Greenhouse Energy Curtains Influence Shoot-tip Temperature of New Guinea Impatiens

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Abstract. **Many greenhouse growers have installed retractable energy curtains to reduce energy losses and heating costs. We performed experiments to quantify the effect of retractable nighttime curtains on plant shoot-tip temperature of New Guinea impatiens (*Impatiens hawkeri* Bull.) grown in glass-glazed greenhouses during winter. Plants were grown in separate greenhouses under different curtain materials and the following measurements were collected: plant shoot tip, aerial wet and dry bulb, and cover (glazing and superstructure or curtain) temperature; net canopy radiation (250 to 60,000 nm); transmitted shortwave radiation (SWR; 300 to 3,000 nm); and air velocity. At night, plants under an extended curtain had a higher (by 0.5 to 2.3 °C) shoot-tip temperature and the net longwave radiation (LWR$_{net}$; 3,000 to 100,000 nm) was 70% to 125% greater than plants without a curtain. Shoot-tip temperature was 0.2 to 0.6 °C lower under a shading curtain with open-weave construction (high air permeability) compared with closed-weave constructed curtains (e.g., blackout). As cover temperature decreased from 21 to 12 °C, measured shoot-tip temperature and LWR$_{net}$ decreased by a mean of 3.0 °C and 39.1 W·m^{-2}, respectively. Under a vapor pressure deficit (VPD) of 0.4 to 0.9 kPa, plant shoot-tip temperature was a mean of 1.0 °C closer to dry-bulb temperature compared with plants under a VPD of 1.4 to 1.8 kPa as a result of decreased transpiration. During the day, shoot-tip temperature was 1.2 °C lower than dry-bulb temperature when transmitted SWR was less than 100 W·m^{-2} and on average 1.6 °C higher than the dry-bulb temperature when SWR was more than 100 W·m^{-2}. Therefore, in addition to reducing greenhouse heating costs, a curtain extended at night over a crop of New Guinea impatiens could increase plant shoot-tip temperature and accelerate development.**

The commercial production of ornamental greenhouse crops demands that plants be accurately scheduled for predetermined market dates (Heins et al., 2000). The ability to schedule crops requires knowledge of how environmental factors (e.g., temperature and light) influence plant growth and develop-ment. The rate of plant development is controlled by the mean daily temperature (MDT) of the apical meristem (e.g., shoot tip) (Faust and Heins, 1993; Niu et al., 2001; Roberts and Summerfield, 1987). For example, as shoot-tip MDT increased from 16 to 24 °C, flower developmental rate (1/days to flower) in campanula (*Campanula carpatica* Jacq.) increased from 0.018 to 0.024 (Niu et al., 2001). Although plant temperature controls developmental rate, many growers use greenhouse air temperature (dry bulb) to predict crop timing. However, depending on environmental conditions, plant temperature can differ considerably from air temperature. For example, Faust and Heins (1998) reported that shoot-tip MDT in vinca (*Catharanthus roseus* L.) grown at 15 and 20 °C was within 2 °C of the air MDT, whereas plants grown at 35 °C had a shoot-tip MDT 4 to 6 °C below the air MDT.

Plant temperature is determined by transpiration and the convective and radiative transfer of energy between the plant and the surround-ing environment and can be calculated with an energy balance equation (Nobel, 2005). Factors that determine plant temperature include the total radiation absorbed by the plant, emitted LWR (3,000 to 100,000 nm), convection, and transpiration (Nobel, 2005). Plant energy balance models have been developed that predict shoot-tip temperature under different greenhouse conditions (Faust and Heins, 1998; Shimizu et al., 2004). During the day, SWR (300 to 3000 nm) and transpiration have the largest influence on energy transfer between the plant and the surrounding environment (Faust and Heins, 1998). During the night, convection and the transfer of LWR between the plant and the greenhouse structure as well as the radiative sky conditions (e.g., clear or cloudy sky) often have the greatest influence on plant temperature.

The exchange of LWR between plants and the surrounding environment is influenced by the temperature and emissivity of radiating surfaces. In temperate climates during winter nights, outside temperatures are low and the greenhouse glazing temperature can be considerably lower than the inside air temperature. As glazing temperature decreases, LWR emitted by the glazing material decreases, and LWR emitted by the plant can become greater than the incoming LWR. This net loss of LWR can cause plant temperature to drop below the air temperature. For example, as glazing temperature at night decreased from 2 to 16 °C below air temperature, vinca shoot-tip temperature decreased from 1 to 5 °C below air temperature (Faust and Heins, 1998).

In response to volatile fuel costs, some commercial growers have made greenhouse structural improvements to reduce energy losses such as the installation of energy curtains (Dieleman and Kempkes, 2006; Lund et al., 2006). Energy curtains are typically extended over a greenhouse crop from sunset to sunrise and retracted during the day (Bailey, 1988; Lund et al., 2006). An energy curtain that has a closed-weave construction (low air permeability) and seals tightly with the greenhouse sidewalls creates a barrier between the heated and unheated space above and below the curtain, respectively (Öztürk and Başçetinçelik, 1997; Zabeltitz and Meyer, 1984). Energy requirements for greenhouse heating can decrease with an energy curtain because the curtain material reduces heat transfer and reduces the air volume that must be heated.

Another potential benefit of energy curtains is an increase in LWR absorbed by the crop (Kittas et al., 2003). During the night, the interior surface temperature of an energy curtain is often higher than the glazing temperature. Therefore, when a curtain is extended over a crop, plants receive more LWR than without a curtain. The higher LWR$_{net}$ exchange can increase plant temperature. For example, a rose (*Rosa hybrida* L.) crop grown under a greenhouse energy curtain with 75% SWR transmission had 100% higher absorbed LWR and 1 to 3 °C higher canopy temperature at night than a crop grown without a curtain (Kittas et al., 2003). Studies with other crops

such as African violet (*Saintpaulia ionantha* Wendl.), tomato (*Lycopersicon esculentum* Mill.), and vinca have also reported higher canopy, leaf, or shoot-tip temperatures under curtains compared with no curtains (Bailey, 1977, 1981a; Faust, 1994).

The objective of this study was to quantify the effect of different curtain materials on shoot-tip temperature of New Guinea impatiens (*Impatiens hawkeri* Bull.) during cold nights when outside temperatures were near or below freezing. New Guinea impatiens was selected because it is among the top 10 bedding plants produced in the United States with a reported wholesale value of $51 million in 2010 (U.S. Department of Agriculture, 2011). In addition, because plant development of New Guinea impatiens is delayed considerably at a low temperature (Erwin, 1995), quantification of how curtains influence shoot-tip temperature could improve production scheduling, energy efficiency, and management of the greenhouse environment.

Materials and Methods

Plant material. On 26 Nov. 2008, rooted vegetative cuttings of New Guinea impatiens 'Supersonic Flame' grown in 50-cell trays (2.5 × 2.5 cm; 27.2-mL volume) were received from a commercial greenhouse (Raker's Acres, Inc., Litchfield, MI). Plants were subsequently transplanted into 11-cm round plastic containers (600-mL volume) filled with a commercial soilless peat-based medium (Suremix; Michigan Grower Products, Inc., Galesburg, MI) and were grown at a constant temperature set point of 23 °C. The photoperiod was a constant 16 h that consisted of natural photoperiods (lat. 42.7° N) with day-extension lighting from 0600 to 2200 HR provided by high-pressure sodium (HPS) lamps that delivered a photosynthetic photon flux of 75 to 100 μmol·m^{-2}·s^{-1} at plant height [as measured with a line quantum sensor (Apogee Instruments, Inc., Logan, UT)]. The HPS lamps were operated by an environmental computer (Priva Intégro 724; Priva, Vineland Station, Ontario, Canada) and were turned on when the outside light intensity was less than 290 μmol·m^{-2}·s^{-1} and turned off above 580 μmol·m^{-2}·s^{-1}.

Ethephon (Florel; Bayer CropScience LP, Research Triangle Park, NC) with a surfactant (Capsil; Aquatrols, Paulsboro, NJ) was applied as a foliar spray at 300 mg·L^{-1} and 0.2 L·m^{-2} every 2 to 3 weeks to abort flower buds. Plants were irrigated as necessary with reverse-osmosis water supplemented with a water-soluble fertilizer providing (mg·L^{-1}) 125 nitrogen, 12 phosphorus, 100 potassium, 65 calcium, 12 magnesium, 1.0 iron and copper, 0.5 manganese and zinc, 0.3 boron, and 0.1 molybdenum (MSU RO Water Special; GreenCare Fertilizers, Inc., Kankakee, IL). After 7.5 weeks, leaf canopy exceeded the container diameter and plants were transferred to different greenhouses for the curtain study.

Greenhouse environment. The research facility for the retractable curtain experiment consisted of a row of six connected (4.8 × 4.1 m) glass-glazed greenhouse compartments oriented east–west. Compartments were separated by a glass wall orientated north–south. Only the middle four compartments were used for the experiment. In each compartment, 25 plants were grown on a bench that was positioned in the middle of the greenhouse. Plants were spaced so that leaves of adjacent plants touched and hence formed a full canopy.

In three compartments, a curtain located horizontally at the height of the greenhouse eave was manually extended over plants at 1700 HR and retracted at 0800 HR. Control plants were grown in one compartment without a curtain. Six 4-d experiments were performed between 20 Jan. and 19 Feb. 2009 with different curtains and under different VPDs. The curtains used in the study were obtained from Ludvig Svensson, Inc. (Charlotte, NC) and included 1) blackout with aluminized (AL) polyester and 0% light transmission (blackout AL); 2) blackout with black polyester and 0% light transmission (blackout BL); 3) closed-weave curtain with alternating 5-mm wide AL and transparent plastic (TP) strips and 46% light transmission (energy AL/TP); 4) open-weave curtain composed of alternating 5-mm-wide AL, TP, and empty strips (X) with 50% light transmission (shade AL/TP/X); 5) closed-weave curtain with 5-mm-wide TP strips and 88% light transmission (energy TP1); and 6) closed-weave curtain with 5-mm-wide TP strips and 83% light transmission (energy TP2) (Table 1).

The temperature in each greenhouse compartment was controlled by the environmental computer that controlled steam heating and passive and active ventilation when needed. The air temperature set point in each compartment was a constant 20 °C, and the actual mean daily dry-bulb temperature was 19.9 ± 0.7 °C (± SD). The mean day and night dry-bulb temperatures were within 0.1 °C. The greenhouse was heated with steam-heating units located below the benches along the knee wall of each compartment. During the study, plants were grown without HPS lamps and under natural photoperiods. The calculated time from sunrise to sunset ranged from 9 h 33 min to 10 h 46 min. Plants were grown with minimal overhead obstructions and were irrigated as previously described without water stress.

Environmental measurements. In each compartment, dry-bulb and wet-bulb temperatures were independently measured by aspirated, shielded thermocouples (0.13-mm type E; Omega Engineering, Stamford, CT) positioned at plant level and adjacent to the canopy. Shoot-tip temperature was independently measured on three randomly selected plants in each compartment by inserting fine-wire thermocouples (Type E; Omega Engineering) ≈0.3 cm below the shoot apex. Thermocouples were reinserted every 4 d as plants unfolded leaves. All of the thermocouples used to measure shoot-tip temperature were compared before the study and no calibration was necessary. At 15 cm above the canopy in each compartment, a pyranometer (LI-200SA; LI-COR, Lincoln, NE) measured SWR (300 to 3000 nm). At the same height, net radiation was measured in two compartments with double-sided total hemispherical radiometers (THR) [(250 to 60,000 nm) THRDS7.1; Radiation and Energy Balance Systems, Inc., Seattle, WA] and in one compartment with a net radiometer [(300 to 50,000 nm) CNR1; Kipp & Zonen USA Inc., Bohemia, NY]. The accuracy of radiation measurements made with net radiometers can differ among instrument models

Table 1. Characteristics of greenhouse curtains used during the experiment.[z]

Curtain treatment	Description	SWR transmission (%)	Energy savings (%)	Emissivity bottom	Product name
Blackout AL	BL woven polyester; top surface: polished AL coating with TP threads; bottom surface: dull AL coating with BL threads	0	75	0.61	XLS Revolux FB A/A
Blackout BL	BL woven polyester with BL threads on both surfaces	0	75	0.88	XLS Obscura Revolux B/B
Energy AL/TP	AL-TP strips[y] woven with TP threads; top surface: polished AL; bottom surface: dull AL	46	57	0.54	XLS 15 FB
Shade AL/TP/X	AL-TP-AL-X-AL-X strips[y] woven with TP threads; top surface: polished AL; bottom surface: dull AL	50	20	0.50	XLS 15 F FB
Energy TP1	TP-TP strips[y] woven with TP threads	88	43	0.50	SLS 10 Ultra Plus
Energy TP2	TP-TP strips[y] woven with TP threads	83	47	0.54	XLS 10 Ultra Revolux

[z]Curtain information was obtained from the manufacturer (Ludvig Svensson, Inc., Charlotte, NC). The bottom side of each curtain was orientated toward the crop. Control plants were grown in a greenhouse without a curtain and were exposed to glass glazing (emissivity = 0.9).
[y]Five-millimeter-wide parallel strips with different materials.
SWR = shortwave radiation, 300 to 3000 nm; AL = aluminum; BL = black; TP = transparent polyethylene; X = empty space crossed with polyester threads.

(Blonquist et al., 2009). Therefore, before the study began, radiation measurements from the two THRs were collected over 2 d (307 measurements per instrument) and compared against the CNR1 net radiometer (reference) and a calibration equation was developed. The equation was subsequently applied to data from the THRs and adjusted values were calculated.

In each compartment, canopy temperature and cover temperature were recorded with infrared (6,500 to 14,000 nm) sensors (Type K, OS36-01; Omega Engineering) positioned 15 cm above the canopy and oriented vertically upward (cover) or downward (canopy). Cover temperature represented the greenhouse glazing and superstructure temperature when the curtain was retracted and the surface temperature of the curtain when it was extended over the crop. Before the study, three new infrared sensors (reference) were compared against the other five sensors at 5 to 30 °C and a calibration equation was developed to standardized values. In two compartments, air velocity transducers (8470 and 8475; TSI, Inc., St. Paul, MN) positioned 2 cm from the shoot tip measured air velocity, which was 0 to 0.1 m·s⁻¹. Active ventilation with fans did not occur during the study. In the other two compartments, air velocity was not measured continuously because of instrument availability. However, air velocity was measured instantaneously at the same location and was found to be within 0.05 m·s⁻¹ of air velocity of the other compartments.

Environmental greenhouse measurements were collected every 10 s and 10-min means were recorded by two data loggers (CR10; Campbell Scientific, Logan, UT). Outside air temperature was measured every 5 min by a Priva weather station located 2 m above the greenhouse peak, and data were recorded by the greenhouse environmental-controlled computer. During three experimental periods, VPD was maintained at 0.4 to 0.8 kPa by the injection of steam into the air. During the other three experimental periods, VPD was not controlled and ranged from 1.4 to 1.8 kPa.

Data analysis. Data for cover temperature, LWR$_{net}$, and the difference between shoot-tip and dry-bulb temperatures were analyzed for each 4-d experimental period by using the 10-min means for each recorded parameter from each treatment. Data were analyzed with SAS (SAS Institute, Inc., Cary, NC) mixed model procedure (PROC MIXED), and pairwise comparisons between treatments were performed with Tukey's honestly significant difference test at $P \leq 0.01$. Each of the six experimental periods was analyzed separately because treatments and environmental conditions were different for each period. For the analysis, treatment was considered to be a fixed effect in the model and the measured parameter (e.g., LWR$_{net}$) was considered to be a dependent variable.

Results and Discussion

During each experimental period and under all treatments, the measured mean shoot-tip temperature during the night was 0.6 to 3.8 °C lower than the mean dry-bulb temperature (Table 2; Fig. 1). This shoot-tip temperature depression at night is in agreement with a poinsettia model that predicted shoot-tip temperature to be 4.2 °C lower than dry-bulb temperature at an air velocity of 0.05 m·s⁻¹, VPD of 0.7 kPa, and a dry-bulb and glazing temperature of 25 and 0 °C, respectively (Shimizu et al., 2004). During the night, shoot-tip temperature depression occurs because energy losses from the plant exceed energy gains. Shoot-tip temperature at night can never be greater than air temperature without an infrared heat source (Rotz and Heins, 1982).

Within each experimental period, plants under a curtain extended during a cold night had a shoot-tip temperature 0.5 to 2.3 °C higher than plants without a curtain (Table 2; Fig. 1). This is in agreement with Faust (1994), who reported that at a nighttime glazing temperature of –1.5 °C, vinca plants had a mean shoot-tip temperature 2.9 °C higher under a curtain compared with without a curtain. Similarly, tomato grown under an energy curtain at night had a leaf temperature 0.5 °C higher than that of uncurtained plants when the outside air temperature was 9 °C below the greenhouse dry-bulb temperature (Bailey, 1977).

The lower shoot-tip temperature in uncurtained plants can be attributed to the loss of LWR from the plant to the glazing at night, which can cause the plant LWR$_{net}$ to be negative (Bailey, 1977; Kittas et al., 2003). In a greenhouse, plants exchange LWR with the superstructure and sky above (Silva et al., 1991). According to the Stephan-Boltzmann law, emission of radiation from an object decreases as the surface temperature of the object decreases (Nobel, 2005). During all experimental periods, the plants that had a curtain extended over them during the night were exposed to a cover with a temperature 0.8 to 6.9 °C higher than the plants that were exposed to the glazing (Table 2). As cover temperature at night decreased, emitted LWR from the curtain or glazing decreased and LWR absorbed by the plant decreased (data not shown). For example, LWR$_{net}$ decreased from 5.7 to –22.9 W·m⁻² and shoot-tip temperature decreased by 1.6 °C as cover temperature decreased from 20.1 to 14.4 °C during Period 1. Combining all experimental periods, for every 1 °C decrease in cover temperature at night, measured shoot-tip temperature and

Table 2. The effects of different curtains on measured net longwave radiation (LWR$_{net}$) exchange between New Guinea impatiens shoot tip and the overhead cover (glazing and superstructure, or curtain) and the difference between measured shoot-tip temperature (T$_{shoot}$) and dry-bulb temperature (T$_{db}$) in glass-glazed greenhouses during the night (1700 to 0800 HR) during winter in East Lansing, MI (lat. 43° N) under different vapor pressure deficits (VPD).[z]

Expt. period (no.)	Mean T$_{outside}$ (°C)	Curtain	VPD (kPa)	Mean T$_{cover}$ (°C)	LWR$_{net}$ (W·m⁻²)	Mean T$_{shoot}$–T$_{db}$ (°C)
1	–6.8	Blackout AL	1.6	20.1 a[y]	5.7 a	–2.1 b
		Energy AL/TP	1.5	18.9 b	1.3 b[x]	–1.9 a
		Shade AL/TP/X	1.6	17.1 c	–2.8 c	–2.3 c
		None	1.8	14.4 d	–22.9 d	–3.7 d
2	–9.8	Blackout AL	0.5	19.5 a	2.7 a	–1.2 a
		Energy AL/TP	0.5	18.5 b	–0.8 b[x]	–1.3 a
		Shade AL/TP/X	0.6	16.4 c	–5.2 c	–1.8 b
		None	0.7	14.0 d	–23.5 d	–2.8 c
3	–4.7	Blackout AL	1.4	19.1 b	1.3 b	–1.5 a
		Blackout BL	1.5	20.1 a	2.2 a	–1.7 a
		Energy AL/TP	1.4	18.6 c	0.2 c[x]	–1.9 b
		None	1.5	13.2 d	–25.4 d	–3.8 c
4	–10.8	Blackout AL	0.6	18.4 a	–0.1 a	–1.6 b
		Blackout BL	0.4	18.6 a	–2.2 b	–1.4 a
		Energy AL/TP	0.5	17.8 b	–1.5 b[x]	–1.3 a
		None	0.9	13.0 c	–27.7 c	–3.2 c
5	–2.9	Blackout AL	1.4	19.4 a	2.1 a	–1.3 a
		Energy TP1	1.4	16.8 c	–4.2 c	–2.3 c
		Energy TP2	1.4	17.7 b	–2.5 b[x]	–1.5 b
		None	1.4	15.0 d	–22.4 d	–3.1 d
6	0.5	Blackout AL	0.6	19.3 a	–0.3 a	–0.6 a
		Energy TP1	0.5	17.3 c	–4.5 c[x]	–0.9 b
		Energy TP2	0.5	17.5 b	–3.3 b	–1.1 c
		None	0.5	16.5 d	–14.8 d	–1.6 d

[z]Each experimental period was 4 d and occurred between 20 Jan. and 19 Feb. 2009. The mean T$_{db}$ during the experiments was 19.5 to 20.2 °C. See Table 1 for a description of curtain materials.
[y]Means within columns and experimental period followed by the same letter are not significantly different by Tukey's honestly significant difference test at $P \leq 0.01$.
[x]LWR$_{net}$ not measured; calculated using an energy-balance equation (Blanchard, 2009) with cover and leaf temperature and curtain and plant emissivity but omitting the shape factor for LWR$_{net}$.
T$_{outside}$ = outside air temperature; T$_{cover}$ = cover temperature (glazing and superstructure, or curtain).
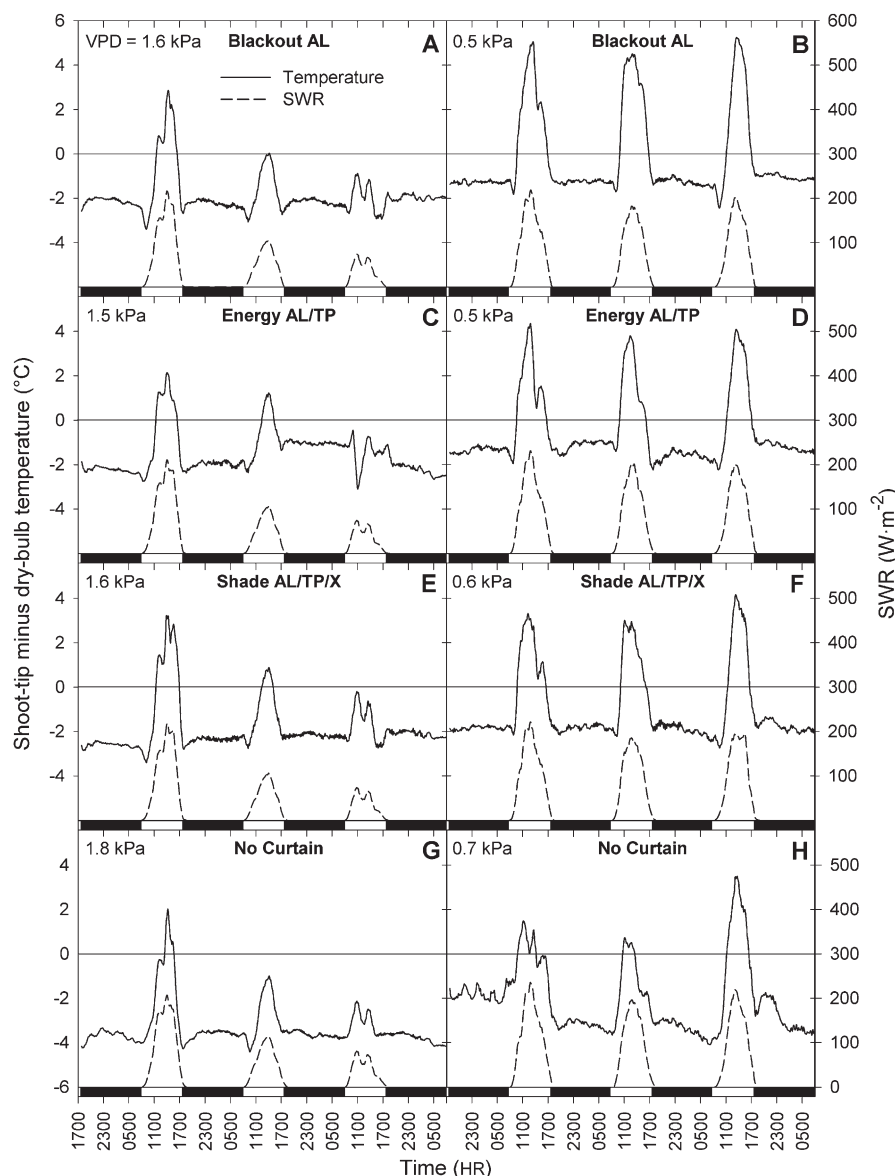
Fig. 1. Measured difference between New Guinea impatiens shoot-tip and dry-bulb temperatures in glass-glazed greenhouses during winter in East Lansing, MI (lat. 43° N) under different vapor pressure deficits (VPDs) and with different curtains extended over plants from 1700 to 0800 HR. Control plants were grown without a curtain above. The air temperature set point was 20 °C. See Table 1 for a description of curtain materials. Data in **A, C, E,** and **G** and **B, D, F,** and **H** were collected during 20 to 24 Jan. and 25 to 29 Jan. 2009, respectively. Black bars represent night from actual sunset to sunrise. SWR = shortwave radiation (300 to 3000 nm).

LWR_{net} decreased by a mean of 0.3 °C and 0.4 W·m^{-2}, respectively (Fig. 2).

Plants under a low VPD (0.4 to 0.9 kPa) had a nighttime shoot-tip temperature a mean of 1.0 °C closer to dry-bulb temperature than that of plants under a high VPD (1.4 to 1.8 kPa) (Fig. 2). If substrate moisture is not limiting, plant water uptake and transpiration increase as VPD increases (Mankin et al., 1998). Because the evaporation of water is an endothermic process, transpiration represents the loss of latent energy from a plant (Nobel, 2005). The relationship between New Guinea impatiens plant temperature and VPD was also reported by Mankin et al. (1998) who quantified that leaf temperature during the day decreased by 1 °C as air VPD increased

from 0.5 to 1.5 kPa. Similarly, vinca shoot-tip temperature decreased by 1 °C when the VPD at night increased from 0.5 to 3.0 kPa (Faust and Heins, 1997).

Several C$_3$ and C$_4$ annual and herbaceous perennial species, including New Guinea impatiens, maintain stomatal conductance and transpiration at night (Mankin et al., 1998; Pang, 1992; Snyder et al., 2003). Therefore, nighttime transpiration is an important factor affecting plant temperature of New Guinea impatiens. To prevent a shoot-tip temperature depression at night, the energy lost from transpiration must be balanced with the energy gained from convection and absorbed LWR. During winter in temperate climates, VPD at night can increase considerably because of

infiltration of outside air containing little water vapor and the subsequent heating of this air (Hanan, 1990). These results indicate that during greenhouse production of New Guinea impatiens, especially during winter, injecting water vapor into the air to decrease VPD would reduce transpiration and increase plant temperature.

Shoot-tip temperature depression at night can also be caused by the convection of energy between the air and the plant. The amount of convection is influenced by the resistance of the boundary layer around the shoot tip or leaf (Nobel, 2005). As air velocity decreases, there is an increase in boundary layer thickness and therefore an increase in resistance to convective heat transfer and a decrease in transpirational cooling. In this study, boundary layer resistance during the night was probably high because horizontal airflow fans (HAFs) were turned off and mean air velocity was 0 m·s^{-1}. New Guinea impatiens shoot-tip temperature at night could have been closer to air temperature with air movement. An energy-balance model developed for New Guinea impatiens predicted that at a dry-bulb, wet-bulb, and cover temperature of 20, 14, 19 °C, respectively, shoot-tip temperature at night would increase from 18.2 to 19.5 °C if air velocity increased from 0 to 0.5 m·s^{-1} (Blanchard, 2009). These results reinforce the importance of operating HAFs at night in commercial greenhouses to increase convective heat transfer and thus plant temperature (Bartok, 2005).

Greenhouse curtains are available from several manufacturers and are constructed of materials with different thermal and radiometric transmission properties (Bailey, 1981b; Cohen and Fuchs, 1999; Winspear and Bailey, 1978). A characteristic that can vary among curtains is the emissivity. Emissivity is the ratio of radiation emitted from a material to the radiation emitted by a black body at the same temperature and ranges from 0 to 1 (Gates, 2003). As the emissivity of a material decreases, reflectivity and emitted radiation increase. The curtains used in this study had a bottom emissivity that ranged from 0.5 to 0.88 (Table 1). Plants under closed-weave curtains constructed of blackout AL, blackout BL, and energy AL/TP had a shoot-tip temperature within 0.4 °C of one another (Table 2). Among these curtains, there were no consistent trends between experimental periods during which a curtain elicited the highest shoot-tip temperature. Similarly, vinca shoot-tip temperature under various closed-weave black or AL blackout curtains was within 0.7 °C (Faust, 1994). Therefore, at the curtain surface temperatures observed during this study, curtain emissivity had little influence on shoot-tip temperature.

Although some of the curtains had a similar emissivity, they had different bottom surface temperatures and different effects on plant shoot-tip temperature. For example, during Periods 5 and 6, curtains constructed of all transparent strips (energy TP1 and energy TP2; emissivity = 0.5 to 0.54) had a nighttime bottom surface temperature 1.7 to 2.6 °C lower than that of plants under
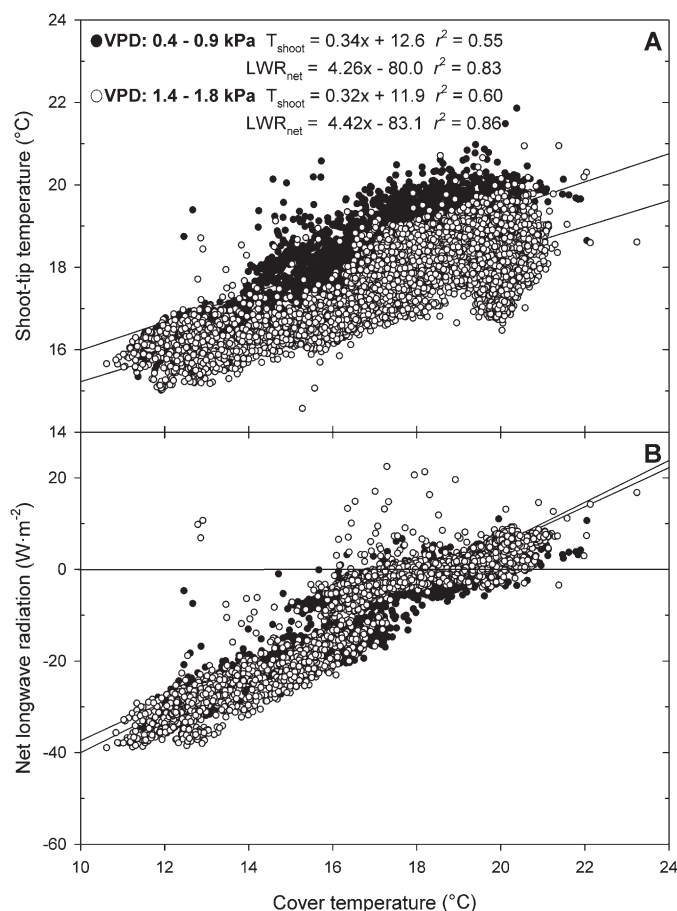
Fig. 2. Relationship between greenhouse cover temperature and New Guinea impatiens shoot-tip temperature (T_{shoot}) (**A**) and longwave radiation exchange between the canopy and surroundings (net longwave radition, LWR_{net}) (**B**) under different ranges of vapor pressure deficits (VPDs) during the night (1700 to 0800 HR). Plants were grown in glass-glazed greenhouses during winter in East Lansing, MI (lat. 43° N) under different VPDs and with different curtains extended over plants at night. Control plants were grown without a curtain above. The air temperature set point was 20 °C. Each panel includes measured data from six 4-d experimental periods and consists of 7717 observations. See Table 1 for a description of curtain materials.

blackout AL (emissivity = 0.6) (Table 2). Under these same curtains, plants had a mean shoot-tip temperature 0.2 to 1.0 °C lower than plants under blackout AL. The lower surface temperatures of some curtains could be related to differences in thermal conductivity, permeability, and thickness of the curtain materials (Miguel et al., 1997; Nijskens et al., 1984; Winspear and Bailey, 1978). Materials that are thick or have low conductivity for heat transfer can elicit a high temperature gradient between the material surfaces (Nijskens et al., 1984). Therefore, a curtain with high thermal conductivity can have a temperature on the upper surface exposed to the glazing similar to that of the lower surface exposed to the canopy. Curtain temperature could be increased by use of multiple horizontal shading or blackout curtains (Heins and Runkle, 2004). The extension of two curtains over a crop at night could increase the surface temperature of the lower curtain and increase LWR absorbed by the plant.

After the curtains were retracted at 0800 HR, dry-bulb and shoot-tip temperatures decreased on some days by up to 1.8 and 5.4 °C,

respectively. This temperature drop generally lasted for 30 to 60 min. During the day, plants had a measured mean shoot-tip temperature 1.2 °C lower than dry-bulb temperature when SWR was less than 100 W·m⁻² and a mean of 1.6 °C higher than dry-bulb temperature when SWR was more than 100 W·m⁻². Linear regression analysis performed on measured data predicted that as SWR increased from 5 to 250 W·m⁻², the difference between shoot-tip and dry-bulb temperatures increased linearly from –2.0 to 3.3 °C (data not shown). In comparison, shoot-tip temperature of African violet was up to 4 °C above the dry-bulb temperature on a sunny day (100 to 150 W·m⁻²) and 1 to 3 °C below the dry-bulb temperature on a cloudy day (50 W·m⁻² or less) (Faust and Heins, 1993).

Some greenhouse growers operate internal shading systems during the day when solar irradiance and outdoor temperature are high to reflect SWR and to prevent high temperature stress on crops (Heins and Runkle, 2004; Hoffmann and Waaijenberg, 2002). In this study, plants under a 50% shade curtain with open-weave construction (shade AL/TP/X) had a nighttime shoot-tip temperature 1.0

to 1.4 °C higher than that of plants without a curtain but 0.2 to 0.6 °C lower than that of plants under blackout AL or energy AL/TP (Table 2). These results indicate that the operation of an open-weave shade curtain to reduce SWR transmission during the day can also increase shoot-tip temperature at night. However, there is a tradeoff between the shading percentage of a curtain and its potential to reduce energy inputs for greenhouse heating. As the light transmission and air permeability of a curtain increase, its insulative value decreases (Ludvig Svennson, Inc., 2011).

Plants directly exposed to the cold glazing had a measured mean nighttime shoot-tip temperature 2.4 to 4.4 °C lower than the greenhouse temperature set point of 20 °C. At temperatures below ≈17 °C, New Guinea impatiens development is severely delayed and there is greater variability in flowering time (Erwin, 1995; Runkle, 2008). Therefore, increased shoot-tip temperature at night under a greenhouse curtain can accelerate plant development. For example, time to flower of New Guinea impatiens 'Celebrette Peach' decreased by 3 d for every 1 °C increase in mean daily air temperature between 18 and 26 °C (Whitman et al., 2000). Assuming the cultivar in this study had a similar developmental response to mean daily shoot-tip temperature, a crop grown under a curtain extended at night would flower up to 5 d earlier than a crop grown without a curtain. These results support that a retractable greenhouse curtain has the potential to decrease energy costs for heating (Brajeul et al., 2005) and also increase plant temperature and reduce production time.

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