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MEASURES TO REDUCE OVERWINTER INJURY TO PLANTED SPRUCE IN THE BOREAL FOREST OF BRITISH COLUMBIA

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Measures to Reduce Overwinter Injury to Planted Spruce in the Boreal Forest of British Columbia

by

Marek J. Krasowski

Red Rock Research Station,
RR#7 RMD#6, Prince George, B.C.
V2N 2J5

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For additional copies and/or further information about the Canada–British Columbia Partnership Agreement on Forest Resource Development: FRDA II, contact:

Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria, B.C. V8Z 1M5
(604) 363-0600

or

B.C. Ministry of Forests
Research Branch
31 Bastion Square
Victoria, B.C. V8W 3E7
(604) 387-6719

ABSTRACT

Freeze-desiccation is probably the main cause of overwinter injury occurring in the southern parts of British Columbia boreal forests. The greatest damage takes place in spring when there is little snow, the soil is frozen, and days are sunny and warm. The severity of injury increases with increasing seedling height (and less significantly, with decreasing stem diameter) and with vigorous growth during the previous growing season. Naturally regenerated seedlings are little affected by this kind of injury. There is often less injury on plowed sites, and, particularly, on mounded sites than on raw-planted sites. The latter findings suggest the relationship between the placement of roots in the soil and the susceptibility of seedlings to overwinter injury. Spring-planted seedlings grow less and decline more in their health during the post-injury growing season than do summer-planted seedlings. Practical recommendations are made regarding selection of planting stock, site preparation, and the choice of planting time.

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1 INTRODUCTION

Overwinter injury to white spruce seedlings planted in the Boreal forest of northeastern British Columbia was one of the ten top research priorities identified at the start of the FRDA II programme. A series of studies began in 1990 with the goal of finding the causes, evaluating the extent, and recommending action to address the problem. This report summarizes results of these studies and provides the anticipated recommendations. More in-depth information can be found in various internal and external reports listed at the end of this report.

Krasowski *et. al,* 1993 discussed the overwinter injury problem in light of the available literature. It was postulated that the injury probably resulted from the climate, or from climate-related phenomena peculiar to the geographic region. Large-scale, recurring seedling losses due to overwinter injury mainly affect the Dawson Creek and Fort St. John forest districts, but, from time to time, problems of this kind may occur on a smaller scale in other forest districts. Overwinter injury appears to be a major problem in the geo-graphic area only during the first post-planting winter. Older plantations, established trees, and naturally regenerated seedlings seemed to be little affected. Therefore, the susceptibility of spruce seedlings to overwinter injury could relate to their morphological and/or physio-logical status early after planting.

2 RESULTS

2.1 Timing of Injury

In 1990 and 1991, seedlings from local seedlots were spring- and summer-planted on two sites in the Dawson Creek Forest District, according to appropriate experimental designs (Krasowski *et al.* 1995 and [1996]). Seedlings that had died before winter were written off. Pre-winter injuries on the remaining seedlings were recorded. Each winter after planting, random samples were collected about once a month and brought to Red Rock Research Station (RRRS) for evaluation. Sampled seedlings were cut at ground level, slowly thawed, placed into water-filled jars, and kept at warm conditions where injury, if present, became visible. Observations were similar in both years, although the overwinter injury was much lower in 1990 than in 1991. Figure 1a shows average foliage injury in samples collected during the 1991–1992 winter, while Figure 1b demonstrates changes in the water content of upper and lower seedling portions during that winter, which was determined from another set of collected samples. There was little injury observed in samples collected between November and mid-March. The low average injury in samples taken until mid-March did not correspond to the greater than 50% average foliar injury detected in the June assessment. This indicates that most of the injury occurred after mid-March. Foliage water content declined towards the end of March (Figure 1b), with the upper shoot portion drying more and faster than the basal seedling part. This is consistent with observations of injury affecting upper seedling parts more than those near the ground.

2.2 Causes of Injury

The winter of 1992–1993 was the most devastating during the study period, but it provided many clues about the overwinter injury. Figure 2a shows minimum and maximum daily temperatures 40 cm above the ground. It shows temperatures below -40°C in January 1993, while the temperature near the ground (10-cm height) did not fall below -20°C, due to snow cover (Figure 2b). Two Chinook events occurred in late January and in February, eliminating snow pack. The return of the Arctic front froze the soil deeply. Diurnal air temperature fluctuation in the spring delayed soil thawing (Figures 3a and 3b). The soil remained frozen at 5 cm until mid-April, and even longer at 10- and 50-cm depths. Young water-absorbing roots were in the frozen soil while daytime air temperatures in March and April rose to about +20°C (Figure 2a). Photosynthetically active radiation and air vapour pressure deficit rose with increasing daylength and high daytime temperatures (not shown).

The conditions described above are conducive to freeze-desiccation (Sakai 1970, Tranquillini 1982, Christersson and Von Fricks 1988). This is probably the primary cause of the observed overwinter injury, although other potentially injuring factors may also have contributed. There was a mid-March cold snap (Figure 2a). After about 2 weeks of mild weather, during which there was no snow, the temperature dropped to -25°C (compare air temperatures at different heights on Figure 2). Such low temperatures could directly injure seedlings (Levitt 1980), as could the higher solar irradiation in March and April. Intense sunlight at subfreezing soil temperatures has been reported to cause photoinjury (DeLuccia *et al.* 1991). Presently, it is not possible to evaluate the degree to which each climatic factor contributed to the observed seedling injuries. However, minimal injury to established seedlings and to natural regeneration, as well as the effects of site preparation on overwinter injury, suggest that intense light and the direct action of low temperature are auxiliary, rather than primary causes of the injury.

Controlled experiments performed at RRRS showed that less-severe environmental conditions than those observed on forest sites caused severe desiccation injury to seedlings with frozen roots (-2°C). Injury to frozen root treated summer-planted seedlings occurred in less than a week, and in less than 3 weeks for spring-planted seedlings (Figure 4a). This was accompanied by corresponding changes in leaf water content (Figure 4b). These data support the notion that climatic conditions recorded on forest sites in early spring can be very damaging to planted seedlings. A significant seedlot effect on foliar injury, water content, and relative water content was also detected. Interestingly, the apparent superiority of spring-planted seedlings in resisting desiccation injury under controlled conditions did not translate into less injury on forest sites. Surprisingly, cuticular conductance of leaves in spring-planted seedlings was significantly greater than in summer-planted seedlings. This indicates greater water loss through leaf surfaces in the spring-planted seedlings than in summer-planted seedlings. The result contradicts those shown in Figures 4a and 4b, but it could be explained by the greater stem volume of the spring-planted seedlings, which are usually larger, creating storage from which water could be withdrawn to drying leaves. It is also possible that the stomata of summer-planted seedlings could be poorly controlled, and, in the light, these seedlings could lose water through the stomata rather than through the cuticle.

2.3 Extent of Injury and Dependence on Silvicultural Factors

2.3.1 Extent of the injury problem

Injuries to foliage and stem were visually estimated as percentages of total foliage and stem of each individual seedling. These data were turned into class-type, categorical data to describe seedling condition on two experimental sites for each of the first 3 years of investigation (planting time and seedlots are pooled), as shown in Table 1.

Although mortality was low, injury was massive after the 1991—1992 and 1992—1993 winters. It was not the spring-frost type that kills swelling buds and extending shoots. The damage varied from partially dead foliage and stem to seedling death, but most often it appeared as severe shoot dieback, leaving just a little green tissue near the ground. In 1993—1994 and 1994—1995 abundant and long-lasting snow cover prevented much of the overwinter injury.

After the disastrous 1992—1993 winter, the Fort **St.** John Forest District contracted out a survey of its spruce plantations that had been established in 1992. The survey focused on mortality rather than on injury. Apart from a few cases of obvious moisture excess, the injury was assumed to be winter-related. The surveyed sites were all spring planted. It should be noted that while the contracted survey data may represent trends, data were neither collected nor analyzed in a statistically legitimate manner.

2.3.2 Site size

The contractor-surveyed sites were arbitrarily divided into large (> 10 ha) and small (< 10 ha) sites, without considering other factors. Large sites had an average 19% mortality and 46% uninjured seedlings, while small sites had an average 15% mortality and 49% uninjured seedlings. Thus, site-size category, as separated by the criteria, did not appear to have much effect on mortality and injury, at least not within the size categories defined.

2.3.3 Site preparation

Average mortality on sites planted without site preparation was 24%, while it was 12% on plowed sites, and only 6% on mounds. About 66% of seedlings on mounds were uninjured, while plowed sites had 38% uninjured seedlings. However, the worst level of mortality (72%) occurred on a large (about 120 ha) plowed site.

Monitoring of some operationally planted sites indicated only slightly lower injury and mortality for seedlings planted on plowed than on raw-planted soil.

2.3.4 Age of planting stock

One-year-old (1+0) planting stock had an average mortality of 16%, somewhat less than the 2+0 stock (21%). The worst recorded mortality involved 2+0 stock (72%). The best plantation (percentage of seedlings with little or no injury) in 1+0 stock had 98% uninjured seedlings — in 2+0 it was 87%.

2.3.5 Exposure of seedlings to environmental variables

The potential dependence of injury on factors that promote or limit the exposure of seedlings to sun and wind (such as the depth and longevity of snow cover) were considered. Snow protects seedlings directly from low air temperatures and exposure to the sunlight that could deharden them, It also influences freezing and thawing of the soil (Spittlehouse and Stathers 1990). The presence of overstory, as well as its type and density, directly affects snow retention and ground freezing (Odin 1992), and may provide sheltering to young seedlings. In 1993, some of the sites in the Fort St. John Forest District that had been summer fill-planted in 1992 were surveyed. Little injury was observed under canopies, even though neighbouring spring-planted clearcuts often had substantial damage. The fill-planted sites had many older saplings and shrubs sheltering the planted seedlings that probably retained snow better than did the open clearcuts. In the fall of 1992, 200 seedlings were sampled on a plowed site near Stewart Lake (Dawson Creek Forest District) for winter injury assessment the following spring. Most of these 2+0 summer-planted seedlings were planted on the top of the berm, but many were also found at the bottom of the trench. Seedling position was individually recorded during the assessment. Both high- and low-planted seedlings suffered overwinter injury, but the low-planted seedlings generally had less injury, and no injury classified as severe was observed. This supports the hypothesis that exposure to environmental factors or lack of sheltering of seedlings increases the chance of overwinter injury. Therefore, taller seedlings may be more susceptible to overwinter injury than shorter ones.

2.3.6 Effects of planting time and seedling characteristics on overwinter injury

The most valuable data for analyses of effects of planting time and seedling characteristics on overwinter injury were obtained in the winter of 1992—1993. This was because of the great number of injuries observed and the large sample size. The data were collected from two unsheltered research sites located 40 km apart in the Dawson Creek Forest District. Seedlings from three local seedlots were spring planted in May 1992, and seedlings from the same seedlots were summer planted in August 1992. A total of 990 seedlings were planted on each site (165 per seedlot/planting time combination) on scarified microsites, in a completely randomized design.

Only 11 seedlings had died by the end of the first post-planting season: 10 of these were summer-planted seedlings, apparently affected by post-planting drought. An assessment performed in the late spring of 1993 showed 57 dead seedlings across both sites, of which 45 were summer planted. While this immediate mortality represented only about 3% of all planted seedlings, almost all surviving seedlings were damaged, many very severely. Average foliar and stem injury per planting timeheedlot (both sites pooled) are shown in Figures 5a and 5b, respectively.

Analysis of variance (ANOVA) showed no significant effect of planting time on foliar and stem injury, but detected a significant effect of seedlot and seedlot*planting time interaction. While choosing planting stock, it was not possible to match all container sizes exactly, so the detected seedlot effect may actually conceal a container-size (or stock-size) effect. Generally, the smaller PSB 313B stock suffered less foliar and stem damage than the larger PSB 415B seedlings, regardless of planting time (Figures 5a and 5b).

The effect of seedling size on overwinter injury was analyzed separately by analysis of covariance. The analysis showed that seedling height was significantly and positively related to foliar and stem injury. Each millimeter increase in seedling height was shown to increase foliar injury by 0.2%. This is very significant, since a height difference of 10 cm before winter could result in 20% more injury. Seedling diameter was also significantly, but inversely, related to overwinter injury. However, an increase in ground-level stem diameter of 1 mm would account for only 2% decrease in foliar injury.

It was speculated that more-vigorous, faster-growing seedlings could have less time in the fall to become frost hardy, and thus be more predisposed to overwinter injury. This possibility was tested in the analysis of covariance using height and diameter increments in the first growing season. The analysis showed that both height and diameter increment were significantly and linearly related to the injury. However, since this effect was not consistent from site to site, its biological significance may have been statistically overestimated.

2.4 The Effect of Overwinter Injury on Seedling Growth and Health Condition in the Post-injury Growing Season

Overwinter injury often caused shoot dieback. Many seedlings were shorter at the end of the 1993 growing season than at the end of the previous growing season (Table 2). This negative annual "height increment" affected spring-planted seedlings more than summer-planted seedlings. This could be partially explained by a greater absolute loss of biomass in much taller spring-planted seedlings than in the summer-planted seedlings. However, spring-planted seedlings also grew less in diameter during the post-injury growing season than did the summer-planted seedlings (Table 2). The detrimental effect of injury on seedling growth is well visualized when comparing the 1992 ground-level stem diameter increment with that of the 1993 growing season. Spring-planted seedlings grew, on average, 1.3 mm of stem diameter in 1992 (both sites and all seedlots pooled). In 1993, they grew less than half a millimeter (0.48 mm). Summer-planted seedlings, on average, increased their stem diameter by about 0.9 mm during the 1993 season. Since spring-planted seedlings were substantially thicker than summer-planted seedlings at the end of the 1992 growing season, their relative stem-diameter growth increment was even poorer compared to the summer-planted seedlings. These observations suggest that overwinter injury significantly affects growth rates, at least during the next growing season, particularly the growth rates of spring-planted seedlings.

In addition to measurements and injury assessments, the health condition of seedlings was categorized. In the spring and fall of 1993, seedling health was scored according to the percentage of foliar and stem injury (spring assessment), and to seedling appearance and its perceived prospect of survival (fall assessment). In the spring, seedlings with less than 35% injury were classified as "good", those with 3640% injury as "medium", and those with more than 60% injury as "poor". This was done separately for foliar and stem injury. In the fall, seedlings were considered "good" if they were green, grew during the past season, and were likely to survive; as "medium" if they were chlorotic, grew only somewhat, and their survival was uncertain; and as "poor" if they had little or no growth, few surviving branches andlor severe discoloration, and little chance of survival. Sixty-two seedlings that died by the end of the 1993 growing season had been bulked into the "poor" category". Sixty of these were considered "poor" in the spring. At the end of the 1993 growing season, the "good" category was reduced to half of its spring-time size. Most seedlings were in the "medium" category, and there were about as many "poor" seedlings as in the spring (Table 3). This means that the spring-time classification into the "good" category was too optimistic. The prognosis for most seedlings (76% were in "medium" and "poor" categories) assessed at the end of the post-injury growing season was unpromising.

The health condition data were analyzed with the repeated measures categorical mode procedure of **SAS.**[1] The analysis showed that there was a significant change in the distribution of seedlings into condition categories over the 1993 growing season. Numerous significant interactions indicated that there was no single factor determining change in seedling condition. However, the significant effect of planting time on condition change that was detected is critically important. Generally, summer-planted seedlings did much better in the categorical analysis than the spring-planted seedlings, which is consistent with greater growth increments of the summer-planted seedlings in the post-injury growing season. It is not known whether this better growth will continue in the future.

2.5 The Relevance of Root Placement in the Soil to Overwinter Injury

There was no destructive sampling from research sites in 1993. In 1994, seedlings that had been planted in 1993 on a site adjacent to one of the research sites (Stewart Lake, Dawson Creek Forest District) used in the 1992—1993 season were excavated to evaluate root egress. Ten standard styroblock PSB 313B were excavated from 140-1 average volume mounds, and another 10 from the adjacent flat ground (raw-planted seedlings). The same number of chemically root-pruned PCT 313B seedlings per site preparation treatment were excavated, as well as five mechanically root-pruned (box-pruned, Finnish Vapo Oy system) seedlings from mounds, and five from flat ground. The box-pruned seedlings had well developed root systems with abundant shallow and deeper roots (Figure 6a). Regardless of whether they had been excavated from mounds or from flat ground, in the PSB seedlings, and in many PCT seedlings, most of the roots grown after planting originated in the lower third of the nursery plug (Figure 6b). This indicated that the effectiveness of chemical root pruning was poor. These observations are consistent with sporadic excavations of PSB seedlings made in other years on other sites, and with observations of root growth in the root-growth capacity tests that are made every year on planting stock used in all experiments.

Soil temperature data (Figures 3a—3c) indicated that water absorption by roots from below a 5-cm depth was unlikely during spring months, since the soil and roots were frozen at these depths. The bottom third of a 313-type of styroblock container would be located more than 8 cm below soil surface. Thus, most new roots grown during the first post-planting season would be below that depth. It is possible that the reduced risk of injury to established seedlings is due to the initiation and growth of adventitious roots near the soil surface. Soil temperature above a 2-cm depth fluctuates above and below zero between day and night during spring months (Figure 7). This could make water uptake from that depth possible for seedlings with many roots in this soil region. The box-pruned seedlings had such root

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[1] SAS Institute Inc., Carry, N.C.

systems (Figure 6a). However, a long-lasting snow pack and a mild spring after the winter of 1993–1994 did not permit a comparison between overwinter injury in box-pruned and styroblock-grown seedlings, since there was no significant injury to any stock type that year.

The potential advantage of shallow root systems in reducing the susceptibility of seedlings to overwinter injury, assuming that such injury results from desiccation, is further supported by observations of the rooting habits of naturally regenerated seedlings. These produce shallow roots at the mineral/organic soil interphase (Figure S), and suffer very little overwinter injury compared to other seedlings planted on the same site (Figure 9). Generally, deploying planting stock capable of initiating roots along the whole length of the nursery plug not only offers potential reduction of freeze-desiccation injury, but should also improve overall seedling performance. Low soil temperature is a major impairment to root growth in boreal forest soils. Encouraging root egress near the soil surface, where diurnal temperature fluctuation is great, should improve seedling growth performance (Sutton, 1991).

The capacity of young seedlings to uptake very cold water was tested by immersing root systems of seedlings planted into PVC tubes into a controlled temperature bath, and subjecting these seedlings to soil and root freeze-thaw cycles lasting several days. Leaf samples were taken every 2 days to determine their water content. As shown in Figure 10, seedling foliage was desiccating rapidly when roots were frozen, but the leaves promptly regained pre-stress water content when the soillroot temperature was brought up just above freezing. This shows that seedlings were capable of rapid water uptake, in spite of the increased viscosity of water at low temperatures (Fitter and Hay 1987).

3 RECOMMENDATIONS

Based on results of the studies performed, the following measures are strongly recommended as both practical and feasible to implement:

1. Choice of planting stock

a) Short, thick, and sturdy planting stock is recommended for planting in areas of low snow cover and fine-textured, slow-thawing soils.

b) Tall, large, planting stock with deep nursery plugs is to be particularly avoided. Shoot die-back and slowed growth following injury (to which such stock is prone) eliminate the size advantage and make the losses more costly.

c) Use planting stock capable of initiating roots along the whole length of the nursery plug, especially in its uppermost portion.

2. Root pruning

a) Chemical root pruning of spruce seedlings should be specifically adjusted for this species to improve its effectiveness if the use of chemically pruned seedlings is to be promoted.

b) New stock types, especially those used successfully elsewhere in the world, should be evaluated for planting in British Columbia boreal forests.

3. Spring or summer planting

a) Whenever and wherever feasible, summer planting, as recommended by Revel *et al.* (1990), should be used rather than spring planting.

b) Summer drought is sometimes a problem delimiting the safe summer-planting window.

Short-plug seedlings may be particularly prone to post-planting drought in summer. Sound judgment must be used about when to terminate planting.

4. Sheltering of planted seedlings

a) Planting seedlings on the northern sides of stumps and terrain features that protect the southern sides of seedlings is recommended.

b) Planting spruce under canopies, where feasible, would probably lower the risk of seedling injury.

c) Snow fencing is an expensive but effective method of retaining snow. It may be the best solution for protecting valuable plantations, such as research trials.

5. Site preparation

a) Plowing and mounding, where appropriate, can be expected to lower the incidence of overwinter injury, compared to raw planting. Herring and Letchford (1987) also observed the beneficial effects of plowing, as did L. Bedford (B.C. Min. For., Silviculture Branch pers. comm., 1992) in his trials near Inga Lake.

b) Bedford also observed an increase in spring-frost damage to expanding buds and young shoots in spruce seedlings growing on mulched sites. Thus, mulching is not recommended.

6. Genetic selection programs

a) Significant seedlot effect on overwinter injury indicates a potential for genetic selection of families and clones resistant to this type of injury.

b) The increased susceptibility of more-vigorous trees to overwinter injury suggests that caution in the development and deployment of fast-growing spruce seedlings in the southern boreal forest is needed.

7. Further research

Important areas for future research should include the following:

a) studies specifically designed to test the relationship between overwinter injury and the rooting habits of planted seedlings; and

b) identification of white spruce families and clones that are less prone to overwinter injury and freeze-desiccation for genetic selection and for producing injury-resistant planting stock.

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TABLE 1. Summary of post-winter seedling condition assessments for two research sites, made on seedlings planted in 1990, 1991, and 1992. Data are pooled across planting times on each site. SLK = Stewart Lake site; BM = Bear Mountain site. Originally published as Table 1 in Krasowski *et al.* (1995). WASP **82**, p. 136; reprinted with kind permission from Kluwer Academic Publishers.

Planting/ assessment year	Site	Number of seedlings assessed	Seedling condition[a] (% of seedlings assessed)			
			Good	Moderate	Poor	Dead
90/91	SLK	265	76	13	8	3
90/91	BM	295	68	16	8	8
91/92	SLK	454	36	28	27	9
91/92	BM	347	25	38	25	12
92/93	SLK	949	24	46	26	4
92/93	BM	954	21	49	28	2

[a] Condition codes relate to % foliage damage, as follows: Good:≤ 30%; Moderate: >30% to <60%; Poor:≤60% to <100%; and Dead: 100%.

TABLE 2. Mean changes in seedling height (Htdif) and ground-level diameter (Diadif) (± standard errors) from fall 1992 to fall 1993. Originally published as Table 5 in Krasowski *et al.* [1996]. New Forests **30**, p. 12; reprinted with kind permission from New Forests.

Planting time	Seedlot	BM site		ST site	
		Htdif (mm)	Diadif (mm)	Htdif (mm)	Diadif (mm)
Spring	4140	-134±9.5	0.4±0.76	-179±10.1	0.4±0.07
	8779	-46±4.5	0.7±0.07	-39± 5.0	0.7±0.06
	8782	-156±9.3	0.3±0.06	-151± 9.4	0.4±0.07
Summer	4140	29±4.4	1.0±0.06	26± 5.3	1.0±0.06
	8779	9±5.3	0.9±0.05	20± 5.4	1.0±0.06
	8782	-32±7.7	0.9±0.07	-44± 6.9	0.8±0.08

TABLE 3. Frequencies of seedlings, per condition class, in the spring 1993, based on the percentage of foliar and stem injury, and in the fall 1993, based on seedling appearance and estimated chance of survival (see the text for class description). Modified from the original Table 6 published in Krasowski *et al.* [1996]. New Forests **30**, p. 13; reprinted with kind permission from New Forests.

Condition class	Spring 1993		Fall 1993
	Condition by foliar injury	Condition by stem injury	
Good	849	853	432
Medium	235	497	908
Poor	761	495	505
Total			1845

Note: Poor condition category in the fall 1993 contains seedlings that died during the 1993 growing season.

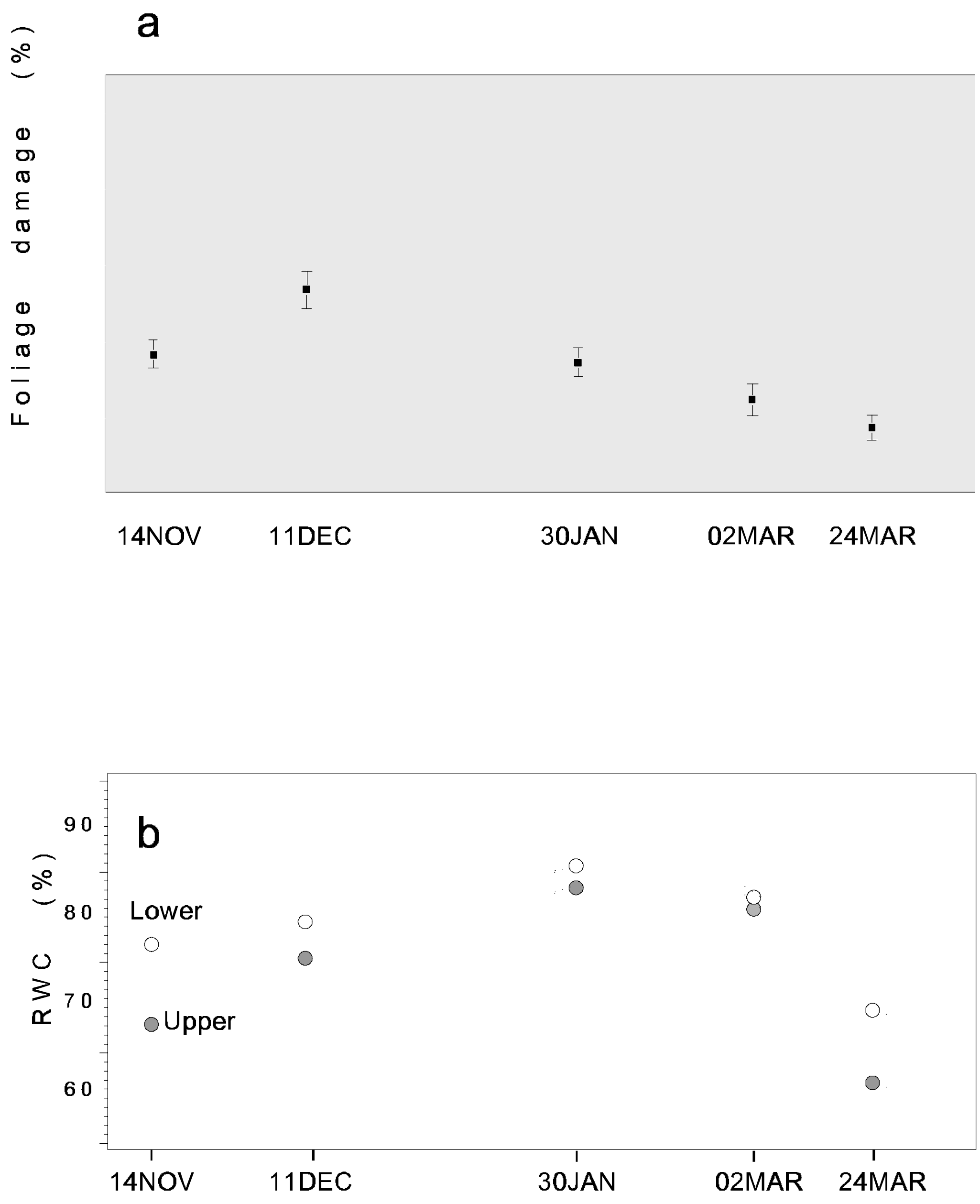

FIGURE 1. (a) Mean foliage injury ± standard errors and (b) relative water content, standard errors negligible (100% x {fresh weight - dry weight}/saturated weight - dry weight), of upper and lower half of seedlings collected from two research sites during the 1991–1992 winter. Shaded area under the dashed line in Figure 1a indicates the average foliage injury across these sites, calculated from seedling assessment made in June 1992. Figure 1a originally published as Figure 1 in Krasowski *et al.* (1995). WASP **82**, p. 137; reprinted with kind permission from Kluwer Academic Publishers.

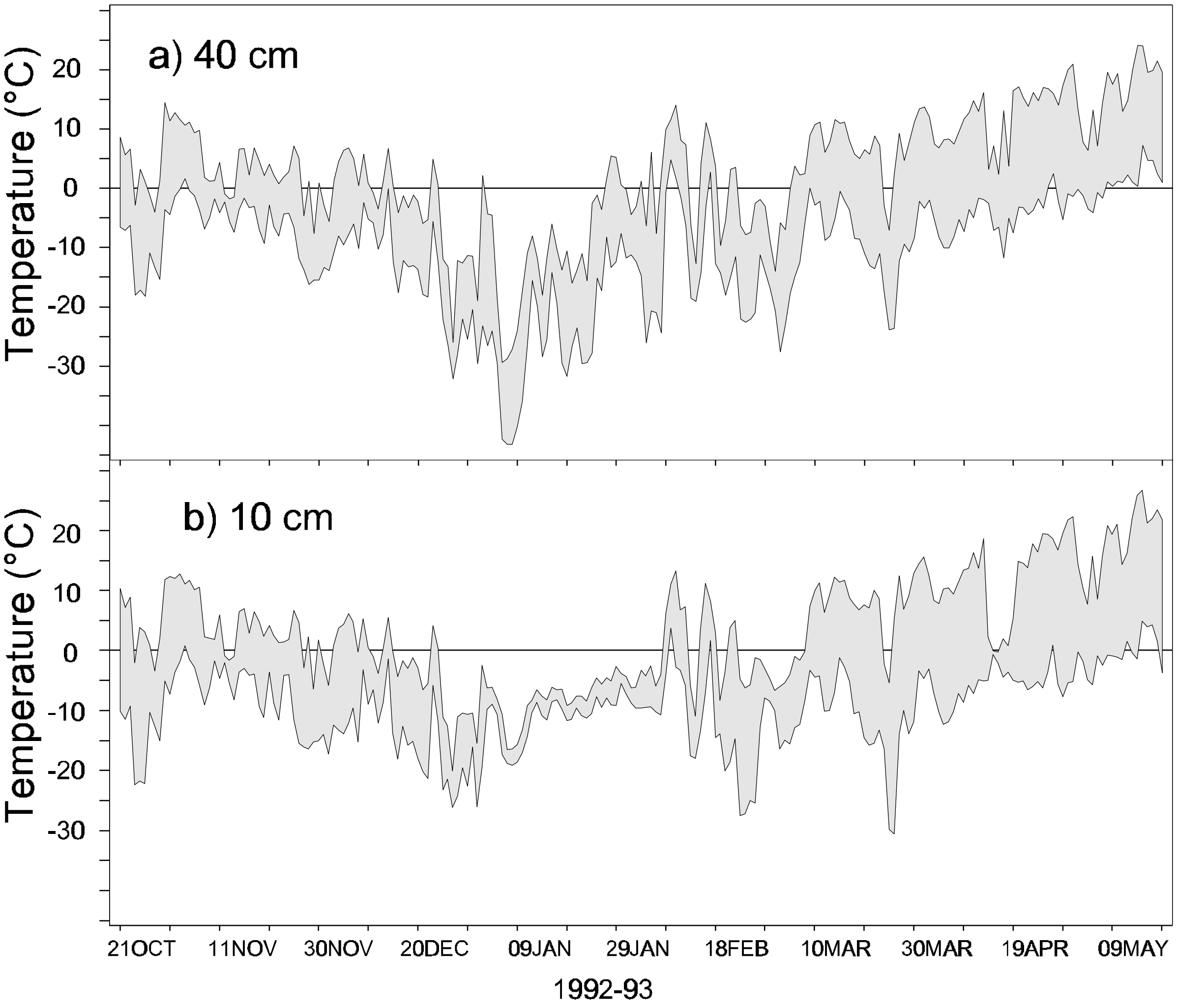

FIGURE 2. Daily maximum and minimum air temperature at (a) 40 cm and (b) 10 cm above the ground. Daily values were averaged from three microsites at Bear Mountain. A part of Figure 3, originally published in Krasowski *et al.* (1995). WASP **82**, p. 139; reprinted with kind permission from Kluwer Academic Publishers.

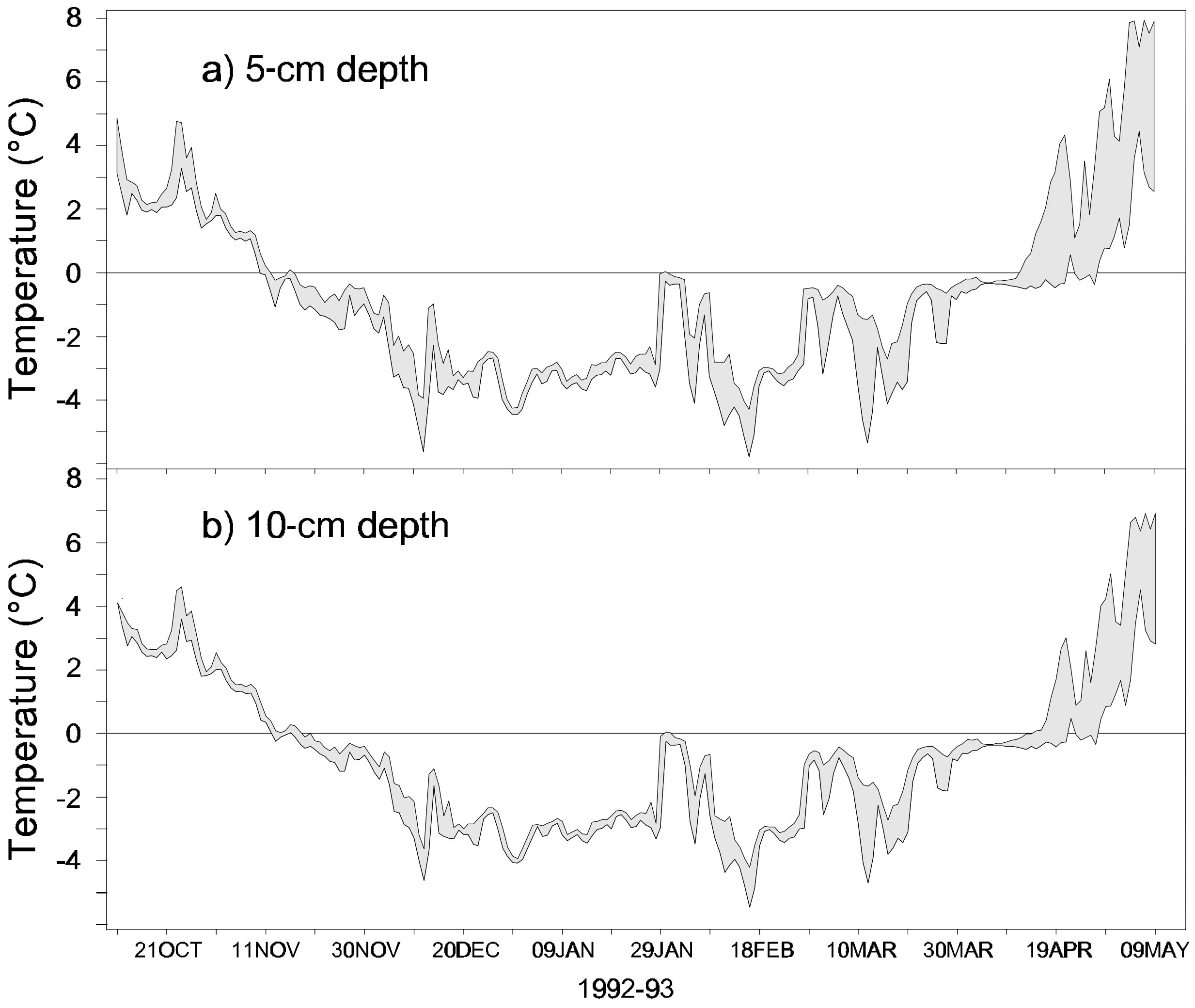

FIGURE 3. Daily maximum and minimum microsite soil temperature at (a) 5-cm and (b) 10-cm depths. Daily values were averaged from three microsites. A part of Figure 5, originally published in Krasowski *et al*. (1995). WASP **82**, p. 141; reprinted with kind permission from Kluwer Academic Publishers.

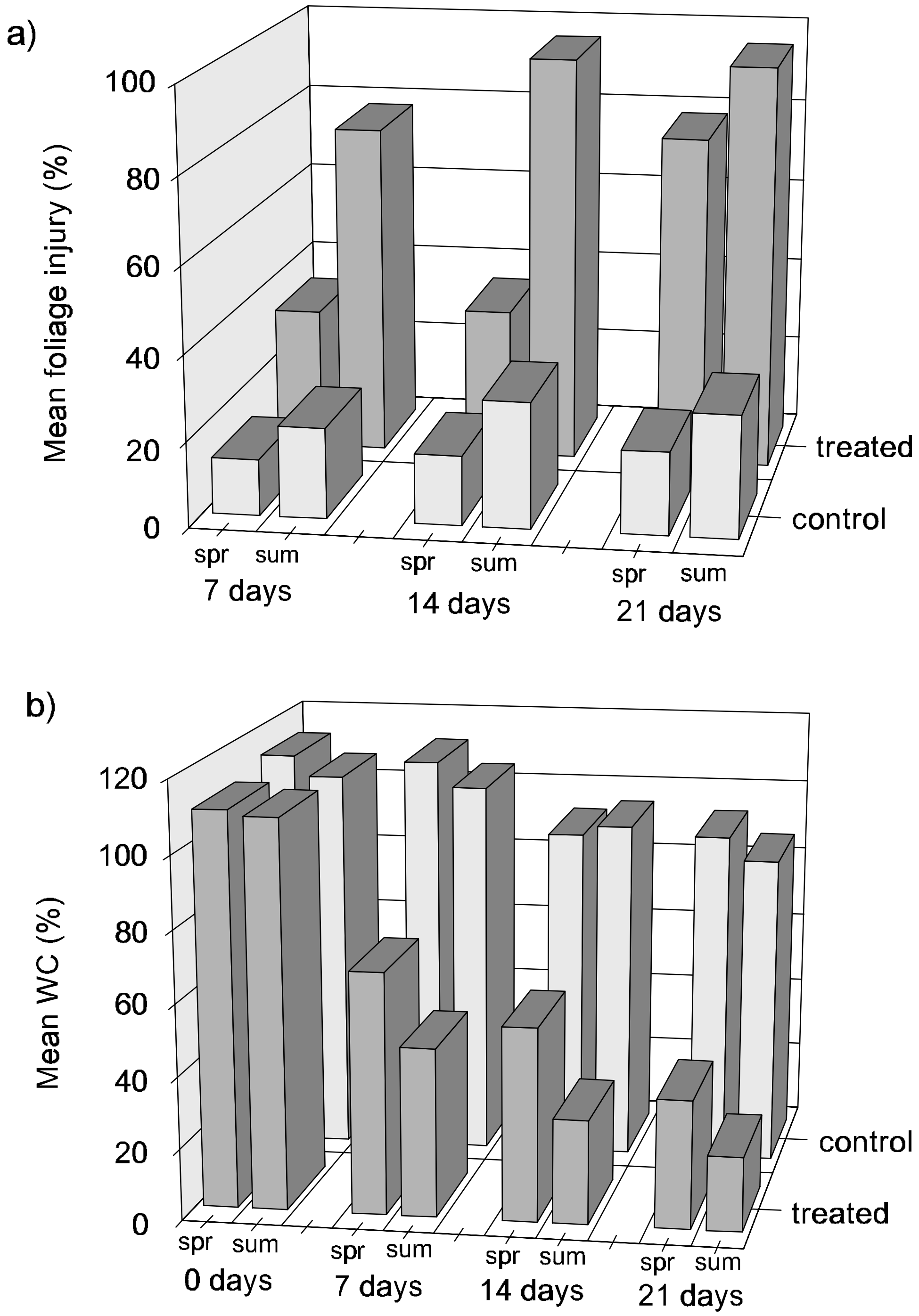

FIGURE 4. (a) Mean foliage injury (a) and water content (100% x {fresh weight - dry weight}/dry weight) of root freezing (-2°C) treated and control (roots not frozen) seedlings after 7, 14, and 21 days in a growth chamber. Air temperature was +10/+4°C, vapour pressure deficit of 0.55/0.20 kPa (day/night), lights (400μmol m^{-2}s^{-1}) on for 10 hr. Seedlots are pooled by treatment∗planting time. Originally published as Figure 6 in Krasowski *et al.* (1995). WASP **82**, p. 137; reprinted with kind permission from Kluwer Academic Publishers.

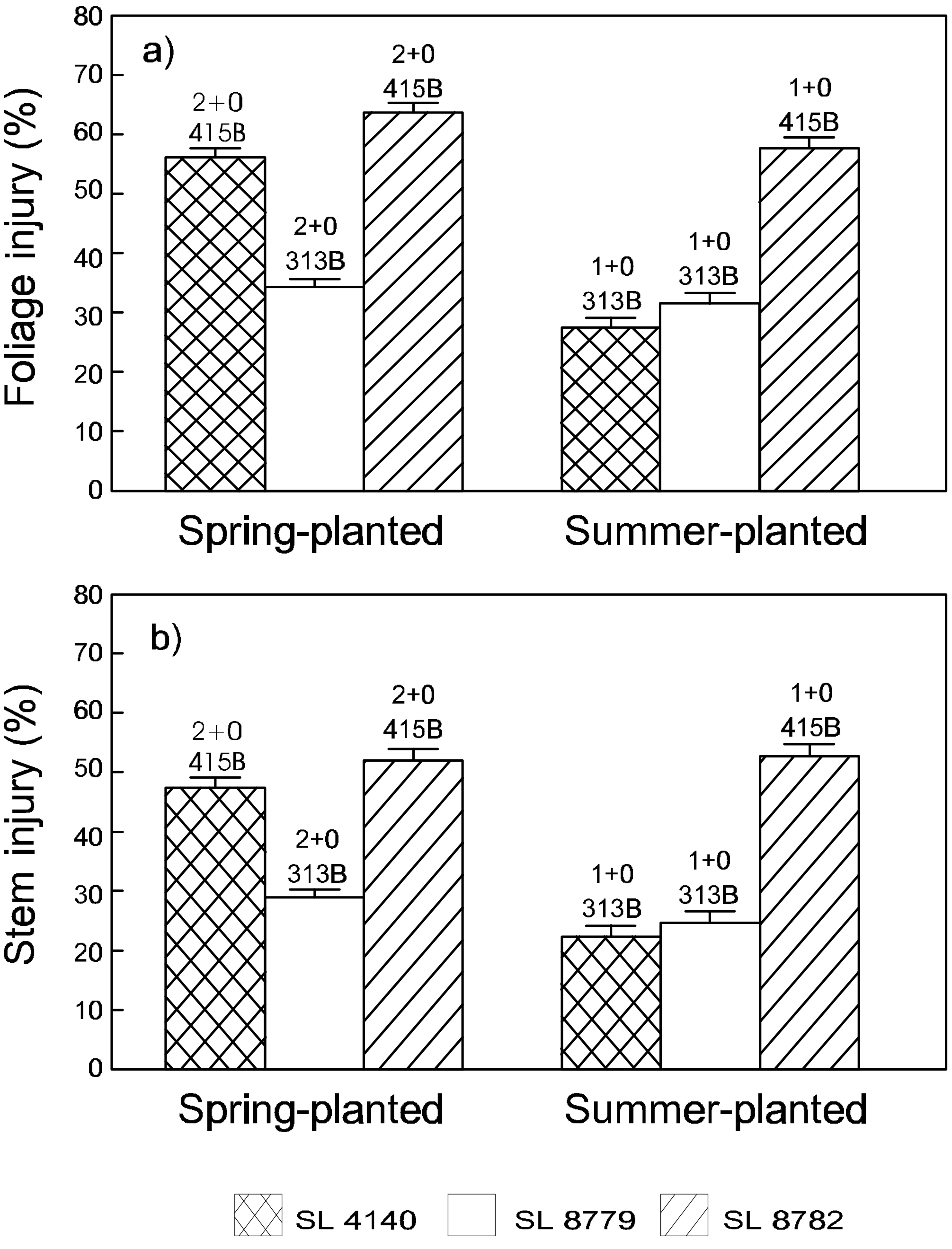

FIGURE 5. (a) Mean foliage and (b) stem injury following the 1992–1993 winter in seedlings planted on two research sites. Data pooled across both sites are shown by seedlot and planting time. Stock type and nursery container size are shown above the standard error bars. Originally published as Figure 1 in Krasowski *et al.* [1996] New Forests **30,** p. 7; reprinted with kind permission from Kluwer Academic Publishers.

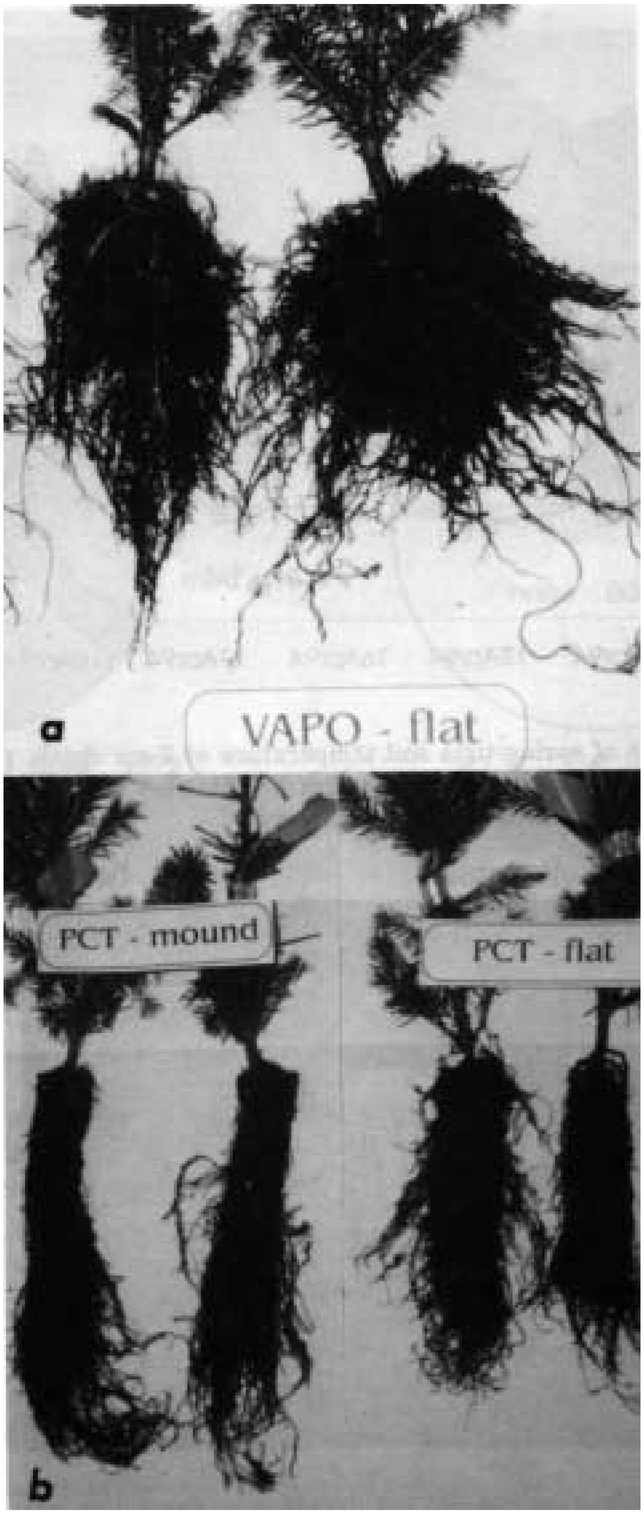

FIGURE 6. Excavated root systems of (a) mechanically (box) pruned Vapo Oy seedlings, (b) chemically pruned (PCT) seedlings from mounds, and from flat ground, 1 year after planting at km 2.5, Stewart Lake Forest Rd. Figure 6b contains a portion of Figure 3 in Krasowski *et al.* [1996] New Forests **30**, p. 11; reprinted with kind permission from Kluwer Academic Publishers.

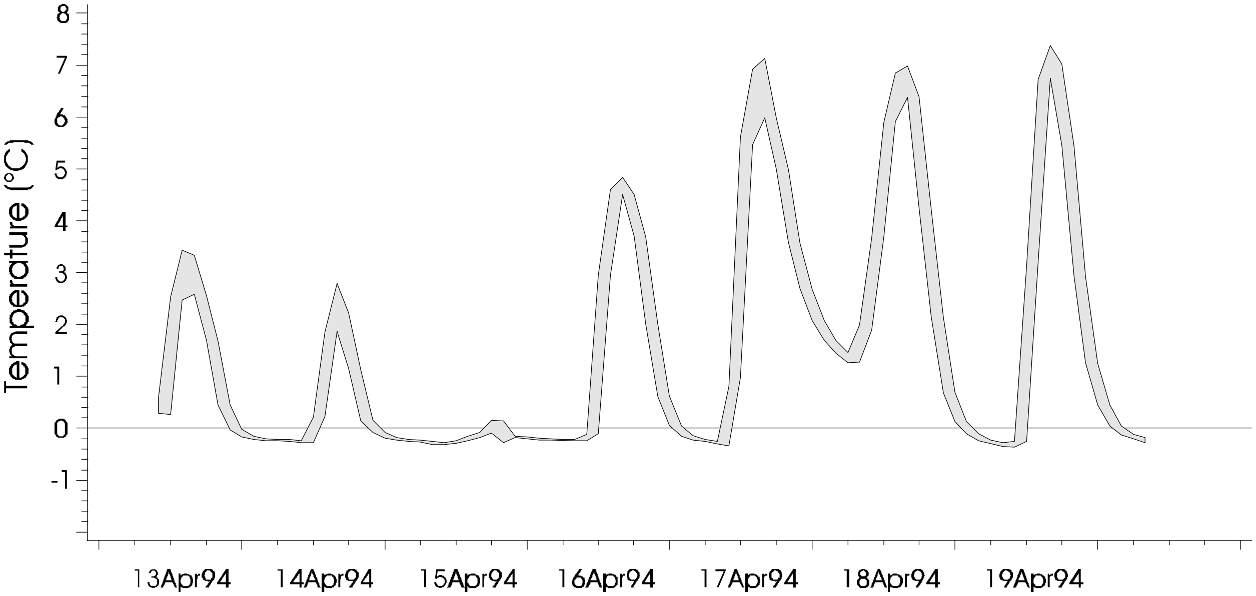

FIGURE 7. An example of spring-time soil temperature at 2-cm depth, recorded in April 1994 at one of six monitored microsites at km 2.5, Stewart Lake Rd. Maximum and minimum temperatures are shown in 2-hour intervals.

FIGURE 8. Naturally regenerated seedling similar in size to a seedling grown in a nursery for planting on forest sites. Note that the majority of seminal and adventitious roots are located near the root collar, forming a shallow, flat root system that is typical for spruce.

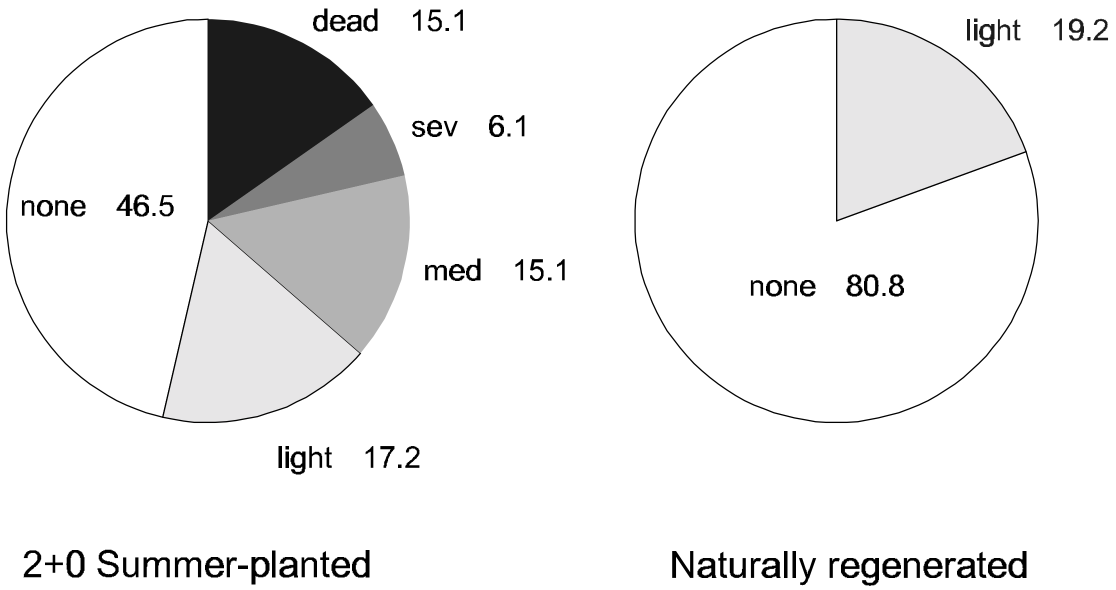

FIGURE 9. Percentage of summer planted (2+0) and current-year naturally regenerated seedlings per foliar injury class on the same disk-trenched site at Lone Prairie, near Chetwynd: none(0–5%), light (6–30%), medium (31–65%), severe (65<100%), and dead.

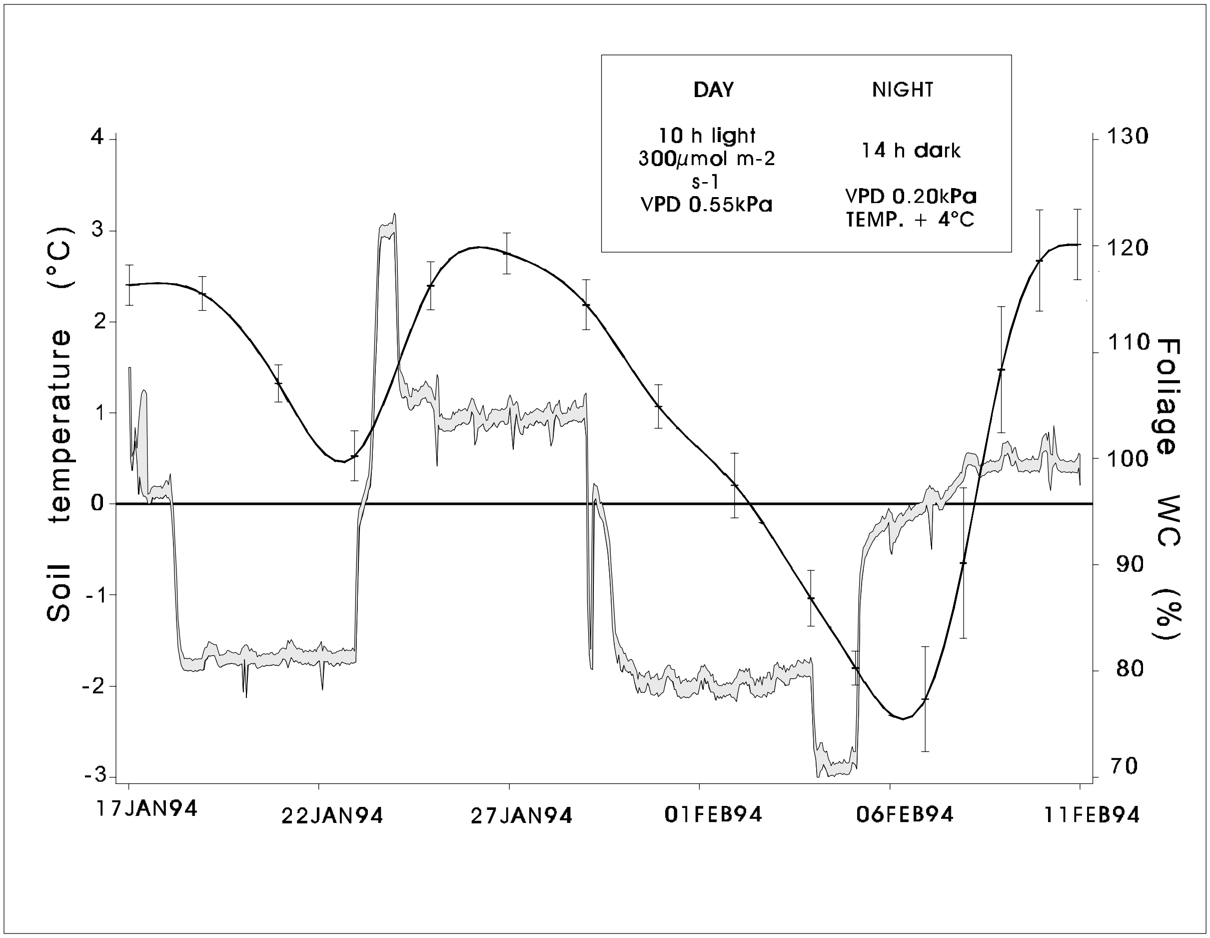

FIGURE 10. Seedling foliage water content (solid black line with standard error bars) during the controlled soil freeze-thaw cycling experiment. Soil temperature (hourly maxima and minima) is graphed as a gray line. Growth chamber conditions other than soil temperature and 300µmol $m^{-2}s^{-1}$ light intensity (shown) are as described in Figure 4. Originally published as Figure 6 in Krasowski *et al.* [1996] New Forests **30**, p. 10; reprinted with kind permission from Kluwer Academic Publishers.