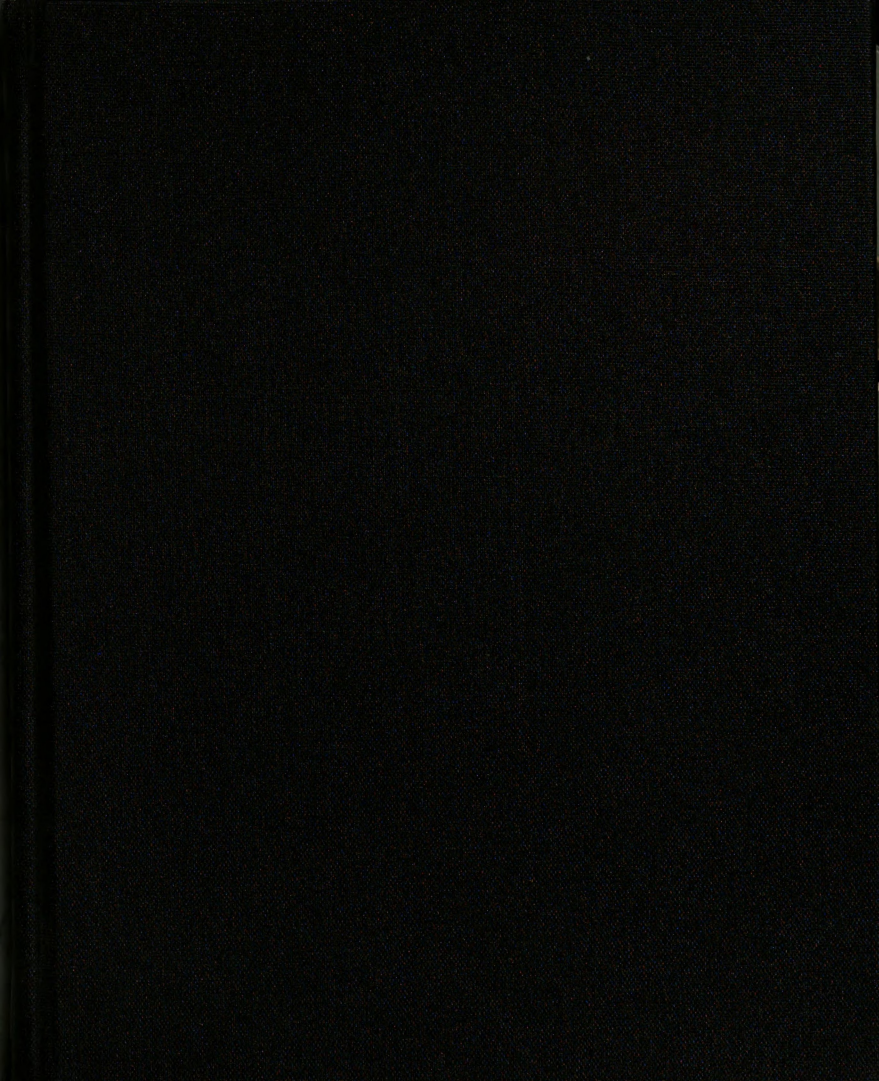




THESIS

2
(1995)



This is to certify that the

dissertation entitled

**Modeling and Managing Shoot-Tip Temperatures
in the Greenhouse Environment**

presented by

James Emerson Faust

has been accepted towards fulfillment
of the requirements for

PhD degree in Horticulture

Royal D. Heinz
Major professor

Date *Jan 4, 1995*

LIBRARY
Michigan State
University

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE
OCT 29 1996 IL 8780366	FEB 23 1997	

MSU is An Affirmative Action/Equal Opportunity Institution

c:\pic\datedue.pm3-p.1

**MODELING AND MANAGING SHOOT-TIP TEMPERATURES
IN THE GREENHOUSE ENVIRONMENT**

By

James Emerson Faust

A DISSERTATION

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

DOCTOR OF PHILOSOPHY

Department of Horticulture

1994

ABSTRACT

MODELING AND MANAGING SHOOT-TIP TEMPERATURES IN THE GREENHOUSE ENVIRONMENT

By

James Emerson Faust

The primary objective of this project was to identify the differences that occur between shoot-tip and air temperature in greenhouse environments. *Vinca (Catharanthus roseus L.)* plants were grown in greenhouses set at 15, 20, 25, 30, or 35C air temperature. In general, shoot-tip temperature was lower than air temperature at night. The difference between shoot-tip and air night temperature increased as the difference between shoot-tip and glazing material temperature increased or as the water vapor pressure deficit increased. During the day, shoot-tip temperature under low air temperature/low vapor pressure deficit conditions increased relative to air temperature as shortwave radiation increased, however shoot-tip temperatures under high air temperature/high vapor pressure deficit conditions initially decreased relative to air temperature at sunrise, then increased later in the morning as shortwave radiation increased. *Vinca* shoot-tip temperatures were also quantified under supplemental lighting and under thermal screens at night. From these data, a shoot-tip temperature model was developed to predict shoot-tip temperatures using four environmental measurements: air temperature, wet-bulb temperature, glazing material temperature, and shortwave radiation. Eighty-one percent of the one-hour average shoot-tip temperatures predicted over a two week period were within $\pm 1^{\circ}\text{C}$ of the measured temperatures.

DEDICATION

To Kimberley Brown-Faust, for your love.

To Warren and Doris Faust, for believing in me.

To Dr. John Griffin, for your inspiration.

ACKNOWLEDGEMENTS

Special thanks to Dr. Royal Heins for his sincere concern for my education and professional success.

I want thank Dr. Bruce Bugbee and Dr. Roar Moe for the opportunity to work in their labs. These experiences were invaluable for me.

I wish to thank the other members of my guidance committee for their time and interest: Drs. Jim Flore, Joe Ritchie, George Merva, and Randy Beaudry.

Finally, I would like to thank all of the individuals that contributed to this effort on my behalf, especially Mark Yelanich, Tom and Cara Wallace, Sven Verlinden, Paul Kiefer, Hiroshi Shimizu, Paul Fisher, and Matteus Nachtmann.

Without your assistance, this project would not have been possible or even any fun.

Guidance committee:

The paper format was adopted for this thesis in accordance with Departmental and University regulations. Sections I and V are to be submitted to the Journal of American Society of Horticultural Science. Section II has been submitted to Acta Horticulturae. Sections III and IV are to be submitted to HortTechnology.

TABLE OF CONTENTS

	Page
LIST OF TABLES	viii
LIST OF FIGURES	x
SECTION I	
Modeling shoot-tip temperatures in the greenhouse environment. . . .	1
Abstract	3
Materials and Methods	7
Results	13
Discussion	16
Literature cited	24
SECTION II	
Quantifying the influence of high-pressure sodium lighting on shoot-tip temperature.	46
Abstract	47
Introduction	48
Materials and Methods	49
Results	51
Discussion	52
References	55
SECTION III	
Quantifying the effect of thermal screens on shoot-tip temperature in glass greenhouses.	69
Abstract	71
Materials and Methods	73
Results and Discussion	74
Literature cited	78
SECTION IV	
Quantifying the effect of plug-flat color on medium-surface temperatures during germination.	82
Abstract	84
Materials and Methods	85
Results and Discussion	86
Literature cited	89

SECTION V

Axillary bud and lateral shoot development of 'Eckespoint Lilo' and 'Eckespoint Redsails' poinsettia (<i>Euphorbia pulcherrima</i> Willd.) are inhibited by high temperatures during stock plant production.	95
Abstract	97
Materials and Methods	100
Results	104
Discussion	107
Literature cited	111

LIST OF TABLES

Table

SECTION I

		Page
1.	Definitions of symbols, units, and default values for parameters in the shoot-tip temperature model described in Eqs. 1-10.	26
2.	Parameter estimates for Eq. 7 ($r^2=0.744$).	27

SECTION II

1.	The estimated effect of HPS lighting on the time of development of Easter lily (Karlsson et al., 1988), poinsettia (unpublished data, 1993), and hibiscus (Karlsson et al., 1991). assuming that the average daily shoot-tip temperature increases 1.5C as a result of lighting at $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For Easter lilies, approximately 80 leaves unfold prior to visible bud. For poinsettia stock plants, 8 leaves unfold before a vegetative cutting can be removed. For hibiscus, 8 leaves unfold prior to flower initiation.	56
----	---	----

SECTION III

1.	The effect of four thermal screens and one shade cloth on the difference between shoot-tip and air temperatures for vinca and African violet during five experiments. AL/AL, aluminum-coated polyester top and aluminum-coated polyester bottom; AL/BL, aluminum-coated polyester top and black polyethylene bottom; BL/BL black polyethylene top and black polyethylene bottom; BL/AL black polyethylene top and aluminum-coated polyester bottom; 40%AL, 40% aluminum-coated polyester shade cloth.	79
----	---	----

SECTION IV

- 1 Parameters estimates for the nonlinear equation describing the effect of shortwave radiation on the difference between media surface and air temperature ($Y=b_0-b_1\exp(-b_2*X)$). 90

SECTION V

1. Air temperature and pinching treatments for Expt. 5. 113
2. The relationship between the axillary bud rating made on a control group and a group of cuttings and the percentage of lateral shoots that developed after pinching. Five acropetal axillary buds on the lateral shoots of stock plants were given the following ratings:
Rating 1. Well-developed bud: The bud was green, necrosis was not present, and the first leaf was visible. Rating 2. Poorly-developed bud: Necrosis covered all or part of the bud, and/or the first leaf was not visible. Rating 3. Axillary bud not visible: The leaf axil was devoid of a visible bud. Half of the lateral shoots were removed from the stock plants and propagated. The lateral shoots remaining on the stock plants and the propagated cuttings were then pinched simultaneously. The same leaf axils as before were later examined to determine whether or not a lateral shoot had developed. 114
3. Effect of the duration of a high day temperature (33/27C) treatment on axillary bud development of 'Eckespoint Red Sails' poinsettias in the leaf axils of nodes 0 to 7. Node 0 refers the most newly unfolded leaf at the time of transfer, while nodes 1 through 7 represent the nodes to consecutively unfold after the start of the experiment. 115

LIST OF FIGURES

Figure		Page
SECTION I		
1.	The relationship between the calculated conductance (g) of water vapor and PPF incident on the canopy. The regression line represents the model described in Eq. 7 ($r^2=0.774$), and symbols represent the one-hour average values calculated with the energy balance equations using the measured shoot-tip temperatures.	29
2.	Predicted (lines) and observed (symbols) difference between vinca shoot-tip and air temperatures recorded in the 15 (○), 25 (●), and 35C (▼) greenhouses on A) a cloudy day (May 27, 1993) and B) a partly sunny day (May 30, 1993).	31
3.	Predicted (▲) and observed (□) difference between vinca shoot-tip temperature and air temperature as influenced by longwave radiation exchange between the canopy and the glazing material. The driving force for longwave radiation exchange is the difference between shoot-tip and glass temperature.. . . .	33
4.	Predicted (▲) and observed (□) difference between vinca shoot-tip temperature and air temperatures observed in a A) 15C, B) 20C, C) 25C, D) 30C, or E) 35C greenhouse shown as a function of PPF incident on the canopy. The average VPD measured in each greenhouse is presented in the individual figures.	35
5.	The predicted (▲) and the observed (□) A) 24-hour average, B) night, and C) day shoot-tip temperature of vinca plants grown in greenhouses set to maintain 15, 20, 25, 30, or 35C air temperature.	37
6.	Predicted versus observed shoot-tip temperatures of vinca plants grown in A) 15, 20, 25, 30, and 35C greenhouses during the model-development experiment or in B) 15, 25, and 35C greenhouses during the model-validation experiment. Symbols represent a one-hour average values in A or 30-minute average values in B.	39

7. A simulation of 24-hour average vinca shoot-tip temperatures under four types of weather conditions: A) cloudy and warm, B) sunny and warm, C) cloudy and cold, or D) sunny and cold conditions. Cold and warm days were defined as days when outside temperatures were -10 to 0C and 10 to 20C, respectively. Cloudy and sunny days were defined as days when shortwave radiation maximum was 120 and 470 W m⁻², respectively. VPD are indicated with different symbols. . 41
8. Comparison of model prediction of shoot-tip temperature over a simulated two day period and model prediction after several model parameters were individually altered as indicated. Weather data simulated greenhouse conditions on a sunny followed by a cloudy day when greenhouse air temperature was maintained at constant 20C. Sunny and cloudy days were defined as days when shortwave radiation maximum was 470 and 120 W·m⁻², respectively. 43
9. Examples of plant temperature measurements (●) and predicted plant temperatures (○) of different species grown in several different greenhouses during different times of the year.
 - A) Poinsettia (*Euphorbia pulcherrima* Willd.) cyathia at Henry Mast's Greenhouses, Byron Center, MI, December 15, 1992 (thermal screens at night).
 - B) Shoot-tip of geranium (*Pelargonium x hortorum*) plugs at Raker's Acres, Litchfield, MI, December 25, 1993 (thermal screens at night, high-pressure sodium lamps from 16 to 2h).
 - C) *Begonia semperflorens* shoot-tip at Snobelt Greenhouses, Kalamazoo, MI, February 17, 1993.
 - D) Easter lily (*Lilium longiflorum* Thunb.) shoot-tip, MSU Research Greenhouses, East Lansing, MI, March 2, 1993.
 - E) Easter lily (*Lilium x hybrida* 'Stargazer') flower buds grown in 15 and 27C air temperature greenhouses at MSU Research Greenhouses, East Lansing, MI, April 3, 1993.
 - F) Poinsettia (*Euphorbia pulcherrima* Willd.) axillary buds at MSU Research Greenhouses, East Lansing, MI, August 8, 1993. 45

SECTION II

- 1 Effect of increasing PPF from HPS lamps on the difference between plant and air temperature of vinca. 58
2. Effect of VPD at different PPF levels on the difference between plant and air temperature of vinca. 60

3.	A. Energy per waveband for HPS lighting system used in experiment. B. Percent reduction in energy from polycarbonate and water filter by waveband.	62
4.	Effect of VPD and PPF from HPS lamps on the difference between plant and air temperature either with or without a water filter.	64
5.	Bud minus air temperature for 'Stargazer' lily lower buds growing under three different air temperatures.	66
6.	The effect of HPS lighting, solar radiation, and VPD on the difference between plant and air temperature of vinca plants on three separate days. Δ and Δ represent measurements under the HPS lamp treatment and the control treatment, respectively. Air temperature setpoints were A) 15, B) 32, or C) 22C.	68

SECTION III

1.	The change in shoot-tip temperature of vinca ($\square$) and African violet (Δ) plants in response to the change in incident radiation. The changes in shoot-tip temperature and incident radiation refer to the differences between the values measured during the control treatment, i.e. exposure to the greenhouse glass, in comparison to the thermal-screen treatments. ($r^2=0.89$ and 0.75 , for vinca and African violet regression lines, respectively).	81
----	--	----

SECTION IV

1.	The effect of plug-flat color on the observed difference between medium-surface and air temperatures recorded on A) a partly sunny day and B) a cloudy day.	92
2.	The effect of plug-flat color on medium-surface temperature shown as a function of the incident shortwave radiation. Air temperature was maintained at 25C, and the water vapor pressure deficit averaged 1.4 kPa.	94

SECTION V

1.	The effect of temperature on the percentage of nodes developing lateral shoots on pinched 'Eckespoint Lilo' poinsettias. Rooted cuttings were placed into the indicated temperature treatments and pinched. Nodes
----	---

	were numbered from the basipetal (Node 1) to the acropetal (Node 5) part of the shoot..	117
2.	The effect of stock plant temperature on the percentage of nodes developing lateral shoots on the first flush of cuttings removed from the 'Eckespoint Lilo' stock plants, after the cuttings were propagated at 26C, and then grown at 21C. Nodes were numbered from the basipetal (Node 1) to the acropetal (Node 6) part of the cutting.	119
3.	The effect of stock plant temperature on the percentage of nodes developing lateral shoots on the second flush of cuttings removed from 'Eckespoint Lilo' the stock plants, after the cuttings were propagated at 26C, and then grown at 21C. Nodes were numbered from the basipetal (Node 1) to the acropetal (Node 6) part of the cutting.	121
4.	The effect of temperature on the percentage of nodes on 'Eckespoint Lilo' poinsettias that produced a lateral shoot > 3 cm in length, a lateral shoot < 3 cm in length, or no lateral shoot. Data represent the nodes shown in Figure 1.	123
5.	The effect of temperature on the percentage of nodes on 'Eckespoint Lilo' poinsettias that produced a lateral shoot > 3 cm in length, a lateral shoot < 3 cm in length, or no lateral shoot. Data represent the nodes shown in Figure 2.	125
6.	The effect of temperature on the percentage of nodes on 'Eckespoint Lilo' poinsettias that produced a lateral shoot > 3 cm in length, a lateral shoot < 3 cm in length, or no lateral shoot. Data represent the nodes shown in Figure 3.	127
7.	Effect of temperature on the axillary bud development of 'Eckespoint Red Sails' poinsettias initially grown at 33/27C and then transferred to 21C. Node 0 indicates the most recently unfolded leaf at the time of transfer. Negative node numbers indicate nodes whose leaves were unfolded prior to transfer, while positive node numbers indicate nodes whose leaves unfolded after transfer. (Node -7 was the oldest; Node +7, the youngest).	129
8.	Effect of timing of the high day temperature and pinching treatments (Table 1) on axillary bud development of 'Eckespoint Red Sails' poinsettias. Node 1 refers to the first node to develop on the lateral shoot after pinching.	131

SECTION I

MODELING SHOOT-TIP TEMPERATURES IN THE GREENHOUSE ENVIRONMENT

Modeling Shoot-tip Temperature in the Greenhouse Environment

James E. Faust¹ and Royal D. Heins²

Department of Horticulture, Michigan State University, East Lansing, MI 48824-1325

Received for publication _____. We acknowledge the financial support of the American Floral Endowment. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹ Former graduate student. Current address: University of Tennessee, Dept. of Ornamental Horticulture and Landscape Design, Knoxville, TN 37901-1071.

²Professor of Horticulture

Production and Culture

Modeling Shoot-tip Temperatures in the Greenhouse Environment

Additional index words. Vinca, *Catharanthus roseus*, energy balance, vapor pressure deficit, shortwave radiation, longwave radiation, convection, transpiration

Abbreviations: PPF, Photosynthetic photon flux density; VPD, vapor pressure deficit

Abstract. An energy-balance model is described that predicts vinca (*Catharanthus roseus* L.) shoot-tip temperature using four environmental measurements: solar radiation, dry bulb, wet bulb, and glazing material temperature. The time and magnitude of the differences between shoot-tip and air temperature were determined in greenhouses maintained at air temperatures of 15, 20, 25, 30, or 35C. At night, shoot-tip temperature was always below air temperature. Shoot-tip temperature decreased from 0.5 to 5C below air temperature as greenhouse glass temperature decreased from 2 to 15C below air temperature. During the photoperiod under low VPD/low air temperature conditions, shoot-tip temperature increased linearly as solar radiation increased. Under high VPD/high air temperature conditions, shoot-tip temperature initially decreased at sunrise, then increased later in the morning as solar radiation increased. The 24-hour average shoot-tip temperature decreased relative to air temperature as air temperature increased. The model predicted shoot-tip temperatures within ± 1 of 81% of the observed one-hour average shoot-tip temperatures. The model was used to simulate

shoot-tip temperatures under different VPD, solar radiation and air temperature conditions.

Successful commercial production of greenhouse crops requires that plants be grown to buyer size and date specifications. Temperature is the primary environmental factor influencing the rate of plant development and the ability to meet date specifications. Accurate timing of a crop can be jeopardized when plant-shoot temperature differs from air temperature since greenhouse climates are typically controlled with air temperature setpoints, while plant developmental rate is controlled by temperature of the meristematic regions, i.e., the shoot tip (Harris and Scott, 1969; Ritchie and NeSmith, 1991; Watts, 1972). A knowledge of shoot-tip temperature 1) improves the ability to precisely time crop development to meet date specifications (Faust and Heins, 1993) and 2) provides the opportunity to control the greenhouse environment based upon a plant temperature setpoint, not air temperature.

Crop development models typically use minimum and maximum air temperatures or mean air temperatures; therefore, improvement of prediction of plant development models requires that the plant temperature model identify the difference between the mean 24-hour plant and air temperature. Use of more frequent measurement, i.e., average hourly temperatures, does not necessarily improve crop development predictions (Faust and Heins, 1993). Average day and night temperatures have been used for a poinsettia stem elongation model (Berghage, 1989; Karlsson and Heins, 1994). More frequent temperature measurements are required for greenhouse climate control; therefore, a plant temperature model used for climate control must be capable of tracking plant temperatures accurately over time.

While commercial greenhouses are currently designed to provide the desired air temperature environment, future climate-control processes will likely control the

environment based on plant temperatures. The "speaking plant" technique is one approach to improving greenhouse control; plant gas exchange (water and carbon dioxide) is measured within the greenhouse and the greenhouse environment is controlled to optimize transpiration and/or photosynthesis (Hashimoto et al., 1985; Udink ten Cate et al., 1978). Considerable expertise is needed to maintain and use the gas-exchange instrumentation required to measure plant growth responses. Although the speaking plant approach has yielded important data concerning the physiological responses of plants in greenhouses, it has not yet proven valuable for commercial greenhouse production.

Canopy temperatures measured by infrared sensors placed above the greenhouse canopy can be used to monitor/control the greenhouse environment (White and Hamilton, 1985). This system is most valuable for greenhouse crops with a long-term full canopy, such as cut-flower roses or greenhouse vegetables. However, container-grown plants frequently have changing canopies because of spacing between plants, rolling bench systems, and empty benches during the shipping seasons.

Greenhouse climate control can also be improved by measuring greenhouse environmental conditions and predicting plant temperatures and responses with a model. This technique's value is that it requires only proper placement and maintenance of the environmental sensors and not instrumentation expertise. Considering the difficulty of calibrating and maintaining sophisticated equipment, models based on physical principles can yield more accurate temperature estimates, i.e., a lower percentage of error, than actual measurements can (Parkinson and Day, 1990).

The physical processes involved in energy transfer between plants and the surrounding environment have been clearly described (Gates and Papian, 1971; Mellor

et al., 1964; Raschke, 1960). Most plant energy balance models have been developed for leaves (Gates and Papian, 1971; Stanghellini, 1987) because leaf temperatures influence transpiration and photosynthesis and, therefore, growth and yield of vegetable and grain crops. However, for ornamental potted plant production, shoot-tip temperature is a more valuable measurement, since the timing of plant development is the primary concern for growers.

Energy transfer is a complex process. Models developed to describe energy transfer in greenhouses are also complex (Kimball, 1973; Kindelan, 1980; Levit and Gaspar, 1988). Mechanistic models often contain many variables that are difficult to quantify and, therefore, difficult to adapt to different greenhouse situations. Functional models contain fewer variables that are developed around readily measured variables and are thus more easily used in different situations (Ritchie and Johnson, 1991). The lack of uniformity among greenhouse structures and plant species indicates that the model must be robust and adaptable to become of practical use in research and/or commercial greenhouses.

The first objective of this project was to identify the conditions under which shoot-tip temperature differed from air temperature. Second, we strived to develop an accurate shoot-tip temperature model that 1) used environmental inputs that could be measured in commercial greenhouses and 2) could be adapted for use in different greenhouses and with different crop species.

Materials and Methods

General Procedure. Vinca (*Catharanthus roseus* L.) plants were grown in 48-cell packs in five-10 m² greenhouses set to maintain air at 15, 20, 25, 30, or 35C. The plants were approximately 10 cm tall at the start of the experiment. Fine-wire (80µm diameter) chromel-constantan thermocouples were inserted in the shoot tip of four plants in each greenhouse. The thermocouples were re-inserted into the shoot tip every two to three days as the shoot elongated. Thermocouples were placed in contact with the inside of the greenhouse glass to calculate the longwave radiation (3,000 to 50,000 nm) emitted from the greenhouse structure. The precision of the thermocouples was approximately ± 0.15 C. LI-COR pyranometers (LI-200SA, LI-COR Instruments, Lincoln, Neb.) were mounted 10 cm below the greenhouse glass and at canopy height to measure the shortwave radiation (300 to 3,000 nm) transmitted to the plant canopy. Wet and dry bulbs measurements were made with thermistors placed inside a shaded, aspirated weather station located at canopy height. A datalogger (CR10 Campbell Scientific, Logan, Utah) recorded environmental data from the sensors from 13 to 31 May 1993.

The greenhouse air temperatures were maintained with an environmental-control computer (PRIVA, De Lier, The Netherlands). Heat was delivered with steam heating units located along the base of the greenhouse walls below bench level. Cooling was controlled with ridge vents and a three-stage forced air cooling system consisting of a low speed fan, high speed fan, and a high speed fan combined with evaporative pads. The greenhouses did not contain horizontal air-flow fans or an infrared heat source above the canopy.

Model Development. Under steady-state conditions, plant temperature is in equilibrium with the surrounding environment. Steady state was assumed since vinca has

a relatively thin stem and thus a short response time relative to the 30-minute data collection interval. Under steady-state conditions, the energy gain equals the energy loss; thus, the sum of the energy transfer, i.e., radiation, convection, and transpiration, is zero.

$$\text{Radiation} + \text{Convection} + \text{Transpiration} = 0 \quad [1]$$

The energy transfer components are described with the following equations:

$$\text{Radiation} = SW_{abs} + LW_{net} \quad [2]$$

$$SW_{abs} = SW_{glass} \cdot t_{SW} \cdot a_{SW} \quad [3]$$

$$LW_{net} = VF \cdot e_{shoot} \cdot a \cdot ((T_{glass} + 273.15)^4 - (T_{shoot} + 273.15)^4) \quad [4]$$

$$\text{Convection} = h_c \cdot (T_{air} - T_{shoot}) \quad [5]$$

$$\text{Transpiration} = -g_{wv} \frac{(VP_{shoot} - VP_{air})}{P_a} \quad [6]$$

$$g_{wv} = (b_0 - b_1 \exp(-b_2 PPF)) \cdot 44 \text{ J} \cdot \text{mmol}^{-1} \quad [7]$$

$$PPF = PPF_{w_m^{-2}} \cdot SW_{glass} \cdot t_{SW} \quad [8]$$

$$VP_{shoot} = \exp(19.0177 - (\frac{5327}{T_{shoot} + 273.15})) \quad [9]$$

$$VP_{wb} = \exp(19.0177 - (\frac{5327}{T_{wb} + 273.15})) \quad [10]$$

$$VP_{air} = VP_{wb} - 0.00066 \cdot (1 + 0.00115 \cdot T_{wb}) \cdot (T_{air} - T_{wb}) \cdot P_a \quad [11]$$

Definitions of symbols, units, and default values are listed in Table 1. Parameter estimates for Eq. [7] are listed in Table 2.

A computer program was written and compiled in Turbo Pascal (Borland International Scotts Valley, CA) to calculate Eqs. [2-11] and find a value for T_{shoot} that solves Eq. [1]. The computer code uses a mathematical recipe (Press, 1989) that uses the "root bisection" technique to find a solution for Eq. [1].

Measurements of shortwave radiation below the glass and at canopy height indicated that approximately 65% was transmitted to the canopy. According to Nobel (1991), approximately 50% of the incident solar shortwave radiation is absorbed by plants. No distinctions were made between direct and diffuse shortwave radiation.

To estimate longwave radiation exchange, a horizontal plane through the shoot tip was considered. We assumed that there was no net longwave radiation exchange between the shoot tip and the surrounding foliage below the horizontal plane. A viewfactor (VF) term was used to estimate the percentage of the hemisphere that was above the horizontal plane and occupied by glass exposed to the outside environment. We calculated that 60% of the surrounding greenhouse structure was exposed to outside temperatures, while the other 40% was occupied by relatively warm sidewalls. The emissivity term (e_{shoot}) estimates the plants' emissivity and absorptivity of longwave radiation.

Conductance of water vapor from the plant to the greenhouse air (g_{wv}) can be defined as the sum of individual conductances, i.e. stomatal, cuticular, boundary layer, and intercellular layer; however, to maintain simplicity only the total conductance was considered. Values for conductance were calculated by using the measured plant

temperatures and the measured environmental variables in the model development experiment to solve the energy balance equations (Eqs. [1-11]) for conductance. In other words, we mathematically determined the conductance necessary to achieve the measured shoot-tip temperature. An exponential function was used to describe conductance as a function of PPF (Eq. [7])(Fig. 1). Parameter estimates for Eq. [7] are shown in Table 2. The dark conductance, i.e., the y-intercept, was estimated from data reported by Faust and Heins (1994) that showed a 1.3C decrease in vinca shoot-tip temperature as VPD increased from 0.5 to 3.0 kPa. The result was a dark conductance of $\sim 30 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The potential amount of evaporative cooling estimated with the model, i.e., the value of g_{wv} at 0, was controlled by the potential amount of convective heat transfer, i.e, the value of h_c . Since analytical determination of the heat-transfer coefficient for irregular shapes such as a shoot tip is not possible, the value of the heat transfer coefficient that was estimated resulted in the $33 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ intercept of Eq. [7].

Validation. The vinca shoot-tip temperature model was tested with data collected on vinca plants grown in a 10-m² greenhouse. The plants were grown for 12 days at air temperatures of 15, 25, or 35C from 21 October to 4 November, 1993. Environmental measurement and data recording were performed in the same fashion as those in the model-development experiment.

Simulation. Environmental data were entered into the model to exhibit possible deviations between average daily shoot-tip temperatures observed on plants grown at air temperatures of 15, 20, 25, 30, or 35C and the average daily VPD of 0.4, 0.8, 1.6, or 2.4 kPa on four types of days: sunny and cold, sunny and warm, cloudy and cold, and cloudy and warm. The following polynomials were developed to estimate the glass

temperature as a function of greenhouse air temperature and shortwave radiation measured below the glass on days when outside air temperature was between 0 and -10C (cold) or 10 and 20C (warm):

$$T_{Glass} = -1.36 + 1.101 \cdot T_{air} - 0.014 \cdot T_{air}^2 + 0.0301 \cdot SW_{Glass} \dots warm \quad [12]$$

$$T_{Glass} = -6.0 + 0.73 \cdot T_{air} - 0.005 \cdot T_{air}^2 + 0.025 \cdot SW_{Glass} \dots cold \quad [13]$$

The maximum solar radiation incident on the crop canopy was 470 W·m⁻² for the simulation of sunny days, while on the simulated cloudy day, solar radiation never exceeded 120 W·m⁻². The daily-integrated PPF for the sunny and cloudy days was 24 and 6 mol·m⁻²·d⁻¹, respectively.

Sensitivity analyses. To assess the effects of model parameters (VF, h_c , g_{wv}) on shoot-tip temperature prediction, a shoot-tip temperature prediction was made for a hypothetical day in which the maximum solar radiation was 470 W·m⁻², the glass temperature ranged from 10C at night to 24C during the day, and air temperature was maintained at 20C. Individual parameter estimates were manipulated to observe the effect of the specific parameter on model prediction. Values were 5 and 25 for h_c , 0.3 and 0.9 for VF, 0.005 and 0.015 for b_2 , and 120 and 220 for b_0 . The b_2 term in Eq. [7] influences the rate of increase in conductance with respect to PPF. The b_0 term in Eq. [7] represented the maximum conductance, i.e., the asymptote. The b_1 term was converted to the same magnitude as the b_0 term so that the intercept, or dark conductance, would be unaffected.

Results

Shoot-tip Temperatures. Vinca shoot-tip temperature was seldom the same as the greenhouse air temperature (Fig. 2). The temperatures of the plants grown at 15C were equal to air temperature for a brief period during the morning and late afternoon, while the temperature of the plants grown at 35C was nearly always below air temperature.

Shoot-tip temperature was always below air temperature during the night and decreased relative to air temperature as glass temperature decreased relative to air temperature (Fig. 3). Shoot-tip temperature was as much as 5C below air temperature when the glazing material temperature was 16C below air temperature. Most of the observed shoot-tip night temperature depression was attributed to the loss of longwave radiation to the glazing material; however, since the model estimates that dark conductance occurred at $33 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, thus any VPD would result in evaporative cooling during the night (Eq. [6]).

Shoot-tip temperature during the photoperiod was influenced by shortwave radiation and VPD (Fig. 4). Under the relatively low VPD conditions (0.44 kPa) in the 15C greenhouse, shoot-tip temperature increased linearly as the incident solar radiation increased (Fig. 4A). Under relatively high VPD conditions (1.76 kPa) in the 35C greenhouse, shoot-tip temperature decreased as the incident shortwave radiation increased from 0 to approximately $100 \text{ W}\cdot\text{m}^{-2}$. Shoot-tip temperature then increased linearly as the incident shortwave radiation increased above $100 \text{ W}\cdot\text{m}^{-2}$ (Fig. 4E). The shortwave radiation at which shoot-tip temperature began to increase relative to air temperature increased as VPD and air temperature increased.

The 24-hour average shoot-tip temperature decreased with respect to air temperature as air temperature increased (Fig. 5A). In the 15 and 20C greenhouses, the 24-hour average shoot-tip temperature was typically within 2C of the air temperature, while in the 35C greenhouse the average daily shoot-tip temperature was typically 4 to 6C below air temperature. Night shoot-tip temperatures were lower than day shoot-tip temperatures (Figs. 5B & C). The scatter of air temperature data was greater during the day in the 15 and 20C greenhouses because of the loss of air temperature control on warm and sunny days. The plants grown at day temperatures cooler than 25C were within ± 2 C of air temperature during the day, while plants grown at day temperatures warmer than 25C were always below air temperature during the day. Shoot-tip night temperatures were always below air temperatures.

Model Prediction. The shoot-tip temperatures predicted by the model are shown with lines in Figure 2 and with solid symbols in Figures 3 through 5. The vinca shoot-tip temperature model accurately described the shoot-tip temperature in all five greenhouse environments throughout a 24-hour period on a sunny (Fig. 2A) and a cloudy day (Fig. 2B). Eighty-one percent of the model's one-hour predictions were within ± 1 C of the measured temperature (Fig. 6A). The predicted 24-hour (Fig. 5A), night (Fig. 5B), and day (Fig. 5A) temperatures were within ± 1 C of 88%, 88%, and 83% of the measured temperatures, respectively.

Validation. Fifty percent of the predicted temperatures were within ± 1 C of the measured temperatures in the validation experiment (Fig. 6B). The plants in this experiment were grown on a bench within 50 cm of a greenhouse sidewall that divided two greenhouses, so the viewfactor was estimated to be 0.30. After this

adjustment was made, 83% of the predicted temperatures were within $\pm 1^{\circ}\text{C}$ of the measured temperatures.

Simulation. The 24-hour average shoot-tip temperatures were nearly always below air temperature (Fig. 7). Only when conditions were sunny and warm and the greenhouse air temperature was 20°C or cooler did the 24-hour average shoot-tip temperature exceed air temperature (Fig. 7B). The 24-hour average shoot-tip temperature was 0.4 to 1.9°C higher on sunny days than cloudy days and 1.0 to 1.3°C higher on warm days than cold days. Thus, the largest difference in shoot-tip temperatures (1.6 to 3.1°C) occurred between sunny and warm versus cloudy and cold days. The 24-hour average shoot-tip temperature decreased 4 - 5°C as VPD increased from 0.4 to 2.4 kPa. In the 15 and 20°C air temperature environments, VPD had a smaller effect on 24-hour shoot-tip temperature since the possible range of VPD was relatively small.

Sensitivity analysis. The convective heat transfer coefficient (h_c) had little effect on shoot-tip temperature during sunny days (Fig. 8A&B). Lowering the value of h_c from 15 to 5 resulted in a larger difference between shoot-tip and air temperature. Increasing the value of h_c from 15 to 25 increases the convective heat transfer between the plant and the greenhouse air, thus resulting in shoot-tip temperatures closer to air temperature.

The VF influences the longwave radiation emitted from the greenhouse glazing material that is incident on the shoot tip (Fig. 8C&D). Increasing VF from 0.6 to 0.9 resulted in decreasing shoot-tip temperature when the glass was colder than the plant and increasing plant temperature when the glass was warmer than the plant. The reverse occurred when the value of VF was changed from 0.6 to 0.3 .

The b_2 parameter in Eq. [7] affected shoot-tip temperature when PPF incident on the canopy was between 0 and $200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Fig. 8E&F). This parameter represented the rate of conductance increase or decrease that was influenced primarily by stomatal opening and closing; thus, the b_2 parameter affected shoot-tip temperatures immediately after sunrise and before sunset. Increasing the value of b_2 increased transpiration and reduced plant temperature, while decreasing the value of b_2 resulted in an increase in plant temperature.

Maximum conductance of water vapor, the b_0 parameter in Eq. 7, influenced the potential transpiration. The value of b_0 was therefore lowered resulting in warmer shoot-tip temperatures during the day; increasing this parameter resulted in cooler day temperatures (Fig. 8G&H). Assuming the y-intercept in Eq. [7], calculated as $b_0 - b_1$, is held constant, neither b_0 or b_2 affect shoot-tip temperatures during the night.

Discussion

The effect of each energy transfer process on plant temperature depends on the other transfer processes; however, the energy balance calculations allow determination of the relative importance of each process throughout the day and night. During the night, the exchange of longwave radiation from the plant canopy to the glazing material is the primary factor influencing plant-air temperature. Unless an infrared heat source is present, the glass temperature will always be below air temperature because of longwave radiation exchange between the glass and the sky. Consequently, plant temperatures are always below air temperature at night because of the net longwave radiation loss. The magnitude of the temperature depression is directly related to the

difference between air and glass temperature. We observed shoot-tip temperatures 5C lower than air temperature when the glass temperature was 16C below air temperature. The magnitude of the shoot-tip temperature depression is limited by convective heat transfer. Convection couples air and plant temperature; therefore, the higher the heat transfer coefficient, the smaller the shoot-tip temperature depression at night. Shoot-tip temperature depression at night can also be a result of transpiration. Faust and Heins (1994) reported a 1.3C decrease in vinca shoot-tip temperature as VPD increased from 0.5 to 3.0 kPa. The estimated dark conductance for vinca was $33 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, which is similar to the dark stomatal conductance for greenhouse cucumber leaves reported at $36 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Yang et al., 1990).

These results underscore the energy savings possible by using thermal screens. Since thermal screens are closer to air temperature than glazing temperature, the net longwave radiation loss from the canopy is reduced. Glazing materials have different transmissivity of longwave radiation. Glass is relatively opaque to longwave radiation; some polyethylene materials, relatively transparent. Consequently, plants under polyethylene would exchange some longwave radiation with the sky, which typically has an effective temperature of 20 to -25C, depending on humidity and cloud cover (Chen and Zhang, 1989; Garzoli, 1985).

Another method of reducing the shoot-tip night temperature drop is to use horizontal air-flow fans to increase convective heat transfer by increasing the air velocity surrounding the canopy. Air velocity was not a required measurement in the proposed shoot-tip model; however, air velocity can have a significant impact on shoot-tip temperatures. Horizontal air-flow fans are often used to provide a constant low air

velocity. High-volume exhaust fans may be used in conjunction of instead of horizontal air-flow fans for large volume air exchange with the outside environment. Therefore, air velocity in commercial greenhouses is relatively constant until high-volume exhaust fans are turned on, at which time errors in prediction are likely to occur. We chose not to include air velocity in our model since greenhouse air velocities are generally low, i.e. less than $20 \text{ cm}\cdot\text{s}^{-1}$, and growers typically do not measure air velocity because expensive and fragile hot-wire anemometers would be required for accurate measurements. Air velocity could easily be added to the model via an equation (Rosenberg et al., 1983) that uses air velocity and a plant dimension term to calculate the heat-transfer coefficient.

During the photoperiod, shortwave radiation and transpiration result in the largest amount of energy transfer, while longwave radiation and convection result in relatively small amounts of energy transfer; therefore, solar radiation and VPD have a strong impact on the difference between shoot-tip and air temperature during the photoperiod. Although it was impossible to separate the effect of air temperature and VPD in this experiment, since VPD increased as air temperature increased, the model predictions suggested that the change in VPD was responsible for much of the difference in plant and air temperatures observed in the different air temperature treatments. In the 15C greenhouse at low VPD, shoot-tip temperatures essentially "tracked" solar radiation, i.e., shoot-tip temperature increased as solar radiation increased, and vice versa. In the morning when the stomata opened under high VPD conditions, the evaporative potential of the canopy was greater than the solar load, so plant temperature initially decreased at sunrise. As solar radiation increased, eventually the additional radiation could not be dissipated by transpiration. At this point plant temperature tracked solar radiation.

Total conductance of water vapor from the shoot tip is influenced by stomatal, boundary layer, cuticular, and intercellular conductance. Stomatal conductance models often use PPF, carbon dioxide, VPD, and soil/leaf water potential data to predict stomatal conductance (Jones, 1992). The complexity of quantifying individual conductances led us to use a total conductance term that was calculated from the measured shoot-tip temperatures and the energy balance equations. The result was an exponential equation that estimated total conductance as a function of incident PPF. Conductance was described as a function of PPF, not shortwave radiation, since stomatal opening and closing was influenced by visible radiation (400-700 nm), not the entire shortwave radiation spectrum.

The model predicts a rapid increase in conductance as PPF increases; which is apparently caused by increased stomatal conductance due to stomatal opening. Conductance asymptotically approached a maximum of $170 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ when the PPF was approximately $250 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. This maximum could be limited by stomatal and/or boundary layer conductance. The maximum conductance estimated compares with the typical leaf conductance for crop species, 80 to 400 mmol, as reported by Nobel (1991).

Soil water potential, carbon dioxide, and VPD can influence stomatal conductance and thus plant tip temperatures, however we did not include these factors in our model. Low soil water potentials caused by drought can lead to increased plant temperatures as a result of stomatal closure; however, most greenhouse crops do not experience water stress conditions. We did not observe shoot-tip temperatures under different carbon dioxide levels. Further studies will be necessary to determine the effect of carbon

dioxide on plant temperatures. Our data do not warrant the inclusion of VPD as a factor influencing conductance.

The net longwave exchange between the plant and the glazing material during the day can be positive or negative. Glazing material temperature increases in direct proportion to solar radiation so that on sunny days the canopy may experience a net radiation gain since the glazing material may be warmer than the plant canopy. We have observed glazing materials at 38C while greenhouse air temperatures were 30C and shortwave radiation was 500 W·m⁻². Whitewash applied to the glazing material to reduce shortwave loads during the summer increases the reflectivity and absorptivity of the glazing. Experimentation is needed to determine the effect of whitewash on the temperature of the glazing material. Longwave radiation gain during the day can also be a problem when shade cloth is used inside the greenhouse and its temperature increases during the day.

Plant morphology certainly influences the energy transfer processes (Gates and Papian, 1971). Preliminary data collected on temperatures of Oriental lily (*Lilium x hybrida* 'Stargazer') flower buds, Easter lily (*Lilium longiflorum*) shoot-tips, poinsettia (*Euphorbia pulcherrima*) cyathia, and fibrous begonia (*Begonia semperflorens*) shoot-tips indicate that most greenhouse-grown plants follow a temperature pattern similar to that of vinca; however, the magnitude of the temperature response may be different (Fig. 9). In other words, during the night, plant temperatures are always below air temperature, but the magnitude of the difference is influenced by shoot-tip exposure to the glazing material and proximity to the medium's surface. During the day, shoot-tip temperature under low VPD conditions increases as solar radiation increases. The magnitude of the

response is influenced by the amount of shortwave radiation incident on the shoot tip and the maximum conductance of the species. If necessary, a plant dimension term can be added to the model by describing the heat-transfer coefficient as a function of air velocity.

The model was kept relatively simple to make it more adaptable to different species and greenhouses. The longwave radiation, convection, and transpiration equations are set up in the form of a driving gradient multiplied by a conductance (1/resistance) term. The driving gradients were determined by environmental measurements. The conductance terms for longwave, convection, and transpiration (V_F , h_c , g_{wv}) provide a means to manipulate model prediction to accommodate different greenhouse structures and crop species. A researcher should be able to adjust some parameters based on knowledge of a particular greenhouse or species; however, based on the observed variation among greenhouses and species, we believe some shoot-tip temperature measurements are necessary to "calibrate" the model to a particular situation. Shoot-tip temperatures could be measured with small hand-held dataloggers that could be placed into the greenhouse for several days after which the measured and predicted temperatures could be compared. Figure 8 displays the effect different parameters have on prediction. These predictions suggest how parameters could be adjusted to accurately match predicted to observed temperatures. Ultimately, a user-friendly software interface that would allow the grower to easily choose different parameter values and immediately view the change in prediction needs to be developed.

We envision that the proposed shoot-tip temperature model will be commercially useful in linking environmental control computers with decision-support systems.

Environmental measurements from the mini-weather stations located inside the greenhouse will be fed to a computer that interfaces with the grower through a decision-support system that will contain record-keeping tools and crop development models. The decision-support system will assist the grower in making climate-control and crop-development decisions.

In order to predict plant temperatures, the proposed mini-weather station must measure air temperature, humidity, and shortwave and longwave radiation. Air temperature and humidity are commonly measured in commercial greenhouses with aspirated and shaded dry- and wet-bulb sensors. Many greenhouses have pyranometers, i.e., shortwave radiation sensors, that are frequently located outside the greenhouse. However, this location cannot account for shortwave radiation reduction caused by shade curtain systems or whitewash applied to the glazing material. Canopy-level sensors are prone to error because of shadows cast by the greenhouse structure. We propose that a line quantum sensor (LI-210SA, Li-Cor Instruments; Lincoln, NE) could be placed above the plant canopy to measure PPF. This sensor integrates PPF measurements over 1 m, which will minimize errors due to shadows. Conversion of PPF to shortwave depends on the radiation source (Thimijan and Heins, 1983), so supplemental lighting would cause some errors in calculating shortwave radiation. Longwave radiation measurements made with sensors attached to the greenhouse glazing material do not provide accurate data when shadecloth or thermal screens are used. A better option would be an infrared sensor placed above the canopy and pointed toward the greenhouse glazing to measure the longwave radiation incident on the plant canopy.

In this paper we show that shoot-tip temperature can be predicted with a model using four environmental variables: dry bulb, wet bulb, solar radiation, and glazing temperature. In all cases observed, the predicted plant temperature more accurately reflected the observed shoot-tip temperature than did air temperature. This model may be useful in developing a climate-control system that is based upon a plant temperature setpoint, not air temperature.

LITERATURE CITED

- Berghage, Robert D. Jr. 1989. Modeling stem elongation in the poinsettia. PhD Diss., Michigan State University, East Lansing.
- Chen, Jing-ming and Ren-hua Zhang. 1989. Studies on the measurements of crop emissivity and sky temperature. *Ag. For. Meteorol.* 49:23-34.
- Faust, J.E. and R.D. Heins. 1993. Modeling leaf development of the African violet (*Saintpaulia ionantha* Wendl.). *J. Amer. Soc. Hort. Sci.* 118(6):747-751.
- Faust, J.E. and R.D. Heins. 1994. Quantifying the influence of high-pressure sodium lighting on shoot-tip temperature. *Acta Hort.* (in review)
- Garzoli, K.V. 1985. Property requirements of a greenhouse covering material for clear sky conditions. *Acta Hort.* 170:59-67.
- Gates, David M. and LaVerne E. Papian. 1971. Atlas of energy budgets of plant leaves. Academic Press, New York.
- Harris, G.P. and M.A. Scott. 1969. Studies on the glasshouse carnation: Effects of light and temperature on the growth and development of the flower. *Ann. Bot.* 33:143-152.
- Hashimoto, Y., T. Morimoto, and T. Fukuyama. 1985. Some speaking plant approach to the synthesis of control system in the greenhouse. *Acta Hort.* 174:219-226.
- Jones, Hamlyn G. 1992. Plants and microclimate. 2nd Edit. Cambridge Univ. Press. pp 153-158.
- Karlsson, Meriam G. and Royal D. Heins. 1994. A model of Chrysanthemum stem elongation. *J. Amer. Soc. Hort. Sci.* 119(3):403-407.
- Kimball, B.A. 1973. Simulation of the energy balance of a greenhouse. *Ag. Meteorol.* 11:243-260.
- Kindelan, M. 1980. Dynamic modeling of greenhouse environment. *Trans. Am. Soc. Ag. Eng.* 1232-1239.
- Levit, H.J. and R. Gaspar. 1988. Energy budget for greenhouses in humid-temperate climate. *Ag. For. Meteorol.* 42:241-254.
- Mellor, Robert S., Frank B. Salisbury, and Klaus Raschke. 1964. Leaf temperatures in controlled environments. *Planta* 61:56-72.

- Nobel, Park S. 1991. Physicochemical and environmental plant physiology. Academic Press, New York.
- Parkinson, K.J. and W. Day. 1990. Design and testing of leaf cuvettes for use in measuring photosynthesis and transpiration. In: Measuring techniques in plant science, Y. Hashimoto, P. Kramer, H. Nonami, and B. Strain (eds.). Academic Press, New York,
- Press, William. 1989. Numerical recipes in Pascal: The art of scientific computing. Cambridge Univ. Press, Cambridge, N.Y.
- Raschke, K. 1960. Heat transfer between the plant and the environment. Ann. Rev. Plant Physiol. 11:111-126.
- Ritchie, J.T. and D.S. NeSmith. 1991. Temperature and crop development. In: Modeling plant and soil systems, Agronomy No. 31, J. Hanks and J.T. Ritchie (eds.). Amer. Soc. Agron., Madison, Wi.
- Ritchie, J.T. and B.S. Johnson. 1991. Soil and plant factors affecting evaporation, p.363-390. In: Irrigation of agricultural crops, Agronomy No. 30. Amer. Soc. Agron., Madison, Wi.
- Rosenberg, Norman J., Blaine L. Blad, and Shashi B. Verna. 1983. Microclimate: The biological environment. Wiley,
- Stanghellini, Cecilia. 1987. Transpiration of greenhouse crops. PhD Dissertation, Agricultural Univ., Wageningen, The Netherlands.
- Thimijan, Richard W. and Royal D. Heins. 1983. Photometric, radiometric, and quantum light units or measure: A review of procedures for interconversion. HortScience 18(6):818-821.
- Udink ten Cate, A.J., G.P.A. Bot, and J.J. van Dixhoorn. 1978. Computer control of greenhouse climates. Acta Hort. 87:265-272.
- Watts, W.R. 1972. Leaf extension in *Zea mays*. J. Expt. Bot. 23(76):713-721.
- White, John W. and John H. Hamilton. 1985. Irradiance and plant temperature monitor/controller. Comp. Elect. Ag. 1:95-103.
- Yang, Xiusheng, Ted H. Short, Robert D. Fox, and William L. Bauerle. 1990. Transpiration, leaf temperature and stomatal resistance of a greenhouse cucumber crop. Ag. For. Meteor. 51:197-209.

Table 1. Definitions of symbols, units, and default values for parameters in the shoot-tip temperature model described in Eqs. [1-10].

Symbol	Definition	Unit	Value
Longwave radiation properties			
e_{shoot}	Shoot emissivity	dimensionless	0.96
a	Stefan-Boltzmann constant		5.67×10^{-8}
VF	Viewfactor	dimensionless	0.60
LW_{net}	Net longwave radiation	$W \cdot m^{-2}$	
Shortwave radiation properties			
SW_{abs}	Shortwave radiation absorbed	$W \cdot m^{-2}$	
t_{sw}	Shortwave transmissivity	dimensionless	0.65
a_{sw}	Shortwave absorptivity	dimensionless	0.50
$PPF_{W \cdot m^{-2}}$	PPF per $W \cdot m^{-2}$ shortwave radiation	$\mu mol \cdot m^{-2} \cdot s^{-1} / W \cdot m^{-2}$	2.0
Convective heat transfer property			
h_c	Shoot-tip heat transfer coefficient	$W \cdot m^{-2} \cdot C^{-1}$	15
Transpiration properties			
g_{wv}	Water vapor conductance	$mmol \cdot m^{-2} \cdot s^{-1}$	
VP_{shoot}	Shoot vapor pressure	kPa	
VP_{air}	Air vapor pressure	kPa	
VP_{wb}	Wet bulb vapor pressure	kPa	
P_a	Atmospheric pressure	kPa	98
Measured parameters			
T_{air}	Air temperature	C	
T_{wb}	Wet bulb temperature	C	
T_{glass}	Glass temperature	C	
SW_{glass}	Shortwave measured below the glass	$W \cdot m^{-2}$	
Predicted parameter			
T_{shoot}	Shoot-tip temperature	C	

Table 2. Parameter estimates for Eq. [7] ($r^2=0.744$).

Parameter	Estimate	Asymptotic std. error	Asymptotic 95% confidence interval	
			Lower	Upper
b_0	167.3	1.94	163.5	171.1
b_1	134.2	2.48	129.4	139.1
b_2	0.0121	0.000856	0.0104	0.0137

Figure 1. The relationship between the calculated conductance (g_{wv}) of water vapor and PPF incident on the canopy. The regression line represents the model described in Eq. [7] ($r^2=0.774$), and symbols represent the mean conductance values calculated for each greenhouse by using the measured shoot-tip temperatures with the energy balance equations.

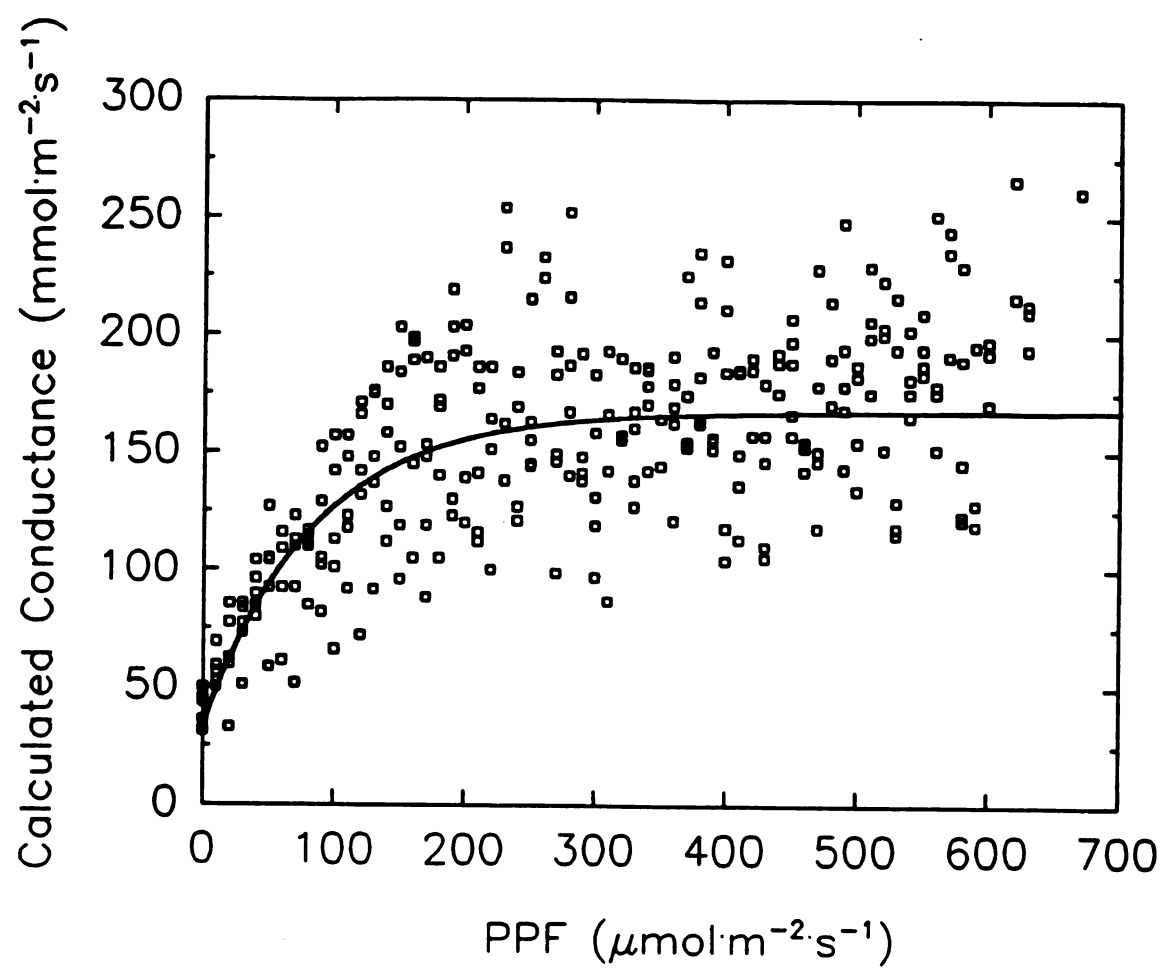


Figure 2. Predicted (lines) and observed (symbols) difference between vinca shoot-tip and air temperatures recorded in the 15 (○), 25 (●), and 35C (▼) greenhouses on A) a cloudy day (May 27, 1993) and B) a partly sunny day (May 30, 1993).

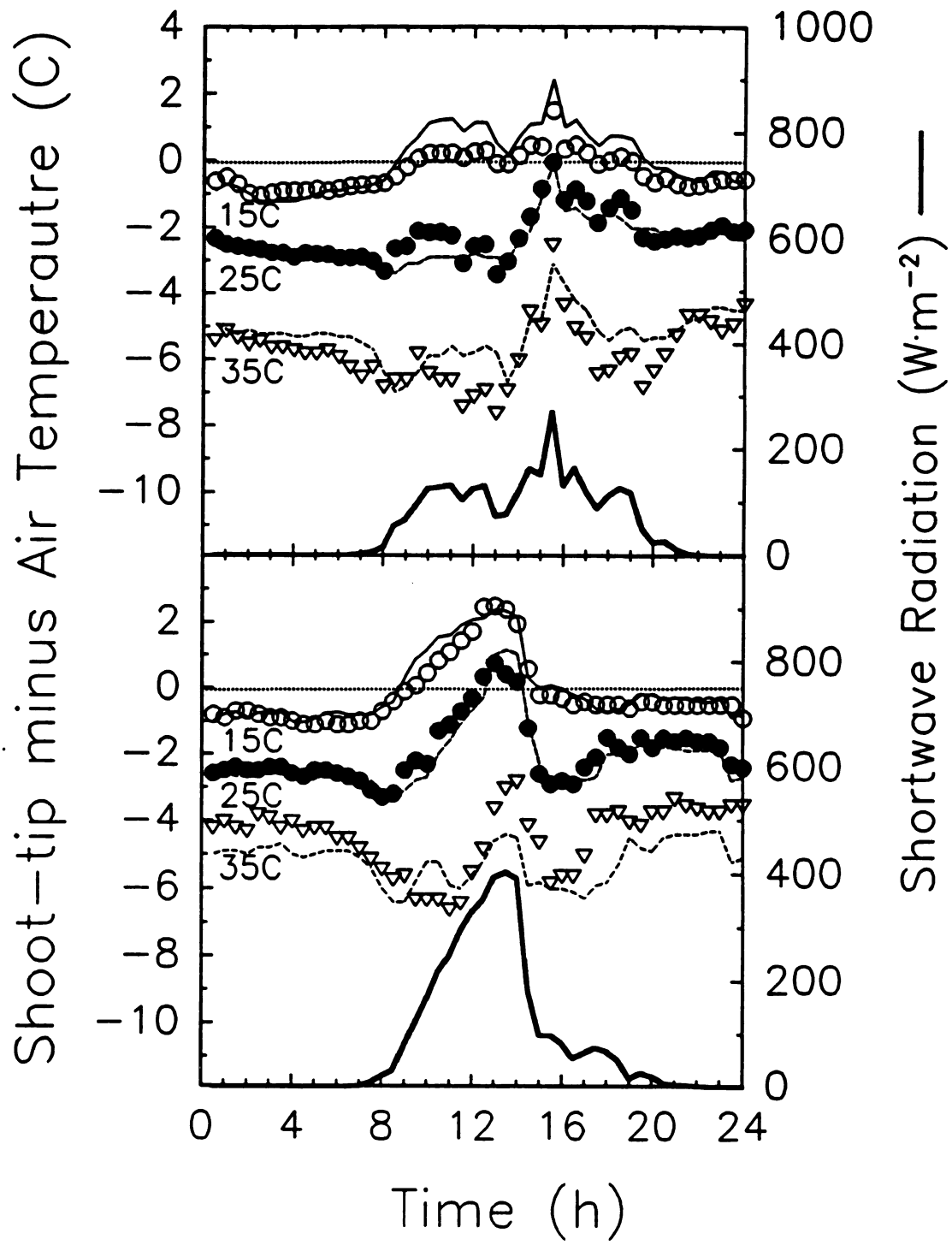


Figure 3. Predicted ($\blacktriangle$) and observed ($\square$) difference between vinca shoot-tip temperature and air temperature as influenced by longwave radiation exchange between the canopy and the glazing material. The driving force for longwave radiation exchange is the difference between shoot-tip and glass temperature.

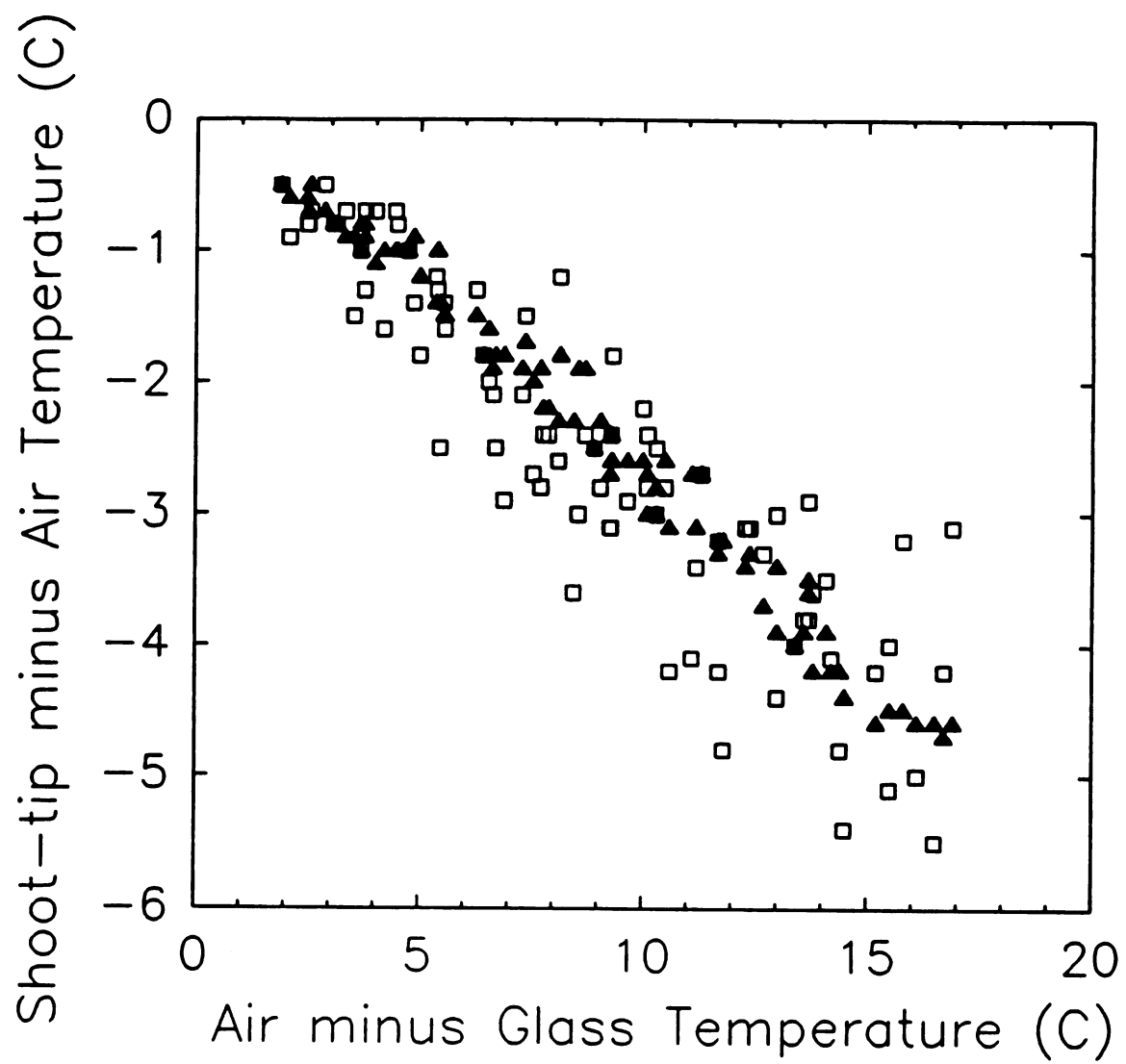


Figure 4. Predicted ($\blacktriangle$) and observed ($\square$) difference between vinca shoot-tip temperature and air temperatures observed in a A) 15C, B) 20C, C) 25C, D) 30C, or E) 35C greenhouse shown as a function of PPF incident on the canopy. The average VPD measured in each greenhouse is presented in the individual figures.

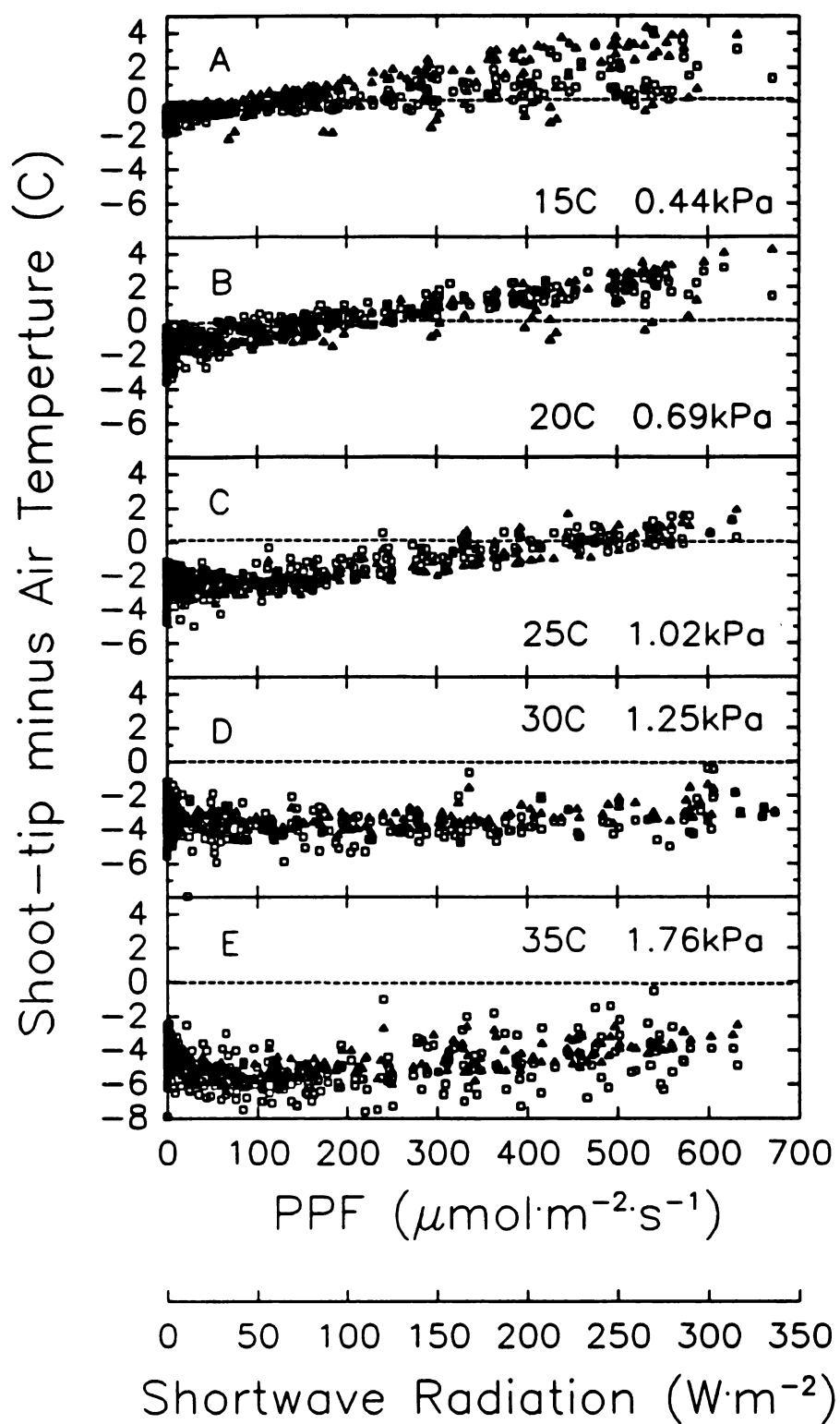


Figure 5. The predicted ($\blacktriangle$) and the observed ($\square$) A) 24-hour average, B) night, and C) day shoot-tip temperature of vinca plants grown in greenhouses set to maintain 15, 20, 25, 30, or 35C air temperature.

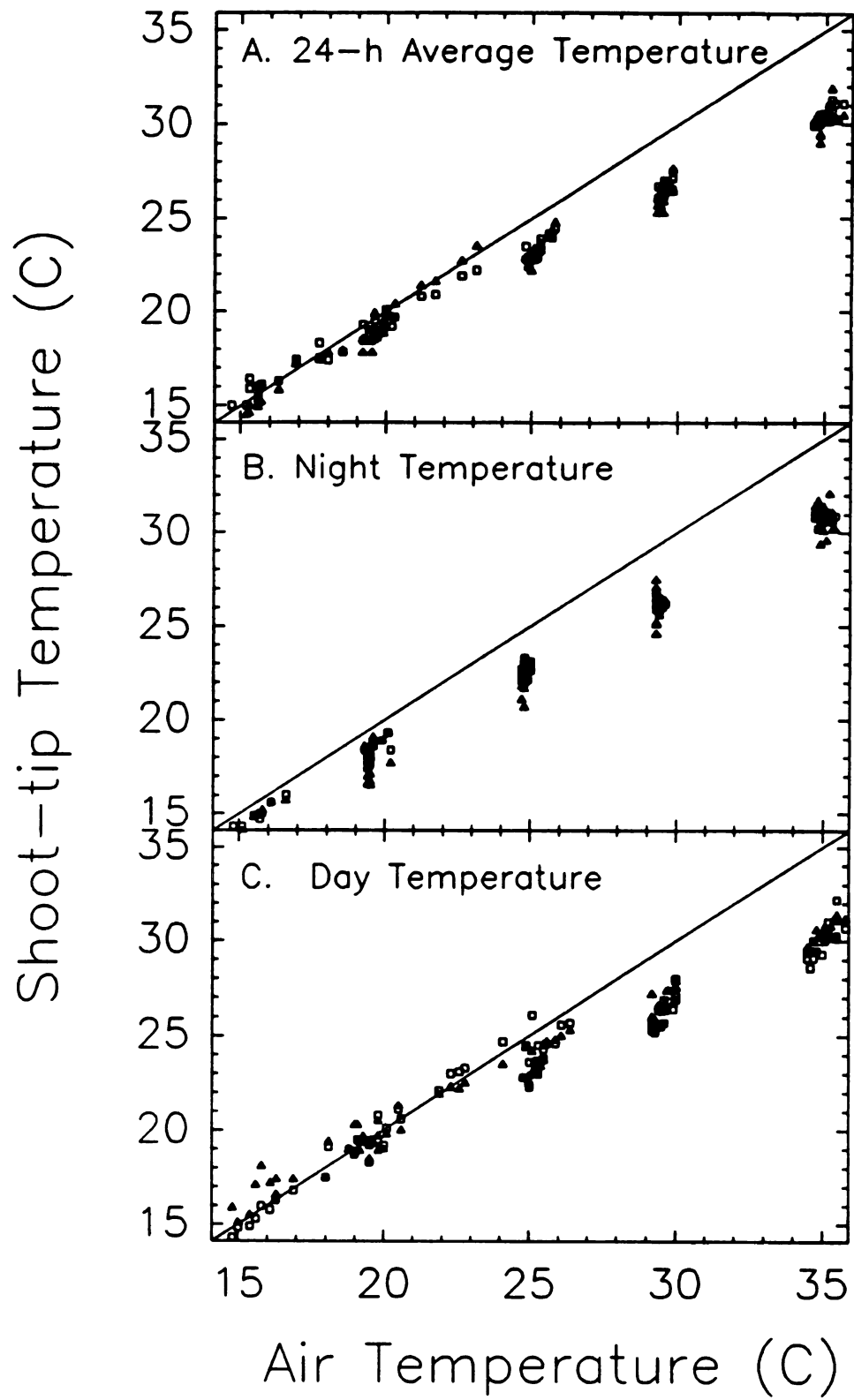


Figure 6. Predicted versus observed shoot-tip temperatures of vinca plants grown in A) 15, 20, 25, 30, and 35C greenhouses during the model-development experiment (one-hour averages) or in B) 15, 25, and 35C greenhouses during the model-validation experiment (30-minute averages).

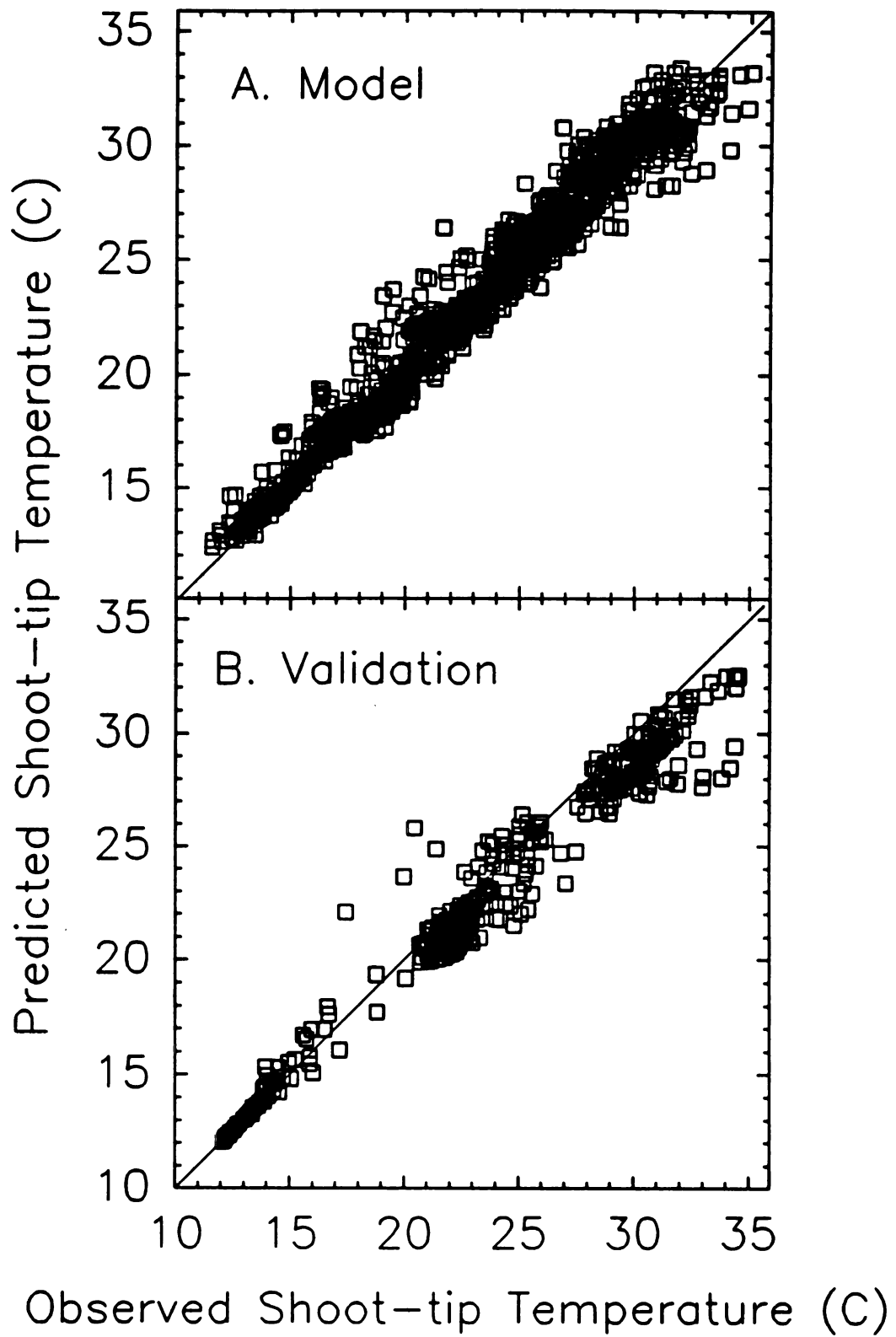


Figure 7. A simulation of 24-hour average vinca shoot-tip temperatures under four types of weather conditions: A) cloudy and warm, B) sunny and warm, C) cloudy and cold, or D) sunny and cold conditions. Cold and warm days were defined as days when outside temperatures were -10 to 0C and 10 to 20C, respectively. Cloudy and sunny days were defined as days when shortwave radiation maximum was 120 and 470 W·m⁻², respectively.

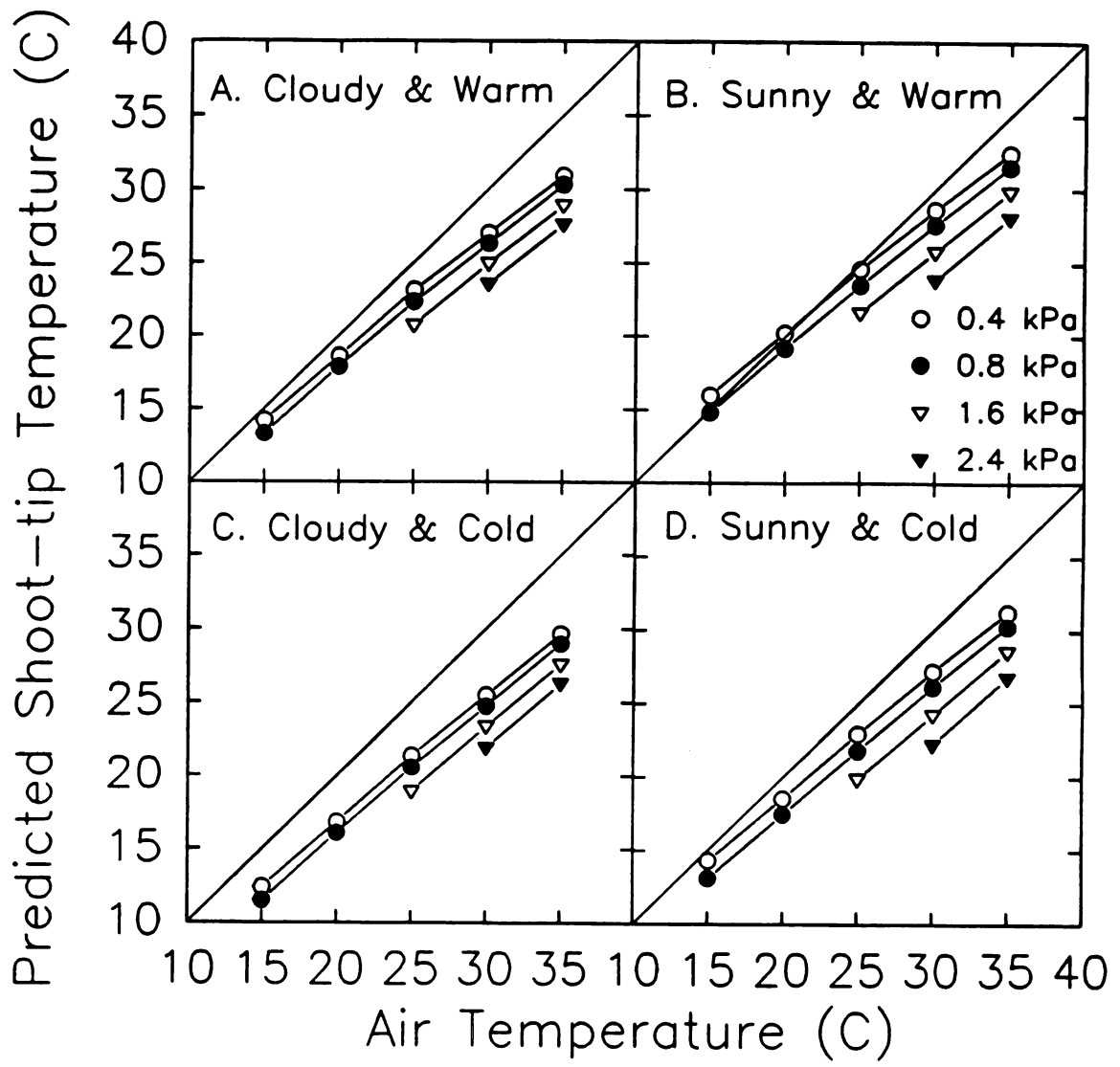


Figure 8. Comparison of model prediction of shoot-tip temperature over a simulated two-day period and model prediction after A&B) the heat transfer coefficient (h_c), C&D) the viewfactor term (VF), E&F) the b_2 term in Eq. 7, and G&H) the maximum conductance (b_0-b_1) were individually altered as indicated by the "new prediction" in the figures. Weather data simulated greenhouse conditions on a sunny followed by a cloudy day when greenhouse air temperature was maintained at constant 20C. Sunny and cloudy days were defined as days when shortwave radiation maximum was 470 and 120 W·m⁻², respectively. Default value was 15 for h_c , 0.6 for VF, 0.0121 for b_2 , and 167 for maximum conductance (b_0-b_1).

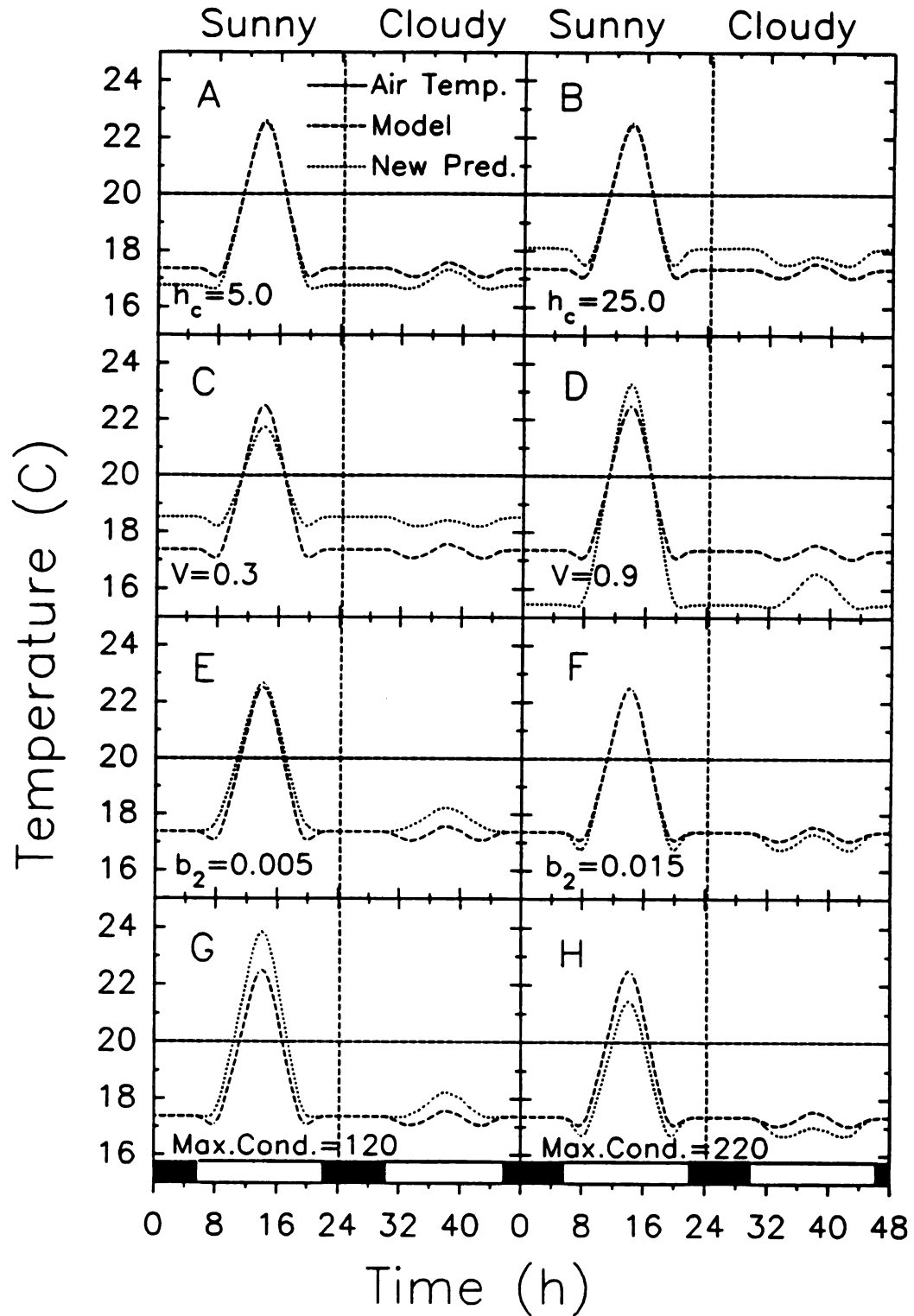


Figure 9. Examples of plant (●) and air (○) temperatures measured on different species grown in several different greenhouses during different times of the year.

A) Poinsettia (*Euphorbia pulcherrima* Willd.) cyathia at Henry Mast's Greenhouses, Bryon Center, MI, December 15, 1992 (thermal screens at night).

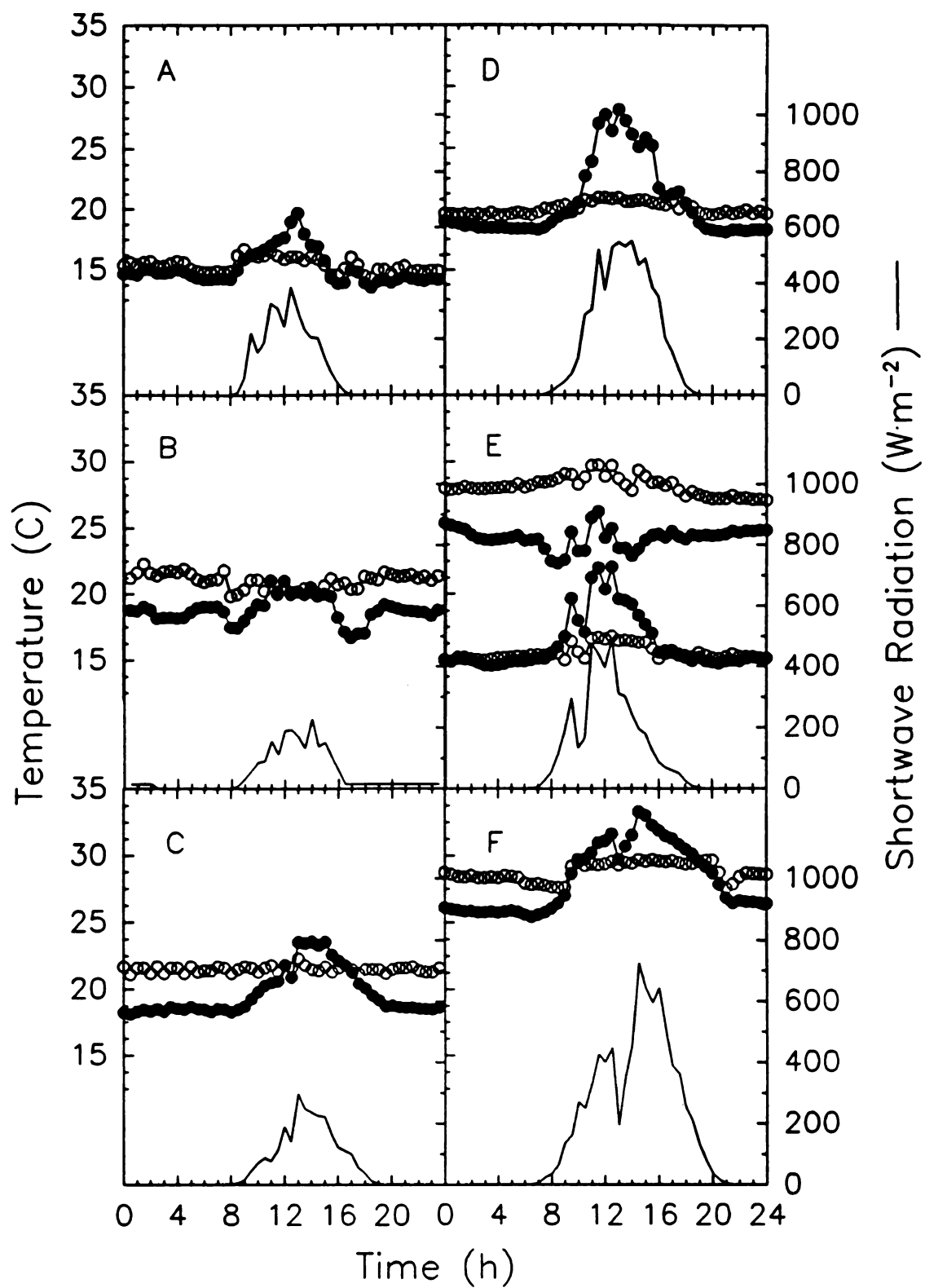
B) Geranium (*Pelargonium x hortorum*) shoot-tip at Raker's Acres, Litchfield, MI, December 25, 1993 (thermal screens at night, high-pressure sodium lamps from 16 to 2h).

C) Fibrous begonia (*Begonia semperflorens*) shoot-tip at Snobelt Greenhouses, Kalamazoo, MI, February 17, 1993.

D) Easter lily (*Lilium longiflorum* Thunb.) shoot-tip, MSU Research Greenhouses, East Lansing, MI, March 2, 1993.

E) Oriental lily (*Lilium x hybrida* 'Stargazer') flower buds grown in 15 and 27C air temperature greenhouses at MSU Research Greenhouses, East Lansing, MI, April 3, 1993.

F) Poinsettia (*Euphorbia pulcherrima* Willd.) axillary buds at MSU Research Greenhouses, East Lansing, MI, August 8, 1993.



SECTION II

QUANTIFYING THE INFLUENCE OF HIGH-PRESSURE SODIUM LIGHTING ON SHOOT-TIP TEMPERATURE

QUANTIFYING THE INFLUENCE OF HIGH-PRESSURE SODIUM LIGHTING ON SHOOT-TIP TEMPERATURE

James E. Faust and Royal D. Heins

Department of Horticulture

Michigan State University

East Lansing, Michigan, USA 48824

Abstract

Vinca (*Catharanthus roseus* L.) plants were placed in a growth chamber under high-pressure sodium (HPS) lamps to quantify the effect of supplemental lighting at 0, 50, 75, or 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ photosynthetic photon flux (PPF) on shoot-tip temperatures. PPF treatments were delivered at air temperatures of 15, 20, 25, and 30C and at a range of vapor-pressure deficits (VPD) from 0.5 to 3.0 kPa. The temperature of plants receiving 50, 75, and 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ was 1.2, 1.5, and 1.7C higher, respectively, than that of plants in the dark, regardless of VPD. Relative to air temperature, plant temperature decreased 1.2C as the VPD increased from 0.5 to 3.0 kPa at each PPF level. A polycarbonate/water filter was used to reduce the long-wave radiation incident on the plant canopy. At 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, plants under the polycarbonate/water filter were 2.7C cooler than those grown at the same PPF without the filter. The effect of supplemental lighting on plant temperature and developmental rates is discussed.

1. Introduction

High-intensity discharge lamps emit a considerable amount of short-wave (300 to 2,800 nm) and long-wave (2,800 to 50,000 nm) radiation. Bubenheim et al. (1988) reported that HPS lamps delivering $400 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ to a plant canopy provided $296 \text{ W}\cdot\text{m}^{-2}$ of total radiation, $80 \text{ W}\cdot\text{m}^{-2}$ (27%) photosynthetic irradiance (400 to 700 nm), $83 \text{ W}\cdot\text{m}^{-2}$ (28%) near-infrared (700 to 2,800 nm), and $133 \text{ W}\cdot\text{m}^{-2}$ (45%) long-wave radiation (2,800 to 100,000 nm). The additional energy absorbed by the plant canopy is primarily converted to heat because less than 2% of the energy in the range of 400 to 700 nm is converted to chemical energy through photosynthesis (Nobel, 1991). This absorbed energy will result in an increase in plant temperature if it is not removed through transpiration, long-wave emission, or convection. Therefore, the degree to which plant temperature is influenced by supplemental HPS lighting depends on the amount of radiation emitted by a lamp, the temperature and emissivity of the surrounding environment, VPD, stomatal conductance, and air velocity.

Many studies have shown the benefits of supplemental lighting on plant growth and yield responses (White, 1987), however, the effects of supplemental lighting on plant development have not been fully explored. Plant development rate, in terms of leaf unfolding, flower initiation, and flower development, is strongly influenced by plant temperature. Most studies on plant temperature have focused on leaf temperatures (Gates and Papian, 1971). While leaf-temperature measurements are valuable for studying plant growth, e.g., photosynthesis and transpiration, plant development primarily occurs at the meristematic regions; therefore, shoot-tip temperature should be measured for plant development studies. Further, many studies show that supplemental lighting promotes

more rapid development, which is often attributed to the added light, not changes in plant temperature. In this study, we measured shoot-tip temperatures to determine the potential impact of supplemental lighting on rates of plant development.

The objective of this research was to quantify the effect of supplemental lighting on shoot-tip temperatures under a range of PPF, VPD, and long-wave radiation conditions.

2. Materials and Methods

2.1 General

Vinca plants grown in cell packs (430 plants m⁻²) were placed in the center of a 32.5-m³ growth room. Four 400-W HPS lamps were mounted 1.2 m above the canopy so that the PPF could be manipulated by sliding the lamps radially away from the center of the chamber.

Vinca (*Catharanthus roseus* L.) plant temperatures were measured with 80 μ m diameter chromel-constantan thermocouples that were inserted into the shoot tip. Wet- and dry-bulb temperatures were measured in an aspirated weather station placed at the same height as, and immediately adjacent to, the canopy. The growth chamber ceiling temperature was also measured with a thermocouple. PPF was monitored with a LI-COR quantum sensor (LI-COR, Lincoln, Nebraska), the radiation environment was measured with an Eppley pyranometer (The Eppley Laboratory, Newport, Rhode Island) (280 to 2,800 nm) and a Schott RG780 filter (The Eppley Laboratory, Newport, Rhode Island) was used to separate the short-wave radiation into the photosynthetic irradiance (400 to 700 nm) and the near infrared irradiance (700 to 2,800 nm). A REBS total

hemispherical radiometer (Radiation and Energy Balance Systems, Seattle, Washington) was used to determine the long-wave radiation (2,800 to 50,000 nm).

2.2 The effect of PPF and VPD on shoot-tip temperature

The air temperature in the chamber was set to deliver four temperature treatments (15, 20, 25, and 30C). During each temperature treatment, the VPD was controlled by pulsing water vapor into the chamber as needed with steam from the heating system. The VPD treatments ranged from 0.5 to 1.0 kPa at 15C to 1.0 to 3.0 kPa at 30C. During each air temperature/VPD treatment combination, the lamps were turned off to provide the 0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ treatment and then turned on and moved to provide the 50, 75, and 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ treatments. After plant and air temperatures came into equilibrium at the beginning of each treatment, data were collected on ten plants for 30 minutes.

2.3 The effect of long-wave radiation on shoot-tip temperature

Vinca plants were given one of two PPF treatments (0 or 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). A sheet of polycarbonate supporting a 1-cm-deep layer of water was used to reduce the thermal load on the canopy. VPD was controlled to provide treatments at 0.5 and 3.0 kPa during each PPF treatment.

3. Results

3.1 Photosynthetic photon flux

In the dark, plant temperature was lower than air temperature (Fig. 1 and 2). Plant temperature exceeded air temperature as PPF from the lamps increased: it increased

1.2C as PPF increased from 0 to 50 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and an additional 0.5C as PPF increased from 50 to 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Short-wave, long-wave, and total radiation from the HPS lamps increased linearly as PPF increased (Fig. 3).

3.2 Vapor-pressure deficit

Plant temperature decreased with respect to air temperature as VPD increased from 0.5 to 3.0 kPa (Fig. 2). In the dark, plant and air temperature were the same when VPD was 0.5 kPa, while plant temperature decreased 1C relative to air temperature as VPD increased to 3.0 kPa. There was no interaction between VPD and PPF.

3.3 Long-wave radiation

Plant temperature increased 1.3C as PPF increased from 0 to 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ without the water filter, but decreased 1.4C as PPF increased from 0 to 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ when the polycarbonate/water filter was added (Fig. 4), a net change of 2.7C despite an identical increase in PPF.

4. Discussion

Supplemental lighting benefits plant production by supplying both photosynthetic (400-700 nm) and non-photosynthetic irradiance (700-50,000 nm). Photosynthetic irradiance improves plant quality, especially during the low-light winter conditions when the daily-integrated PPF may be as low as 1 to 3 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. HPS lamps delivering 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF for 24 hours provide 8.6 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Both photosynthetic and non-

photosynthetic radiation provide energy that increases plant temperature. Since temperature is the primary environmental factor influencing the rate of plant development, the use of HPS lamps will increase the rate of development and decrease production time.

We observed that HPS lamps delivering 50 to 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ provided 35 to 72 $\text{W}\cdot\text{m}^{-2}$ radiant energy. These measurements are similar to those in a previous report which showed HPS lamps provided 0.74 $\text{W}\cdot\text{m}^{-2}$ (300 to 100,000 nm) per $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (400 to 700 nm) (Bubenheim et al., 1988). This same report showed that the ratio of irradiance to PPF for metal-halide and low-pressure sodium lamps was 1.0 and 0.58, respectively, indicating the effect of supplemental lighting on plant temperature is dependent on the lamp type.

The degree to which plant temperature deviates from air temperature depends on the plant energy balance. For example, we observed in a separate experiment that Oriental lily bud (1-2 cm) temperature seldom equals air temperature (Fig 5). Bud temperature at night was always cooler than the surrounding air, the difference was proportional to the difference between the plant temperature and the glass temperature, i.e. the amount of long-wave radiative cooling. During the day, plant temperature increased as solar radiation increased under low VPD conditions; however, plant temperature decreased after sunrise, then began to increase after the solar radiation increased above approximately 100 $\text{W}\cdot\text{m}^{-2}$ under high VPD conditions. It appears that rapid stomatal opening after sunrise on these buds allowed for more energy to be initially lost via transpiration than was absorbed from solar radiation. However, once the stomata

were fully open, further increases in solar radiation resulted in increased plant temperature.

The effect of HPS lighting on the difference between plant and air temperature is a function of VPD and net radiation (short-wave and long-wave). For example, under low VPD conditions (Fig. 6A), plant temperature increased with supplemental irradiance. The shoot-tip temperature of plants receiving HPS lighting was generally above air temperature while the lamps were on, while plants receiving ambient PPF were always below air temperature. Under high VPD conditions (Fig. 6B), the temperature of both lighted and unlighted plants decreased after sunrise and remained below air temperature throughout the day. Under low solar radiation (Fig. 6C), plant temperature under HPS lamps was consistently 2C higher than plants under ambient PPF conditions.

While shoot-tip temperature did not decrease when light from HPS lamps was added to vinca plants (Fig. 1,2, and 6B), adding sunlight to buds under high VPD conditions (>2.5 kPa) resulted in bud temperature decreasing (Fig. 5). We hypothesize that the different responses to additional PPF is related to light quality and the relative ratio of energy in the 400 to 700 nm waveband with the 700 to 50,000 nm waveband. HPS radiation is notably deficient in blue light and stomatal opening is considered a quantitative blue-light response (Zeiger, et al., 1987). Therefore, we hypothesize that stomata do not open as fully under HPS lamps as under solar radiation at the same PPF. Further, for each watt of 400 to 700 nm radiation delivered from HPS lamps, an additional 1.76 watts of 700 to 50,000 nm radiation is received; for sunlight, only an additional 1.18 watts is received (Thimijan and Heins, 1983). The impact of the additional energy from long-wave radiation from HPS lamps on plant temperature was

shown when the total irradiance from the HPS lamps was reduced with a water/polycarbonate filter. Plant temperature under the filter was 2.7C cooler than that not under the filter and was 1.4C cooler than in the dark. Apparently, stomatal conductance had increased when the plants were placed under the HPS light, enough to more than compensate for incoming radiation on plants under the water filter, but not enough for those directly exposed to the lamps. Stomatal conductance measurements must be made to confirm this hypothesis.

The change in plant temperature under HPS lighting can have a significant impact on crop timing. For example, if we assume that average temperature increases 1.5C as a result of the HPS lighting of an Easter lily crop (*Lilium longiflorum* Thunb.), the number of days for 80 leaves to unfold decreases by 6 days, a 10% decrease in time to visible bud (Table 1). HPS lighting will have a greater effect on crop timing when rate of development is low, i.e., low air temperature, and on species that have high base temperature.

5. Acknowledgement

This project was funded in part by the American Floral Endowment. The authors appreciate the technical assistance of Tom Wallace and Matthias Nachtmann.

6. References

- Bubenheim, D.L., Bugbee, B., and Salisbury, F.B., 1988. Radiation in controlled environments: Influence of lamp type and filter material. *J. Amer. Soc. Hort. Sci.* 113(3):468-474.
- Gates, D.M., and Papian, L.E., 1971. *Atlas of Energy Budgets of Plant Leaves*. Academic Press, New York.
- Karlsson, M.G., Heins, R.D., and Erwin, J.E., 1988. Quantifying temperature-controlled leaf unfolding rates in 'Nellie White' Easter lily. *J. Amer. Soc. Hort. Sci.* 113(1):70-74.
- Karlsson, M.G., Heins, R.D., Gerberick, J.O., and Hackmann, M.E., 1991. Temperature driven leaf unfolding rate in *Hibiscus rosa-sinensis*. *Scientia Hortic.* 45:323-331.
- Nobel, Park S. 1991. *Physicochemical and environmental plant physiology*. Academic Press, Inc.
- Thimijan, Richard W. and Royal D. Heins. 1983. Photometric, radiometric, and quantum light units or measure: A review of procedures for interconversion. *Hortsci.* 18(6):818-821.
- White, J.W., 1987. Annotated bibliography on plant growth response to irradiance including artificial lighting. *Pennsylvania Flower Growers Bull.* 375:5-7 and *Bull.* 377:2-5.
- Zeiger, E., Iino, M., Shimazaki, K., and Ogawa, T., 1987. The blue-light response of stomata: Mechanism and function. In: *Stomatal Function*. 1987:209-227.

Table 1. The estimated effect of HPS lighting on the time of development of Easter lily (Karlsson et al., 1988), poinsettia (unpublished data, 1993), and hibiscus (Karlsson et al., 1991). assuming that the average daily shoot-tip temperature increases 1.5C as a result of lighting at $100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For Easter lilies, approximately 80 leaves unfold prior to visible bud. For poinsettia stock plants, 8 leaves unfold before a vegetative cutting can be removed. For hibiscus, 8 leaves unfold prior to flower initiation.

Species	Temperature (C)		Irradiance		Difference (days)	Percent decrease
	Base	Air	Ambient	Ambient + HPS		
			Days to 80 unfolded leaves			
Easter lily	1.2	15	61	55	6	10
	1.2	25	36	34	2	6
			Days to 8 unfolded leaves			
Poinsettia	5.6	15	55	48	8	14
	5.6	25	27	25	2	7
			Days to 8 unfolded leaves			
Hibiscus	9.8	15	135	105	30	23
	9.8	25	46	42	4	9

Figure 1. Effect of increasing PPF from HPS lamps on the difference between plant and air temperature of vinca.

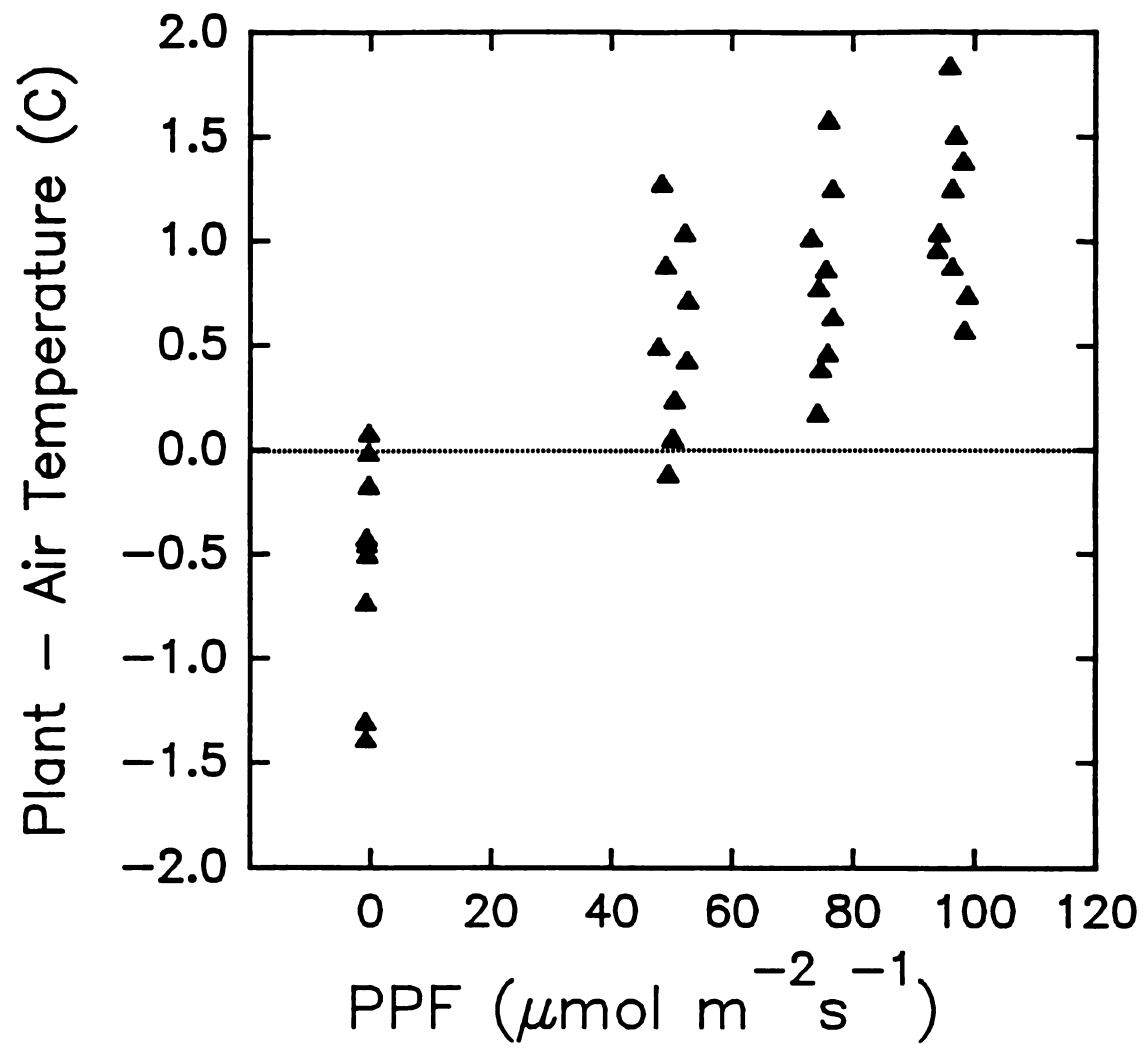


Figure 2. Effect of VPD at different PPF levels on the difference between plant and air temperature of vinca.

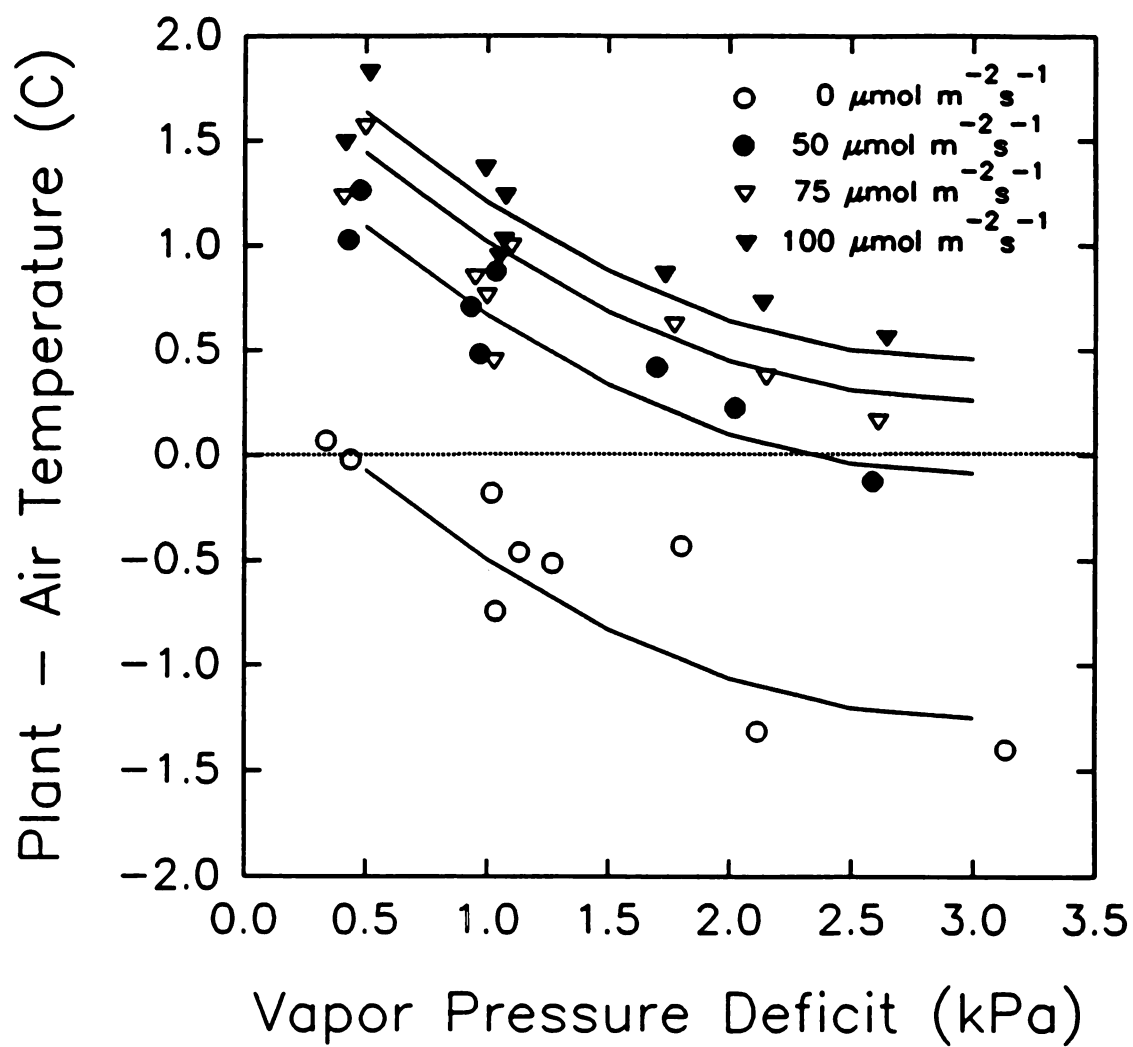


Figure 3. A. Energy per waveband for HPS lighting system used in experiment. B. Percent reduction in energy from polycarbonate and water filter by waveband.

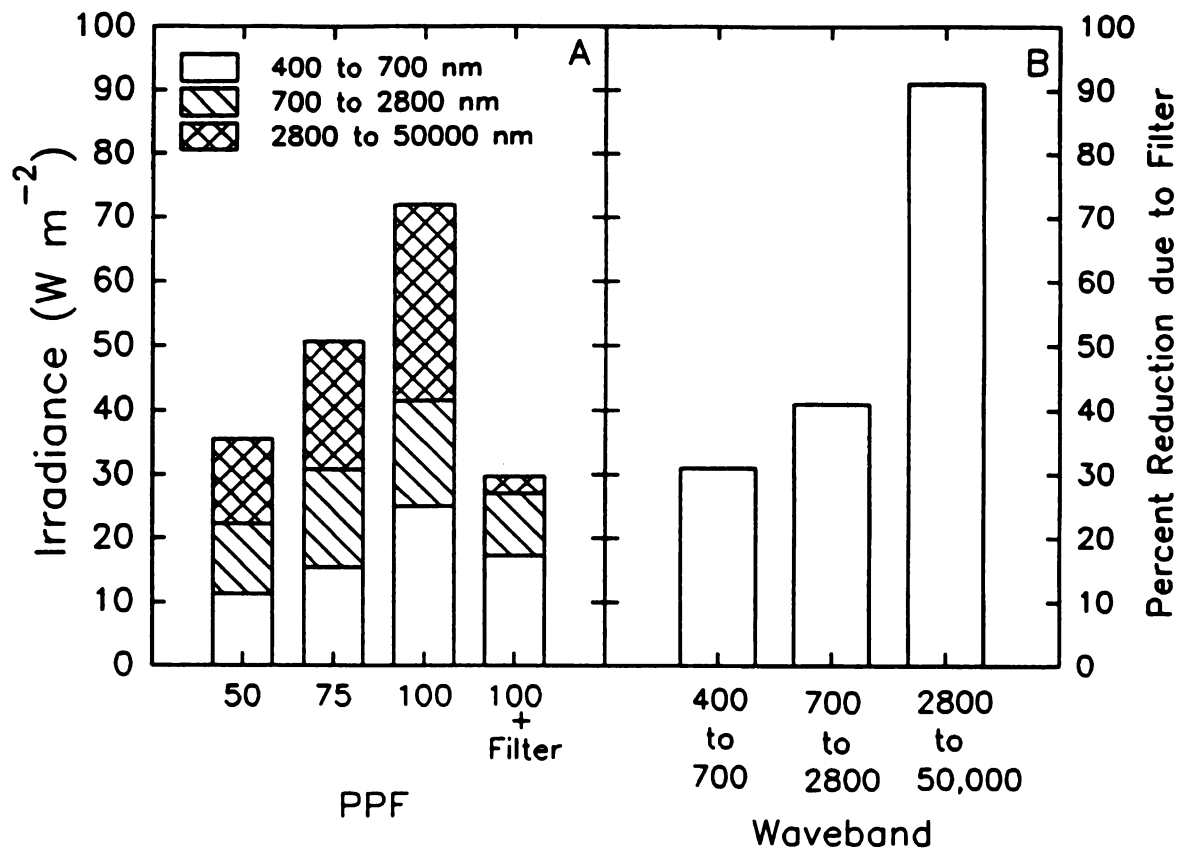


Figure 4. Effect of VPD and PPF from HPS lamps on the difference between plant and air temperature either with or without a water filter.

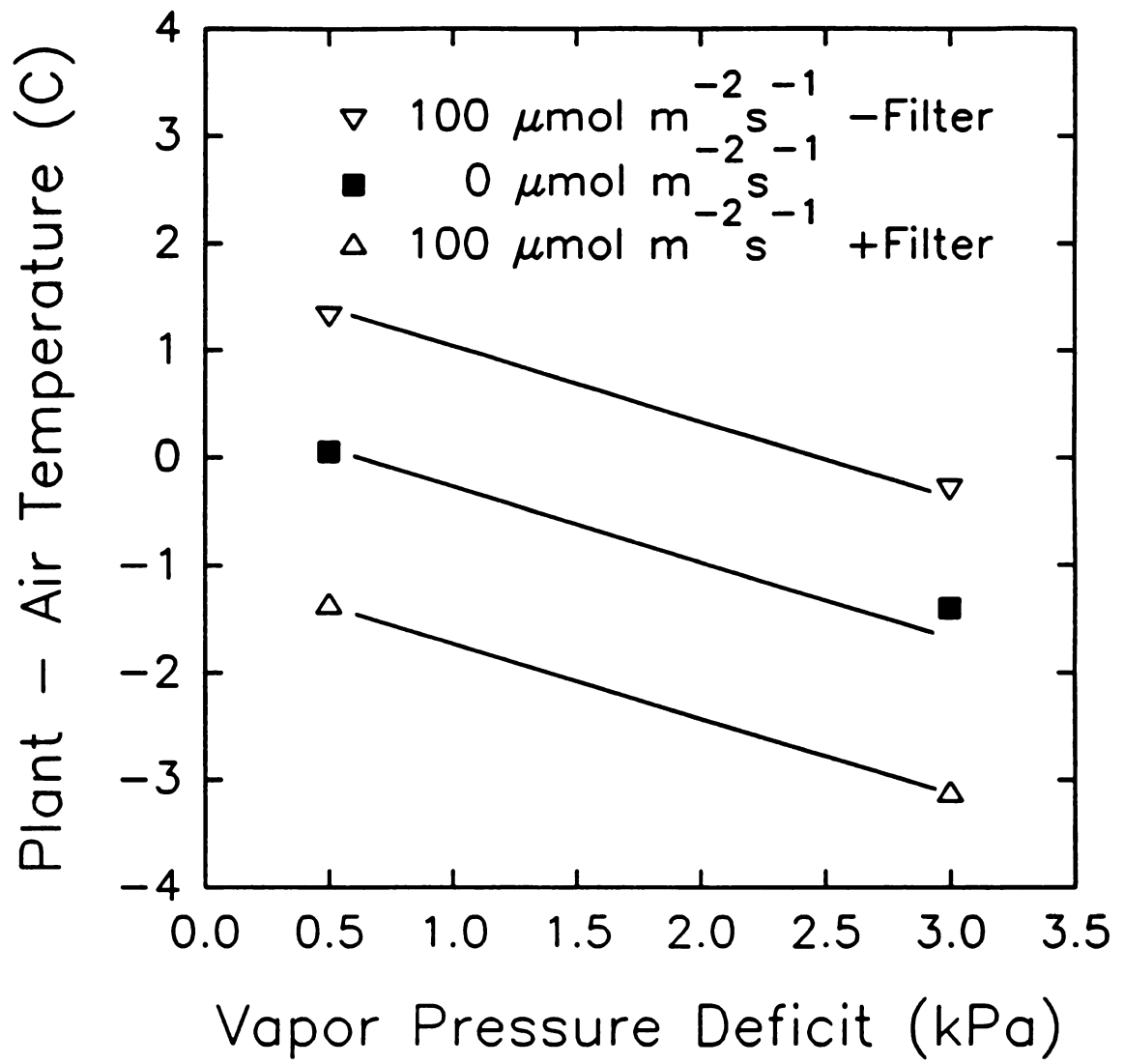


Figure 5. Bud minus air temperature for 'Stargazer' lily lower buds growing under three different air temperature/VPD conditions.

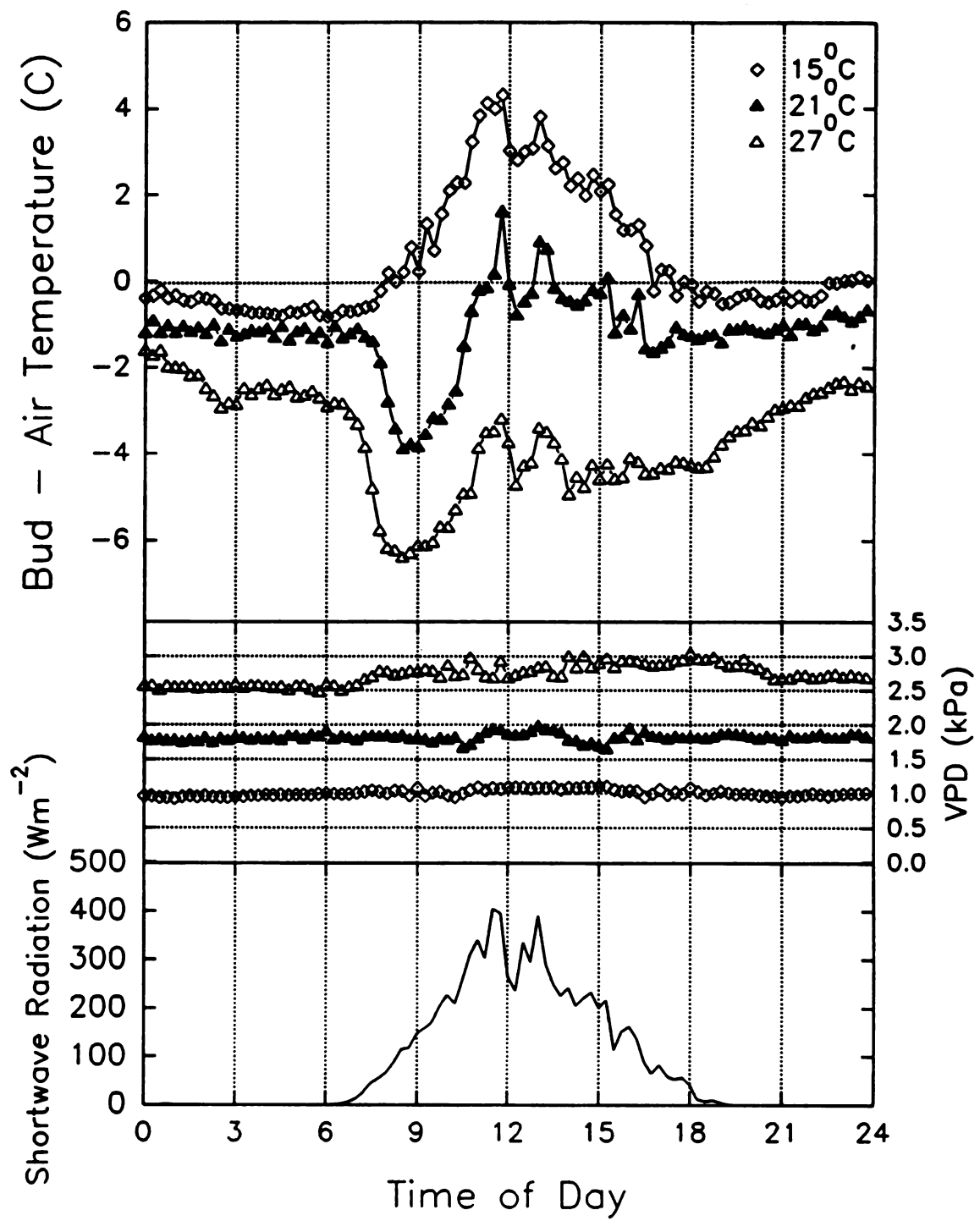
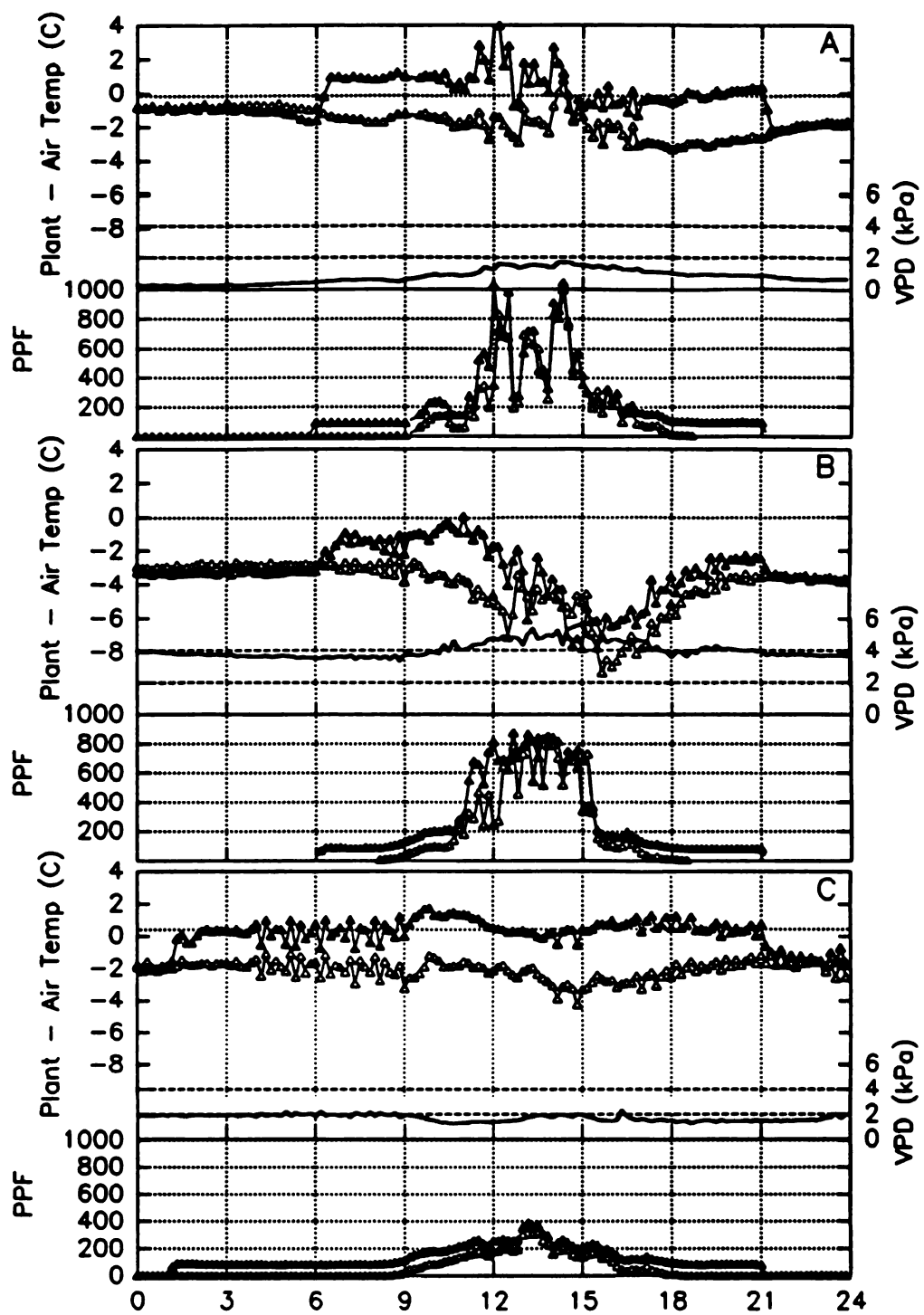


Figure 6 The effect of HPS lighting, solar radiation, and VPD on the difference between plant and air temperature of vinca plants on three separate days. ▲ and △ represent measurements under the HPS lamp treatment and the control treatment, respectively. Air temperature setpoints were A) 15, B) 32, or C) 22C.



SECTION III

QUANTIFYING THE EFFECT OF THERMAL SCREENS ON SHOOT-TIP TEMPERATURE IN GLASS GREENHOUSES

Quantifying the Effect of Thermal Screens on Shoot-tip Temperatures in Glass Greenhouses.

James E. Faust¹, Royal D. Heins², and Paul Kiefer³

Michigan State University, East Lansing, MI 48824

Received for publication _____. Accepted for publication _____. This research was supported in part by the Fred C. Gloeckner Foundation, Inc and the American Floral Endowment. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹ Former graduate student. Current address: University of Tennessee, Dept. of Ornamental Horticulture and Landscape Design, Knoxville, TN 37901-1071.

² Professor.

³ Undergraduate student.

Quantifying the Effect of Thermal Screens on Shoot-tip Temperatures in Glass Greenhouses

Additional index words. Longwave radiation, night temperature, vinca, *Catharanthus roseus*, African violet, *Saintpaulia ionantha*.

Abstract. The effect of thermal screen material on shoot-tip temperature was quantified in a glass greenhouse. At night, vinca (*Catharanthus roseus* L.) and African violet (*Saintpaulia ionantha* Wendl.) plants were exposed to the greenhouse glass then to several thermal screen treatments consisting of aluminum-coated polyester and black polyethylene screens under constant air temperature. Under the glass, vinca temperature decreased from 1.4 to 4.6°C below air temperature as glass temperature decreased from 13.5 to -2.5°C. The effect of thermal screens on the longwave radiation incident on the plant canopy depended on glazing temperature, i.e. the colder the glazing material, the larger the increase in the incident radiation after the thermal screen was pulled above the canopy. Vinca shoot-tip temperature increased 3°C relative to air temperature when longwave radiation increased 40 W·m⁻² as a result of the thermal screen treatments, and African violet shoot-tip temperature increased 1.4°C relative to air temperature when longwave radiation increased 27 W·m⁻². No consistent benefit in terms of shoot-tip temperatures were observed between the aluminum-coated polyester and black polyethylene screen treatments. A 40% aluminum shade cloth resulted in increased shoot-tip temperatures, but to a lesser degree than the "solid" thermal screens.

Thermal screens consist of materials such as polyester, polyethylene or aluminum that are extended above a greenhouse crop at night. These screens were developed to reduce greenhouse heating costs by reducing energy loss at night (Zabeltitz and Meyer, 1984; Bailey, 1988). The reduction in energy loss from the greenhouse occurs because 1) the volume of air to be heated in the greenhouse is reduced, 2) the screen creates an insulating barrier between the heated greenhouse air and the non-heated air above the screen but below the greenhouse glazing, and 3) there is a reduction in longwave, or thermal, radiation (3,000 to 100,000 nm) loss from the greenhouse crop to the cold glazing material.

In a greenhouse at night, plant temperatures are usually lower than the surrounding air temperatures, unless a longwave, or infrared, heat source is used in the greenhouse (Faust and Heins, 1994a). The lower plant-than-air temperature is caused by a net loss of energy via longwave radiation to the colder greenhouse glazing. Thermal screens have the potential to reduce the plant night-temperature depression by reducing the longwave energy losses to the glazing material. Such increased plant temperatures, specifically shoot-tip temperatures, should result in higher plant developmental rates without increasing greenhouse air temperatures.

Some thermal screens consist of two layers of film-strip fabric, the top one consisting of clear polyester coated with aluminum and the bottom made of black polyester or polyethylene fabric. This combination is used so that the thermal screen can also serve as a black cloth to shorten the photoperiod perceived by the greenhouse crop. The advantage of this combination is that the outer aluminum layer reflects shortwave solar radiation (300 to 3,000 nm) to prevent heat buildup during the late afternoon on

sunny days while the black inner layer absorbs photons that pass through the aluminum screen.

While aluminum and black polyester fabric screens are effective at modifying photoperiod, gray-body radiation theory suggests that thermal screens manufactured with aluminum on both sides would be more effective in preventing longwave energy loss from plants at night because of its high longwave reflectivity (Meinders, 1984). Since longwave radiation exchange requires that the surfaces of two objects are exposed to each other for energy transfer to occur, plant morphology will influence longwave radiation exchange between the shoot-tip and the glazing material and possibly shoot tip temperature. Theoretically, the more exposed the shoot-tip is to the glazing material, the greater the impact of longwave radiation exchange on shoot-tip temperatures.

The objective of this project was to determine the effect of thermal screen material in a glass greenhouse on night-time shoot-tip temperature of two species with different shoot-tip morphology.

Materials and Methods

Two species with different morphologies were chosen for this study. Vinca (*Catharanthus roseus* L.) has a 1- to 2-mm diameter shoot that is relatively visible from the top of the plant, while African violet (*Saintpaulia ionantha* Wendl.) has a 5 to 7-mm diameter shoot that is completely covered by the leaf canopy, and the shoot-tip is 1 to 3 cm above the medium surface.

African violets grown in 10-cm-diameter pots (450 cm³) and vinca plants grown in 72-cell packs were placed in the center of a 10 m² greenhouse maintained at 20C air

temperature. Fine-wire Type E thermocouples (80 μ m diameter chromel-constantan) were inserted into the shoot-tip of four plants per species, and two thermocouples were taped to the glass above the canopy. The precision of the thermocouples was approximately $\pm 0.15^\circ\text{C}$. A total hemispherical radiometer (REBS; Seattle, WA) was placed at canopy height to measure total radiation (280 to 50,000 nm) incident on the canopy. Air temperature was measured in the plant canopy and also in an aspirated, shaded weather station adjacent to the canopy. All sensors were measured with a CR10 datalogger (Campbell Scientific Inc.; Logan, UT). One-minute average values for each sensor were recorded during each experiment.

Five experiments were conducted from January 17 to March 30, 1994. Each experiment began approximately one hour after sunset. Treatments consisted of first exposing plants to the glass greenhouse structure for 30 minutes (control group), then sequentially placing 2 or 3 of the five thermal screens 0.7 to 0.8 m above the canopy for 30 minutes to one hour for each thermal screen. Three screens were used: aluminum-coated clear polyester (LS11), black high-density polyethylene (LS1), and 40% aluminum-coated clear polyester, 60% open (OLS40) (L. Svensen Co.; Charlotte, NC). The five thermal-screen treatments examined were: 1) aluminum top and bottom, 2) aluminum top and black polyethylene bottom, 3) black polyethylene top and bottom, 4) black polyethylene top and aluminum bottom, and a 40% aluminum shade cloth.

Results and Discussion

During the five experiments, outside air temperature ranged from -14.4 to 12.5°C . During the time when plants were exposed to the greenhouse glass, glass temperature

ranged from -1.4 to 14.4C, and the incident longwave radiation ranged from 368 to 399 W·m⁻² (Table 1). Vinca shoot-tip temperatures were 4.6 and 1.5C below air temperature when the glass temperatures were -2.5 and 13.5C, respectively (Table 1). African violet shoot-tip minus air temperature under the glass treatment ranged from -3.9 to -1.7C when the glass temperature was 2.8 and 14.4C, respectively.

Shoot-tip temperature of both species increased relative to air temperature when exposed to the thermal screen treatments. The magnitude of the shoot-tip temperature change was greatest when glass temperature was coldest. Vinca shoot-tip temperature increased 3C above the control group when the thermal screens were pulled above the canopy and the longwave radiation increased 40 W·m⁻² (Fig. 1). African violet shoot-tip temperature increased 1.4C when thermal screens were pulled over the canopy and longwave radiation increased 27 W·m⁻².

Although significant differences were observed between shoot-tip minus air temperatures of the thermal screen treatments, no consistent pattern was observed, except that the 40% aluminum shade cloth treatment had less of an effect on shoot-tip temperature than the other four screen treatments (Table 1).

The Stefan-Boltzmann law states that the amount of energy emitted or absorbed from a gray body is a function of the body's temperature and the surface emissivity. Longwave energy incident on a surface must be absorbed, transmitted or reflected. High emissivity/low reflectivity surfaces such as black polyethylene will exchange considerable radiation with the greenhouse crop and the glazing material. If the temperature of the thermal screen is lower than the crop, the crop will experience a net loss of radiation to the screen, thus lowering the crop temperature. Low emissivity/high reflectivity

materials, such as polished aluminum, reflect a considerable amount of the longwave energy, thus the temperature of the screen should have little effect on the temperature of the greenhouse crop. However, in this study we did not observe any benefit in terms of shoot-tip temperature from the different combination of aluminum and black thermal screens. Measurements of thermal screens temperatures indicated that screen temperatures were usually within 2C of the surrounding air temperature during these experiments. Under these conditions we would not expect that thermal screen emissivity would influence shoot-tip temperature. It is also possible that the thermal screen can be warmer than the plant due to stratification of air, i.e. the air near the thermal screen is warmer than the air near the canopy. Thus, high emissivity thermal screens could actually increase shoot-tip temperatures. This is more likely to occur when two screens are used, so that the bottom screen is not exposed to the cold glazing material.

The incident radiation measured at canopy height under the cold glass control group was higher than one would estimate, using the Stefan-Boltzmann equation, based upon the measured glass temperature. The reason for this is that the greenhouse used in this study was relatively small (10 m²). Two sidewalls were connected to warm, adjacent greenhouses and one sidewall was insulated. We calculated that 60 to 70% of the greenhouse structure "seen" by the shoot-tip, i.e. the viewfactor, was glazing material exposed to the outside environment. Consequently, we estimate that commercial greenhouses would have larger viewfactors; therefore, we expect commercial greenhouses would observe larger shoot-tip temperature depressions at night and would observe greater benefits from using thermal screens.

Shoot-tip temperatures were always less than air temperature despite the success of thermal screens at removing the driving force for longwave radiation exchange. Night transpiration can reduce plant temperature in greenhouses (Seginer, 1984). The vapor-pressure deficits measured during these experiments were 0.8 to 1.2 kPa, and this gradient would reduce shoot-tip temperatures approximately 0.5C (Faust and Heins, 1994b). Evaporative cooling from the medium surface could possibly reduce shoot-tip temperature. It is also possible that inserting the thermocouple into the shoot-tip prior to each experiment caused free water to evaporate from the wound resulting in localized evaporative cooling around the thermocouple.

From these results, we conclude that a thermal screen coated with aluminum or a black polyester screen placed between the greenhouse crop and the greenhouse glazing will increase shoot-tip temperatures, however the magnitude of the response is dependent on the glazing temperature and species. The colder the glazing material, the greater the shoot-tip temperature increase when a thermal screen is used. The increase in shoot-tip temperatures when the incident longwave radiation increased was greater for vinca than for African violets. It appears that the shoot-tip of species that are exposed to the glazing material are more sensitive to the longwave radiation environment than species in which the shoot-tip is below the foliar canopy. Therefore, the benefit of thermal screens on shoot-tip temperatures appears to be greater for species with relatively exposed shoot-tips.

LITERATURE CITED

- Bailey, B.J. 1988. Improved control strategies for greenhouse thermal screens. *Acta Hortic.* 230:485-492.
- Faust, James E. and Royal D. Heins. 1994a. Modeling shoot-tip temperatures in the greenhouse environment. *J.A.S.H.S.* (in review).
- Faust, James E. and Royal D. Heins. 1994b. Quantifying the influence of high-pressure sodium lighting on shoot-tip temperature. *Acta Hortic.* (in review).
- Meinders, H. 1984. Technical developments in thermal screening systems. *Acta Hortic.* 148:443-452.
- Seginer, Ido. 1984. On the night transpiration of greenhouse roses under glass or plastic cover. *Agric. Meteor.* 30:257-268.
- Zabeltitz, C.V., and J. Meyer. 1984. Evaluation of movable thermal screens in commercial greenhouses. *Acta Hortic.* 148:437-442.

Table 1. The effect of four thermal screens and one shade cloth on the difference between shoot-tip and air temperatures at night for vinca and African violet on five dates. AL/AL, aluminum-coated polyester top and aluminum-coated polyester bottom; AL/BL, aluminum-coated polyester top and black polyethylene bottom; BL/BL black polyethylene top and black polyethylene bottom; BL/AL black polyethylene top and aluminum-coated polyester bottom; 40%AL, 40% aluminum-coated polyester shade cloth.

Date	Outside Air Temp (C)	Glass Temp (C)	Incident Radiation ^x (W·m ⁻²)	Species	Plant-air temperatures (C)					
					Glass	AL/AL	AL/BL	BL/BL	BL/AL	40%AL
Jan. 17	-13.5	-1.5	368	Vinca	-4.58 a ^z	-1.42 c	-	-1.70 b	-1.79 b	-
				African violet	-	-	-	-	-	-
Feb. 14	-0.4	7.2	387	Vinca	-3.28 a	-	-	-1.81 b	-1.39 c	-
				African violet	-2.22 a	-	-	-1.35 b	-1.05 b	-
Mar. 22	14.2	14.4	399	Vinca	-1.37 a	-0.91 c	-	-0.95 c	-	-1.04 b
				African violet	-1.68 a	-1.26 b	-	-1.59 a	-	-1.57 a
Mar. 24	2.8	8.2	387	Vinca	-4.03 a	-	-1.61 c	-	-2.02 b	-
				African violet	-3.94 a	-	-2.17 c	-	-2.87 b	-
Mar. 30	3.6	7.6	388	Vinca	-2.71 a	-1.88 c	-	-1.59 d	-	-2.27 b
				African violet	-3.54 a	-3.12 c	-	-2.77 d	-	-3.25 b

Species^y

Thermal Screen

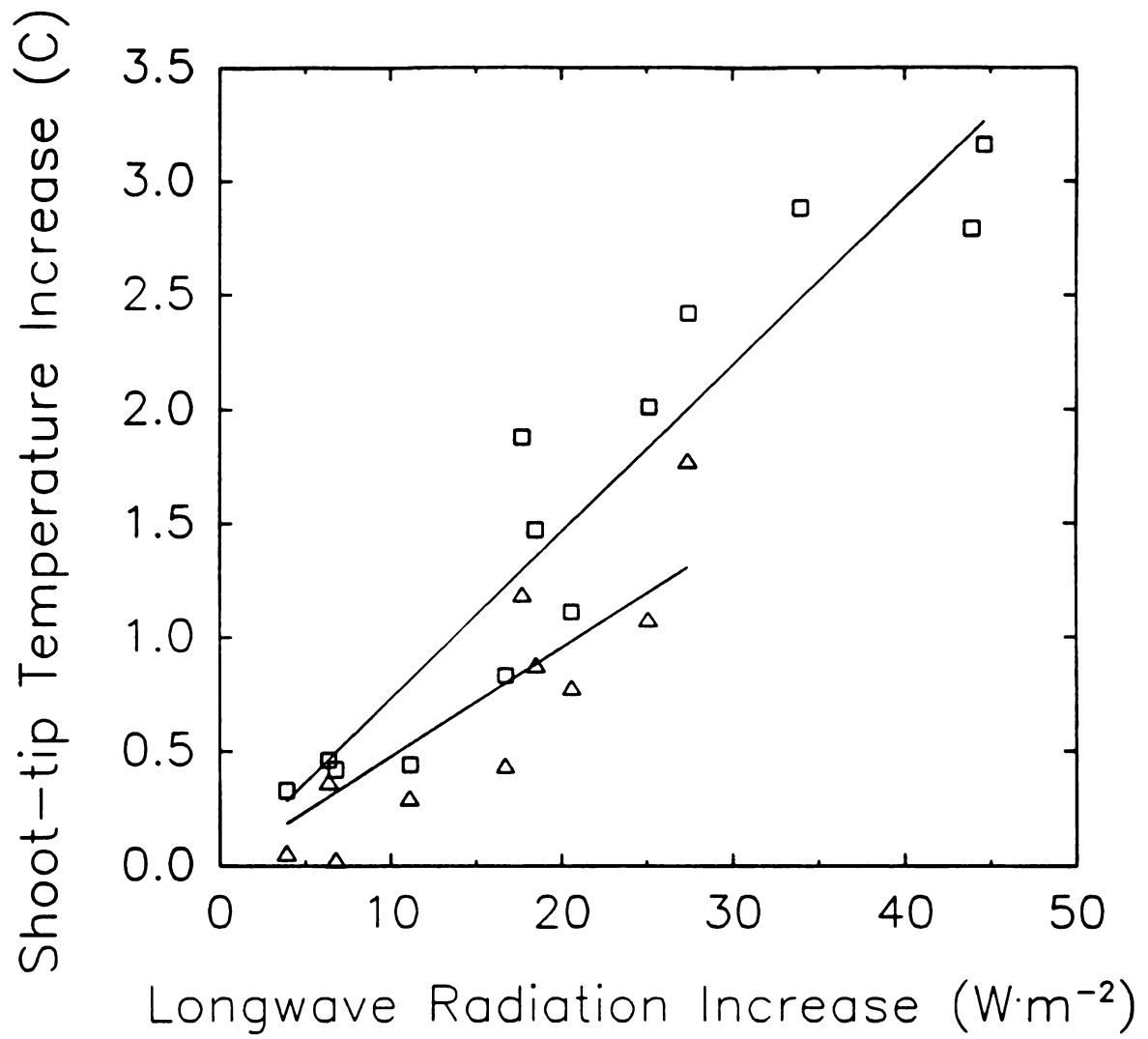
Species*Thermal Screen

^z Mean separation within rows by Student-Newman-Keuls' test, $P \leq 0.01$.

^y Analysis of variance, *** indicates significance at 0.001.

^x Measured during exposure to the greenhouse glazing material.

Figure 1. The change in shoot-tip temperature of vinca ($\square$) and African violet (Δ) plants in response to the change in incident radiation. The changes in shoot-tip temperature and incident radiation refer to the differences between the values measured during the control treatment, i.e. exposure to the greenhouse glass, in comparison to the thermal-screen treatments. $Y=0.0731X$ ($r^2=0.895$) for vinca and $Y=0.0476X$ ($r^2=0.752$) for African violet regression lines.



SECTION IV

QUANTIFYING THE EFFECT OF PLUG-FLAT COLOR ON MEDIUM-SURFACE TEMPERATURES DURING GERMINATION

Quantifying the Effect of Plug-flat Color on Medium-Surface Temperatures during Germination.

James E. Faust¹ and Royal D. Heins²

Michigan State University, East Lansing, MI 48824

Hiroshi Shimizu³

Kyoto University, Kyoto, Japan.

Received for publication _____. Accepted for publication _____. This research was supported in part by the American Floral Endowment. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹ Former graduate student. Current address: University of Tennessee, Dept. of Ornamental Horticulture and Landscape Design, Knoxville, TN 37901-1071.

² Professor.

³ Agric. Engineering Instructor.

Quantifying the Effect of Plug-flat Color on Medium-Surface Temperatures during Germination.

Additional index words. shortwave radiation, longwave radiation, evaporation.

Abstract. Medium-surface temperature of black, gray, and white plug sheets were measured with thermocouples and an infrared camera. Medium-surface temperature in the black, gray, and white flats was 6.3, 6.1, and 5.3C above air temperature, respectively, when $300 \text{ W}\cdot\text{m}^{-2}$ shortwave radiation (30% of the maximum shortwave radiation during the summer) was incident on the medium surface. During the night, no differences were observed between the different plug flats, however medium-surface temperature was 3C below air temperature due to evaporative cooling and longwave radiation loss to the cooler glazing material. Medium-surface temperature increased as short-wave radiation increased. Approximately $80 \text{ W}\cdot\text{m}^{-2}$ of shortwave radiation were incident of the plug-flat surface before medium-surface temperature equaled air temperature.

Commercial bedding plant growers typically germinate seeds in plug sheets designed with 128 to 800 cells per flat (800 to 5000 plants m²)(Karlovich and Koranski, 1994). While most seeds are germinated directly on top of the medium surface, germination of some species is improved by covering the seeds with a fine coating (1 to 2 mm deep) of a material such as vermiculite. After seeds are sown, the plug flats are either placed into a germination chamber or in the greenhouse.

Temperature is a critical factor influencing seed germination (Carpenter, 1994). Whenever seed temperatures are not optimal, germination will decrease or be delayed. The temperature of the germinating seed is primarily influenced by the medium-surface temperature. Many variables influence medium-surface temperature, one of which is the plug-flat color. Plug-flat color influences the amount of solar, or shortwave, radiation absorbed. Black plug flats are most commonly used by commercial growers, however to reduce excessively high temperatures, white plug flats are marketed for use during the summer. Excessively high soil temperatures often occur during container-grown plant production during periods of high solar radiation (Martin and Ingram, 1992).

The objective of this project was to quantify the effect of plug-flat color on medium-surface temperature under different irradiance conditions.

Materials and Methods

White, gray, and black 406-cell plug flats obtained from Blackmore Co., Inc. (Belleville, MI) were filled with a peat-based medium. The flats were placed on a solid aluminum subirrigation bench in a greenhouse maintained at 25C air temperature, the optimum temperature for germination of many bedding plant species (Karlovich and

Koranski, 1994). The medium was kept moist for the duration of the experiment which was conducted over a 10-day period during July 1993 in a glass greenhouse.

The medium surface temperature in the center of the nine plug cells per treatment was measured with 80 μm diameter fine-wire thermocouples. The precision of the thermocouples was approximately $\pm 0.15^\circ\text{C}$. An Inframetrics Model 740 infrared imaging radiometer (Inframetrics, Billerica, MA) was used to create a visual image of the plug flat and medium surface temperatures. An Eppley pyranometer (The Eppley Laboratory, Inc., Newport, RI) was used to measure shortwave radiation (280 to 3,000 nm). Air temperature was measured in an aspirated, shaded weather station adjacent to the canopy. One-minute average values for each sensor were recorded with a CR10 datalogger (Campbell Scientific Inc.; Logan, UT).

Results and Discussion

Medium surface temperature was seldom equal to air temperature (Fig. 1). At night, the medium-surface temperature was always 2 to 3°C below the greenhouse air temperature, regardless of plug-flat color. Medium-surface temperature at night was not influenced by plug-flat color. The lack of a difference between flats of different colors at night is expected since the emissivity of the plug flat is a function of the surface material, not color, and energy loss from water evaporation and longwave radiation (3,000 to 50,000 nm) loss to the surrounding greenhouse structure would be the same among the different colored flats.

During the day, medium-surface temperature increased 13 to 16°C relative to air temperature as shortwave radiation increased from 0 to 700 $\text{W}\cdot\text{m}^{-2}$ (Fig. 2).

Approximately $80 \text{ W}\cdot\text{m}^{-2}$ (8% of maximum shortwave radiation at noon in the summer) of shortwave radiation were required to offset evaporative and thermal cooling so the medium-surface temperature equaled air temperature. When solar radiation was $300 \text{ W}\cdot\text{m}^{-2}$, the medium temperature in the white flat was 1°C cooler than that of the black and gray flats. However, the white and black flats were 5.3 to 6.3°C above air temperature; therefore, since the air temperature was 25°C , medium-surface temperature was 30 to 31°C . When solar radiation was $700 \text{ W}\cdot\text{m}^{-2}$, the medium in the white flat was 3°C cooler than in the black flat. However, the medium in the white plug flat was 10°C above air temperature.

As observed from the thermal-image camera, the surface temperatures across the plug flat varied considerably. The temperature of the plastic was always higher than the medium temperature during the day and the black plastic was always warmer than the white plastic. However, large temperature differences between black and white plastic did not translate into large differences in medium temperatures. When the black plastic was 5 to 6°C warmer than the white plastic, the difference between the medium-surface temperatures measured in the center of the black and white plug flats was only 1°C . A temperature gradient was observed from the medium adjacent to the plastic to the center of the plug cell; therefore, seeds placed near the edge of the cell will be more greatly influenced by the plastic temperature/plastic color than seeds in the center of the plug cell.

The results of this experiment underscore the value of using a closed chamber for germination. The environment inside a germination chamber allows no solar radiation, provides high humidity, and has warm surrounding walls. All three of these factors

contribute to providing a uniform medium-surface temperature that remains very close to the surrounding air temperature.

Exact control of medium temperature when germinating in the greenhouse is much more difficult than in a germination chamber. Best control comes from reducing solar radiation as needed with a shading system. Use of white plug flats will help limit temperature rise if solar radiation will be high, but media temperatures may still be excessive. During the night, maintaining high humidity and use of thermal screens will help limit cooling of the media. The amount of bottom heat required to maintain medium temperature will depend on how much thermal and evaporative losses can be minimized (Yang and Albright, 1985).

We observed that the medium in the black plug flats dried out faster than that in the white flats. The more rapid drying was due to the higher temperatures, and thus higher evaporation rates. Black flats may be beneficial during the winter when overwatering and cool medium temperatures can be a problem in plug production.

Not all plug flats are designed alike. The greater the plastic-surface area, the greater the potential impact on medium temperature. Some plug flat manufacturers place holes in the plastic between plug cell. The holes reduce the plastic surface absorbing shortwave radiation and also increase air movement through the plug flat, thus this design should reduce the effect of shortwave radiation on medium-surface.

LITERATURE CITED

- Carpenter, W.J. 1994. Germination. In: Tips on growing bedding plants. Third Ed.
- Karlovich, P.T. and D.S. Koranski. 1994. Plug culture. In: Tips on growing bedding plants. Third Ed.
- Martin, Chris A. and Dewayne L. Ingram. 1992. Simulation modeling of temperatures in root container media. J. Amer. Soc. Hort. Sci. 117(4):571-577.
- Yang, X and L.D. Albright. 1985. Finite element analysis of temperatures in a bottom-heated nursery container. Acta Hortic. 174:155-165.

Table 1. Parameters estimates for the nonlinear equation describing the effect of shortwave radiation on the difference between media surface and air temperature ($Y=b_0-b_1\exp(-b_2*X)$).

Plug-flat Color	Parameter	Estimate	Asymptotic 95% Confidence Interval	
			Lower	Upper
White	b_0	12.6	11.9	13.4
	b_1	-15.8	-16.5	-15.1
	b_2	-0.00259	-0.00279	-0.00239
Gray	b_0	16.2	15.1	17.2
	b_1	-19.2	-20.2	-18.2
	b_2	-0.00219	-0.00237	-0.00202
Black	b_0	18.5	17.0	20.0
	b_1	-21.8	-23.3	-20.4
	b_2	-0.00195	-0.00214	-0.00175

Figure 1. The effect of plug-flat color on the observed difference between medium-surface and air temperatures recorded on A) a partly sunny day and B) a cloudy day.

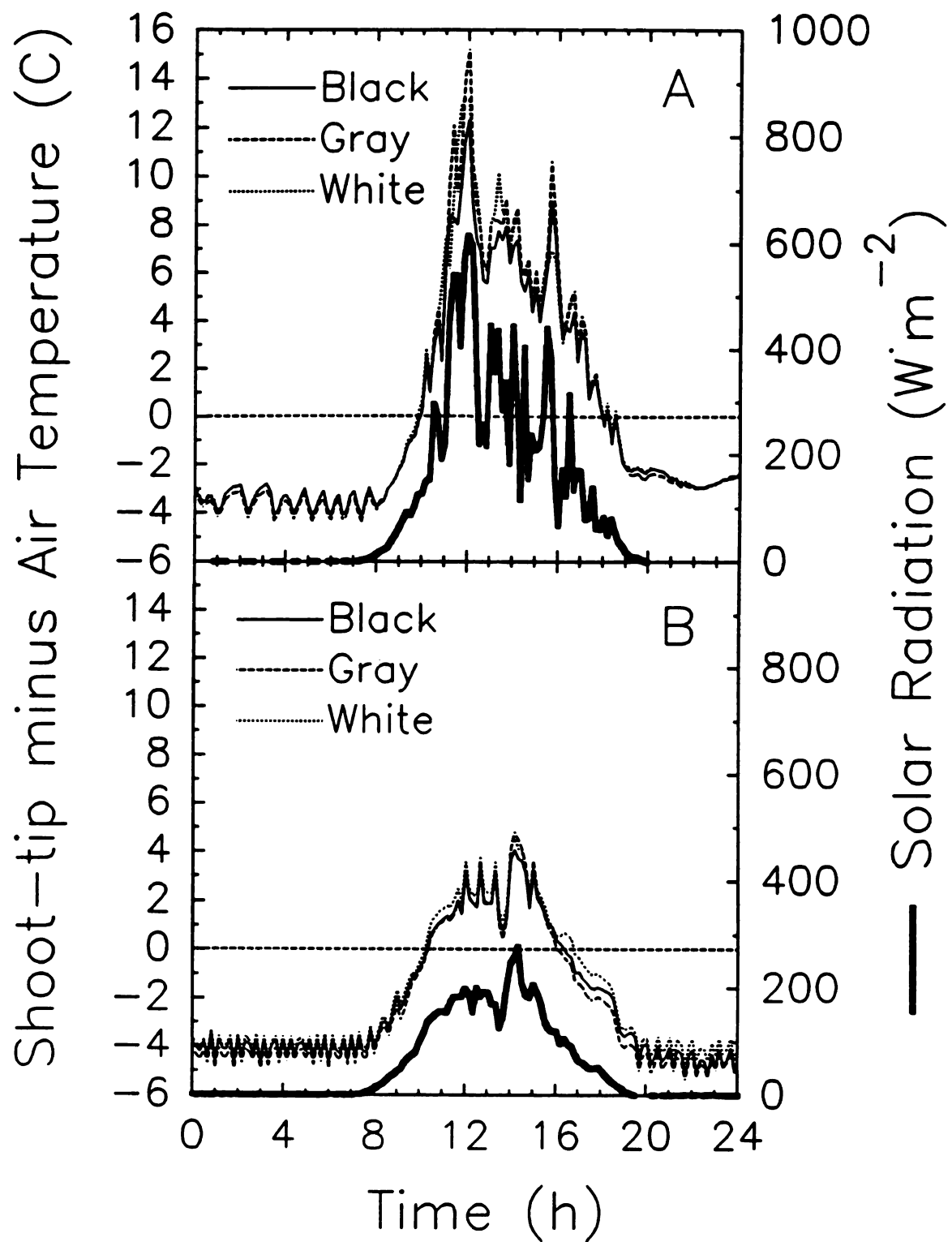
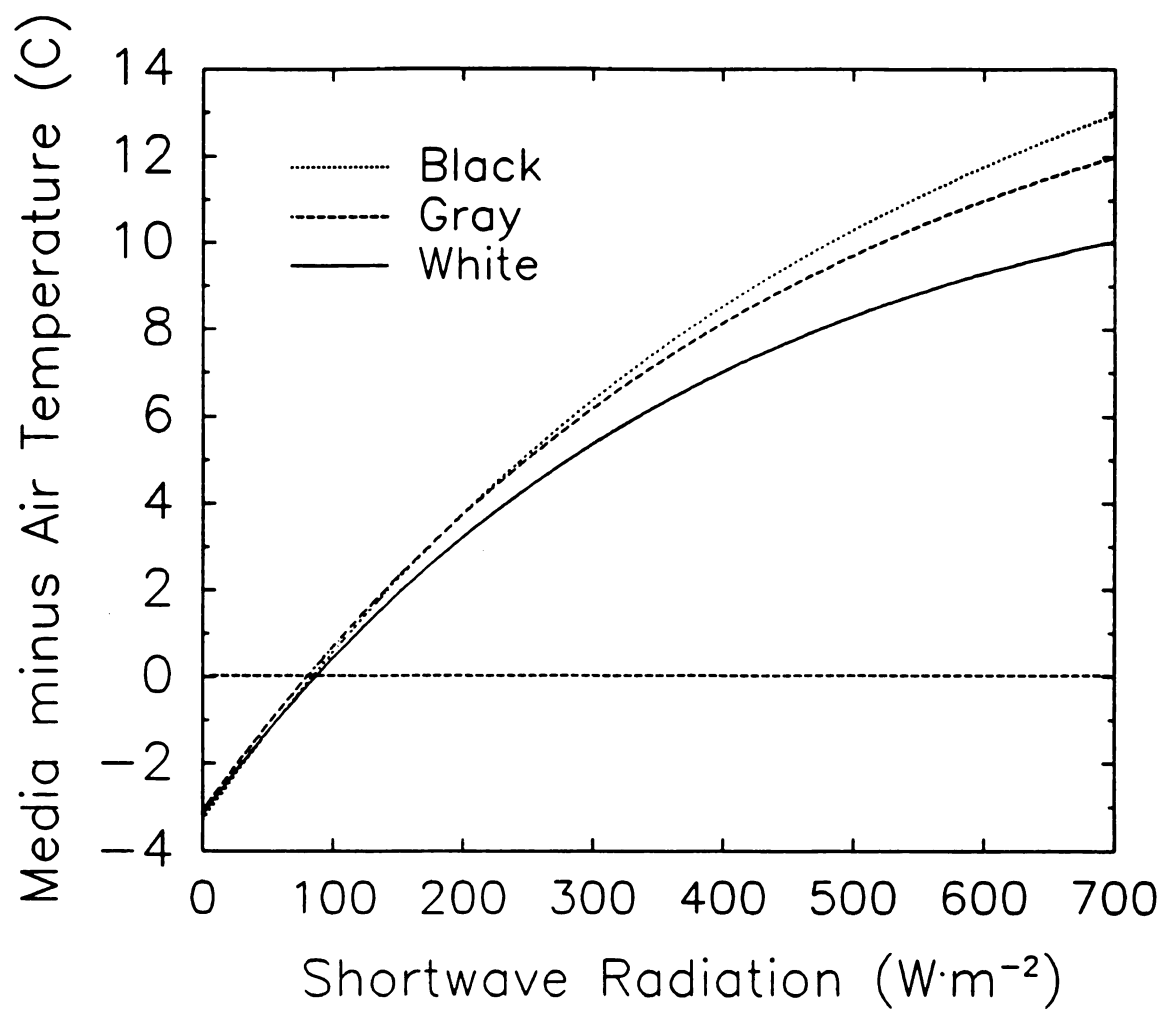


Figure 2. The effect of plug-flat color on medium-surface temperature shown as a function of the incident shortwave radiation. Air temperature was maintained at 25C, and the water vapor pressure deficit averaged 1.4 kPa.



SECTION V

**AXILLARY BUD AND LATERAL SHOOT DEVELOPMENT OF POINSETTIA
'ECKESPOINT LILO' AND 'ECKESPOINT REDSAILS' (*Euphorbia pulcherrima*
Willd.) ARE INHIBITED BY HIGH TEMPERATURES DURING STOCK
PLANT PRODUCTION.**

Axillary Bud and Lateral Shoot Development of Poinsettia 'Eckespoint Lilo' and 'Eckespoint Redsails' (*Euphorbia pulcherrima* Willd.) are Inhibited by High Temperatures during Stock Plant Production.

James E. Faust¹ and Royal D. Heins²

Michigan State University, East Lansing, MI 48824

Received for publication _____. Accepted for publication _____. This research was supported in part by the Paul Ecke Poinsettia Ranch. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹ Former graduate student. Current address: University of Tennessee, Dept. of Ornamental Horticulture and Landscape Design, Knoxville, TN 37901-1071.

² Professor.

Production and Culture.

Axillary Bud and Lateral Shoot Development of Poinsettia 'Eckespoint Lilo' and 'Eckespoint Redsails' (*Euphorbia pulcherrima* Willd.) are Inhibited by High Temperatures during Stock Plant Production.

Additional index words. apical dominance, branching

Abstract. The effect of temperature on axillary bud and lateral shoot development of poinsettia (*Euphorbia pulcherrima* Willd.) 'Eckespoint Lilo' and 'Eckespoint Redsails' was examined. Rooted 'Eckespoint Lilo' cuttings were transplanted, placed into growth chambers maintained at 21, 24, 27, or 30C for 2 weeks, and then the apex was removed. The percentage of nodes developing lateral shoots after apex removal was 68, 69, 73, and 76% in the 21, 24, 27, and 30C environments, respectively. Cuttings were removed from the lateral shoots, propagated, placed into a 21C greenhouse, and the apex removed. The percentage of nodes developing lateral shoots from the cuttings removed from the 21, 24, 27, 30C environments were 74, 65, 66, and 21%, respectively. The percentage of shoots from the second flush of cuttings harvested from the stock plants in the 21, 24, 27, and 30C were 96, 96, 87, and 60%, respectively. The temperature of the stock plant environment affected subsequent lateral shoot development on the harvested cuttings, not the temperature of the environment after cutting removal. Eighty-three percent of the nodes not producing a lateral shoot on the first flush of cuttings in the 30C treatment had poorly developed axillary buds or no visible axillary bud development. Visual rating of

axillary bud viability decreased from 100% to 0% viable buds when 'Eckespoint Redsails' stock plants were transferred from a 21C greenhouse to a high temperature treatment where the night temperature was 27C and the day temperature was 30, 33, and 30C for 3, 10, and 3 hours, respectively. Transfer from the high temperature greenhouse to a 21C greenhouse resulted in axillary bud viability increasing from 0 to 95%. Buds in the axils of leaves not yet unfolded were sensitive to high temperatures, whereas buds in the leaf axils of unfolded leaves, i.e. fully developed correlatively inhibited buds, were not sensitive to the high temperature treatment. Sixteen consecutive days in the high temperature treatment were required for axillary bud development of 'Eckespoint Redsails' to be negatively affected.

The commercial success of the poinsettia is due at least in part to the development of the "Annette Hegg" family of cultivars that branch freely upon removal of the shoot apex (pinching). However, certain cultivars introduced in recent years have displayed a problem in that branching is occasionally poor. We define poor branching as when less than 70% of the existing nodes on a pinched plant produce a lateral shoot. 'Eckespoint Lilo' (Lilo) and 'Eckespoint Redsails' (Redsails) are examples of cultivars that branch inconsistently, i.e. sometime the plants branch freely while at other times the plants branch poorly.

Poorly branched poinsettias can result in significant economic losses for two reasons. First, poinsettias are vegetatively propagated from shoot-tip cuttings; therefore, poorly branched stock plants do not produce a sufficient number of cuttings. Second, market specifications typically require five or more shoots on the finished plant. Plants that do not produce five flowering shoots after pinching are either sold at a reduced price or not sold at all. We have observed pinched Lilo and Redsails plants which failed to develop even one lateral shoot.

Poinsettia cultivars differ in their capacity to branch after pinching. Considerable work has been undertaken to determine the factor that influences branching. Reciprocal grafting of free-branching and restricted-branching experiments suggest that the branching factor is graft-transmissible (Stimart, 1983). A virus has been proposed as the branching factor since poinsettias regenerated from heat treatment (Dole and Wilkins, 1994) or suspension culture (Preil and Engelhart, 1982; Preil, 1994)) do not have the free-branching characteristic, however the specific factor has not been identified (Dole and Wilkins, 1991; Dole and Wilkins, 1992; Dole et al., (in press)).

The cause of inconsistent branching in Lilo and Redsails is not currently known, although the problem appears to be temperature-related since poor branching occurs more frequently in the southern United States (personal communication, Dr. David Hartley). High temperature has been linked to the inhibition of axillary bud development of chrysanthemum (Faust and Heins, 1992) and peach (Boonprakob, et. al., 1993). Visual observations indicate that axillary buds often fail to develop properly in the leaf axils of poor branching cultivars (Faust and Heins, 1993). Poor axillary bud development ranges from the absence of any differentiation in the leaf axil, i.e. a "blind" leaf axil, to the appearance of undifferentiated tissue that, with time, develops a necrotic surface.

It is not currently known whether poor branching is a result of poor axillary bud development or the correlative inhibition of viable axillary buds. If the problem is associated with poor axillary bud development, it is not known if axillary bud development is affected during stock plant production, propagation, or finished plant production.

The objective of this research was to test the hypothesis that high temperature inhibits axillary bud development in poinsettia, resulting in poor lateral shoot development.

Materials and Methods

Expt. #1. Rooted 'Eckespoint Lilo' cuttings were received from the Paul Ecke Poinsettia Ranch, Encinatas, California on March 15, 1990. The cuttings were transplanted into 15-cm diameter pots (1200 cm³) and placed into a greenhouse

maintained at $21 \pm 1^\circ\text{C}$. Fifty percent PPF-reduction shade cloth was placed above the plants for one week.

Roots had grown to the sides of the pots after two weeks in the greenhouse. At this time, twenty-five 'Eckespoint Lilo' plants were placed into each of five growth chambers (Convion, Model E-15; Ashville, NC) maintained at 21, 24, 27, 30, and 33C. Plants were exposed to a PPF of $600 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 16 hours per day from fluorescent and incandescent lamps.

Stock plants were established by removing the shoot apex leaving five nodes on the plants one day after being placed into the growth chambers. Severe interveinal chlorosis had developed on the stock plant leaves by the twelfth day after pinching, especially at 30 and 33C. Therefore, the PPF was reduced to $300 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in all of the growth chambers, and the night temperature in the 30 and 33C chambers was reduced to 21C.

The number of lateral shoots that developed on each stock plant was recorded. Cuttings were taken from these lateral shoots when seven to eight leaves had unfolded leaving two nodes below each cutting. The number of lateral shoots that developed from these two nodes were recorded, and a second group of cuttings was removed from the stock plants.

When cuttings were removed from the stock plants, one half of the cuttings were shipped via overnight delivery to the Paul Ecke Poinsettia Ranch and the other half were rooted at the Michigan State University Research Greenhouses. Cuttings were rooted in oasis strip maintained at 26C medium temperature. Three to four weeks were required for propagation, after which the rooted cuttings were transplanted into 15-cm pots and

placed into a greenhouse maintained at $21 \pm 1^\circ\text{C}$. These plants were pinched one to two weeks after being transplanted, and the number of lateral shoots that developed were recorded. Experimental results from Michigan and California-grown plants did not differ statistically; therefore, the data presented have been pooled for this paper.

The following grading system was used to describe lateral shoot development from the first and second flush of shoots from the plants grown in Michigan:

1. Shoot $> 3\text{cm}$ long.
2. Shoot $< 3\text{cm}$ long.
3. No shoot developed.

Expt. #2. Rooted 'Eckespoint Lilo' poinsettia cuttings were transplanted into 15-cm diameter (1200 cm^3) pots, placed into a greenhouse maintained at 21°C and pinched so that five nodes remained on the stock plant. After ten leaves unfolded on the first flush of lateral shoots, axillary buds were rated according to the following scale:

1. Well-developed bud: The bud was green, necrosis was not present, and the first leaf was visible.
2. Poorly-developed bud: Necrosis covered all or part of the bud, and/or the first leaf was not visible.
3. Axillary bud not visible: The leaf axil was devoid of an axillary bud.

Cuttings were removed from the stock plants, however some lateral shoots were left on the stock plants to provide a control group consisting of shoots and axillary buds that did not go through the propagation sequence. In general, a cutting possessed eight unfolded leaves, four that were fully expanded. The cuttings were propagated for three

to four weeks and then transplanted.' After roots had reached the sides of the pot (two weeks after transplanting), the cuttings were pinched to leave five nodes on the rooted cutting, and the axillary buds were rated. At the same time, equivalent axillary buds on the control group were rated and the lateral shoots were pinched above the eighth node. The top five nodes on the control plants were morphologically the same aged nodes to develop lateral shoots on the propagated and pinched cuttings. The leaf axils of the cuttings and stock plants (control group) were examined five weeks after pinching to observe lateral shoot development.

Expt. 3. Poinsettia 'Eckespoint Red Sails' stock plants grown at 21C were moved into a high temperature treatment for 0, 2, 4, 8, 16, or 32 days, then returned to the 21C greenhouse. The high temperature treatment, hereafter referred to as 33/27C, consisted of 3, 10, and 3 hours at 30, 33, and 30C, respectively during the day and 27C for 8 hours during the night. The location of the most recently unfolded leaf (node 0), defined as a leaf greater than one cm in length and reflexed to at least 45° from the lateral shoot axis, was recorded at the time of transfer to the 33/27C greenhouse. The seven leaves unfolded prior to the start of the experiment were assigned negative numbers, with -7 being the oldest node recorded. The seven leaves that unfolded after the start of the experiment were assigned positive numbers, with 7 being the youngest node. Axillary buds were rated as viable or not viable after approximately twelve additional leaves unfolded on the lateral shoots. Viable axillary buds were defined by Rating 1 in Expt. 2, while non-viable buds were defined by Ratings 2 and 3 in Expt. 2.

Expt. 4. Poinsettia 'Eckespoint Red Sails' stock plants were initially grown in the 33/27C treatment for one month then moved into a 21C greenhouse. The axillary buds

were examined at the time of transfer to verify that all visible leaf axils were devoid of a viable axillary bud prior to start of the experiment. The most recently unfolded leaf was recorded at the time of transfer (node 0). Axillary buds were rated in the same manner as Expt. 3 after seven or more leaves unfolded during the 21C treatment.

Expt. 5. Poinsettia 'Eckespoint Red Sails' stock plants were grown at 21C, and all axillary buds were examined to verify that all visible leaf axils possessed a viable bud at the start of the experiment. The stock plants were then placed into greenhouse air treatments of 21C (Trt. 1 and 2) or 33/27C (Trt. 3 and 4)(Table 1). One-half of the plants in each greenhouse were pinched at the start of the experiment, Day 1 (Trt. 1 and 3). The remainder of the plants were pinched on Day 35 (Trt. 2 and 4). When pinching on Day 35, many more nodes were removed than during the Day 1 pinch so that all four treatments would have the same nodes released from apical dominance. After 35 days, all plants were placed into a greenhouse maintained at 21C. The six basipetal axillary buds on the lateral shoots that developed after the Day 1 and 35 pinch dates were rated in the same manner as Expt. 3 after six or more leaves unfolded on the lateral shoots.

Results

Expt. 1. The percentage of lateral shoots that developed on the stock plants in Expt. 1 was not affected by the temperatures at which the shoots developed (Fig. 1), however nodal position influenced the percentage of lateral shoots that developed. Thirty-five percent of the first nodes, i.e. the basipetal node, produced lateral shoots that contributed to the final plant canopy, while 90% of the fifth, or acropetal, nodes

produced a lateral shoot. The plants grown at 33C developed severe chlorosis and died before data were collected.

The percentage of lateral shoots that developed from the first flush of cuttings removed from the stock plants grown at 30C was only 21% while the cuttings from stock plants grown at 21, 24, and 27C were 74, 65, and 66%, respectively (Fig. 2). Nodal location influenced the percentage of shoots that developed on plants from the 21, 24, and 27C treatments. In general, the basipetal nodes produced fewer shoots than the acropetal nodes.

The percentage of lateral shoots that developed from the second flush of cuttings was significantly higher than from the first flush of cuttings (Fig. 3). As in plants from the first flush of cuttings, the percentage of lateral shoots that developed in the 30C treatment was significantly lower than in the cooler temperature treatments. However, the percentage of lateral shoots developing on the second flush of cuttings at 30C was considerably higher than on the first flush of cuttings from the 30C treatment. Similar to the first flush of cuttings, the basipetal nodes developed a lower percentage of lateral shoots than the acropetal nodes.

Twenty to 30% of the nodes on the initial cuttings did not produce a cutting after pinching (Fig. 4). Of those nodes not producing a cutting, the majority of the nodes produced a shoot that was less than 3 cm in length. Less than 7% of the axillary buds failed to produce any shoot. On the first (Fig. 5) and second (Fig. 6) flush of cuttings, the majority of the nodes not producing a cutting was due to the lack of any shoot development. Eighty-three percent of the nodes on the first flush of cuttings removed from the stock plants grown at 30C did not produce any lateral shoot (Fig. 5).

Expt 2. Axillary buds rated at the time of cutting removal provided an accurate representation of lateral shoot development after propagation and pinching (Table 2). Eighty-four percent of the buds rated as viable prior to cutting removal developed a lateral shoot after propagation, while 0% of the nodes without a bud or with a completely necrotic bud at the time of cutting removal produced a lateral shoot. Thirty-eight percent of the buds that were partially necrotic or did not have a visible leaf developed a lateral shoot after propagation. The percentage of lateral shoots developed on the stock plant (control group) was considerably lower than on the propagated plants.

Expt 3. Transferring plants from 21 to 33/27C for 16 or 32 days reduced the percentage of viable axillary buds in Nodes 3 through 7 (Table 3), while plants transferred to the 33/27C treatment for 2 to 4 days had no effect on axillary bud viability. The first two leaves that unfolded after the initial transfer were not influenced by the 33/27C treatment, while Node 4 was the first node to be completely inhibited, i.e. 0% viability, in the 32-day treatment. One-hundred percent of the buds in the axils of leaves that unfolded prior to the initial transfer were viable (data not shown).

Expt. 4. Transferring plants from 33/27 to 21C resulted in an increase in the percentage of viable axillary buds (Fig. 7). Nodes -8 to -4 were not influenced by the temperature change, while nodes -3 to 0, i.e. the four youngest nodes to unfold prior to transfer to 21C, displayed an increase in bud viability. Sixty-two to 95% of the nodes unfolded after being transferred to 21C produced viable axillary buds.

Expt. 5. No significant differences of axillary bud viability were observed on the lateral shoots of plants grown at 21C and pinched on Day 1 (Trt. 1) or Day 35 (Trt. 2)(Fig. 8). Also, axillary bud development of plants grown at 33/27C for 35 days,

then pinched and placed at 21C on Day 35 (Trt. 4) was not affected by the high temperature treatment. However, only 22% of the nodes on plants pinched on Day 1 and grown at 33/27C for 35 days (Trt. 3) produced viable axillary buds.

Discussion

The results presented in this paper support the hypothesis that high temperatures inhibit axillary bud development in poinsettia, resulting in poor lateral shoot development. Visual observations of poinsettia leaf axils indicate that at times no differentiation occurred in the leaf axil, i.e. the axil is completely devoid of an axillary bud, while at other times bud initiation obviously occurred; however, the bud appeared as a mass of undifferentiated cells, indicating that bud development was inhibited. High temperatures, 30C or higher, interrupt or prevent axillary bud initiation and/or development. Poorly developed axillary buds or "blind" leaf axils do not produce lateral shoots. Axillary buds initiating and developing in the meristematic leaf axils, i.e. not yet unfolded leaves, are sensitive to high temperatures. By the time of visible leaf unfolding and development, axillary bud development was no longer sensitive to high temperatures. Viable axillary buds released from apical dominance develop into lateral shoots regardless of temperature. Consequently, the cause of poor branching in poinsettias is high temperature. For plants pinched shortly after propagation, the high temperatures occur during stock plant production, prior to propagation.

Expt 5. tested the effect of a high temperature treatment delivered to axillary bud primordia in the leaf axil of correlatively inhibited axillary buds (Trt. 4). We observed no difference in development of the buds from these primordia between the axillary buds

that developed after the correlatively inhibited buds were exposed to 21 and 33/27C for 35 days prior to pinching (Trts. 2 & 4). However, when plants were pinched and then exposed to high temperatures (Trt. 3), axillary bud development on the developing lateral shoot was poor. These results support the previous conclusion that high temperatures only affect actively initiating and developing axillary buds. Correlatively inhibited, viable buds will always produce a lateral shoot assuming correlative inhibition is removed, and the axillary bud primordia inside the correlatively inhibited bud are not affected by high temperatures. Thus, high temperatures that often occur during propagation will not influence branching of a plant pinched two to three weeks after the propagation phase ends.

The maximum percent axillary bud or lateral shoot development varied between experiments. For example, in Expt. 1, nearly 90% of the second flush of cuttings grown at 21 to 27C developed lateral shoots while only 70% of the first flush of cuttings grown at 21 to 27C branched well. The reason for the variability is not clear, although it is possibly due to an interaction with some other environmental factor. For example, this response may have been influenced by PPF, since the first flush of cuttings were exposed to $600 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 2 weeks, while the second flush was only exposed to $300 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The higher PPF may have increased plant temperatures, especially considering that fluorescent and incandescent lamps were used without a thermal energy filter (Faust and Heins, 1994).

Transferring stock plants from 33/27C to 21C resulted in an improvement of axillary bud development. The leaves which unfolded after transfer had 70% viable axillary buds. However, when stock plants were transferred from 21 to 33/27C for 32

days, three leaves unfolded after the transfer before bud development was affected. Perhaps the negative affect of high temperatures during early stages of bud development can be overcome by cooler temperatures later in development, and later stages of bud development are less sensitive to high temperatures.

Sixteen consecutive days at high temperatures were required to cause poor development of 'Eckespoint Redsails' in Expt. 4, however we expect that the response of poinsettias to high-temperature is quantitative. In other words, as temperature increases above the critical 30C, fewer days are likely to be required to elicit poor axillary bud development. Likewise, different degrees of high temperature sensitivity are shown by different poinsettia cultivars. Our observations indicate that 'Eckespoint Lilo' would likely require fewer days at high temperatures than 'Eckespoint Redsails', i.e. it is more sensitive to high temperatures. In separate experiments where plants were grown continuously at 33/27C, we have observed a reduction in lateral shoot development in a new cultivar, 'Eckespoint Freedom'. However, Freedom is considerably less sensitive to high temperatures than 'Eckespoint Redsails'.

Poor branching appears to be a result of at least two factors. First, apical dominance results in a decreasing percentage of lateral shoots developing on nodes positioned lower on the stem. Second and more importantly, incomplete development of axillary buds prohibits lateral shoot development after pinching. Our observations indicate that poor axillary bud development is the major problem that occurs during commercial production of 'Eckespoint Lilo' and 'Eckespoint Redsails'.

Poinsettias regenerated from heat treatment or suspension culture are poor branching. Observation of these plants indicates that, in general, the axillary buds are

well-developed (personal communication, Kirsten Rasmussen, Aaslev, Denmark), however after apex removal, only one or two shoots develop (personal communication, Walter Preil, Germany) indicating that these plants possess extremely strong correlative inhibition. Considerable research has been undertaken to identify the factor that promotes branching of poinsettia, however even if it is possible to identify the 'branching agent' proposed by Dole and Wilkins (1994), this solution may only solve the apical dominance problem, not the axillary bud development problem.

The goal for the commercial poinsettia grower is to produce viable axillary buds on the stock plants. The results from these experiments indicate that this can be accomplished by maintaining temperatures less than 30°C during stock plant production of cultivars such as Lilo and Redsails. Since outside temperatures often exceed 30°C, increased shading and misting plants with water may be beneficial at reducing plant temperatures. Bud viability on stock plants may be monitored prior to harvesting cuttings, to prevent the propagation of cuttings that will not produce well branched plants. The soft-pinch leaf removal technique (Berghage et al., 1989) can be used to improve branching by providing more nodes and thus more potential lateral shoots (Hughes et al., 1991) on shoots where basipetal buds are not properly differentiated. Ultimately, the problem of poor lateral branching in poinsettias must be resolved by the selection of cultivars not sensitive to or only slightly sensitive to high temperature-induced axillary bud inhibition.

LITERATURE CITED

- Berghage, Robert D., Royal D. Heins, Meriam Karlsson, John E. Erwin, and William Carlson. 1989. Pinching technique influences lateral shoot development in poinsettia. *J. Amer. Soc. Hort. Sci.* 114(6):909-914.
- Boonprakob, U., D. H. Byrne, R. E. Rouse, and D. M. J. Mueller. 1993. Anatomy of blind nodes in peach. *HortScience* 28(5):568.
- Dole, John M. and Harold F. Wilkins. 1991. Vegetative and reproductive characteristics of poinsettia altered by a graft-transmissible agent. *J. Amer. Soc. Hort. Sci.* 116(2):307-311.
- Dole, John M. and Harold F. Wilkins. 1992. In vivo characterization of a graft-transmissible free-branching agent in poinsettia. *J. Amer. Soc. Hort. Sci.* 117:972-975.
- Dole, John M. and Harold F. Wilkins. 1994. Graft-transmissible branching agent. In: *The scientific basis of poinsettia production*. Ed. E. Stromme. Agric. Univ. of Norway, Aas, Norway pp 45-48.
- Dole, J.M., H.F. Wilkins, and S.L. Desborough. Investigation on the nature of a graft-transmissible agent in poinsettia. *Can. J. Bot.* (in press).
- Faust, James E. and Royal D. Heins. 1992. High night temperatures do not cause poor lateral branching of chrysanthemum. *HortScience* 27(9):981-982.
- Faust, James E. and Royal D. Heins. 1993. Stop poor poinsettia branching. *Greenhouse Grower* 11(8):66-70.
- Faust, James E. and Royal D. Heins. 1994. Quantifying the influence of high-pressure sodium lighting on shoot-tip temperature. *Acta Hortic.* (in press).
- Hughes, John, Wayne Brown, Graeme Murphy, Jim Tsujita, and Theo Blom. 1991. The influence of pinching on poinsettia growth. *Greenhouse Canada* January pp21-23.
- Preil, W. and M. Engelhart. 1982. In vitro separation of chimeras by suspension cultures of *Euphorbia pulcherrima* Willd. *Gartenbauwissenschaft* 47:241-244.
- Preil, Walter. 1994. The study of chimerism, elimination of virus, and the induction of mutagenesis in poinsettia. In: *The scientific basis of poinsettia production*. Ed. E. Stromme. Agric. Univ. of Norway, Aas, Norway pp 57-63.

Stimart, Dennis P. 1983. Promotion and inhibition of branching in poinsettia in grafts between self-branching and nonbranching cultivars. J. Amer. Soc. Hort. Sci. 108(3):419-422.

Table 1. Air temperature and pinching treatments for Expt. 5.

Treatments:		
	Day 1	Day 35
1.	21C (Pinch)	21C
2.	21C	21C (Pinch)
3.	33/27C (Pinch)	21C
4.	33/27C	21C (Pinch)

Table 2. The relationship between the axillary bud rating made on a control group and a group of cuttings and the percentage of lateral shoots that developed after pinching. Five acropetal axillary buds on the lateral shoots of stock plants were given the following ratings: Rating 1. Well-developed bud: The bud was green, necrosis was not present, and the first leaf was visible. Rating 2. Poorly-developed bud: Necrosis covered all or part of the bud, and/or the first leaf was not visible. Rating 3. Axillary bud not visible: The leaf axil was devoid of a visible bud. Half of the lateral shoots were removed from the stock plants and propagated. The lateral shoots remaining on the stock plants and the propagated cuttings were then pinched simultaneously. The same leaf axils as before were later examined to determine whether or not a lateral shoot had developed.

Initial Rating	Percentage of Nodes Rated as Indicated Prior to Cutting Removal that Developed Lateral Shoots after Pinching	
	Control	Cuttings
1	45	83
2	5	38
3	0	0

Table 3. Effect of the duration of a high day temperature (33/27C) treatment on axillary bud development of 'Eckespoint Red Sails' poinsettias in the leaf axils of nodes 0 to 7. Node 0 refers the most newly unfolded leaf at the time of transfer, while nodes 1 through 7 represent the nodes to consecutively unfold after the start of the experiment.

Days at 33/27C	Node Number							
	0	1	2	3	4	5	6	7
0	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
4	100	100	100	100	100	100	100	100
8	100	100	100	100	100	85	100	100
16	83	100	83	83	38	38	67	83
32	100	100	100	83	0	0	0	0

Figure 1. The effect of temperature on the percentage of nodes developing lateral shoots on pinched 'Eckespoint Lilo' poinsettias. Rooted cuttings were placed into the indicated temperature treatments and pinched. Nodes were numbered from the basipetal (Node 1) to the acropetal (Node 5) part of the shoot.

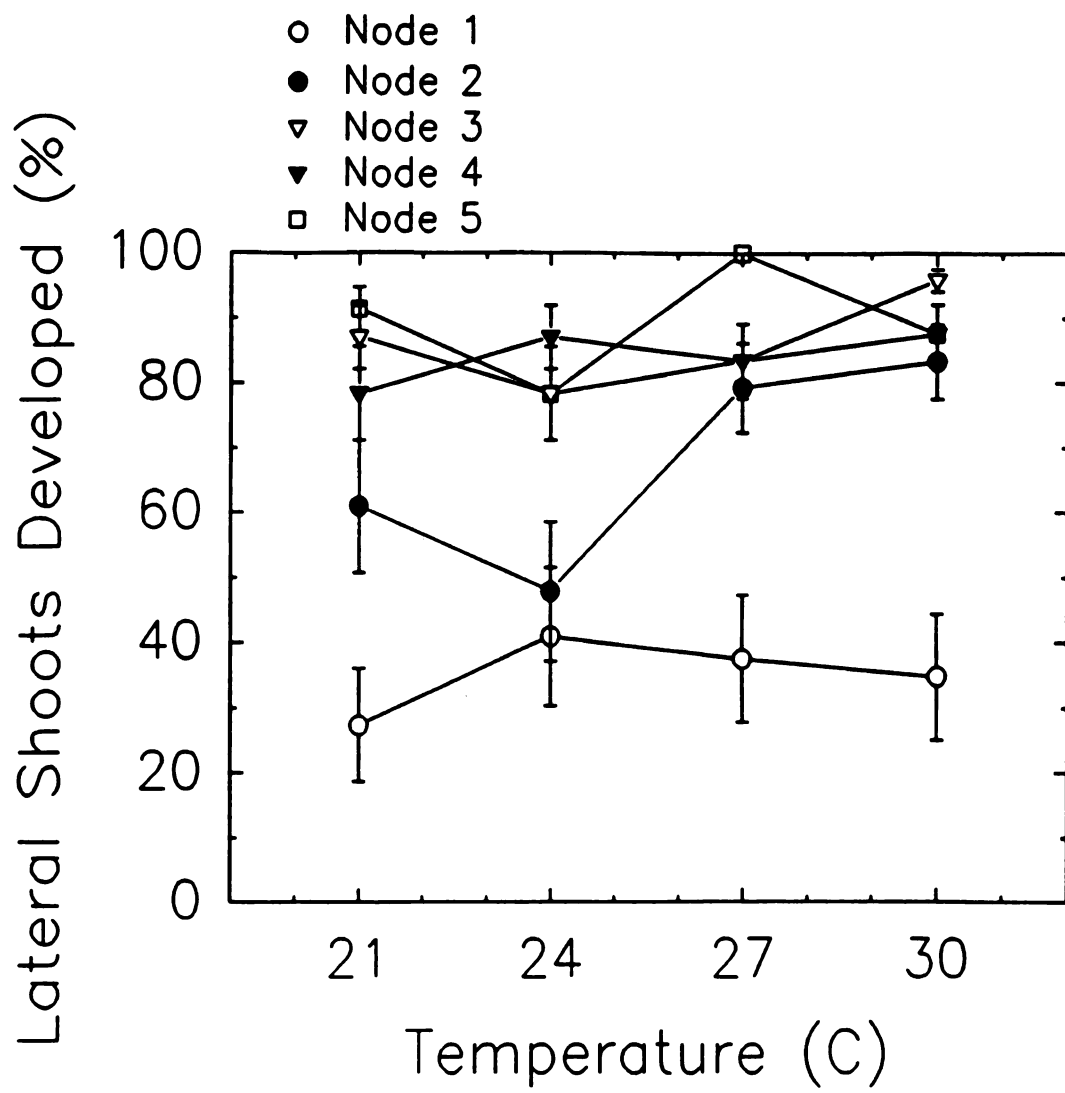


Figure 2. The effect of stock plant temperature on the percentage of nodes developing lateral shoots on the first flush of cuttings removed from the 'Eckespoint Lilo' stock plants, after the cuttings were propagated at 26C, and then grown at 21C. Nodes were numbered from the basipetal (Node 1) to the acropetal (Node 6) part of the cutting.

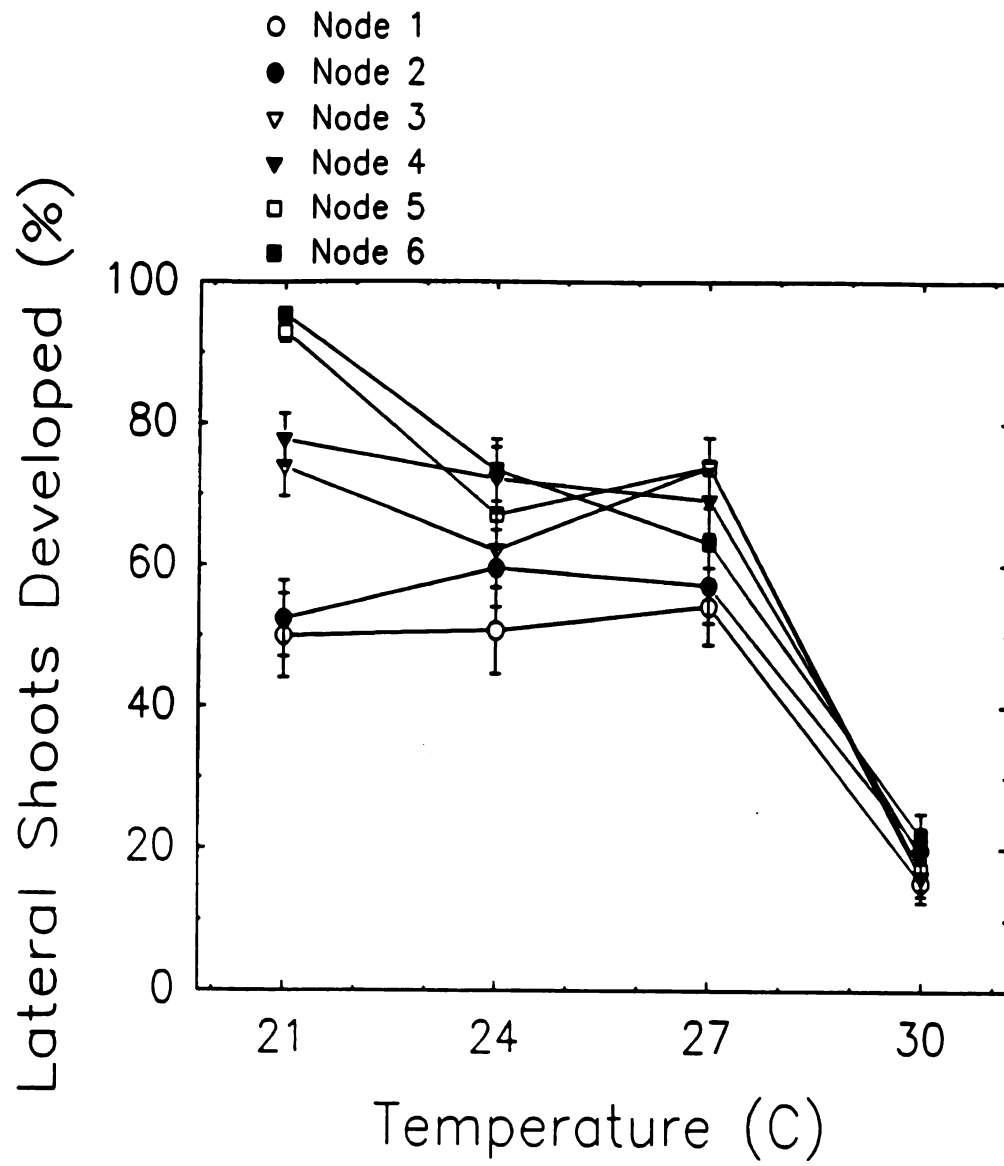


Figure 3. The effect of stock plant temperature on the percentage of nodes developing lateral shoots on the second flush of cuttings removed from 'Eckespoint Lilo' the stock plants, after the cuttings were propagated at 26C, and then grown at 21C. Nodes were numbered from the basipetal (Node 1) to the acropetal (Node 6) part of the cutting.

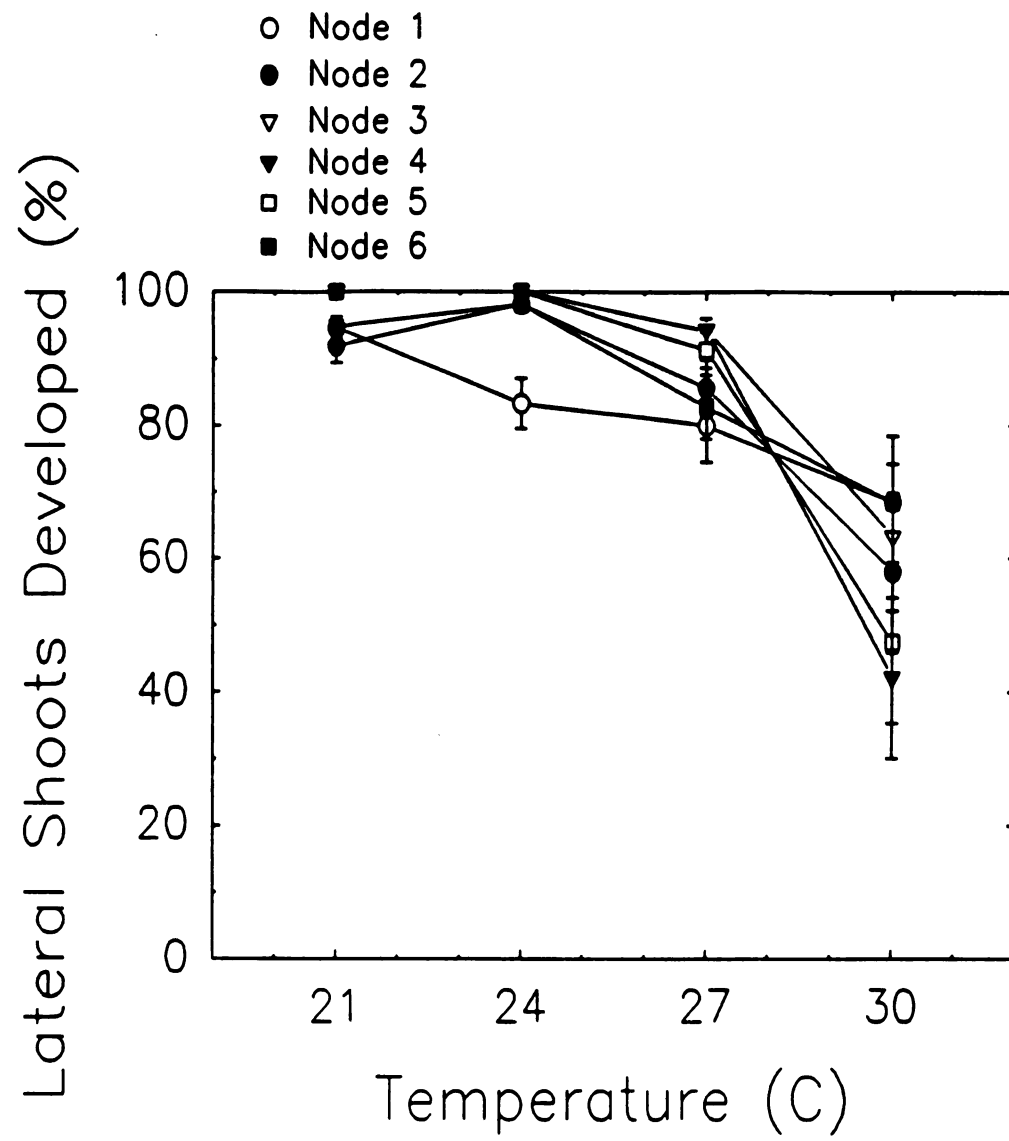


Figure 4. The effect of temperature on the percentage of nodes on 'Eckespoint Lilo' poinsettias that produced a lateral shoot > 3 cm in length, a lateral shoot < 3 cm in length, or no lateral shoot. Data represent the nodes shown in Figure 1.

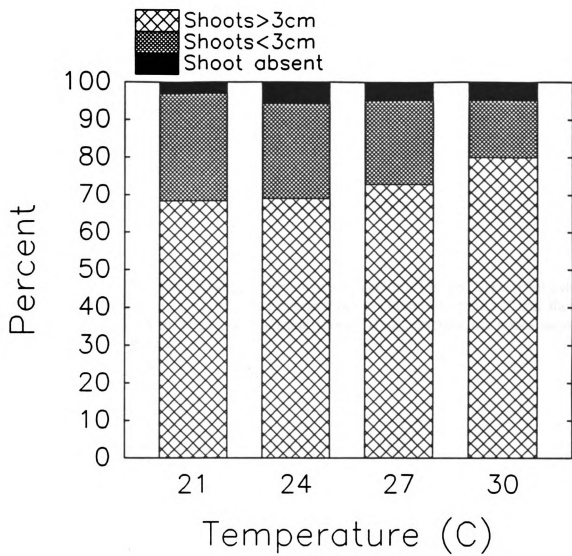
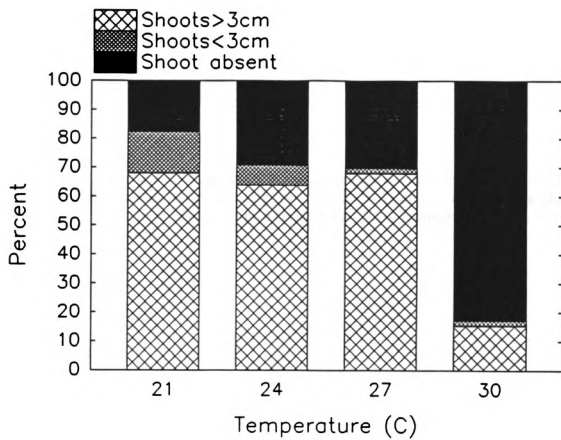


Figure 5. The effect of temperature on the percentage of nodes on 'Eckespoint Lilo' poinsettias that produced a lateral shoot > 3 cm in length, a lateral shoot < 3 cm in length, or no lateral shoot. Data represent the nodes shown in Figure 2.



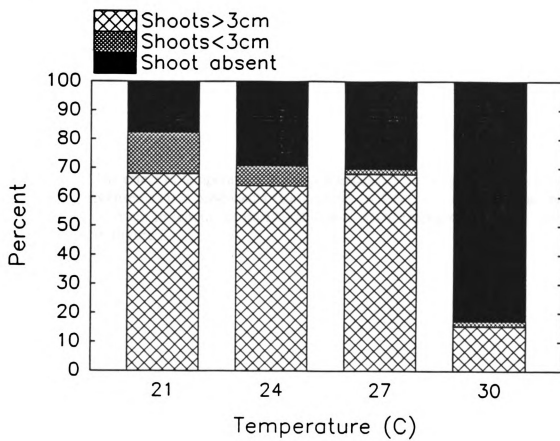


Figure 6. The effect of temperature on the percentage of nodes on 'Eckespoint Lilo' poinsettias that produced a lateral shoot > 3 cm in length, a lateral shoot < 3 cm in length, or no lateral shoot. Data represent the nodes shown in Figure 3.

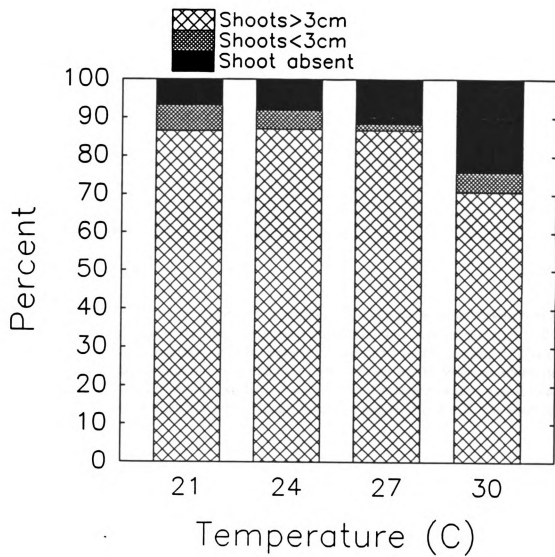


Figure 7. Effect of temperature on the axillary bud development of 'Eckespoint Red Sails' poinsettias initially grown at 33/27C and then transferred to 21C. Node 0 indicates the most recently unfolded leaf at the time of transfer. Negative node numbers indicate nodes whose leaves were unfolded prior to transfer, while positive node numbers indicate nodes whose leaves unfolded after transfer. (Node -7 was the oldest; Node +7, the youngest.)

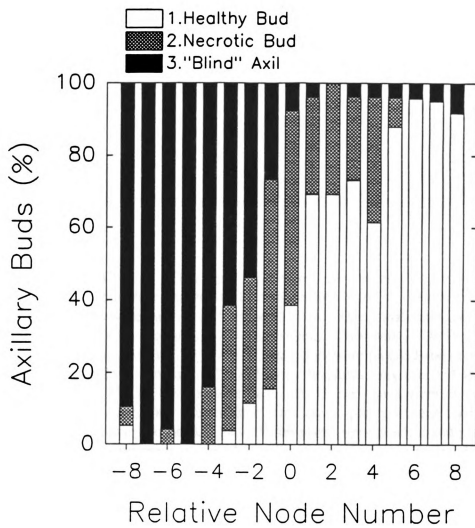


Figure 8. Effect of timing of the high day temperature and pinching treatments on axillary bud development of 'Eckespoint Red Sails' poinsettias. Treatment 1: Plants were pinched and placed at 21C on Day 1 and continued to grow at 21C for the remainder of the experiment. Treatment 2: On Day 1, plants were placed at 21C. On Day 35, the plants were pinched and continued to grow at 21C. Treatment 3: On Day 1, the plants were pinched and placed into the 33/27C environment. On Day 35, the plants were moved to the 21C environment. Treatment 4: On Day 1, plants were placed into the 33/27C environment. On Day 35, the plants were pinched and placed into the 21C environment. Node 1 refers to the first node to develop on the lateral shoot after pinching.

MICHIGAN STATE UNIV. LIBRARIES



31293014110583