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Influence of Four Tree Shelter Types on Microclimate and Seedling Performance of Oregon White Oak and Western Redcedar

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Cover

Four tree shelter types tested in this study. From left to right: blue unvented, fine-mesh fabric, white unvented, and whited vented.

Abstract

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Four types of tree shelters were evaluated in southwestern Washington for their effects on seedling microenvironment and performance of two tree species. Shelter types were fine-mesh fabric shelters, solid-walled white shelters with and without vent holes, and solid-walled blue unvented shelters. Summer mean and daily maximum air temperatures were increased by 0.8 °C and 3.6 °C, respectively, in solid-walled tree shelters. Shelter color and shelter venting did not influence air temperatures. Tree shelters only affected vapor pressure deficit late in the growing season. Midday photosynthetically active radiation within shelters ranged from 54 percent of full sun in fine-mesh fabric shelters to 15 percent of full sun in blue solid-walled shelters. In the first year after planting, height and diameter growth of western redcedar (*Thuja plicata* Donn ex D. Don) were significantly increased by all shelter types, with blue solid-walled shelters resulting in the greatest height growth. However, in blue solid-walled shelters, photosynthesis and stem diameter growth of Oregon white oak (*Quercus garryana* Dougl. ex Hook.) seedlings were significantly less than for unsheltered seedlings.

Keywords: Tree shelter, microclimate, photosynthesis, *Thuja plicata*, *Quercus garryana*.

Summary

Tree shelters are used to protect planted seedlings from herbivory and to create a microenvironment conducive to rapid seedling growth. Numerous types of tree shelters are commercially available; the most common varieties are plastic solid-walled and mesh-walled shelters. This study, conducted in southwestern Washington, was designed to examine the effects of solid-walled shelters, fine-mesh shelters, vented shelters, shelters of different colors, and unsheltered controls in the context of the regional climate. Shelters tested were fine-mesh fabric (ME), solid-walled white unvented (WU), solid-walled white vented (WV), and solid-walled blue unvented (BU). Tree shelters were applied to seedlings of two frequently browsed tree species native to the Pacific Northwest: Oregon white oak (*Quercus garryana* Dougl. ex Hook.) and western redcedar (*Thuja plicata* Donn ex D. Don).

Relative to ambient conditions, summer mean and maximum daily air temperatures were increased by 0.8 °C and 3.6 °C, respectively, in solid-walled tree shelters. On the five hottest days of the summer, temperatures in solid-walled shelters reached an average maximum of 42.9 °C, significantly hotter than ambient conditions (40.0 °C). Air temperatures in the ME shelter treatment did not differ from ambient conditions except on hot, clear days when air was cooler within the ME shelters. Venting of solid-walled shelters had no effect on interior air temperature, and shelter color affected air temperature only in September and October when blue shelters were cooler than white shelters. Leaf temperature, measured in early September, was somewhat increased by solid-walled shelters and decreased by mesh shelters. Although none of the tree shelters had a significant effect on vapor pressure deficit between June and August, in September, vapor pressure deficit in solid-walled shelters was greater than that of ambient conditions. Intensity of midday photosynthetically active radiation within shelters, relative to full sunlight, was 54 percent in the ME treatment, 38 percent in the WU and WV treatments, and 15 percent in the BU treatment. The ratio of red to far-red light was significantly lower for the BU shelter than for the other shelters, which did not differ from one another.

In the first year after planting, both height and diameter growth of western redcedar were significantly increased by all shelter types. The BU shelter treatment resulted in significantly greater height growth and height:diameter ratio compared to the other shelter treatments. For Oregon white oak seedlings, however, the BU shelter treatment also was associated with a reduced rate of photosynthesis and reduced stem diameter compared to the unsheltered treatment. The various tree shelter designs altered microclimate in a variety of ways, particularly in regard to the light environment. These effects on microclimate, and the differing growth responses of species to the same shelter types, suggest that tree shelter selection should be based on the light requirements of the planted species, among other factors.

Contents

Introduction

Tree shelters were first developed in 1979 to protect planted seedlings from animal browse and to create a greenhouse-like environment for the seedlings (Tuley 1985). It soon became apparent that tree shelters significantly increased early survival and height growth of some species of tree seedlings (Potter 1988). Although tree shelters are expensive relative to most other establishment costs, they may be justified where browse pressure is severe or where a high value is placed on the success of individual tree seedlings. Although the most common type of tree shelter is a 0.6- to 1.5-m-tall plastic tube, numerous varieties are commercially available including shelters with single- and double-layer walls, shelters with vented walls, plastic mesh shelters, and fabric shelters.

The microclimate within a solid-walled shelter is often substantially different than ambient conditions.

The effect of a tree shelter on a seedling's microenvironment is a function of shelter design and local climatic conditions. Although the ventilation of mesh-walled tree shelters attenuates their effects on microclimate, the microclimate within a solid-walled shelter is often substantially different than ambient conditions. For solid-walled tree shelters, interior air temperature is greater than ambient conditions during the daytime (Bellot et al. 2002, Evans and Potter 1985, Kjelgren and Rupp 1997, Ponder 1995). In some regions, air temperature in tree shelters is high enough to negatively affect seedling performance (Kjelgren and Rupp 1997); however, the addition of vents to solid-walled shelters has been shown to moderate shelter air temperature (Bellot et al. 2002, Swistock et al. 1999). The environment within a solid-walled tree shelter is typically more humid than ambient conditions, particularly when a shelter contains a large, transpiring seedling (Kjelgren et al. 1997, Minter et al. 1992, Potter 1988). Carbon dioxide (CO_2) concentration also is affected by solid-walled tree shelters. The CO_2 concentration rises above the ambient level at night as a result of soil respiration but then decreases rapidly in the morning and remains below the ambient level during the day owing to the combination of assimilation by the seedling and a lack of air circulation (Dupraz and Bergez 1999, Peterson et al. 1995). Tree shelter color and material also significantly affect the amount and quality of solar radiation reaching the seedling (Jacobs and Steinbeck 2001, Kjelgren 1994, Sharew and Hairston-Strang 2005). In a Mediterranean climate with a dry growing season, solid-walled tree shelters have been shown to improve soil water availability owing to the condensation that flows down the inside of the shelter and enters the soil in the vicinity of the seedling (del Campo et al. 2006).

The effect of solid-walled tree shelters on seedling height growth is positive and often dramatic (e.g., Burger et al. 1992, McCreary and Tecklin 2001, Potter 1988, Sharrow 2001), but the effects of shelters on other growth variables differ widely by study. For example, diameter growth of seedlings has been increased (Dubois et al. 2000, Sharrow 2001) or decreased (Quilhó et al. 2003, Sharew and Hairston-Strang 2005) by solid-walled shelters. Root growth also has been shown to increase (Bellot et al. 2002, Ponder 1995) or decrease (Burger et al. 1997, Mayhead and Boothman 1997) for seedlings grown in tree shelters. This variation in seedling response to tree shelter is apparently the result of multiple interacting variables including tree species, environment, and shelter type.

To predict how a tree shelter will influence seedling performance, it is necessary to understand how the shelter affects the seedling microclimate under local environmental conditions and how this altered microclimate will affect seedling development. Potential shelter effects on tree seedlings are numerous and include form, phenology, and water use. For example, the reduced photosynthetic photon flux density (PPFD; i.e., sunlight) and lack of stem movement within many solid-walled shelters were suggested to be the cause of the tall, slender form of sheltered seedlings (McCreary and Tecklin 2001). Where cool air temperatures limit seedling development, tree shelters may provide a warmer microclimate leading to earlier budbreak (Sharrow 2001, Svihra et al. 1993). Additionally, the increased humidity that typically occurs within tree shelters reduces the vapor pressure deficit (VPD), which may substantially reduce seedling water use (Bergez and Dupraz 1997, Kjelgren 1994).

In this study in southwestern Washington, our objective was to determine how four tree shelter types influence microclimate and performance of western redcedar (*Thuja plicata* Donn ex D. Don; redcedar) and Oregon white oak (*Quercus garryana* Dougl. ex Hook.; oak) seedlings in the context of the mild maritime climate typical of the coastal Pacific Northwest. These species were selected because they are the preferred browse species of black-tailed deer (*Odocoileus hemionus columbianus*) and therefore would likely benefit from tree shelter application. The two species differ in shade tolerance, with oak rated moderately intolerant and redcedar rated tolerant (Minore 1990, Stein 1990). We examined vented and unvented, white- and blue-colored solid-walled shelters, a mesh-walled shelter, and an unsheltered control treatment. We tested the following hypotheses regarding shelter effects on microclimate and seedlings:

Microenvironment Hypotheses

Hypothesis M1: Summer daytime air temperatures within solid-walled tree shelters are greater than ambient air temperatures owing to the combination of insolation and a reduction in convective heat loss.

Hypothesis M2: Daytime VPD will be decreased in solid-walled shelters relative to ambient conditions owing to increased humidity from the transpiration of seedlings and reduced air movement.

Hypothesis M3: Fine-mesh fabric shelters will reduce insolation relative to ambient conditions while allowing mixing of internal and external air; thus, summer daytime temperatures in fine-mesh shelters will be lower than ambient.

Hypothesis M4: Venting of solid-walled tree shelters will moderate their effects on air temperature and VPD.

Seedling Growth Hypothesis

Hypothesis G1: Seedling height growth will be increased by tree shelters as a result of the shelters' effect on light, specifically the reduction of the ratio of red to far-red light. Thus, the positive height growth effect will be greatest for shelter types that have the greatest reduction in the ratio of red to far-red light.

Photosynthesis Hypothesis

Hypothesis P1: Previous research showed substantially greater height growth for outplanted Oregon white oak seedlings in solid-walled tree shelters, regardless of shelter color (Devine et al. 2007); thus, we expect rates of net photosynthesis to be greater for seedlings in solid-walled tree shelters than for unsheltered seedlings because of shelter microclimate conditions including warmer temperatures.

This research was conducted in two phases at the Forestry Sciences Laboratory in Olympia, Washington

Methods

Study Area

This research was conducted in two phases, hereafter referred to as the 2005 study and the 2007 study. Both studies took place at the Forestry Sciences Laboratory in Olympia, Washington (46° 57´ N; 122° 58´ W) at an elevation of 50 m above mean sea level. The study area was level and unshaded; soil was a Cagey loamy sand (mixed, mesic Aquic Xeropsamment) (Soil Survey Staff 2006). Annual precipitation in Olympia averages 1291 mm, with 191 mm occurring between 1 May and 30 September (Western Regional Climate Center 2007). Mean annual air temperature is 10 °C, and mean temperatures in January and July are 3 °C and 17 °C, respectively (Western Regional Climate Center 2007). Competing vegetation in the area of the 2005 study was controlled by a layer of water-permeable landscape fabric covered with bark mulch. In the 2007 study, weeds were pulled by hand throughout the growing season. The study was conducted in a fenced area that prevented damage from deer browse on the unsheltered seedlings.

2005 Study

Study design—
The 2005 study followed a randomized, complete-block design with 12 blocks. Each block consisted of 21 seedling locations (the experimental unit) on a 1.0- by 1.0-m grid. Treatments, arranged in a factorial design, were tree shelter (five levels) and species (two levels). The tree shelter treatment consisted of four shelter types[1] (table 1) and a nonsheltered control (NO). The two species were Oregon white oak and western redcedar. Within each block, the 10 treatment combinations were randomly assigned to two locations each. The extra location in each block was assigned the unsheltered treatment, with oak in six blocks and redcedar in six blocks.

Oak seedlings were 2 + 0 bare-root nursery stock purchased from Mineral Springs Ornamentals nursery in Carlton, Oregon. The seed source was trees adjacent to the nursery. Western redcedar seedlings were Plug + 1 bare-root stock (Puget Sound seed zone) purchased from the Washington Department of Natural Resources Webster Nursery in Olympia. Throughout the study, seedlings were grown in containers set in the ground to prevent rodent damage and to provide the option of root biomass sampling. Ultimately, sampling of root biomass was excluded from the study when it was determined that the majority of oak seedlings grew poorly. The bare-root seedlings were potted in plastic containers, 10- by 10-cm square and 55-cm deep, between 24 February and 3 March 2005. Potting media was Sunshine Mix #2 (SunGro, Vancouver, Canada). To achieve uniform length, oak seedling taproots were pruned at 30 cm below the root collar prior to potting. A piece of copper-impregnated fabric at the base of the container allowed drainage but prevented roots from growing beyond the container. After potting, seedlings remained outside until 5 to 7 April 2005, when containers were buried at their

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1—Four types of tree shelters tested

	Manufacturer/type			
Parameter	**Freegro® fine mesh**	**Tree Pro® unvented**	**Tree Pro® vented**	**ProTex®Pro/Gro solid tube**
Abbreviation	ME	WU	WV	BU
Wall type[a]	2-mm mesh	Double layer	Double layer with holes[b]	Single layer
Color[c]	Beige	White	White	Blue
Height (cm)	91.4	121.9	121.9	121.9
Diameter (cm)	15.2	11.4	11.4	10.2
Vented	Yes	No	Yes	No
Price[d]	$1.88	$2.79	$2.79	$1.91

[a] All shelters are made of polyethylene.

[b] Vent holes are circular, 0.8-cm diameter, and spaced approximately 9 cm apart. Holes are present on the upper 61 cm of the shelter.

[c] All shelters are translucent.

[d] Price per unit for an order of 500 units in 2007; price varies with quantity purchased. Price does not include stake or other installation materials.

specified planting locations so that the soil level within the pot was equal to that of the surrounding ground, and only the lip of the pot (≤1.0 cm) protruded. After pots were placed in the ground, tree shelter treatments were installed. Shelters were supported with wooden stakes located on their north side. The WU, WV, and BU shelters were attached to stakes with plastic cable ties; the ME shelter design included friction clips, which were used to secure the shelter to the wooden stake. The base of each shelter was flush with the ground, and soil was mounded to a height of 2 to 3 cm around the shelter base to prevent air exchange at the bottom of the shelter.

Seedlings were irrigated as needed throughout the growing season (approximately once per week) to maintain adequate soil moisture, and were fertilized at an 8-week interval with water-soluble 20-20-20 fertilizer (The Scotts Company, Marysville, Ohio).

Seedling growth—

After potting, seedling height and stem diameter (at a marked location 15 cm above ground level) were measured. Midway through the growing season (13 July 2005), and at the end of the growing season, seedling height and stem diameter at 15 cm were remeasured.

Air temperature and relative humidity—
Air temperature and relative humidity were measured at 30-min intervals in all treatments using Hobo® Pro Series 08 temperature/relative humidity dataloggers (Onset Computer Corp., Bourne, Massachusetts). Two dataloggers per tree shelter treatment (one per seedling) were installed on 8 April 2005, and two additional dataloggers per tree shelter treatment were installed on 3 June 2005, for a total of four dataloggers per shelter treatment, with two per species-shelter combination. Dataloggers were installed inside randomly selected shelters at a height of 30 cm above ground level. A small plastic shield was used to protect the humidity sensor from direct precipitation. In the NO treatment, dataloggers were mounted approximately 15 cm west of the seedling at a height of 30 cm. Dataloggers in the NO treatment were protected from direct sunlight and precipitation with an 18-cm-diameter, round white plastic shield. This shield was placed above the datalogger and did not impede air movement in its vicinity. Vapor pressure deficit was calculated from simultaneous temperature and relative humidity readings (Lee 1978).

Leaf temperature—
Leaf temperature and air temperature inside shelters were measured in each of the five shelter treatments using paired type-T thermocouples and a Campbell CR10X datalogger and AM25T multiplexer system (Campbell Scientific, Logan, Utah). Two oak seedlings from each shelter treatment were selected for this measurement. On each seedling, one leaf near the top of the terminal shoot was selected for measurement. A type-T thermocouple (38-gauge wire) was woven through the leaf and mounted flush with the abaxial side of the leaf so that it gently pressed against the surface. An identical thermocouple was mounted 30 cm above the seedling to measure air temperature. This thermocouple was shaded by a 4-cm-wide square of white plastic mounted 1 cm above it. Temperatures were recorded every 30 minutes during early September.

Photosynthetically active radiation—
Photosynthetically active solar radiation, measured as PPFD, was recorded simultaneously in the five tree shelter treatments using five LI-190 Quantum sensors (LI-COR Biosciences, Lincoln, Nebraska) and two LI-1400 dataloggers (LI-COR Biosciences). For the purpose of these measurements, a group of shelters was installed without seedlings. Quantum sensors were installed and leveled 30 cm above the ground in the center of each shelter. For the NO treatment, an unsheltered sensor was installed at the same height to receive full sunlight. Data were recorded every 15 minutes from 5:15 until 20:00 PST during August and early September 2005.

Photosynthesis rate—

Photosynthesis rate (net carbon assimilation; A_n) was measured on four oak seedlings per treatment between 10:00 and 14:00 PST on 26 September 2005 using an open-system gas analyzer (CIRAS-1 Portable Photosynthesis System with automatic Parkinson leaf cuvette, PP Systems, Amesbury, Massachusetts). Conditions were clear, and air temperature averaged 22.0 °C during measurements. For sheltered seedlings, an 8.0- by 8.0-cm door was cut in the side of the shelter at the location of the terminal shoot. This door was taped shut other than when the cuvette was inserted to make measurements. On each seedling, measurements of A_n were made at 2-s intervals for at least 120 s on one leaf from the terminal shoot.

2007 Study

Study design—

Owing to generally poor growth of the oak seedlings in the 2005 study (see results), a followup study was implemented in 2007 to again examine the influence of tree shelters on the rate of photosynthesis of Oregon white oak seedlings and to determine how shelters affected seedling morphology. This study was conducted on the same site as the 2005 study, but seedlings were grown in 57-cm-tall raised beds constructed in February 2007. The 24 oak seedlings in this study were 2-year-old bare-root stock from an Olympia, Washington, seed source that were grown in Webster State Nursery in Olympia and planted in the raised beds in March 2007. In early May, prior to budbreak, eight each of the ME and BU shelters were installed around seedlings. An additional eight seedlings were designated as the NO treatment. The 24 seedlings were irrigated daily from July through September using a drip irrigation system (0.63 liters per seedling per day over a period of 20 minutes).

Seedling growth and morphology—

Seedling height and diameter at groundline were measured after planting. The seedlings were harvested on 17 October 2007 and destructively sampled. For each seedling, we recorded height, diameter, average leaf area of 10 typical first- and second-flush leaves (LI-3100 area meter, Li-Cor, Lincoln, Nebraska), number of leaves in first flush, number of leaves in subsequent flushes, and dry weight of stem, foliar, and root components. Dry weights were determined by drying samples to constant weight at 65 °C. Predictions of pre-growing-season dry weight were based on data from 56 seedlings that were destructively sampled at the time the 24 study seedlings were planted. The destructively sampled seedlings were measured for height and diameter, divided into root and shoot components, dried, and weighed.

Data from the destructively sampled seedlings were used to create equations to predict shoot and root dry weight of the 24 study seedlings at the time of planting, based on measurements of height and diameter. Equations were:

$$W_S = 0.8175 + 0.0017D^2H$$
$$R^2 = 0.93$$
$$W_R = - 5.5448 + 2.5664D - 0.062D^2$$
$$R^2 = 0.66$$

where W_S and W_R are dry weights of above- and belowground woody components, respectively, D is seedling diameter, and H is seedling height. Stem and root dry weight growth increments for each seedling in the 2007 study were estimated based on predicted dry weight at the beginning of the growing season and the measured weight at the end of the growing season.

An S2000 spectrometer was used to measure the light spectra within ME, WU, and BU tree shelters.

Ratio of red-to-far-red light—
An S2000 spectrometer (Ocean Optics, Inc., Dunedin, Florida) was used to measure the light spectra within ME, WU, and BU tree shelters containing no seedlings that were installed near the 2007 plantings. The sensor was installed within the shelter at 45 degrees from vertical, facing due south. Four measurements were made in each treatment within 2 hours of solar noon on 26 June 2007. From these measurements of irradiance across spectra (310 to 780 nm), we calculated the ratio of red (655 to 665 nm) to far-red light (725 to 735 nm) for each reading in each shelter treatment.

Photosynthesis rate—
On 3 July 2007, A_n was measured on the study's 24 oak seedlings between 10:00 and 14:00 PST using the CIRAS-1 Portable Photosynthesis System. The sky was clear, and air temperature averaged 21.0 °C during measurements. For these measurements, the same procedure as that used in 2005 was followed. On 9 July 2007, four sets of photosynthesis measurements were made at the following times: 6:30 to 7:30 PST, 9:00 to 10:00 PST, 11:15 to 12:15 PST, and 15:30 to 16:30 PST. On this date, conditions were clear and air temperature averaged 24.9 °C. On 24 August 2007, photosynthesis measurements were made on fully developed second-flush leaves between 12:00 PST and 14:00 PST. Conditions were clear and air temperature averaged 23.8 °C.

Data Analysis

Shelter air temperatures and VPD were analyzed by month and for selected dates using repeated-measures analysis of variance (ANOVA), with tree shelter treatment as a fixed effect and block as a random effect (PROC MIXED, SAS Institute

2005). For monthly analyses, day was the repeating unit of time. For single-day analyses, days representative of typical weather conditions were chosen, and all measurements within 4 hours of solar noon were analyzed. Degree-day accumulation (base temperature = 5.0 °C) was calculated but not analyzed statistically because data from April and May, and therefore all cumulative data, had a sample size of only two sensors per treatment. Leaf temperature and PPFD were assessed graphically but not statistically, as there were only two replicates. Seedling growth and photosynthesis were analyzed with ANOVA. In all ANOVA models, assumptions of normality and equal variance were met. Post-ANOVA mean separations were performed using contrasts (Zar 1999). Contrasts included mesh shelter (ME) versus ambient conditions (NO), solid-walled shelters (WU, WV, BU) versus ambient conditions (NO), vented (WV) versus unvented (WU) solid-walled shelters, and white (WU) versus blue (BU) solid-walled shelters. Significance was judged at the $P = 0.05$ level.

Results

Shelter Effects on Microclimate

Air temperature—

Mean ambient air temperature (i.e., NO treatment) peaked during July and August, averaging 18.6 ºC (table 2). The coolest months of the study were April and October, when the ambient temperature averaged 10.6 ºC and 11.0 ºC, respectively. For all months analyzed (June through October), mean air temperatures within the three solid-walled tree shelter treatments were significantly higher than the ambient temperature. The greatest temperature difference occurred in July when the solid-walled shelters averaged 0.9 ºC warmer. There were no significant differences between the mean ambient air temperature and air temperature in the mesh shelter or between the vented and unvented treatments, but the mean air temperature in the white shelter (WU) was significantly warmer (a difference of 0.3 ºC) than the blue shelter (BU) in October.

From June through October, maximum air temperature was significantly higher in solid-walled tree shelters than in the ambient conditions.

Maximum daily air temperature was greatest in August (33.6 ºC in ambient conditions) (table 3). From June through October, maximum air temperature was significantly higher in solid-walled tree shelters than in the NO treatment, with a difference of 3.6 ºC and 3.3 ºC in July and August, respectively. There were no significant differences in maximum air temperature between the unsheltered and mesh shelter treatments or between the vented and unvented treatments. Maximum air temperature in the white shelter was significantly greater than that in the blue shelter in September and October.

Table 2—Mean monthly air temperature (2005) for five tree shelter treatments, with contrasts testing differences among treatment combinations

Treatment[a]/ contrast	Month						
	Apr	May	Jun	Jul	Aug	Sep	Oct
	°C						
NO	10.6	14.5	15.8 ±0.2	18.5 ±0.2	18.7 ±0.2	13.4 ±0.2	11.0 ±0.1
ME	10.5	14.1	15.7 ±0.2	18.3 ±0.2	18.5 ±0.2	13.4 ±0.2	10.9 ±0.1
WU	11.6	15.3	16.7 ±0.2	19.6 ±0.2	19.6 ±0.2	14.2 ±0.2	11.4 ±0.1
WV	11.9	15.6	16.8 ±0.2	19.3 ±0.2	19.3 ±0.2	14.1 ±0.2	11.3 ±0.1
BU	11.4	15.0	16.4 ±0.2	19.2 ±0.2	19.3 ±0.2	13.9 ±0.2	11.1 ±0.1
	P > F						
NO vs. ME	—	—	0.844	0.679	0.654	0.921	0.308
NO vs. WU, WV, BU	—	—	**<0.001**	**0.003**	**0.015**	**0.002**	**0.003**
WU vs. WV	—	—	0.644	0.481	0.520	0.615	0.411
BU vs. WU	—	—	0.231	0.254	0.518	0.270	**0.020**

Note: n = 2 for April and May; n = 4 for June through October. Standard error is shown where n = 4. Significant contrasts are bolded.

[a] Treatments are no shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

Table 3—Maximum daily air temperature, by month, for five tree shelter treatments in 2005, with contrasts testing differences among treatment combinations

Treatment[a]/ contrast	Month						
	Apr	May	Jun	Jul	Aug	Sep	Oct
	°C						
NO	19.5	24.0	25.9 ±0.4	30.9 ±0.5	33.6 ±0.5	27.1 ±0.4	17.7 ±0.2
ME	20.1	23.7	26.2 ±0.4	30.9 ±0.5	33.4 ±0.5	27.2 ±0.4	18.0 ±0.2
WU	24.0	27.4	29.6 ±0.4	34.6 ±0.5	37.1 ±0.5	31.7 ±0.4	21.4 ±0.2
WV	25.9	28.7	30.6 ±0.4	35.2 ±0.5	37.3 ±0.5	32.3 ±0.4	21.3 ±0.2
BU	22.9	26.3	28.8 ±0.4	33.7 ±0.5	36.3 ±0.5	30.2 ±0.4	19.7 ±0.2
	P > F						
NO vs. ME	—	—	0.597	0.998	0.859	0.878	0.153
NO vs. WU, WV, BU	—	—	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
WU vs. WV	—	—	0.108	0.441	0.733	0.294	0.862
BU vs. WU	—	—	0.190	0.205	0.300	**0.016**	**<0.001**

Note: n = 2 for April and May; n = 4 for June through October. Standard error is shown where n = 4. Significant contrasts are bolded.

[a] Treatments are no shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

On the five hottest days, there were no significant differences in maximum temperature.

On the five hottest days of the summer (as measured in the NO treatment), the solid-walled shelters reached a significantly ($P < 0.001$) higher maximum air temperature (42.9 °C) than the unsheltered treatment (40.0 °C). On the five hottest days, there were no significant differences in maximum temperature between unsheltered and mesh-shelter (39.6 °C) treatments, between unvented and vented treatments (43.0 and 43.3 °C, respectively), or between white (43.0 °C) and blue (42.2 °C) shelter treatments. The total number of hours for the 2005 growing season during which the air temperature was above 35.0 °C were 73, 72, 199, 200, and 170 for the NO, ME, WU, WV, and BU treatments, respectively. The total number of hours during which the air temperature was above 40.0 °C were 5, 3, 47, 51, and 34 for the NO, ME, WU, WV, and BU treatments, respectively. The highest recorded temperature was 45.2 °C, occurring on 19 July in the WV treatment.

On a typical, partly cloudy June day, air temperature in solid-walled tree shelters was significantly warmer than ambient conditions ($P = 0.001$), particularly during periods when the sky was clear (afternoon temperature peaks shown in the larger graph in fig. 1). Air temperature in the mesh shelter treatment did not differ from ambient conditions ($P = 0.156$), and air temperatures among the three types of solid-walled tree shelters did not differ. On a very hot, clear July day, air temperatures in solid-walled shelters were below ambient from 6:00 until 10:00 PST; after 10:00 PST, air temperatures in solid-walled shelters remained above ambient for the rest of the day (fig. 2). Air temperature in the mesh-shelter treatment was cooler than the ambient temperature until 16:00 PST, and remained above ambient until 24:00 PST.

On a typical clear day with morning fog (1 September), air temperatures in solid-walled shelters began near ambient temperature but by afternoon had warmed to approximately 5 °C above ambient (fig. 3). Air temperature in the mesh-shelter treatment was generally cooler than the ambient temperature ($P = 0.035$) and surpassed ambient only in the late afternoon. On an overcast day (4 September), air temperature in the solid-walled tree shelters was 1 to 5 °C above ambient temperature ($P < 0.001$), whereas air temperature in the mesh shelter did not differ significantly from ambient temperature ($P = 0.733$) (fig. 4).

From 9 April through 31 May, 852 degree-days accumulated in the NO treatment. During the same interval, degree-day accumulation in the WV, WU, BU, and ME shelter treatments was 115, 111, 108, and 97 percent of that in the NO treatment, respectively (fig. 5). For the period 9 April through 31 August, degree-day

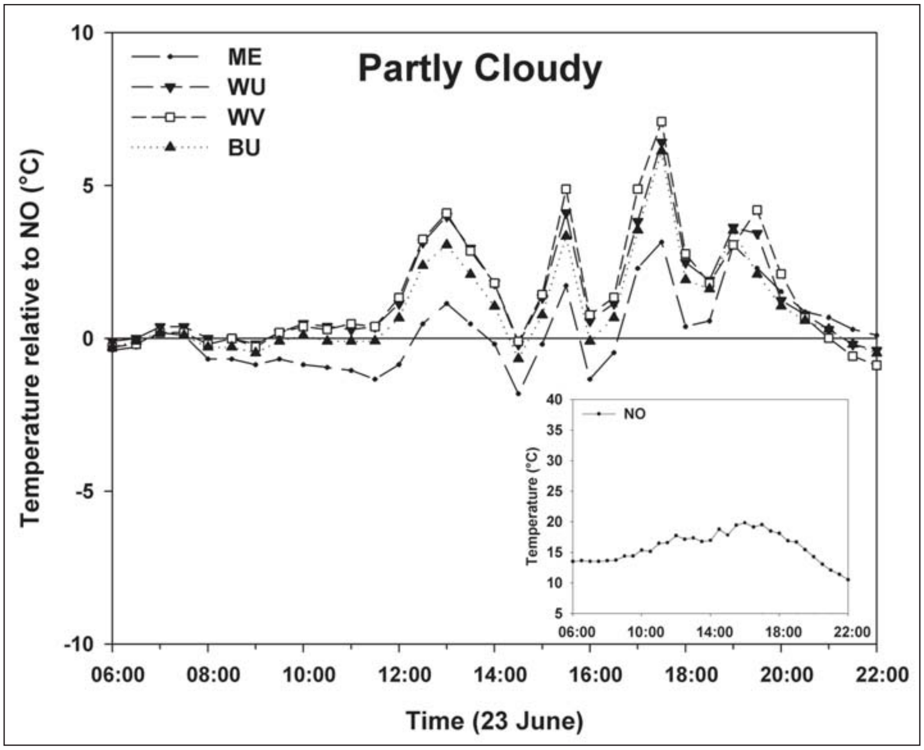

Figure 1—Air temperature in four tree shelter treatments, relative to no shelter, on 23 June 2005, a typical, partly cloudy day. Inset graph shows air temperature with no shelter (ambient condition). Treatments are no tree shelter (NO; the 0 line in the large graph), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

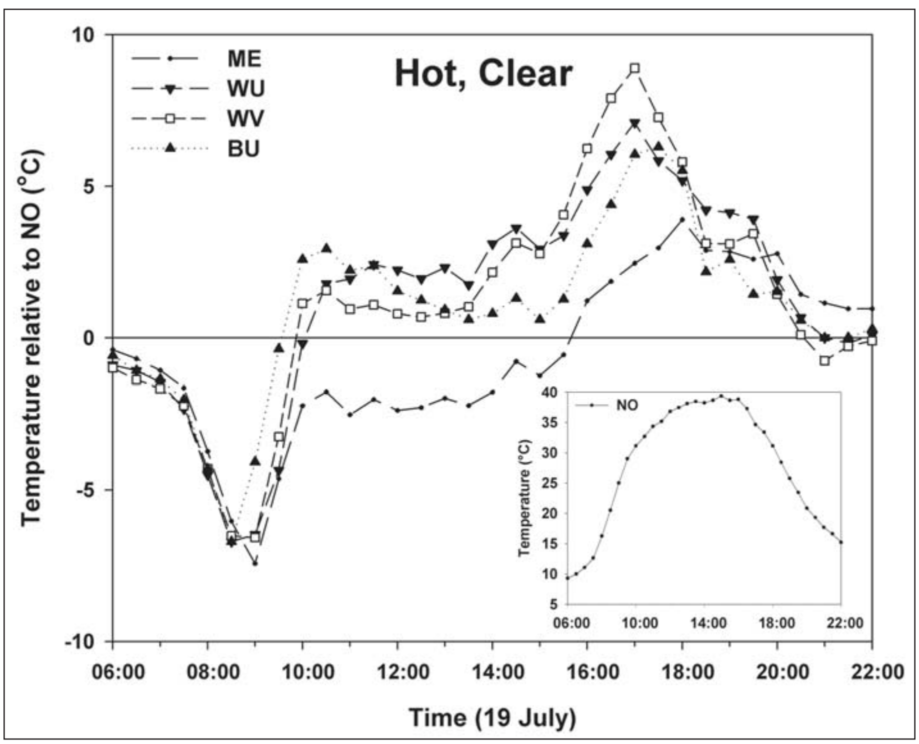

Figure 2—Air temperature in four tree shelter treatments, relative to no shelter, on 19 July 2005, a very hot, clear day. Inset graph shows air temperature with no shelter (ambient condition). Treatments are no tree shelter (NO; the 0 line in the large graph), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

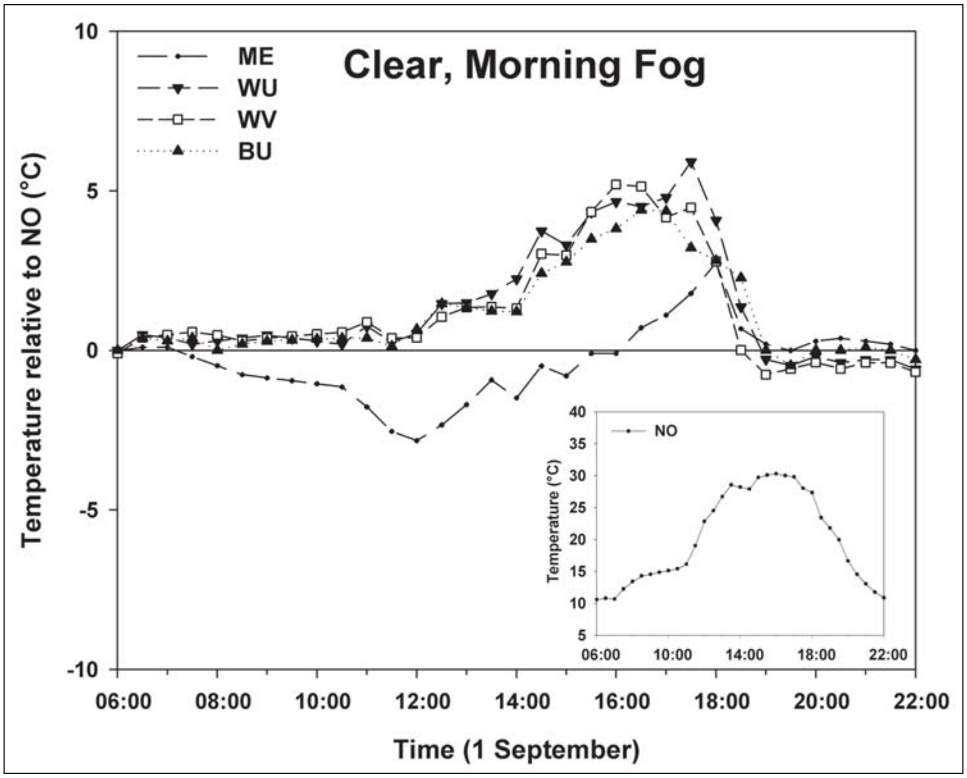

Figure 3—Air temperature in four tree shelter treatments, relative to no shelter, on 1 September 2005, a clear day with morning fog. Inset graph shows air temperature with no shelter (ambient condition). Treatments are no tree shelter (NO; the 0 line in the large graph), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

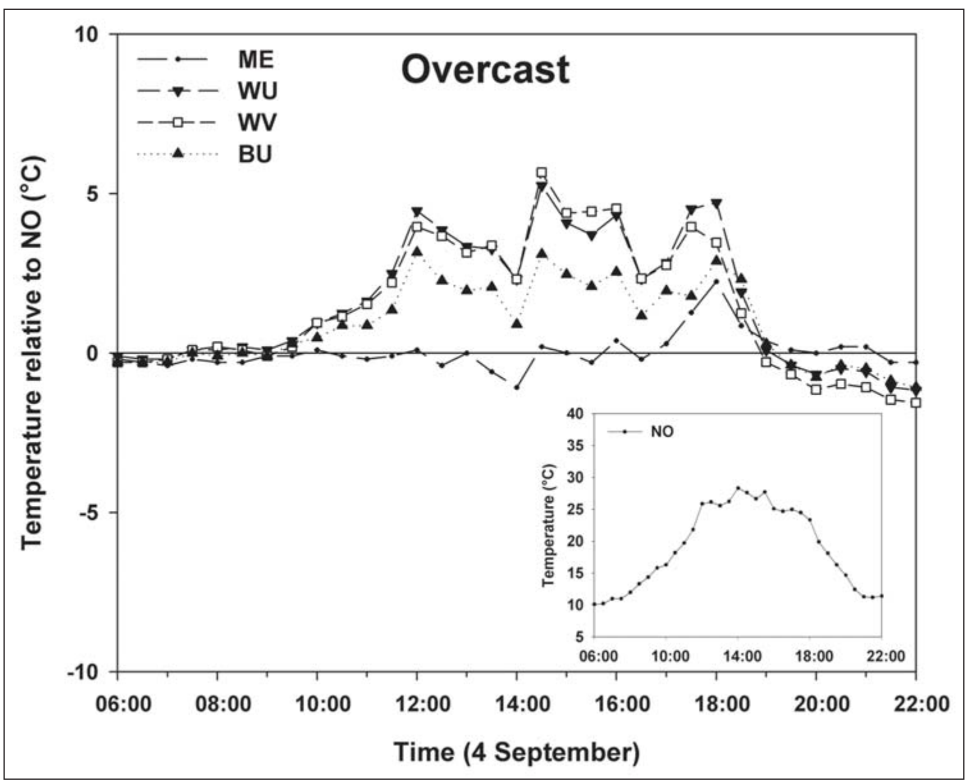

Figure 4—Air temperature in four tree shelter treatments, relative to no shelter, on 4 September 2005, an overcast day. Inset graph shows air temperature with no shelter (ambient condition). Treatments are no tree shelter (NO; the 0 line in the large graph), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

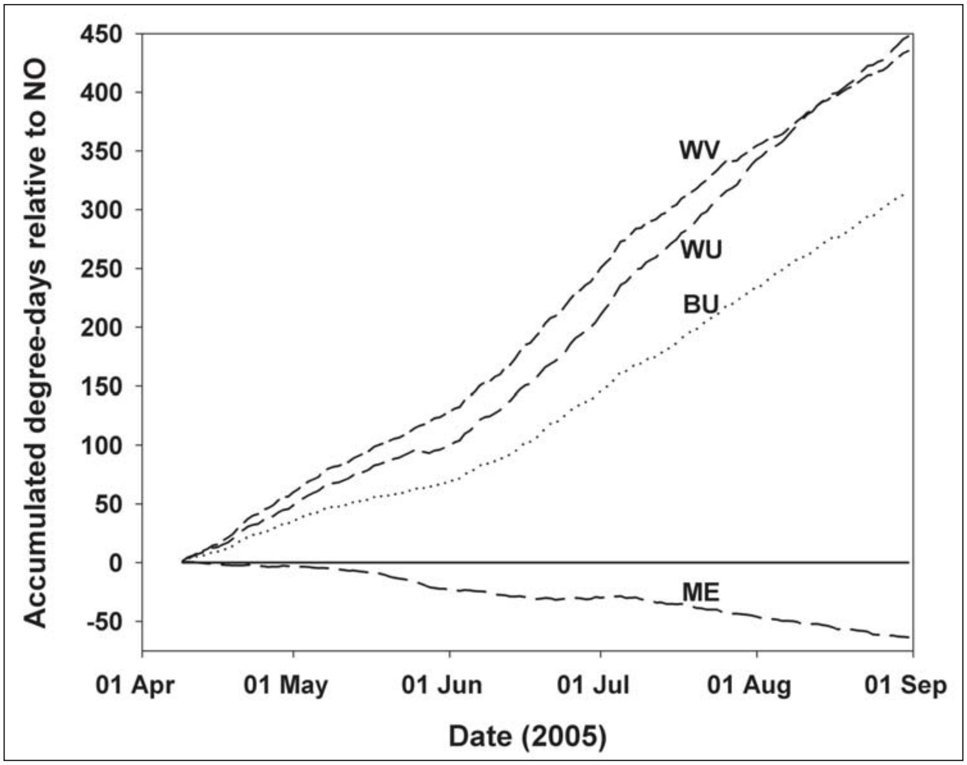

Figure 5—Accumulated degree days (base temperature = 5.0 °C) relative to ambient conditions (NO treatment; the 0 line) during the 2005 growing season for four tree shelter treatments. Treatments are a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

accumulation for the WU and WV treatments was 108 percent that of the NO treatment, and degree-day accumulation in the BU and ME treatments was 106 and 99 percent of the NO treatment, respectively.

Vapor pressure deficit—

Maximum daily VPD was greatest during July and August but was generally similar among treatments (table 4). The only significant treatment effect occurred in September when the solid-walled shelter treatments had a higher maximum VPD than the NO treatment (3.0 vs. 2.5 kPa). Diurnal patterns in VPD also were similar among treatments (fig. 6). Under very hot, clear conditions (19 July 2005), VPD in the NO treatment increased earlier in the day than in the other treatments, and the WV treatment reached the greatest maximum VPD in the afternoon. However, these treatment differences were not statistically significant.

Table 4—Maximum daily vapor pressure deficit, by month, for five tree shelter treatments in 2005, with contrasts testing differences among treatment combinations

Treatment[a]/ Contrast	Month Apr	May	Jun	Jul	Aug	Sep	Oct
	Kilopascal						
NO	1.2	1.7	2.1 ±0.2	3.3 ±0.3	4.0 ±0.3	2.5 ±0.2	0.7 ±0.1
ME	1.3	1.6	2.1 ±0.2	3.1 ±0.3	3.8 ±0.3	2.5 ±0.2	0.7 ±0.1
WU	1.6	1.7	2.2 ±0.2	3.3 ±0.3	4.0 ±0.3	2.9 ±0.2	0.8 ±0.1
WV	1.7	2.0	2.5 ±0.2	3.7 ±0.3	4.4 ±0.3	3.2 ±0.2	1.0 ±0.1
BU	1.6	1.7	2.3 ±0.2	3.4 ±0.3	4.2 ±0.3	2.9 ±0.2	0.8 ±0.1
	P > F						
NO vs. ME	—	—	0.791	0.602	0.524	0.743	0.703
NO vs. WU, WV, BU	—	—	0.252	0.702	0.577	**0.026**	0.081
WU vs. WV	—	—	0.272	0.307	0.373	0.332	0.128
BU vs. WU	—	—	0.630	0.788	0.564	0.809	0.685

Note: n = 2 for April and May; n = 4 for June through October. Standard error is shown where n = 4. Significant contrasts are bolded.

[a] Treatments are: no shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

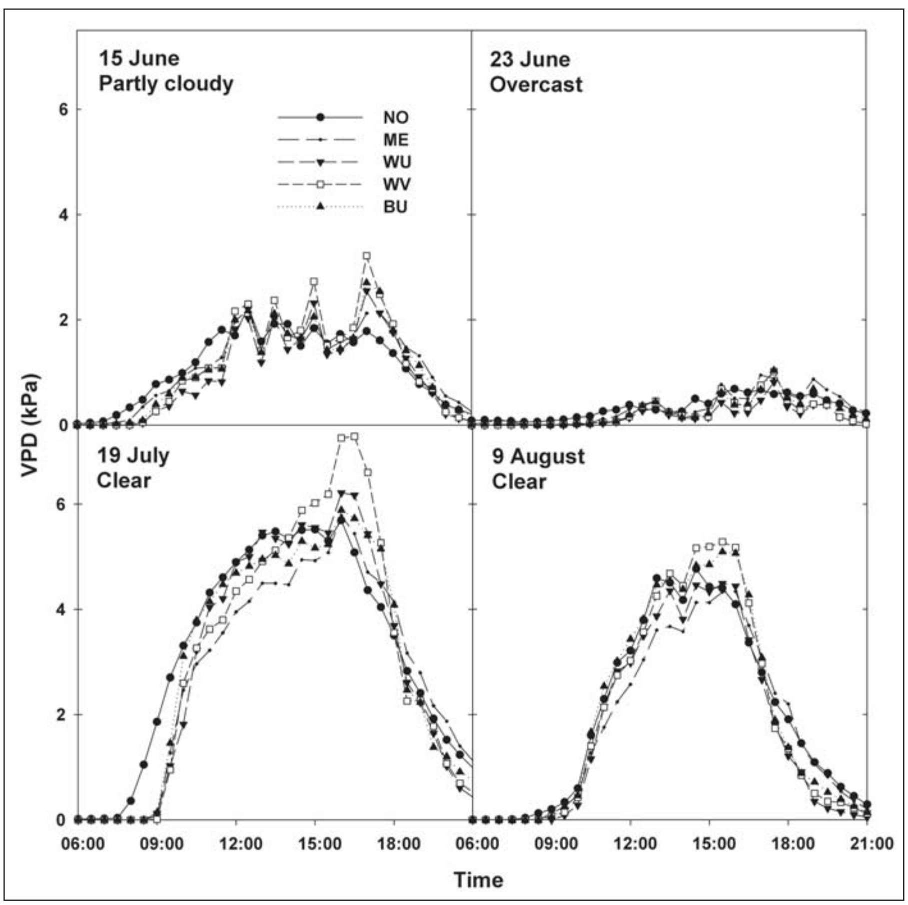

Figure 6—Vapor pressure deficit (VPD) in five tree shelter treatments on four days in 2005. Treatments are no tree shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

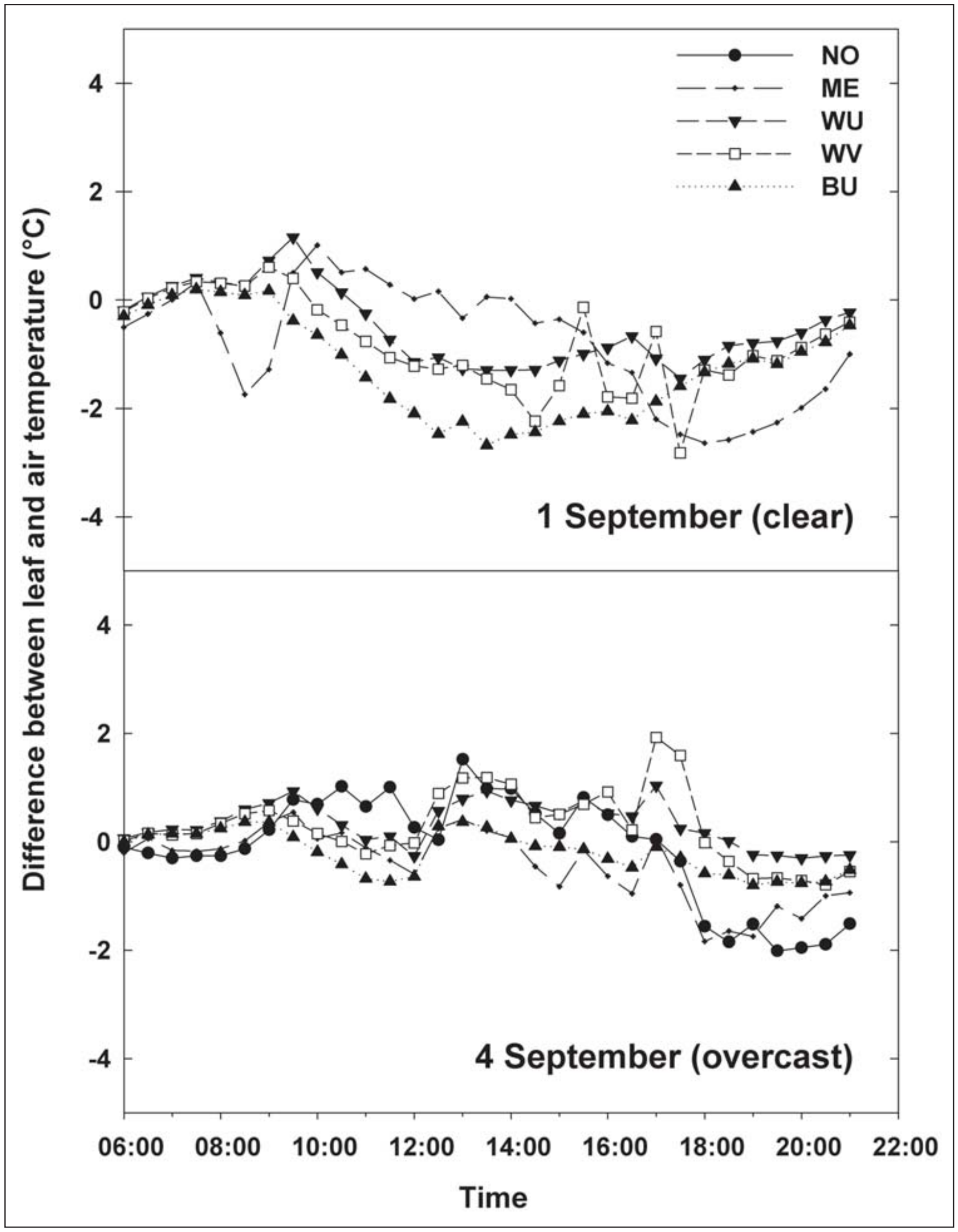

Figure 7—Difference between leaf temperature (abaxial side of Oregon white oak seedling leaf) and air temperature in the same treatment for seedlings (n = 2) in various tree shelter treatments on a clear day with morning fog (1 September 2005) and on an overcast day (4 September 2005). Treatments are no tree shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU). Data for NO on 1 September are missing.

Leaf temperature—

During the three hours prior to solar noon on a clear day, leaf temperatures in each of the solid-walled shelter treatments declined slightly relative to air temperatures in the same treatments (fig. 7). During the afternoon, leaf temperatures in solid-walled shelter treatments remained 1 to 3 °C below air temperatures in the same treatments. On an overcast day, leaf temperature remained similar to air temperature in all treatments.

Relative to leaf temperatures in the unsheltered treatment, leaf temperatures in the solid-walled shelters were approximately 3 to 5 °C higher in late afternoon on a clear day, with the WU treatment reaching the highest temperature (fig. 8). Leaf temperature in the mesh-shelter treatment was as much as 4 °C cooler than the unsheltered treatment during late morning. On an overcast day, leaf temperature of seedlings in the solid-walled shelters remained approximately 2 °C above that of the unsheltered seedlings.

Photosynthetically active radiation—

On a clear day when maximum PPFD reached 1473 mmol$\cdot$m$^{-2}\cdot$s^{-1} at solar noon, PPFD within the ME, WU, and BU shelter treatments remained at approximately 600 to 800, 600, and 250 mmol$\cdot$m$^{-2}\cdot$s^{-1}, respectively, during daylight hours (fig. 9). Photosynthetic photon flux density in the ME, WU, and BU treatments averaged 54, 38, and 15 percent of full sunlight (i.e., the NO treatment) during the 2-hour interval centered on solar noon, but these percentages increased earlier and later in the day. On an overcast day, where maximum PPFD exceeded 700 mmol$\cdot$m$^{-2}\cdot$s^{-1} only for short periods of time, PPFD in the shelter treatments remained relatively constant when expressed as a percentage of full sunlight (fig. 10). Photosynthetic photon flux density in the ME, WU, and BU treatments averaged 53, 40, and 20 percent of full sunlight, respectively. The relationship between PPFD under full sunlight and PPFD within shelters is shown in figure 11. As ambient PPFD levels increased, all shelters showed a tendency toward a lower fraction of PPFD admitted.

As ambient PPFD levels increased, all shelters showed a tendency toward a lower fraction of PPFD admitted.

Ratio of red-to-far-red light—

The ratio of red (655 to 665 nm) to far-red light (725 to 735 nm) on a clear day (26 June 2007) was significantly lower inside the BU shelter (0.46 ± 0.01) than within the ME shelter (0.67 ± 0.01) or the WU shelter (0.69 ± 0.01). The latter two shelter treatments did not differ significantly.

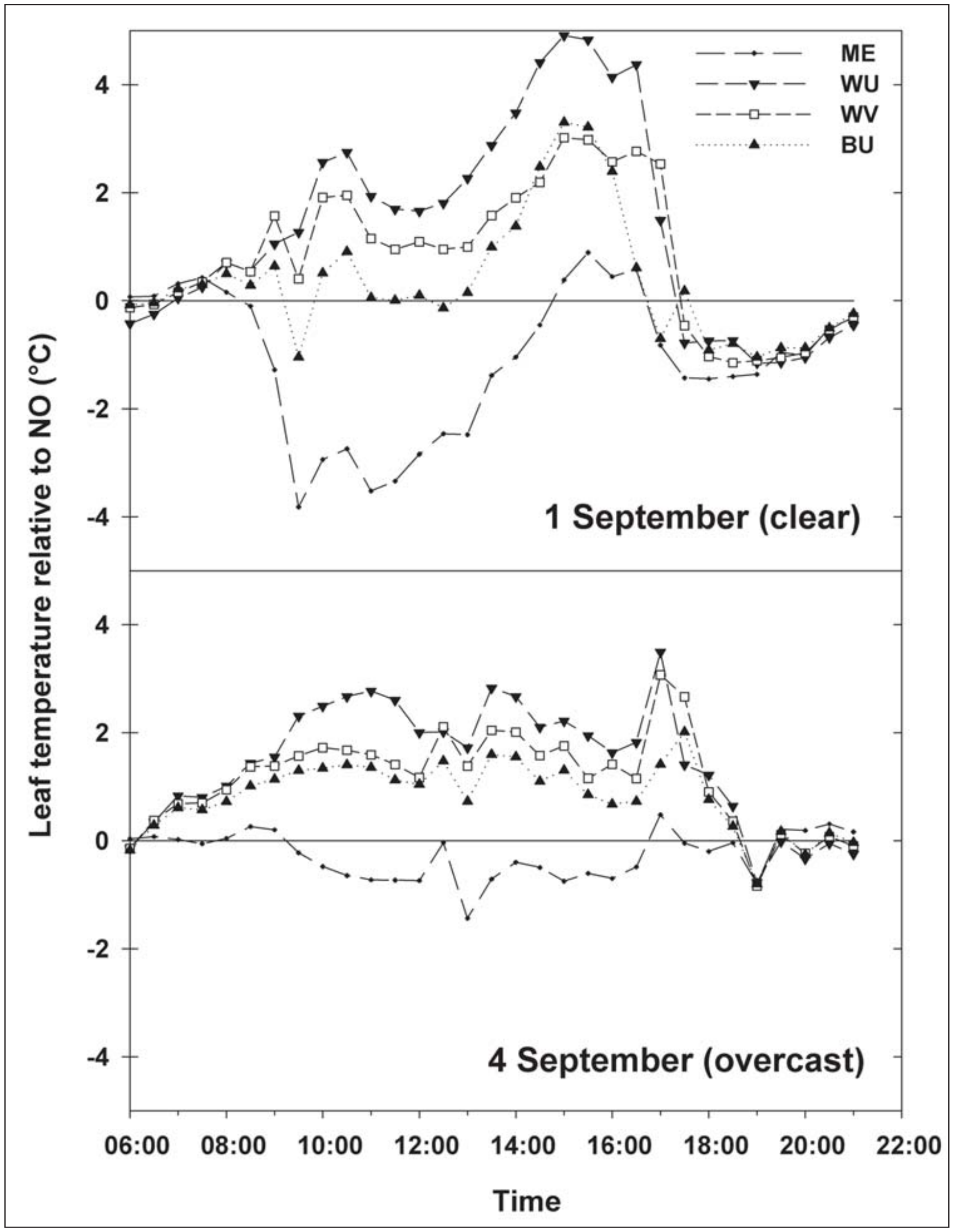

Figure 8—Leaf temperature (abaxial side of Oregon white oak seedling leaf) for seedlings (n = 2) in four tree shelter treatments, relative to leaf temperature of seedlings in ambient conditions (NO treatment; the 0 line) on a clear day with morning fog (1 September 2005) and on an overcast day (4 September 2005). Tree shelter treatments are a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

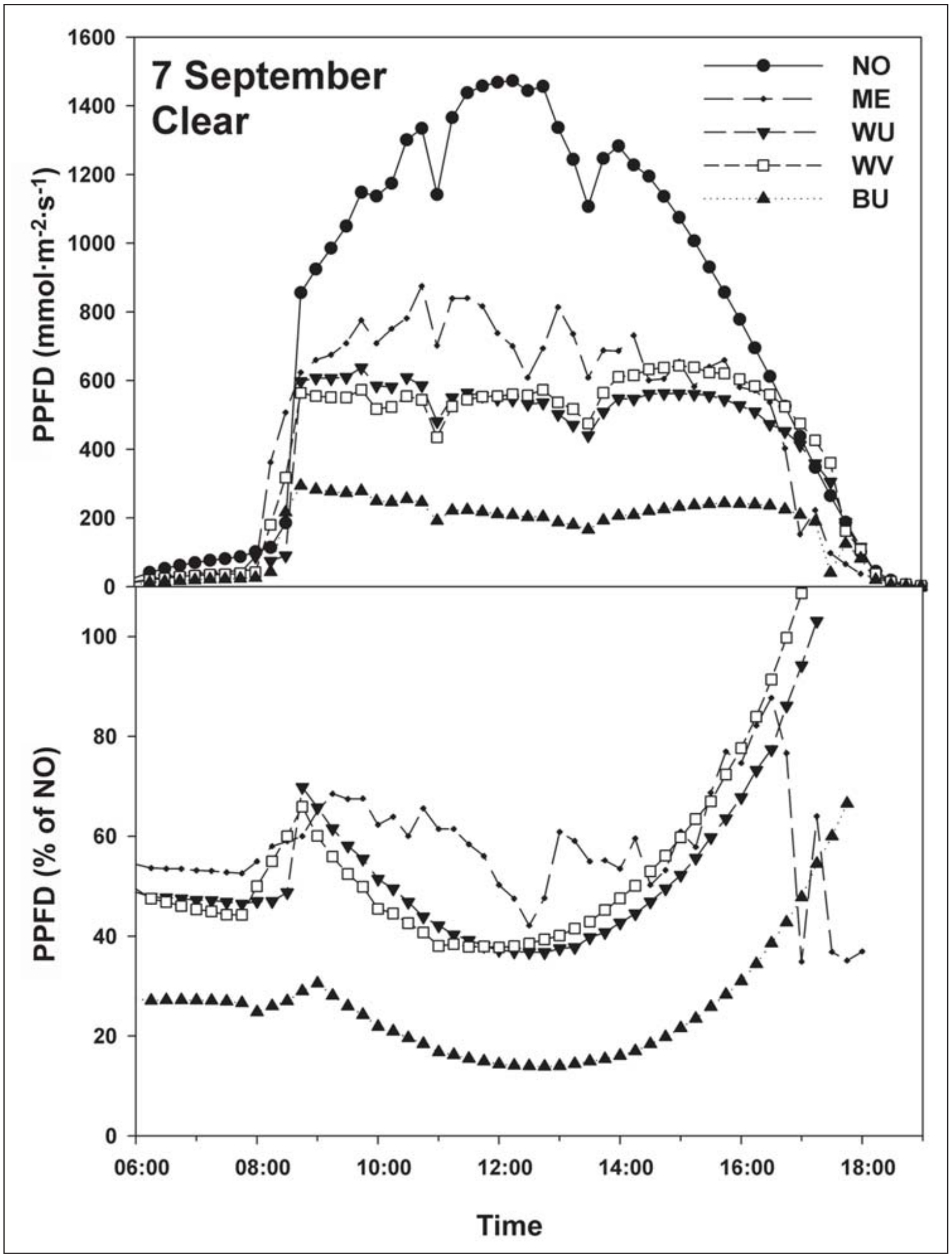

Figure 9—Photosynthetic photon flux density (PPFD) in five tree shelter treatments and PPFD relative to ambient conditions (NO treatment) on 7 September 2005, a clear day. Treatments are no tree shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

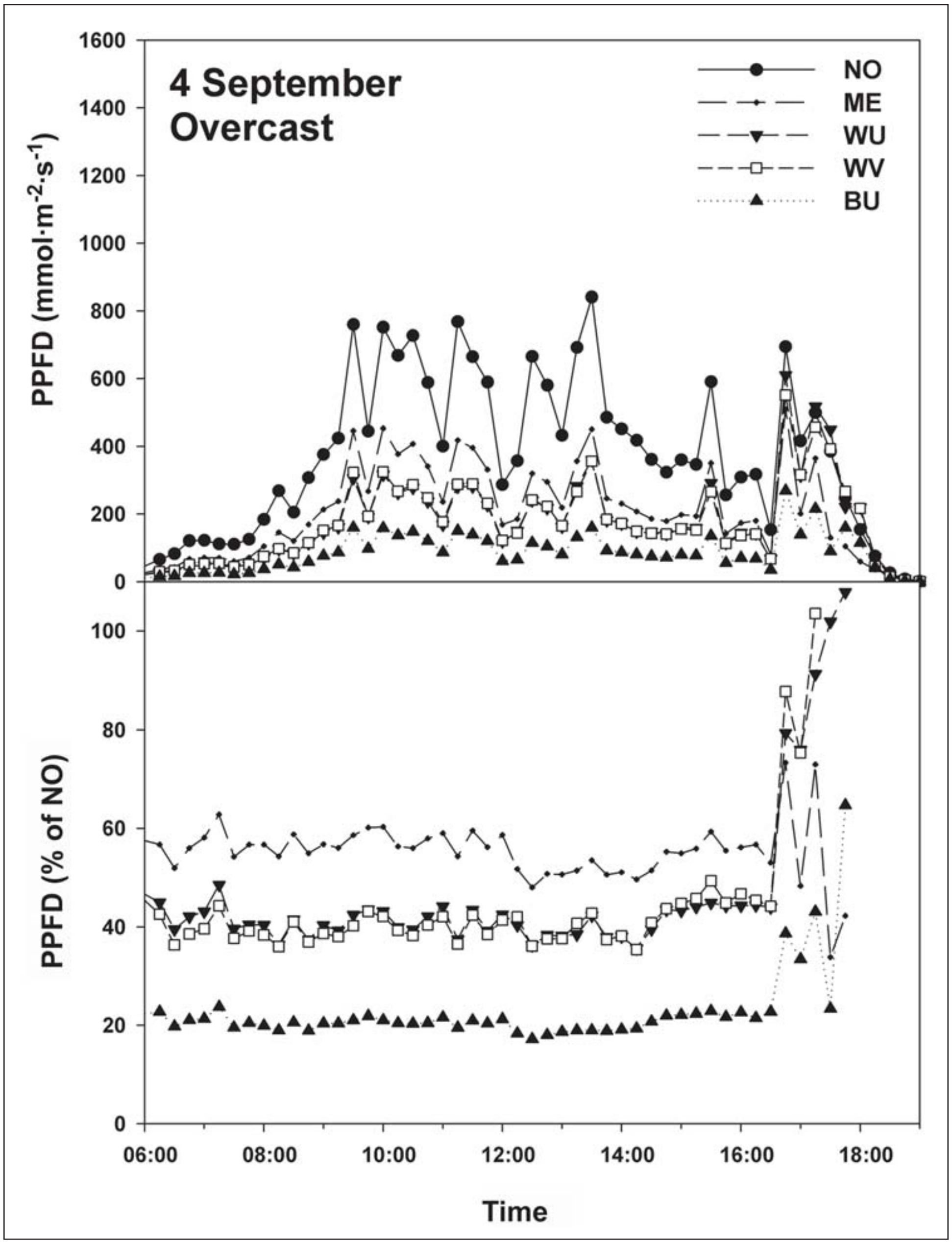

Figure 10—Photosynthetic photon flux density (PPFD) in five tree shelter treatments and PPFD relative to ambient conditions (NO treatment) on 4 September 2005, an overcast day. Treatments are no tree shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

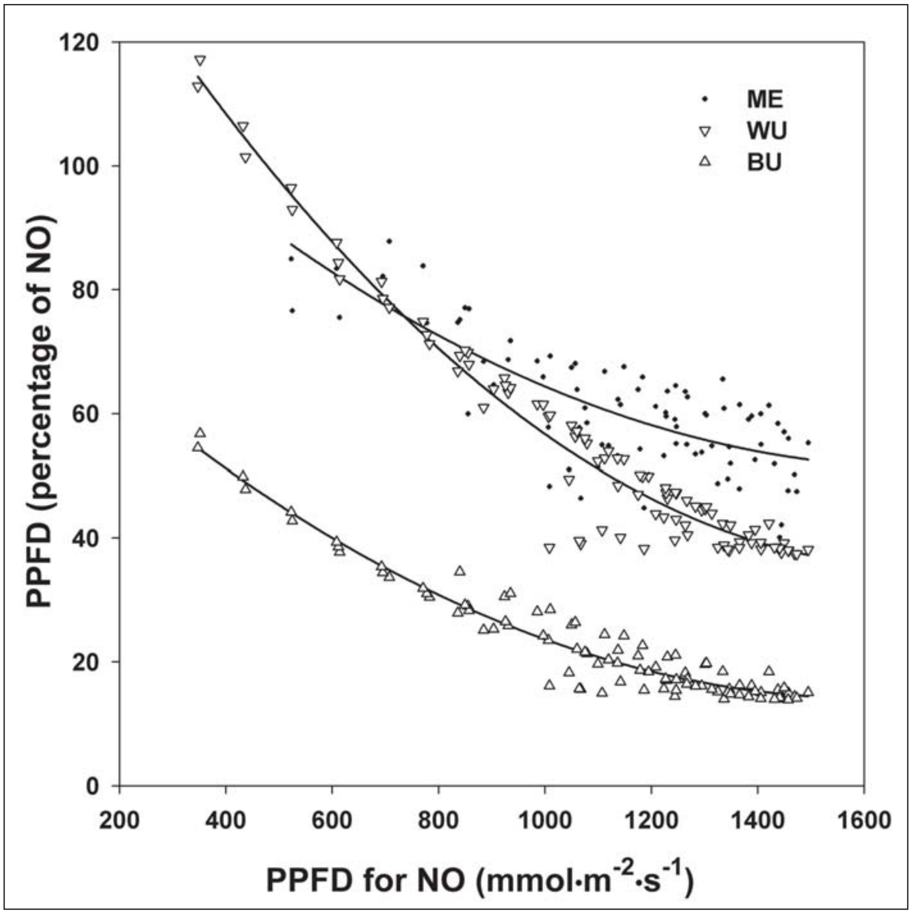

Figure 11—Photosynthetic photon flux density (PPFD), as a percentage of ambient conditions (NO treatment), in three tree shelters under a range of ambient PPFD values. Data were collected on three clear days (6 to 8 September 2005). Treatments are a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), and a solid-walled blue unvented shelter (BU).

Shelter Effects on Seedlings

Seedling survival, growth, and morphology—

The survival rate for oak seedlings in the 2005 study was 79 percent after 1 year, with similar rates among tree shelter treatments. Growth of oak seedlings in the 2005 study was generally very poor: only 22 percent of seedlings had height growth greater than 5.0 cm. This poor performance was attributed to planting shock probably owing to a scarcity of fine roots on most of the planting stock. Because seedling performance was atypically poor, growth results for oak seedlings are not presented. However, a small number of oak seedlings grew well and appeared vigorous throughout the growing season; these seedlings were used for A_n assessments. No animal damage occurred during the 2005 or 2007 studies.

Height growth in all shelter treatments was greater than that of unsheltered seedlings.

All oak seedlings in the 2007 study survived the growing season. Diameter growth in the BU treatment was significantly less than that in the NO and ME treatments in the 2007 study, although height growth did not differ significantly among treatments (table 5). Estimated belowground biomass growth was significantly greater in the NO treatment than in the BU treatment; aboveground biomass growth followed a similar trend but did not differ significantly among treatments. Estimated leaf area of first and second flushes did not differ among treatments, nor did specific leaf area.

Height growth of redcedar was significantly affected by shelter treatments ($P < 0.001$). The ranking of height growth among treatments did not differ between midseason (13 July) and the end of the growing season (fig. 12). Height growth in all shelter treatments was greater than that of unsheltered seedlings, with the BU treatment yielding the greatest growth (34.9 cm). Redcedar diameter growth was significantly greater in all shelter treatments (mean = 2.3 mm) compared to the unsheltered treatment (1.6 mm) (fig. 13). At the end of the growing season, redcedar seedlings in the BU treatment had a significantly greater height-to-diameter ratio (126.7) than the WU (115.4), WV (111.3), ME (110.6), or NO (101.9) treatments. During the growing season, the height-to-diameter ratio increased by 11.2 percent in the BU treatment, remained virtually unchanged in the WU and WV treatments, and decreased in the ME and NO treatments by 6.7 and 11.3 percent, respectively. Only one redcedar seedling died during the growing season.

Physiological variables—

On 9 July 2007, A_n was significantly higher for unsheltered oak seedlings than for seedlings in the ME treatment at 7:00, 11:45, and 16:00 PST. There was no significant difference between these two treatments at 9:30 PST (fig. 14). At all four measurement times, A_n in both the unsheltered and the ME treatments was significantly greater than that in the BU treatment. Measurements of A_n on second-flush leaves (12:00 to 14:00 PST on 24 August 2007) showed that the NO and ME treatments did not differ (7.3 ± 1.2 and 7.9 ± 1.3 µmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, respectively), but that both were significantly greater than the BU treatment (0.8 ± 1.7 µmol $CO_2 \cdot m^{-2} \cdot s^{-1}$). When A_n for the three shelter types (2005 and 2007 data) was expressed relative to A_n in the NO treatment, there was a strong relationship between net assimilation of CO_2 and PPFD (fig. 15).

Table 5—Growth and morphological response of Oregon white oak seedlings in 2007 to three tree shelter treatments

	Tree shelter treatment[a]		
Variable	NO	ME	BU
Diameter growth (mm)	3.9 ± 0.5 a	3.7 ± 0.5 a	1.8 ± 0.5 b
Height growth (cm)	38.5 ± 9.0	32.2 ± 9.0	29.4 ± 8.9
Estimated belowground growth (g)	15.8 ± 1.8 a	10.5 ± 1.8 ab	7.3 ± 1.8 b
Estimated aboveground growth (g)[b]	9.3 ± 1.7	7.5 ± 1.7	5.3 ± 1.7
Total foliar dry weight (g)	17.6 ± 3.0	16.5 ± 3.0	11.1 ± 3.0
Estimated leaf area, 1st flush (cm^2)[c]	589 ± 91	366 ± 91	520 ± 89
Estimated leaf area, 2nd flush (cm^2)[c]	999 ± 304	609 ± 276	708 ± 320
Specific leaf area, 1st flush (cm^2/g)	184 ± 22	147 ± 22	226 ± 21
Specific leaf area, 2nd flush (cm^2/g)	131 ± 12	127 ± 11	169 ± 13

[a] Treatments are no shelter (NO), a fine-mesh fabric shelter (ME), and a blue unvented shelter (BU). Means with standard error are shown. Within each row, values not followed by the same letter are significantly different ($P < 0.05$).

[b] Woody components only.

[c] Average leaf area of 10 leaves multiplied by the total number of leaves.

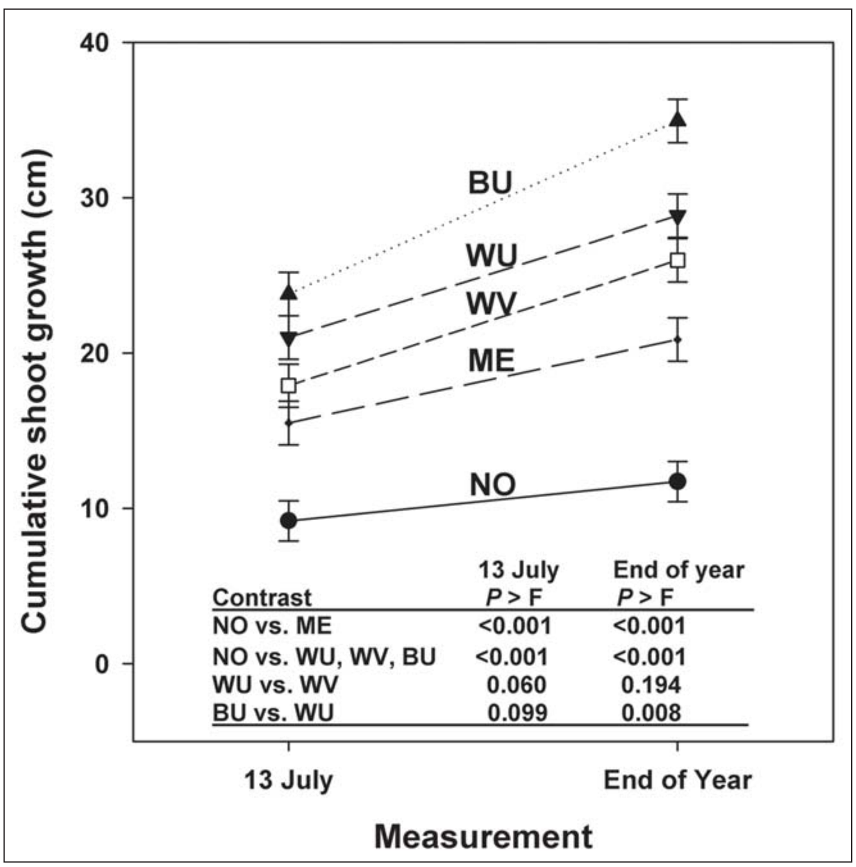

Figure 12—Cumulative height growth (with standard error) at midseason and at the end of the 2005 growing season for western red-cedar seedlings in five tree shelter treatments. Contrasts compare treatment combinations for both measurement periods. Treatments are no tree shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

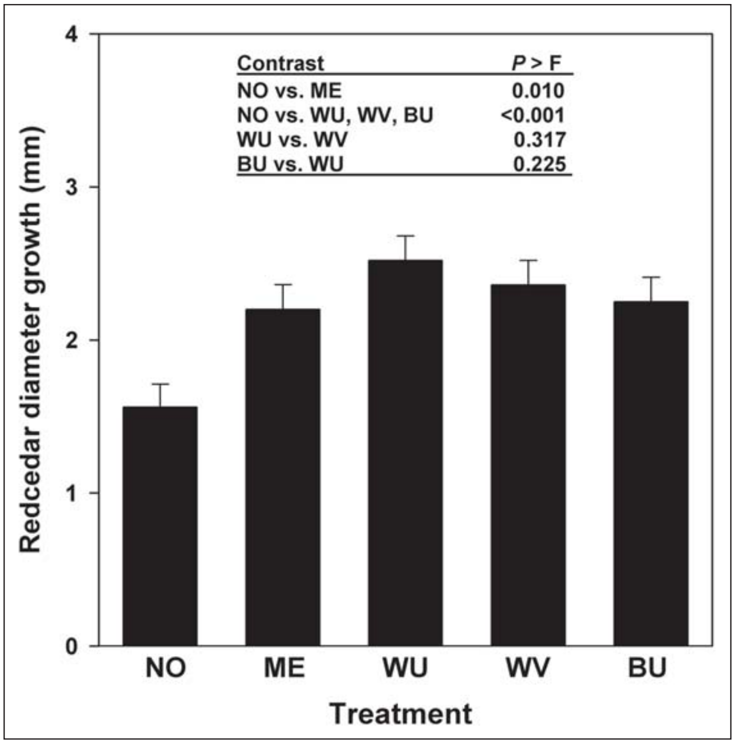

Figure 13—Diameter growth (with standard error) for western redcedar seedlings in five tree shelter treatments after 1 year in the 2005 study. Contrasts are shown indicating the significance of various treatment comparisons. Treatments are no tree shelter (NO), a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU), a solid-walled white vented shelter (WV), and a solid-walled blue unvented shelter (BU).

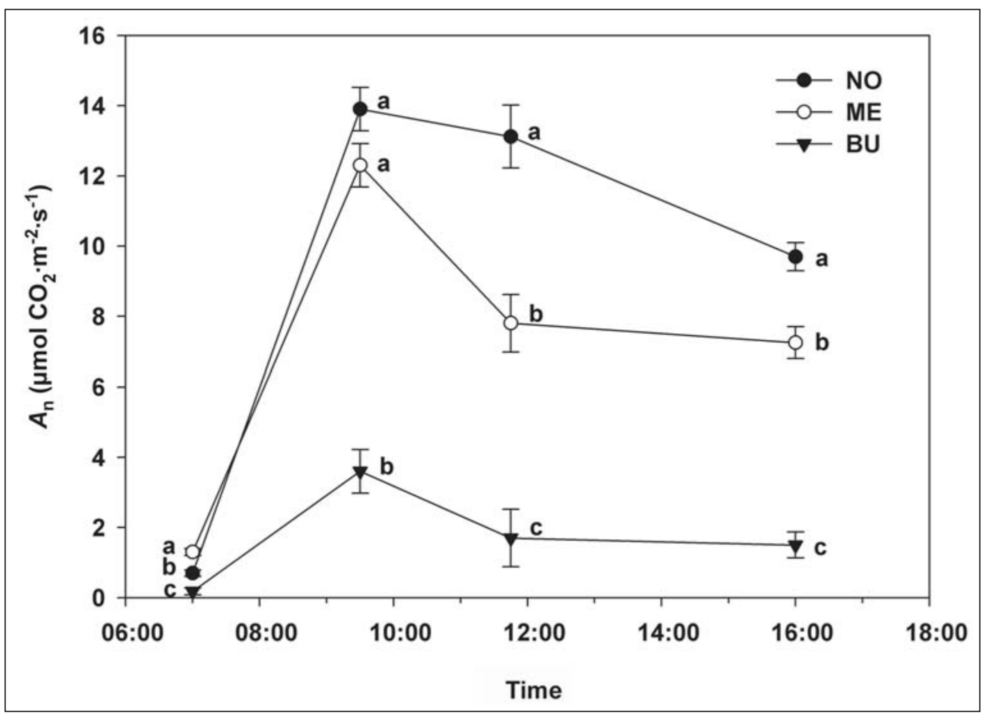

Figure 14—Net assimilation of CO_2 (A_n) via photosynthesis for Oregon white oak seedlings on 9 July 2007 in three treatments: no tree shelter (NO), a fine-mesh fabric shelter (ME), and a solid-walled blue unvented shelter (BU). Different letters within each time of measurement indicate that means differ significantly ($P < 0.05$) at that time.

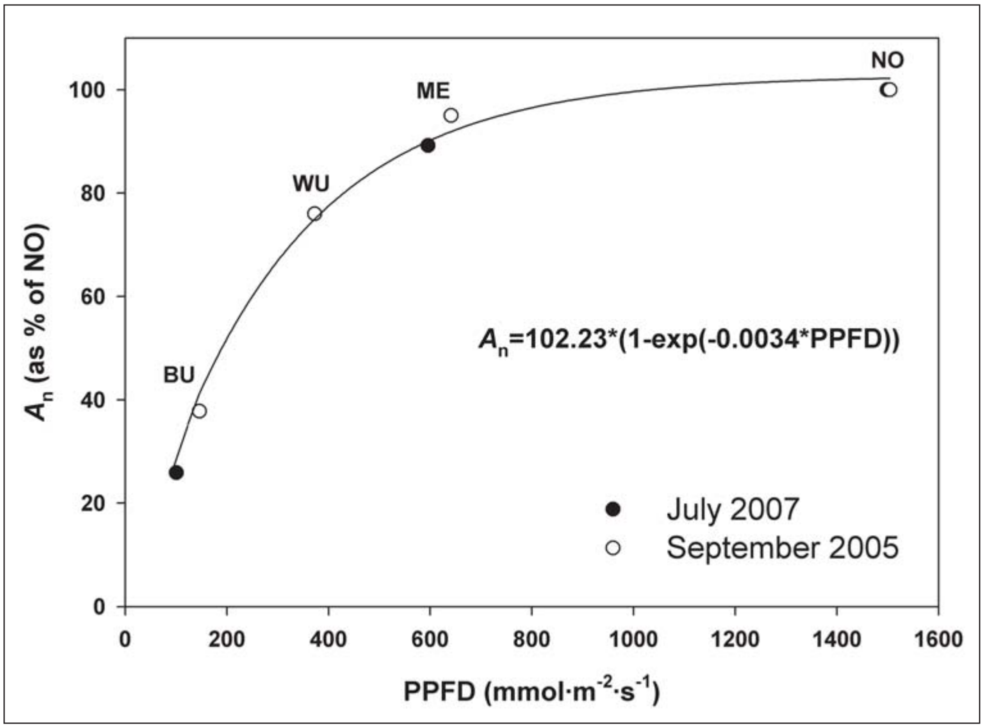

Figure 15—Photosynthesis rate, measured as net CO_2 assimilation (A_n), for Oregon white oak seedlings in three tree shelter types, relative to that of unsheltered seedlings (NO treatment), as a function of photosynthetic photon flux density (PPFD). Tree shelters are a fine-mesh fabric shelter (ME), a solid-walled white unvented shelter (WU; 2005 data only), and a solid-walled blue unvented shelter (BU). Data were collected on 2 clear days: 26 September 2005 and 3 July 2007.

Discussion

Shelter Effects on Microclimate

Solid-walled tree shelters increased air temperature and leaf temperature relative to ambient conditions. Maximum daily air temperatures in solid-walled shelters were often at least 4 to 5 °C higher than ambient conditions. These results support Hypothesis M1 regarding greater air temperatures in solid-walled shelters. Although these temperature increases may have influenced seedling physiology, they were not great enough to have caused mortality. Compared to previous studies, the difference in VPD between the unsheltered condition and unvented solid-walled shelters was small (Kjelgren 1994, Kjelgren et al. 1997). The finding of high VPD in solid-walled shelters in our study is contrary to Hypothesis M2 in which we anticipated decreased VPD in solid-walled shelters owing to seedling transpiration and reduced air movement. This result suggests that the seedlings produced little water vapor through transpiration or that this water vapor was produced but lost

Maximum daily air temperatures in solid-walled shelters were often at least 4 to 5 °C higher than ambient conditions.

from the shelter through air circulation. For shelters with oak seedlings, the seedlings were small and transpiration rates were low owing to limited leaf area and root development. Solid-walled tree shelters were constructed of a flat sheet that was formed into a tube using tabs but not sealed along the vertical joint; thus, there was an unknown amount of air exchange through this seam through which humid air may have been lost.

Mesh-walled shelters may have advantages relative to solid-walled shelters for growing shade-intolerant species.

Mesh-walled tree shelters had no significant effect on monthly air temperatures, although there was a trend in which midday temperatures were slightly cooler in mesh shelters than in unsheltered conditions on clear summer days. Although the lack of significant air temperature reduction in the mesh shelter failed to support our hypothesis (Hypothesis M3), the mesh-walled shelter was the only shelter to cause a reduction in seedling leaf temperature relative to unsheltered seedlings. Previous studies examining various types of mesh-walled shelters have reported that summer air temperatures within mesh shelters are closer to ambient conditions than temperatures within solid-walled shelters, where mean and maximum temperatures are consistently higher than ambient (Bellot et al. 2002, LePage and Banner 2005, Sharew and Hairston-Strang 2005). Although not significant, VPD values in mesh-walled shelters were generally slightly lower than in the other tree shelter treatments, apparently owing to slightly (but not significantly) cooler air temperatures. Mesh-walled shelters had higher PPFD levels than solid-walled shelters and a red-to-far-red ratio that was closer to unobstructed sky than that of the BU shelter. Thus, mesh-walled shelters may have advantages relative to solid-walled shelters for growing shade-intolerant species.

The presence of vent holes in solid-walled tree shelters did not significantly reduce monthly air temperature or VPD as we had hypothesized (Hypothesis M4), although leaf temperatures were generally slightly lower in the vented shelter. The trend toward slightly higher afternoon VPD in vented shelters (fig. 6) may be due to the venting of water vapor produced by seedling transpiration (Bergez and Dupraz 1997). Other shelter designs with more vent holes or larger vent holes have produced greater effects on the interior microclimate (vents in the WV shelters were circular holes, 0.8-cm in diameter, spaced approximately 9 cm apart). Twelve 1.3-cm diameter holes reduced maximum daily air temperature in 1.5-m-tall shelters by an average of 2.8 °C in Pennsylvania (Swistock et al. 1999). As few as four 2-cm-diameter holes reduced air temperature by approximately 5 °C in 0.6-m-tall shelters in southeastern Spain (Bellot et al. 2002). Small (0.6-cm diameter), closely spaced (5-cm) vent holes significantly reduced humidity but not air temperature or PPFD for tree shelters in Virginia (Peterson et al. 1995).

The primary effect of shelter color on the microenvironment was the reduced PPFD within the blue (BU) shelter compared to the white (WU) shelter. Although the blue shelter showed a trend toward slightly cooler leaf and air temperatures than the white shelter, differences were not significant, even on hot summer days. Studies in Indiana and Maryland showed summer air temperatures among translucent white and translucent nonwhite shelters to be similar (Minter et al. 1992, Sharew and Hairston-Strang 2005). In Utah, air temperatures were slightly higher in white shelters than in brown shelters (Kjelgren et al. 1997).

Shelter Effects on Seedlings

Both height and diameter growth of redcedar were increased by the fine-mesh fabric shelters relative to unsheltered seedlings. A positive effect on redcedar height growth for this type of mesh shelter also was reported in coastal British Columbia (LePage and Banner 2005), but effects of this shelter type on diameter growth have not previously been reported. Some species perform poorly within mesh shelters owing to lateral shoots becoming entangled in the mesh, but the fine-mesh fabric of the shelters in this study did not allow foliage to penetrate the wall of the shelter. The larger diameter of the fine-mesh shelters (i.e., 15.2 cm) also may have permitted greater development of branches compared to smaller diameter (10 cm) shelters commonly used such as Vexar® mesh shelters, which may sometimes result in growth losses because of physical restriction of seedlings (Brandeis et al. 2002).

Height growth of redcedar increases rapidly from 0 to approximately 20 percent full sunlight but then does not respond to further increases after reaching 30 percent full sunlight (Drever and Lertzman 2001). Thus, we can infer that even the BU shelter, with the lowest PPFD, did not limit height growth of redcedar owing to its light environment. Rather, the ranking of shelter PPFD relative to full sunlight was inversely related to the ranking of redcedar height growth (figs. 9, 10, and 12). Height growth differed significantly between two solid-walled shelter treatments (BU and WU) of similar size and with similar temperature and VPD patterns; the growth difference may have been caused by different light environments within these two shelter types. In addition to reducing PPFD to a greater extent than the white shelter, the blue shelter had a red:far-red ratio of 0.46, which was substantially lower than that of the white shelter (0.69) or the fine-mesh fabric shelter (0.67). The red:far-red ratio of the blue shelter is somewhat closer to that of the forest understory (0.29) (Sharew and Hairston-Strang 2005). Western redcedar has a very high tolerance of shade (Minore 1990); its shade tolerance may be an

The blue shelter had a red:far-red ratio of 0.46, which was substantially lower than that of the white shelter (0.69) or the fine-mesh fabric shelter (0.67).

adaptation to not only the low PPFD in a forest understory but also to the red:far-red light conditions typical of those environments. Overall, the growth response of redcedar to tree shelters supported our hypothesis (Hypothesis G1) that height growth would be greatest in the shelter in which the ratio of red to far-red light was lowest.

In the 2007 study, Oregon white oak seedling growth did not follow patterns reported previously in which substantial height growth increases were observed for seedlings in BU shelters compared to those in mesh shelters or unsheltered seedlings (Devine et al. 2007). Contrary to our hypothesis (Hypothesis G1), height growth in the 2007 study was similar across treatments; additionally, diameter growth was significantly less in the BU treatment (table 5). Aside from potentially warmer soils of the raised beds that may have improved root growth, the primary difference between the 2007 study and the research reported by Devine et al. (2007) is that, in the 2007 study, seedlings were irrigated daily throughout the summer, whereas in the previous studies, seedlings were generally not irrigated and water was a growth-limiting factor. Tree shelters have been shown to reduce seedling transpiration rates compared to seedlings in unsheltered conditions (Bergez and Dupraz 1997, Kjelgren 1994, Kjelgren and Rupp 1997). Bergez and Dupraz (1997) concluded that lower solar radiation within tree shelters was one of the primary factors reducing evaporative water loss and increasing water use efficiency. We observed dramatic reductions in solar radiation within tree shelters, and it is possible that the positive growth effects of tree shelters reported previously for nonirrigated Oregon white oak were due to increased water use efficiency of sheltered seedlings. But because soil water was abundant across treatments in our 2007 study, we would not expect to observe growth effects owing to differences in seedling water use efficiency.

The significantly lower A_n rate for oak seedlings in solid-walled tree shelters was unexpected because of the consistently greater height growth rates previously reported in these shelters.

The significantly lower A_n rate for oak seedlings in solid-walled tree shelters was contrary to our hypothesis (Hypothesis P1) and unexpected because of the consistently greater height growth rates previously reported in these shelters, specifically in the BU shelter type (Devine et al. 2007). The lower A_n observed in the solid-walled shelter types in this study was clearly related to the reduced light levels within those shelters (fig. 15). This relationship between light and A_n is in agreement with the findings of Hinckley et al. (1978) who reported, for eastern white oak (*Q. alba* L.), relatively high A_n at PPFD values above approximately 350 mmol·m^{-2}·s^{-1} and rapidly declining A_n at lower light intensities. In our study, PPFD in the BU treatment averaged only 124 mmol·m^{-2}·s^{-1} during A_n measurements, whereas the WU, ME, and NO treatments averaged 373, 619, and 1502 mmol·m^{-2}·s^{-1}, respectively. The BU shelters, which had the lowest A_n rates, also had the lowest diameter growth and estimated belowground growth (table 5). Additionally, there was no significant difference in estimated leaf area among shelter treatments for either first or second flushes, indicating that the lower A_n was not compensated for by greater leaf area of seedlings in the BU shelters. Thus, under conditions where soil water was nonlimiting, light availability appears to be the factor that limited photosynthesis and growth of Oregon white oak seedlings.

Net assimilation of carbon by white oak has been shown to decline when air temperatures reach 35 to 40 °C (Sharkey et al. 1996) and to cease when leaf temperatures reach 44.5 °C (Hinckley et al. 1978). Given the daily maximum temperatures in this study (table 3), and the similarity between eastern white oak and Oregon white oak, it is likely that temperature-induced reductions in A_n occurred on the hottest days, probably to a greater extent for oak seedlings in solid-walled shelters than for those in other treatments. Based on air temperatures throughout the growing season, full cessation of A_n owing to temperature probably occurred little or not at all. Maximum recorded air temperatures in the NO, ME, WU, WV, and BU treatments were 42.0, 41.5, 46.4, 48.0, and 44.9 °C, respectively, and leaf temperatures during the hottest part of the day (late afternoon) were generally slightly lower than air temperatures (fig. 7).

Conclusions

Fine-mesh fabric tree shelters may be well-suited for some sites or species.

There has been little research on fine-mesh fabric tree shelters, but there are several characteristics that may make this shelter type particularly well-suited for certain sites or species. The ventilation permitted by this shelter type apparently prevented the increased air and leaf temperatures produced by solid-walled shelters. Also, light availability within the mesh shelter was greater than within solid-walled shelters, which may be advantageous for shade-intolerant species. Although tree shelters with large mesh openings (e.g., Vexar® shelters) are problematic for some species because of entanglement or herbivory of branches that grow through the mesh, the small opening size of fine-mesh fabric shelters in this study prevented growth of branches through shelter walls.

Solid-walled tree shelters increased air temperatures as anticipated, and significantly increased height and diameter growth of redcedar. Although we observed no effect of shelter venting, vent holes larger than the ones in this study may provide greater air circulation, thus moderating temperature increases caused by solid-walled shelters. The most dramatic effect of solid-walled tree shelters was on the

Oregon white oak, had less stem diameter growth within the low-light environment of blue-colored shelters than in an unsheltered environment.

light environment, with a greater than twofold difference in PPFD between white and blue shelters. However, because the shelter with lowest PPFD produced redcedar seedlings with the greatest height growth and no reduction in diameter growth, it is clear that this shade-tolerant species is well-suited to the microenvironment of blue shelters. Alternatively, Oregon white oak, which is less tolerant of shade, had less stem diameter growth within the low-light environment of blue-colored shelters than in an unsheltered environment, when grown under conditions of no water limitation. Under field conditions, where water is often limiting, solid-walled shelters, regardless of color, increased the rate of Oregon white oak height growth (Devine et al. 2007). We would suggest, however, that the reduction in PPFD in solid-walled blue shelters has the potential to limit growth of some shade-intolerant species. Although certain combinations of seedling, site, and environmental conditions may cause seedling growth to be more limited by factors other than light, it seems prudent to consider shade tolerance when selecting shelter color.

Our findings illustrate several examples of the numerous influences that tree shelter design can have on microclimate and seedling performance. Because shelter design may alter microclimate in a variety of ways, and because optimal microclimate conditions differ among species, selection of an appropriate tree shelter design must involve these and other considerations, such as cost, durability, and ease of installation. There are currently many varieties of tree shelters commercially available, encompassing a wide range of dimensions, materials, and designs (appendix). These shelters, and the option of constructing shelters from other materials, provide numerous options for altering seedling microenvironment while protecting from animal damage.

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English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Square centimeters (cm^2)	0.155	Square inches
Degrees Celsius (C)	1.8 C + 32	Degrees Fahrenheit
Kilopascals (kPa)	0.145	Pounds per square inch
Millimole per square meter per second ($mmol \cdot m^{-2} \cdot s^{-1}$)	10.76	Millimole per square foot per second
Micromole per square meter per second ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	10.76	Micromole per square foot per second
Liters	0.265	Gallons
Nanometer (nm)	39.370×10^{-9}	Inches
Square centimeters per gram (cm^2/g)	0.228	Square inches per ounce

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Appendix: Tree Shelter Types

Table 6—Examples of some commercially available tree shelters

Shelter	Type	Manufacturer	Web site
Freegro®	Fabric mesh	Freegro, Prince Rupert, BC, Canada	http://www.freegro.com/
Tree Protector & Miracle Tube®	Solid-walled	Tree Pro, West Lafayette, IN	http://www.treepro.com/
ProTex® Pro/Gro	Solid-walled	Norplex, Inc., Auburn, WA	none
Vexar®	Plastic mesh	Norplex, Inc., Auburn, WA	none
Tubex® Treeshelters and NetGuard®	Solid-walled and mesh	Tubex, Ltd., Aberaman Park, Aberaman, South Wales, U.K.	http://www.tubex.com/
Blue-X® Treeshelters	Solid-walled, two-layer	Blue-X Enterprises, Inc., Elk Grove, CA	http://www.growtube.com/

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