A Comparison of Seedling Growth and Light Transmission Among Tree Shelters

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ABSTRACT: *Survival, height, and diameter growth of seedlings were evaluated for three years after planting using five types of tree shelters and seven species: green ash (Fraxinus pennylvanica), northern red oak (Quercus rubra L.), pin oak (Q. palustris), American sycamore (Platanus occidentalis), black walnut (Juglans nigra L.) and flowering dogwood (Cornus florida), and eastern white pine (Pinus strobus). Differences in shelter environments were measured, including: light transmission measured as percent photosynthetic photon flux (PPF), ratio of red:far red (r:f-r) light from the red and far-red wavelengths, and air temperature inside the tubes. The differences seen in seedling survival were not significant (*$p < 0.05$*) for the presence or type of tree tube, with an average survival of 96% for all but 2 species. For most species, seedlings grown in high light-transmitting tubes with proportional r:f-r ratio light showed superior height growth (e.g., Miracle Tube, Tree-Pro, and Protex). Diameter growth generally decreased in shelters. Sycamore showed no significant benefit from the use of tubes. The lowest diameter increments were seen using Tubex brown and Mesh Guard shelters, which had low light transmission with high r:f-r ratio and mechanical damage respectively. Light transmission in translucent tree tubes was within the ranges found in open canopy forest, but the proportion of growth-promoting far-red wavelength was generally lower. In tubes with higher light transmission, r:f-r ratio is closer to natural ranges for that light level. For tubes with lower light transmissivity, this information suggests that seedling height growth might be improved if red wavelengths were blocked more strongly.*

Key Words: Tree shelter, light transmission, photosynthetic photon flux, red:far-red ratio, air temperature, deer repellent, oak-hickory forest, seedling growth.

A Comparison of Seedling Growth and Light Transmission Among Tree Shelters

Different types of tree shelters are being increasingly used to protect newly planted tree seedlings from animal damage such as deer browse. Previous studies on translucent plastic tree shelters provide information on seedling survival and growth (Smith 1993, Schultz and Thompson 1996, Ward et al. 2000); tree shelters microenvironment: temperature, light transmission, relative humidity, and carbon dioxide (Potter 1988, Ponder 1995, Kjelgren et al. 1997); tree shelter durability (Minter et al. 1992); and cost (Minter et al. 1992, Kays 1996). Most of these studies investigated the brown Tubex or white/tan Tubex tree shelters; Tree pro (Strobl and Wagner 1996), and homemade tree shelters (Minter et al. 1992, Ward et al. 2000). Independent information on newer tree shelters and relevant microenvironment features is less available, in a market with an increasing number of choices for tree protection.

The light quantity and quality available to the sheltered seedling depends on design and color. Translucent tree shelters designs include solid tube, open on the side, single wall, double wall or film inserted in an opaque plastic sheath, and colors vary from ivory, to blue, green, white and brown. Details on the quality of light transmitted inside tree shelters can help tailor tube choices to species or situation and improve future design.

This study hypothesized that tubes that mimic natural conditions, matching light intensity and spectral distribution, would result in greater height growth. The forest understory light is characterized by low photosynthetic photon flux (PPF), a low proportion of blue light, and low r:f-r ratio (Holmes 1981). The low r:f-r ratio is known to be especially important in plant photomorphogenesis (Corré 1983, Smith 1986). Several studies have demonstrated the morphogenetic responses of increased seedling height growth by shade intolerant and intermediate species, (Kwesiga and Grace 1986, Warrington et al. 1989, Sharew et al. 1996). Where light transmission is reduced, supplying lower r:f-r ratios could take advantage of seedlings' morphogenetic responses. Temperature also affects physiological processes of plants and indirectly influences their seasonal cycle of development, responses that depend upon conditions they experience in their natural environments (Fowells and Means 1990).

The objectives of this study were to: compare PPF, r:f-r ratio, inside air temperature among commonly used shelters, and to natural conditions in local forests; relate shelter light & and temperature characteristics to seedling growth; and evaluate response of seedlings to different types of shelters. Linking the shelter characteristics with natural conditions & seedling performance creates an information base from which to predict performance of additional tubes and improve characteristics of future tubes.

Materials and Methods

Study Area

This field trial was undertaken at Monocacy Natural Resources Management Area (NRMA), southern Frederick County, in the Maryland Piedmont (39º15' N, 77º26' E) between Apr. 1999 and Nov. 2001. The site is a crop field situated on north-east facing slopes of about 8% to 15% on Hagerstown loam (fine, mixed, semiactive, mesic Typic Hapludalfs). The site has been double cropped over the years and shows evidence of soil loss.

The forest light and air temperature conditions were measured under three oak-hickory forests, Monocacy NRMA, Thurmont area, and Green Ridge State Forest, representative of upland forests in western Maryland. The Monocacy NRMA forest is close to the shelter trial site, and has a dense, fully stocked overstory dominated by mixed oaks, hickory, and tulip-poplar. The understory contains shade-tolerant species (American beech, black gum, red maple and mountain laurel) and good natural regeneration of beech, maple, and oaks, with sparse ground cover. The Thurmont site (40º26' N, 77º25' E) is in the northern part of the same county, with rocky, less fertile soils and sparse ground cover. Chestnut and red oaks dominate the 97% stocked overstory. The understory and regeneration are similar to the Monocacy site, except that white pine replaces beech. The Green Ridge State Forest site (42º30' N, 78º27' E) is west of the field trial site, and is less densely stocked (88%) than the two other instrumented sites. White and red oaks dominate the upper canopy, while the understory is composed of white and chestnut oaks, red maple, serviceberry, white pine and hop hornbeam. There is good natural regeneration of white and red oaks, white pine and red maple. The ground cover includes blueberry, Japanese honeysuckle, greenbrier, poison ivy, and some multiflora rose. There is clear indication of deer damage to natural regeneration on all three sites.

Plant materials

A total of 140 bareroot Maryland-grown seedlings were machine planted for each of the seven species (1-yr-old green ash, American sycamore, pin oak, northern red oak, black walnut, and flowering dogwood, and 2-yr-old eastern white pine). Seedling size ranged from 10.2 ± 0.11 (mean ± SE) inches in height and 0.04 ± 0.0004 inches in diameter for white pine to 18.3 ± 0.24 inches in height and 0.13 ± 0.0001 inches diameter for green ash. Before planting, seedlings were stratified into different sizes based on height and diameter.

Tree shelters/treatments

Five makes of four-foot tall and 3inch to 4½ inch diameter tree shelters (Figure 1) were used for field trial treatments. The tree shelters included four translucent - (1) Miracle Tube (3 in. to 4½ in. diameter ivory color from Tree-Pro), (2) Tree-Pro (4" in. diameter double-wall ivory color open on the side from Tree-Pro), (3) Protex (4 in. diameter blue color open on the side from Forestry Suppliers), (4) Tubex (3 in. to 4½" in. diameter double-wall brown color tube from Treessentials) and (5) Mesh Guard (a flexible green plastic-mesh from Treessentials). Deer repellent chemical spray (DEE - 1080 Ready to Use from Deer Busters) was included to evaluate the effectiveness of the chemical spry against deer damage. Blue-X (3 in. diameter blue polyester film in an opaque plastic sheath from McKnew Enterprises) and Tubex (3 in. to 4½ in diameter double-wall green color tube from Treessentials) translucent tree shelters were not available at the beginning of the field trial, and were included in the study to characterize the light environment (PPF and r:f-r ratio).

Each treatment/species combination had 20 seedlings, assigned randomly for planting position. Overall, 980 seedlings representing seven species were planted at 10 x 10 feet spacing, and received one of six treatments or the control (no protection). The deer repellent was applied every week on new growth as it emerged, and every three months on the entire seedling. To avoid shading of tree shelters and seedlings, weed growth was controlled through mowing and herbicide application. Rodenticide was applied to control field mice and meadow voles.

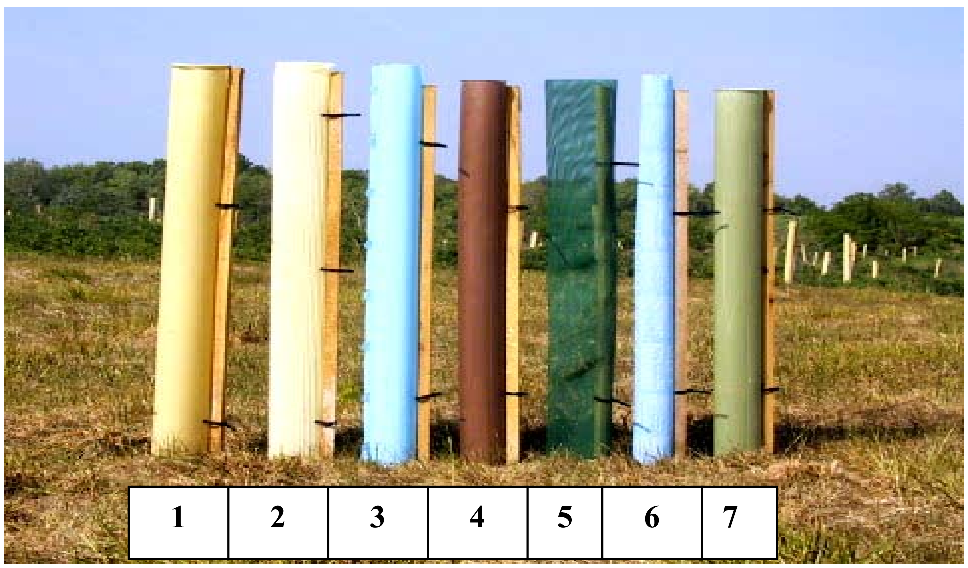

Figure 1. Photograph showing various tree shelters. *1,* Miracle Tube® *2,* Tree-Pro®; *3,* Protex®; *4,* Tubex® brown; *5,* Mesh Guard; *6,* Blue-X®; *7,* Tubex® green. Tree shelters *6* and *7* are new designs and not included in the seedling growth field trial.

Data collection and analyses

Quantum sensors (Li-190SA, Li-Cor, Inc.) were used to measure the penetration of (PPF) inside tree shelters and under the canopy of oak-hickory forest. For tree shelters, one sensor was permanently located in the open, and a second sensor inside the shelter. The sensor pairs were installed on five shelters for each type above the foliage (at 24 in.). PPF was measured in the open and at one of five different forest floor locations with a range of canopy densities in the three forest areas. A r:f-r ratio sensor (SKR 110, Skye Instruments Ltd.) was used to measure r:f-r ratio, defined as photon fluence rate centered at 660 and 730 nm. A portable data acquisition system (Li-2000 Plant Canopy Analyzer, Li-Cor, Inc.) was used for both PPF and r:f-r ratio, and data were recorded at 15-seconds intervals in July and Apr. between noon and 3:00 pm on a clear day when light levels were expected to be high and stable.

Air temperatures were measured both inside tree shelters and forest floors, and comparisons made with an open site. Air temperature measurements were made using six Optic StowAway Temp sensors and data loggers.

Seedling height and diameter at 6 inches above ground level were measured at the beginning of the field trial following planting. Seedling survival, height and diameter increment were assessed at the end of the field trial during fall 2001. Mean height and diameter increment after the initial measurement were calculated. Information on rodent, deer and/or rabbit damage was also recorded.

The effect of variables was investigated by analysis of variance (ANOVA), including main effects and treatment-species interactions in models. Because initial height and diameter varied within and between species, initial seedling size was included as a covariate. Where the overall treatment effect was significant at $p \leq 0.05$, Tukey's honestly significant difference (HSD) test was used to identify significant differences among treatments and species (Johnson 2000).

Results

Light transmission (PPF), red:far-red ratio and air temperatures

Forest understory

The proportion of light intercepted at the oak-hickory forest floor varied considerably, with percent PPF transmitted through the open canopy averaging more than three times that of the denser forest (Table 1). The mean percent light transmitted in the forest understory was related to the stocking density, which was 88%, 97% and >100% for Green Ridge, Thurmont, and Monocacy NRMA respectively.

The mean r:f-r ratio in the oak-hickory forest understory averaged a third of the value in the open (Table 1). Overall values of the r:f-r ratio in the oak-hickory forest understory varied, ranging from 0.1 to about 0.8, with the r:f-r ratio in the understory of the open canopy being higher.

The average daytime air temperature over 7 days (between 9:00 am to 4:00 pm) in the oak-hickory forest understory averaged 6 to 14° F lower than in the open (Table 2). This was not directly related to the stocking density, probably because of differences in elevation and aspect.

Tree shelters

The mean percent light transmission inside tree shelters ranged from 12 ± 0.20 in the Tubex brown to 34 ± 0.16 in the Miracle Tube, while it was 46 ± 0.10 in the Mesh Guard (Table 1). Comparing translucent shelters, the percent light transmissions in the Protex and Tree-Pro, were more than twice, and Miracle Tube shelters were about three times, that of the Tubex brown shelter. The percent light transmission in the new Tubex green was not significantly higher than the Tubex brown ($p \leq 0.05$).

The r:f-r ratio in the open was 1.00. The mean r:f-r ratio values inside Blue-X shelter (0.40 ± 0.006) and Protex shelter (0.49 ± 0.002) were lower than values obtained inside Tubex brown, Miracle Tube, Tree-Pro and Mesh Guard shelters, with Tubex green in between (Table 1).

The maximum temperature inside translucent shelters was 13-20° F higher than outside through the afternoon, and generally higher than native forest understory conditions (Table 2). Protex and Tree-Pro shelters (designs with side vents) were cooler than Tubex brown and Miracle Tube.

Table 1: Summary of mean percent PPF transmission and R:f-r ratio of oak-hickory forest understory open canopy (OC) and closed canopy (CC) tree shelters.[a]

	Light transmission %				Red:far-red ratio			
Forest understory	Mean±SE	OC	CC	Range	Mean±SE	OC	CC	Range
Green Ridge State Forest	6.4±0.9	16.3±2.84	4.9±1.83	0.7-65	0.29±0.02	0.34±0.03	0.16±0.01	0.18-0.69
Thurmont area	3.6±0.7	9.1±2.22	2.7±1.41	0.5-33	0.28±0.02	0.33±0.02	0.15±0.02	0.10-0.70
Monocacy NRMA	2.3±0.5	6.8±2.51	1.8±1.92	1.8-33	0.30±0.02	0.35±0.04	0.17±0.02	0.10-0.80
Tree shelters								
Mesh Guard	46±0.10	--	--	45-46	0.96±0.002	--	--	0.94-0.98
Miracle Tube®	34±0.16	--	--	31-41	0.86±0.001	--	--	0.86-0.87
Tree-Pro®	30±0.31	--	--	29-35	0.87±0.001	--	--	0.87-0.88
Protex®	28±0.12	--	--	27-29	0.49±0.002	--	--	0.48-0.51
Blue-X®	22±0.36	--	--	18-24	0.40±0.006	--	--	0.35-0.43
Tubex® green	16±0.36	--	--	15-16	0.66±0.001	--	--	0.65-0.66
Tubex® brown	12±0.20	--	--	10-13	0.81±0.001	--	--	0.79-0.82

[a] Measurements at the oak-hickory forests were made in July 2001 between 12:00 and 3:00 pm on a clear day. Measurements inside tree shelters were made above seedlings (at a height of 24 in. above ground) in July 2000 and Apr. 2001 between noon and 3:00 pm on a clear day when light levels are expected to be high. Values of PPF transmission are mean percent open light transmitted into the tree shelters. Mean ± (standard srror) (SE) of 50 readings for both PPF and r:f-r ratios.

Table 2: Summary of daytime air temperature (°F) of oak-hickory forest and tree shelters.[b]

Oak-hickory forest understory air temperatures					Tree shelters air temperatures			
	Open	Understory		Temp. Differences				Temp. Differences
Forest Locations	(Range)	Mean ± SE	Range	U-O	Tree shelters	Mean±SE	Range	T-O
Green Ridge	85-100	80 ± 0.8	73-83	-14 ± 0.9	Mesh Guard	87 ± 1.8	75-92	7
Thurmont	92-100	90 ± 1.2	83-97	-6 ± 0.8	Protex®	92 ± 2.6	75-100	13
Monocacy NRMA	83-100	86 ± 1.6	77-92	-10 ± 1.0	Tree-Pro®	93 ± 2.5	77-99	18
					Tubex® brown	96 ± 2.5	78-101	19
					Miracle Tube®	96 ± 2.5	78-101	20

[b] Oak-hickory forest understory mean, range and temperature differences between the understory and open (U-O). Mean ± SE for 7 days observation between July 7 and July 30, 2001. The temperature was calculated from 8 hours (9:00 am to 4:00 pm) data to avoid the shading effect of trees in the open. Tree shelters mean, range and temperature differences from adjacent open area (T-O). mean ± SE for inside tree shelters (30 days observation between July 7 and August 8, 2000). The values were obtained 24 in above ground for the hours (between 9:00am to 5:00pm) for each day when temperatures are expected to be high.

Seedling survival, height and diameter increment

Seedling survival

Mean survival was high for most species and did not differ significantly among treatments at $p \leq 0.05$ (Table 3, Figure 2). Survival of flowering dogwood (54%) and black walnut (79%) were lower than that of other species, which averaged over 96% (Figure 2). Interaction effects of species and treatments, although not large, were significant, complicating interpretation.

Height increment

Seedlings in tree shelters had significantly greater height increment than unsheltered ones, averaged over all species, the greatest treatment effect seen (Table 3, Figure 3). For translucent types, tree shelters that transmitted greater light showed greater average height increments for most species, i.e. Tubex brown < Protex < Tree-Pro < Miracle Tube (Figure 3, Table 1b). Mean height increments of all species grown inside the high-light-transmitting Miracle Tube were significantly taller (16 in.) than the low-light-transmitting Tubex brown shelters, and more than twice as tall (66 in.) as unsheltered seedlings (28 in.). The mean height increments of green ash, black walnut and oak seedlings with shelters after three growing seasons was three times that of unsheltered seedlings, while flowering dogwood seedlings' increment was more than twice. Generally, seedlings of all species grown in the Mesh guard had lower height increment compared to translucent shelters, except for American sycamore and flowering dogwood, where increment was higher than Tubex brown. Also, American sycamore seedlings increment without shelters were taller than in Mesh guard or Tubex brown shelters. There was a very highly significant difference in height increment among species (Table 3, Figure 3). Green ash and American sycamore seedlings had significantly higher increments, while black walnut and eastern white pine had significantly lower increments.

Diameter increment

Diameter increments were significantly lower for sheltered seedlings ($p \leq 0.01$), all species combined (Table 3, Figure 4). However, looking at individual species, green ash and northern red oak seedlings averaged lower diameter increments when unsheltered. Also, diameter increments did not differ significantly among treatments for pin oak, black walnut and flowering dogwood. Overall, diameter increments were significantly lower in seedlings grown in the Mesh Guard and Tubex brown than their counterparts. Generally, seedlings inside translucent tree shelters increased in diameter with increasing light transmission: Tubex brown < Protex <

Tree-Pro < Miracle Tube. Increments were significantly lower in seedlings grown in the Mesh Guard and Tubex brown than their counterparts. Generally, seedlings inside translucent tree shelters increased in diameter with increasing light transmission: Tubex brown < Protex < Tree-Pro < Miracle Tube.

Table 3: Effects of tree shelters (Tubex brown, Protex, Tree-Pro, Miracle tube and Mesh guard) and no shelter on seedling survival percent, height and diameter increment of seven tree species after three growing seasons.[c]

Variables	Source	F-ratio	Level of Significance
Seedling survival %	Initial size	0.71	ns
	Treatment	1.89	ns
	Species	59.51	***
	Treatment-Species	1.79	*
Height	Initial height	4.50	*
	Treatment	48.82	***
	Species	101.55	***
	Treatment-Species	4.86	*
Diameter	Initial diameter	6.11	*
	Treatment	12.84	**
	Species	182.97	***
	Treatment-Species	3.00	*

[c] ANOVA (NS, not significance; * = @ $p \leq 0.05$; ** = @ $p \leq 0.01$; *** = @ $p \leq 0.001$).

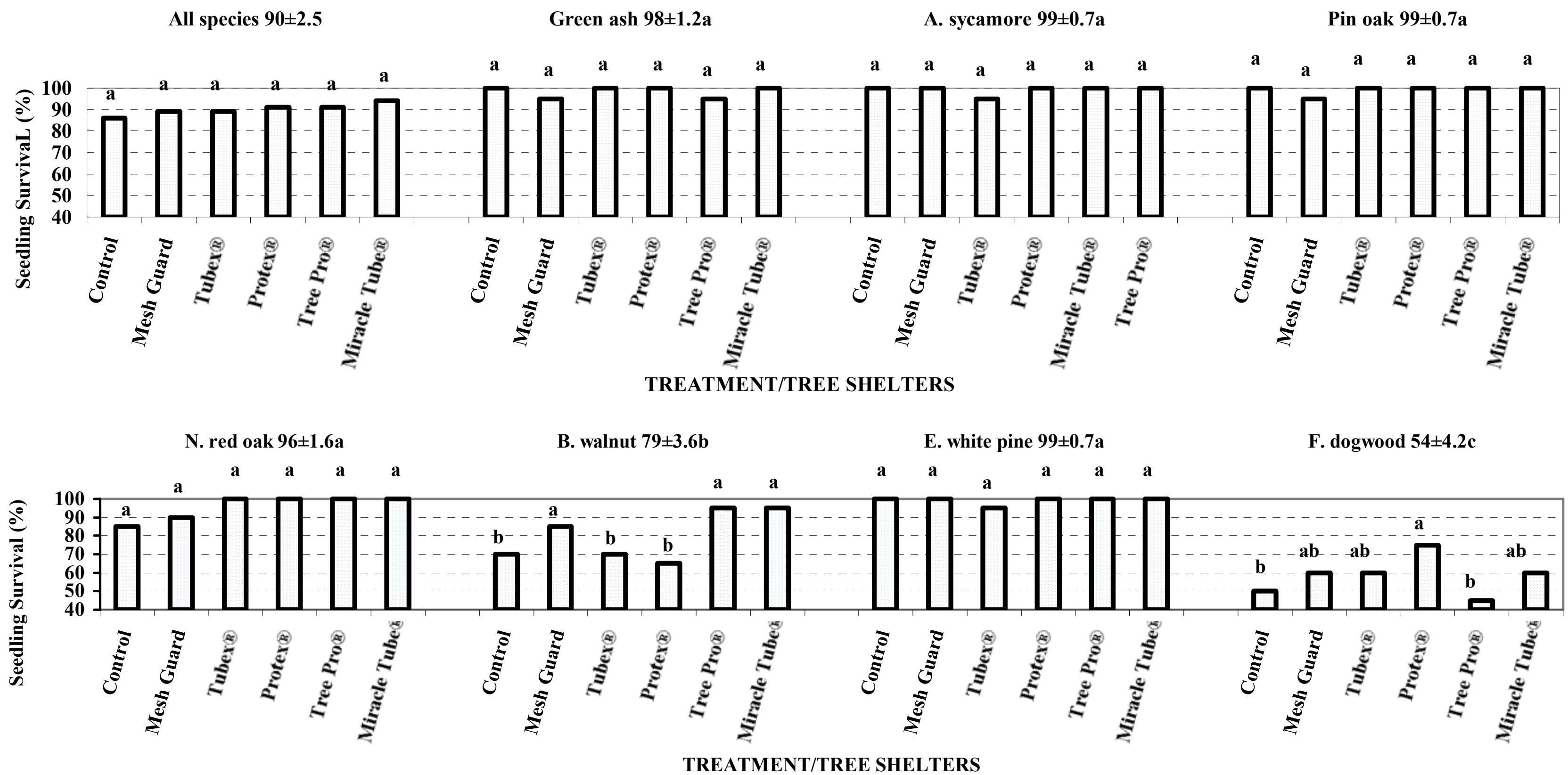

Figure 2: Seedling survival (%) for different species grown inside different tree shelters and control (unsheltered) at the end of third growing season. ANOVA level of significance $p \leq 0.05$. Mean ± standard error (SE) of 140 seedlings. Tukey's HSD test. Mean followed by the same letter(s) are not significantly different from each other @ $p \leq 0.05$.

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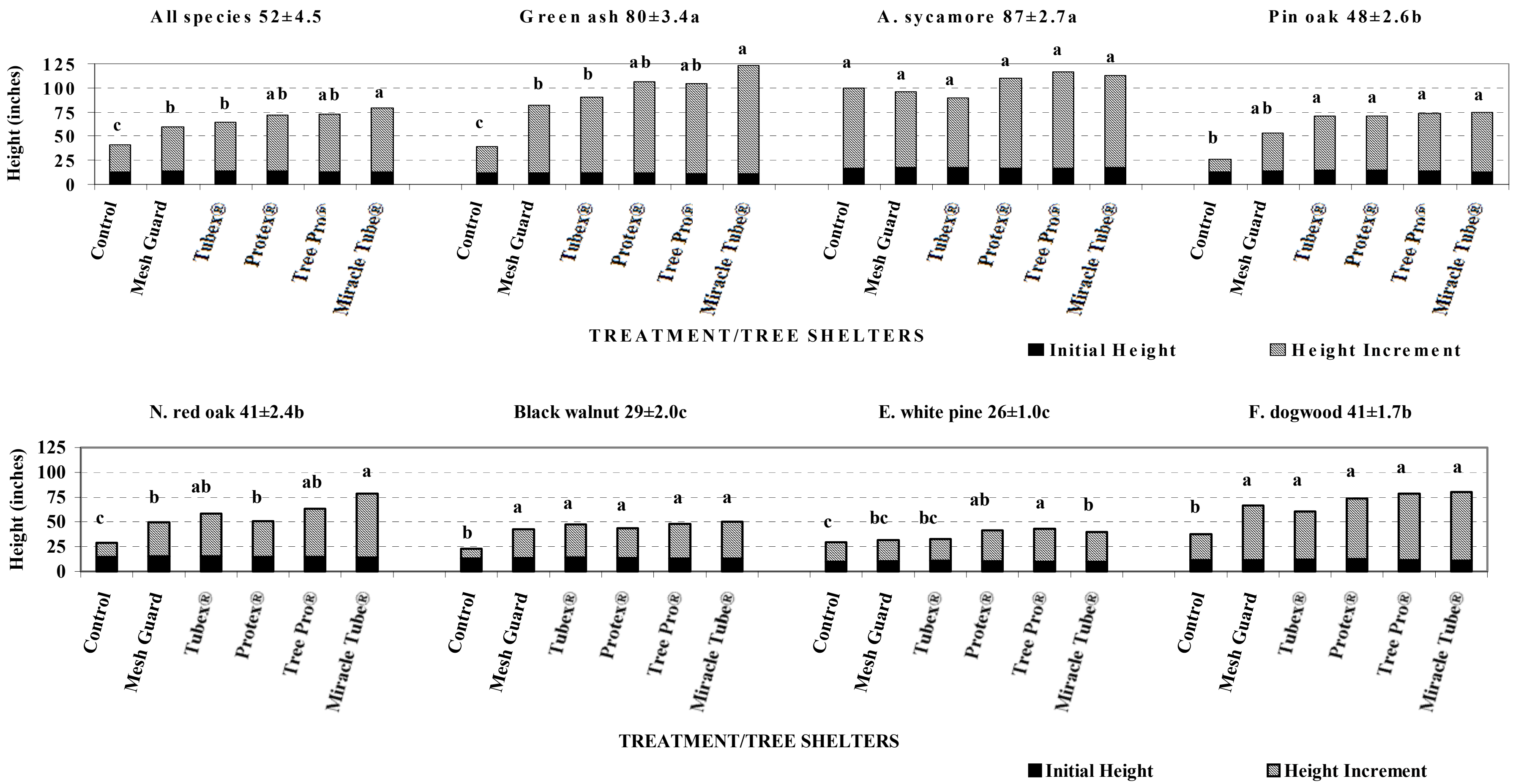
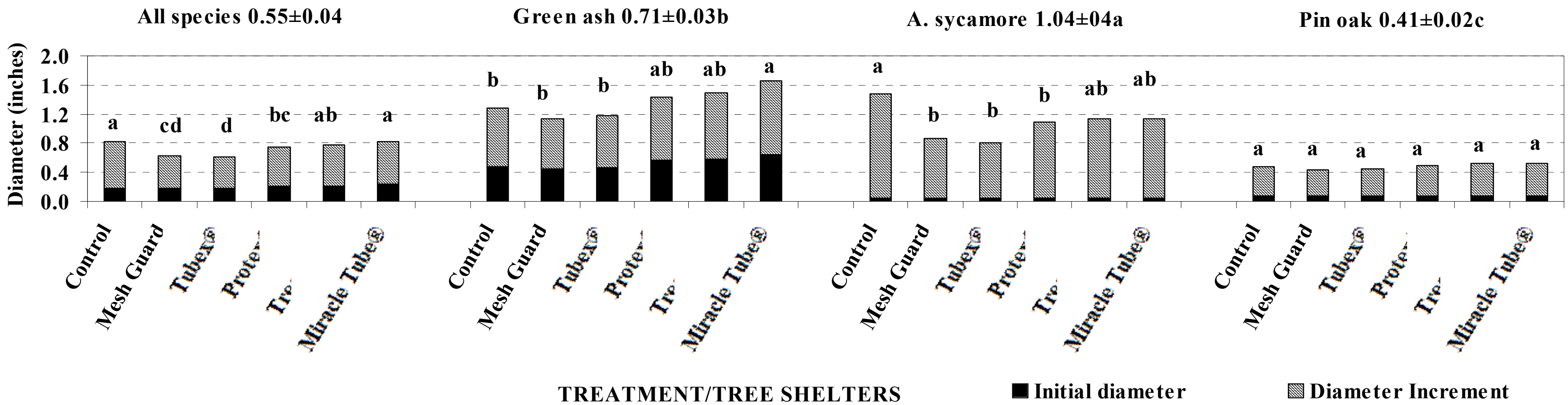


Figure 3: Summary of the effect of percent light transmission inside tree shelters on height increment after three growing seasons inside four 48-in.-tall translucent shelters, mesh guard shelters, and control. Mean ± SE height increment of live seedlings. Mean ± SE height increment comparing the different species is given at the top of the Figure. ANOVA and Tukey's HSD test. Mean followed by the same letter(s) are not significantly different from each other @ $p \leq 0.05$.



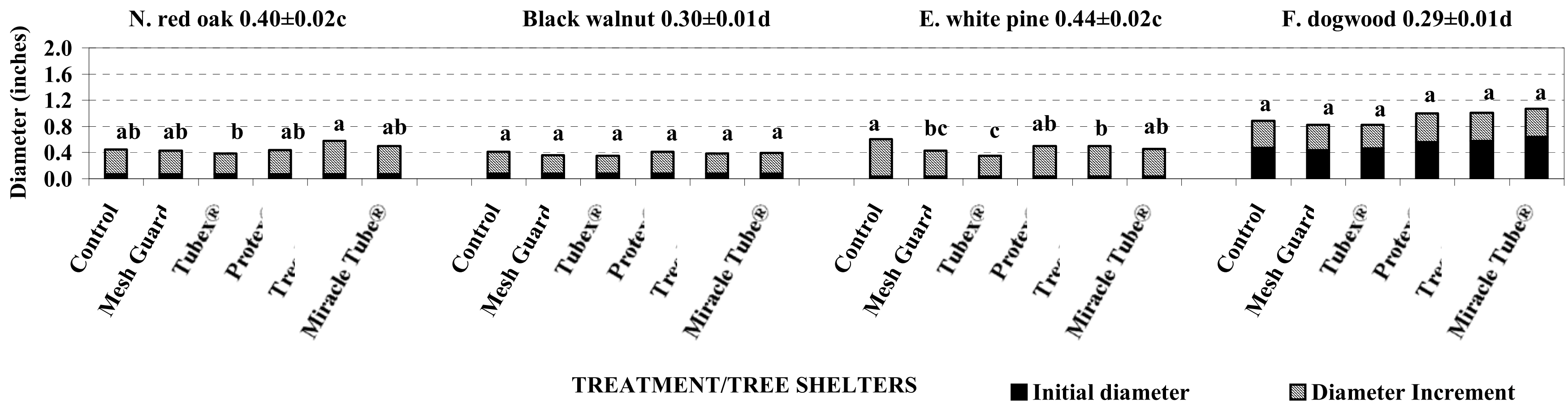


Figure 4: Summary of the effect of percent light transmission inside tree shelters on diameter increment after three growing seasons inside four 48-in.-tall translucent shelters, Mesh Guard shelters, and control. Mean ± SE diameter increment of live seedlings. Mean ± SE diameter increment comparing the different species is given at the top of the Figure. ANOVA and Tukey's HSD test. Mean followed by the same letter(s) are not significantly different from each other @ P ≤ 0.05.

Discussion

Light Transmission (PPF), red:far-red Ratio and Temperature Environment

Irradiance values found here were generally similar to results from other studies in temperate forests, although the methods and equipment used by different workers varied. Canham *et al.* 1990, using hemispherical photography, reported mean values of 0.6% and 1.3% global photosynthetically active radiation (PAR) transmission for temperate forests of Douglas-fir-hemlock forest in the Cascade Mountains and hardwood forests in Ohio. These light levels are apparently considerably lower than the mean transmission values of 2.3-6.4% (Table 1) obtained in this study. They are, however, comparable to the transmission values of 2.6 to 56.7% reported for the coniferous forest stand in Vancouver Island, British Columbia, Canada (Vales and Bunnell 1988), 5.2% in spruce - balsam fir forest in Great Smoky Mountain National Park, (Canham et al. 1990), 2.9-33.1% for *Juniperus – Afrocarpus* forest in Arba-gugu, Ethiopia (Sharew et al. 1996, Sharew et al. 1997).

Levels of mean percent light transmissions inside tree shelters were higher than the mean percent light transmissions recorded at the oak-hickory forest floors. The three main features of forest understory shade-the reduction of light with an appropriate reduction in the r:f-r ratio; lower daytime air temperature, and shifting light/energy patterns such as sunflecks-are lacking inside tree shelters. These features are particularly important when considering rapid fluctuations of the environment, in particular sunflecks, wind and rain (Pearcy et al. 1985). Light transmission in the Protex, Tree-Pro, Blue-X and Miracle Tube shelters is close to the upper range of the open canopy light transmitted at the oak-hickory forest floor. We noted lower light transmission values inside Tubex brown shelter than values reported by other authors (Minter et al. 1992, Kjelgren et al. 1997), probably due to the difference in the time of the day when measurements were taken. Light transmission values in sheltered locations are usually close to open during hazy and overcast days compared to clear days (Morgan and Smith 1981). We measured light transmission on a clear sunny day between noon and 3:00 pm, when light levels are expected to be high, compared to the values averaged over 12-hour days for different days. However, all tree shelters light transmission values reported by other authors are much lower than those suggested by tree shelter suppliers.

The r:f-r ratio obtained in the oak-hickory forest understory in the present study (Table 1), is similar to the values reported by other authors for other deciduous forests (e.g., Morgan and

Smith 1981). The r:f-r ratio values in the forest understory decreased with decreasing light transmission, proportional to the crown density. Crowns in the overstory absorb part of the blue and red light and reflect or transmit green, yellow and far-red, resulting in a strong depletion of the red waveband and relatively weak attenuation of the far-red waveband (Lee 1987). This change in the light environment of understory plants is important in triggering the onset of growth of seedlings and saplings (Canham et al. 1990). Several studies have demonstrated the morphogenetic responses of increased seedling height growth of shade intolerant and intermediate species (e.g., *Terminalia ivorensis, Juniperus procera, Afrocarpus gracilior, Pinus radiata*), (Kwesiga and Grace 1986, Warrington et al. 1989, Sharew et al. 1996). The mean r:f-r ratios recorded in the oak-hickory forest understory were much lower than the values obtained inside most tree shelters in this study, and no sources of published r:f-r ratio data on tree shelters were found for comparison. The higher r:f-r ratios recorded inside Miracle Tube, Tree-Pro, Protex and Blue-X shelters were within the natural range for that light level (Table1). In contrast, the r:f-r ratios inside lower light transmitting Tubex brown and Tubex green shelters were higher than the natural range. It may be difficult to simulate all features of the forest understory inside tree shelters. However, matching reductions in light transmission with increases in proportion of far-red light could take advantage of seedling growth stimulation in tree shelters.

Temperature values obtained inside tree shelters in this study are similar to the values reported by other authors (Potter 1988, Minter et al. 1992, Kjelgren et al. 1997). Despite a lower light transmission inside translucent tree shelters (Table 1), daytime temperatures inside tree shelters were generally higher than the temperature values obtained in the oak-hickory forest understory, Mesh guard shelter, and the ambient (Table 2), probably due to minimal convective cooling inside translucent tree shelters (Kjelgreen 1994). On the other hand, air temperatures are lower near the forest floor than those at the top of the canopy during the periods when the radiation balance is positive (Lee 1987). Leaves in the canopy intercept most of the solar radiation, so that leaf and air temperatures at the forest floor are moderated (Wenger, 1984).

Seedling survival, height and diameter increment

Tree shelters did not significantly affect seedling survival in this trial, although survival was uniformly high for all but two species and species interaction effects were present. Some other studies (Minter et al. 1992, Ward et al. 2000) did not find significant effects on survival, although many others have. The increase in seedling height and decrease in diameter increment inside translucent shelters compared to those without shelters is consistent with other reports (Ponder 1995, Strobl and Wagner 1996, Kjelgren et al. 1997). The presence of treatment-species interactions complicates interpretations, but the increased height growth with shelters was consistent except for sycamore. Seedlings averaged 15% - 31% more height and 26% - 30% more diameter increment in the higher light transmitting translucent tree shelters - Protex, Tree-Pro and Miracle Tube shelters - than in the low light transmitting Tubex shelter with high r:f-r ratios (Figure 3 and 4).

Generally, seedlings grown in shelters had slim stems with thinner and wider leaves compared to the unsheltered seedlings, with the greatest effects in the low light transmitting and smaller diameter shelters. The smaller diameter increment under low light probably was a result of forced directional growth and absence of wind-induced trunk movement to stimulate diametric growth (Harris et al. 1976).

Seedlings in the ventilated, wider-diameter Protex and Tree-Pro shelters with lower temperatures were stronger than their counterparts. Unventilated tubes created tall, slim seedlings with less ability to resist winds following shelter removal, arguing for the use of ventilated wider diameter tree shelters. Reduced diameter growth in low light and in the absence of wind-induced trunk movement is known to results in weak stems that cannot stay upright without support (Kjelgren et al. 1997). However, the ventilated shelters expose lateral growth through the side openings to deer browse.

The increased temperatures seen in the tubes may increase the rate of growth and metabolism of seedlings inside tree shelters, especially since the maximum temperature seen (101º F) was lower than the 115º F limit where respiration rates exceed photosynthesis (Swistock et al. 1999). Furthermore, temperatures at the leaf surfaces are lower than the tree shelters internal air temperature (Potter 1988).

Despite higher light transmission and lower air temperature, the reduced seedling growth in the Mesh guard shelter may be attributed to factors other than light transmission. The flexible plastic mesh closes together to cover or shade the seedling leaves, restricting lateral shoot expansion, and shoots growing through the mesh are browsed heavily, reducing leaf area and ability to capture available light.

Individual species differences are important, seen in the large species effects in all results. All species except American sycamore showed a significant height increment, with few increases and some decreases for diameter growth. Sycamore showed no benefit from the use of tree shelters. Some authors group American sycamore with those species that do not exhibit increased growth rate when grown in shelters (Torbert and Johnson 1993). American sycamore seedlings manifested good height and diameter growth without deer damage, under all light conditions, and faster growth than other species under lower light. Sycamore may have an early advantage competing with rapidly germinating herbaceous growth, and the use of tree shelters may not be necessary. Despite the dieback problem with black walnut, we recorded a higher height increment in sheltered seedlings, also reported by other authors (Schultz and Thompson 1996). We obtained good height and diameter growth for eastern white pine inside high light transmitting tubes. Although they did not specify the kind of shelter used, Ward et al. (2000) noted increased height growth for sheltered eastern white pine seedlings. Green ash, pin and northern red oaks, and flowering dogwood unsheltered seedlings averaged lower or equal diameter growth compared to high light transmitting shelters because these seedlings were frequently browsed and re-measurements were taken from re-growth.

Recommendations

The results of this study suggest the use of higher light transmitting tree shelters (e.g., Protex, Tree-Pro and Miracle Tube) for a taller seedling with better diameter growth within a shelter. The light transmission characteristics of two new makes of tubes available only after the installation of field trial can give insight on probable utility. Based on the light values examined, the Blue-X tree shelter is close to the Protex for both light transmission and r:f-r ratio, and may have similar performance, especially if the construction is improved to facilitate installation. The new green Tubex shelter had somewhat higher light transmission and lower r:f-r ratio than the earlier brown shelter, suggesting that growth is likely to be greater in the new green version. Time and cost estimates for installation of tree shelters were not recorded during this study but could be significant, especially with shelters such as Protex, Tree Pro and Blue-X that must be assembled before installation. Generally, pre-assembled shelters with pre-inserted attachment ties speed up installation. Other recommendations include:

- To encourage a better seedling height increment, tree shelter suppliers should consider simulating natural forest floor ranges of r:f-r ratios, with lower ratios for shelters with low light transmission, similar to Protex and Blue-X.

- Ventilated tubes (e.g., Protex and Tree-Pro) can be used to encourage stronger stems and diameter growth, although deer severely browsed branches growing out side openings.
- The use of shelters on American sycamore seedlings may not be necessary.
- The use of tree shelters >3.5 inches diameter (at least 4 in.), and >48" (at least 54 in") tall may improve seedling growth and protect from deer browse. Smaller diameters restricted lateral shoot and twig growth, and deer browse was observed on most species where foliage grew out of the shelters.
- Deer repellent spray treatment did not protect the seedlings either from deer or rabbit damages in this field trial.

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