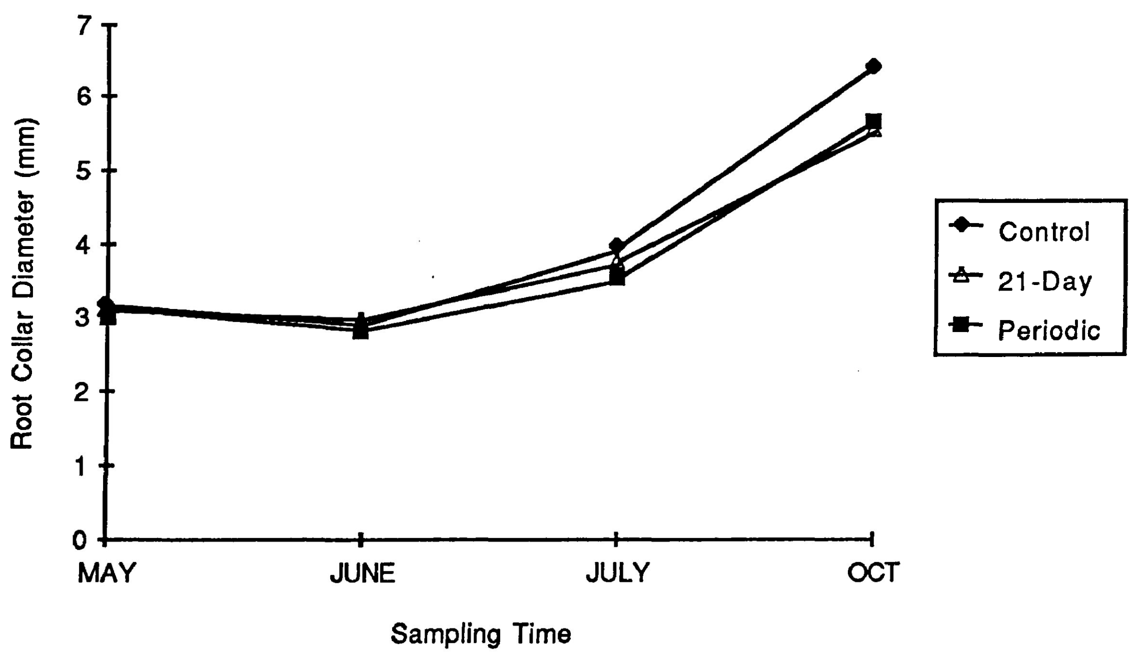


Figure 8. Root collar diameter growth of control and root conditioned 2+2 white spruce transplants on the Thunder Bay Forest Station in 1985.

Table 6. The size classes of fall-lifted 2+2 white spruce transplants subjected to root conditioning treatments in 1985, according to northern Ontario nursery stock standards (Day 1980).

Treatment	Size Class Ht RCD RAI	Type	Comments
Control	MCN - HBM - MAM	Ht<RCD<RAI	Roots adequate, top short and sturdy
21 - day	MDN - LBM - HAM	Ht<<RCD<<RAI	Roots large, top very short and sturdy
Periodic	HDN - LBN - MAM	Ht<<RCD<RAI	Roots adequate, top short and sturdy

Potassium Fertilization

Potassium fertilizer had no effect on the morphological characteristics of the stock in 1985 (Table 7). There was a significant difference in initial RCD, with fertilized plots having slightly larger initial RCDs than controls, but over the season this difference was lost and by fall neither final RCD nor RCD increment were significantly different between the treatments.

Table 7. Effect of potassium fertilizer on the morphological characteristics of 2+2 white spruce transplants from the 1985 root conditioning trial.

Treatment kg/ha	Initial Height (cm)	Final Height (cm)	Initial RCD (mm)	Final RCD (mm)	RAI (cm^2)	TDW (g)	RDW (g)	T/R Ratio	Bud Diam. (mm)	# of Primordia
0.0	11.9	20.3	3.0b	5.8	85	5.9	2.6	2.4	3.6	281
75.0	11.8	20.5	3.2a	6.0	89	6.4	2.7	2.5	3.7	295

* Values in columns followed by the different letters are significantly different at the 95% level of confidence.

Soil Characteristics

Root conditioning, particularly wrenching, reduced the bulk density of the soil by 7, 12 and 2% respectively for the first three wrenching treatments applied to Treatment 2, and kept it significantly lower than that of the control beds throughout the summer (Figure 9). Fluctuations occurred between conditioning treatments in response to the packing effect of rainfall. In Figure 9, vertical lines indicate an immediate decrease in bulk density due to wrenching. In general, bulk density increased slightly for all treatments over the summer months through compaction caused by rain and irrigation. Treatment 3 is not shown in Figure 9 because of its similarity with Treatment 2.

Similarly, the percent moisture content of the soil in Treatment 2 was 1 to 2% lower than that of Treatment 1 throughout the summer (Figure 10), except for one sampling time mid-season which was immediately after a rain. Both Treatments 1 and 2 showed the same changes in moisture content, related to wetting by rainfall and irrigation and subsequent drying. Treatment 3 is not shown in Figure 10 because of its similarity with Treatment 2.

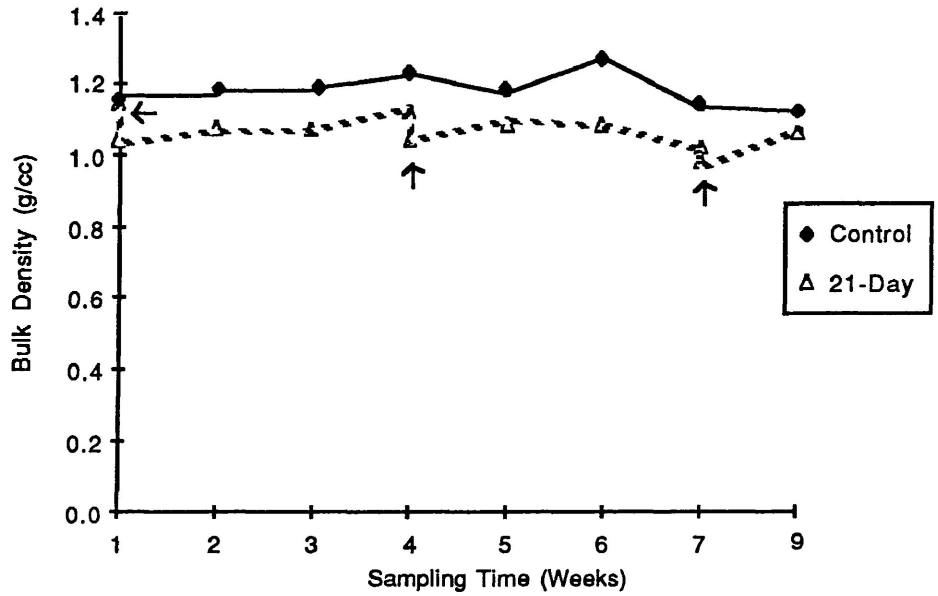


Figure 9. Bulk density of control and root conditioned beds sampled at weekly intervals throughout the summer of 1985. (Arrows show when wrenching treatments were applied.)

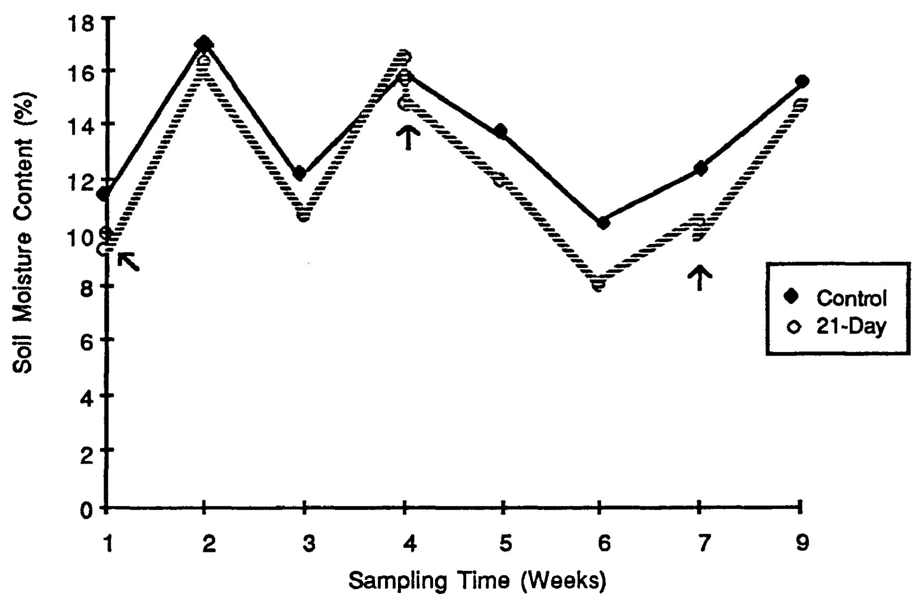


Figure 10. Moisture content of the soil for control and root conditioned beds sampled at weekly intervals throughout the summer of 1985. (Arrows indicate when wrenching occurred)

GROWTH POTENTIAL TESTS DURING STORAGE

Root Growth Potential

1984-85 Results

The stock slated for overwinter frozen storage was lifted November 1st, 1984. The soil froze as the day progressed allowing removal of only three replicates of each of the treatments. The RGP tests conducted in the growth chamber with Treatments 1 and 2 indicated that root conditioned stock had a significantly better ability to produce roots throughout the period of storage than non-conditioned stock, except in December and May when the differences in root growth between the two treatments were not significant (Appendix 5, Table 5A). Both the treatments followed similar patterns of root growth, with root number (RN) (Figure 11) and root elongation (RE) (Figure 12) increasing from December through January and February, then decreasing towards the spring. The February test went for 25 days rather than 21, so the peak in root growth probably occurred in January. Figure 11 compares small, medium and long RN during the winter months. Small roots were less than 0.5 cm in length, medium roots were from 0.5 to 1 cm in length and long roots were over 1 cm. A gradual decline in the number of medium and long roots was evident after January, whereas the number of small roots increased. Thus, the rate of root initiation increased but the rate of elongation decreased throughout the period of storage. Figure 12 presents the rise in RE through January and the gradual decline towards spring. Most of the RE was accounted for by long roots as would be expected.

Results of the mist chamber study indicated that in December the Treatment 2 stock initiated roots faster than that of Treatment 1. By day 18, all of the Treatment 2 stock had regenerated roots compared to only 70% of that from Treatment 1. In January, the mist apparatus malfunctioned overnight early in the study, causing the seedlings to dry down for 4 to 8 hours. The result of this was that 80% of Treatment 2 stock regenerated roots compared with only 30% of Treatment 1 stock. In February and March, stock from both treatments regenerated roots at approximately the same speed. The minimum time to initiate new root growth after placing 2+2 white spruce transplants from overwinter storage into warm, moist growing conditions was found to be six days.

1985-86 Results

The stock slated for overwinter storage in 1985 was lifted October 22 - 24th, 1985 after a rain. The RGP tests conducted in the growth chamber showed a gradual decline in both RN (Figures 13 and 14) and RE (Figures 15 and 16) from November through May for all Treatments. There were no significant differences in root growth between the Treatments, except that in November Treatment 1 had higher RN and RE long, but in February had less RE than the other treatments (Appendix 5, Table 5B). RN remained fairly constant for Treatment 2 from December through March (Figure 13), while that of

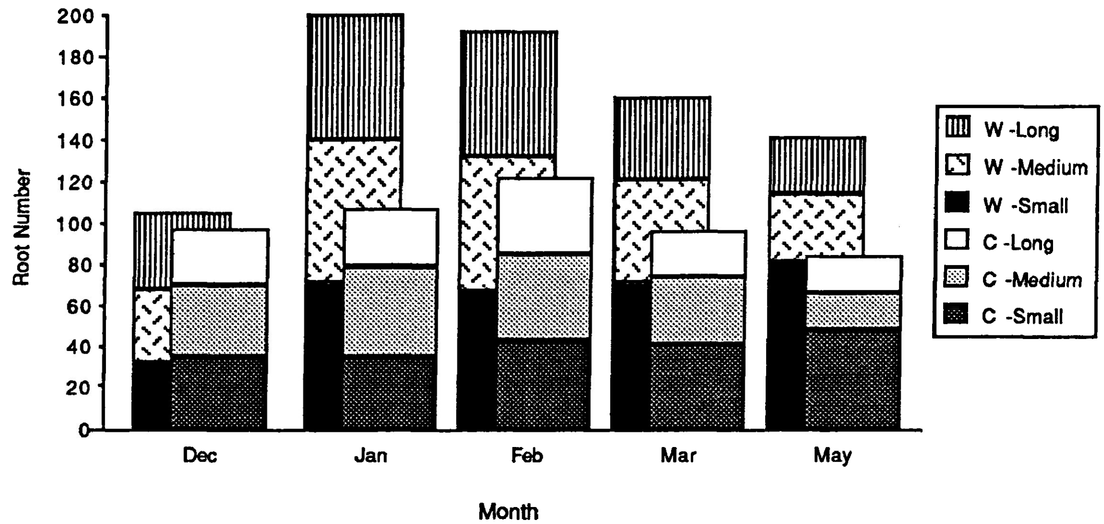


Figure 11. Small, medium and long roots comprising total root number produced by control (C) and pre-flush pruned (W) white spruce transplants during 21-day root growth potential trials in the winter of 1984-85.

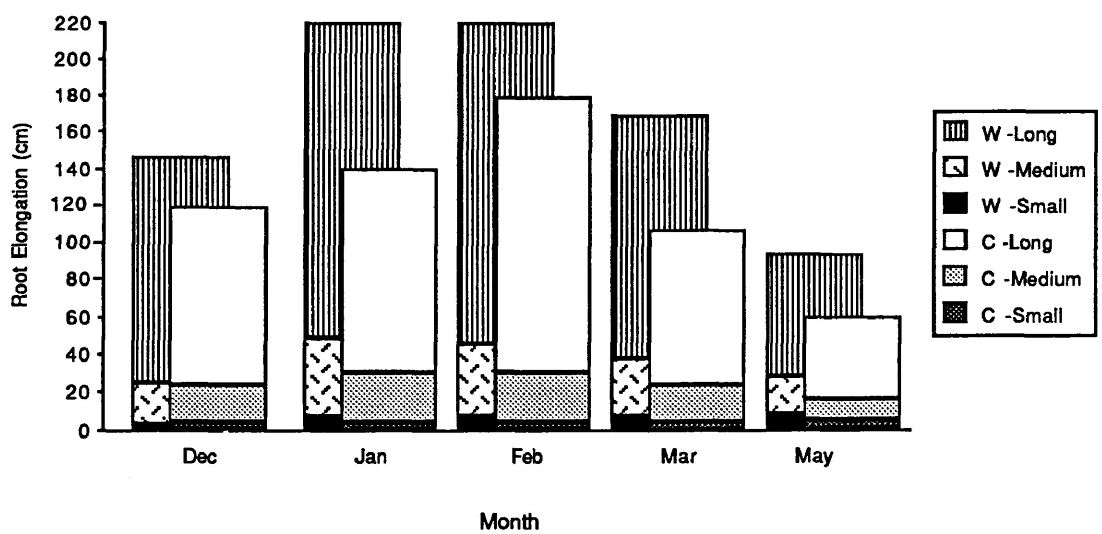


Figure 12. Small, medium and long roots comprising total root elongation produced by control (C) and pre-flush pruned (W) white spruce transplants during 21-day root growth potential trials in the winter of 1984-85.

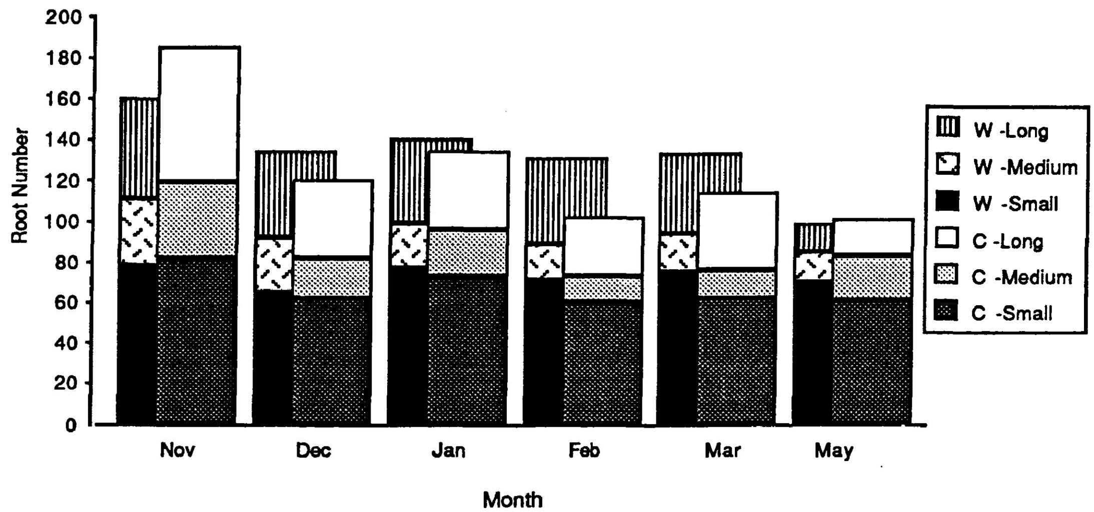


Figure 13. Small, medium and long roots comprising total root number produced by control (C) and 21-day wrenched (W) white spruce transplants during 21-day root growth potential trials in the winter of 1985-86.

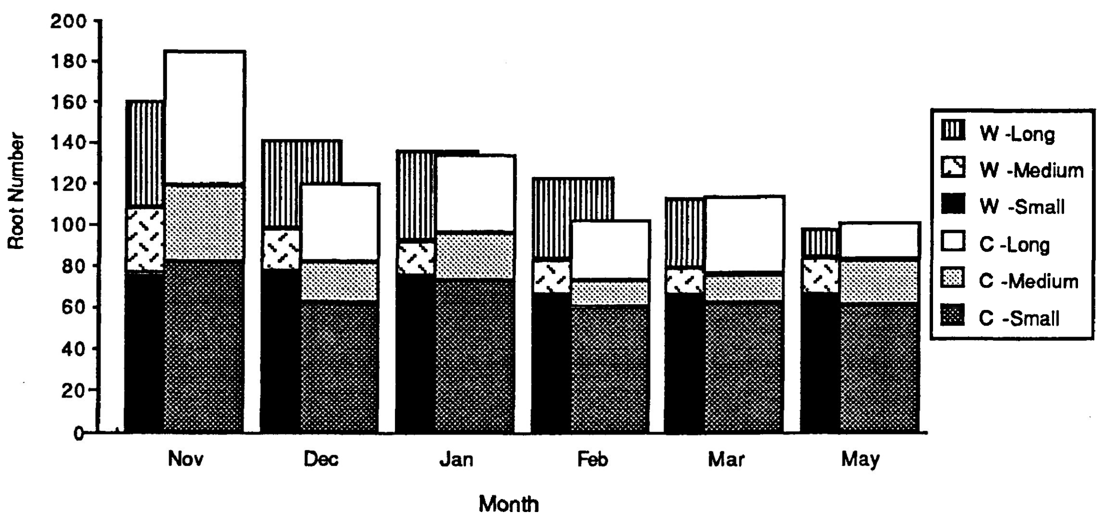


Figure 14. Small, medium and long roots comprising total root number produced by control (C) and periodically wrenched (W) white spruce transplants during 21-day root growth potential trials in the winter of 1985-86.

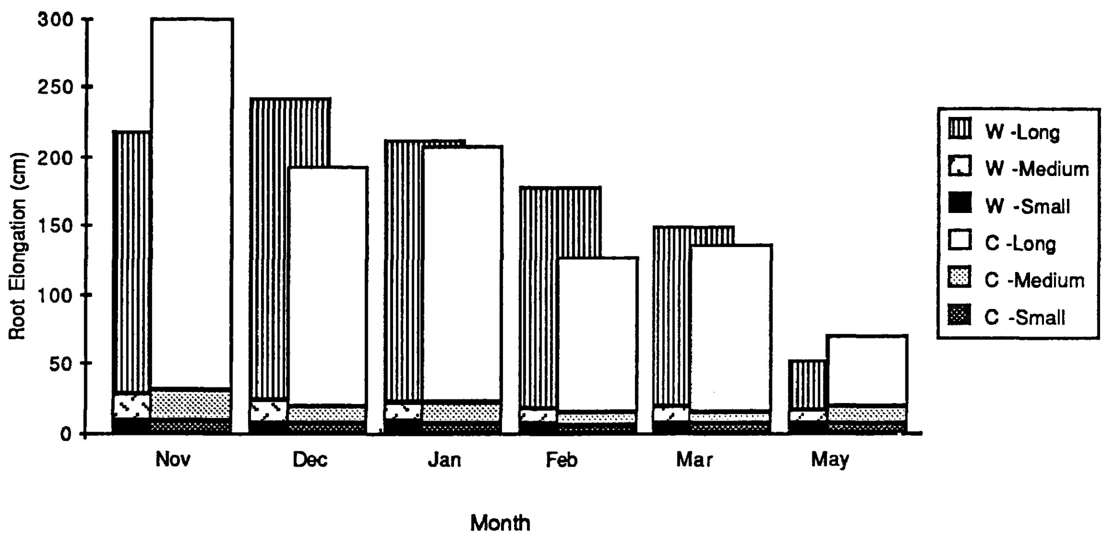


Figure 15. Small, medium and long roots comprising total root elongation produced by control (C) and 21-day wrenched (W) white spruce transplants during 21-day root growth potential trials in the winter of 1985-86.

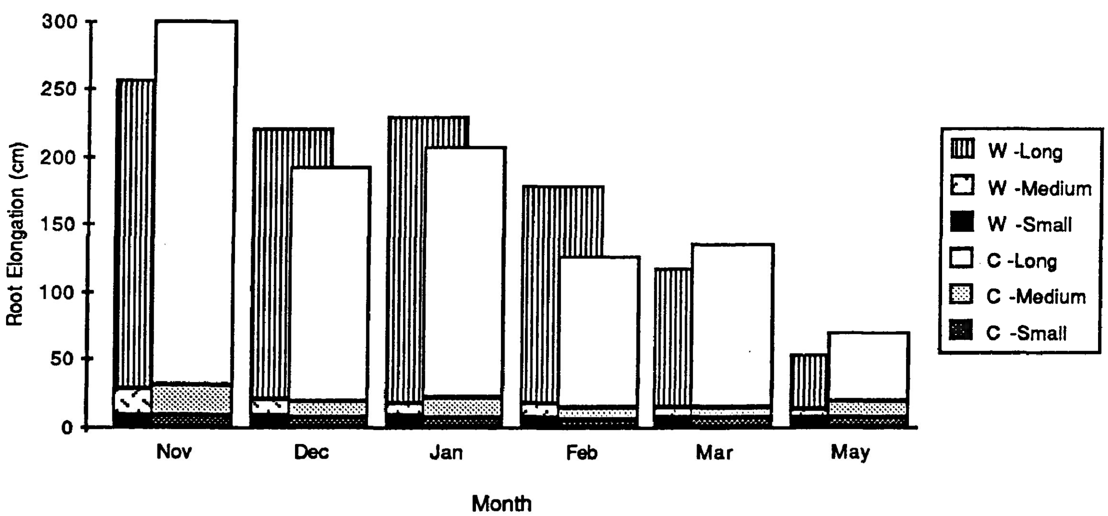


Figure 16. Small, medium and long roots comprising total root elongation produced by control (C) and periodically wrenched (W) white spruce transplants during 21-day root growth potential trials in the winter of 1985-86.

Treatment 1 fluctuated and that of Treatment 3 gradually decreased (Figure 14). The change in RE over the winter months was attributable mainly to a reduction in long roots. There was little change in small and medium root elongation (Figures 15 and 16).

Comparison Between Years

A comparison between years is not statistically valid, because of the different treatments applied and the restriction error associated with the tests, but is still interesting to note the differences. Figures 17 and 18 compare RN and Figures 19 and 20 compare RE throughout overwinter frozen storage for the two years respectively. The pattern as well as the amount of root growth throughout storage was very different. In 1984-85, unwrenched stock regenerated fewer roots than in 1985-86, but RE was lower only in December and January. Root conditioning had a more positive effect on RN and RE in 1984-85. The classical pattern of root growth was evident in 1984-85, whereas in 1985-86 there was no mid-winter peak in root growth.

Shoot Growth Potential

1984-85 Results

By the time of lifting on November 1st, 1984, the stock had accumulated 255 negative degree days (NDD), according to the air temperature method of calculation. 170 NDD are considered adequate to prepare white spruce for overwinter frozen storage (Day *et. al.* 1985). Figure 21 shows the progression of bud flushing through the 21-days for the winter months. In December an average of 14% of the buds had flushed at the end of the test. After December, buds flushed to maximum potential in each test. The average time of flushing was reduced gradually over the winter but the minimum time required for flushing after removal of stock from frozen storage was 10-15 days. A greater percentage of the buds of Treatment 2 stock flushed in the February test by day 15 (Appendix 5, Table 5C) but otherwise there were no significant differences in the percent of buds flushed between the treatments.

1985-86 Results

By the time of lifting on October 22-24th, 1985, the stock had accumulated 229 NDD, well in excess of the amount required for overwinter storage. The results of the bud flushing trials were similar to those in the previous year but a much higher percentage of buds flushed in December and January (Figure 22). Once again, a minimum of 9-15 days were required for flushing to begin. In March, the buds of Treatment 2 and 3 stock flushed significantly faster than those of Treatment 1 stock but there were no significant differences in the other tests (Appendix 5, Table 5C).

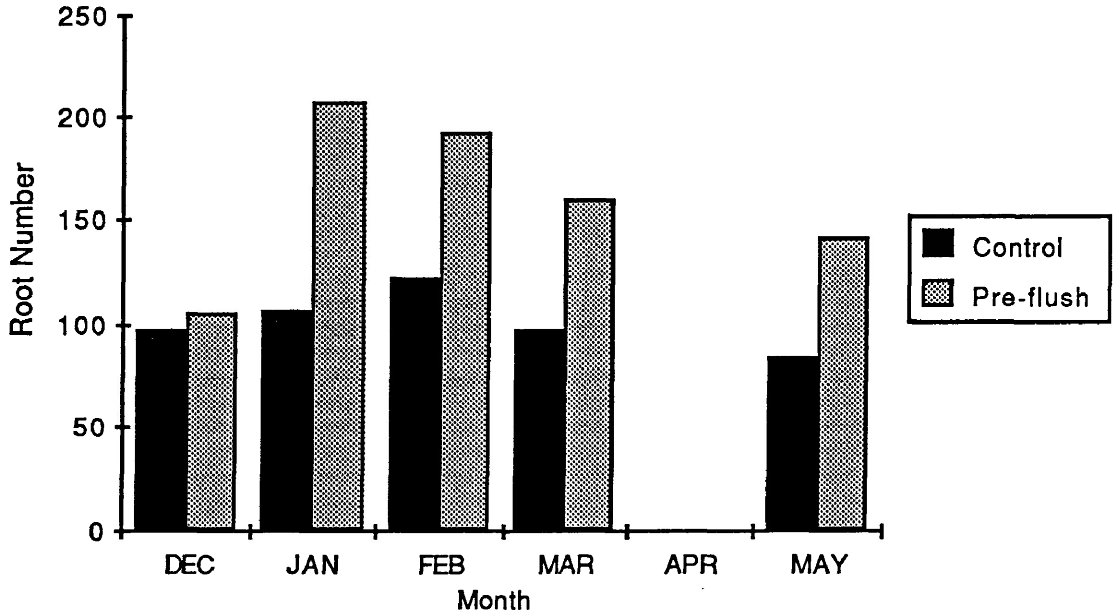


Figure 17. Total root number produced by white spruce transplants during 21-day root growth potential tests in the winter of 1984-85.

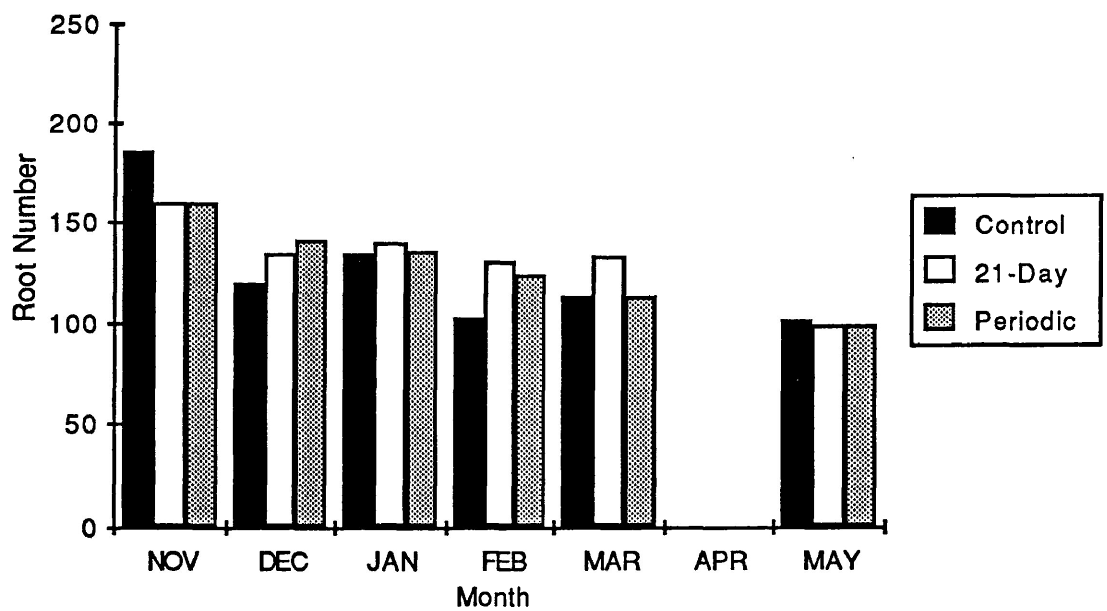


Figure 18. Total root number produced by white spruce transplants during 21-day root growth potential tests in the winter of 1985-86.

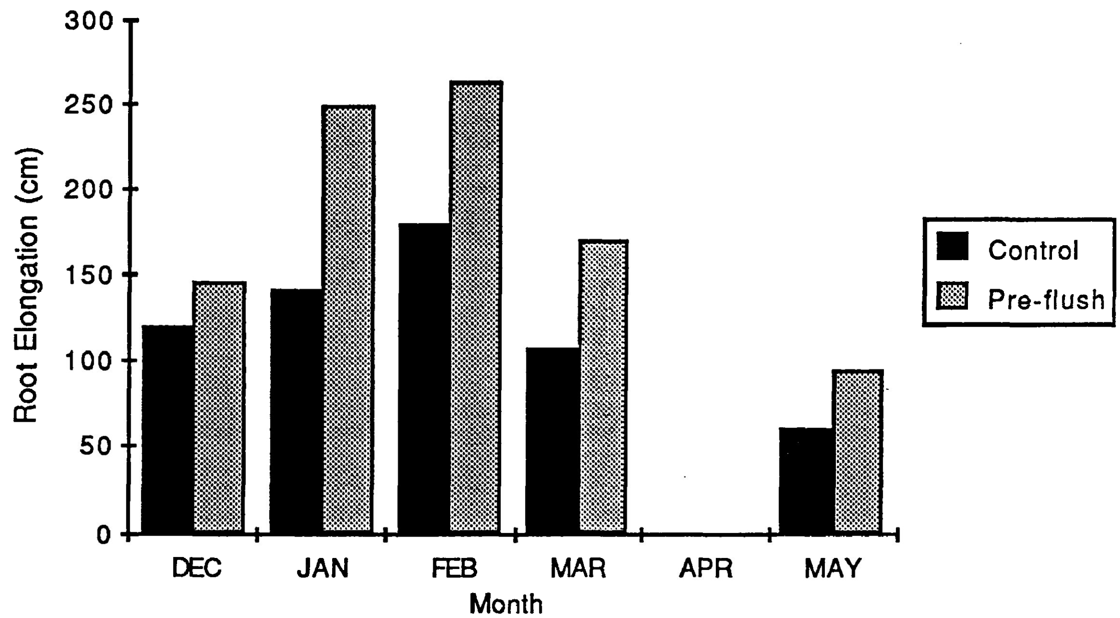


Figure 19. Total root elongation of white spruce transplants during 21-day root growth potential tests in the winter of 1984-85.

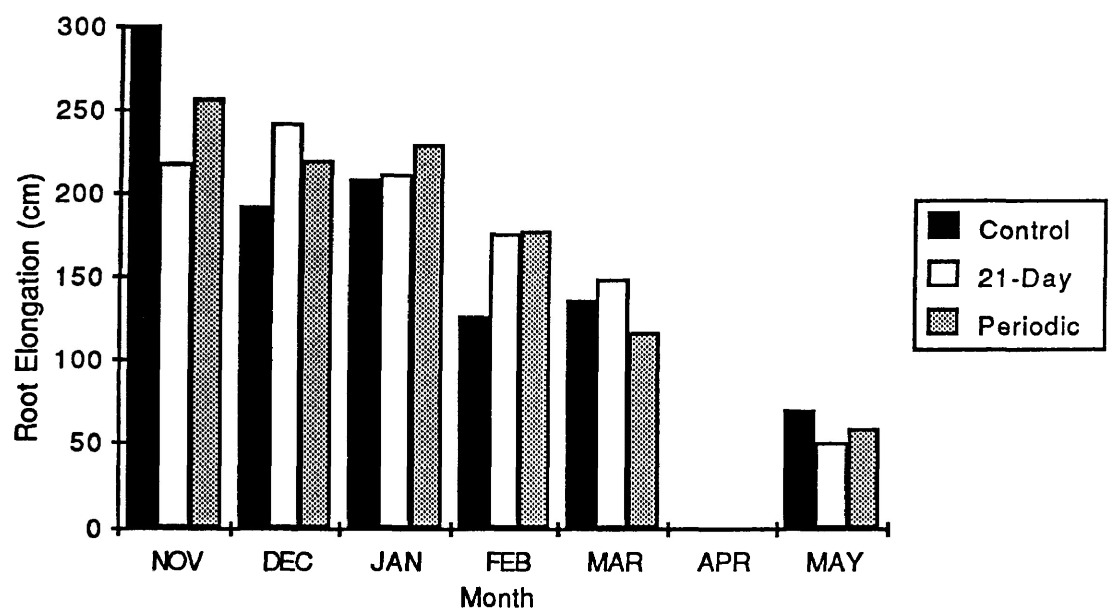
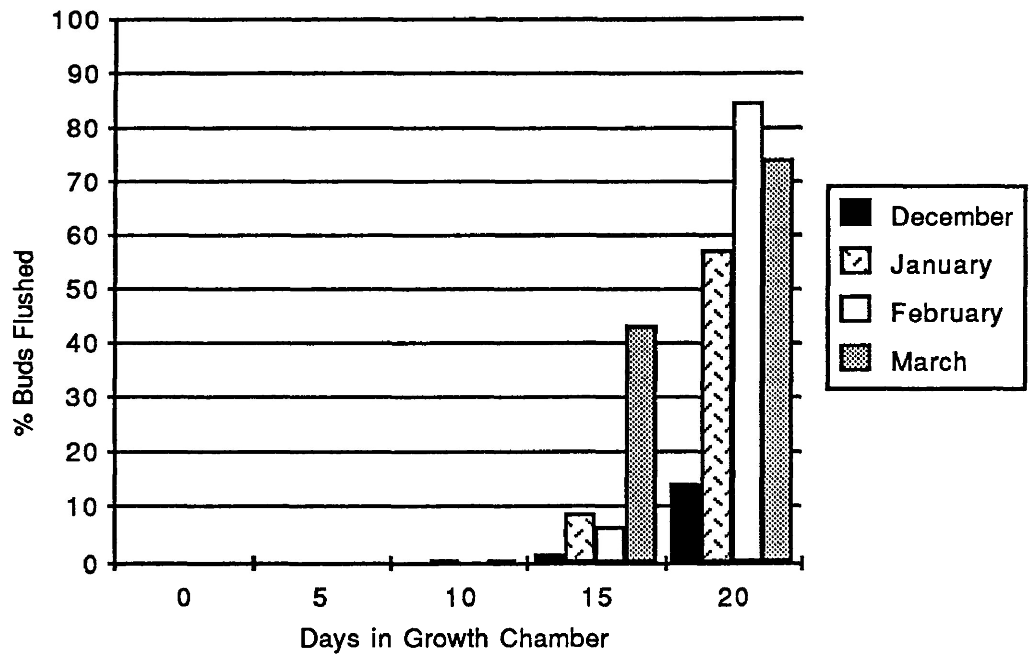


Figure 20. Total root elongation of white spruce transplants during 21-day root growth potential tests in the winter of 1985-86.



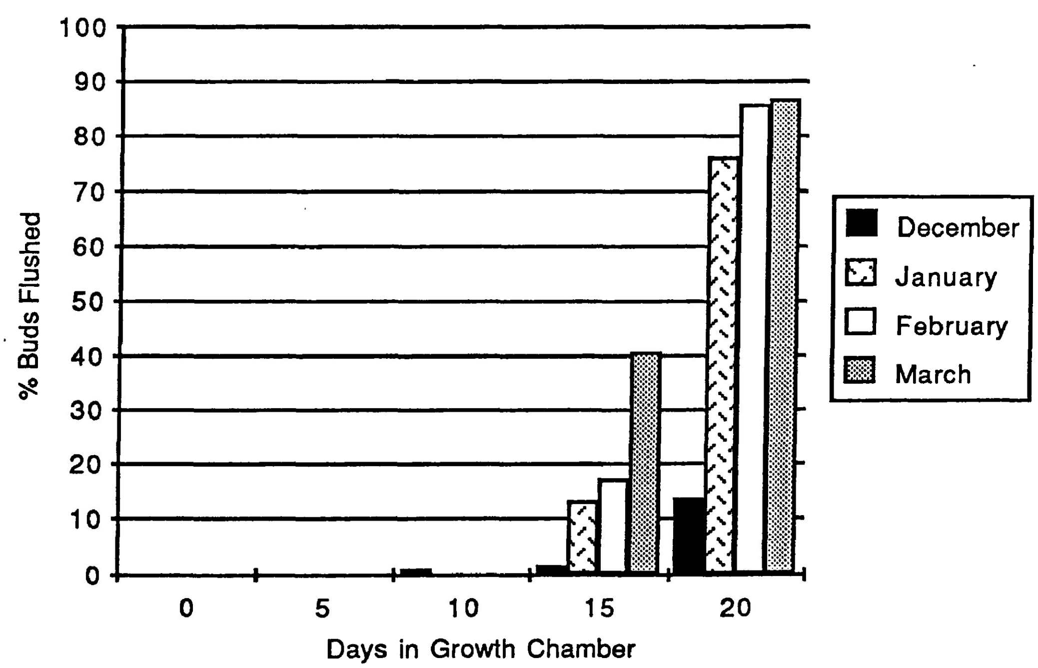


Figure 21. Progression of bud flushing for Treatments 1 (top) and 2 (bottom) throughout 21-day growth chamber tests in the winter of 1984-85.

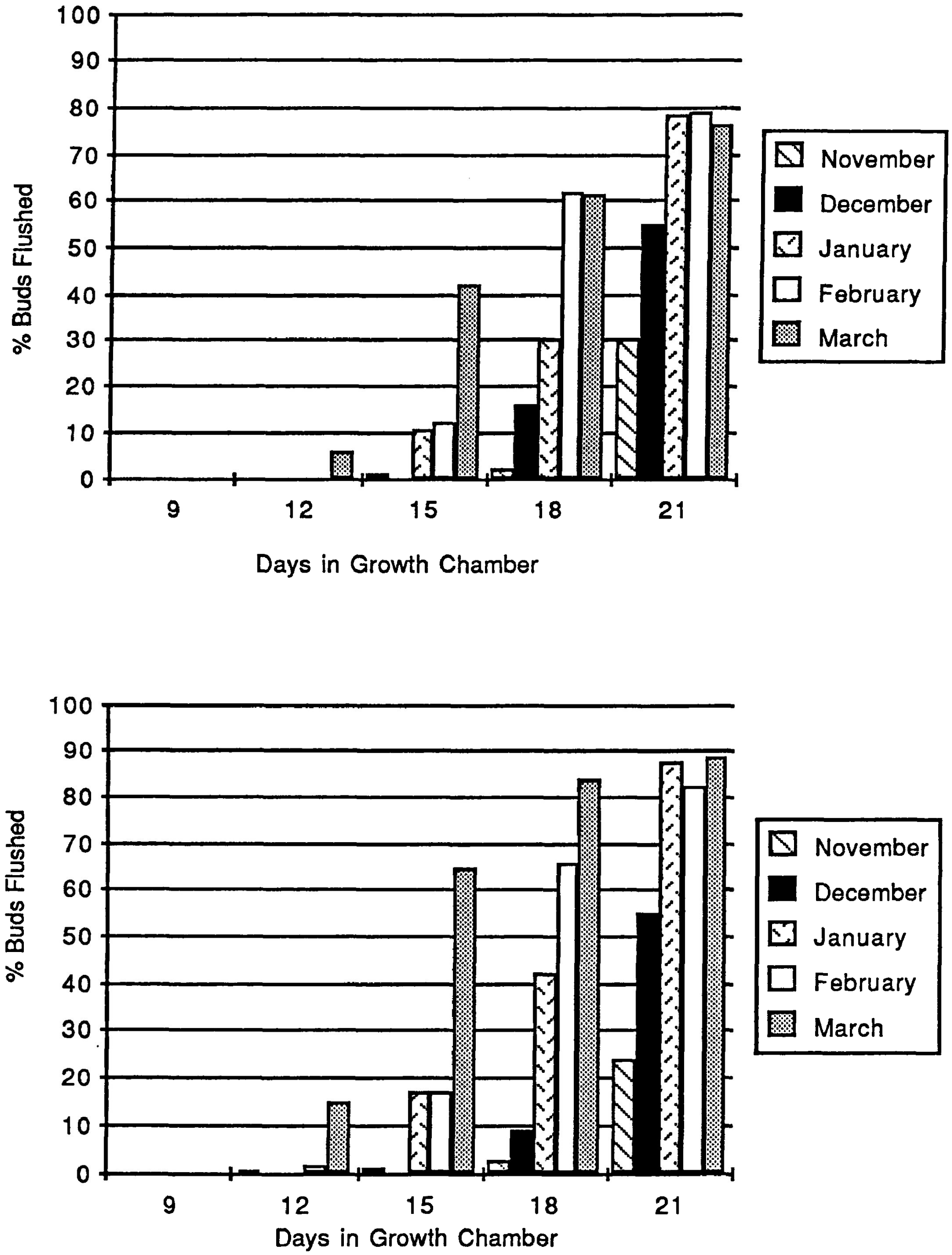


Figure 22. Progression of bud flushing for Treatments 1 (top) and 2 (bottom) throughout 21-day growth chamber tests in the winter of 1985-86.

Comparison Between Years

Although no statistical tests between years could be made, it is interesting to note that the progression of bud flushing through the winter months was different in the two years of the study (Figures 23 and 24). A much higher percentage of buds flushed in December and January in 1985-86 than the previous year and even in November 25-35% of the buds had flushed by the end of the 21-day test indicating that the stock was no longer dormant.

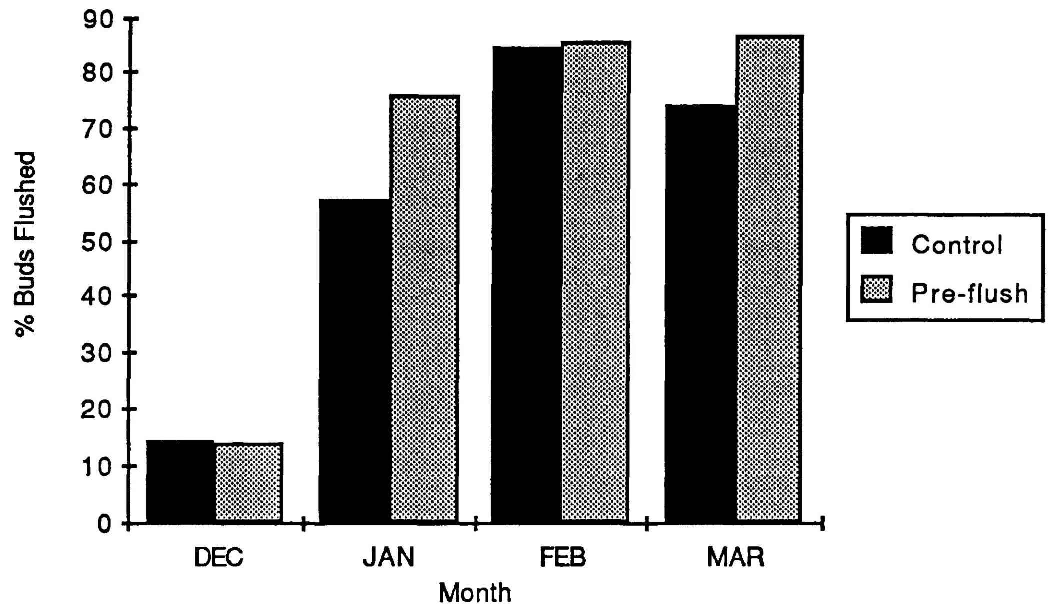


Figure 23. Percent of buds of white spruce transplants flushed after 21-day growth chamber trials in1984-85.

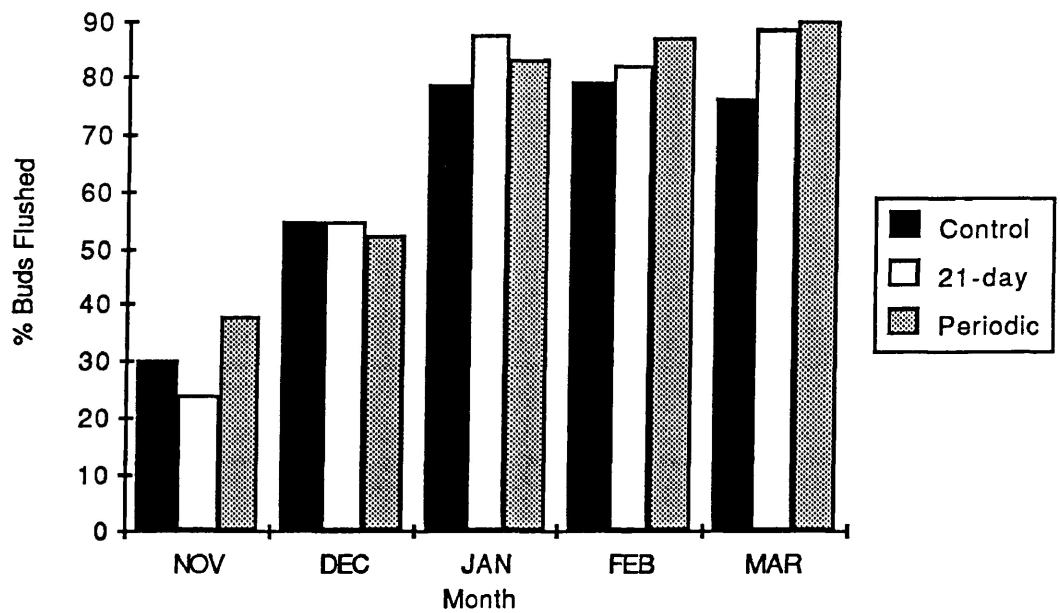


Figure 24. Percent of buds ofwhite spruce transplants flushed after 21-day growth chamber trials in1985-86 .

OUTPLANTING TRIAL

Root Growth Potential

May 1985

The RGP of both root conditioned and control stock, which were either fall lifted and overwinter stored or spring lifted, was compared after 21-days in the growth chamber and the field (Figure 25). The results emphasize the difference between RGP under ideal conditions in the growth chamber and after the stock is planted in the field. In both environments, frozen stored root conditioned stock elongated more roots than frozen stored control stock but the differences were only significant for small roots (Appendix 5, Table 5D). There were no significant differences between the spring lifted treatments.

Table 8 compares the percent of stock with no roots and the percent with adequate root development for establishment after 21-days in the field and the growth chamber, using Day and Harvey's (1984a) criteria. Root conditioned stock had consistantly greater RN but neither root conditioned nor control stock was well established in the field after 21 days. RN was closer to adequate than RE owing to the high number of small roots, indicating that the stock was initiating roots but not elongating them.

Table 8. The percentage of white spruce transplants with no root development versus the percentage with adequate root development for establishment after 21 day tests in 1985.

Time of Lifting	Location	Treatment	% with no roots SM	MED	LG	% with RE>35cm	% with RN>35
Frozen	Chamber	Control	3.3	16.7	16.7	50.0	63.3
Stored		Wrenched	0.0	0.0	0.0	83.3	100.0
	Field	Control	13.3	56.7	63.3	0.0	23.3
		Wrenched	3.4	37.9	62.1	0.0	60.0
Spring	Chamber	Control	0.0	10.0	0.0	76.7	90.0
Lifted		Wrenched	3.3	3.3	3.3	86.7	96.6
	Field	Control	10.0	60.0	70.0	0.0	0.0
		Wrenched	3.3	60.0	83.3	0.0	0.0

An attempt to correlate height growth with root growth and initial root system size with final root system size showed no relationship between height and root growth nor between initial, final or change in root area index and RGP. Changes in root area index were generally negative with frozen stored stock losing an average of 28% of its root area index in the field and 13% in the growth chamber during the 21-day trials compared with 20% in the field and 7% in the chamber for the spring lifted stock.

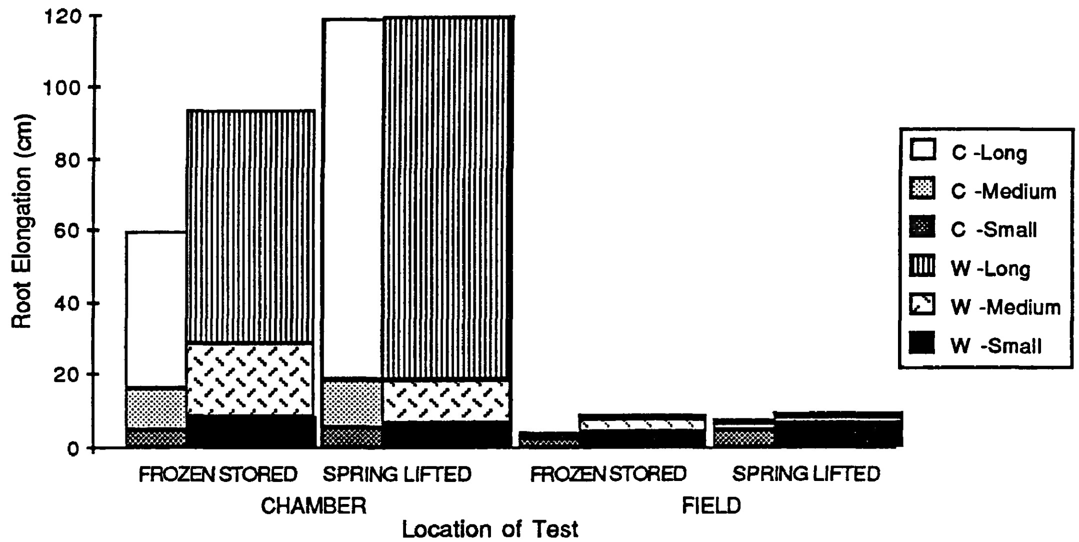


Figure 25. Small, medium and long roots comprising total root elongation for control (C) versus root conditioned (W) fall lifted, overwinter frozen stored and spring lifted white spruce transplants after 21-day root growth potential trials in the field and the growth chamber in May1985.

May 1986

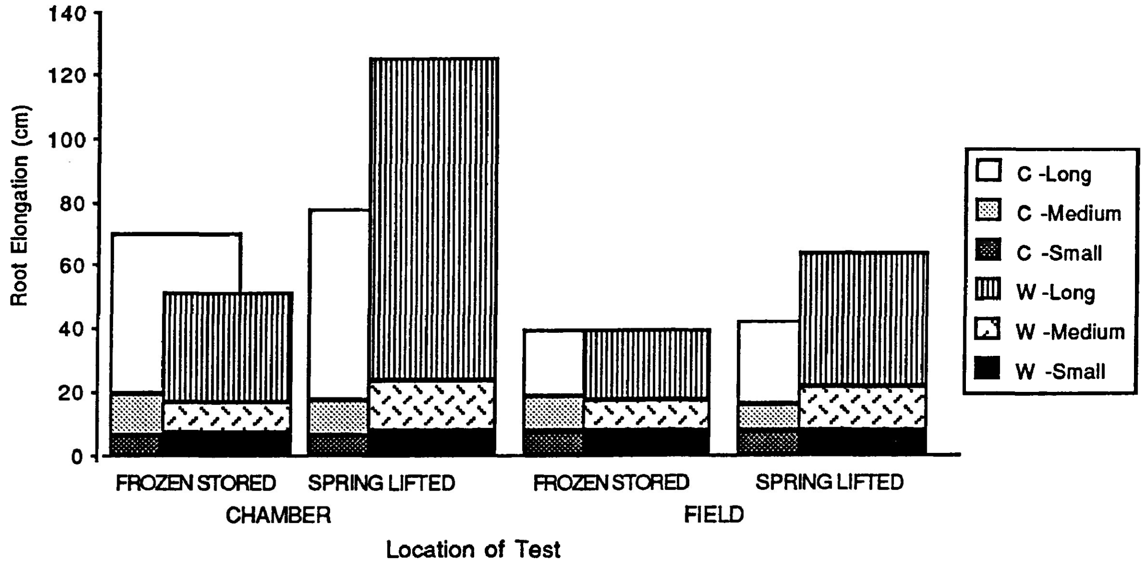
The RGP both root conditioned and control stock, which were fall lifted and overwinter stored or spring lifted, were compared after 21 days in the growth chamber and the field (Figure 26). The trends for RE are similar in the growth chamber and in the field but 22-33% less root growth was produced in the field by the frozen stored stock and 46-53% less was produced by the spring lifted stock. In 1986, there were no significant differences between the root conditioning treatments in either RN or RE (Appendix 5, Table 5E) during the first 21 days after outplanting.

Table 9 shows the percentage of stock in each treatment with no roots versus that with adequate root systems for establishment again using Day and Harvey's (1984a) criteria. All stock was in good physiological condition for growth in 1986.

Table 9. The percentage of white spruce transplants with no root development versus the percentage with adequate root development for establishment after 21 day tests in 1986.

Time of Lifting	Location	Treatment	% with no roots SM	MED	LG	% with RE>35cm	% with RN>35
Frozen Stored	Chamber	Control	0.0	5.0	0.0	83.3	96.7
		21-Day	0.0	0.0	0.0	83.3	100.0
		Periodic	0.0	0.0	0.0	80.0	100.0
	Field	Control	0.0	10.0	5.0	80.0	96.7
		21-Day	0.0	5.0	5.0	76.7	96.7
		Periodic	0.0	0.0	0.0	80.0	100.0
Spring Lifted	Chamber	Control	0.0	0.0	0.0	85.0	100.0
		21-Day	0.0	0.0	0.0	90.0	100.0
		Periodic	0.0	0.0	0.0	85.0	96.7
	Field	Control	0.0	0.0	5.0	50.0	96.7
		21-Day	0.0	0.0	5.0	65.0	100.0
		Periodic	0.0	0.0	5.0	70.0	96.7

Again, no correlation could be found between height and root growth nor between root area index and RGP. Changes in root area index were mainly negative with frozen stored stock losing an average of 19% of its root area in the field and 10% in the chamber in the 21 day test while the spring lifted stock lost 17% in the field and 12% in the chamber.



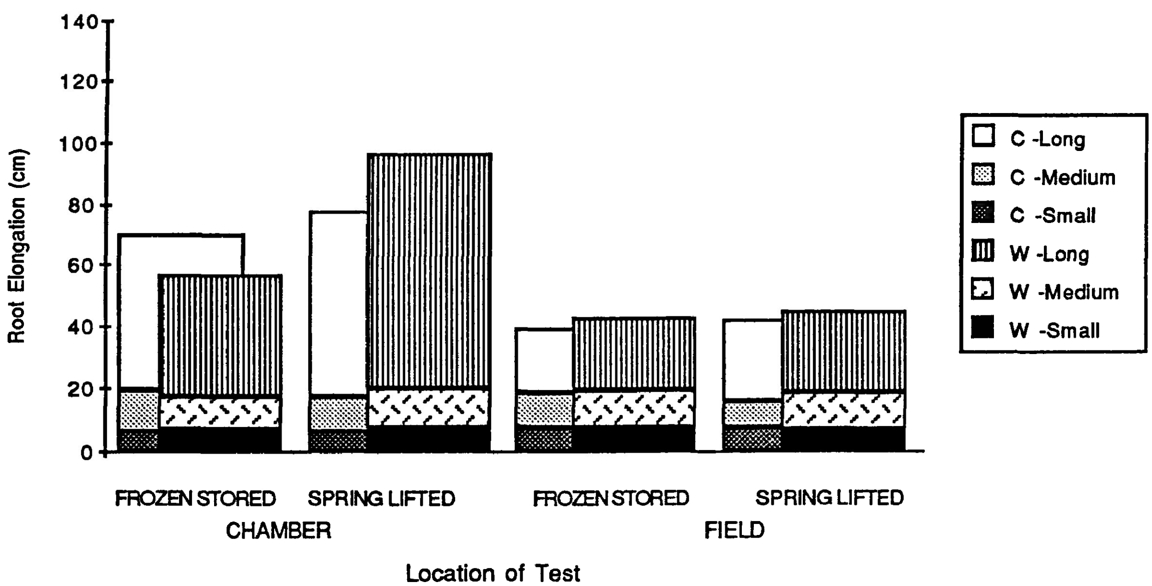


Figure 26. Small, medium and long roots comprising total root elongation of control (C) versus 21-day wrenching (W)(top), and periodic wrenching (W) (bottom) for fall lifted, overwinter stored and spring lifted 2+2 white spruce transplants during 21-day root growth potential trials in May of 1986.

Outplanting Performance

1985 - First Year Results

The stock was planted May 23-25th, 1985. End of season measurements were made in October. Preplanting measurements indicated that stock from Treatments 1 and 4 were significantly taller (Figure 27) and had larger RCDs than that from Treatments 2 and 3 as a result of the root conditioning treatments (Figure 28). Bud diameters of stock from Treatments 1 and 4 were also significantly larger than those of stock from Treatments 2 and 3. There were no differences in initial height or RCD between fall lifted and overwinter frozen stored and spring lifted stock. Height and root collar diameter measurements were combined and are reported as seedling volume. Seedling volume was smaller for Treatments 2 than the other Treatments but differences are not as clearcut as when height and RCD are evaluated separately. Initial and final morphological characteristics for the 1985 outplant are compared in Table 10.

Table 10. A summary of the morphological characteristics of root conditioned white spruce transplants the first season after outplanting in 1985.

Lifting time	Wrenching treatment	Initial Volume cm3	Volume Increm. cm3	Terminal dry wgt. g	Shoot dry wgt. g	Root dry wgt. g	T/R Ratio mm	Final bud diam. mm
Frozen Stored	1) Control	3.78a*	1.19	0.37a	11.0a	3.9cd	3.3a	2.5a
	2) Pre-flush	2.77c	1.04	0.26c	9.8b	4.0cd	2.8b	2.4a
	3) Mid-flush	3.08abc	0.82	0.26c	9.3b	3.7d	2.8b	2.4a
	4) Post-flush	3.93a	1.06	0.34b	11.2a	4.3c	3.0a	2.6a
Spring Lifted	1) Control	3.70ab	1.90	0.43a	12.9a	6.0a	2.7b	2.6a
	2) Pre-flush	2.85bc	1.41	0.33b	10.4ab	5.3b	2.4c	2.4a
	3) Mid-flush	3.30abc	1.36	0.27c	10.5ab	5.1b	2.4c	2.3a
	4) Post-flush	3.41abc	1.78	0.39a	11.8a	5.8a	2.4c	2.5a

*Values in the same column followed by different letters are significantly different at the 95% level of confidence.

The year end measurements showed significantly greater height growth for stock from Treatments 1 and 4 than that from Treatments 2 and 3 (Figure 27). Thus, root conditioning unless done late in the season, negatively affected height growth in the first year after outplanting. Unfertilized stock grew more than stock fertilized with potassium with the exception that frozen stored stock fertilized with 100kg/ha potassium grew 1 cm more than any other treatment.

After one season in the field the RCDs of spring lifted stock were significantly larger than those of frozen stock. Treatment 1 and 4 stock maintained larger RCDs when compared with Treatments 2 and 3 (Figure 28). There were no significant differences in volume increment between

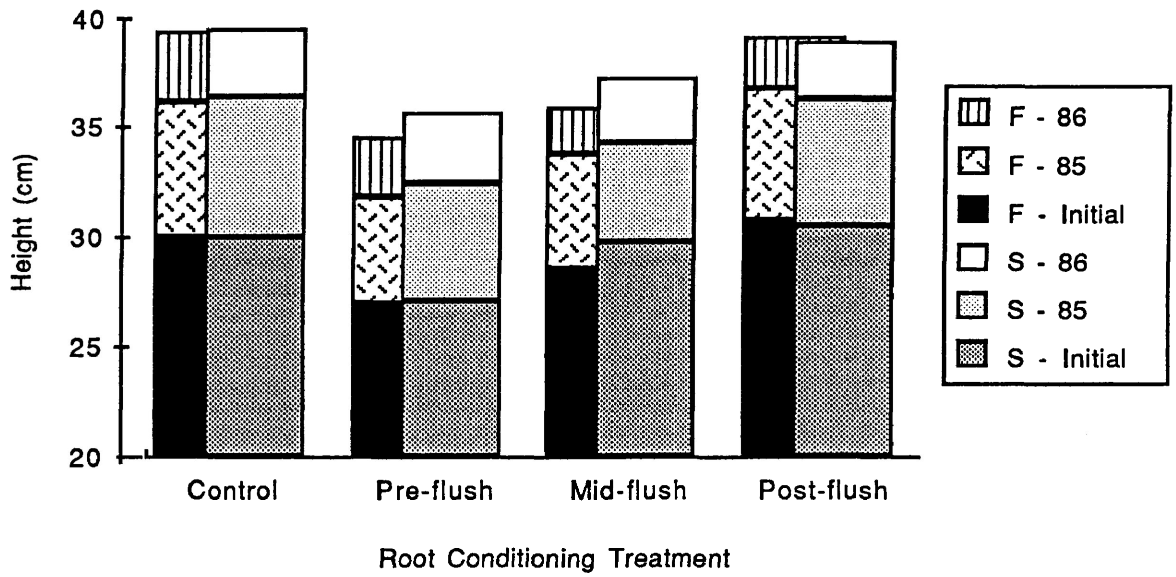


Figure 27. Initial height and 1985 and 1986 height increments of frozen stored (F) and spring lifted (S) white spruce transplants after outplanting in 1985.

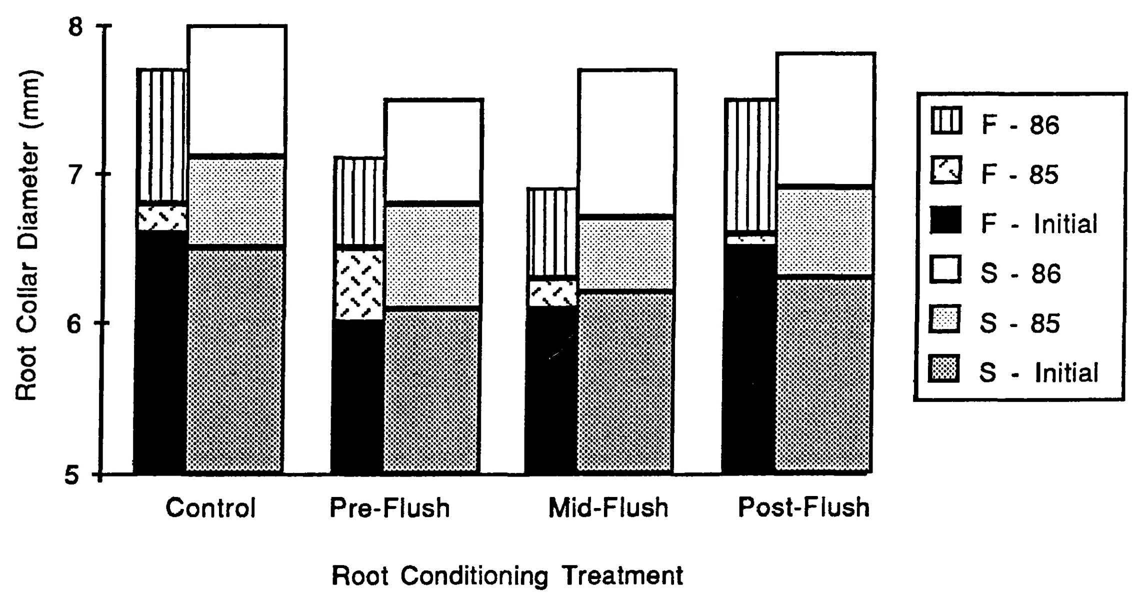


Figure 28. Initial root collar diameter and 1985 and 1986 increments of frozen stored (F) and spring lifted (S) white spruce transplants after outplanting in 1985.

the root conditioning or potassium treatments after the first season in the field. However, spring lifted stock had significantly more volume growth than the frozen stored stock (95% confidence interval) (Table 10).

Destructive samples were made to compare the dry weights of the treatments at the end of the first year. The terminal shoot dry weights and total top dry weights followed the trends of height and height growth with stock from Treatments 1 and 4 being heavier than that from Treatments 2 and 3. There were no significant differences in final bud diameter. Spring lifted stock had higher shoot and root dry weights and lower shoot/root ratios than the frozen stored stock (Table 10).

Condition codes, used to describe percent browning and defoliation of the stock, were ordinal data and thus could not be subjected to conventional statistical analysis. Counts for each class were made, then median and interquartile ranges were determined. Potassium fertilization had no effect on the condition codes of spring lifted trees. However, overwinter frozen, root conditioned stock with high potassium had lower condition codes than that with moderate or no potassium fertilization but overwinter frozen control stock with potassium had higher condition codes than unfertilized stock (Appendix 3, Figure 3A).

First year survival tallies indicated that no more than one percent mortality had occurred in any treatment. Overall, more fall lifted overwinter frozen trees died than spring lifted but there were no significant differences.

1985 - Second Year Results

The final measurements for the 1985 outplanting trial were collected in late August of 1986. Figure 27 compares the height and Figure 28 the RCD growth of the four treatments in the first and second seasons after outplanting. There were no significant differences in height growth, RCD increment or bud diameter between any of the root conditioning treatments in 1986 (95% level of confidence). Potassium fertilization significantly reduced the height growth of control stock whereas it increased the height growth of root conditioned stock. There were no significant differences in seedling volume increment between the root conditioning or potassium fertilizer treatments but once again spring lifted stock had 11% more volume growth than frozen stored stock (significant at 99% level of confidence).

Some multiple leadering was evident which may have affected height growth. Six percent of spring lifted trees had multiple leaders as compared with only one percent of the frozen stored stock. There were no differences in the number of multiple leadered trees between the root conditioning or potassium treatments.

As in the first year, condition codes indicated that the high potassium fertilizer level was detrimental to the condition of overwinter stored root conditioned stock, but that it was beneficial for overwinter stored control stock (Appendix 3, Figure 3B). No differences in condition were found between the spring lifted treatments. Survival checks on the permanent samples (all of which were living at the end of year one) indicated less than one percent mortality with slightly higher numbers of frozen stored trees dying but again, the differences were not significant.

1986 - First Year Results

The stock was planted May 13 - 15th, 1986 and monitored twice during the summer, once in early July and again in late August. Pre-plant measurements showed that the control stock was significantly taller and had larger buds and larger RCDs than the root conditioned stock. There were no significant differences betwen initial height or RCD of fall lifted and overwinter frozen and spring lifted stock (Figures 29 and 30).

A summary of the end of season results are presented in Table 11. Analysis of height growth data indicated no significant difference between the treatments for the July measurements, however by the end of the season Treatment 1 stock had grown significantly more than that of Treatments 2 or 3 (Figure 29). In addition, stock fertilized with potassium grew an average of 0.5 cm more than non-fertilized stock. Frozen stored stock grew more in height than spring lifted stock.

There was no significant difference in RCD increment between the treatments and by the end of the season the RCDs of Treatment 1 stock were still significantly larger than those of Treatment 2 and 3 stock (Figure 30).

Height and RCD data were combined and analysed as seedling volume. These data gave the same results as the height and root collar diameter data for the initial measurements but there were no significant differences in volume increment between either the root conditioning or the potassium treatments.

Table 11. A summary of the morphological characteristics of root conditioned white spruce transplants the first season after outplanting in 1986.

Lifting time	Wrenching treatment	Initial Volume cm3	Volume Increm. cm3	Terminal dry wgt. g	Root dry wgt. g	Final bud diam. mm
Frozen Stored	1) Control	2.87b*	1.77	0.58a	5.8a	2.9a
	2) 21-Day	1.89c	1.45	0.39b	5.1b	2.6a
	3) Periodic	2.22c	1.52	0.43b	6.1a	2.7a
Spring Lifted	1) Control	3.52a	1.62	0.56a	5.6a	3.0a
	2) 21-Day	2.14c	1.62	0.43b	5.9a	3.1a
	3) Periodic	2.27c	1.64	0.38b	5.7a	2.9a

*Values in the same column followed by different letters are significantly different at the 95% level of confidence.

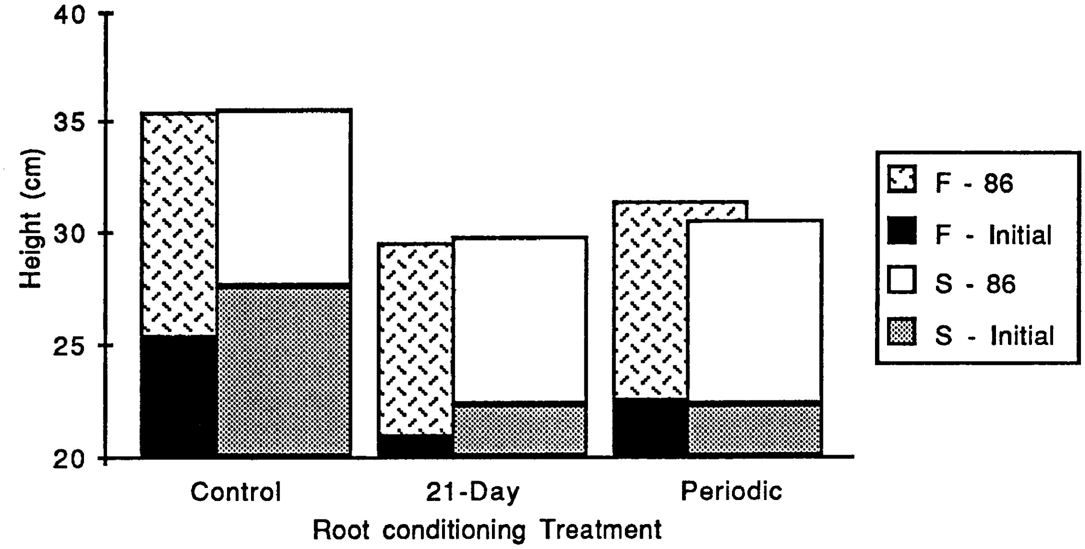


Figure 29. Initial height and 1986 height growth of spring lifted (S) and frozen stored (F) white spruce tranplants after outplanting in 1986.

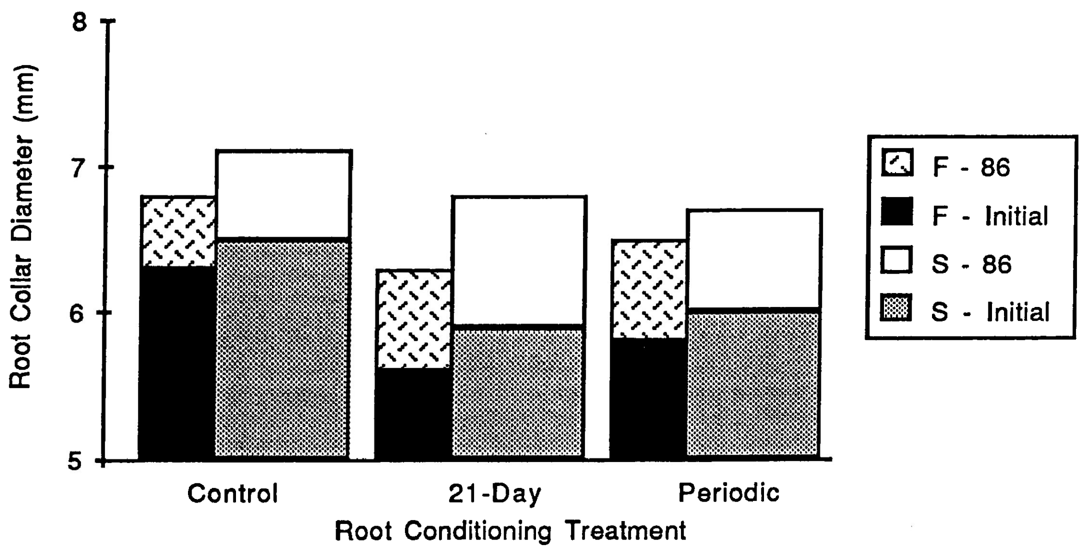


Figure 30. Initial root collar and 1986 increment for spring lifted (S) and frozen stored (F) white spruce transplants after outplanting in 1986.

Destructive samples of stock used for plant moisture stress measurements were taken to compare terminal shoot dry weights and root dry weights between the treatments. Following the pattern of height growth, Treatment 1 had significantly higher terminal shoot dry weights than Treatments 2 or 3. There were no significant differences in root dry weights between the treatments except that frozen stored Treatment 2 had significantly less root mass than the other treatments (Table 11). There were no differences in final bud diameter.

First year survival was high overall being 98.5% for spring lifted and 97.7% for frozen stored stock. When subdivided by root conditioning treatments, survival was 94.5% for Treatment 1, 98.5% for Treatment 2 and 97.5% for Treatment 3, but none of the differences were significant at the 95% level of confidence. Potassium had no effect on survival nor on the condition of the stock in the first season after outplanting. There were no significant differences in condition codes between the treatments (Appendix 3, Figure 3C).

Plant Moisture Stress

1985 Results

In 1985, the plant moisture stress (PMS) of the stock was monitored during overwinter frozen storage. The PMS levels of the white spruce transplants taken from storage varied between -1.7 and -2.3 mPa through the winter months (Table 12). There did not seem to be any pattern to the fluctuations nor were there any significant differences between the PMS levels of Treatments 1 and 2 measured at one month intervals during storage.

Table 12. Plant moisture stress (mPa) of 2+2 white spruce transplants taken from storage at one month intervals in the winter of 1984-85. Sample size was 10, standard error is given in brackets.

Treatment	December	January	February	March
1) Control	-2.0 (0.2)	-1.7 (0.3)	-2.2 (0.2)	-2.1 (0.3)
2) Pre-flush	-2.3 (0.2)	-2.0 (0.3)	-1.7 (0.3)	-1.7 (0.4)

The results of the 1985 spring plant moisture stress trial are summarized in Table 13. No differences were apparent between the pre-dawn PMS levels of spring lifted and frozen stored stock even though the spring lifted stock was flushing and the frozen stored stock was externally inactive. However, the stress values obtained within treatments were extremely variable. In order to assess PMS at an acceptable level of statistical probability, much more intensive sampling would have been required. Twelve transplants per treatment were sampled but the variances indicated that from 7 and 100 were required for statistically sound estimates of PMS (Freese 1962). The range in PMS for the three week period after outplanting was from -0.9 to -1.5 mPa. This was in the 'low' to 'moderate' range on the PMS calculator when adjusted by temperature at the time of measurement (Day and Walsh 1980). However, the values were high for pre-dawn measurements.

Table 13. Plant moisture stress (mPa) of 2+2 white spruce transplants from storage and for the first three weeks after outplanting in 1985.

Lifting Time	Treatment	Storage	Week 1	Week 2	Week 3
Frozen Stored	1) Control	-1.8	-1.4	-1.6	-1.4
	2) Pre-flush	- 2.0	-1.1	-1.3	-1.2
	3) Mid-flush	-	-1.0	-1.3	-0.9
	4) Post-flush	-	-0.9	-1.2	-1.0
Spring Lifted	1) Control	-	-1.2	-1.4	-1.1
	2) Pre-flush	-	-1.5	-1.5	-1.1
	3) Mid-flush	-	-1.1	-1.5	-1.1
	4) Post-flush	-	-1.3	-1.3	-1.1

1986 Results

The results of the 1986 plant moisture stress trial are summarized in Table 14. When the spring lifted stock was removed from storage at +2^{o}C, it was under more water stress than the frozen

Table 14. Plant moisture stress (mPa) of 2+2 white spruce transplants from storage and for the first three weeks after outplanting in 1986.

Lifting Time	Treatment	Storage	Week 1	Week 2	Week 3
Fall Lifted	1) Control	-0.9	-2.1	-1.8	-1.1
	2) 21-Day	-1.1	-1.9	-1.8	-1.3
	3) Periodic	-1.0	-1.7	-1.5	-1.1
Spring Lifted	1) Control	-1.3	-2.0	-2.1	-1.3
	2) 21-Day	-1.2	-2.1	-1.5	-1.4
	2) Periodic	-1.1	-1.9	-1.4	-1.2

stored stock. After one week in the field with no rain, the plant moisture stress of the trees ranged from -0.9 to -2.2 mPa. This was in the 'high' range on the PMS calculator based on temperature at the time of measurement. The spring-lifted stock had moderately higher levels of PMS than the frozen stored stock. The wrenched stock seemed to be under less stress than the controls for the frozen stored stock. At the end of the second week, also without rain, some of the buds of the frozen stored stock had begun to swell while the spring lifted seedlings were beginning to flush. At this time the PMS values were in the 'moderate' to 'high' range on the PMS calculator (-1.5 to -2.2 mPa). No differences were apparent between any of the treatments. In the third week, rain fell three days before PMS was measured but the PMS levels remained in the 'moderate' to 'high' range (-0.9 to -1.4 mPa). The frozen stored stock, which had now begun to flush, had lower levels of PMS than the spring lifted stock which was elongating. Again, sample size was not adequate to allow statistical analysis of the data. According to Freese's method of sample size estimation, seven to sixty samples per treatment would have been required but only ten were collected.

Pressure-Volume Curves

Results of the pressure-volume curves for frozen stored and spring lifted seedlings taken from the coolers after 7-9 weeks of storage at + 2^{o}C in 1986, indicated little difference between the osmotic potential and wilting points of wrenched versus unwrenched stock (Table 15). However, the osmotic potential and wilting points of the frozen stored stock were more negative than those of the spring lifted stock. In addition, stock fertilized with potassium had more negative values for osmotic potential and wilting point than that without.

Table 15. The water status of spring lifted and frozen stored white spruce transplants after 7-9 weeks at +2^{o}C (all values are in mPa).

	Frozen stored		Spring Lifted	
	Control	Potassium	Control	Potassium
Plant water potential at full turgor	-0.4	-0.5	-0.6	-0.5
Osmotic potential	-1.8	-2.1	-1.6	-1.8
Wilting point	-2.1	-2.3	-1.9	-2.2

The same results were obtained from the original and the corrected curves indicating that the original curves adequately estimated osmotic potential and wilting point. The modifications described in the methods section were unnecessary. It should be noted that there are statistical problems with extrapolating from pressure-volume curves and the results obtained are not statistically sound based on a given confidence interval. However, the values are commonly accepted as a good estimate of the desired attributes (Kandiko *et al.* 1980).

SOILS AND CLIMATE

Nursery Trials

Monthly water balances for the Thunder Bay Forest Station for the two years in which root conditioning trials were undertaken are given in Figure 31. In 1984, potential evapotranspiration exceeded actual evapotranspiration for April and from late June until late September. In 1985, this situation only occurred for one month from late June to late July with large excesses of precipitation occurring before and after that time. Using data summarized by Day (1984), the probability of a year such as 1985 occurring in Thunder Bay was determined to be less than 43%. In an average year on the Thunder Bay nursery, the water deficiency is 103 mm over a four month period. In 1985, it was 71 mm over three months and in 1985 it was only 35 mm in one month. Thus, the years in which the root conditioning trials were carried out precipitation was above average.

Outplanting Trials

Mean daily temperatures for the first thirty days after outplanting in 1985 and 1986 are shown in Figure 32. In 1985, moderate temperatures were followed by a short warm up, then cool temperatures. In 1986, moderate and cool temperatures were followed by a long warm spell. Unfortunately, soil temperatures were not monitored. Mean weekly temperatures, shown in Figure 33, indicate that in general 1986 was warmer than 1985.

The soil moisture retention curves for both the 1985 and 1986 outplanting sites are shown in Figure 34. The 1985 site had a sandy loam soil (68.4% sand, 26% silt, 5.6% clay) with an organic matter content of 7% in the top 25 cm. The average depth of the site was 1 m. The 1986 site was a loamy sand (83.6% sand, 11.7% silt, and 4.7% clay) with only 3% organic matter in the seedling rooting depth. The field capacities of the soils, taken as the water holding capacity at 1/10 bar, were 39% and 18% respectively. The 1985 site had an approximate porosity of 60% resulting in an air space capacity of 21% at field capacity; whereas, the 1986 site had a porosity of 58% and an air space capacity of 40% at field capacity.

Although there was not much difference in the total amount of precipitation during the field seasons of the two years, the differences in the water retention capacity of the two soils resulted in different moisture relations at the two sites. The daily water balances, averaged by week, for the two growing seasons are shown in Figures 35 and 36. The soil moisture content at the 1985 site remained between 18 and 25% throughout the 1985 season. The moisture relations at this site for the 1986 season were not much different except that the soil moisture content dropped to 16% near the end of the summer. The water content of the soil at this site never fell below the wilting point (soil moisture content at a tension of 15 bars). On the other hand, the soil moisture content at the 1986 site remained between 6 and 12% throughout the 1986 season and fell below the wilting point for all of August.

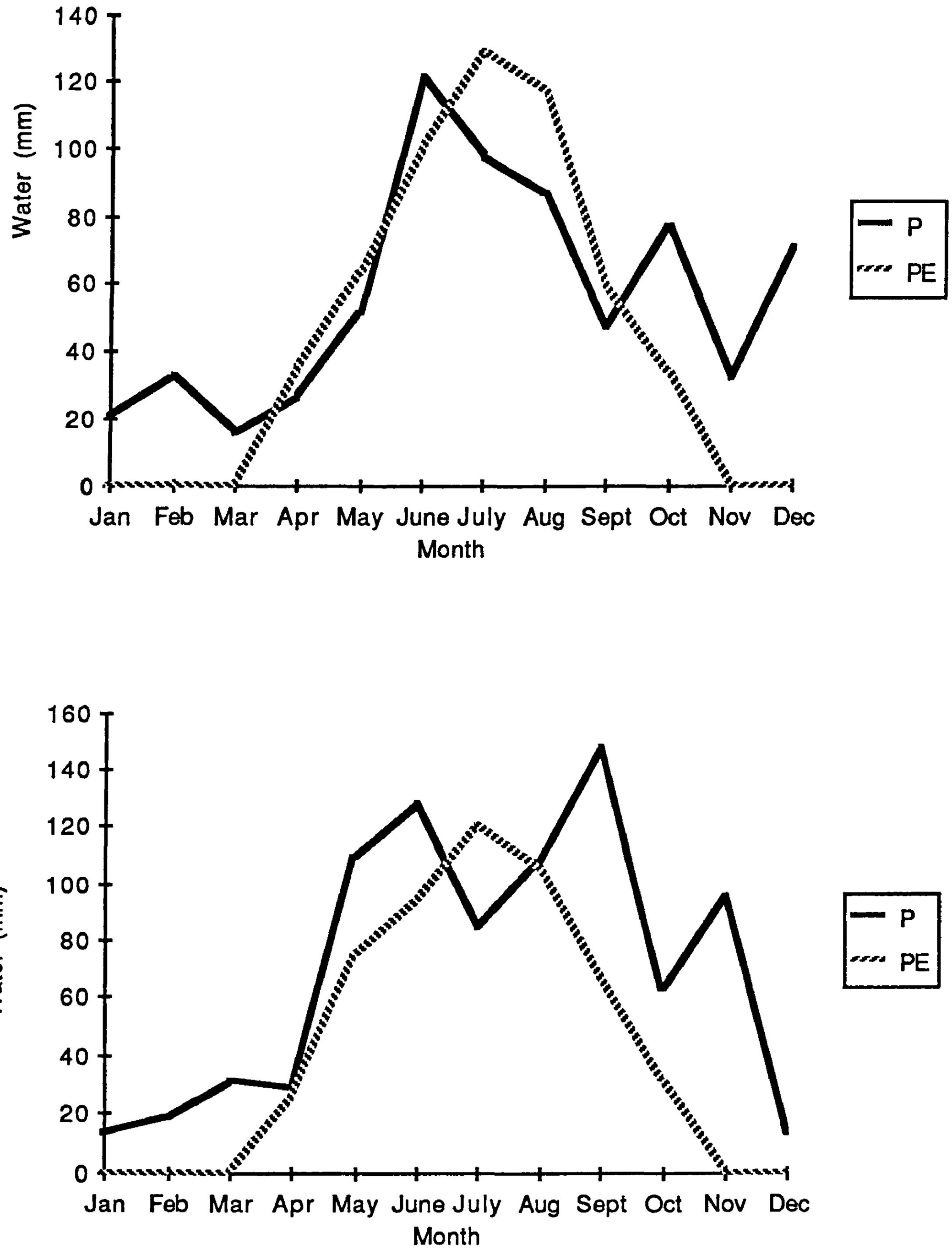


Figure 31. Precipitation (P) and potential evapotranspiration (PE) for the Thunder Bay Forest Station in 1984 (top) and 1985 (bottom).

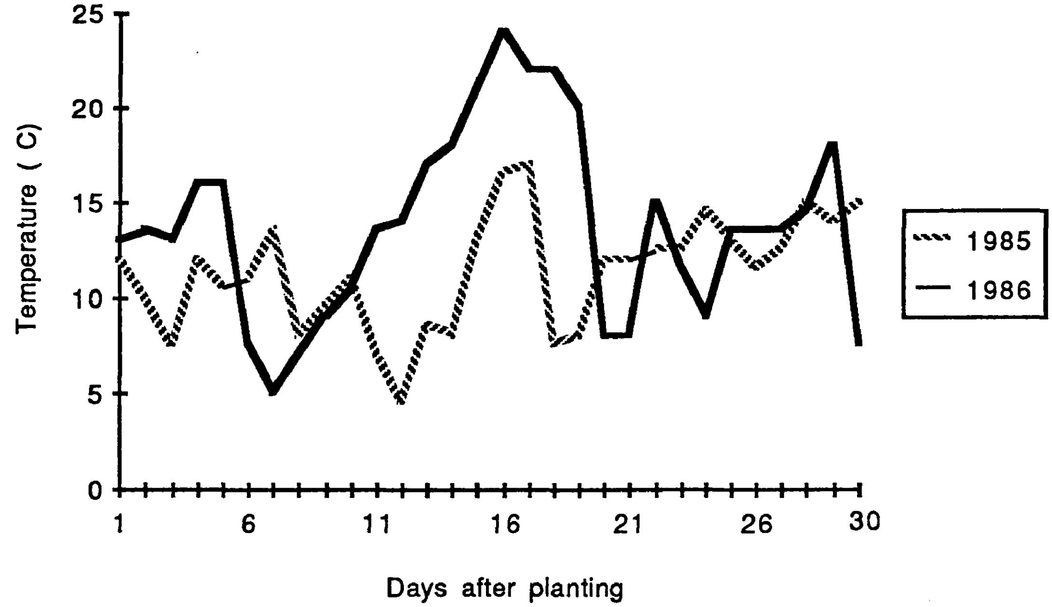


Figure 32. Mean daily temperatures for the first 30 days after outplanting in 1985 and 1986.

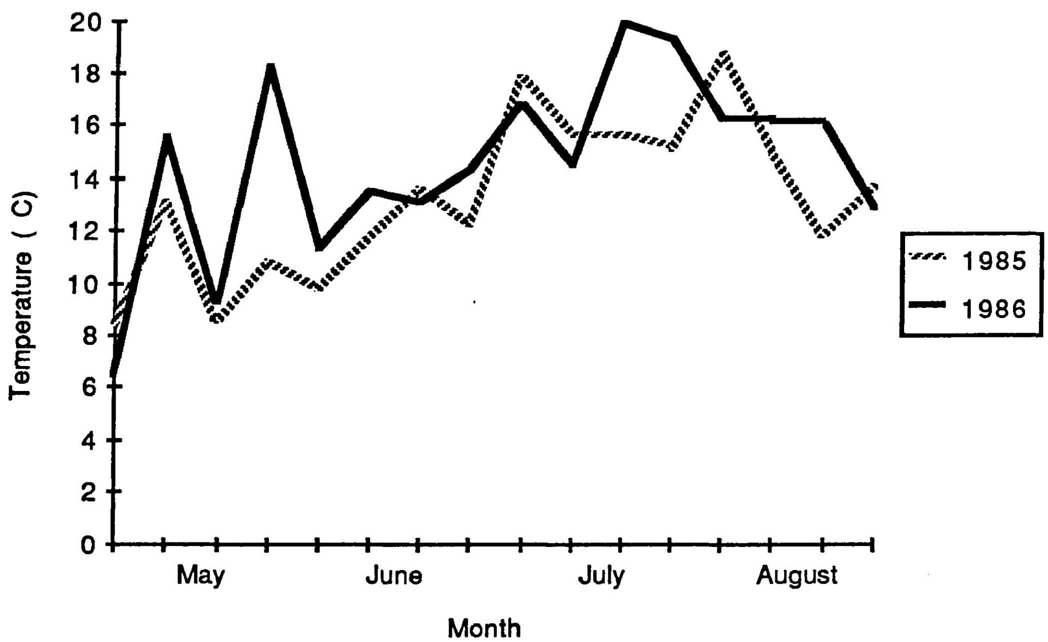


Figure 33. Mean weekly temperatures for the summer months of 1985 and1986.

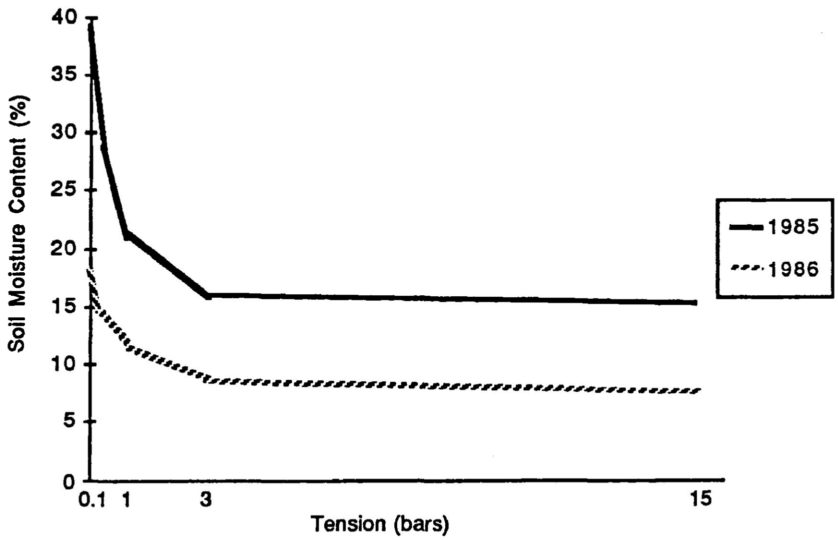


Figure 34. Soil moisture retention curves for the 1985 and 1986 outplanting sites.

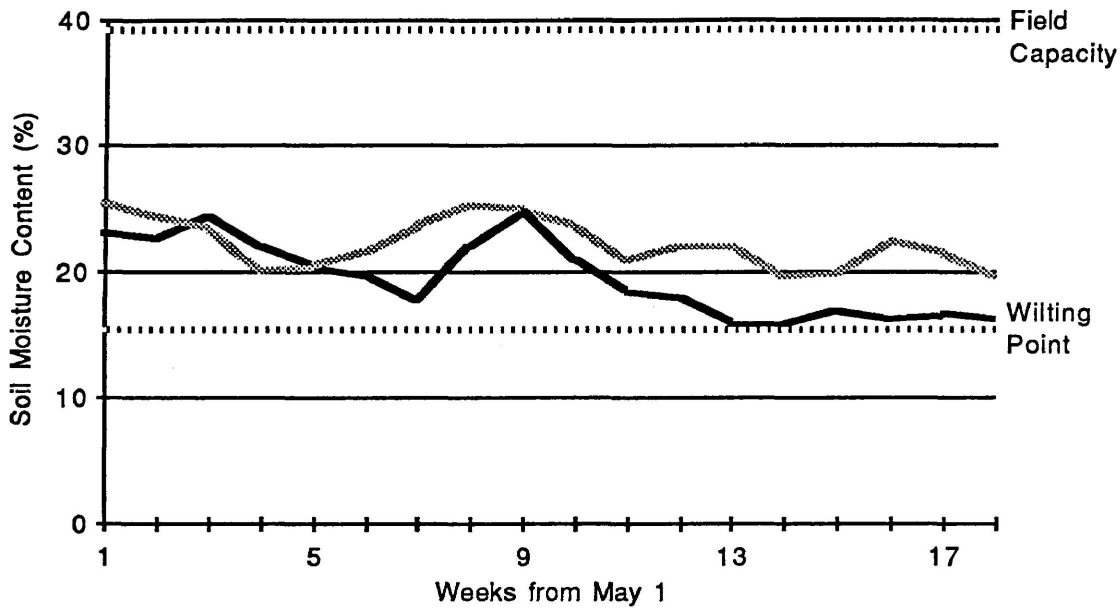


Figure 35. Soil moisture content throughout the summer months for the1985 outplanting site (1985, 1986)

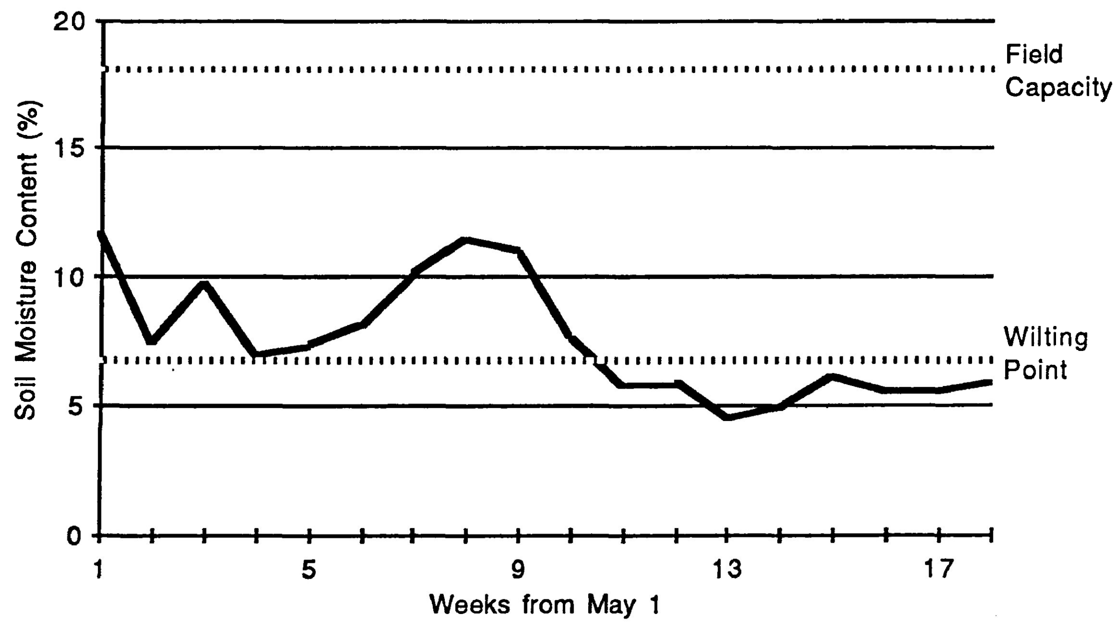


Figure 36. *Soil moisture content throughout the summer months for the1986 outplanting site.*

DISCUSSION

ROOT PRUNING AND WRENCHING TRIALS

Morphological Quality

Root pruning and wrenching treatments in the nursery have been successfully used to reduce height and improve root system form for species such as Monterey pine (van Dorrser and Rook 1972), Douglas-fir (Duryea and Lavender 1982), red pine (Bunting and McLeod 1984abc) and white spruce (Harvey 1984). This study confirms Harvey's (1984) results that root pruning of white spruce transplants early in the season followed by root wrenching at regular intervals throughout the growing season decreases height, RCD, shoot dry weight and top/root ratio (Tables 2 and 5). However, Harvey (1984) found that root pruning and wrenching had no effect on root dry weight. In the first year of this study, root conditioning decreased root dry weight while in the second year it had no effect. Varying effects of root conditioning on root dry weight have also been found with Douglas-fir (compare Tanaka *et. al.* 1976, Koon and O'Dell 1977, Duryea and Lavender 1982, van den Driessche 1983, and Stein 1984).

As in previous studies (for example Tanaka *et. al.* 1976, Bunting and McLeod 1984abc, Harvey 1984), the effect of root conditioning on the morphology of the stock in the nursery in this study was most apparent when the treatments were applied during the period of shoot elongation. Early season root pruning combined with all summer wrenching was the most effective treatment for reducing height and top/root ratio and increasing root area index. Mid-flush root pruning followed by all summer wrenching affected height in the same manner as the early season pruning but had little effect on root system size. Late season pruning and wrenching had no significant effect on height, RCD, or top or root dry weight but did decrease the top/root ratio and increase the root area index of the stock. Thus, this treatment modified root growth without affecting shoot growth.

Draper *et. al.* (1985) found that the RCD of white spruce transplants decreased in mid-summer concurrent with the peak in shoot elongation and mid-season drying. In 1985 RCD, measured throughout the growing season, decreased initially then began to increase in mid-June (Figure 7). The shrinkage was not significantly greater for root conditioned than control stock indicating that it is probably caused by shoot elongation rather than drying since root conditioned beds were shown to be drier than control beds in this study (Figure 9).

A reduction in the final RCD of root conditioned stock relative to controls is apparent in both years (Tables 2 and 5). This reduction is considered to be an undesirable effect of root conditioning because RCD is indicative of a seedling's sturdiness and reserves (Burdett 1983). However, the ratios of height to diameter for root conditioned stock were the same or smaller than those of the control stock. The small ratios indicated that the root conditioned stock was more balanced than the control stock. Thus, the negative effect of root conditioning on RCD may not be detrimental to seedling quality. The ratios of height to diameter for white spruce transplants in 1984 were 44:1 for control, mid-flush pruned and post-flush pruned stock and 42:1 for pre-flush pruned stock. In 1985 they were 36:1 for control, 33:1 for 21-day and 34:1 for periodically wrenched stock. Early season root pruning followed by all summer wrenching produced the sturdiest stock in both 1984 and 1985. Root conditioning in this study did not have as great an effect on the height to diameter ratios as that found by Rook (1971) with Monterey pine which had ratios of 50:1 and 33:1 for control and root conditioned seedlings respectively. However, the ratios were similar to those found by Harvey (1984) for control and root conditioned white spruce transplants which had ratios of 47:1 and 43:1 in 1982 and 35:1 and 34:1 in 1983 respectively.

A comparison of stock produced in the two years of this study with standards set by the Thunder Bay Forest Station for conventional 2+2 white spruce stock (Phillion 1985) indicated that in 1984 despite the root conditioning treatments, the stock was large for this nursery. Both the height and RCD of all stock was in the large class (>23 cm and >4.2 mm respectively) while root area indices were medium or large (58-72 cm^2 and >73 cm respectively). In 1985, although RCD and root area indices were large for all stock from the trial, height was small (15-19 cm) for the root conditioned stock and medium for the control stock. Similarly, Harvey (1984) obtained larger than average stock in 1982 and average stock in 1983 from his root conditioning trials with white spruce transplants.

The size differences of the stock produced in the two years in this study could have been caused by genetic, cultural or environmental factors. Stock from two different seed sources, which may have had different potentials for growth (Radsliff *et. al.* 1983), were used. Culturally, there were no differences between the two years except that the fertilizer levels applied by the nursery in 1985 were higher which should have resulted in larger stock (van den Driessche 1983). The size differences in the two years were probably attributable to weather conditions since precipitation in 1985 ranged from 110 to 170% of normal during the growing season. In addition, both during the time of primordia initiation in the fall of 1984 and during extension growth in the spring of 1985, solar insolation was 60-90% of normal and temperature (measured in Degree days) was 90-100% of normal (Environ. Can. 1986). This may have decreased the number of primordia in the buds and/or reduced carbohydrate accumulation in the stock, both of which may have reduced leader growth in the spring of 1985 (Little 1974, Owens and Molder 1984).

According to Lyr and Hoffman (1967), trees have larger root systems in dry soil. This concurs with the effects of root conditioning which causes drying of the soil and increases root system size. However, the root area index of the 1985 stock was much higher than that produced in 1984 even though the growing season was much wetter (Figure 30). Harvey (1984) obtained similar height and diameter differences in the two years of his study but also showed a corresponding decrease in root area index which was not found in this study. No explanation for this could be found in the literature. A study with red pine showed that temperature regimes affected allocation of assimilates between root and shoot (Drew 1982). Perhaps the temperatures or water relations during the 1985 growing season were optimal for dry matter allocation to roots.

Normally, 20-30% of tree biomass is below ground (Herman 1977). For nursery stock, the biomass distribution between shoot and root varies according to the cultural treatments applied. In 1985, the root systems of the root conditioned stock ranged from 28-34% of the total plant weight whereas that of the control stock ranged from 25-30%, indicating that the root conditioned stock had relatively more below ground biomass. It is generally agreed in the literature that root growth reduces top growth because of the high physiological cost of maintaining a fine root system (see Marshall and Waring 1985) which utilizes most of the plants photosynthates. Comparing the morphological parameters of bed run 3+0 black spruce seedlings, Clarke (1975) found that fine root textured seedlings had smaller height and RCD values but larger root area indices than coarse root textured seedlings. Thus, the effects produced by root conditioning may occur naturally in some stock under the proper environmental conditions. This appears to be what happened in 1985 when short sturdy stock with large root systems were produced even without root conditioning treatments.

The results indicated that the timing of root pruning and wrenching treatments can be modified to produce desirable morphological characteristics in the stock. Early season pruning and all summer wrenching can be used to reduce shoot size and increase root system size. Early season root pruning followed by periodic wrenching has similar but less noticable effects than if followed by all summer wrenching. Late season pruning and wrenching has little effect on shoot size but increases root system size and improves its form. In 1984, root conditioning controlled height growth producing more balanced stock that was easier to handle during lifting, processing and packing. In 1985 however, root conditioning reduced the height of stock which was already negatively affected by environmental conditions resulting in very small, sturdy stock. Root conditioning was probably not necessary in 1985 but was beneficial in 1984. Nursery managers wanting to use root conditioning as a cultural treatment will have to be aware of the interaction effects of root conditioning with the environment if they are to apply it effectively.

Bud Primordia

Developing buds are sensitive to seedling size and may reflect the assimilatory capacity of the plant, with smaller seedlings forming less primordia (Pollard 1974). Root conditioning decreases the size of the stock through stressing caused mainly by reduction of moisture (Stupendick and

Shepherd 1980, Duryea and Lavender 1982) and causes most of the assimilates to be shunted to the root system (Rook 1969,1971). Water stress has been shown to decrease the number of primordia in the developing buds of red pine and black spruce (Garret and Zahner 1973, Pollard and Logan 1977). The combined effects of reduced seedling size and increased water stress should result in less primordia formed in the buds of root conditioned stock. Harvey (1984) found a 16% decrease in the number of primordia in the terminal buds of root conditioned white spruce transplants compared to controls. In this study in 1984, root conditioning reduced the number of primordia in the terminal buds by 24% for mid-flush pruned stock, 22% for pre-flush pruned stock and 18% for post-flush pruned stock compared with controls. Late season root pruning and wrenching did not have as great an effect on the number of primordia as early season pruning followed by all summer wrenching. In 1985, no difference in the number of primordia in the terminal buds was found between the treatments. It could be that stressing was not achieved because of the cool and wet weather conditions or that because sampling was done in early September but primordia development is not complete until mid- to late- October (Owens and Molder 1984), the differences between the treatments were not yet apparent.

Some authors have found that bud height is related to the number of needle primordia in the bud and is a good measure of shoot growth potential after outplanting (Thompson 1985). No correlation was found between height, diameter or volume of the bud and the number of primordia in the 1985 root conditioning trial, either in the control or the root conditioned stock, but sampling was done early in the season as discussed above.

Bed Density

There has been some discussion in the literature about the effect of varying nursery bed densities on root conditioning treatments. Van Dorsser and Rook (1972) found that Monterey pine seedlings responded better to root conditioning when bed densities were low. Bunting (1985) suggested that if bed density was too high, no height response would be obtained and root development might not be as extensive as expected. Bed densities were not monitored in this study but the theoretical densities were 100/m^2 and 133/m^2 for the 1984 and 1985 root conditioning trials respectively. The difference between years is the result of the nursery switching from six row transplants to eight row transplants. Koon and O'Dell (1977) had very low bed densities (62/m^2) and indicated that root wrenching was successful in decreasing height in the nursery but also decreased the root dry weight of Douglas-fir seedlings. Tanaka *et. al.* (1976) obtained no decrease in height but did show an increase in the root dry weight of Douglas-fir seedlings grown at moderate bed densities (377/m^2) through root conditioning. Duryea and Lavender (1982) had bed densities ranging from moderate to high (258-700/m^2) and consistantly obtained decreased height but no effect on the root dry weight of root conditioned Douglas-fir seedlings. Van den Driessche (1983) indicated that root wrenching decreased the height and increased the root dry weight of Douglas-fir seedlings grown at relatively low bed densities (179 and 195/m^2). The results of the above studies are quite variable and seem to independant of bed density; thus, the slightly different bed densities in the two years of this study probably did not play a major role in the effectiveness of the root conditioning treatments.

Potassium Fertilization

The results of the additional potassium fertilizer trials were variable and indefinite. The benefits of potassium fertilization combined with root conditioning as synergistic treatments for improving survival after overwinter storage are questionable. Root conditioning decreases shoot growth and plants with depressed growth rates absorb less potassium as well as showing reduced translocation of potassium to the shoot (Mengel and Kirkby 1978). Root conditioning also decreases soil water content and a review of the data on nutrient availability in relation to soil moisture indicated that decreased water supply resulted in decreased potassium concentration in plants. However, root growth plays an important role in nutrient uptake because roots can grow up to 5.0 cm per day while ions can only diffuse 1.0 to 5.0 mm per day (Viets 1972). The negative effect of root conditioning on nutrient uptake may be compensated for by the increased numbers of absorbing roots in root conditioned stock. Donald and Simpson (1985) found that the reduced nutrient content caused by shallow root conditioning (10 cm) as compared with standard root conditioning (20 cm) was compensated for by late fertilization. The authors attributed this to higher root activity in the shallow root conditioned seedlings.

In the 1984 study, potassium fertilizer affected both bud diameter and root area index in the nursery. The timing of fertilizer application relative to the root wrenching treatments seemed to influence the effectiveness of the potassium fertilizer on the above attributes. Treatment 4 was fertilized just before wrenching and no effect on root area index or bud diameter was apparent. Treatment 3 was fertilized approximately two weeks after wrenching and the high potassium level was detrimental to root area index. Treatment 2 showed a positive response in bud diameter but a decrease in mean root area index as a result of the potassium fertilizer treatments. This stock was fertilized less than one week after wrenching. The above results suggest that fertilization at the time of root development may have been detrimental to root growth but beneficial for bud development. In 1985, the stock was fertilized two weeks after wrenching. The lack of effect of additional potassium on seedling morphology in the nursery could have been the result of low application rates rather than the timing of the treatment.

Fertilizer application rates were very different in the two years. The 1985 trial was carried out in a newer part of the nursery where the nursery's routine fertilizer applications were much higher in order to build up soil fertility. Without nutrient analysis it is impossible to know what effect the different rates of fertilizer, in conjunction with the root conditioning treatments, had on the nutrient content of the stock. The literature gives some idea of the effect they might have had. Van den Driessche (1983) found that late season fertilization of Douglas-fir increased the needle content of nitrogen and potassium and the total seedling content of nitrogen, potassium and phosphorous but that root wrenching treatments decreased the potassium content of the seedlings. Concentrating on potassium, Sadreika (1973) states that the foliage potassium content of white spruce transplants increased with application rates, from 0.48% with no additional potassium to 0.55% with 112 kg/ha and 0.60% with 224 kg/ha of elemental potassium fertilizer. Donald and Simpson (1985) found that the potassium content of the needles of interior spruce seedlings machine pruned and wrenched at a 20 cm depth increased from 0.55% to 0.60% when fertilized with 200 kg/ha potassium but those pruned and wrenched at a depth of 10 cm increased their needle potassium contents from 0.45% to 0.56% as a result of higher root activity. These increases depend on the soils and many other factors but fertilization with potassium should have increased the potassium levels of the stock in 1984 whereas the rate applied in 1985 may have been too low to have any effect.

Bulk Density

Root wrenching reduced the bulk density of the soil in the root conditioned beds and kept it lower than that of the control beds throughout the entire growing season (Figure 8). This may have allowed easier root extension and probably also caused faster soil drying and an increase in soil temperature. In a climatically normal year such as 1984, the effect of root pruning and wrenching at intervals throughout the growing season was to periodically 'stress' the stock in the warmer and drier soil of the conditioned beds and to modify both the morphology and physiology of the stock. In the moister growing season of 1985, these effects were less pronounced.

GROWTH POTENTIAL TESTS DURING STORAGE

Root Growth Potential

Studies done in growth chambers, where environmental factors are not limiting, give a good indication of endogenous controls on root and shoot growth. A difference in the physiological quality of the seedlings as measured by RGP and time to bud flushing throughout the period of storage is apparent in the two years of this study. In 1984-85, the RGP curves peaked in January or February then decreased until spring (Figures 16 and 18). This pattern of root growth is similar to that found by other authors (Ritchie and Dunlap 1980, Harvey 1984) and is considered to be the classical pattern of root growth with some variation occurring between species, seed sources and nurseries (Ritchie and Dunlap 1980).

Storage did not maintain RGP at a constant level, nor did it stop the endogenous rhythms in root growth from occurring. Other authors have also found that root growth shows a strong seasonal periodicity (Ritchie and Dunlap 1980). Stone and Schubert (1959) found that root growth of ponderosa pine (*Pinus ponderosa* Laws.) seedlings brought into the greenhouse peaked in the spring before budbreak then declined to amost nothing in July and August. Stone *et. al.* (1962) showed a similar pattern for Douglas-fir. Jack pine was shown to have a spring and a summer peak (Stupendick 1974) whereas white spruce has the spring peak with additional peaks occurring in July and early September (Mullin 1963b, Day *et. al.* 1976).

RGP periodicity may be related to bud dormancy cycles. Using white spruce as an example, the cycles of root growth can be related to shoot growth as follows. The spring pulse in root growth occurs when shoots become mitotically active, then declines as bud flushing and shoot elongation progress. The summer pulse in root growth coincides with budset; that is, the end of bud scale initiation and the onset of primordia initiation (Owens *et. al.* 1977). Root growth decreases as the rapid stage of leaf primordia initiation occurs. The final pulse of root growth in the fall is associated with the development of bud dormancy (Day 1985). The majority of the studies discussed above did not follow root growth through the winter so that the relationship between root growth and dormancy release could be examined. However, Draper *et. al.* (1985) found that the RGP of white spruce transplants was high at the time of lifting in the fall, increased early in cold storage, decreased, then increased again at planting time. Johnson-Flanagan and Owens (1985) found that the root growth of white spruce container stock increased until January then decreased and was minimal from early March until late April. Working with white spruce transplants, Harvey (1984) found a winter root growth pattern similar to that found in 1984-85 in this study with a peak in January followed by a decline until spring. He associated the January peak in root growth with dormancy release in the buds. This is possible considering the relationship between root and shoot growth at other times of the year (discussed above) and fits well with the pattern of growth found in 1984-85 in this study.

In 1985-86, root growth was high in November then decreased with some slight but non-significant variation until spring (Figures 17 and 19). A close relationship between frost hardiness at lifting and the ability of white spruce seedlings to maintain root growth during storage has been shown to exist (Burdett and Simpson 1984). The decline in RGP throughout the winter in the 1985-86 trial indicates that the stock may not have been frost hardy when lifted. Alternatively, it may be that the chilling requirements of the stock were fulfilled before the initial RGP test causing the post-dormancy release peak in root growth, found by Harvey (1984) to occur in January, to occur in November, after which the usual decline occurred. This is unlikely, however, because white spruce requires 4-6 weeks near 0oC to fulfill its chilling requirement (Nienstadt 1966). DHD at the time of lifting were similar for the two years and in 1984 the stock was in storage for one month before the growth potential tests were started but did not show any signs of dormancy release, whereas in 1985 the tests were started after only one week of storage.

Food reserves have also been suggested to be important in the control of root growth cycles since carbohydrate peaks in the winter and early spring coincide with maximum RGP (Ritchie and Dunlap 1980). Krueger and Trappe (1967) found that starch concentrations in roots reached a maximum in April, then decreased during bud break and shoot elongation. This is consistent with the earlier onset of growth in roots and suggests some internal, although indirect, regulation of root growth. When the supply of photosynthates required for shoot elongation does not meet the demand, root growth, which depends mainly on current photosynthates (Lyr and Hoffman 1967, van den Driessche 1978), is restricted. Johnson-Flanagan and Owens (1985) noted a decrease in the root elongation of white spruce seedlings during bud flushing and shoot elongation in the spring. Root elongation was accompanied by losses of starch and bound carbohydrates suggesting either that stored carbohydrates may also be used for root growth or more likely that these are mobilized to the shoot at this time. The pulse of root growth in mid-summer occurs between the end of bud scale initiation and the onset of leaf primordia initiation. Again in the fall when shoot development ceases, root growth resumes. Thus, the roots seem to be an alternate sink for assimilates at times when the requirements in the shoot are low.

It appears that during the growing season RGP is highly correlated with carbohydrate availability and follows a source-sink pattern fairly consistently. When shoots are actively growing root growth is inhibited but when shoot growth is reduced root growth resumes. However, changes in RGP during storage do not seem to be directly related to carbohydrate reserves because these decrease throughout storage. For example, Hellmers (1963) found that after 4 months in storage pine seedlings had starch only in the roots, whereas fresh dug seedlings had starch reserves in the stems and buds as well as the roots. RGP during storage normally increases, then decreases (Ritchie *et. al.* 1985) as was shown in the 1984-85 RGP tests in this study and by Harvey (1984). However, the 1985-86 RGP tests showed a gradual decrease in RGP which fits the carbohydrate reduction theory well.

In 1984-85, root conditioning increased RGP significantly throughout storage which is similar to results found by Harvey (1984). This could be the result of increased assimilate translocation to the roots as a result of the root conditioning treatments (Rook 1969) or that more sites were available for root initiation on the root conditioned stock because of higher root area indices. However, root conditioning had little effect on RGP during storage in 1985-86. Root area indices and RGP were high for all stock indicating that root conditioning had little effect on the physiological condition of the stock in this season.

Shoot Growth Potential

In both 1984-85 and 1985-86, the buds of white spruce transplants required a minimum of 10-15 days to begin flushing when placed in the growth chamber. This supports work by Harvey

(1984) which reported a requirement of 7-14 days for flushing of white spruce. A greater percentage of buds flushed in December and January in 1985-86 than in 1984-85. This may have been because the stock was non-dormant when placed into the coolers. Although assessment of DHD indicated that the stock was ready for lifting, precipitation prior to lifting may have resulted in some dehardening. Alternatively, the chilling requirements of the stock may have been fulfilled before it was placed into storage, but this is unlikely as discussed above.

The percentage of buds flushed during the growth chamber trials increased gradually throughout the winter in both years, then levelled off in February and March at a maximum. This gradual progression of flushing fits with a gradual fulfillment of the chilling requirements of the stock. In a similar study, Harvey (1984) found that the percentage of buds flushed after 28 day growth chamber trials peaked in December and April but were low the rest of the winter. Either there were physiological differences between the stock in his study and that in this study that did not affect the RGP test results or some unknown factor affected bud flushing in his study.

OUTPLANTING PERFORMANCE

Root Growth Potential

Although root growth in the growth chamber in the spring of 1985 indicated that the stock had good RGP at the time of outplanting, field trials resulted in very poor root growth. Although spring lifted stock had higher root elongation in the growth chamber no differences between the root growth of spring lifted and frozen stored stock were apparent in the field. Under optimal conditions in the growth chamber the minimum time required for new root growth after removing stock from overwinter frozen storage was determined to be six days. Under field conditions, moisture availability and soil temperature at the microsite are major determinants of the time required for root growth to commence. Weather data indicated that wet, cool conditions prevailed during the period of the RGP test in 1985. Wet soil is colder than dry soil because the high specific heat of water reduces the rate of warming (Cooper 1973). Lopushinski and Kaufman (1984) found that low soil temperatures (1.0 - 3.0^{o}C) completely prevented root growth in Douglas-fir seedlings. Soil temperatures as high as 10 and 16^{o}C have been shown to reduce white spruce root growth after planting (Grossnickle and Blake 1985). The lack of root growth in cold soil could be caused by a combination of factors such as decreased metabolic activity or decreased root cell turgor resulting from reduced water uptake (Lopushinski and Kaufman 1984). In addition, photosynthesis may be reduced in cold soil because of increased plant moisture stress and decreased stomatal conductance (Anderson *et. al.* 1986). Since root growth depends mainly on current photosynthates, this could also decrease root growth in cold soil.

Frozen stored root conditioned stock had better root growth than control stock both in the field and the growth chamber in the spring of 1985. Although the differences were non significant because of the large variation within treatments, root conditioning may have aided in the early establishment of the frozen stored stock in the field after outplanting. Harvey (1984) obtained a three fold increase in the RGP of root conditioned white spruce stock after outplanting. No such increases were found in this study despite the significantly higher RGP of root conditioned stock during overwinter storage.

In 1986, root growth in the field was comparable to that in the growth chambers although not quite as high. There were no significant differences between the root growth of root conditioned and control stock during the first 21 days after outplanting which agrees with the results obtained during the winter growth potential tests. There were also no significant differences between spring lifted and frozen stored stock in the field although spring lifted root conditioned stock had higher root growth in the growth chamber. It appears that the effect of root conditioning on root growth after outplanting is variable, and depends both on the environmental conditions at the nursery during the season of root conditioning and those in the field after outplanting.

Day and Harvey (1983, 1984ab) did an indepth study of RGP of both overwinter frozen stored and spring lifted and cold stored 1.5+1.5 white spruce transplants on sand and till sites. In 1981, soil and air temperatures were moderate (average 13°C) and precipitation during the 21-day period after outplanting was 132cm. The spring lifted stock had very low root growth on the till site (average RE 4 cm, RN 18) and moderate root growth on the sandy site (average RE 27 cm, RN 75) whereas the overwinter frozen stock showed no root growth on either site. In 1982, under similar soil and air temperature conditions but with only 40 cm of precipitation, both spring lifted and frozen stored stock had good root growth (RN 50-100, RE 15-26 cm) on both sites. In 1983, soil and air temperatures were very low, averaging 6 and 8°C respectively and 50 cm of precipitation fell during the 21-day RGP test. RN was good for both spring lifted and frozen stored stock on both sites (average 80-85) but RE was poor (average 3-8 cm). In all three years the root growth of both stock types was better on the sand than on the till site. Moderate temperatures and moderate levels of precipitation seemed to be optimal for root growth of white spruce after outplanting.

In this study in 1985, air temperature averaged 11°C with 22.5 cm of precipitation falling during the 21-day RGP test. Thus, conditions were drier but temperatures were only slightly lower than those in Day and Harvey's (1983,1984a) 1981 and 1982 trials. RN was moderate (23-69) but RE was poor (4-9 cm). In 1986, air temperature averaged 13°C with 65 cm of precipitation falling during the 21-day period after outplanting, which was similar to Day and Harvey's (1984a) 1982 conditions. Both RN and RE were high (98-120 and 39-64 cm respectively). In 1986, RN was double and RE was six times greater than in 1985 for both frozen stored and spring lifted stock in the field despite similar RGP responses in the growth chamber in the two years. The soil on the two sites varied with the 1986 site being sandier, having more air space and thus being less prone to water logging than the 1985 site (Figure 34). The results of this study may not only be a function of treatments but rather of climatic and site differences in the two years.

1985 Field Trial Results

First year height growth in the field was determined by the initial differences in height between the treatments when outplanted with Treatment 2 and 3 stock growing less than Treatment 1 and 4 stock. The decreased growth after planting may have been the result of the decreased number of primordia found in the terminal buds. Reduced height growth of root pruned and wrenched stock in the first year after outplanting was also found by Harvey (1984), Bunting and McLeod (1984a,c) and Duryea and McClain (1982).

The time of bud flushing in white spruce is under strong genetic control (Nienstadt and Teich 1972). Once chilling requirements are fulfilled (after approximately four to six weeks near $0^{o}C$ (Nienstadt 1966), the stock remains in an imposed state of dormany (eco-dormancy) controlled by temperature (Wilkinson 1977). If exposed to temperatures above $0^{o}C$, the stock becomes progressively less cold tolerant and more susceptible to spring outplanting stresses such as dehydration and late spring frosts (Clements *et. al.* 1971). Stock lifted directly from the nursery often flushes earlier than frozen stored stock because it has been exposed to warmer conditions after chilling is complete (van den Driessche 1977). The energy for bud flushing in the spring is obtained mainly from current photosynthate but to some extent also from carbohydrate reserves accumulated the previous fall (Little 1974). The delay in bud flushing of the overwinter frozen stored seedlings may be related to a shortage of carbohydrate reserves which are depleted during storage (Ritchie 1982). Overwinter stored stock also requires time to adjust to the environment and begin photosynthesis (Grossnickle and Blake 1985). Harvey (1984) found that frozen stored white spruce transplants flushed later than spring lifted stock and noted that this resulted in less frost damage the first year after outplanting. In 1985, many of the frozen stored transplants were just beginning to flush in July, whereas by this time most of the spring lifted stock had completed extension growth. This did not cause any significant difference in the first year height growth of the two stock types nor did it result in any notable amount of frost damage the second year. Similar results were found by Nyland (1974). A study with Norway spruce showed that there was a significant difference in the growth of frozen stored conditioned and spring lifted, cold stored stock the first year after planting but the difference was not detectable by the second year (Neily 1982).

In this study, no significant differences in height growth were evident between the treatments the second year after outplanting although the root conditioned stock remained smaller than the control stock due to initial differences in height when planted. Similar results have been found in many root conditioning trials (for eg. van den Driessche 1983, Bunting and McLeod 1984a). No significnat differences in height between frozen stored and spring lifted stock were apparent at the end of the second season indicating that overwinter storage was not detrimental to height growth in this study. However, spring lifted stock had signficantly larger root collar diameters which would eventually result in higher volumes.

Height growth, when averaged over all the treatments, was reduced by 50% in the second season after outplanting compared to that of the first year. Height growth has been found to be related to bud size (Hellum 1967, Thompson 1985) with 3.0 mm diameter buds producing 5.0 cm leaders and 7.0 mm diameter buds producing 30.0 cm leaders on average (Hellum 1967). At the end of the first growing season in the field, the bud diameters of the white spruce in this study were significantly smaller (2.4-2.6 mm) than those set the final year on the nursery (3.6-4.4 mm) indicating less potential for growth. Height growth was reduced more than would be expected from the decrease in bud diameter indicating that the stock may have gone into 'planting check'. At the end of the 1985 growing season many of the transplants were chlorotic and were in standing water in the furrows. Mullin (1963a) found that trees in check were usually chlorotic, had short needles and shoots and that these symptoms were most severe on wet sites.

Stock lifted and planted during the succulent stage have been shown to be more susceptible to transplanting shock than that which is lifted while quiescent (Burgar and Lyon 1978). Racey and Hutchinson (1983) found that height growth was reduced in spring lifted white spruce stock which was active at lifting time. In addition, Mullin (1967) found that root exposure reduced growth in both active and dormant seedlings but more mortality occurred in active seedlings as a result of exposure and handling. In 1985, spring lifted stock, which had swollen or flushing buds at the time of lifting, was handled extensively because of the neccessity of heeling it in before and after measuring and before planting. Both the time of lifting and the excessive handling of the spring lifted stock in 1985 were probably detrimental to its growth and may have induced planting check. However, environmental factors must also have had an effect since the frozen stored stock was equally affected in the second year after planting.

1986 Field Trial Results

In 1986, first year height growth again reflected initial differences in height between the treatments, with non-root conditioned stock growing more than conditioned stock. The spring lifted stock was lifted from the nursery beds early in the spring and placed in cold storage and thus had not been exposed to spring environmental conditions. The frozen stored stock flushed much earlier than that planted in 1985, requiring only two weeks after planting to begin bud swell. Unlike 1985, little difference between flushing times was apparent for the two stock types. Cold storage of the spring lifted stock probably delayed flushing. No significant differences in height growth were apparent between the frozen stored and spring lifted treatments; however, as in 1985, spring lifted stock had larger root collar diameters at the end of the season.

In previous studies, three to five years have been required for the beneficial effects of root conditioning on seedling growth to become apparent (eg. Bunting and McLeod 1984), thus future monitoring of this study may show different results. Burdett *et. al.* (1983) found that RGP accounted for 82-96% of the variation in height growth and survival of white spruce in British Columbia the first year after outplanting. McMinn (1980) found that RGP predicted the survival of white spruce independantly of stock type and seedling size. No relationship between RGP and survival or growth could be found in this study although the low RGP 21 days after planting in 1985 was indicative of poor establishment and may have been partially responsible for the stock going into planting check in the second year. Harvey (1984) also found no relationship between RGP and height growth or survival the first year after outplanting white spruce. Both Harvey's and this study had high survival rates which may have precluded the use of RGP as a predictor of field performance since Ritchie *et. al.* (1985) emphasized that RGP is only a good predictor of performance under stressful conditions.

Potassium Fertilization

Donald and Simpson (1985) found that late fertilization had no effect on the survival of overwinter stored stock after outplanting. In 1984, high potassium fertilizer levels were detrimental to frozen stored, root conditioned stock after outplanting but were beneficial for non-conditioned stock. Potassium fertilization had no effect on the condition of spring lifted stock after outplanting and did not affect the survival of any treatment. In 1985, potassium fertilization did not seem to affect either the condition or survival of the stock in any of the treatments. It may be that the fertilizer application rate was too low to affect the seedlings in the 1985 trial or that the high survival rates masked any differences between the treatments. In general, potassium fertilization combined with wrenching does not appear to be an ideal treatment for white spruce transplants being overwinter frozen stored but potassium fertilization does appear to benefit non-root conditioned frozen stored stock.

WATER RELATIONS

Plant Moisture Stress

Herman *et. al.* (1972) found that PMS levels of -2.0 mPa were acceptable for spruce during the period of overwinter frozen storage but spruce survival has been shown to decrease after storage when PMS was less than -2.0 mPa at planting (Ruetz 1976). During the winter of 1984-85, PMS of the frozen stored seedlings ranged between -1.6 and -2.3 mPa. Survival was high and growth after outplanting was acceptable but the high survival rates may be attributable to the moist season. Jorgenson and Stanek (1962) and Day and Harvey (1984ab) found that in a dry year the survival and growth of stored stock was reduced compared to that of fresh lifted stock but there was less difference between the treatments in a wet year. In 1986, the PMS of the frozen stored and fresh lifted cold stored stock ranged from -0.9 to -1.3 mPa when removed from storage so it was well within the acceptable range. Survival and growth after outplanting were excellent.

In this study, no difference could be found between the PMS levels of frozen stored and fresh lifted stock or root conditioned and non-conditioned stock up to 21 days after outplanting. This is supported by the lack of a clear relationship between the PMS of fresh lifted versus frozen stored 1.5+1.5 white spruce transplants in the work of Racey and Hutchinson (1983). Harvey (1984) also found no difference in PMS between root conditioned and non-conditioned white spruce transplants 21 days after outplanting. Duryea and Lavender (1982) found no difference in the plant water potential or leaf conductance of root conditioned versus non-conditioned Douglas-fir after outplanting. These studies suggest that overwinter frozen storage does not affect the water relations of stock after outplanting and that root conditioning does not increase the resistance of stock to water stress after outplanting. None of the above studies found beneficial effects of root conditioning on the survival or growth of the stock however both Harvey's (1984) and this study were done during moist seasons. No weather data were available for the other studies.

On the other hand, Bacon and Bachelard (1978) found that root conditioned Monterey pine seedlings had greater water losses (as measured by transpiration rates) than non-conditioned seedlings after transplanting, without a decrease in water potential, indicating that the root systems were meeting the demands of the shoot more effectively but don't comment on their effects on survival or growth. Blake (1983) found that frozen stored 2+0 white spruce seedlings had lower transpiration rates and diffusive resistances than spring lifted stock. Frozen stored seedlings also showed increased stomatal resistance in response to drought which was not apparent in the spring lifted stock, and they maintained lower PMS levels. Nambiar *et. al.* (1979) showed that root pruning and wrenching decreased PMS of Monterey pine seedlings after planting but field trials to determine the effects of the treatments on survival and growth of the stock were not included in the study. Studies which have shown increases in survival and growth after outplanting root pruned and wrenched stock (eg. van Dorsser and Rook 1972, Tanaka et. al. 1976, Koon and O'Dell 1977, Bunting and McLeod 1984abc) did not monitor water relations after outplanting.

Studies with white spruce in British Columbia have found that pre-dawn water potentials of white spruce after outplanting should not be less than -1.0 mPa for best survival (B.C. Min. For. 1985) and if the water potential of the stock can be maintained at or above -1.5 mPa throughout the day, stomatal closure will not occur (Draper *et. al.* 1985). Studies with Scots pine and Norway spruce seedlings have shown that stomatal closure began at xylem pressure potentials of -1.0 mPa and was complete at -2.5 mPa (Christersson 1976). Pre-dawn water potentials in this study in 1985 ranged from an average of -0.9 to -1.6 mPa during the first three weeks after outplanting and in 1986 measurements just after dawn ranged from an average of -1.1 to -2.1 mPa, indicating that the stomata were probably closed much of the time and the stock was relying heavily on stored carbohydrates for growth.

Christersson (1973, 1976) found that potassium increased the survival of Norway spruce seedlings after planting. On the other hand, McClain (1986) found no relationship between potassium fertilizer and the survival of Douglas-fir and jack pine container seedlings after drought stress. In this study, potassium fertilization did not appear to have any significant effect on the water relations of the stock after outplanting but possible effects may have been lost through insufficient sample size.

Pressure-Volume Curves

Turgor potential is the positive force exerted inward on a plant cell by the rigid cell wall. The water potential of a plant at zero turgor is thought to be the critical point beyond which a plant will not recover from stress (Ritchie 1984). The wilting point describes the osmotic potential of a plant at zero turgor. A low wilting point allows the plant to maintain positive turgor while under water stress (Hennessey and Dougherty 1984) and thus allows it to continue growth at more extreme levels of PMS. Kandiko *et. al.* (1980) obtained osmotic potentials of -2.0 and -1.7 mPa for water stressed and non-stressed western hemlock transplants respectively, whereas wilting points were -2.6 and -2.1 mPa. Values obtained in this study for frozen stored and spring lifted white spruce transplants were similar. Frozen stored stock had osmotic potentials of -1.8 and -2.1 mPa for control and potassium fertilizer treatments respectively, while spring lifted stock had values of -1.6 and -1.8 mPa. Wilting points of the respective treatments were -2.1, -2.3, -1.9 and -2.2 mPa. Lower osmotic potentials and wilting points indicate that an osmotic adjustment may have occurred (Columbo 1985). A low osmotic potential allows the seedling to conserve water, because of a higher solute concentration which increases its ability to draw water from the soil and retain water by decreased transpiration. Thus, frozen stored stock should be more resistant to water stresses than spring lifted stock and stock fertilized with potassium should be more resistant than unfertilized stock. It should be noted that the ability of these operational pressure-volume curves to indicate osmotic adjustment has been questioned. Osmotic adjustment can occur through an increase in solutes or a decrease in the elasticity of the cells as well as decreased water content so these results should be viewed with caution (McClain 1987, pers. comm.).

Ritchie (1984) found that the wilting point for Douglas-fir was lowest in midwinter and late summer, and highest in the spring indicating that seedlings are most sensitive to handling in the spring. Although root conditioning did not have an effect on osmotic potential or wilting points of the 1985 stock, it also had no effect on primordia development, root growth etc. Overall, the treatments were not effective in modifying physiological quality in 1985. Root conditioning may show an effect on cell water relations in other studies. Buxton *et. al.* (1985) found highest resistance to loss of turgor and maximum adjustment to moisture stress in white spruce as compared to jack pine and black spruce, indicating that white spruce is a good species to manipulate to increase drought tolerance.

CONCLUSIONS AND RECOMMENDATIONS

The variable nature of the results of the experiments makes drawing conclusions difficult; however, the following points should be emphasized. The effects of the root conditioning treatments on the morphological quality of the stock was consistent between years and with previous studies. Root pruning and wrenching successfully modified the morphology of 2+2 white spruce stock by decreasing height and increasing root system size. Early season root pruning followed by wrenching at regular intervals throughout the summer results in the smallest, sturdiest stock. Late season root pruning followed by wrenching has no effect on height or root collar diameter but does improve root system form. Therefore, root pruning followed by all season wrenching should be used as cultural treatments in the nursery when control of height growth and modification of root form are necessary to produce stock of desirable size.

The effects of root conditioning depend to a great extent on environmental conditions both in the year of treatment at the nursery and after outplanting. Reduction of height growth in the nursery is not desirable except in years like 1984 when stock becomes too large to be handled easily at the planting site. If used, root conditioning treatments must be tailored to environmental conditions in the year of treatment to avoid reducing height growth to the extent that the stock is too small for shipping.

Root conditioning did not appear to have any effect on the water relations of the stock during storage or after outplanting. Neither did it improve the survival of the stock after outplanting but it resulted in an initial height disadvantage which remained at the end of the second season. However, height growth of the root conditioned stock equalled that of the control stock in the second season after outplanting. Root collar diameter was also reduced by root conditioning but root collar diameter growth of the root conditioned stock equalled that of the non-conditioned stock after the second season in the field. Although the effects of root conditioning in the nursery remained with the stock after outplanting, growth after the first season in the field was not reduced by root conditioning.

The effects of root pruning and wrenching on the morphology of the stock do not necessarily result in desirable physiological quality. Root conditioning had variable effects on the root growth potential of the stock during and after storage in the two years and seemed to be a result of environmental conditions at the nursery during the season of root conditioning and after outplanting and site differences after outplanting as well as endogenous factors in the plant. Root conditioning is not recommended as a standard cultural treatment for white spruce transplants because it does not provide consistent, reliable results after outplanting and increases the stock production costs.

Potassium fertilization is not recommended as a synergistic conditioning treatment with root pruning and wrenching but may improve the survival and growth of overwinter frozen stock which has not been root conditioned. This hypothesis requires further testing to be confirmed.

The early establishment and growth of white spruce needs to be improved but other methods may be more cost effective than root pruning followed by all summer wrenching and/or fertilizer treatments. A more effective way of preparing white spruce for overwinter storage and subsequent outplanting may be to combine drought stressing with late season root conditioning. Drought stressing has been shown to provide the stressing effect of root wrenching, aid in hardening of the foliage at the end of the season, increase resistance to exposure during lifting, handling and planting, increase cold hardiness and increase field survival (Duryea 1984, Hennessey and Dougherty 1984). For example, drought stress increased the survival of container grown Douglas-fir and jack pine without affecting the growth of the surviving seedlings (McClain 1986).

The desired modification in root form which is lacking in a drought stressing regime could be effected through a late season root pruning followed by one or two root wrenching treatments depending on the stock and the environmental conditions prevailing in that season. Late season root pruning followed by wrenching has been shown to increase root fibrosity of Douglas-fir seedlings (Stein 1984) and white spruce in this study. The increased fibrosity of late season pruned and wrenched stock compared to control stock was still apparent after the first season in the field in this study. Thus, drought stressing combined with late season pruning and wrenching treatments may provide a more effective and cost efficient means of conditioning white spruce for overwinter frozen storage and outplanting.

RECOMMENDATIONS FOR SIMILAR RESEARCH

If this type of study were to be continued on other species or stock types, the following suggestions should be taken into consideration:

ROOT PRUNING AND WRENCHING TRIAL

1. More information could be gained from these studies if the experimental designs were more carefully planned.

2. Soil water relations play an important part in the effectiveness of the treatments and therefore should be closely monitored throughout the growing season.

3. Bed densities should be determined at the outset as these may play a role in the effectiveness of the treatments.

4. Plant moisture stress should be monitored throughout the root conditioning trials to document the effect the treatments are having on the water potential of the seedlings.

5. If fertilizer trials are a part of the experiment, some effort should be made to monitor plant nutrient content to see if the nutrients are being absorbed and how the root conditioning treatments are affecting uptake.

6. Percent cull should be monitored during lifting to determine whether root conditioning increases the amount of stock culled because of reduced size and/or root damage during lifting and handling.

GROWTH POTENTIAL TESTS

1. If fertility trials are included in the experiments, adequate space must be allocated in the growth chamber to allow monitoring of the fertilized stock throughout the winter.

2. Carbohydrate concentrations of the stock should be monitored to determine energy relations throughout the period of storage.

3. Root growth should be assessed for place of origin and root order to determine if root conditioning is changing the pattern as well as the amount of root growth.

4. Stress tests, such as those used in the Pacific Northwest (Ritchie 1984), might be considered as a less time consuming alternative to RGP tests for determining the differences in physiological quality between treatments.

OUTPLANTING TRIALS

1. Soil temperature and moisture content after outplanting should be monitored.

2. Plant moisture stress measurements should be correlated with the physiological state of the stock at the time of measurement, ie. buds swelling, flushing, elongating etc., as well as the environmental conditions.

3. More than one season is required to adequately evaluate the response of the stock to the treatments.

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APPENDIX 1

EXPECTED MEAN SQUARES TABLES

EXPECTED MEAN SQUARES TABLES

In the following tables symbols are used repetitively to represent the treatments so a summary of the symbols used is given at the outset for the reader to refer to for all of the tables.

Wr	Root pruning and wrenching	β	Blocks
K	Potassium	ε	Within treatment error
Per	Period	δ	Subsampling error
T	Time	ω,η,τ	Restriction errors
Lift	Lifting time		
Loc	Planting location		

ROOT PRUNING AND WRENCHING TRIALS

Table 1A: Expected mean squares table for the 1984 root pruning and wrenching trial.

Linear Model:

$$Y_{ijkl} = \mu + Wr_i + \sigma_{\omega(i)} + K_j + WrK_{ij} + \varepsilon_{(ij)k} + \delta_{(ijk)l}$$

where: i = 1,2,3,4 j = 1,2,3 k = 1,2,3 l = 1,2...25

Source of Variation	Degrees of Freedom	Expected Mean Squares
Wr_i	3	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 225\,\sigma_\omega^2 + 225\,\phi\,[Wr]$
Whole $Plot_{\omega(i)}$	8	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 225\,\sigma_\omega^2$
K_j	2	$\sigma2 + 25\,\sigma_\varepsilon^2 + 300\,\phi\,[K]$
Wr x K_{ij}	6	$\sigma2 + 25\,\sigma_\varepsilon^2 + 75\,\phi\,[WrK]$
$Subplot_{(ij)k}$	16	$\sigma^2 + 25\,\sigma_\varepsilon^2$
$Subsamples_{(ijk)l}$	864	σ^2
Total (900)	899	

Table 1B: Expected mean squares table for the 1984 bud primordia test.

Linear Model:

$$Y_{ijkl} = \mu + Wr_i + \sigma_{\omega(i)} + K_j + WrK_{ij} + \varepsilon_{(ij)k} + \delta_{(ijk)l}$$

where: i = 1,2,3,4 j = 1,2,3 k = 1,2,3,4 l = 1,2...10

Source of Variation	Degrees of Freedom	Expected Mean Squares
Wr_i	3	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 120\,\sigma_\omega^2 + 120\,\phi\,[Wr]$
Whole $Plot_{\omega(i)}$	12	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 120\,\sigma_\omega^2$
K_j	2	$\sigma2 + 10\,\sigma_\varepsilon^2 + 160\,\phi\,[K]$
Wr x K_{ij}	6	$\sigma2 + 10\,\sigma_\varepsilon^2 + 40\,\phi\,[WrK]$
$Subplot_{(ij)k}$	24	$\sigma^2 + 10\,\sigma_\varepsilon^2$
$Subsamples_{(ijk)l}$	432	σ^2
Total (480)	479	

Table 1C: Expected mean squares table for the 1985 root pruning and wrenching trial.

Linear Model:

$$Yijklm = \mu + \beta_i + \sigma_{\omega(i)} + Wr_j + \beta Wr_{ij} + \sigma_{\eta(ij)} + K_k + \beta K_{ik} + WrK_{jk} + \beta WrK_{ijk} + \varepsilon_{(ijk)l} + \delta_{(ijkl)m}$$

where: i = 1,2,3,4   j = 1,2,3   k = 1,2   l = 1   m = 1,2,...25

Source of Variation	Degrees of Freedom	Expected Mean Squares
β_i	3	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\eta^2 + 150\,\sigma_\omega^2 + 150\,\phi\,[\beta]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\eta^2 + 150\,\sigma_\omega^2$
Wr_j	2	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\eta^2 + 200\,\phi\,[Wr]$
$\beta \times Wr_{ij}$	6	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\eta^2 + 50\,\phi\,[\beta Wr]$
$\sigma_{\eta(ij)}$	0	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\eta^2$
K_k	1	$\sigma 2 + 25\,\sigma_\varepsilon^2 + 300\,\phi\,[K]$
$\beta \times K_{ik}$	3	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 75\,\phi\,[\beta K]$
$Wr \times K_{jk}$	2	$\sigma 2 + 25\,\sigma_\varepsilon^2 + 100\,\phi\,[WrK]$
$\beta \times Wr \times K_{ijk}$	6	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 25\,\phi\,[\beta WrK]$
$Error_{(ijk)l}$	0	$\sigma^2 + 25\,\sigma_\varepsilon^2$
$Subsamples_{(ijkl)m}$	576	σ^2
Total (600)	599	

Note: Interactions with blocks were assumed to be zero and were used to test main and subplot effects.

Table 1D: Expected mean squares table for the 1985 bud primordia test.

Linear Model:

$$Yijklm = \mu + \beta_i + \sigma_{\omega(i)} + Wr_j + \beta Wr_{ij} + \sigma_{\eta(ij)} + K_k + \beta K_{ik} + WrK_{jk} + \beta WrK_{ijk} + \varepsilon_{(ijk)l} + \delta_{(ijkl)m}$$

where: i = 1,2,3,4 j = 1,2 k = 1,2 l = 1 m = 1,2,...10

Source of Variation	Degrees of Freedom	Expected Mean Squares
β_i	3	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 20\,\sigma_\eta^2 + 40\,\sigma_\omega^2 + 40\,\phi\,[\beta]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 20\,\sigma_\eta^2 + 40\,\sigma_\omega^2$
Wr_j	1	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 20\,\sigma_\eta^2 + 80\,\phi\,[Wr]$
$\beta \times Wr_{ij}$	3	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 20\,\sigma_\eta^2 + 20\,\phi\,[\beta Wr]$
$\sigma_{\eta(ij)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 20\,\sigma_\eta^2$
K_k	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 80\,\phi\,[K]$
$\beta \times K_{ik}$	3	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 20\,\phi\,[\beta K]$
$Wr \times K_{jk}$	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 40\,\phi\,[WrK]$
$\beta \times Wr \times K_{ijk}$	3	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 10\,\phi\,[\beta WrK]$
$Error_{(ijk)l}$	0	$\sigma^2 + 10\,\sigma_\varepsilon^2$
$Subsamples_{(ijkl)m}$	144	σ^2
Total (160)	159	

Note: Interactions with blocks were assumed to be zero and were used to test main and subplot effects.

Table 1E: Expected mean squares table for the 1985 bulk density and soil moisture content trial.

Linear Model:

$$Yijklm = \mu + Per_i + \sigma_{\omega(i)} + T_j + PerT_{ij} + \sigma_{\eta(ij)} + \beta_k + Per\beta ik + T\beta jk + PT\beta ijk + \sigma_{\tau(ijk)} + Wr_l + PerWr_{il} + TWr_{jl} + PerTWr_{ijl} + \beta Wr_{kl} + Per\beta Wr_{ikl} + T\beta Wr_{jkl} + PT\beta Wr_{ijkl} + \varepsilon_{(ijkl)m} + \delta_{(ijklm)n}$$

where: i = 1,2,3 j = 1,2,3,4 k = 1,2,3,4 l = 1,2,3 m = 1 n= 1,2,...5

Source of Variation	Degrees of Freedom	Expected Mean Squares
Per_i	2	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 240\,\sigma_\omega^2 + 240\,\phi$ [Per]
$\sigma_{\omega(i)}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 240\,\sigma_\omega^2$
T_j	3	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 180\,\phi$ [T]
Per x T_{ij}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 60\,\phi$ [PerT]
$\sigma_{\eta(ij)}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 60\,\sigma_\eta^2$
β_k	3	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 180\,\phi$ [β]
Per x β_{ik}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 60\,\phi$ [Perβ]
T x β_{jk}	9	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 45\,\phi$ [Tβ]
Per x T x β_{ijk}	18	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2 + 15\,\phi$ [PerTβ]
$\sigma_{\tau(ijk)}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 150\,\sigma_\tau^2$
Wr_l	2	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 240\,\phi$ [Wr]
Per x Wr_{il}	4	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 80\,\phi$ [PerWr]
T x Wr_{jl}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 60\,\phi$ [TWr]
Per x T x Wr_{ijl}	12	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 20\,\phi$ [PerTWr]
β x Wr_{kl}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 60\,\phi$ [βWr]
Per x β x Wr_{ikl}	12	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 20\,\phi$ [PerβWr]
T x β x Wr_{jkl}	18	$\sigma2 + 5\,\sigma_\varepsilon^2 + 15\,\phi$ [TβWr]
Per x T x β x Wr_{ijkl}	36	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 5\,\phi$ [PerTβWr]
$Error_{(ijkl)m}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2$
$Subsamples_{(ijklm)n}$	576	σ^2
Total (720)	719	

GROWTH POTENTIAL TESTS DURING STORAGE

Note: In the following tables Time (T) acts as a block effect. One full replicate of the experiment was carried out at each time.

Table 1F: Expected mean squares table for the 1984-85 root growth potential tests.

Linear Model:

$$Y_{ijkl} = \mu + T_i + \sigma_{\omega(i)} + Wr_j + TWr_{ij} + \varepsilon_{(ij)k} + \delta_{(ijk)l}$$

where: $i = 1,2,...5$ $j = 1,2$ $k = 1,2,3$ $l = 1,2...10$

Source of Variation	Degrees of Freedom	Expected Mean Squares
T_i	4	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\,\sigma_\omega^2 + 60\,\phi\,[T]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\,\sigma_\omega^2$
Wr_j	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 150\,\phi\,[Wr]$
$T \times Wr_{ij}$	4	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 30\,\phi\,[TWr]$
$Error_{(ij)k}$	20	$\sigma^2 + 10\,\sigma_\varepsilon^2$
$Subsamples_{(ijk)l}$	270	σ^2
Total (300)	299	

Table 1G: Expected mean squares table for the 1984-85 bud development tests.

Linear Model:

$$Y_{ijkl} = \mu + T_i + \sigma_{\omega(i)} + Wr_j + TWr_{ij} + \varepsilon_{(ij)k} + \delta_{(ijk)l}$$

where: $i = 1,2,3,4$ $j = 1,2$ $k = 1,2,3$ $l = 1,2...10$

Source of Variation	Degrees of Freedom	Expected Mean Squares
T_i	3	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\,\sigma_\omega^2 + 60\,\phi\,[T]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\,\sigma_\omega^2$
Wr_j	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 120\,\phi\,[Wr]$
$T \times Wr_{ij}$	3	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 30\,\phi\,[TWr]$
$Error_{(ij)k}$	16	$\sigma^2 + 10\,\sigma_\varepsilon^2$
$Subsamples_{(ijk)l}$	216	σ^2
Total (240)	239	

Table 1H: Expected mean squares table for the 1985-86 root growth potential tests.

Linear Model:

$$Y_{ijkl} = \mu + T_i + \sigma_{\omega(i)} + \beta_j + T\beta_{ij} + \sigma_{\eta(ij)} + Wr_k + TWr_{ik} + \beta Wr_{jk} + T\beta Wr_{ijk} + \varepsilon_{(ijk)l} + \delta_{(ijkl)m}$$

where: i = 1,2,...6 j = 1,2...4 k = 1,2,3 l = 1 m = 1,2,...10

Source of Variation	Degrees of Freedom	Expected Mean Squares
T_i	5	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 120\,\sigma_\omega{}^2 + 120\,\phi\,[T]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 120\,\sigma_\omega{}^2$
β_j	3	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 180\,\phi\,[\beta]$
$T \times \beta_{ij}$	15	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 30\,\phi\,[T\beta]$
$\sigma_{\eta(ij)}$	0	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2$
Wr_k	2	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 240\,\phi\,[Wr]$
$T \times Wr_{ik}$	10	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 40\,\phi\,[TWr]$
$\beta \times Wr_{jk}$	6	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 60\,\phi\,[\beta Wr]$
$T \times \beta \times Wr_{ijk}$	30	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 10\,\phi\,[T\beta Wr]$
$Error_{(ijk)l}$	16	$\sigma^2 + 10\,\sigma_\varepsilon{}^2$
$Subsamples_{(ijkl)m}$	588	σ^2
Total (660)	659	

Table 1I: Expected mean squares table for the 1985-86 bud development tests.

Linear Model:

$$Y_{ijkl} = \mu + T_i + \sigma_{\omega(i)} + \beta_j + T\beta_{ij} + \sigma_{\eta(ij)} + Wr_k + TWr_{ik} + \beta Wr_{jk} + T\beta Wr_{ijk} + \varepsilon_{(ijk)l} + \delta_{(ijkl)m}$$

where: $i = 1,2,...5$ $j = 1,2...4$ $k = 1,2,3$ $l = 1$ $m = 1,2,...10$

Source of Variation	Degrees of Freedom	Expected Mean Squares
T_i	4	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 120\,\sigma_\omega{}^2 + 120\,\phi\,[T]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 120\,\sigma_\omega{}^2$
β_j	3	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 150\,\phi\,[\beta]$
$T \times \beta_{ij}$	12	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2 + 30\,\phi\,[T\beta]$
$\sigma_{\eta(ij)}$	0	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 30\sigma_\eta{}^2$
Wr_k	2	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 200\,\phi\,[Wr]$
$T \times Wr_{ik}$	8	$\sigma 2 + 10\,\sigma_\varepsilon{}^2 + 40\,\phi\,[TWr]$
$\beta \times Wr_{jk}$	6	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 50\,\phi\,[\beta Wr]$
$T \times \beta \times Wr_{ijk}$	24	$\sigma^2 + 10\,\sigma_\varepsilon{}^2 + 10\,\phi\,[T\beta Wr]$
$Error_{(ijk)l}$	0	$\sigma^2 + 10\,\sigma_\varepsilon{}^2$
$Subsamples_{(ijkl)m}$	540	σ^2
Total (600)	599	

OUTPLANTING TRIALS

Table 11: Expected mean squares table for root growth potential tests after outplanting in May 1985.

Linear Model:

$$Y_{ijkl} = \mu + Loc_i + \sigma_{\omega(i)} + Lift_j + LocLift_{ij} + \sigma_{\eta(ij)} + Wr_k + LocWr_{ik} + LiftWr_{jk} + LocLiftWr_{ijk} + \varepsilon_{(ijk)l} + \delta_{(ijkl)m}$$

where: $i = 1,2$ $j = 1,2$ $k = 1,2$ $l = 1,2,3$ $m = 1,2,...10$

Source of Variation	Degrees of Freedom	Expected Mean Squares
Loc_i	1	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\sigma_\eta^2 + 120\,\sigma_\omega^2 + 120\,\phi$ [Loc]
$\sigma_{\omega(i)}$	0	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\sigma_\eta^2 + 120\,\sigma_\omega^2$
$Lift_j$	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 60\sigma_\eta^2 + 120\,\phi$ [Lift]
Loc x $Lift_{ij}$	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 60\sigma_\eta^2 + 60\,\phi$ [LocLift]
$\sigma_{\eta(ij)}$	0	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 60\sigma_\eta^2$
Wr_k	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 120\,\phi$ [Wr]
Loc x Wr_{ik}	1	$\sigma 2 + 10\,\sigma_\varepsilon^2 + 60\,\phi$ [LocWr]
Lift x Wr_{jk}	1	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 60\,\phi$ [LiftWr]
Loc x Lift x Wr_{ijk}	1	$\sigma^2 + 10\,\sigma_\varepsilon^2 + 30\,\phi$ [LocLiftWr]
$Error_{(ijk)l}$	16	$\sigma^2 + 10\,\sigma_\varepsilon^2$
$Subsamples_{(ijkl)m}$	216	σ^2
Total (240)	239	

Table 1K: Expected mean squares table for the 1985 outplanting trial.

Linear Model:

$$Y_{ijkl} = \mu + \beta_i + \sigma_{\omega(i)} + Lift_j + \beta Lift_{ij} + \sigma_{\eta(ij)} + Wr_k + \beta Wr_{ik} + LiftWr_{jk} + \beta LiftWr_{ijk} + \sigma_{\tau(ijk)} + K_l + \beta K_{il} + LiftK_{jl} + \beta LiftK_{ijl} + WrK_{kl} + \beta WrK_{ikl} + LiftWrK_{jkl} + \beta LiftWrK_{ijkl} + \varepsilon_{(ijkl)m} + \delta_{(ijklm)n}$$

where: i = 1,2,3 j = 1,2 k = 1,2,3,4 l = 1,2,3 m = 1 n = 27

Source of Variation	Degrees of Freedom	Expected Mean Squares
β_i	2	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 424\,\sigma_\eta^2 + 848\,\sigma_\omega^2 + 848\,\phi$ [β]
$\sigma_{\omega(i)}$	0	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 424\,\sigma_\eta^2 + 848\,\sigma_\omega^2$
$Lift_j$	1	$\sigma2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 424\,\sigma_\eta^2 + 1272\,\phi$ [Lift]
β x $Lift_{ij}$	2	$\sigma2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 424\,\sigma_\eta^2 + 424\,\phi$ [βLift]
$\sigma_{\eta(ij)}$	0	$\sigma2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 424\,\sigma_\eta^2$
Wr_k	3	$\sigma2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 486\,\phi$ [Wr]
β x Wr_{ik}	6	$\sigma2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 162\,\phi$ [βWr]
Lift x Wr_{jk}	3	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 243\,\phi$ [LiftWr]
β x Lift x Wr_{ijk}	6	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2 + 81\,\phi$ [bLiftWr]
$\sigma_{\tau(ijk)}$	0	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 81\,\sigma_\tau^2$
K	2	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 848\,\phi$ [K]
β x K_{il}	4	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 216\,\phi$ [βK]
Lift x K_{jl}	2	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 424\,\phi$ [LiftK]
β x Lift x K_{ijl}	4	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 108\,\phi$ [βLiftK]
Wr x K_{kl}	6	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 162\,\phi$ [WrK]
β x Wr x K_{ikl}	12	$\sigma2 + 27\,\sigma_\varepsilon^2 + 54\,\phi$ [βWrK]
Lift x Wr x K_{jkl}	6	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 81\,\phi$ [LiftWrK]
β x Lift x Wr x K_{ijkl}	12	$\sigma^2 + 27\,\sigma_\varepsilon^2 + 27\,\phi$ [βLiftWrK]
$Error_{(ijkl)m}$	0	$\sigma^2 + 27\,\sigma_\varepsilon^2$
$Subsamples_{(ijklm)n}$	1872	σ^2
Total (1945)	1944	

Table 1L: Expected mean squares table for the May 1986 root growth potential tests.

Linear Model:

$$Y_{ijkl} = \mu + Loc_i + \sigma_{\omega(i)} + \beta_j + Loc\beta_{ij} + \sigma_{\eta(ij)} + Lift_k + LocLift_{ik} + \beta Lift_{jk} + Loc\beta Lift_{ijk} + \sigma_{\tau(ijk)} + Wr_l + LocWr_{il} + \beta Wr_{jl} + Loc\beta Wrijl + LiftWr_{kl} + LocLiftWr_{ikl} + \beta LiftWr_{jkl} + Loc\beta LiftWr_{ijkl} + \varepsilon_{(ijkl)m} + \delta_{(ijklm)n}$$

where: $i = 1,2$ $j = 1,2,3,4$ $k = 1,2$ $l = 1,2,3$ $m = 1$ $n = 5$

Source of Variation	Degrees of Freedom	Expected Mean Squares
Loc_i	1	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 120\,\sigma_\omega^2 + 120\,\phi$ [Loc]
$\sigma_{\omega(i)}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 120\,\sigma_\omega^2$
β_j	3	$\sigma 2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 120\,\phi$ [β]
β x Loc_{ij}	3	$\sigma 2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 60\,\sigma_\eta^2 + 60\,\phi$ [Locβ]
$\sigma_{\eta(ij)}$	0	$\sigma 2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 60\,\sigma_\eta^2$
$Lift_k$	1	$\sigma 2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 60\,\phi$ [Lift]
Loc x $Lift_{ik}$	1	$\sigma 2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 30\,\phi$ [LocLift]
β x $Lift_{jk}$	3	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 30\,\phi$ [βLift]
Loc x β x $Lift_{ijk}$	3	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2 + 15\,\phi$ [LocβLift]
$\sigma_{\tau(ijk)}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 15\,\sigma_\tau^2$
Wr_l	2	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 80\,\phi$ [Wr]
Loc x Wr_{il}	2	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 40\,\phi$ [LocWr]
β x Wr_{jl}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 20\,\phi$ [βWr]
Loc x β x Wr_{ijl}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 10\,\phi$ [LocβWr]
Lift x Wr_{kl}	2	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 40\,\phi$ [LiftWr]
Loc x Lift x Wr_{ikl}	2	$\sigma 2 + 5\,\sigma_\varepsilon^2 + 20\,\phi$ [LocLiftWr]
β x Lift x Wr_{jkl}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 10\,\phi$ [βLiftWr]
Loc x β x Lift x Wr_{ijkl}	6	$\sigma^2 + 5\,\sigma_\varepsilon^2 + 5\,\phi$ [LocβLiftWr]
$Error_{(ijkl)m}$	0	$\sigma^2 + 5\,\sigma_\varepsilon^2$
$Subsamples_{(ijklm)n}$	192	σ^2
Total (240)	239	

Table 1M: Expected mean squares table for the 1986 outplanting trial.

Linear Model:

$$Y_{ijkl} = \mu + \beta_i + \sigma_{\omega(i)} + Lift_j + \beta Lift_{ij} + \sigma_{\eta(ij)} + Wr_k + \beta Wr_{ik} + LiftWr_{jk} + \beta LiftWr_{ijk} + \sigma_{\tau(ijk)} + K_l + \beta K_{il} + LiftK_{jl} + \beta LiftK_{ijl} + WrK_{kl} + \beta WrK_{ikl} + LiftWrK_{jkl} + \beta LiftWrK_{ijkl} + \varepsilon_{(ijkl)m} + \delta_{(ijklm)n}$$

where: i = 1,2,3,4 j = 1,2 k = 1,2,3 l = 1,2 m = 1 n = 25

Source of Variation	Degrees of Freedom	Expected Mean Squares
β_i	3	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 150\,\sigma_\eta^2 + 300\,\sigma_\omega^2 + 300\,\phi\,[\beta]$
$\sigma_{\omega(i)}$	0	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 150\,\sigma_\eta^2 + 300\,\sigma_\omega^2$
$Lift_j$	1	$\sigma2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 150\,\sigma_\eta^2 + 600\,\phi\,[Lift]$
β x $Lift_{ij}$	3	$\sigma2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 150\,\sigma_\eta^2 + 150\,\phi\,[\beta Lift]$
$\sigma_{\eta(ij)}$	0	$\sigma2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 150\,\sigma_\eta^2$
Wr_k	2	$\sigma2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 400\,\phi\,[Wr]$
β x Wr_{ik}	6	$\sigma2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 100\,\phi\,[\beta Wr]$
Lift x Wr_{jk}	2	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 200\,\phi\,[LiftWr]$
β x Lift x Wr_{ijk}	6	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2 + 50\,\phi\,[bLiftWr]$
$\sigma_{\tau(ijk)}$	0	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 50\,\sigma_\tau^2$
K	1	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 600\,\phi\,[K]$
β x K_{il}	3	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 150\,\phi\,[\beta K]$
Lift x K_{jl}	1	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 300\,\phi\,[LiftK]$
β x Lift x K_{ijl}	3	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 75\,\phi\,[\beta LiftK]$
Wr x K_{kl}	2	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 200\,\phi\,[WrK]$
β x Wr x K_{ikl}	6	$\sigma2 + 25\,\sigma_\varepsilon^2 + 50\,\phi\,[\beta WrK]$
Lift x Wr x K_{jkl}	2	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 100\,\phi\,[LiftWrK]$
β x Lift x Wr x K_{ijkl}	6	$\sigma^2 + 25\,\sigma_\varepsilon^2 + 25\,\phi\,[\beta LiftWrK]$
$Error_{(ijkl)m}$	0	$\sigma^2 + 25\,\sigma_\varepsilon^2$
$Subsamples_{(ijklm)n}$	1152	σ^2
Total (1200)	1199	

APPENDIX 2

LOCATION AND PLOT MAPS FOR OUTPLANTING TRIALS

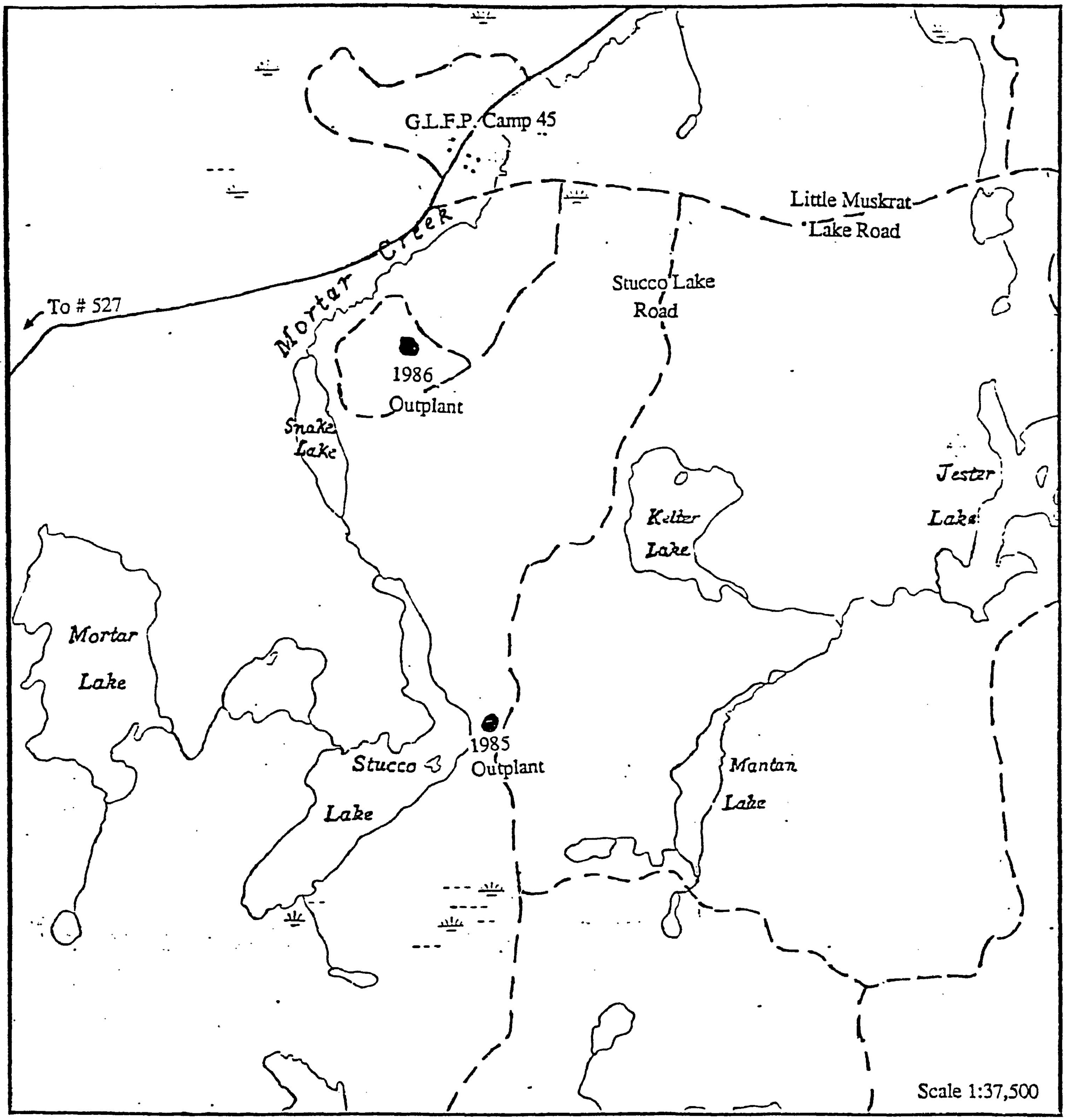

Figure 2A. Map of the location of the 1985 and 1986 outplanting sites.

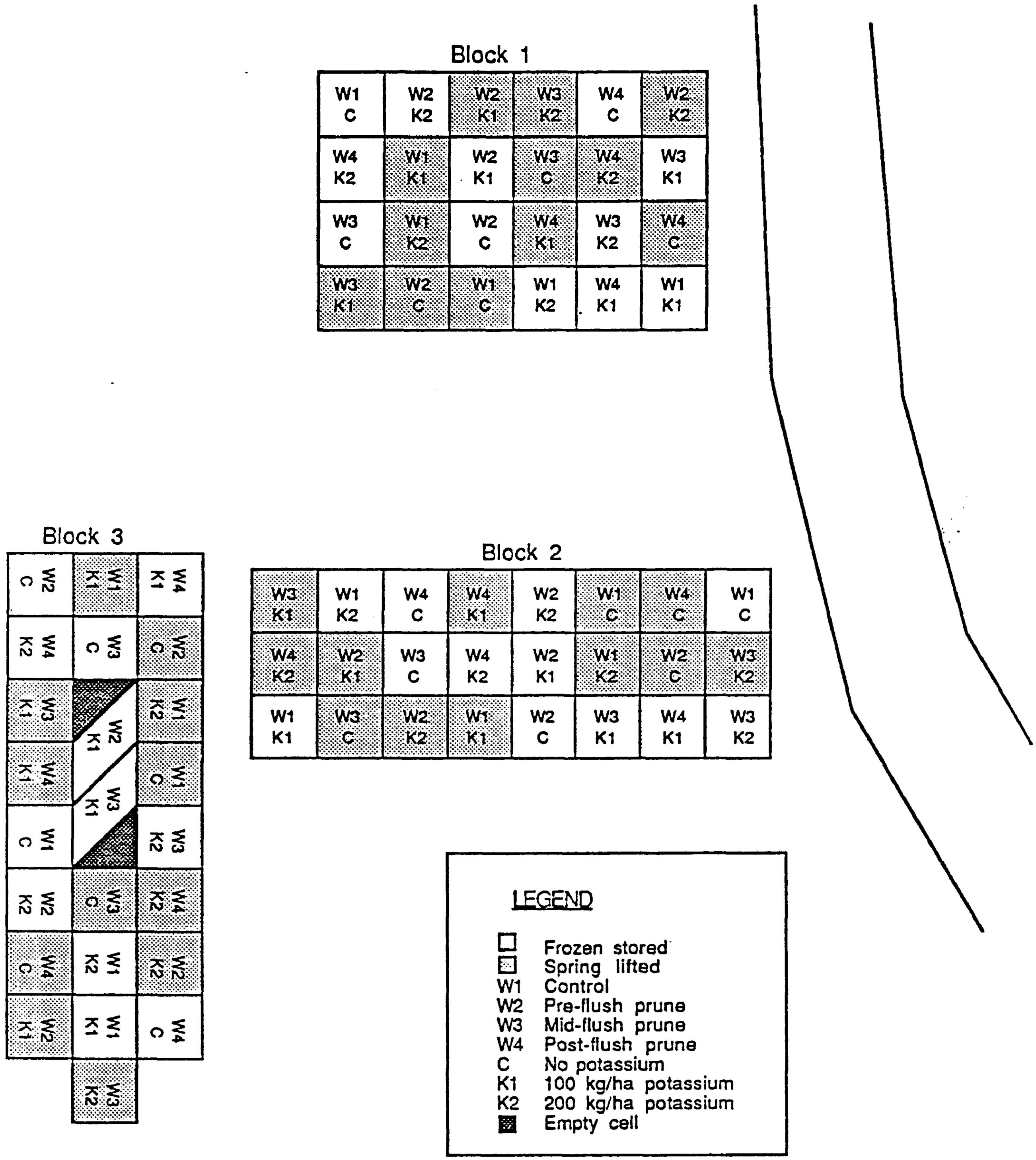

Figure 2B. Plot layout for the 1985 outplanting trial.

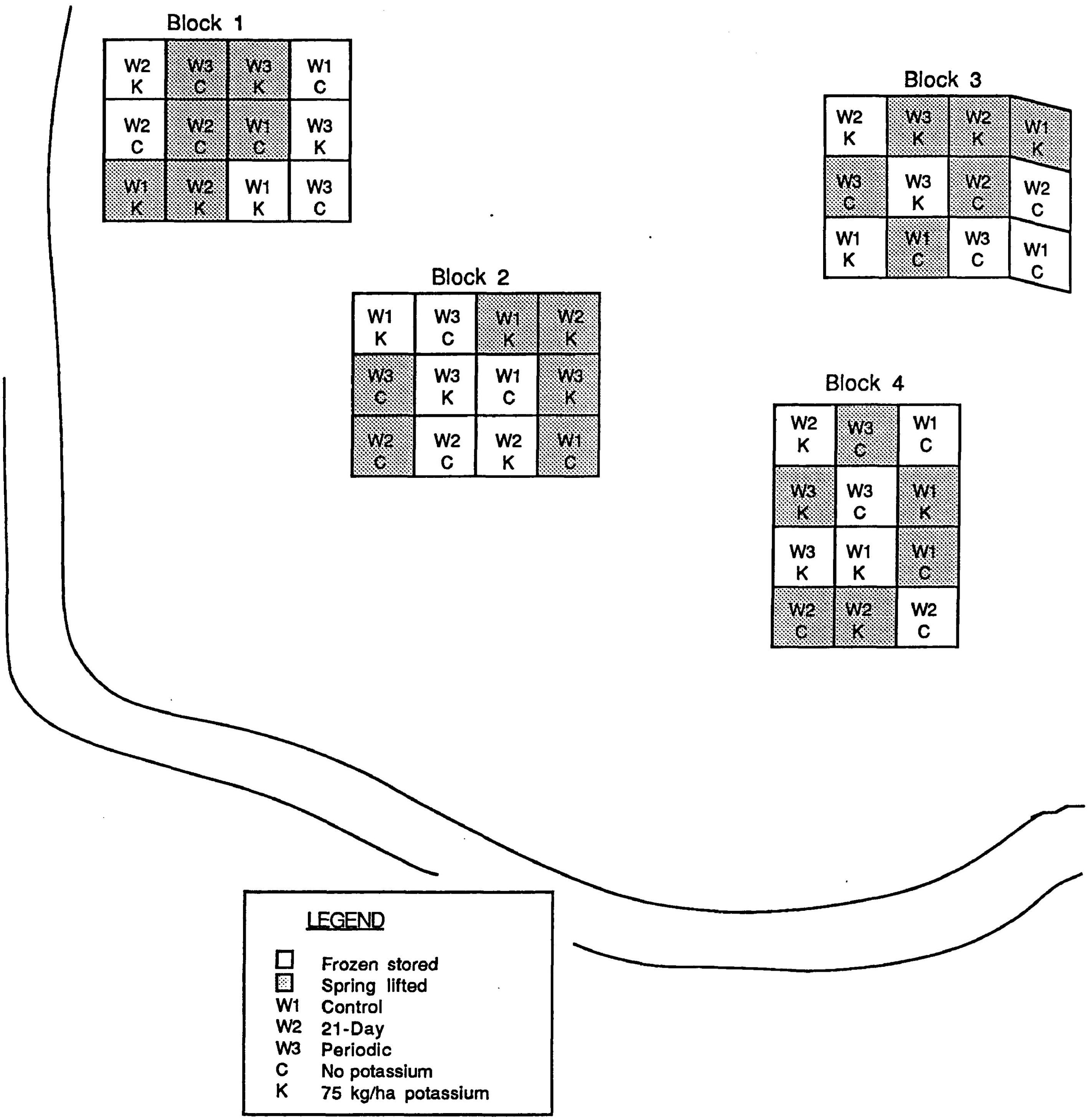

Figure 2C. Plot layout for the 1986 outplanting trial.

APPENDIX 3

CONDITION CODES

CONDITION CODES

Seedlings in the outplanting trials were coded subjectively according to the following criteria in order to differentiate between treatments which were growing but barely alive and those which were growing and vigorous. The coding system was taken from Day and Harvey (1984a).

CODE	CONDITION
0	Healthy seedling with green foliage
1	Seedling 1-25% brown or defoliated
2	Seedling 26-50% brown or defoliated
3	Seedling 51-75% brown or defoliated
4	Seedling 76-100% brown or defoliated, inner bark green
5	Seedling 100% brown or defoliated, inner bark brown

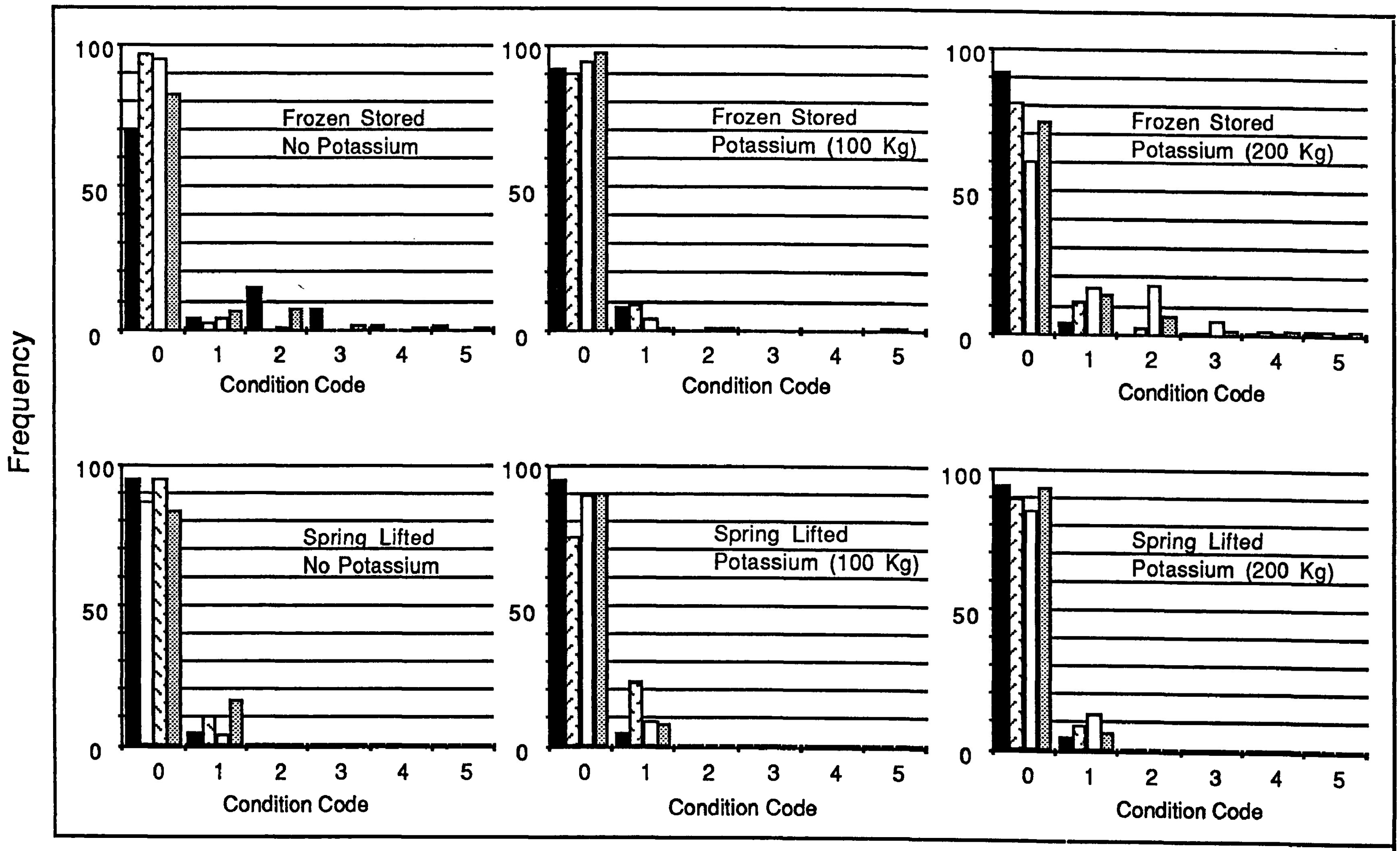

Figure 3A. Condition code frequency graphs for the 1985 outplant - First year results. Treatment 1 ■, Treatment 2 ▨, Treatment 3 □, Treatment 4 ▩ .

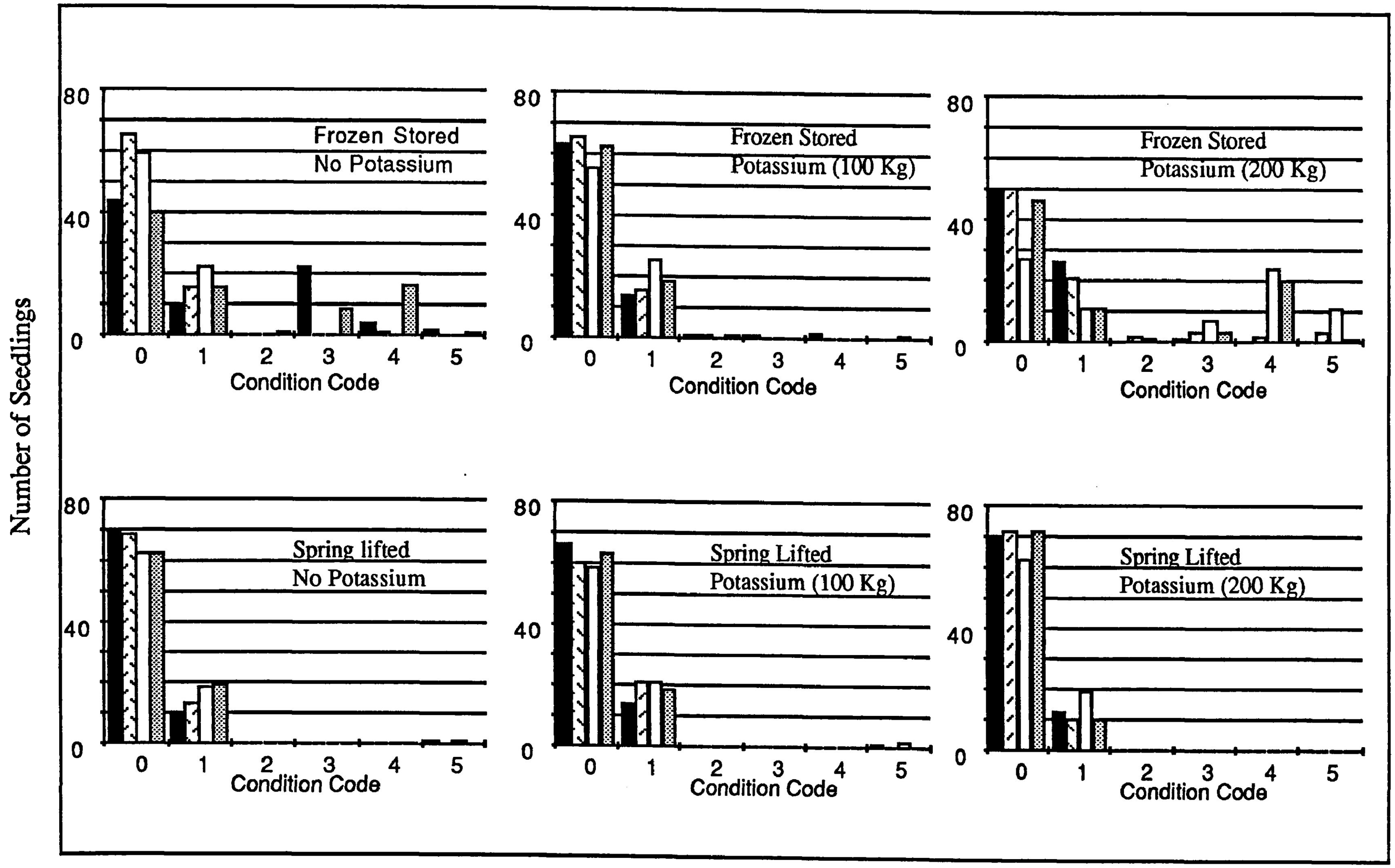

Figure 3B: Condition code frequency graphs for the 1985 outplanting trial - Second year results. Treatment 1 ■, Treatment 2 ▨, Treatment 3 □, Treatment 4 ▩.

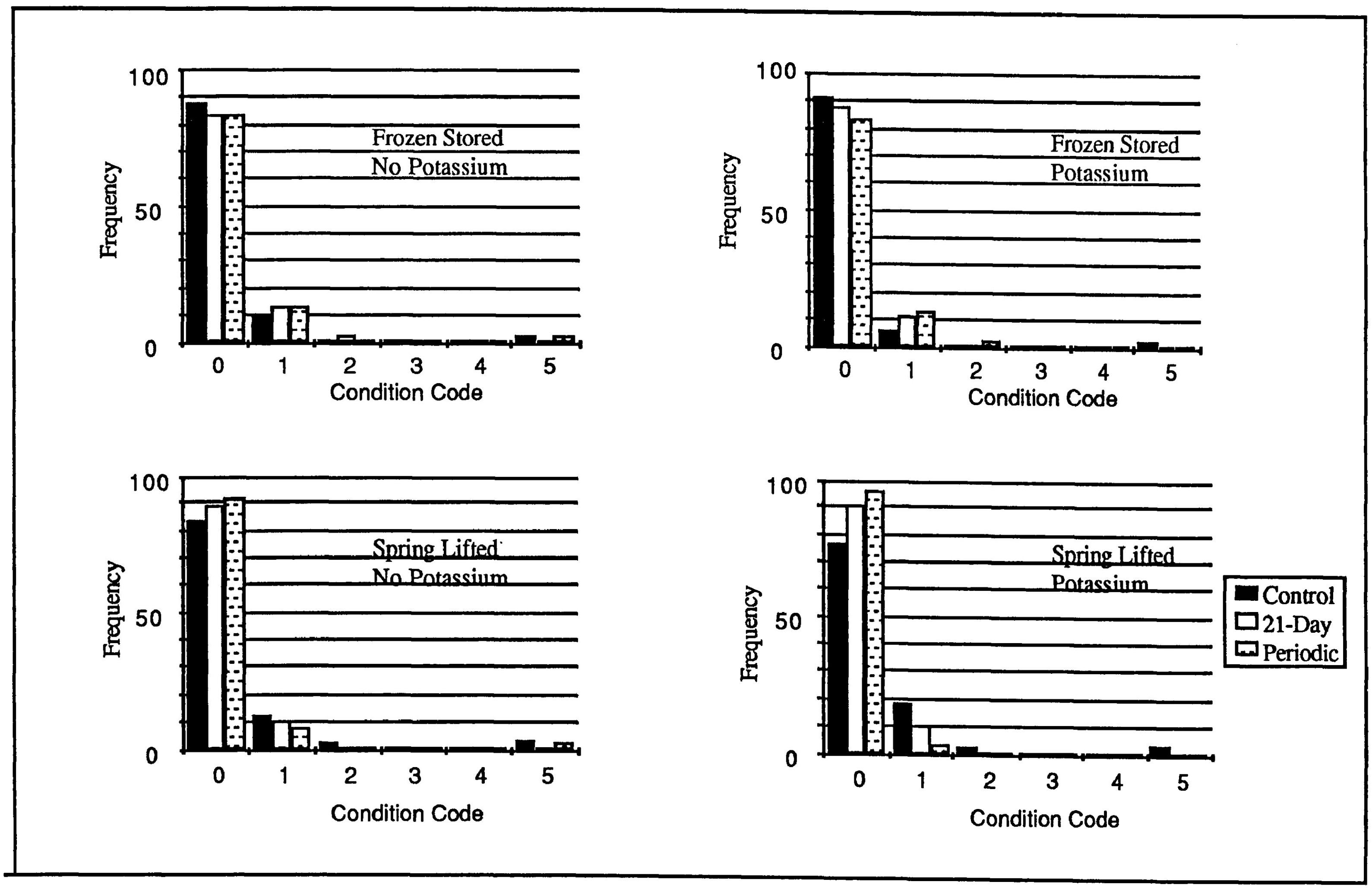

Figure 3C: Condition code frequency graphs for the 1986 outplanting trial - First year results.

APPENDIX 4

GLOSSARY OF BOTANICAL NAMES

GLOSSARY OF BOTANICAL NAMES

(as used in this thesis)

PINE	
Austrian pine	*Pinus nigra* Arn.
Caribbean pine	*Pinus caribbaea* Mor. var. *hondurensis*
Jack pine	*Pinus banksiana* Lamb.
Loblolly pine	*Pinus taeda* L.
Longleaf pine	*Pinus palustris* Mill.
Monterey pine	*Pinus radiata* D. Don.
Red pine	*Pinus resinosa* Ait.
Scots pine	*Pinus sylvestris* L.
Shortleaf pine	*Pinus echinata* Mill.
Slash Pine	*Pinus elliottii* Engelm. var. *elliottii*
SPRUCE	
Black spruce	*Picea mariana* Mill. B.S.P.
Norway spruce	*Picea abies* (L.) Karst.
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
White spruce	*Picea glauca* (Moench) Voss
FIR	
Balsam fir	*Abies balsamea* (L.) Michx.
Noble fir	*Abies procera* Rehd.
DOUGLAS-FIR	
Douglas-fir	*Pseudotsuga menseizeii* (Mirb.) Franco
HEMLOCK	
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
POPLAR	
Aspen	*Populus tremuloides* Michx.
BIRCH	
White birch	*Betula papyrifera* Marsh.

APPENDIX 5

TABLES OF SIGNIFICANCE FOR GROWTH POTENTIAL TESTS

TABLES OF RESULTS

In the following tables, symbols for significance levels will be used repetitively and thus are defined at the outset as being:

NS not significant
* significant at the 90% level of confidence
** significant at the 95% level of confidence
*** significant at the 99% level of confidence

Root Growth Potential Tests During Storage

Table 5A. Means and significance of differences for root elongation (RE) and root number (RN) produced by white spruce tranplants during 21-day root growth potential tests in 1984-85.

Month	RE (cm) Treatment 1	2	Significance	RN 1	2	Significance
December						
Total	119	146	NS	97	105	NS
Long	96	122	NS	26	37	NS
Medium	19	21	NS	35	37	NS
Small	3	3	NS	36	32	NS
January						
Total	140	248	***	107	207	***
Long	110	200	**	27	67	***
Medium	27	41	***	44	69	***
Small	3	7	***	35	71	***
February						
Total	179	262	*	122	192	**
Long	149	216	*	37	60	*
Medium	25	38	**	42	64	**
Small	4	7	**	43	68	**
March						
Total	107	170	**	97	160	***
Long	83	132	**	22	38	**
Medium	20	30	***	33	50	***
Small	4	7	***	41	72	***
May						
Total	60	93	NS	84	142	NS
Long	44	65	NS	18	27	NS
Medium	11	20	NS	18	34	NS
Small	5	8	*	48	81	*

Table 5B. Means and significance of differences for root elongation (RE) and root number (RN) produced by white spruce transplants during 21-day root growth potential tests in 1985-86.

Treatment Month	RE (cm) 1	2	3	Significance	RN 1	2	3	Significance
November								
Total	300	218	257	*	185	159	159	***
Long	270	190	230	*	67	48	51	***
Medium	22	20	20	NS	37	33	32	NS
Small	8	8	8	NS	82	78	76	NS
December								
Total	192	242	220	NS	120	134	159	NS
Long	174	219	199	NS	38	42	42	NS
Medium	12	16	13	NS	20	27	22	NS
Small	6	7	8	NS	62	65	77	NS
January								
Total	207	211	229	NS	134	140	136	NS
Long	187	190	211	NS	39	41	44	NS
Medium	14	13	10	NS	23	22	17	NS
Small	7	8	8	NS	73	77	76	NS
February								
Total	126	176	178	*	102	131	123	NS
Long	112	158	161	*	28	42	40	NS
Medium	8	11	10	NS	13	18	17	NS
Small	6	7	7	NS	60	71	66	NS
March								
Total	136	148	117	NS	114	133	113	NS
Long	122	129	102	NS	38	39	33	NS
Medium	8	12	8	*	14	19	14	*
Small	6	8	7	NS	62	75	66	NS
May								
Total	74	88	77	NS	101	118	111	NS
Long	56	68	58	NS	20	25	21	NS
Medium	12	13	12	NS	20	21	19	NS
Small	6	7	7	NS	61	72	71	NS

Shoot Growth Potential Tests During Storage

Table 5C. Means and significance of differences of percent of buds flushed on the terminal whorl of white spruce transplants during 21-day growth chamber trials (- indicates data not available).

	1984-85			1985-86				
Treatment	1	2	Significance	Day	1	2	3	Significance
November								
0	-	-		0	0	0	0	NS
5	-	-		3	0	0	0	NS
				6	0	0	0	NS
10	-	-		9	0	0	0	NS
				12	0	0	0	NS
15	-	-		15	0	1	2	NS
				18	1	3	3	NS
20	-	-		21	30	24	38	NS
December								
0	0	0	NS	0	0	0	0	NS
5	0	0	NS	3	0	0	0	NS
				6	0	0	0	NS
10	0	0	NS	9	0	0	0	NS
				12	0	0	0	NS
15	1	1	NS	15	0	0	0	NS
				18	16	9	4	NS
20	14	14	NS	21	55	55	52	NS
January								
0	0	0	NS	0	0	0	0	NS
5	0	0	NS	3	0	0	0	NS
				6	0	0	0	NS
10	1	0	NS	9	0	0	0	NS
				12	0	0	1	NS
15	9	13	NS	15	9	17	15	NS
				18	-	-	-	
20	60	76	NS	21	79	88	83	NS
February								
0	0	0	NS	0	0	0	0	NS
5	0	0	NS	3	0	0	0	NS
				6	0	0	0	NS
10	0	0	NS	9	0	0	0	NS
				12	0	1	1	NS
15	6	17	***	15	12	17	22	NS
				18	62	66	73	NS
20	85	86	NS	21	79	82	87	NS
March								
0	0	0	NS	0	0	0	0	NS
5	0	0	NS	3	0	0	0	NS
				6	0	0	0	NS
10	0	0	NS	9	0	0	0	NS
				12	6	15	11	NS
15	43	41	NS	15	42	65	69	*
				18	61	84	87	**
20	74	87	NS	21	76	88	90	*

Root Growth Potential Tests After Outplanting

Table 5D. Means and significance of differences for root elongation (cm) of white spruce transplants during 21-day root growth potential tests in the spring of 1985.

Treatment	Frozen stored 1	2	Significance	Spring lifted 1	2	Significance
Chamber						
Total	60	93	NS	119	119	NS
Long	44	65	NS	101	101	NS
Medium	11	20	NS	13	12	NS
Small	5	8	*	5	6	NS
Field						
Total	4	9	NS	7	9	NS
Long	1	2	NS	1	1	NS
Medium	1	4	NS	2	2	NS
Small	2	4	***	5	7	NS

Table 5E. Means and significance of differences for root elongation (cm) of white spruce transplants during 21-day root growth potential tests in the spring of 1986.

Treatment	Frozen stored 1	2	3	Significance	Spring lifted 1	2	3	Significance
Chamber								
Total	70	51	57	NS	78	125	96	NS
Long	51	35	40	NS	61	101	76	NS
Medium	13	9	11	NS	11	16	13	NS
Small	6	7	7	NS	6	7	8	NS
Field								
Total	39	39	43	NS	42	64	45	NS
Long	21	22	23	NS	27	43	26	NS
Medium	11	10	12	NS	8	14	12	NS
Small	8	7	7	NS	7	8	7	NS