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USE OF SUPPLEMENTAL LIGHT BENEFITS

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INTRODUCTION

Tree seedlings grown in greenhouses for reforestation purposes or for use in tree improvement programs are known to have improved growth from the use of supplemental lights. Various types of supplemental lighting systems extend normal day lengths. This is of particular importance during our winters, when the critical day length is much less than the optimal photoperiod for good seedling growth. Day-length extension can play a significant role in achieving close to optimum growth rates if the intensity of the supplemental lights is sufficiently high for seedlings to reach near-optimal rates of photosynthesis.

To reach near-optimum growth rates, seedlings in the greenhouse must be exposed to sufficiently high levels of photosynthetically active radiation (PAR). This is defined as those wavelengths of light energy between 400 and 700 nm and covers the blue to red segments of visible light energy, with the red and blue light playing the greatest role in photosynthesis (Kramer and Kozlowski 1979; Vince-Prue and Canham 1983).

A light meter equipped with a quantum sensor is specifically designed for the accurate measurement of PAR. Output is expressed as the photon flux density of PAR, also referred to as the photosynthetic photon flux density (PPFD), which can be defined as the number of photons in the 400-700 nm waveband incident per unit time on a unit surface. Using the International System of Units (SI), PPFD is expressed in micromoles per square metre per second ($\mu mol \cdot m^{-2} \cdot s^{-1}$). Any supplemental lighting source that is used in a greenhouse environment can thus be evaluated for its output of PAR using a light meter equipped with a quantum sensor. For maximum photosynthesis to occur the available light should be relatively high in PAR, particularly in the red and blue spectra (Kramer and Kozlowski 1979). It is generally considered that it is the spectral balance of the light source rather than its overall light output that is likely to be important for morphogenetic effects (Vince-Prue and Canham 1983; Smith 1982), but the intensity and the duration of supplemental light are two components that cannot be overlooked and will be addressed in this paper.

At the 1984 Prairie Federal-Provincial Nurserymen's meeting, a report was presented by Dr. Ian Dymock (Dymock and Wilson 1986) on the effectiveness of using fluorescent versus high pressure sodium vapor lights as supplemental light sources in greenhouses for rearing conifer seedlings. The use of extended photoperiods with these two light sources was also examined. At the time of that report, the use of the combination of fluorescent plus incandescent lights had been reported on by Wheeler (1979). He reported significant increases in growth of greenhouse-grown lodgepole pine seedlings over nursery-grown controls using continuous lighting (24-h photoperiod). The lighting used was a combination of fluorescent and incandescent lights during the first 6 months of growth in a heated greenhouse.

At that time, it was also reported that experiments had been initiated at the Northern Forestry Centre (NoFC) during the late fall of 1983 to more fully examine the phenomenon of early accelerated growth in conifers. Of major interest was the interaction of photoperiod with the three different types of supplemental lighting systems that were most available to greenhouse growers. This included the fluorescent plus incandescent combination used by Wheeler (1979) and those reported by Dymock and Wilson (1986).

This report will specifically concern itself with some of the results obtained to date for lodgepole pine, jack pine, white spruce, and black spruce. It will also address the costs, benefits, advantages, and disadvantages that are associated with the use of fluorescent lights (Fl), fluorescent plus incandescent lights (Fl + In), and high pressure sodium vapor lights (Na).

MATERIALS AND METHODS

Seedlings of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), white spruce (*Picea glauca* [Moench] Voss), jack pine (*Pinus banksiana* Lamb.), and black spruce (*Picea mariana* [Mill] B.S.P.) were grown under each of the experimental lighting systems (Fl, Fl + In, or Na) as shown in Figure 1. Seedlings were reared in peat moss in 5.4-L square plastic pots in heated greenhouses at NoFC using the rapid growth fertilizer regime of Carlson (1983). The technical information pertaining to each supplemental lighting system (Fig. 1) is shown in Table 1.

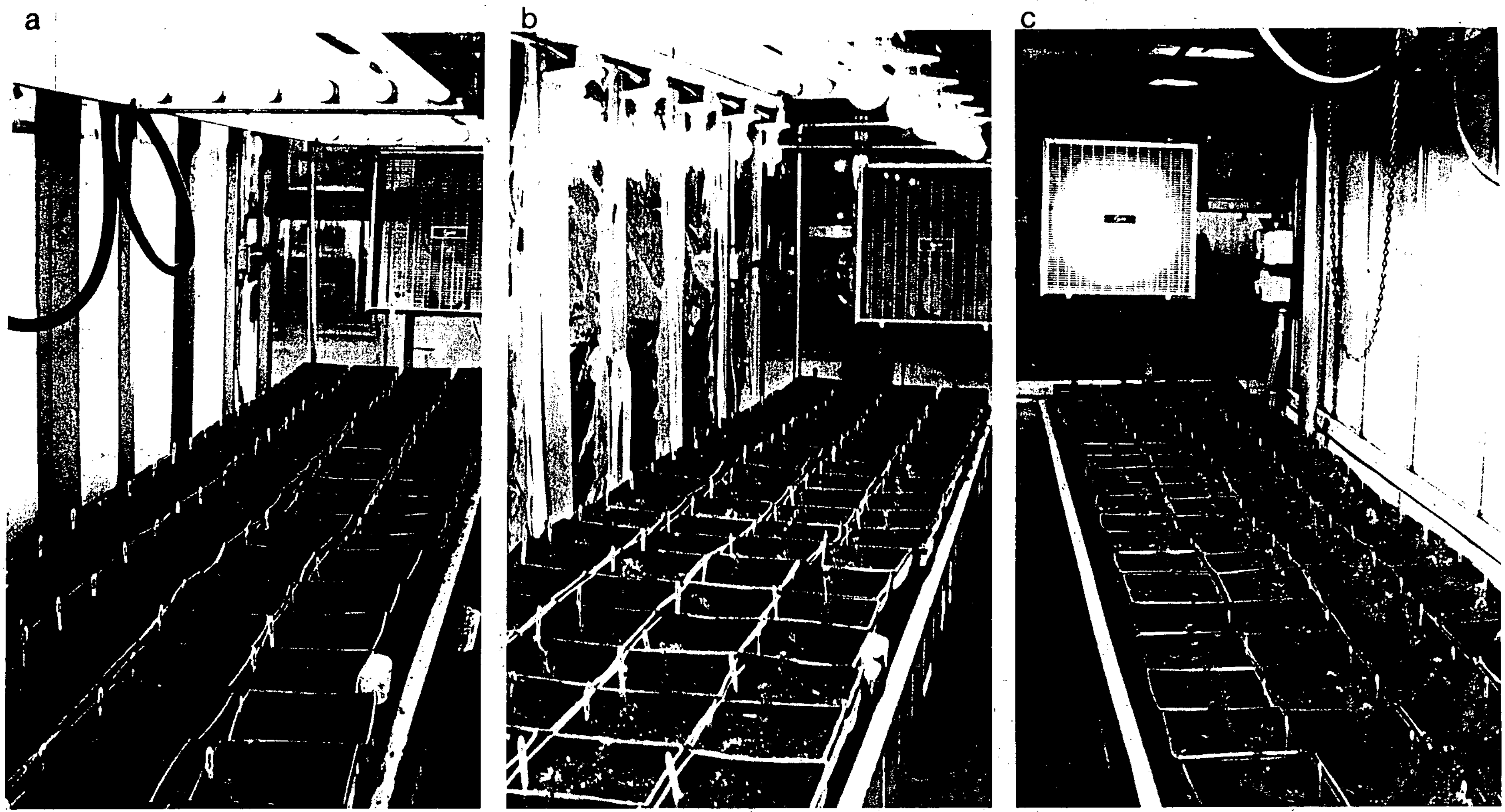
Two photoperiods were used throughout these studies. The first was the standard photoperiod used by research staff at NoFC, which consists of an the 18-h day and 6-h night. The second photoperiod was continuous light, or 24-h day. Each experiment was initiated during the late fall and ran for 32 weeks in the greenhouses. This was followed by a hardening-off period (Carlson 1983) that normally began in late May or early June of the following year, ran for 4-6 weeks, and was followed by outplanting of trees from all treatments in the NoFC nursery complex.

Prior to the start of the experiments, both the light quality and light quantity in each compartment under each of the respective lighting and photoperiod combinations was measured. This was accomplished using a LI-1800 Portable Spectroradiometer. The total spectrum for each system from 300 to 1100 nm was measured and recorded as shown in Figure 2. From these spectra the PPFD for each system was calculated (Table 1, Fig. 2). During each experiment the PPFD was monitored using an LI-185B Quantum Radiometer/Photometer equipped with a LI-190SB Quantum Sensor. Irradiance (W/m^2) and illuminance (lux) were also measured using LI-200SB Pyranometer and LI-210SB Photometric Sensors respectively. All light measurements were made well after dark, in the absence of any natural daylight or light from other interfering sources.

The standard bench size in these experiments was 5 m^2 for each supplemental lighting system (Fig. 1, Table 1). Each bench could hold 120 pots.

The PPFD for each lighting system was converted to the daily available supplemental PPFD ($mol \cdot m^{-2} \cdot d^{-1}$ (Table 1). From the technical data in Table 1 the power consumption per bench per day was then calculated, and the cost of electricity per bench per day was then calculated as shown (Table 1). For these calculations the peak power cost charged by Edmonton Power ($0.039/kW•h) was used to simplify the calculations.

Height measurements were made biweekly, usually from week 12 through to week 32. Stem diameter measurements were made at the beginning and end of each study. There were 24 trees per treatment in each case. Mean values were calculated, and the data were analyzed by one-way ANOVA followed by



Fluorescent lights

Fluorescent plus incandescent lights

Sodium lights

Figure 1. Layout of each of the supplemental lighting systems shortly after the initiation of the experiment on black spruce.

Greenhouse compartments were equipped with a) Fl, b) Fl + In, and c) Na lights in the configurations outlined in Table 1.

Table 1. Characteristics of the three types of supplemental lighting systems used throughout the studies on early, accelerated growth in conifers. Bench area = 5.0 m^2.

	Fluorescent lamps (Fl)	Fluorescent plus incandescent lamps (Fl + In)	High pressure sodium vapor lamps (Na)
Bulb type, output, and numbers	Cool white 45 W fluorescent 6 X F96T12/CW/HO 6 X F72T12/CW/HO	Cool white 45 W fluorescent 6 X F96T12/CW/HO 6 X F72T12/CW/HO plus 20 X 100 W incandescent	High pressure sodium 5 X 400 W
PPFD (PAR 400-700 nm) ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	59.6 ± 2.4	84.8 ± 2.4	214.4 ± 5.5
Daily available PPFD ($mol \cdot m^{-2} \cdot d^{-1}$)			
18-h day	3.86	5.50	13.89
24-h day	5.14	7.34	18.52
Power consumption (per bench per day)			
18-h day	9.72 kW	45.72 kW	36.0 kW
24-h day	12.96 kW	60.96 kW	48.0 kW
Cost of electricity (per bench per day)			
18-h day	$0.38	$1.78	$1.40
24-h day	$0.51	$2.38	$1.87
Influence on height (% of Fl as control)	100%	90-176%	136-230%
Influence on stem diameter (% of Fl as control)	100%	86-137%	182-325%
Heating costs	Minimal effect	Costs decreased	Costs decreased substantially
Seedling vigour/health	Least vigorous, increased pathological problems	Better than Fl, increased pathological problems	Very vigorous, few pathological problems

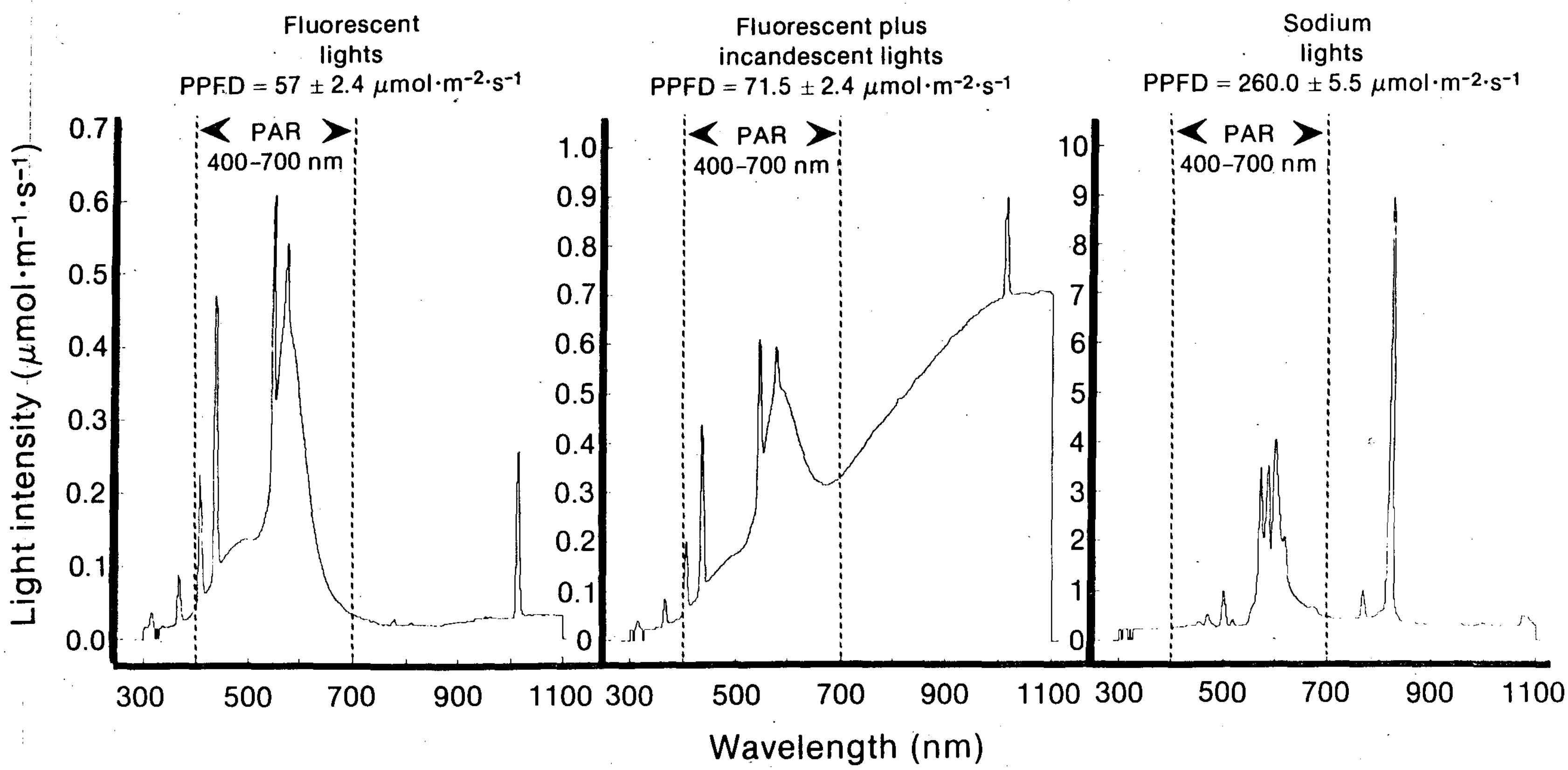


Figure 2. **Comparison of the spectral distribution, photosynthetically active radiation (PAR) and photosynthetic photon flux densities (PPFD) of each of the supplemental lighting systems.**

Spectrographs were obtained from each greenhouse compartment equipped with a) Fl, b) Fl + In, and c) Na lights as shown in Figure 1 and Table 1. The spectra shown are typical for each of the light sources employed. Spectra were recorded well after dark in the total absence of any other light sources. Measurements were taken 0.75 m below the fluorescent tube for Fl and Fl + In lights and 1.20 m below the bulb for Na lights.

Duncan's Multiple Range Test to show where significant qualitative differences exist between means for each parameter within a species.

RESULTS

Characteristics of Supplemental Lights

The spectral distributions and PPFD (Fig. 2) for each light source in Figure 1 show that major differences exist in light quality and quantity for each system. It is apparent, however, that Na lights provide the best levels of PPFD to supplement natural daylight. The sodium lights were 1.2 m above seedling tops; Fl and Fl + In lights were approximately 0.75 m above. At these distances, the distribution of supplemental light from each type was optimal and allowed for the maximum amount of exposure to natural daylight with the least amount of shading. To place any of the lighting systems closer to the seedlings resulted in overheating problems with the Na and Fl + In lights or too much shading from natural daylight for the Fl and Fl + In lights.

Data from Table 1 and Figure 2 indicate that Na lights provided 4.5 and 3.6 times more usable light (PPFD) than Fl and Fl + In lights, respectively. This is also reflected in the figures for daily available PPFD from supplemental sources (Table 1). It should be noted that seedlings under each of the light and photoperiod combinations received comparable levels of natural daylight between sunrise and sunset (data not shown). The supplemental lights were left on continuously during the daylight hours to provide the same minimum levels of PPFD for each of the treatments.

Height Growth

The influence of the light and photoperiod combinations on height growth of lodgepole pine can be se in Figures 3a and 4a. Figure 3a sho the height growth of lodgepole pi from age 13 weeks to 31 weeks for ea treatment. No significant differen ($P > 0.05$) exists in the height lodgepole pine seedlings at 31 wee between 18-h Na, 24-h Na, 18-h Fl In, or 24-h Fl + In treatments. Thi can also be seen in Figure 4a, whic is a photograph of the trees from eac treatment that were closest to th mean height per treatment out of total of 24 trees per treatment. Bot Fl photoperiodic treatments (18- an 24-h) were significantly shorter (P 0.05) than the other treatments Obvious differences in vigor are apparent from Figure 4a.

Jack pine show a more diverse response to the light and photoperio treatments in their height growth thar do lodgepole pine, as shown in Figures 3a and b and 4a and b. The 18-h Na seedlings were significantly taller ($P < 0.05$) than the 24-h Fl + In seedlings after 32 weeks. The 24-h Fl + In seedlings were in turn significantly taller ($P < 0.05$) than either of the 24-h Na or 18-h Fl + In seedlings (Fig. 3b). As with lodgepole pine, both Fl treatments produced the shortest seedlings. Figure 4b shows clearly that the 18-h Na seedlings were the most vigorous and, as with lodgepole pine (Fig. 4a), had the best root development.

White spruce also shows quite diverse height growth responses to each of the light and photoperiod treatments (Figs. 3c, 4c). As with jack pine, and to a lesser extent (although not statistically significant, $P > 0.05$) with lodgepole pine, the 18-h Na white spruce seedlings achieved the greatest height growth, being significantly taller ($P < 0.05$) than the 24-h Na seedlings (Fig. 3c). These in turn were significantly taller ($P < 0.05$) than the 24-h Fl + In seedlings, but the 24-h Fl + In seedlings were not significantly taller ($P > 0.05$) than the 24-h Fl seedlings. No

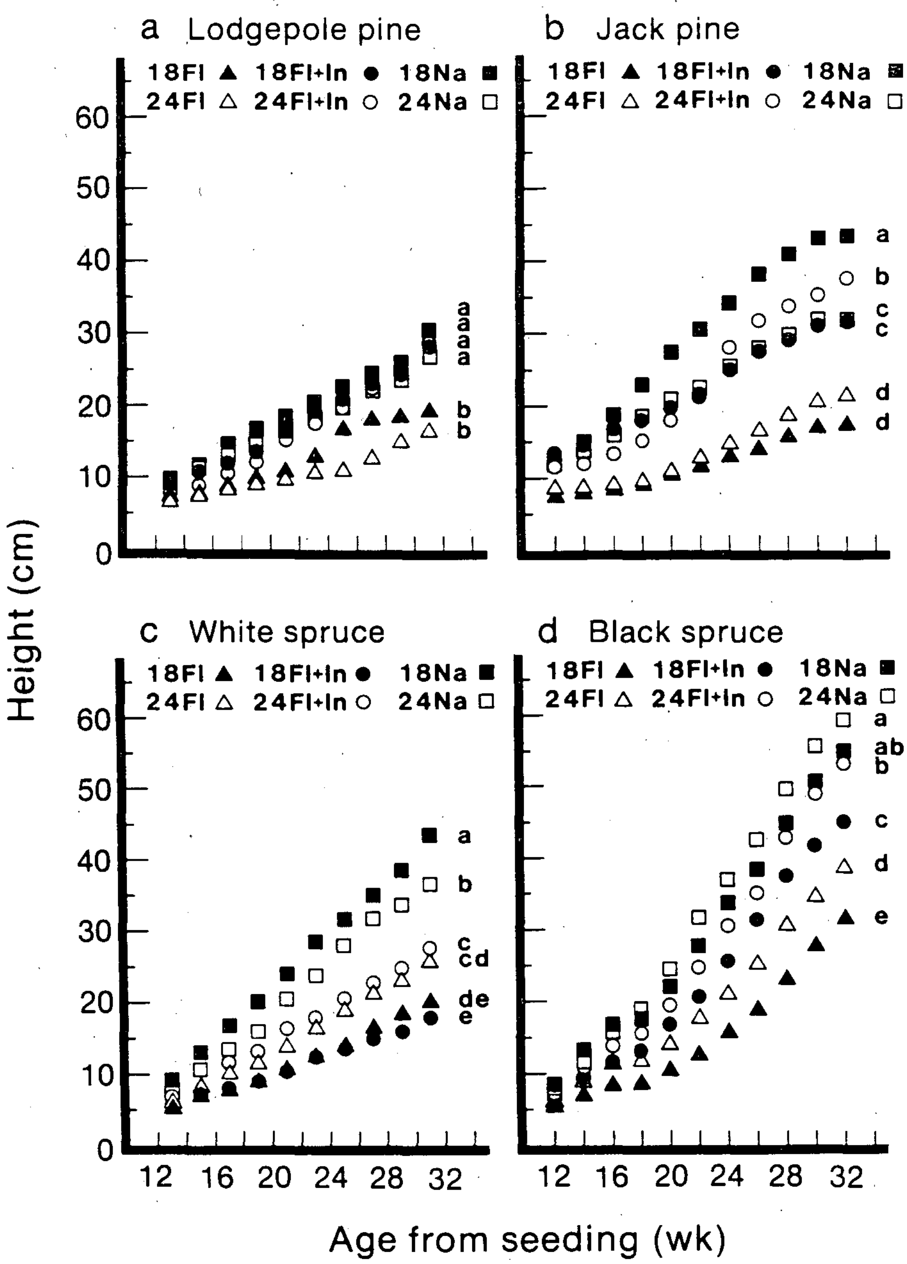


Figure 3. Comparative height growth of lodgepole pine, jack pine, white spruce, and black spruce under each light and photoperiod treatment from the age of 12 weeks up to 32 weeks.

Biweekly height measurements of seedlings were made starting 12-13 weeks after seeding through to the end of the rapid growth period for each species a) lodgepole pine, b) jack pine, c) white spruce, and d) black spruce. Each data point represents the mean value for 24 trees. Data were analyzed after week 31 or 32 by one-way ANOVA followed by Duncan's Multiple Range Test. Means for each species not followed by the same letter are significantly different ($P < 0.05$).

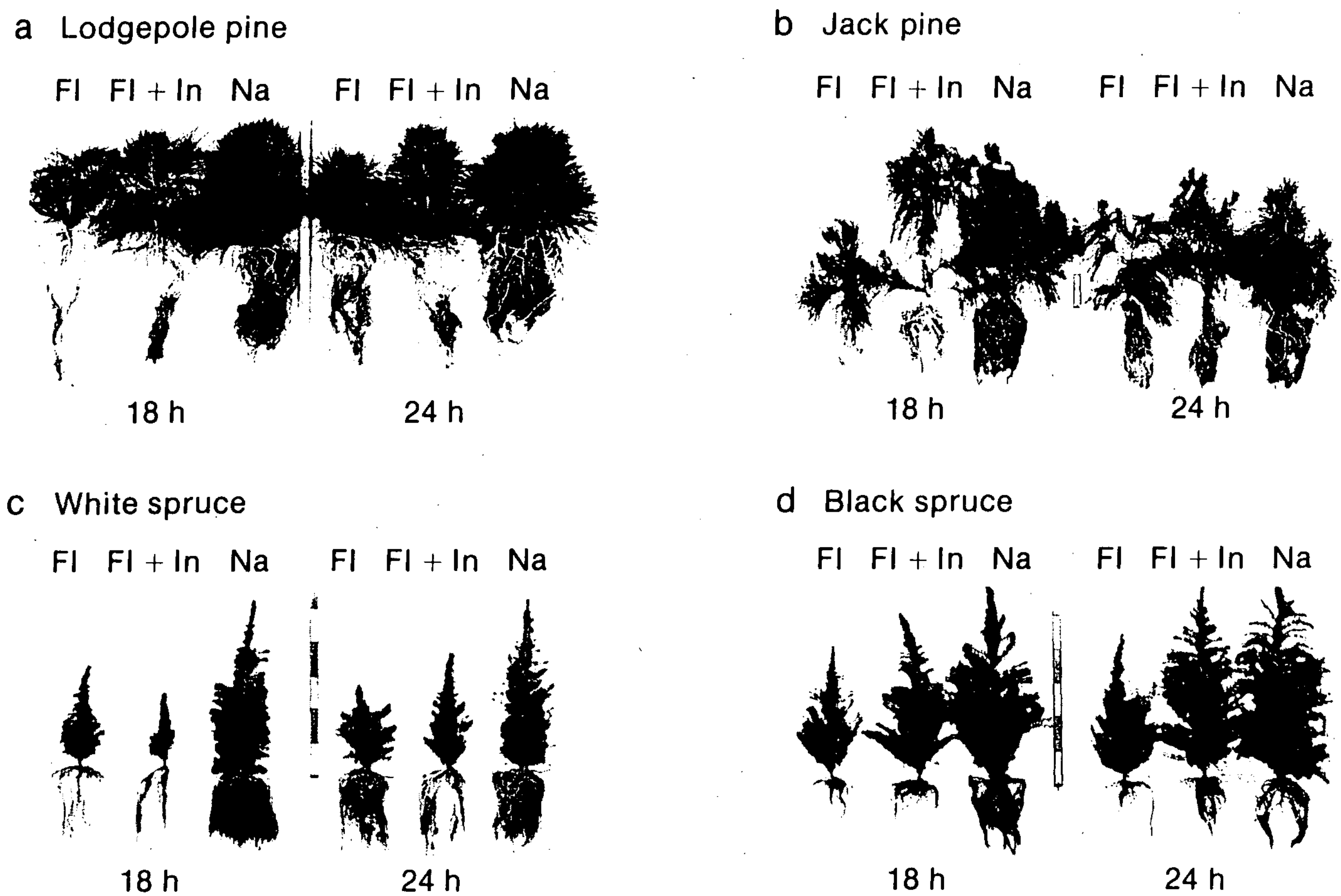


Figure 4. Comparative morphology of lodgepole pine, jack pine, white spruce, and black spruce on completion of the rapid growth phase under each light and photoperiod treatment.

The photographs of a) lodgepole pine, b) jack pine, c) white spruce, and d) black spruce were taken at the seedling age of 32 weeks. Each tree shown is the one that at that time was closest to the mean value for height growth out of 24 trees per treatment. The vertical line at the edge of the photograph for each species represents a scale of 225 cm. This easily facilitates relative comparisons of shoot and root morphologies of the seedlings grown under each light and photoperiod treatment.

significant differences ($P > 0.05$) in heights were noted between 24-h Fl and 18-h Fl seedlings or between 18-h Fl and 18-h Fl + In seedlings. It should be noted, however, that a 24-h photoperiod could improve height growth of white spruce seedlings if either Fl or Fl + In lighting systems were employed, but other problems could arise with respect to poor root growth and poor seedling vigor (Table 1), which can be observed in Figure 4c.

Black spruce seedlings showed the greatest height growth under the 24-h Na lights, but it was not significantly greater ($P > 0.05$) than was seen under the 18-h Na treatment (Figs. 3d, 4d). Black spruce seedlings under the 24-h Na lights were significantly taller ($P < 0.05$) than 24-h Fl + In seedlings, but there was no significant difference in height ($P > 0.05$) between 18-h Na and 24-h Fl + In seedlings. Each of the other three treatments (18-h Fl + In, 24-h Fl, and 18-h Fl) were significantly different ($P < 0.05$) from the other treatments and from each other (Fig. 3d). The results are corroborated in Figure 4d. As was seen with white spruce seedlings, the 24-h photoperiod resulted in significantly increased height growth ($P < 0.05$) of black spruce seedlings grown under Fl + In lights. This was also true for black spruce seedlings grown under Fl lights.

These results for height growth are confirmed with respect to height growth for each species when the final heights are plotted against the daily PPFD as shown in Figure 5. For each species the greatest height growth could be reached under 18-h Na lights, based on 13.89 mol PAR/m^2 of bench space per day. Above this level for jack pine and white spruce there were significant reductions ($P < 0.05$) in height growth under the 24-h Na lights. For lodgepole pine and black spruce there were no significant differences ($P > 0.05$) in height growth with 24-h Na lights.

Stem Diameter

Biweekly measurements of stem diameters were not carried out throughout the experiments due to the difficulties associated with reaching around vigorously growing trees that were spaced four deep on each bench. Pines during active leader elongation were very susceptible to physical damage. Initial and final stem diameters were measured, however.

Figure 5 shows the final stem diameter measurements plotted against the daily PPFD in the lower half of the figure. It is readily apparent that the best stem diameter growth was achieved under the 18-h Na lights for three of the species examined (lodgepole pine, jack pine, and white spruce). Photoperiod extension using Na lights from the 18-h day to a 24-h day resulted in significant reductions in stem diameter growth ($P < 0.05$) in these three cases. For black spruce, there was a marginally significant ($P < 0.05$) increase in stem diameter under 24-h Na lights over that achieved with the 18-h Na lights (Fig. 5). These results generally paralleled those seen for height growth in all four species.

Power Consumption and Electricity Costs

Data shown in Table 1 indicate that the Fl + In combination of lights was the largest consumer of power. Using the 18-h day, Fl + In lights consumed 4.7 and 1.3 times more power than did Fl and Na lights, respectively; Na lights consumed 3.7 times more power than Fl lights. Of primary consideration to the data on power consumption, however, is the usable light (PPFD) generated by each light source. Although Na lights used the second highest amounts of electricity, they generated 4.5 and 3.6 times more usable light (PPFD) than did the Fl + In and the Fl lights, respectively.

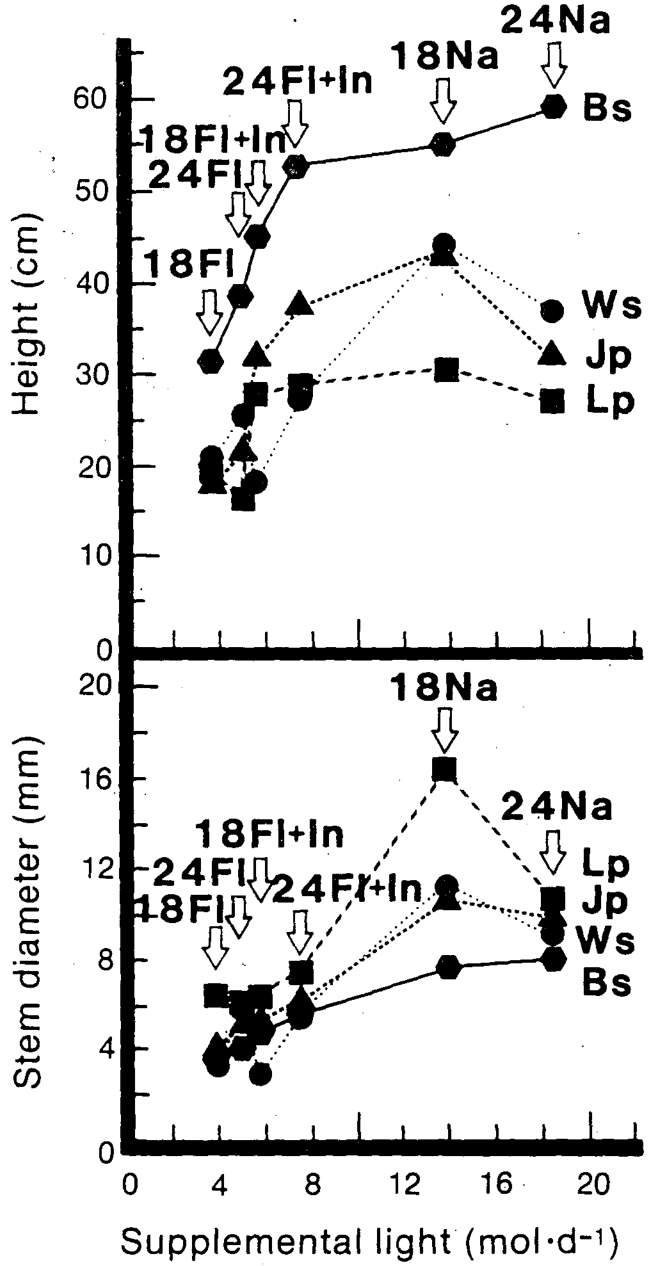


Figure 5. Comparison of height and stem diameter with daily photosynthetic photon flux density (PPFD in mol•m^{-2}•d^{-1} of PAR, 400-700 nm) after the rapid growth phase for each light and photoperiod treatment.

Data shown represents the mean values for 24 trees per treatment. Values for PPFD were taken from Table 1. The height values were those values shown at the end of the rapid growth phase in Figure 1. Stem diameters had been measured at the same time.

This resulted in significantly greater height and stem diameter growth for all four species. This is a direct result of more available (usable) photosynthetically active radiation being generated by the Na light sources (Table 1, Fig. 2).

Other Considerations

Both Na and Fl + In lights generate substantial amounts of heat energy in addition to the usable light (PPFD). It has been observed during the course of these studies over four winters that while the Na lights (and to a lesser extent the Fl + In lights) were on, the steam-heating systems in each of the compartments with these lights rarely came on. Only when the outdoor temperatures reached below -25°C, and under windy conditions, did the steam heating remain on constantly. Although it was not actually quantified, the excess heat generated by the Na lights substantially reduced greenhouse heating costs. This was particularly evident after internal fans were installed to circulate this excess heat.

This result is not particularly surprising when one considers that Na lights are far more efficient than the other systems at converting electrical energy to light energy. Sodium lights are 25% efficient, whereas incandescent lights are no more than 6.5% efficient (Stolze et al. 1985), and Fl lights are even less efficient. This is corroborated by the PPFD and power consumption data from Table 1.

Seedling vigour was greatest under 18-h Na lights, as was seen for each species in Figure 4. Fewer pathological problems (insect or disease) were seen on seedlings grown under 18-h Na lights. Some mortality occurred during the course of these studies, but it was mostly under continuous daylight (24-h day) conditions using Fl and Fl + In lights (data not shown).

Outplanting survival has been extremely high for most treatments. During the winter of 1984-85 only one lodgepole pine mortality occurred out of 300 trees. There have been equally few mortalities among outplanted white spruce and jack pine that could be attributed to treatment effects (data not shown). Black spruce were only outplanted in July 1987 and have yet to experience their first winter.

DISCUSSION AND CONCLUSIONS

It is apparent from the data presented that the most effective lights for use in greenhouses to rear conifers are high pressure sodium vapor (Na) lights. From the results presented, Na lights using the 18-h day and 6-h night photoperiod provided the best growth in the four species examined. These results confirm those in the earlier report of Dymock and Wilson (1986). The results presented in this report were for seedlings reared in 5.4-L pots, while those of Dymock and Wilson (1986) were for seedlings reared in Spencer-Lemaire Super 45s.

In other studies (Dymock and Dendwick 1987; Edwards 1987; Edwards 1986) where seedlings have been reared in the NoFC greenhouses in Spencer-Lemaire 5s or Ferdinands (Spencer-Lemaire Industries, Edmonton, Alberta) or Styro 20 containers (Beaver Plastics, Edmonton, Alberta), we have achieved comparable seedling heights for each species (Fig. 3) during the equivalent 14-16 week rapid growth stage in the greenhouse. The results reported for pots and larger containers have thus been readily translated to the smaller volume container situation.

The increased efficiency of Na lights as measured by daily available PPFD and the growth rates achieved more than compensate for increased electrical costs. When capital and operating costs are averaged out over the lifetime of a greenhouse operation, the cost of power per seedling is minor when compared to all other operating costs (Stolze et al. 1985). The end result is a superior seedling ready for outplanting.

It is apparent that the spectral balance of the Na lights (Table 1, Figs. 2, 4) exerts very significant morphogenetic effects on the seedlings in each of the species that were examined, corroborating previous findings of Vince-Prue and Canham (1983). It is also apparent from the results that light intensity can also have very significant morphogenetic effects (Fig. 4) and that the duration of exposure to supplemental Na lighting can reach an optimum (Fig. 5). It would appear from Figure 5 that saturation of the photosynthetic apparatus can be reached for these species, as reflected by the levelling off of both height and stem diameter growth. This apparently occurs when the total daily available PPFD surpasses levels achieved using 18-h Na lights. This, then, is a point that must be kept in mind when planning what type of supplemental lights will be used in a greenhouse environment. This consideration, as well as the maximum light intensity incident per unit area per unit time (Kramer and Kozlowski 1979; Smith 1982) will have a significant impact on the results expected.

Supplemental lighting systems that use Na lights under the 18-h day and 6-h night photoperiod combined with proven container production procedures and schedules (Carlson 1983) should yield greatly increased benefits through the production of superior planting stock.

When this is combined with the potential benefits of indoor hardening procedures such as the Extended Greenhouse Culture Method (Colombo et al. 1984), proven methods for monitoring the development of dormancy and cold hardiness (Colombo and Cameron 1986; Dymock and Dendwick 1987), and the development of efficient cold storage facilities for container stock, it should be possible to move to year-round container stock production. These steps could greatly reduce production times for high-quality seedlings for outplanting. Container-grown stock that is equivalent in size to 2-0 and 3-0 bare-root stock (or to equivalent-sized container transplants) could be produced continuously by production greenhouses throughout the year, with at least two fully developed crops possible per year. This would be based on a 14-week rapid growth phase followed by 10 weeks to completely harden-off each crop.

This system would partially meet the increasing demands for larger numbers of high-quality seedlings for reforestation purposes in a much shorter time frame.

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