Environmental Modification Inside Photoselective Shadehouses

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Abstract. Shade nets are widely used to protect floricultural crops from excessive radiation, wind, hail, and birds. Although black nets are most frequently used, growers are experimenting with colored, gray, and white dispersive netting to impact vegetative vigor, dwarfing, branching, leaf variegation, and timing of flowering. We monitored environmental data inside replicated shadehouse structures (10 × 10 × 3 m high) with full covering of red, blue, pearl, and black nets (all 50% nominal shading factor) in central Florida over 12 months. Actual photosynthetically active radiation (PAR , $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was reduced most by black nets (55% to 60% shading factor depending on the season) and least under red nets (41% to 51%) with blue and pearl nets intermediate. Spectral analysis revealed blue nets had distinctive peaks at the blue (450 to 495 nm) and far-red beyond 750 nm. Red nets had a minor peak ≈ 400 nm and major transmittance beyond 590 nm. Pearl nets transmitted more light above 400 nm compared with black nets but did not otherwise alter spectral composition in the visible range. No nets had red/far-red (R/FR) ratios (600 to 700/700 to 800 nm) significantly greater than ambient (close to 1), whereas blue nets had a consistently lowest R/FR ratio of ≈ 0.8 . Both ultraviolet-B and ultraviolet-A (280 to 400 nm) were reduced most by pearl nets and least by red nets. We also noted elevated temperatures and wind resistance (but not relative humidity) under colored and pearl nets compared with black, probably as a result of the different net porosities. Our study documents the different environmental modifications inside structures covered with black, colored, and photoneutral translucent nets, which will help predict or interpret specific plant responses.

An emerging approach in the production of ornamental crops is the use of photoselective (colored) and color-neutral dispersive shade netting. Modern shade nets are manufactured from woven polypropylene materials or knitted polyethylene materials with different dimensions of fibers and holes to achieve specific shade levels. Traditional black nets are completely opaque and the spectral quality of radiation is not modified by the net; hence, the shading factor is almost directly proportional to net porosity (Castellano et al., 2008a). Dispersive shade nets are less opaque and scatter radiation, creating more diffused light that can penetrate inside plant canopies

(Oren-Shamir et al., 2001). Colored nets contain additives that selectively filter solar radiation to promote specific wavelengths of light (Castellano et al., 2008b; Stamps, 2009).

The combination of light-scattering spectral manipulation can modify desirable plant growth characteristics. For example, compared with black nets, *Aspidistra* plants were more compact under red and blue nets, *Philodendron* grew more leaves under red and fewer under blue nets, and *Pittosporum* growth indices (plant height and internode length) were highest under red and gray nets (Stamps and Chandler, 2008). Oren-Shamir et al. (2001) reported branch elongation of variegated *Pittosporum* under the red nets and dwarfing under blue nets. Studies in Brazil showed that *Phalaenopsis* cultivars generally grew larger leaves under blue nets compared with black and red but showed earliest blooming under red nets (Leite et al., 2008). Additional studies indicate some beneficial aspects of colored nets for the production of fruits (Basile et al., 2008; Retamales et al., 2008; Shahak et al., 2008; Takeda et al., 2010) and vegetable crops (Ilic et al., 2012; Kong et al., 2012; Shahak, 2008) grown under red, blue, green, and yellow nets. Recent reports from Israel also suggest additional benefits of photoselective nets regarding suppressive effects on plant pests or diseases (Ben-Yakir et al., 2012; Elad et al., 2007).

However, although photoselective shade nets show promise for plant production, the variability of results among crops suggests that the physiological aspects involved in these photoreponses are not yet fully understood. Variability of results may also reflect the different optical properties of shade nets produced by different manufacturers. An additional problem is that few studies report the specific environmental conditions present under various shadehouse structures. Seasonal variation in environmental conditions inside shadehouses is expected to impact cultivation of floricultural and other crops. In addition to light, shade nets may modify environmental variables such as temperatures, wind speed, or relative humidities inside the canopy. By contrast, more studies are available on the radiometric properties of metallic thermal screens and insect screens (Cohen and Fuchs, 1999; Klose and Tantau, 2004; Nijskens et al., 1985; Papadakis et al., 2000; Soni et al., 2005).

Fig. 1. Shade nets used to cover the structures at the Mid-Florida Research and Education Center.

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Fig. 2. Photosynthetically active radiation (PAR) measured at solar noon ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, 400 to 700 nm) in photosensitive (red and blue) and color-neutral (black and pearl) nets. Data are means $\pm$ SEM from four replicate houses.

Here we evaluate light quantity and quality and other environmental variables inside replicated shadehouses fitted with full-covering photosensitive and color-neutral nets during a full year. This information should be of interest to growers, horticulturists, and agricultural engineers.

Materials and Methods

Study location. Studies were conducted at the Mid-Florida Research and Education Center (lat. 28.7° N, long. 81.5° W) in 2011 and 2012. Sixteen shadehouse structures (each $10.4 \times 10.4 \times 3.0$ m height) were covered on the top and all sides with one of two photosensitive (red and blue) or one of two color-neutral (black and pearl) nets (ChromatiNet[®]; Polysack Plastic Industries, D.N. Negev, Israel; <<http://www.polysack.com>>) (Fig. 1). A nominal shade factor of 50% was indicated by the manufacturer for all four nets. This setup allowed us to monitor the impact of the full spectrum of environmental conditions (not just light) independently. Shadehouse structures were arranged in four blocks with

Fig. 3. Transmittance spectra of solar radiation measured under photosensitive (red and blue) and color-neutral (black and pearl) nets during different seasons: January (A), April (B), July (C), and October (D). Data are the ratio between radiation ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) measured inside and outside shadehouses. Recordings were taken at solar noon and are average of four replicate shadehouses.

each block containing all colors. The uncovered central area of each block was also used as a control (full sun) comparison.

Environmental measurements. Light measurements were taken monthly for 12 months (Sept. 2011 to Aug. 2012). *PAR* (400 to 700 nm) was recorded with a LI-185A light meter fitted with a LI-190 quantum sensor (LI-COR, Lincoln, NE). Spectral analysis (200 to 1100 nm) was measured using an optical ultraviolet/VIS spectrometer (OSM2-400 DUV; Oriel™ Newport Corp., CT). For standardization, all readings were taken in the middle of shadehouses at 1 m height on a clear day within 45 min of solar noon. Shade temperature (at 1 m) was recorded hourly inside all shadehouses and uncovered areas using 20 data loggers with internal thermistors (HOBO H08-032-08; Onset Computer Corp., Pocasset, MA) placed inside a rain shield. Relative humidity during wet or overcast conditions (ambient greater than 50% RH) was recorded manually in each house on 20 separate occasions using a portable meter (Model TH-1; Amprobe, Everett, WA). Similarly, wind speed during breezy conditions (greater than 3 m·s⁻¹) was recorded inside houses using a portable anemometer (Model 48020; Celestron LLC, Torrance, CA). All environmental readings were taken concurrently in the shadehouses and the uncovered control blocks. Where appropriate, treatments were compared through one-way analysis of variance and means separated with Tukey's

honestly significant difference test at $P < 0.05$ (SAS, 2008).

Results and Discussion

Photosynthetically active radiation. All shade nets reduced *PAR* compared with uncovered sites but there were differences between colors. Observed *PAR* values ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) were reduced most under black nets and least under red nets with blue and pearl nets intermediate (Fig. 2). Calculated photosynthetic shading values were black (55% to 60%), blue (51% to 57%), pearl (52% to 54%), and red (41% to 51%), depending on the season. These results are consistent with previous work where *PAR* was reduced less by 70% red netting compared with 70% black or 70% blue netting in unreplicated structure (Stamps and Chandler, 2008). The elevated *PAR* in the red may be considered an artifact of the net manufacturing process, suggesting that nominal shade factor designations do not necessarily precisely determine actual *PAR*. The data show that although transmitted *PAR* may be sufficient for plant growth under nets during the spring and summer months, lower values obtained during late fall and winter months may be limiting for some ornamental crops (Baloch et al., 2009; Fletcher et al., 2005).

Light quality. Spectral analysis from representative months revealed differences among

nets (i.e., proportion of *PAR* in blue, green, red, and FR spectra) (Fig. 3). Blue nets transmitted distinctive peaks in the blue (450 to 495 nm) as well as FR/near infrared beyond 750 nm. The red net had a minor peak ≈ 400 nm and major transmittance beyond 600 nm. Pearl nets transmitted more light above 400 nm compared with black nets but did not otherwise alter spectral composition in the visible range compared with black nets. There were no clear seasonal trends in transmittance efficiency of the blue and red spectral peaks nor for transmittance of black and pearl nets in the *PAR* range (data not shown).

The effect of light quality on plants is complex involving the combined action of several photoreceptor systems with different wavelength adsorption peaks (Smith, 2000). Higher plants have receptors for blue, green, and ultraviolet light (phototropins and cryptochrome) and R/FR receptors (phytochromes). Different photoreceptors can induce distinctive morphological and physiological responses that allow adaptation to different environmental conditions (Lee et al., 2000; Schuerger et al., 1997; Stuefer and Huber, 1998). For example, several studies show that enhanced blue light can increase plant compactness, that some blue light is necessary for normal growth and development, and also that the effects of blue light appear to be species-dependent (Cope and Bugbee, 2013). It has also been proposed that plants respond to the

Fig. 4. Comparisons of wavelength spectra amongst shade nets. Data were measured at solar noon on clear days and integrated over ultraviolet-B, 280 to 320 nm (A), ultraviolet-A, 320 to 400 nm (B), blue, 400 to 500 nm (C), and red/far-red, 600 to 700/700 to 800 nm (D). Data are mean $\pm$ SEM from four shadehouses; letters indicate significant differences between nets for a specific month ($P < 0.05$, Tukey's honestly significant difference test).

absolute amount of blue light rather than the relative amount of blue light in the photosynthetic range (Yorio et al., 1998, but see Cope and Bugbee, 2013). Our data showed blue nets increased light intensity between 400 and 500 nm over other nets by 34% to 44%, depending on the season, and even more in the 450- to 500-nm range (Figs. 3 and 4A).

Manipulation of the R/FR has been proposed as a way to modify horticultural crops. For example, high R/FR ratios induce beneficial physiological responses, most notably reduced stem extension and increased plant compactness (Fletcher et al., 2005; Mata and Botto, 2009; Rajapakse and Kelly, 1992). By contrast, low R/FR ratios may cause less desirable traits such as stem elongation, strengthening of apical dominance and reduced branching (Smith and Whitelam, 1997). In our study, no nets had R/FR ratios significantly greater than ambient (close to 1), whereas blue nets had consistently lowest R/FR ratio of ≈ 0.8 (Fig. 4B). Red and pearl nets had statistically reduced R/FR ratio during fall and winter and summer and fall, respectively, whereas the R/FR ratio of black nets was never different from ambient. This finding contrasts with Oren-Shamir et al. (2001), who reported ratios of light transmitted through blue nets were the same as the natural light, whereas R/FR under red nets was slightly lower, and green net was significantly lower than that of the natural irradiation. Reduced R/FR ratios are associated with underneath canopies of vegetation and the plant response of elongation termed the “shade avoidance syndrome.” The reduced R/FR values found under blue nets in our studies are not considered to be high enough to trigger the “shade avoidance syndrome” in most plants (Franklin and Whitelam, 2005).

Various studies also indicate that light in the ultraviolet range plays an important role in plant defenses. For example, natural or attenuated ultraviolet (especially ultraviolet-B) radiation helps protect plants from herbivores and microbial pathogens, possibly through the production of phenolic compounds and/or antioxidants (Ballaré et al., 2012; Wei et al., 2013). All shade nets reduced light intensity between 280 and 400 nm compared with ambient conditions, but there were differences between net colors (Fig. 4C and D). Both ultraviolet-B and ultraviolet-A were reduced most by pearl nets and least by red nets. In all cases, proportionally, more radiation was found in the ultraviolet-A range compared with ultraviolet-B. It has also been reported that low R/FR values (i.e., less than 1, typical of closed canopies) may lead to reduced plant defense against herbivorous insects, for example through inactivation of phytochrome B, which regulates defense hormones (Moreno et al., 2009).

Other environmental effects. Our data show that shade nets affect environmental variables other than radiation. Temperature and RH impact plant growth and physiology, including disease development, in various ways (Grantz, 1990; Went, 1953). In our studies, average daily maximum air temperatures were higher inside shadehouses with colored nets compared with black nets or ambient (Fig. 5). Highest air

temperatures were recorded under red (range, 1.9 to 3.7 °C higher than black). Black nets were consistently cooler compared with ambient, recording an average 0.4 °C (range, 0.1 to 0.9 °C) lower daily maximum temperatures. Blue and pearl recorded similar temperatures (on average 0.2 °C warmer for blue) and were intermediate between red and black nets. Wind speeds were different under shade nets ($F_{4,99} = 182.1$, $P < 0.0001$), with red, blue, and pearl providing greater wind resistance compared with black nets (Fig. 6). Because colored nets contain threads that are partially transparent, higher thread counts are needed to create the same shade factor compared with black threads, which results in smaller holes and less open area in the netting compared with traditional black nets (Fig. 1). The differences in hole sizes were sufficient to impact wind speed (and likely temperature), but not RH values, which remained within $\pm 1\%$ of ambient conditions inside shadehouses and were not statistically affected ($F_{4,99} = 0.01$,

$P = 0.99$). Despite differences in relative porosity, measurements of netting mass per unit area ($n = 5$) were similar among colors, i.e., 101 g·m⁻² (pearl), 99 g·m⁻² (black), and 95 g·m⁻² (red and blue nets).

Use of photosensitive nets. Shadenets are popular for growing ornamental plants. The most recent figures available (2011) show that 43% of floricultural crop production in the United States occurred under shade or other temporary cover (USDA/NASS, 2013). With modern mass weaving methods reducing costs, we can expect more photosensitive nets to be used. Shadenet structures constructed on trellises are inexpensive compared with glass or plastic film greenhouses, which may require more solid construction and additional climate controls. Although black nets are most frequently used, growers are experimenting with colored, gray, and white dispersive netting in an attempt to impact vegetative vigor, dwarfing, branching, leaf variegation, and timing of flowering (Leite et al., 2008; Oren-Shamir

Fig. 5. Daily maximum temperatures (°C) recorded inside and outside shadehouses. Data are means $\pm$ SEM averaged over each month from four replicate houses.

Fig. 6. Wind speeds recorded inside and outside shadehouses when ambient conditions greater than 3 m·s⁻¹. Data are mean $\pm$ SEM of 20 replicates (four houses per replicate). Letters indicate significant differences between nets ($P < 0.05$, Tukey's honestly significant difference test).

et al., 2000; Stamps, 2009). The use of colored nets might thus replace applications of chemical growth regulators or pruning practices. The tighter weaves of colored shadenets may provide additional protection from wind, hail, and animals. Our study documents the different environmental modifications inside structures covered with black and colored nets, which will help predict or interpret specific plant responses. However, a review of the literature also suggests that the responses of different plant species to modified light conditions are often variable. There is a need for additional information on how this technology is best harnessed to meet the needs of a diverse floricultural industry.

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