Establishment in Treeshelters II: Effect of Shelter Color on Gas Exchange and Hardiness

Roger Kjelgren¹, David T. Montague², and Larry A. Rupp³

Department of Plants, Soils, and Biometeorology, Utah State University, Logan, UT 84322

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Abstract. We investigated the microclimate, gas exchange, and growth of field-grown Norway maple (*Acer platanoides* L.) and green ash (*Fraxinus pennsylvanica* Marsh) trees nonsheltered, and in brown and white shelters. Shelter microclimate—air temperature (T_a), vapor pressure deficit (VPD), and radiation—and tree leaf area, growth in diameter, stomatal conductance (g_s), and photosynthesis were measured during the first growing season after bare-root transplanting. Bark temperatures in midwinter were also measured. Treeshelter microclimate was greenhouse-like compared to ambient conditions, as shortwave radiation was lower, and midday T_a and relative humidity were higher. Although trees in shelters had greater shoot elongation and higher g_s than trees grown without shelters, photosynthesis was not different. White shelters allowed 25% more shortwave radiation penetration and increased T_a by 2 to 4 °C and VPD by 0.5–1 kPa over brown shelters. However, tree growth and gas exchange generally were not affected by shelter color. Winter injury was increased for trees in shelters and varied with species and shelter color. Both species exhibited shoot dieback in shelters the spring following a winter where bark temperatures varied 40 to 50 °C diurnally. More new growth died on maple, particularly in white shelters where several trees were killed. These data suggest that supraoptimal summer and winter temperatures may reduce vigor and interfere with cold tolerance of some species grown in shelters.

Previous work with translucent plastic shelters used in establishing small trees has demonstrated reduced herbivory (Potter, 1988), more shoot elongation (Burger et al., 1992; Kjelgren, 1994), increased survival (Kjelgren and Cleveland, 1994), and reduced water use (Kjelgren, 1994). However, shelters reduced expansive trunk growth (Burger et al., 1992; Kjelgren, 1994), increased shade acclimation, and resulted in supraoptimal air temperatures (Kjelgren, 1994), and possibly decreased winter hardiness (Kjelgren and Rupp, 1997). How greenhouse-like conditions in shelters affect photosynthesis, which in turn would affect a number of growth processes, and winter hardiness of different species has not been investigated. Also, color of the plastic used for the shelter may alter irradiance and temperature patterns. Consequently, the effect of shelter color on shade and heat, and thus on photosynthesis, also may vary with species. This study

investigated how shelter color affects growth, gas exchange, and winter hardiness of two tree species during first-year establishment.

Materials and Methods

The study was conducted at the Utah State Univ. farm in Logan. We planted 2-m-high, bare-root seedlings of Norway maple and green ash in a randomized complete-block design with five replicates on a well-drained Millville silt loam (Kjelgren and Rupp, 1996) in Mar. 1993. Each block was a row of six trees, with 2-m-tall brown, white, and nonsheltered control treatments for each species randomly assigned within a row. Prior to shelter placement, all trees were pruned to 0.3-m height just above the most basal latent bud to ensure that the current-year's shoot growth originated from about the same point on each tree. Immediately after pruning, translucent brown and white shelters (Treessentials, St. Paul, Minn.), ranging in interior diameter from 80 to 100 mm, were placed over the sheltered trees and buried 50 mm into the soil to eliminate air movement through the shelter. Shelters were then secured to a same-height metal rebar anchored 200 mm into the soil. Trees were irrigated with 23 L of water weekly, sufficient to meet anticipated tree water requirements, using a drip emitter supplying 4 L·h⁻¹ (Kjelgren and Rupp, 1997).

We investigated shelter microclimate by measuring ambient shortwave radiation, air temperature, and relative humidity (RH). On 7

d at various intervals in August, a horizontally leveled pyranometer (model 200SA; LI-COR, Lincoln, Nebr.) was fixed to the wall of one shelter of each color at 0.5-m height, immediately above the tree crown. Since the limited spectral response of this pyranometer was calibrated to the full-sun daylight spectrum, values were later corrected to a star pyranometer (model 3020; Weathertronics, Sacramento, Calif.) with a broader spectral response in the blue and infrared wavebands. A combination humidity/temperature sensor (HMP35 sensor; CSI, Logan, Utah) was also inserted 40 mm into the shelter at canopy level (0.75 m) to measure shelter air temperature and RH. The sensor was shaded by foliage to avoid errors from direct exposure to solar radiation. Indicated microclimate parameters were scanned every 10 s and averaged with a datalogger (model 900; Omnidata, Logan, Utah) every 15 min. Ambient radiation, temperature, wind speed, and humidity were measured ≈50 m away from the study site at a fixed weather station with identical sensors positioned at 2-m height.

In mid-August, midday stomatal conductance (g_s) and photosynthesis were measured with a steady-state porometer and infrared gas analyzer (models 1600 and 6200, respectively; LI-COR) on three representative, fully illuminated, mature leaves per tree. Sheltered g_s was measured through a small window cut into the south side of the shelter at midcanopy level. Measurements were taken as rapidly as possible after the window was opened so outside conditions did not affect g_s (Kjelgren, 1994). The window was taped shut between measurements to prevent air movement into the shelter. Photosynthesis was similarly measured, except that an excised section of shelter was placed over the cuvette so that light levels were similar to those inside the shelter.

Growth was also measured. In late summer, 2-cm² disks were removed from five separate leaves per tree, dried at 60 °C for 1 d, weighed, and then specific leaf area (SLA) was determined as cm²·g⁻¹ of leaf tissue. Trunk diameter was measured prior to budbreak in early spring and after leaf drop in the fall with a digital caliper at 0.15-m height, below the elongated basal bud. New shoot elongation from the basal bud was measured after budset in early August. In early October, all leaves from each tree were harvested and leaf area was measured with a leaf area meter (model 3100; LI-COR). In late Apr. 1994, winter damage was assessed by removing small sections of bark on the lateral branches, new stem growth, and older basal stem to observe whether the cambium was green and alive. Damage was rated on a scale between 0 and 3, where 0 = cambium from all sections dead; 1 = cambium of all new growth dead but basal stem cambium alive; 2 = basal and new stem cambium alive, but cambium of lateral branches dead; and 3 = no cambial damage.

The effect of winter solar radiation on bark temperatures was measured on consecutive cloudless days on 12–16 Feb. 1994. One tree of each species × shelter treatment in each of three randomly selected replicates was cho-

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¹Assistant Professor. Current address: Dept. of Plants, Soils, and Biometeorology, Utah State Univ., Logan UT 84322.

²Graduate Student.

³Associate Professor.

sen, and a 16-mm² section of bark on the south side of the tree cut on the top, bottom, and one side. A 0.03-gauge copper-constantan thermocouple was then slid under the middle of the partially removed bark section, just beyond the length of the lateral cuts, such that the thermocouple tip was in good contact with the bark and cambium. The area of bark that was separated from the cambium was minimal. Shelter air temperature for these trees was also measured by placing a thermocouple at midcrown level through the bottom of a styrofoam cup, with its opening oriented north to avoid confounding radiation errors. Thermocouple output was scanned every 15 s and recorded as 15-min averages.

Analysis of variance of the growth and gas exchange data means were performed according to the randomized complete-block experimental design. When model analysis showed a significant interaction between shelters and species, species means within a shelter treatment were compared with *t* tests, and shelter means within a species were compared using Duncan's multiple range test. Vapor pressure deficit (VPD) was calculated from RH and air temperature (T_a) measurements, and T_a , VPD, and solar radiation were then plotted vs. time. Bark temperatures and T_a were plotted vs. time for three representative days. Mean bark temperature for the three trees within a treatment was plotted vs. time for three 24-h periods. Variation in bark temperature within a treatment was expressed with a single error term; the sums of squares were calculated for each 15-min measurement period from midmorning until midafternoon, the period of rapid temperature change, for each day of measurement. The sums of squares were averaged over midmorning to midafternoon, and this average used to calculate the SD.

Results and Discussion

Consistent with other studies, shelter microclimate was similar to that in a greenhouse over the course of a representative summer day, 6 Aug. (Fig. 1). Shortwave radiation was reduced $\approx 30\%$ in the white shelters and 50% in the brown shelters compared to ambient levels. Despite less incoming radiation, T_a in the shelters was substantially higher than ambient (Potter, 1988), due to minimal convective cooling inside the shelters (Kjelgren, 1994). Through the afternoon, air temperatures of shelters of both colors were 14 to 18 °C higher than ambient. Vapor pressure deficits in the shelters were generally 1 kPa lower than ambient from midmorning through late afternoon, which is similar to previous results (Burger et al., 1992; Kjelgren, 1994).

The $\approx 20\%$ higher irradiance in white vs. brown shelters on 6 Aug. affected T_a more than VPD. Air temperatures in the white shelters were 2 to 4 °C warmer than those in the brown shelters through the afternoon, although they converged during the evening and most of the morning. The trend of higher T_a in white vs. brown shelters, and the convergence of shelter temperatures at lower sun angles in morning and evening, were consistent on all study

Fig. 1. Effect of brown or white tree shelter on dawn-to-dusk microclimate on 6 Aug. 1993. (a) Shortwave radiation, (b) vapor pressure deficit, and (c) air temperature.

Table 1. Stomatal conductance and photosynthesis of Norway maple and green ash grown in brown, white, or no tree shelters. Means of variables for which differences were nonsignificant are not shown.

	Stomatal conductance (mmol·m ⁻² ·s ⁻¹)				Photosynthesis (μmol·m ⁻² ·s ⁻¹)			
	18 Aug.		23 Aug.		11 Aug.		12 Aug.	
	Maple	Ash	Maple	Ash	Maple	Ash	Maple	Ash
No shelter	138 b ^z	145 c	168 c		**16.2 a	**30.5 a ^y	---	
Brown shelter	378 a	393 b	416 b		15.3 a	15.0 b	---	
White shelter	**338 a	**447 a ^y	459 a		*13.4 a	*11.1 b ^x	---	
Species	284	328	314	381	14.9	18.9	16.6	20.3
Significance ^z								
Shelter	**		**		**		NS	
Species	**		**		**		**	
Shelter × species	**		NS		**		NS	

^zMean separation within columns by Duncan's multiple range, $P \leq 0.05$.

^ySignificantly different from value for maple, $P \leq 0.05$.

^xSignificantly different from value for maple, $P \leq 0.01$.

NS, **, *Nonsignificant or significant at $P \leq 0.01$ or 0.05, respectively.

dates. In the white shelters, VPD was 0.2–0.5 kPa higher than in the brown shelters, but these levels were low compared to VPD measurements on other dates. Midday VPD (1100–1400 hr) averaged over the other six study dates was 1.1 ± 0.4 kPa higher in the white than in the brown shelters, ranging from 0.5 to 1.5 kPa for the brown and from 1.5 to 2.5 kPa for the white. These values, though, were still substantially <3.5–4.0 kPa ambient VPD that occurred during the study dates.

Gas exchange varied between species and among treatments (Table 1). Conductance of trees in shelters was more than twice that of the nonsheltered trees, similar to results reported by Kjelgren (1994). While trees in white shelters had significantly higher g_s than trees in brown shelters, these differences were small compared to overall g_s levels of the sheltered trees, which were more than twice that of the nonsheltered trees. Higher g_s in shelters, however, did not translate into higher photosynthesis. On 12 Aug. for both species, and 11 Aug. for maple, photosynthesis rates did not differ among shelter treatments. We have no explanation why photosynthesis of nonsheltered green ash was double that of the sheltered treatments on 11 Aug. Carbon dioxide concentrations were probably not limiting (Burger et al., 1992), so lower assimilation rates of sheltered trees, despite more open stomata, resulted from other factors. Higher SLA (Table 2), lower light levels, or higher shelter temperatures that would increase respiration could have limited photosynthesis of the sheltered trees. High SLA, or more leaf area per gram of leaf, is typically associated with less chlorophyll per unit leaf area and lower photosynthetic rates (Bjorkman, 1981), and light levels 50% to 70% of full sun may have been below the light saturation point for these species. In addition, higher T_a , and thus supraoptimal leaf temperatures (Mebrahtu and Hanover, 1991), could have also limited photosynthesis in shelters.

Overall growth of trees in shelters was spindly compared to those growing under ambient conditions (Table 2). While total leaf area was not affected, trees in the shelters had long, narrow stems and very thin leaves. The greater SLA of the sheltered foliage was probably due to a combination of less radiation,

inducing some degree of shade acclimation (Bjorkman, 1981) and higher humidity. Stem elongation in sheltered trees was nearly 0.5 m greater than in trees growing without shelters, but trunk diameter was 35% less. Smaller trunk diameter probably was a result of forced directional growth and absence of wind-induced trunk movement to stimulate diametric growth (Harris et al., 1976), but shade acclimation could have also contributed (Bjorkman, 1981). In addition, green ash was clearly more vigorous than maple. Ash, with generally higher g_s and photosynthesis than maple, had 20% more stem elongation, double the stem diameter, and 60% more leaf area than maple.

Bark temperatures during midwinter were higher in shelters, and exhibited extreme diurnal variation (Fig. 2). Since differences in bark temperatures between brown and white shelters were nonsignificant, values were combined. Maximum bark temperatures reached about the same level all 3 d within a species $\times$ shelter combination. Trees in the shelters had maximum bark temperatures 8 to 12 °C warmer than nonsheltered trees, and 22 to 30 °C warmer than T_a , by early afternoon. Maximum T_a in the shelters (data not shown) was ≈ 16 to 20 °C warmer than ambient. Ash had ≈ 4 °C higher bark temperatures than maple under ambient conditions, but this difference between species increased to 8 °C in shelters. Ash appeared to have darker bark that may have absorbed more radiation. Bark temperatures fell sharply to 2 to 4 °C cooler than ambient T_a at night. For trees in shelters, the diurnal bark temperature range was extreme, ≈ 40 °C for maple to ≈ 50 °C for ash.

Shelters diminished the cold tolerance of trees growing within them (Table 2). The site of the experiment is within U.S. Dept. of Agriculture (USDA) hardiness zone 4B (–29 to –32 °C), but in Winter 1993 the lowest temperature was –22 °C on 28 Jan., and in early February temperatures reached nighttime lows of –18 °C on 2 d. *Acer platanoides* species are rated hardy to USDA zone 4, and *Fraxinus pennsylvanica* species are rated tolerant to zone 3 and are normally resistant to cold damage in zone 4B. Consistent with these cold tolerance ratings, nonsheltered trees were undamaged. However, all sheltered trees sus-

tained winter damage; almost all new growth was killed, but the stem base survived. Maple exhibited more injury than ash, particularly in white shelters. Only lateral ash shoots were killed in white shelters, while several maples were killed to the ground. Extreme diurnal temperature variation in winter bark temperatures may account for the overall increased winter injury of sheltered trees, either directly via rapid temperature changes or, possibly, through dehardening as a function of higher bark temperatures. Diurnal extremes in bark temperature do not explain species differences in winter injury, as sheltered ash exhibited higher daytime bark temperatures but less injury than maple. Norway maple's less general cold tolerance than green ash may have affected its greater injury in shelters, and reduced photosynthesis, hence less overall growth, may also have played a role.

Greater insolation in white shelters resulted in a warmer and drier interior microclimate than in brown shelters, although still much more humid than ambient. While g_s for maple and ash in white shelters increased somewhat, vegetative growth and photosynthesis were unaffected by shelter color. These results suggest that shelter color confers little advantage for establishment within a species, and may create unfavorable conditions for growth in areas with intense and frequent sunlight.

In general, shelters have a mixed effect on tree establishment. They reduce animal damage and transpiration and increase stem elongation (Kjelgren 1994; Potter, 1988). However, low light and high temperatures appear to limit photosynthesis despite more open stomata, and forced directional growth and low light promote stem elongation at the expense of trunk expansion. Reduced expansive growth, in the absence of wind-induced trunk movement, results in weak stems that cannot stay upright without shelter support. If one defines establishment of a tree as the time to resumption of normal growth, shelters in essence delay establishment until enhanced elongation allows the tree to emerge beyond the shelter. Once emerged, the opportunity for wind movement to increase expansive stem growth and structural strength along the length of the trunk is enhanced.

Table 2. Growth responses and winter injury of Norway maple and green ash grown in brown, white, or no tree shelters. Means of variables for which differences were nonsignificant are not shown.

	Leaf area (m ²)		New stem elongation (m)		New stem diameter (mm)		Specific leaf area (cm ² ·g ⁻¹)		Dieback ²	
	Maple	Ash	Maple	Ash	Maple	Ash	Maple	Ash	Maple	Ash
No shelter			1.40 b ³		13.8 a		78 b		3.0 a	3.0 a
Brown shelter			1.84 a		8.5 b		148 a		1.0 b	1.8 b
White shelter			1.86 a		9.5 b		143 a		**0.6 b	**2.0 b ⁴
Species	0.500	0.836	1.53	1.88	1.05	2.32			1.5	2.3
	Significance									
Shelter		NS		**		**		**		**
Species		**		**		**		NS		**
Shelter $\times$ species		NS		NS		NS		NS		**

²Cambial injury was rated on a scale between 0 and 4, where 0 = all shoot tissue dead; 1 = all new growth dead, but basal stem alive; 2 = basal and new stem alive, but lateral branches dead; and 3 = no injury.

³Mean separation within columns by Duncan's multiple range, $P \leq 0.05$.

⁴Significantly different from value for maple, $P \leq 0.01$.

NS, **Nonsignificant or significant at $P \leq 0.01$.

Fig. 2. Ambient air temperature vs. bark temperature of sheltered and nonsheltered green ash and Norway maple trees during 12–14 Feb. 1994. Shelter temperatures represent the mean of white and brown shelters, and error bars represent the average deviation in temperature of three replications during daylight hours.

Winter injury observed in this study is likely related to the extreme diurnal bark temperature variation during sunny winter days. We could not determine whether this injury resulted from temperature extremes, lack of hardening, or both. Injury may be a function of the high winter insolation typical of the local high-desert climate, and thus may not be a problem in a climate with less winter insolation. Potential injury will apparently vary with species, e.g., maple died back more than ash despite cooler bark temperatures. Consequently, the local climate and species should be considered in deciding whether to use shelters to benefit tree establishment.

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