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# Planting frozen conifer seedlings: Warming trends and effects on seedling performance

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**Abstract.** In temperate climates, conifer seedlings are often held in frozen storage (−2 °C) for extended periods and then placed in cool storage (+2 °C) so the root plug can thaw prior to outplanting. Two plug temperature treatments were used to test the hypothesis that thawing seedlings prior to outplanting may be unnecessary: seedlings were planted with frozen root plugs ('frozen seedlings') and with thawed root plugs ('thawed seedlings'). The experiment was conducted under two watering regimes (irregular, regular) and with three conifer species (lodgepole pine [*Pinus contorta* var. *latifolia*], western larch [*Larix occidentalis*], interior spruce [*Picea glauca* × *engelmannii*]) to increase the generality of the results. The warming of root plugs after planting was examined. Thawed root plugs warmed to soil temperature rapidly (about 30 min) while frozen root plugs took longer (to 2 h) because ice in the plug had to melt before temperatures rose. Larger root plugs took longer to warm to soil temperature. Several aspects of seedling field performance were also assessed. For all species, variable fluorescence did not differ between frozen and thawed seedlings. Bud break was faster for thawed than frozen western larch seedlings but did not differ between frozen and thawed seedlings for either lodgepole pine or interior spruce. Height increment differed significantly between frozen and thawed seedlings that received the irregular watering regime; this effect was likely a response to the positioning of irrigation nozzles, which resulted in sporadic and non-uniform irrigation patterns. Height increment did not differ between frozen and thawed seedlings that received the regular watering regime. Root collar diameter and volume increments were not significantly affected by plug temperature treatment under either watering regime. Planting seedlings with frozen root plugs did not hinder field performance over one growing season under these watering regimes.

## Introduction

In temperate climates, the seedling production process often involves the storage of dormant seedlings at temperatures below freezing (−2 °C; 'frozen storage') or near freezing (+2 °C; 'cool storage'). When stored under proper conditions, seedlings of most species can be kept for several months with relatively minor effects on seedling physiology (Harper and Camm 1993). Frozen storage provides flexibility in scheduling seedling delivery to planting sites. In British Columbia, for example, three-quarters of all container-grown stock is destined for spring planting but is lifted in the autumn (Anonymous 1998). This stock is lifted, graded, and bundled in the autumn, placed in frozen storage until spring, thawed at a moderate (5–10 days at 5–10 °C) or slow (21–35 days at 0–3 °C) rate, and held in cool storage until it is shipped to the field for planting (Kooistra and Ostafew 1995). Although it is recommended that planting occur immediately after thawing, it is not uncommon for seedlings to be kept in cool storage for several weeks because of logistic constraints or environmental conditions such as snow-covered planting sites.

While several reasons have been espoused for thawing seedlings and storing them at cool temperatures until they are shipped for planting, recent technological innovation and research lead us to question the importance of these reasons. First, thawing is currently required because frozen seedlings cannot be separated from one another, but advances in automated nursery technology now enable seedlings to be packaged individually and would allow frozen seedlings to be separated. Second, there is some thought that melting ice could cause the plug to contract, thereby reducing contact between it and the soil (Camm et al. 1995). While we are not aware of studies investigating the effect of frozen planting on plug–soil contact, we believe that this is a minor concern if plugs have been planted properly. Third, cool storage allows normal physiological processes to be resumed before planting occurs, but research indicates that this delay may not be necessary for seedlings to be successfully planted. For example, planting lodgepole pine (*Pinus contorta* Dougl. Ex. Loud. var. *latifolia* Engelm.) and interior spruce (white spruce [*Picea glauca* (Moench) Voss] and Engelmann spruce [*Picea engelmannii* Parry] hybrid complex) seedlings while they were still frozen had brief and transient effects on xylem water potential and other aspects of seedling physiology (Camm et al. 1995; Silim et al. 1998); after one growing season, growth parameters did not differ between seedlings planted while frozen and those planted after being thawed. Similarly, black spruce (*Picea mariana* [Mill.] BSP.) seedlings planted while frozen and after being thawed did not differ in height increment after one growing season (Prezio 1997).

Most studies of storage and planting practices have focused on the effects of frozen storage duration and have neglected to distinguish between the effects of frozen storage and the effects of subsequent cool storage (e.g., Ritchie et al. (1985), Chomba et al. (1993), Harper and Camm (1993)). Similarly, reviews of cold storage techniques have either paid little attention to the thawing process (Camm et al. 1994) or simply noted that the rate of thawing is unlikely to cause damage (McKay 1997).

Several lines of evidence suggest that cool storage can have negative effects on seedling health. First, respiration occurs at a faster rate during cool storage than frozen storage. Since respiration consumes carbohydrate reserves, these reserves are depleted more rapidly during cool storage. The absence of light during cool storage prevents seedlings from maintaining their carbohydrate reserves (Wang and Zwiazek 1999). Interior spruce and lodgepole pine seedlings had significantly lower total carbohydrate reserves if stored for 2 weeks at 2 °C than if rapidly thawed for 24 h at 15 °C (Silim et al. 1998). Second, cool storage can rapidly reduce seedling cold hardiness (Schaberg et al. 1996) through increased respiration and consumption of the intracellular sugars that function as cryoprotectants (Ogren 1997). Four months of storage at 5.5 °C reduced sugar concentrations in Scots pine (*Pinus sylvestris* L.)

by 54% and increased the temperature at which 10% of cells were damaged ($LT_{10}$) from −24.5 °C to about −10 °C. In comparison, storage at −8.5 °C reduced sugar concentrations by only 9% and increased $LT_{10}$ to about −22 °C (Ogren 1997). Third, root growth in a number of species (e.g., Sitka spruce [*Picea sitchensis* (Carr.) Bong.] and western redcedar [*Thuja plicata* D. Don]) is initiated from stored reserves; the loss of carbohydrate reserves during prolonged cool storage can reduce the establishment success of such species (McKay 1997). In black spruce, root growth potential was significantly higher for frozen than thawed seedlings (Prezio 1997). Fourth, storage moulds are much more of a problem during cool storage than frozen storage (Sutherland et al. 1989).

These considerations suggest that thawing seedlings prior to outplanting may be unnecessary or even deleterious. Planting seedlings while their root plugs are still frozen would avoid the thawing process and cool storage. We used two plug temperature treatments (seedlings planted with frozen root plugs ['frozen seedlings'] and seedlings planted with thawed root plugs ['thawed seedlings']) to test this hypothesis. To increase the generality of the results, we conducted the experiment under two watering regimes (regular and irregular) and with three species (lodgepole pine, interior spruce, and western larch [*Larix occidentalis* Nutt.]). One potential concern with planting frozen stock is that seedlings could experience drought stress while the root plug is frozen and unable to provide replacement moisture to meet transpirational losses. To document how long root plugs remain frozen, we monitored the temperatures of frozen and thawed root plugs as they warmed to soil temperature. We also assessed the effects of the plug temperature treatments on several aspects of seedling field performance.

## Materials and methods

### *Experimental design*

Lodgepole pine (seedlot 30582), western larch (seedlot 05101), and interior spruce (seedlot 06582) 1+0 seedlings were grown under contract for the British Columbia Ministry of Forests using standard operational methods. Lodgepole pine and western larch were grown in 80-ml (PCT 410) containers and interior spruce was grown in 250-ml (PSB 515A) containers. In the fall of 1997, seedlings were wrapped individually in nursery grade plastic wrap and placed in frozen storage. Packaging seedlings individually permitted seedlings with frozen root plugs to be easily separated during planting. In the spring of 1998, half of the seedlings were randomly assigned to each of two plug temperature treatments: seedlings were planted either with frozen root plugs ('frozen seedlings') or thawed root plugs ('thawed seedlings'). Thawed seedlings were held for 4–5 days at ~ 10 °C to thaw prior to planting. Frozen seedlings were kept in the freezer until planting. All seedlings were kept in the dark in the freezer and/or cooler. All three species had root growth capacities of approximately 4 on Burdett's (1979) Index of Root

*Table 1.* Average soil temperatures (°C; 5-cm depth) when lodgepole pine, western larch, and interior spruce seedlings with frozen and thawed root plugs were planted in sites that received irregular and regular watering regimes.

| Species | Watering Regime | Plug Temp. Treatment | |
|---|---|---|---|
| | | Frozen | Thawed |
| Lodgepole pine | Irregular | 26–27 | 26–27 |
| | Regular | 25–32 | 25–32 |
| Western larch | Irregular | 18–22 | 18–22 |
| | Regular | 19–25 | 19–25 |
| Interior spruce | Regular | 23–29 | 23–29 |

Growth in May 1998. Initial growth parameters and pre-plant variable fluorescence measurements are summarized in Figure 2 and Table 2, respectively.

Seedlings were planted in bareroot beds at Grandview Nursery, Armstrong, British Columbia. The soils at Grandview Nursery are orthic black chernozems with a sandy loam texture (67% sand, 18% silt, 15% clay). Two sites were selected about 200 m apart that appeared to be identical. The locations of these sites relative to the irrigation system and to other seedling crops in the field, however, resulted in large differences in watering regime. One site was irrigated irregularly from sprinkler heads on one side of the bed (irregular watering regime), and the other site was regularly and abundantly irrigated from sprinkler heads on both sides of the bed (regular watering regime). In addition to this difference, the two sites were planted at different times: May 6–7 1998 in the site receiving the irregular watering regime and June 4–5 1998 in the site receiving the regular watering regime. Thus seedlings that received the irregular watering regime experienced a longer growing season than those that received the regular watering regime. Planting dates fell within the range in which planting occurs operationally. Lodgepole pine and western larch were planted in both sites. Interior spruce was only planted on the site that received the regular watering regime due to logistic constraints. Species and plug temperature treatments were planted sequentially (western larch in the morning, lodgepole pine and interior spruce in the afternoon) to simplify the planting process.

The experiment did not have a complete factorial design but focused on the effects of the plug temperature treatment. Species and treatments were not interspersed because of the apparent environmental uniformity at the time of planting. Four replicate plots of each combination of species and plug temperature treatment were planted at each site for a total of forty plots. Each plot contained 15 seedlings. A border of seedlings was planted around the entire experimental design to reduce edge effects.

Planting occurred between 09:00 and 16:00 each day. In May, the weather was sunny with a maximum air temperature of 31 °C. In June, the weather was partly cloudy with rain showers and a maximum air temperature of 24 °C. Soil temperatures were similar in May and June but varied with time of day: temperatures ranged from 18–23 °C in the morning and 25–27 °C in the afternoon (Table 1).

*Warming trends*

We examined the warming of root plugs by comparing the temperatures of seedling root plugs ($T_p$) and the soil ($T_s$). $T_p$ was measured by planting a pair of seedlings side by side and placing a temperature probe at the 5-cm soil depth between them. Two probes were used per plot, for a total of 8 probes per combination of species, plug temperature treatment, and site. Readings were taken every 15 min for about two h.

Soil temperature ($T_s$) was measured using a temperature probe placed 5 cm into the soil. Readings were taken every 15 min. Quadratic equations were fit to the soil temperature data ($R^2 = 0.84$ to 0.99) and used to estimate $T_s$ at the time of each $T_p$ measurement. The temperature differential ($T_d$) was calculated as:

$$T_d = T_p - T_s$$

$T_d$ is negative immediately after planting and rises towards 0. Warming trends were described by graphing $T_d$ as a function of time since planting and fitting a polynomial line to the data. To compare the warming trends of frozen and thawed root plugs, we examined the time elapsed before $T_d = -5$ °C.

We expected the rate at which root plugs warmed to be a function of root plug volume, $T_p$, and $T_s$. Warming trends in 80-ml and 250-ml containers were studied separately. $T_p$ varied with plug temperature treatment (frozen or thawed root plugs). $T_s$ was similar among planting dates, so we assumed that planting date did not affect the warming trends. Measurements obtained in the morning and afternoon were examined separately to assess warming trends under two distinct temperature regimes.

*Seedling performance*

Seedling performance was assessed by measuring variable fluorescence, days to bud break, condition at the end of the growing season, and initial and final growth parameters. In the site receiving the irregular watering regime, paired seedlings used for temperature measurements were not thinned so seedling measurements were not taken from the paired seedlings. In the site receiving the regular watering regime, one seedling from each pair was removed after the temperature measurements were completed and so measurements were taken from all seedlings.

Photosynthetic processes are affected by environmental stresses such as water deficits, $CO_2$ limitation, pollution, and light saturation (Binder et al. 1997). Variable fluorescence assesses the health of the photosynthetic apparatus and therefore can serve as a non-destructive, integrated measure of plant health (Vidaver et al. 1991). Variable fluorescence was measured using an EARS-PPM fluorometer (EARS, Delft, The Netherlands) with a modulated (7.2 kHz) 637 nm light to measure fluorescence and an $\approx$1800 W m$^{-2}$ saturing light (Anonymous 1993). The fluorometer measured the photosynthetic quantum yield of dark-adapted plants ($\phi_{P,dark}$, in %), which is the ratio of fluorescence under ambient light conditions to maximum fluorescence induced by a saturating light pulse. Quantum yield has a maximum value of about 82% in the dark (Anonymous 1993). Measurements were taken in the dark to permit comparisons among tests conducted at different dates and locations. One measurement was taken in the top third of the shoot of each seedling. Fluorescence measurements for western larch were taken on the stem (cambial tissue) while measurements for lodgepole pine and interior spruce were taken on the foliage. Unmeasured seedlings were not exposed to the light pulse produced while measuring other seedlings. We began to make fluorescence measurements on seedlings planted in the site receiving the regular watering regime but experienced equipment failure. In late June, therefore, we took fluorescence measurements on an additional 12 frozen and 12 thawed seedlings from each seedlot. 'Pre-plant' measurements were taken on frozen seedlings immediately after they were removed from the freezer, and on thawed seedlings after thawing had occurred. Measurements were also taken between 23:30 and 01:00 on the night after planting and the next two nights. Data obtained from these measurements were similar to the partial results from the site receiving the regular watering regime (data not shown), suggesting that these measurements are representative of the differences in fluorescence among the frozen and thawed seedlings used in this experiment.

The terminal bud of each seedling was assessed daily for bud burst (i.e., when green growth was evident between the bud scales), up to a maximum of 21 days.

At the end of the growing season (October 20 1998), seedlings were assessed and subjectively assigned to one of five condition classes (excellent, good, fair, poor, dead).

Two growth parameters, height (H) and root collar diameter (RCD), were measured immediately after planting and at the end of the growing season. In order to examine the integrated response of height and RCD, we calculated initial and final stem volumes (V; $cm^3$) using the equation for the volume of a cone:

$$V=\frac{\pi\times H\times RCD^2}{12}=0.2618\times H\times RCD^2$$

where H and RCD are measured in cm. The equation for a cone was sufficient for these purposes as we did not require actual seedling stem volumes. Height, RCD, and volume increments were calculated by subtracting initial from final values.

Species and sites were not interspersed and therefore could not be compared statistically. Instead, *t*-tests examined differences between frozen and thawed seedlings for each combination of species and site. Variables tested were fluorescence, days to bud break, initial height, initial RCD, initial volume, height increment, RCD increment, and volume increment. Seedling condition was not tested statistically because the data were not continuous or normally distributed. For each species and plug temperature treatment, differences in fluorescence value among days were tested using one-way analyses of variance (ANOVAs). When these results were significant, values that differed from one another were identified using Fisher's least significant difference.

## Results

### *Warming trends*

The $R^2$ values of all warming trend equations were 0.76 or greater (Figure 1), indicating that third-order quadratic equations adequately explained the warming trends of frozen and thawed root plugs.

Seedlings with 80-ml root plugs were planted when soil temperatures were 26–27 °C or 18–23 °C (Figure 1A & 1B). The rate at which thawed root plugs warmed was not affected by soil temperature: $T_d$ was $\geq -5$ °C after about 25 min in both situations. Frozen root plugs warmed at a much slower rate, and the rate of warming differed between the two soil temperatures. In cooler soils, there was about a 40-min lag before $T_d$ began to rise and $T_d$ was $\geq -5$ °C after about 105 min(Figure 1B). In warmer soils, there was no lag in temperature rise and $T_d$ was $\geq -5$ °C after about 75 min (Figure 1A).

Seedlings with 250-ml root plugs were planted when soil temperatures were 23–29 °C. For thawed root plugs, $T_d$ was $\geq -5$ °C after about 35 min (Figure 1C). Frozen root plugs exhibited a lag of about 40 min before temperatures began to rise and $T_d$ was $\geq -5$ °C after about 115 min.

### *Seedling performance*

Fluorescence measurements did not vary among frozen and thawed seedlings for any species (Table 2). Interspecific differences between species were evident, however. Initial fluorescence values were highest for lodgepole pine and lowest for interior spruce. Lodgepole pine and western larch fluorescence values declined significantly after planting while interior spruce fluorescence values rose significantly by the first night after planting.

Bud break occurred significantly faster for thawed than frozen western larch seedlings (Table 3). Bud break did not differ between plug temperature treatments for either lodgepole pine or interior spruce. Western larch seedlings broke bud first, followed by lodgepole pine and then interior spruce.

All seedlings broke bud and flushed. Seedling mortality after one growing season was highest for western larch, especially for frozen seedlings in the site that received the irregular watering regime (Table 3). For all other combinations of species and site, ≥ 94% of the seedlings were in Excellent or Good condition and differences between plug temperature treatments were minimal.

Initial height, initial RCD, and initial volume did not vary between frozen and thawed seedlings for any combination of species and site (Figure 2).

In the site that received the irregular watering regime, height increment was significantly lower for frozen than thawed western larch seedlings but significantly higher for frozen than thawed lodgepole pine seedlings (Figure 2). In the site that received the regular watering regime, height increment did not differ between frozen and thawed seedlings. Overall, height increment was largest for western larch and

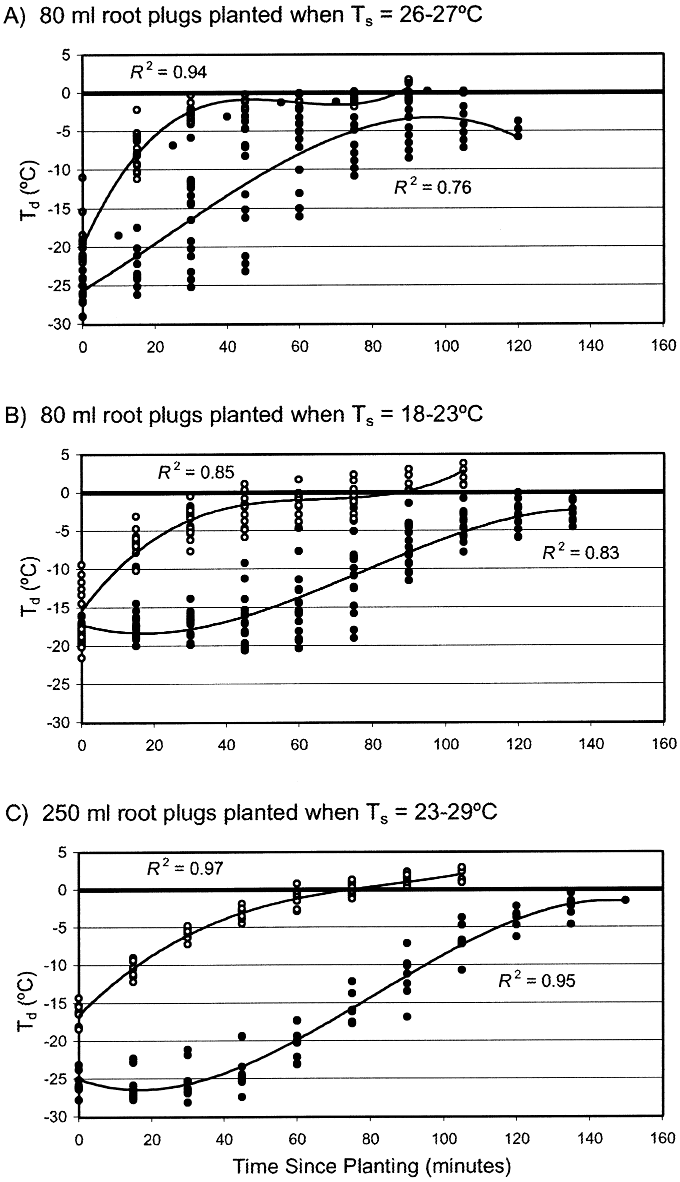


*Figure 1.* Difference in temperature ($T_d$; °C) between the soil ($T_s$) and frozen (●) and thawed (○) root plugs as a function of time since planting. A) 80 ml root plugs (PCT 410 containers) planted when $T_s$ was 26–27 °C. B) 80 ml root plugs (PCT 410 containers) planted when $T_s$ was 18–23 °C. C) 250 ml root plugs (PSB 515A containers) planted when $T_s$ was 23–29 °C. Plug temperature equals $T_s$ when $T_d$=0.

*Table 2.* Variable fluorescence (quantum yield ($\phi_{P,dark}$) in %, mean ± SD) of dark-adapted lodgepole pine, western larch, and interior spruce seedlings planted with frozen and thawed root plugs. Measurements were taken the night before planting (preplant), the night after planting (night 0), and the next two nights (nights 1 and 2). N = 12 seedlings per combination of species and plug temperature treatment. Differences between frozen and thawed seedlings for any species were not statistically significant. For each combination of species and plug temperature treatment, different letters indicate significant differences ($P \leq 0.05$) in fluorescence among days.

| Species | Plug Temp. Treatment | Variable Fluorescence | | | |
|---|---|---|---|---|---|
| | | Preplant | Night 0 | Night 1 | Night 2 |
| Lodgepole pine | Frozen | 78.8 ± 1.9a | 75.6 ± 1.5bc | 74.2 ± 2.9b | 76.3 ± 1.8c |
| | Thawed | 77.9 ± 1.9a | 76.1 ± 2.2b | 74.4 ± 1.8c | 76.6 ± 1.2b |
| Western larch | Frozen | 66.0 ± 6.0a | 62.8 ± 3.7a | 59.8 ± 4.7a | 63.1 ± 6.2a |
| | Thawed | 65.9 ± 5.2a | 62.3 ± 2.9b | 60.2 ± 4.5b | 62.3 ± 3.4b |
| Interior spruce | Frozen | 60.3 ± 7.2a | 69.9 ± 3.9b | 74.6 ± 2.6c | 76.1 ± 2.1c |
| | Thawed | 59.5 ± 7.7a | 71.8 ± 4.4b | 74.1 ± 4.0b | 75.2 ± 3.2b |

*Table 3.* Days to bud break (mean ± SD) and condition (% in each class) after one growing season for lodgepole pine, western larch, and interior spruce seedlings planted with frozen and thawed root plugs in sites receiving irregular and regular watering regimes. N = 4 plots (15 trees/plot) for days to bud break; N = 52 to 60 seedlings for condition. For days to bud break, different letters indicate significant differences ($P \leq 0.05$) between plug temperature treatments for each combination of species and watering regime.

| Species | Watering Regime | Plug Temp. Treatment | Days to Bud Break | Condition[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | E | G | F | P | D |
| Lodgepole pine | Irregular | Frozen | 6.5 ± 0.6a | 51 | 47 | 2 | 0 | 0 |
| | Irregular | Thawed | 5.6 ± 1.0a | 54 | 40 | 6 | 0 | 0 |
| | Regular | Frozen | 4.9 ± 0.3a | 67 | 30 | 3 | 0 | 0 |
| | Regular | Thawed | 5.1 ± 0.3a | 83 | 17 | 0 | 0 | 0 |
| Western larch | Irregular | Frozen | 4.2 ± 0.4a | 0 | 65 | 10 | 0 | 25 |
| | Irregular | Thawed | 0.6 ± 0.2b | 0 | 90 | 2 | 2 | 6 |
| | Regular | Frozen | 2.0 ± 0.3a | 80 | 16 | 2 | 0 | 2 |
| | Regular | Thawed | 1.1 ± 0.1b | 83 | 15 | 2 | 0 | 0 |
| Interior spruce | Regular | Frozen | 9.8 ± 1.1a | 78 | 19 | 3 | 0 | 0 |
| | Regular | Thawed | 8.6 ± 0.6a | 93 | 5 | 2 | 0 | 0 |

[1]Condition codes: E = Excellent; G = Good; F = Fair; P = Poor; D = Dead

smallest for lodgepole pine. Height increments were almost 4 times greater for seedlings grown under the regular watering regime than under the irregular watering regime.

RCD increment did not vary between frozen and thawed seedlings for any combination of species and site (Figure 2). Western larch had the largest RCD increment when grown under the regular watering regime but the smallest RCD increment when grown under the irregular watering regime. Lodgepole pine and interior spruce had similar RCD increments (~ 4 mm) when grown under the regular

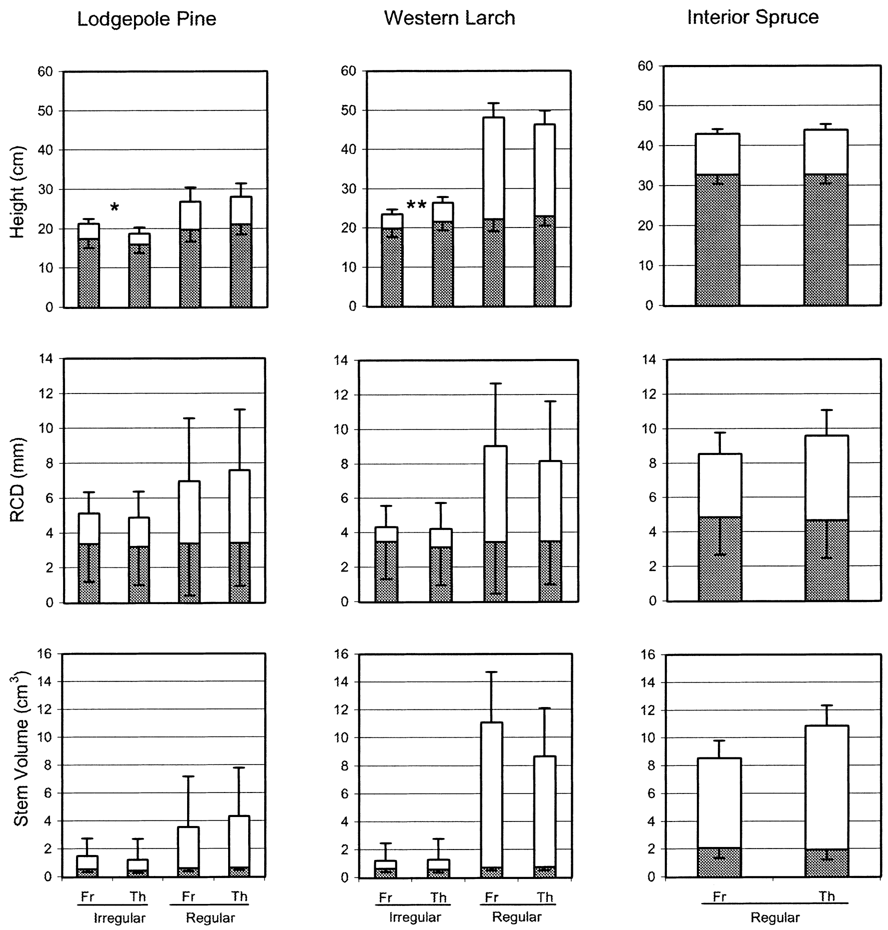


*Figure 2.* Height, root collar diameter (RCD), and stem volume (mean ± SD) of frozen (Fr) and thawed (Th) seedlings of lodgepole pine, western larch, and interior spruce growing in sites receiving irregular and regular watering regimes. For each bar, the shaded portion shows the initial value and the clear portion shows the growth increment over one growing season. Lodgepole pine and western larch were grown with 80 ml root plugs (PCT 410 containers) and interior spruce was grown with 250 ml root plugs (PSB 515A containers). For pairs of bars within watering regimes: * = $P < 0.05$; ** = $P < 0.01$.

watering regime. RCD increments were about 3 times greater for seedlings grown under the regular watering regime than under the irregular watering regime.

Volume increment did not vary between frozen and thawed seedlings for any combination of species and site (Figure 2). Western larch had the largest volume increment when grown under the regular watering regime but the smallest volume increment when grown under the irregular watering regime. Volume increments were more than 8 times greater for seedlings grown under the regular watering regime than under the irregular watering regime.

## Discussion

### *Warming trends*

The water within frozen root plugs absorbs heat as it changes state from a solid to a liquid. This change of state explains the lag in the warming of frozen root plugs (Figure 1B & 1C). A lag in warming was not evident in the 80-ml root plugs planted in 26–27 °C soil (Figure 1A), probably because the warm soil temperature and smaller root plug volumes caused rapid warming. Large root plugs have more ice and lower surface area: volume ratios and therefore warm slower than smaller root plugs.

Frozen root plugs warmed to soil temperature within about two h. This timeframe is comparable to the observations of other researchers. Camm et al. (1995) noted that all of the ice was gone from frozen root plugs in 40 min when soil temperatures at a 7.5-cm depth were 20–22 °C. Prezio (1997) commented that the temperature of frozen plugs reached that of the surrounding soil within 2 h when the air temperature ranged from 3–21 °C. It should be noted that we used paired seedlings to measure plug temperatures. Warming would occur faster in seedlings that were planted individually. Therefore, the warming periods determined in this study should probably be regarded as maxima under these conditions rather than as averages.

Root plugs warmed to soil temperature faster in warm than cold soils. Prezio (1997) suggested that planting seedlings with frozen root plugs could have a more significant effect on performance if it occurs under cool rather than warm conditions. We did not test the effects of planting frozen seedlings in the cooler soils that would be experienced in early spring or at high elevations. Future research should examine warming trends and seedling performance over a wider range of soil temperatures.

### *Seedling performance*

Seedlings planted with frozen and thawed root plugs differed significantly in only two aspects: bud break in western larch, and height increment in the site receiving the irregular watering regime. Bud break occurs after species-specific heat sums have been received (Hannerz 1999); thawed western larch seedlings received these heat sums during cool storage and therefore broke bud a day after planting (Table 3). Rapid bud break of thawed western larch seedlings is frequently observed in operational situations. Seedling performance could be hindered by rapid bud break because buds that are enlarging are more susceptible to breakage during transport and planting. In addition, flushing prior to outplanting can result in solarization of the new foliage once planted. Delaying bud break by planting western larch seedlings with frozen root plugs may be preferred in operational situations.

The significant difference in height increment between frozen and thawed seedlings in the site receiving the irregular watering regime (Figure 2) is likely related to sporadic and non-uniform irrigation patterns. When irrigation patterns were superimposed over the experimental design it was apparent that frozen western larch and thawed lodgepole pine seedlings were located in the area that received the least irrigation (data not shown). The greater drought stress experienced by these seedlings may have reduced their height increment, producing significant differences in height increment between frozen and thawed seedlings of these species (Figure 2). Variable irrigation patterns likely also contributed to the mortality of western larch at this site (Table 3).

Watering regime had a very strong effect on seedling performance. Seedlings that received the regular watering regime had a shorter growing season than those that received the irregular watering regime yet had much larger growth increments (Figure 2). The favourable growing conditions under the regular watering regime accentuated the differences between species but not between frozen and thawed seedlings. These results suggest that seedling performance may be more strongly affected by microsite environment than by whether the seedling root plug is frozen or thawed at the time of planting.

Interspecific differences among species in seedling performance likely reflect differences in species attributes and growth strategies. For example, bud break and fluorescence vary widely among species (Vidaver et al. 1991). Rapid juvenile growth in western larch resulted in much larger final growth parameters for it than for lodgepole pine even though both species had similar initial growth parameters (Figure 2). Interior spruce was the largest stock type initially but its final growth parameters were matched or exceeded by those of western larch.

Since differences among species and sites were much greater than differences between frozen and thawed seedlings, we conclude that planting seedlings while they are frozen does not appear to hinder seedling performance. Our results agree with those of an earlier study: physiological differences between frozen and thawed seedlings are minor compared to the major physiological stresses experienced due to the planting process and the effects of differing planting sites and environments (Camm et al. 1995).

Further research should examine the effects of planting seedlings with frozen root plugs under other climatic conditions, especially cooler temperatures, and in a range of growing environments. Trials are also needed to assess the effect of planting frozen stock of other species.

### *Conclusions*

Under the conditions of this trial, planting seedlings while they were frozen did not affect seedling performance. Seedlings with thawed root plugs warmed to soil temperature in about a half-h; seedlings with frozen root plugs took longer because of the heat required to melt ice into water. Performance differences among species and watering regimes were much greater than the variation in performance between frozen and thawed seedlings.

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