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Growth and cold hardiness of container-grown Douglas-fir, noble fir, and Sitka spruce seedlings in simulated greenhouse regimes[1,2]

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Seedlings of *Pseudotsuga menziesii* (Mirb.) Franco, *Abies procera* Rehd., and *Picea sitchensis* (Bong.) Carr. were grown for 5 months in growth rooms which simulated hot, warm, or cool growing regimes in greenhouses in western Oregon. Temperature, humidity, light intensity, and photoperiod were changed diurnally and seasonally. In all three species, maximum heights of seedlings were attained in the hot regime, whereas stem diameters were similar under the hot and warm regimes. Dry weight increment was greatest in the warm regime. The cool regime was suboptimal for all aspects of growth. Seedlings grown in the hot regime were least resistant to cold in early fall. Differences in resistance to cold of seedlings grown in the warm and cool regimes varied by species and type of damage.

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Des plantules du *Pseudotsuga menziesii* (Mirb.) Franco, de l'*Abies procera* Rehd., et du *Picea sitchensis* (Bong.) Carr. ont été cultivées durant 5 mois dans des chambres de croissance en simulant des régimes de températures élevée, moyenne ou froide, rencontrées lors de culture en serre dans l'ouest de l'Oregon. La température, l'humidité. l'intensité lumineuse et la photopériode ont été changées quotidiennement et saisonnièrement. Chez les trois espèces, la hauteur maximale des plantules a été atteinte sous un régime à température élevée, alors que le diamètre de la tige était semblable sous un régime à température élevée ou moyenne. L'augmentation de la masse de matière sèche a été plus forte sous un régime à température moyenne. Le régime à température froide s'est révélé suboptimal pour tous les aspects de la croissance. Les plantules cultivées sous un régime à température élevée étaient moins résistance au froid au début de l'automne. Les différences de résistance au froid des plantules cultivées sous des régimes à températures moyenne et froide variaient selon l'espèce et la nature du dommage.

[Traduit par le journal]

Introduction

Production of forest planting stock in greenhouses provides more opportunities to manipulate seedling environment than is possible in conventional outdoor nurseries. Additional information about effects of greenhouse environments on growth and conditioning of seedlings is needed, however. This paper reports on season-long development of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), noble fir (*Abies procera* Rehd.), and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) seedlings under three temperature regimes in the University of Wisconsin Biotron. The objective was to obtain information that would help in developing information such as types of facilities, sowing schedules, and temperature targets for greenhouse nurseries in the Pacific Northwest of the United States. Use of this type of phytotron facility permits study of critical growth and conditioning factors without the confounding problems associated with less controlled conditions in greenhouses or the more limited environments of standard growth chambers. Results for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) were reported earlier (Owston and Kozlowski 1976).

The treatments simulated hot, warm, and cool regimes that could be attained in production-size greenhouses in western Oregon. The hot regime simulated season-long conditions in greenhouses that are cooled

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[3]Revised manuscript received January 21, 1981.

only by ventilation. The warm regime was similar to what would be expected either in well-controlled greenhouses that can maintain ambient temperatures or in outdoor conditions under light shade. The cool regime was one that would require cooling. Temperature, light intensity, photoperiod, and humidity were changed diurnally and seasonally. The study also examined effects of the simulated greenhouse regimes combined with short days on induction of bud set and early season cold hardiness of the three species.

As reviewed by Hellmers (1962) and Spurr and Barnes (1973), other studies of temperature effects on seedling growth have generally used combinations of constant day – constant night temperatures not attainable in large greenhouses. Temperature studies specific to Douglas-fir have been reported by Hellmers and Sundahl (1959), Brix (1967 and 1971), and Lavender and Overton (1972). Brix (1972) and Mergen *et al.* (1974) studied temperature in relation to growth of Sitka spruce. Studies of dormancy induction and (or) cold hardiness development have been reported by van den Driessche (1969), Lavender and Overton (1972), and Timmis and Worrall (1975) for Douglas-fir and by Malcolm and Pymar (1975) for Sitka spruce.

Methods

Seeds collected from different parts of the Pacific Northwest were used; Douglas-fir from coastal Oregon (600-m elevation) and the Cascade Range in southern Oregon (1000-m elevation), noble fir from the Cascade Range in northern Washington (1500 m elevation) and southern Washington (900-m elevation), and Sitka spruce from coastal Washington (300-m elevation) and coastal Oregon (150-m elevation). Noble fir seeds were stratified for 6 weeks prior to sowing; those of the other species, for 4 weeks.

Three or four seeds of each source of each species were sown in individual cavities of styroblock-4 containers, one of the common type of seedling containers in widespread use. They are rectangular blocks of polystyrene, each containing 160 round, tapered cavities 3 cm in top diameter and 13 cm deep. Each cavity has a drainage hole in the bottom. The cavities had been filled with a commercial 1:1 (v/v) mixture of peat moss and vermiculite that contained sufficient balanced N, P, K fertilizer to sustain good growth for several weeks. A thin layer of silica grit was placed over the seeds to hold them in place and reduce growth of moss and algae.

Seeds in the containers were germinated in growth chambers at 25°C for a 15-h day and 16°C night for Douglas-fir and noble fir seeds and at 20°C during the day and 16°C at night for Sitka spruce seed. After 3 weeks, temperatures in both chambers were lowered to 20°C during the day and 12°C at night for 3 days prior to moving the seedlings to the Biotron to help acclimate those destined for the cool regime. The styroblocks were transferred to Biotron growth rooms and adjusted to one seedling per cavity by thinning of the smallest seedling(s) or by transplanting.

Ninety-six seedlings of each seed source of each species were placed in each of three Biotron rooms. These seedlings were further divided into 6 groups of 16 individuals each, and seed sources were randomized within species. The species were separated to avoid possible shading effects caused by inherent differences in growth rates. Any edge effects were accounted for by the replication and randomization procedures.

Each growth room simulated a different greenhouse regime (hot, warm, or cool). Each room was 3 m^2 in size, identical in construction, and operated by the same physical plant and computer control. Variations between growth rooms, other than in the programmed temperatures, were considered so small that the data were subjected to standard analyses of variance for completely randomized designs. Orthogonal comparisons were used for analyzing differences between individual treatments (temperature regimes and seed sources within species). Differences between species were not of particular interest in this study and were not analyzed.

A simulated growing season from late April through early October was divided into the germination period (in standard growth chambers as described) and six growth periods (Fig. 1). The three temperature designations were related to climate rather than to assumed growth requirements. Maximum temperatures for the warm regime were based on average monthly maxima for Corvallis, Oregon. Maxima for the hot and cool regimes were set at 6°C–8°C higher or lower. Minimum temperatures were determined partly from the average Corvallis temperatures and partly from previous greenhouse records. Minima were also adjusted to give approximately the same day–night differential in both the hot and warm regimes. The day–night differential for the cool regime was always less than for the hot or warm regime. Dates mentioned later in the text refer to simulated dates.

Diurnal temperature changes were determined by averaging typical daily greenhouse patterns occurring on days having the particular maximum and minimum temperatures used. Thus, for example, maximum temperatures in the hot and warm regimes occurred for only 1 or 2 h, whereas maximum temperatures in the cool regime were usually maintained for 4 h. Daily degree-hours and maximum and minimum temperatures for each period and regime are shown in Table 1.

Lighting was provided by a combination of 27% incandescent light energy (474 $W \cdot m^{-2}$ at full intensity) and 73% fluorescent light energy (1270 $W \cdot m^{-2}$). Programmed light intensities were the same for each growth room and varied diurnally to simulate sunrise and sunset and seasonally to simulate change in sun angle. Maximum light intensities at tree-top level ranged from 2500 to 3000 ft-c (400–500 $\mu E \cdot m^{-2} \cdot s^{-1}$) in the spring and fall to 3500 to 4500 ft-c (600–775 $\mu E \cdot m^{-2} \cdot s^{-1}$) in summer. These maxima were maintained for about 50% of each light period. Photoperiods from the time of sowing to August 23 were set at the natural daylength at 45° N latitude for the middle of each growing period. Days were shortened to 8 h after August 23 to induce bud set. This could be done operationally by use of blackout curtains.

Relative humidities were programmed to simulate seasonal and diurnal changes occurring in the Corvallis area. These ranged from 40 to 70% during the day and 70 to 85% at night. Relative humidities, however, were reduced 10–20% during

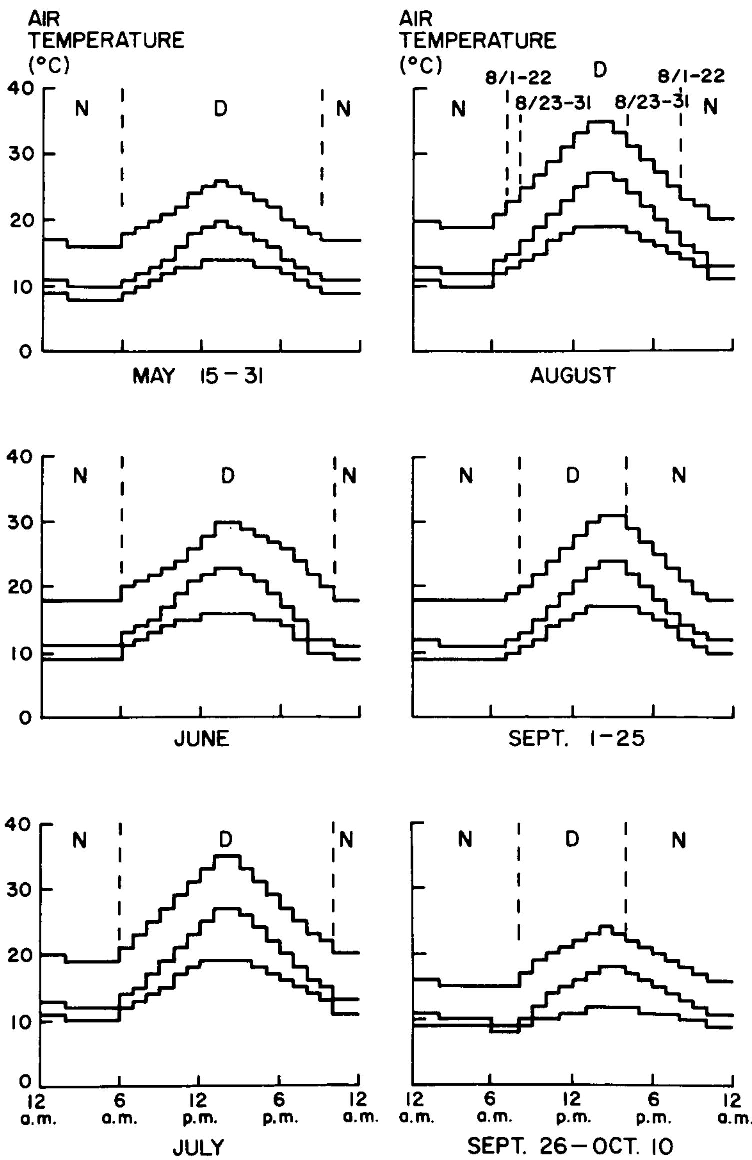

FIG. 1. Diurnal temperature and photoperiod regimes for the Biotron growth rooms. The lines on each graph represent, from top to bottom, the hot, warm, and cool regimes. Vertical dashed lines separate day (D) and night (N) periods.

the last month to lessen the chance of gray mold infection in the dense foliage.

Irrigation and fertilization were similar to operational schedules and amounts. Plants were watered with a sprinkling can two to three times each week, depending on temperatures and seedling sizes. All waterings were heavy and uniform. The tepid water was acidified to pH 5.0−5.5. Fertilizers were mixed with the water. During the most active growth period, 20−19−18 fertilizer was supplemented periodically with half-strength Hoagland solution. Nitrogen was withheld for 10 days during mid-August, and fertilizer was again added in late August: 9−45−15 fertilizer plus periodic additions of one-fourth-strength Hoagland solution.

Environmental conditions in the growth rooms varied somewhat from those planned, but they generally supported the assumption that variations between rooms were related to treatment regimes rather than to room location or functioning. Air temperatures in the Biotron rooms stayed within ± 1°C of those programmed. Light intensities at tree-top level varied more within rooms than between them. For example, in July maximum light intensities 1 ft (1 ft = 0.305 m) from the side walls of the rooms were 70−80% of those in the center, whereas light intensities in the center of the darkest room were 90% of those in the center of the brightest room. Some of the latter difference was due to differences in seedling heights between regimes. Relative humidity tended to be 10−20%

TABLE 1. Daily degree-hours and maximum and minimum temperatures for each Biotron period and regime

	Hot regime			Warm regime			Cool regime		
Period	Degree-hours	Max. temp., °C	Min. temp., °C	Degree-hours	Max. temp., °C	Min. temp., °C	Degree-hours	Max. temp., °C	Min. temp., °C
May 15–31	475	26	16	303	20	10	260	14	8
June 1–30	544	30	18	373	23	11	292	16	9
July 1–31	605	35	19	429	27	12	342	19	10
Aug. 1–31	605	35	19	429	27	12	342	19	10
Sept. 1–25	537	31	18	374	24	11	299	17	9
Sept. 26–Oct. 10	440	24	15	309	18	9	240	12	8
Average	536			370			296		

NOTE: Degree-hours were calculated by multiplying the numerical value of the temperature above 0°C times the length of time in hours that the plants were at that temperature during a 24-hour day. Daily degree-hours is the sum of degree-hours for a 24-hour day. The Biotron is a controlled-environment research facility. Dates are simulated.

higher in the hot regime than in the warm or cool regime. This difference was acceptable because hot greenhouses tend to have high humidities because of rapid transpiration and the need for frequent irrigation.

Stem elongation of five seedlings from each seed source in each growth room was measured periodically. The seedlings were chosen at random from those of average development early in the season.

At the conclusion of the growing cycle, counts were made of all surviving seedlings and of physically plantable seedlings. To qualify as plantable, a seedling had to have a root collar diameter 1.2 mm or greater, top height of at least 6 cm, a root ball that remained intact when extracted from the styroblock, and live, green needles. Height of the main stem was measured on all live seedlings. Five seedlings from each source in each of the six replications per growth room were chosen at random from the plantable seedlings. Diameters of sample seedlings were measured at the root collar, and oven-dry weights were determined separately for stems, foliage, taproots, and lateral roots.

At the end of the growing schedule a freezing test was made on sample seedlings from each regime. An experiment with randomized complete block design was conducted by combining the sources of each species. Fifteen seedlings of each species were placed in each of six blocks, randomized in one growth room, and the temperature was lowered from 10°C to −5°C at 2.5° per hour, maintained for 4 h, and then increased to 15°C at about 5° per hour. The seedlings were then placed in a warm, sunny greenhouse and kept well watered for 3 weeks. A set of unfrozen control seedlings was also placed in the greenhouse. After this 3-week period, damage to foliage, cambium, buds, and roots was assessed visually for individual seedlings. The data were subjected to analysis of variance, and orthogonal comparisons were used to test for individual treatment differences.

Results

Stem elongation

During the spring, rate of height growth for each of the species and seed sources was greatest for seedlings in the hot regime and lowest for those in the cool regime (Table 2). Differences between regimes were significant at the 1% level, and there were no regime × source interactions. In midsummer, elongation rates of seedlings in the warm regime increased substantially, whereas those in the hot regime declined slightly for Douglas-fir and increased only slightly for other species, resulting in insignificant differences between these two regimes. Height growth of seedlings in the cool regime increased, but it was significantly less than in the other two regimes at the 1% level.

During late summer, rate of stem elongation declined rapidly. The reduction was most prominant in the hot regime, and Douglas-fir and noble fir seedlings in the warm regime grew significantly (1% level) faster. Reduced elongation was least evident in the cool regime, and these seedlings grew at about the same rate as those in the warm regime.

Observations of terminal bud development of all three species were made in late summer. Buds on seedlings in the hot and warm regimes became visible sooner and appeared to grow larger than those in the cool regime.

Seedling production

Survival of seedlings in warm and cool regimes was very high for all species and seed sources and also high in the hot regime for noble fir sources; survival of Douglas-fir and Sitka spruce was lower in the hot regime (Tables 3 and 4). Almost all mortality was the result of damping-off early in the season.

The lowest percentage of plantable Douglas-fir seedlings was in the hot regime. This was due primarily to the mortality mentioned above. The cool regime had lowest percentages of planted noble fir and Sitka spruce seedlings. This reflected failure of a high proportion of the seedlings to reach plantable size. Noble fir from northern Washington produced fewer plantable seedlings in all regimes than did the southern Washington source. This resulted from greater failure of the nor-

TABLE 2. Average daily epicotyl elongation (in millimetres) by season for Douglas-fir, noble fir, and Sitka spruce seedlings grown in different Biotron regimes

		Growth regime and seed source[b]					
		Hot		Warm		Cool	
Species	Season[a]	1	2	1	2	1	2
Douglas-fir	Spring	3.0	2.7	1.2	1.1	0.1	0.3
	Midsummer	2.7	2.6	2.5	2.6	1.8	1.9
	Late summer	0.4	0.3	0.6	0.8	0.7	0.7
Noble fir	Spring	1.3	1:5	0.4	0.5	0.4	0.4
	Midsummer	1.4	1.6	1.6	1.7	1.0	0.8
	Late summer	0.1	<0.1	0.2	0.2	0.2	0.2
Sitka spruce	Spring	0.9	1.2	0.3	0.3	0.1	0.2
	Midsummer	1.7	2.2	1.7	1.3	1.0	0.8
	Late summer	0.3	0.7	0.5	0.8	0.7	0.7

[a]Spring, late May through June; midsummer, early July through mid-August; late summer, mid-August through late September.
[b]Seed source code: Douglas-fir: 1, Oregon coast; 2, Oregon Cascades; noble fir: 1, northern Washington; 2, sourthern Washington; Sitka spruce: 1, Washington coast; 2, Oregon coast.

TABLE 3. Percentages, sizes, weights, and top–root ratios of seedlings at the end of the Biotron growth period

Species and seed source	Regime	Seedlings % live	Seedlings % plantable	Average size per seedling: Top height, cm	Average size per seedling: Stem diam., mm	Average ovendry weight per seedling, mg: Total	Foliage	Lateral roots
Douglas-fir,	Hot	83	80	26	2.7	1776	867	239
Oregon coast	Warm	99	97	21	2.6	1916	1017	225
	Cool	96	85	14	2.0	1143	642	184
Douglas-fir,	Hot	88	86	26	2.6	2002	1084	252
Oregon Cascades	Warm	100	99	21	2.6	1874	1020	249
	Cool	98	93	14	2.1	1397	772	230
Noble fir,	Hot	95	92	13	2.4	1202	569	202
southern Wash-	Warm	98	90	12	2.4	1372	668	192
ington Cascades	Cool	98	67	8	2.2	1136	600	167
Noble fir,	Hot	96	81	13	2.5	1271	602	202
northern Wash-	Warm	96	78	11	2.5	1525	739	262
ington Cascades	Cool	96	49	8	2.2	977	532	136
Sitka spruce,	Hot	91	88	18	2.6	1132	538	157
Oregon coast	Warm	98	93	14	2.4	1410	698	213
	Cool	98	72	9	1.9	1006	548	179
Sitka spruce,	Hot	90	83	18	2.6	1166	571	166
Washington coast	Warm	95	93	14	2.4	1377	656	235
	Cool	99	61	9	1.8	914	507	163

them source to reach plantable size rather than from mortality. The northern source was also obtained from a higher elevation that the southern source.

Heights of all surviving seedlings of all species and seed sources were greatest in the hot regime, intermediate in the warm regime, and lowest in the cool regime (Figs. 2 and 3). There were no seed source differences within species.

Stem diameters at the root collar of plantable seedlings were larger in hot and warm regimes than in the cool regime. Sitka spruce seedlings in the hot regime had slightly greater diameters than seedlings in the warm regime. Differences in stem diameter between seedlings in hot and warm regimes were not significant for Douglas-fir and noble fir. There were no seed source differences within species.

Dry weight of noble fir and Sitka spruce seedlings in the warm regime was greater than in the hot regime. This difference was not significant for Douglas-fir seedlings. For all species and seed sources, dry weight of

TABLE 4. Significance of orthogonal contrasts for percentage, sizes, weights, and top–root ratio of seedlings at the end of the Biotron growth period

Species	Orthogonal contrast	Seedlings		Seedling size		Seedling ovendry weight		
		Live	Plantable	Top height	Stem diam.	Total	Foliage	Lateral roots
Douglas-fir	Hot and warm vs. cool	ns	ns	**	**	**	**	**
	Hot vs. warm	**	**	**	ns	ns	ns	ns
	Seed source	ns	ns	ns	ns	ns	**	ns
	Regime × source	ns	ns	ns	ns	ns	ns	ns
Noble fir	Hot and warm vs. cool	ns	**	**	**	**	*	**
	Hot vs. warm	ns	ns	**	ns	**	**	ns
	Seed source	ns	*	ns	ns	ns	ns	ns
	Regime × source	ns	ns	ns	ns	ns	ns	**
Sitka spruce	Hot and warm vs. cool	**	**	**	**	**	**	ns
	Hot vs. warm	**	ns	**	**	**	**	**
	Seed source	ns	ns	ns	ns	ns	ns	ns
	Regime × source	ns	ns	ns	ns	ns	ns	ns

NOTE: ns, non significant; *, significant at 5% level; **, significant at 1% level.

the seedlings grown in the cool regime were the lowest.

Dry weights of foliage were greatest for seedlings in the warm regime. The only exception was the Cascade source of Douglas-fir, which had heavier foliage in the hot regime than in the warm regime. Over all regimes, the Cascade source of Douglas-fir had heavier foliage than the coastal source. No significant seed source differences were found in leaf dry weights of the other two species.

Dry weights of lateral roots of seedlings grown in the hot and warm regimes were similar for Douglas-fir and the southern source of noble fir. For Sitka spruce and the northern source of noble fir, greatest weights of lateral roots were in seedlings grown in the warm regime.

Cold hardiness

For all three species, seedlings grown in the hot regime were injured more by freezing than seedlings from other regimes (Table 5). Differences were significant for all four indices of damage, namely, percent of seedlings with: (1) partially or completely dead foliage, (2) partially or completely dead cambium just above the root collar, (3) inhibition of root initiation, and (4) dead terminal buds. Most injury to the foliage and cambium was partial rather than complete, but all foliage was dead in a few of the seedlings from the hot regime.

Differences in susceptibility to freezing between seedlings from warm and cool regimes were generally less pronounced and, in some cases, differed among species (Table 5). In terms of foliage damage, the interaction of species and temperature regime was significant; least damage occurred to Douglas-fir from the warm regime and to noble fir from the cool regime. Foliage damage to Sitka spruce was essentially the same in both the warm and cool regimes. Douglas-fir and noble fir seedlings from the warm regime sustained more damage to the cambium than seedlings from the cool regime. No significant differences in damage to roots and terminal buds between seedlings in the warm and in the cool regimes were observed. There was, however, a species difference in bud injury. Injury to buds was greatest in Douglas-fir, intermediate in Sitka spruce, and least in noble fir.

All unfrozen control seedlings were in good condition at the end of the 3-week greenhouse period.

Discussion

Survival and growth

Survival was high enough for all sources so that seedling density (number per square foot) was considered to have a negligible effect on between-treatment growth differences. Failure of live seedlings to reach plantable size was related to the growth potential of the various seed sources in the three regimes; the cool regime was least conducive to good growth. The relatively low percentage of plantable seedlings of noble fir from northern Washington in all three regimes was probably due to a natural tendency for seedlings from that northern, high-elevation source to grow slowly during the 1st year.

The rate of height growth of all three species was

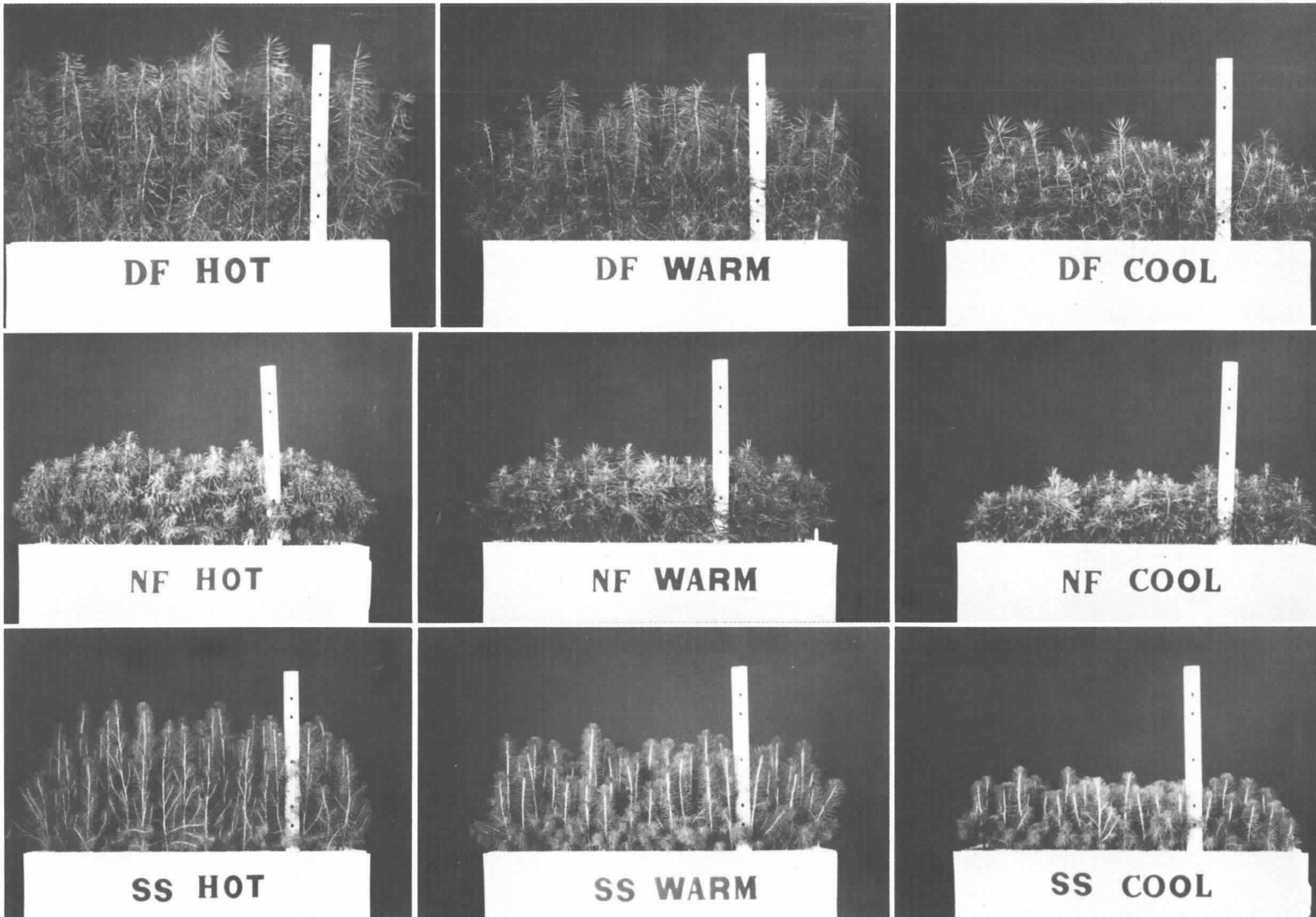

FIG. 2. Side view of styroblocks containing 24-week-old seedlings of Douglas-fir (DF), noble fir (NF), and Sitka spruce (SS) grown under three simulated greenhouse regimes. Scale with each tray of seedlings is 30 cm long.

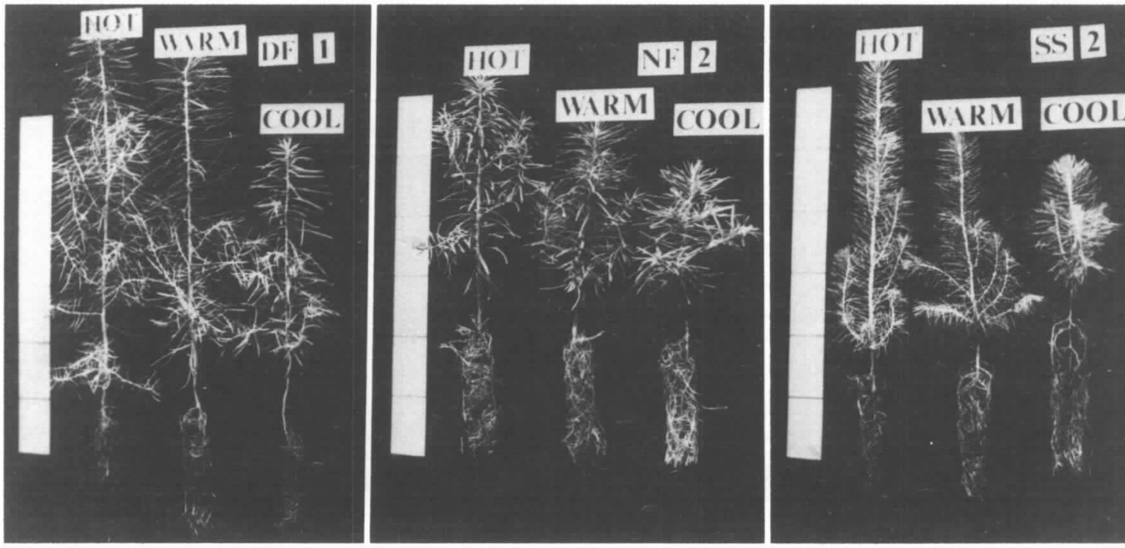

FIG. 3. Typical 24-week-old seedlings of Douglas-fir (DF), noble fir (NF), and Sitka spruce (SS) grown under three simulated greenhouse regimes. Potting mixture has been washed from root balls. Scale divisions are 5 cm apart.

TABLE 5. Damage to 24-week-old seedlings from 4-h exposure to −5°C

Species	Regime	Dead foliage, %	Dead cambium at root collar, %	No root initiation, %	Dead terminal bud, %
Douglas-fir	Hot	38	26	17	19
	Warm	14	6	1	3
	Cool	30	0	1	9
Noble fir	Hot	45	19	15	3
	Warm	32	11	10	1
	Cool	0	0	2	0
Sitka spruce	Hot	47	16	24	11
	Warm	12	0	1	1
	Cool	10	0	2	3

NOTE: Damage was assessed after 3 weeks in a warm, sunny greenhouse. Each damage factor was assessed on each seedling; thus, one individual could be counted in more than one column.

greater during periods when maximum daily temperatures increased to the middle to high 20's than when maximum temperatures rose above 30°C. Hence, the final height advantage of seedlings from the hot regime mainly reflected rapid early growth rather than a sustained high rate of growth through the hot part of the summer. Growth was suboptimal during periods when day temperatures did not exceed 20°C.

The generally greater dry weight of seedlings in the warm regime than of those in the hot regime probably reflects inhibitory effects of the 30°C and higher temperatures that occurred in the simulated midsummer periods. The only seed source with maximum dry-weight increment in the hot regime, Douglas-fir from the southern Oregon Cascades, was one adapted to hot summer weather.

This study, as well as others, shows a common pattern of dry weight production of seedlings: highest production at moderate temperatures and reduced growth at high temperatures (Brix 1971; Hellmers and Sundahl 1959; Kramer and Kozlowski 1979). The inhibitory effect of high temperature on growth probably is the result of a combination of decreased net assimilation caused by high respiration (Brix 1967), inactivation of enzymes (Spurr and Barnes 1973), and high midday moisture stresses. Studies using constant or constant day and constant night temperatures often show reduced growth at a lower maximum temperature than the midsummer maxima in the present study (Brix 1971 and 1972; Hellmers and Sundahl 1959; and Mergen *et al*. 1974). This difference probably occurred because high temperatures in the present study were maintained for a shorter time, both diurnally and seasonally, than in studies using constant temperature regimes.

Reduced growth at the moderately low temperatures of the cool regime was undoubtedly associated with generally lowered metabolic rates.

The fact that production of foliage in one seed source of noble fir and Sitka spruce and production of lateral roots in one source of Sitka spruce were greater in the cool regime than in the hot regime probably reflects adaptation to their cool, natural habitats. Douglas-fir, on the other hand, grows on hotter sites, even in the Coast Ranges.

Development of dormancy and cold hardiness

Cessation of height growth and bud formation, the first visible stages of dormancy in conifer seedlings, can be readily induced by short days, but short days do not completely eliminate effects of temperature. The delay of bud set under cool temperatures as shown in this study was also reported by Hellmers and Hesketh (1974), Lavender and Overton (1972), and Malcolm and Pymar (1975). Delayed development and small size of buds in seedlings from the cool regime were probably the results of low temperatures and less elapsed time between bud set and time of observations.

The freezing test was conducted when the seedlings were not completely cold hardy. It was, however, done at a time when fall outplanting begins on some sites in the Pacific Northwest. Furthermore, the freeze was no more severe than might be expected at that time of year. The data do not provide insight on whether late, early, or full-season exposure to the hot regime contributed most to the relatively low resistance of seedlings from that regime to freezing. Previous work indicates that both photoperiod and night temperature are critical factors in development of cold hardiness of Douglas-fir (van den Driessche 1969), but that short days alone induce less hardiness than when plants are given a subsequent chilling treatment (Timmis and Worrall 1975). In fact, chilling induced a certain level of frost hardiness regardless of preceding warm, short days (Timmis and Worrall 1975).

The relatively high level of injury to foliage and buds of Douglas-fir from the cool regime indicates that suboptimal growth conditons for a full growing season may predispose seedlings to damage from freezing.

Correlation between delayed bud set and greater resistance to freezing for noble firs and Sitka spruces in the cool regime indicates that bud set is not always a good indication of cold hardiness.

Application of results

Information from this study and similar studies can be used to develop general growing schedules for large-scale production of seedlings in greenhouses. Such schedules should be derived for specific ecotypes, planting sites, and seasons of planting. For example, a temperature regime warmer than outdoor conditions could be used in the spring to stimulate early height growth of Douglas-fir and Sitka spruce to be planted on brushy coastal sites. But such stimulation of height growth would be detrimental to Cascade Mountain sources of Douglas-fir which benefit from being sturdier so as to withstand downhill movement of soil and debris on steep slopes or bending by snow.

If seedlings are to be planted in the fall, conditions to improve cold hardiness have priority. For noble fir seed sources in this study, hot or warm conditions early in the season are needed to stimulate growth. But it is important to switch to cool conditions by midsummer if noble fir is to be planted in the fall. The relatively slow growth of this species also suggests the need for an early sowing date.

Maintaining greenhouse temperatures of 6–8°C above outdoor temperatures in western Oregon beyond springtime appears disadvantageous for both growth and cold hardiness of the three species tested. Although the cool regime had a definite advantage in cold hardiness of noble fir, it cannot be recommended for season-long use because of the low percentages of plantable seedlings and small diameters of seedlings produced in the cool regime.

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