Non–Water–Stressed Baseline as a Tool for Dynamic Control of a Misting System for Propagation of Poinsettias

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ABSTRACT. *A technique is presented for dynamically adjusting misting intervals during propagation of vegetative cuttings. A crop setpoint temperature for activation of misting was defined by a "non–water–stressed baseline" concept, using infrared thermometry to acquire canopy temperature for plant feedback. The critical crop setpoint temperature was calculated from instantaneous values of air temperature, incident radiation, and air vapor pressure deficit (VPD_{air}). Misting was activated when the actual crop temperature exceeded the critical crop setpoint temperature. The dynamic control was shown to have the potential to reduce the amount of applied water from 9 to 12 times during low levels of VPD_{air} (0.8 to 1.1 kPa) and under dark conditions when compared to a conventional on/off misting interval of 5 s each 5 min. In addition, misting intervals were reduced three–fold, from 30 to 11 min, when incident radiation increased from 0 to 100 W m^{-2} and VPD_{air} was maintained in the range from 2.3 to 2.6 kPa. Further increases in radiation levels from 200 to 300 W m^{-2} did not appreciably change the misting frequency. The dynamic misting control provides a large potential for increasing the period between misting events under dark conditions and with low to moderate levels of incident radiation. It automatically increases misting frequency as VPD_{air} and/or radiation increase.*

Keywords. Poinsettia, Vegetative propagation, Misting systems, Infrared thermometry, Vapor pressure deficit.

P oinsettia plants are a popular commodity for Christmas–time marketing in the United States, with 1997 wholesale value of over $222 M (USDA, 1998). Commercial poinsettia production is initiated with propagation of vegetative terminal cuttings and requires 3 to 4 weeks to produce a well–developed root system (Ecke et al., 1990).

The majority of poinsettia propagation systems in the U.S. use fixed misting or movable booms to apply water. Misting control is generally accomplished with interval timers, which activate solenoid valves. Typical on/off intervals of 5 s each 5 min are empirically recommended as a general rule. Although these on/off intervals are acceptable under moderate radiation levels, the cuttings may receive too much water at night and during cloudy days, and perhaps insufficient water under the highest levels of radiation. Excess water leaches nutrients from the plants and can reduce root–zone oxygen.

Remotely measured canopy temperatures, obtained with infrared thermometry, have been used successfully by many researchers to schedule irrigation of rooted plants. The validity of the method is associated with the fact that canopy temperature is an outcome of the energy balance (Berliner et

al., 1984; Stanghellini, 1985). Thus, because sensible heat flux from a canopy is coupled with latent heat flux, canopy surface temperature increases as transpiration decreases.

Although artificial leaf sensors (Sigrimis and Papageor-giou, 1994), "virtual" leaf sensors (Sigrimis et al., 2000), leaf water potential, or stomatal resistances (Zolnier, 1999) can also be used to assess plant water status, these techniques have difficulties for implementation. They provide only localized measurements, they are invasive and time consuming, and they require a large number of samples so that the results can be extrapolated for the whole canopy (Peñuelas et al., 1992). In contrast, methods that use plant feedback and inputs from the physical environment, such as solar radiation, air temperature, and relative humidity, can overcome the disadvantages associated with point measure-ment techniques, offering the possibility of operating misting systems in an automated and dynamic fashion.

Several approaches have been used to implement infrared thermometry for irrigation management. A simplified method was proposed by Idso et al. (1981). The canopy–air temperature differential ($t_{crop} - t_{air}$) for well–watered plants was estimated from air vapor pressure deficit (VPD_{air}) only, eliminating the need for measurements or estimates of the energy balance components. This method incorporates all environmental effects into two constants of a linear equation, which can be obtained from experimental data. Because of the linearity of this relationship for most plants and the fact that it was obtained for well–watered crops, it was denoted "non–water–stressed baseline."

One of the problems in obtaining the non–water–stressed baseline under greenhouse conditions is associated with uncontrolled moving shade patterns caused by the greenhouse structure, which impose spatial variation on the incident radiation. In addition, on partially cloudy days, dynamic changes in radiation also affect the thermal environment of the greenhouse. Thus, any changes in the environmental conditions will affect the magnitude of the energy balance components and, consequently, the magni-

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tude and spatial variation of the canopy–air temperature differential.

To precisely evaluate the effect of radiation and air vapor pressure deficit on the canopy–air temperature differential, it is necessary to obtain the non–water–stressed baseline under steady–state conditions, which is possible using environmental chambers in which radiation and air vapor pressure can be controlled independently. Environmental chambers have been designed and constructed to implement canopy surface temperature control (Bates and Bubenheim, 1994), to reduce or control vapor pressure deficit during summer conditions (Mach, 2000; Tao, 1998), and to develop vapor pressure deficit control strategies for plant production (Gates and Mach, 2000; Mach et al., 1999, 2000; Zolnier et al., 2000).

The objectives of the present study were two–fold:

1) To develop a relationship between canopy–air temperature differential ($t_{crop} - t_{air}$) as a function of incident radiation and air vapor pressure deficit (VPD_{air}), which can be used as a setpoint to control misting intervals for poinsettia propagation.

2) To evaluate a dynamic misting control technique under different radiation and air vapor pressure deficit combinations to provide general guidelines to be applied in greenhouses where misting is triggered by a timer.

THEORY

NON–WATER–STRESSED BASELINE

A theoretical equation for canopy–air temperature differential was presented by Jackson et al. (1981), based on a total (sensible + latent) energy balance at the canopy level:

$$(t_{crop} - t_{air}) = \frac{(R_n - G)(r_h + r_{csf})}{\rho_{air}\, c_{pa}\left(1 + \frac{\Delta}{\gamma} + \frac{r_{csf}}{r_h}\right)} - \frac{VPD_{air}}{\gamma\left(1 + \frac{\Delta}{\gamma} + \frac{r_{csf}}{r_h}\right)} \quad (1)$$

Equation 1 was used to develop a crop water stress index (CWSI) based on the relationship between canopy temperature and air vapor pressure deficit (Jackson et al., 1981). Idso et al. (1981) proposed a modification by assuming that R_n, G, r_{csf}, and r_h are constants during certain conditions (small variability in solar radiation, such as observed on clear or completely overcast days, and steady air velocity). For these conditions, the canopy–air temperature differential for well–watered plants depends only on plant species (through the constant r_h and r_{csf}) and can be estimated from air vapor pressure deficit measurements. Under these assumptions, equation 1 can be simplified to:

$$(t_{crop} - t_{air}) = a - b(VPD_{air}) \quad (2)$$

which yields

$$a = \frac{(R_n - G)(r_h + r_{csf})}{\rho_{air}\, c_{pa}\left(1 + \frac{\Delta}{\gamma} + \frac{r_{csf}}{r_h}\right)} \quad (3)$$

and

$$b = \frac{1}{\gamma\left(1 + \frac{\Delta}{\gamma} + \frac{r_{csf}}{r_h}\right)} \quad (4)$$

To be applied to irrigation scheduling, the non–water–stressed baseline technique, developed by Idso et al. (1981), requires experimental evaluation of a and b in equation 2. These constants represent the effect on ($t_{crop} - t_{air}$) of high radiant loads and of specific values for the other parameters given in equation 1. Although this simplified approach can be used for misting control under constant radiation levels, such as dark conditions, a slight modification is necessary to account for the variable radiation effect from sunrise until sunset. Thus, by introducing the incident radiation for daylight conditions, equation 1 can be rewritten as:

$$(t_{crop} - t_{air}) = a(R_i) - b(VPD_{air}) \quad (5)$$

When applied under greenhouse conditions, this equation assumes that long–wave radiation exchanges are negligible. In addition, by assuming that the heat flux into the propagation medium (G) can be neglected, the constant a now represents the following parameters:

$$a = \frac{(1-r)(r_h + r_{csf})}{\rho c_{pa}\left(1 + \frac{\Delta}{\gamma} + \frac{r_{csf}}{r_h}\right)} \quad (6)$$

where r is the reflection coefficient (albedo). The constant b remains as shown in equation 4.

SETPOINT FOR MISTING CONTROL

For plants propagated under periodic misting, the standard deviation of leaf temperature decreases immediately after the water is applied and then increases progressively until a maximum value is achieved (Zolnier, 1999). This behavior can be seen by plotting the standard deviation of leaf temperature, measured with thermocouples, as a function of time.

The two main reasons for the oscillatory behavior of the standard deviation are differences of water storage capacity and the magnitude of the components of the energy balance among leaves. When the top of the canopy becomes partially wetted, the rate of evapotranspiration is not uniform, resulting in differences of temperature among leaves. Leaf angle with respect to solar angle also affects the variation in leaf temperatures.

The surface temperature of a partially wetted canopy represents an instantaneous average of all leaves surveyed by an infrared sensor. This does not account for the fact that, for some of the leaves, the canopy–air temperature differential ($t_{crop} - t_{air}$) will possibly be above the non–water–stressed baseline. To be applied to misting control, the baseline needs to be associated with a probability–based threshold value, which can be determined by incorporating the maximum standard deviation of leaf temperature into equations 2 and 5.

By applying the "non–water–stressed baseline" concept, an environmentally sensitive setpoint for misting control can be defined by using a threshold value at the 5% level of significance. For dark conditions, the setpoint can be evaluated by:

$$t_{set} = -t_{0.05}\, std_{max} + t_{air} + a - b\, VPD_{air} \quad (7)$$

For daylight conditions, it can be evaluated by:

$$t_{set} = -t_{0.05}\, std_{max} + t_{air} + a\, R_i - b\, VPD_{air} \quad (8)$$

Theoretically, it is expected that at most 5% of the area surveyed by the infrared sensor exceeds the critical crop temperature given by equations 7 and 8. Therefore, this setpoint represents an upper–bound temperature for dynamic misting control. The 5% level of significance was chosen because unrooted poinsettia cuttings are extremely sensitive to water shortage and cannot be compared to fully rooted plants, which can tolerate water stress for several hours. Depending on the environment, water shortage on the leaf surface for a few minutes can severely affect cutting survival (Erstad and Gislerød, 1994; Ecke et al., 1990).

Zolnier (1999) conducted an experiment to obtain a relationship between VPD_{air} and std_{max} for dark and light conditions. The regression equations obtained from that experiment allow std_{max} estimates from VPD_{air} measurements, eliminating the need for thermocouple installation. For dark conditions, the adjusted coefficient of determination was 0.95 and std_{max} can be found by:

$$std_{max} = -(0.43 \pm 0.14) + (1.13 \pm 0.07)VPD_{air} \qquad (9)$$

For light conditions ($r^2_{adj} = 0.79$), std_{max} can be estimated by:

$$std_{max} = (1.18 \pm 0.02)VPD_{air} \qquad (10)$$

The maximum standard deviation was obtained from 5 thermocouples, and the corresponding t–value for misting control is 2.132, based on four degrees of freedom and a one–tailed t–distribution. Another t–value should be applied when a different method or number of thermocouples is used to obtain the standard deviation.

MATERIALS AND METHODS

Different combinations of incident radiation and air vapor pressure deficit were used to validate the dynamic method. A complete description of the experimental chambers and experimental procedures was presented by Zolnier (1999).

EXPERIMENT I: NON–WATER–STRESSED BASELINE PARAMETERS

Two experiments, designated "dark" and "light", were performed on the three groups of fully rooted plants. Each lot formed a dense square canopy (7 rows × 7 columns = 49 cuttings) with area of approximately 0.47 m^2. These experiments were carried out as a completely randomized design with 3 replications (3 environmental chambers). Levels of incident radiation and air vapor pressure deficit were combined according to a two–way factorial treatment structure. In the dark experiment, cuttings received five different levels of air vapor pressure deficit (0.5, 1.0, 1.5, 2.0, and 2.5 kPa). In the 6 × 3 radiation–VPD_{air} factorial experiment, plants were randomly subjected to six levels of incident radiation (50, 100, 150, 200, 250, and 300 W m^{-2}) and three levels of air vapor pressure deficit (1.5, 2.0, and 2.5 kPa). Incident radiation was provided by three different sources of artificial radiation. In the range from 50 to 150 W m^{-2}, only fluorescent lamps and high–pressure sodium bulbs were used. In the range from 200 to 300 W m^{-2}, high–pressure sodium radiation was intensified and incandescent bulbs were used as supplemental light.

The leaf area index (LAI) was estimated by measuring length and width of all leaves of 16 cuttings randomly sampled from each chamber. These dimensions were taken at the end of the experiment, which lasted approximately 1 week. The measurements were used in a non–linear equation (Zolnier, 1999) to estimate the LAI for the three groups of plants, resulting in the following values: 2.60, 2.91, and 3.11.

EXPERIMENT II: DYNAMIC CONTROL OF THE MISTING SYSTEM

This study was carried out with two lots of 49 homogeneous unrooted cuttings. Potted stock plants were transported to the lab, where cutting excision took place. Cuttings were randomly excised one at a time and then placed in the propagation medium, which consisted of expanded plastic foam blocks (Oasis™ rootcubes, Model 5245, Smithers–Oasis, Kent, Ohio). While the cuttings were being placed in the medium, low levels of artificial radiation and air vapor pressure deficit were maintained in the environmental chambers to minimize transpirational water loss.

Two environmental chambers (replicates), denoted in this experiment as Chambers 1 and 2, were used to examine the ability of the temperature–based misting control to adjust misting intervals under different levels of incident radiation and ranges of VPD_{air}. Under dark conditions, four ranges of VPD_{air} were applied (0.8 – 1.1; 1.3 – 1.6; 1.8 – 2.1, and 2.3 – 2.6 kPa). Under light conditions, three levels of incident radiation (100, 200, and 300 W m^{-2}) were combined with three ranges of VPD_{air} (1.3 – 1.6; 1.8 – 2.1, and 2.3 – 2.6 kPa). Different environmental combinations were applied in a random order.

Canopy surface temperature was monitored with one infrared sensor installed outside each environmental chamber. Additionally, a temperature and relative humidity probe was installed in each environmental chamber for adjusting the desired range of VPD_{air}. Silicon–cell pyranometers were used for adjusting incident radiation and were then removed from the chambers. Data collection started 1 h after the new environmental treatment was applied and continued for 3 h. (Instrumentation is referenced under "Data Acquisition.")

A relay control board (Model ERA–01, Keithley Metrabyte, Cleveland, Ohio) was connected to the data acquisition board installed in the computer to activate solenoid valves. To provide the "maximum canopy surface water storage capacity," as measured by digital scales (Model B50S05, Ohaus Corp., Florham Park, N. J.), the duration of each misting event was adjusted to 5 s approximately. Water pressure in the supply line oscillated between 138 and 414 kPa (20 and 60 psi) during each misting event. Leak prevention devices were connected to the misting nozzles to prevent dripping and to shut down the mist when the pressure reduced to 138 kPa.

Rooting media moisture content was adjusted to approximately 50 g/rootcube cell at the beginning of each environmental treatment. Because excess water was not removed during treatments, moisture content of the media increased from 50 g/rootcube cell to a maximum value depending on the difference between applied water and evapotranspiration. The maximum value in the experiment was 57 g/rootcube cell, and it was observed when cuttings were subjected to 200 W m^{-2} and 2.5 kPa. At the end of each

environmental treatment, excess water was drained by capillary mats and the moisture content returned to 50 g/rootcube cell, which is approximately equivalent to a water tension of 5 cm of water.

DATA ACQUISITION

A PC–based data acquisition and control system was designed to input analog signals from the sensors, which were connected to a data acquisition board (Model DAS–1601, Keithley Metrabyte, Cleveland, Ohio). Data were sampled at a frequency of 1 sample/s and stored at intervals of 1 min, where each data record represented the average of the last 5 s.

Canopy surface temperature was measured with a 15° field of view infrared temperature transducer (Model 4000.4GL, Everest Interscience Inc., Tucson, Ariz.). Two holes were provided on the acrylic walls of each environmental chamber so that the sensor could be used to measure the crop temperature while being positioned outside the chambers. In the first experiment, one infrared sensor was periodically hand–held at 30° from the horizontal in order to measure the crop temperature in each environmental chamber. The estimated target area used for canopy temperature measurement was 0.13 m², approximately. Even though measurements could not be obtained at the same time in both chambers, only differences within the precision of the sensors were observed during each environmental treatment because of the steady–state conditions in the lab.

In the second experiment, which was carried out to evaluate the environmental performance of the temperature–based misting control, two infrared thermometers were permanently positioned at 45° from the horizontal in two environmental chambers. In this case, the sensors were installed at the upper hole to prevent the sensor from receiving water droplets delivered by the misting nozzles.

According to Robinson and Davis (1972), emissivity of water can be assumed as 0.98, which is the same value used for crop temperature measurements performed under non–wet conditions. Consequently, temperature measurements under partially wetted conditions were also carried out with the emissivity set to 0.98 on the infrared sensor.

Artificial radiation was measured with silicon–cell pyranometers (Model LI 200SA, Licor Inc., Lincoln, Nebr.). For experiments performed under misted conditions, the pyranometers were used to adjust incident radiation at the beginning of the experiment and then were removed from the chambers. Under non–misted conditions, the sensors were permanently installed in the center of each environmental chamber with the incident radiation sensor positioned at approximately 10 cm above the canopy level. The silicon–cell pyranometers were individually calibrated in each chamber for all sources of light against an Eppley pyranometer, which was previously calibrated at the Eppley laboratory. Due to irregular radiation flux density, a spatial calibration was also performed in each chamber by measuring the incident radiation with the Eppley pyranometer in five different points at the top of the canopy.

A combination probe for temperature and relative humidity measurements (Model HT46W50, Rotronic Instrument Corp., Huntington, N.Y.) was enclosed in an aspirated radiation shield and installed in each environmental chamber at 0.4 m above the canopy surface level. The probe was inserted into the radiation shield through a small hole (2

cm in diameter) drilled on the acrylic wall. The probe was positioned at this level to prevent both the shield and the probe from receiving large water droplets sprayed by the misting nozzles. Additionally, for experiments carried out under misted conditions, the shield was protected by a thin layer of cloth to obstruct small droplets transported by the convection currents in the chambers.

RESULTS AND DISCUSSION

EXPERIMENT I: NON–WATER–STRESSED BASELINE PARAMETERS

The relationship between canopy–air temperature differential and air vapor pressure deficit during dark conditions is presented in figure 1. A linear relation was observed from 0.5 to 2.5 kPa, with the non–water–stressed baseline for poinsettia cuttings given by:

$$(t_{crop} - t_{air}) = -(0.27 \pm 0.07) - (0.31 \pm 0.04)VPD_{air} \qquad (11)$$
$$r^2_{adj} = 0.77$$

where the standard errors are shown with each regression coefficient and the units for temperature and VPD_{air} are °C and kPa, respectively.

The non–zero intercept can be explained by differences in the accuracy of the infrared and air temperature measurements. However, this difference is within the expected accuracy range of those sensors. Theoretically, under steady–state conditions and no radiative and evaporative cooling, the crop temperature should be equal to the air temperature and the baseline would pass through the origin.
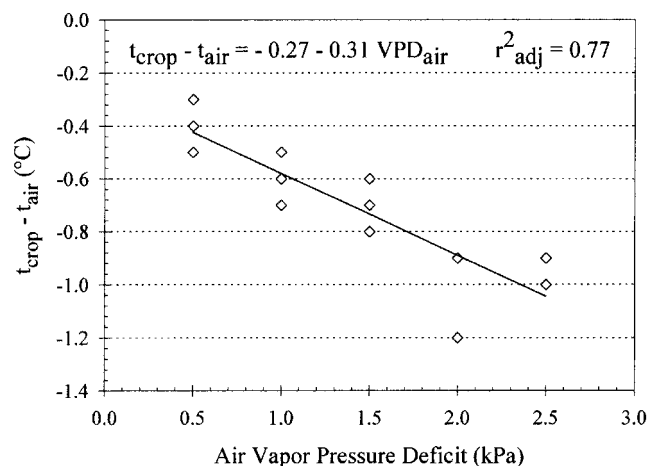

Figure 1. Canopy–air temperature differential as a function of air vapor pressure deficit for fully rooted poinsettia cuttings under dark conditions.

Under dark conditions the canopy–air temperature differential was always negative because of the latent heat transfer by convection, showing that the crop was a sink for sensible heat. The absolute values of $(t_{crop} - t_{air})$ increased when VPD_{air} changed from 0.5 to 2.5 kPa, indicating more evaporative cooling at higher VPD_{air} levels.

The effects of incident radiation and VPD_{air} on the canopy–air temperature differential during light conditions are represented by equation 5. In the range from 50 to 300 W m^{-2}, the parameters of equations 4 and 6 were only slightly

influenced by environmental conditions and can be treated as constants. Consequently, the non–water–stressed baseline of fully rooted poinsettia cuttings during light conditions is given by:

$$(t_{crop} - t_{air}) = (0.91 \pm 0.04) \times 10^{-2} R_i - (0.85 \pm 0.03)VPD_{air} \quad (12)$$
$$r^2_{adj} = 0.93$$

where the units for temperature, incident radiation (R_i), and VPD_{air} are °C, W m^{-2}, and kPa, respectively.

Incident radiation and air vapor pressure deficit have opposite effects coefficients. The variation of ($t_{crop} - t_{air}$) during light conditions is depicted in figure 2. Comparisons of the results for dark and light conditions show that the relationship between ($t_{crop} - t_{air}$) and VPD_{air} is still linear for light conditions, but the radiation factor yielded a displacement of the non–water–stressed baselines, as would be expected.

Comparison of the slopes of regression lines in figures 1 and 2 indicates that the effect of VPD_{air} on the canopy–air temperature differential is intensified under light conditions due to reduction of r_{csf} (Zolnier, 1999). Differences in the slopes of the baselines suggest that higher levels of VPD_{air} will result in stronger evaporative cooling during light conditions because of stomatal opening. In contrast, the displacement of the non–water–stressed baselines is explained by the radiation effect.

It is worth noting that equations 11 and 12 (for dark and light conditions, respectively) were obtained in controlled environments where air velocity was 0.5 m s^{-1}, approximately. Comparisons between field and laboratory conditions of the VPD_{air} effect on ($t_{crop} - t_{air}$) are difficult to perform. Generally, air velocity is not always specified, and it is never constant in the natural environment. In field scale, the non–water–stressed baseline is usually determined during midday hours when incident radiation reaches its maximum value, and thus it is presented as a function of VPD_{air} exclusively.

Idso (1982) presented the results of the linear regression between ($t_{crop} - t_{air}$) and VPD_{air} for 26 different species. Measurements were carried out under clear sky conditions, but the air velocity was not specified. Except for four crops, the correlation coefficient (r) between ($t_{crop} - t_{air}$) and VPD_{air} was above 0.90, showing that ($t_{crop} - t_{air}$) was affected linearly by VPD_{air}. The slope of the regression lines varied from –1.23 to –3.25 for barley at post–heading and wheat at pre–heading stage, respectively. Under the assumption that other environmental factors, such as incident radiation and air velocity, were identical during the measurements, these values suggest that large differences between the parameters of the non–water–stressed baseline can be found among crops.

Similarly, Olufayo et al. (1993) evaluated the effect of air vapor pressure on the canopy–air temperature differential of sorghum (*Sorghum bicolor* L. Moench) at solar noon during clear days and with wind speed < 3 m s^{-1}. The slope of the regression line between VPD_{air} and ($t_{crop} - t_{air}$) was –1.88. Results of regression analysis for all data (91 measurements) indicated a coefficient of determination (r^2) of 0.71.
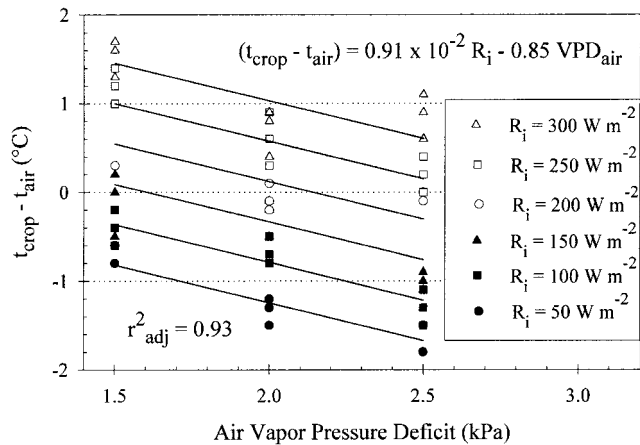

Figure 2. Canopy–air temperature differential as a function of air vapor pressure deficit for well–watered fully rooted poinsettia cuttings under light conditions. Each level of air vapor pressure deficit is associated with 6 levels of incident radiation (50, 100, 150, 200, 250, and 300 W m^{-2}) and three replicates.

Compared to the slope of the regression lines presented in figure 2, which was –0.85 (± 0.03), the results presented in the previous research clearly indicated that the effect of VPD_{air} on ($t_{crop} - t_{air}$) was enhanced under field conditions. Larger canopy–air temperature differentials can be attributed to differences of transpiration among crops, which are in turn regulated by the canopy stomatal resistance and the boundary layer resistance. Typically, air velocities under open field conditions are much higher than 0.5 m s^{-1} and therefore intensify the evapotranspiration process. In addition, Baille et al. (1994) concluded that poinsettia crops present very low evapotranspiration rates compared to other greenhouse pot plant crops. Therefore, differences in slope of the regression lines can also be explained by the xerophytic nature of poinsettia plants.

EXPERIMENT II: DYNAMIC CONTROL OF THE MISTING SYSTEM

Misting Intervals Under Dark Conditions

The effect of misting on crop and air temperatures under dark conditions for four ranges of VPD_{air} (0.8 – 1.1; 1.3 – 1.6; 1.8 – 2.1, and 2.3 – 2.6 kPa) is shown in figure 3. Periodic misting prevents the crop temperature from increasing above the dynamic setpoint. Dynamic misting intervals were the result of the canopy temperature–based control, with the setpoint estimated from equation 7. It can be observed that air and crop temperatures, as well as air vapor pressure deficit, are perturbed by periodic misting.

The dynamic misting control technique based on crop temperature was sensitive to imposed ranges of air vapor pressure deficit during dark conditions. Misting was activated only 3 to 4 times during three hours under low levels of VPD_{air} (0.8 to 1.1kPa). In contrast, the cuttings would be subjected to a total of 36 misting events during the same period if a conventional static control approach was used instead. In greenhouse conditions, misting intervals of 5 min have been typically used for poinsettia propagation (Ecke et al., 1990). Consequently, the temperature–based misting control has the potential of reducing the amount of applied water from 9 to 12 times under low levels of VPD_{air}. This

analysis is based on the assumption that misting is continued at night for plants propagated under conventional static control.

Misting frequency increased progressively with increased levels of air vapor pressure deficit, indicating the sensitivity of the dynamic control to environmental changes. Misting was activated 6 times during the 3–h period when VPD_{air} ranged from 2.3 to 2.6 kPa. In general terms, this strategy represents one misting cycle each 30 min.

These results can be used to define misting intervals for cuttings propagated with conventional static control. Misting every 30 min would be satisfactory because it is unlikely that VPD_{air} will be above 2.5 kPa at this time. During cold winter nights, air vapor pressure deficit in the heated greenhouse reaches only 1.5 kPa (Hanan, 1998).

Misting Intervals Under Light Conditions

The effect of misting on crop and air temperatures with incident radiation constant at 100, 200, and 300 W m^{-2} is presented in figures 4, 5, and 6, respectively. These levels of incident radiation were combined with three ranges of VPD_{air} (1.3 – 1.6, 1.8 – 2.1, 2.3 – 2.6 kPa). Misting intervals were defined by the canopy temperature–based control with the setpoint estimated from equation 8.

Comparison of the results for high VPD_{air} (2.3 to 2.6 kPa) under dark and light conditions illustrates a nonlinear influence of incident radiation on misting intervals. The misting was activated only 6 times during the 3–h period in each environmental chamber under dark conditions. In contrast, misting was activated 16 and 17 times in chambers 2 and 1, respectively, when incident radiation was held constant at 100 W m^{-2}. However, the canopy temperature–based control was insensitive to further increases in incident radiation. The approximate number of misting cycles in the 3–h period was found to be 16 and 17 with incident radiation at 200 and 300 W m^{-2}, respectively. Therefore, the temperature setpoint must be readjusted for improving the sensitivity of this technique under variable levels of incident radiation.

The dynamic misting strategy developed in this research can be used to better match water use requirements with severity of environment in which cuttings are placed. Because most poinsettia cuttings are propagated during late summer with peak radiation loads, the proposed dynamic method has potential for water savings without compromising propagation efficiency or vigor (Zolnier et al., 1999).

Summary and Conclusions

Incident radiation and air vapor pressure deficit (VPD_{air}) had opposite effects on the canopy–air temperature differential ($t_{crop} - t_{air}$), as indicated by the signs of the regression coefficients. Comparisons of the results for dark and light conditions showed that the relationship between ($t_{crop} - t_{air}$) and VPD_{air} is linear for light conditions, but the radiation factor yielded an offset from the non–water–stressed baselines obtained in dark conditions.

The dynamic control has the potential of reducing the amount of applied water from 9 to 12 times under low levels of VPD_{air} (0.8 to 1.1 kPa) during dark conditions. Under higher VPD_{air} levels (2.3 – 2.6 kPa), the misting intervals were approximately 30 min. Information presented in this research can also be used to recommend misting intervals for cuttings propagated in systems controlled by the static approach. For example, misting intervals could be set to 30 min at night, regardless of the environmental conditions.

Experimental results suggest that misting intervals determined by this dynamic temperature–based control technique are close to those generally mentioned in the literature for conventional static control. Thus, it can be concluded that the empirical value of 5 min for misting intervals might be acceptable for moderately high levels of radiation and VPD_{air} but not for dark conditions or the mild radiation typical during cloudy days, early morning, and late afternoon. It was observed that misting intervals were reduced from 30 to 11 min when incident radiation increased from 0 to 100 W m^{-2} and VPD_{air} was maintained in the range from 2.3 to 2.6 kPa. However, further increases in radiation levels up to 300 W m^{-2} did not appreciably change the misting intervals.

These results demonstrate that the dynamic misting control has a potential for increasing the period between misting events under dark conditions and with low to moderate levels of incident radiation. This will enhance the water usage efficiency in the propagation system and therefore reduce the quantity of runoff to be treated.

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LIST OF SYMBOLS

c_{pa} = specific heat of air at constant pressure (J kg^{-1} °C^{-1})

G = propagation medium heat flux (W m^{-2})

r = reflection coefficient (albedo), dimensionless

r_{csf} = canopy surface resistance (s m^{-1})

r_h = resistance to sensible heat transfer by convection for the whole canopy (s m^{-1})

R_i = incident radiation (W m^{-2})

R_n = net radiation at the canopy level (W m^{-2})

std_{max} = maximum standard deviation of leaf temperature at the top of the canopy (°C)

t_{set} = crop temperature setpoint for misting control (°C)

$(t_{crop}-t_{air})$ = canopy–air temperature differential (°C)

$t_{0.05}$ = critical value for one–sided t–distribution at the 5% level of significance.

VPD_{air} = air vapor pressure deficit (kPa)

ρ_{air} = density of air (kg m^{-3})

Δ = slope of the saturated vapor pressure curve (Pa °C^{-1})
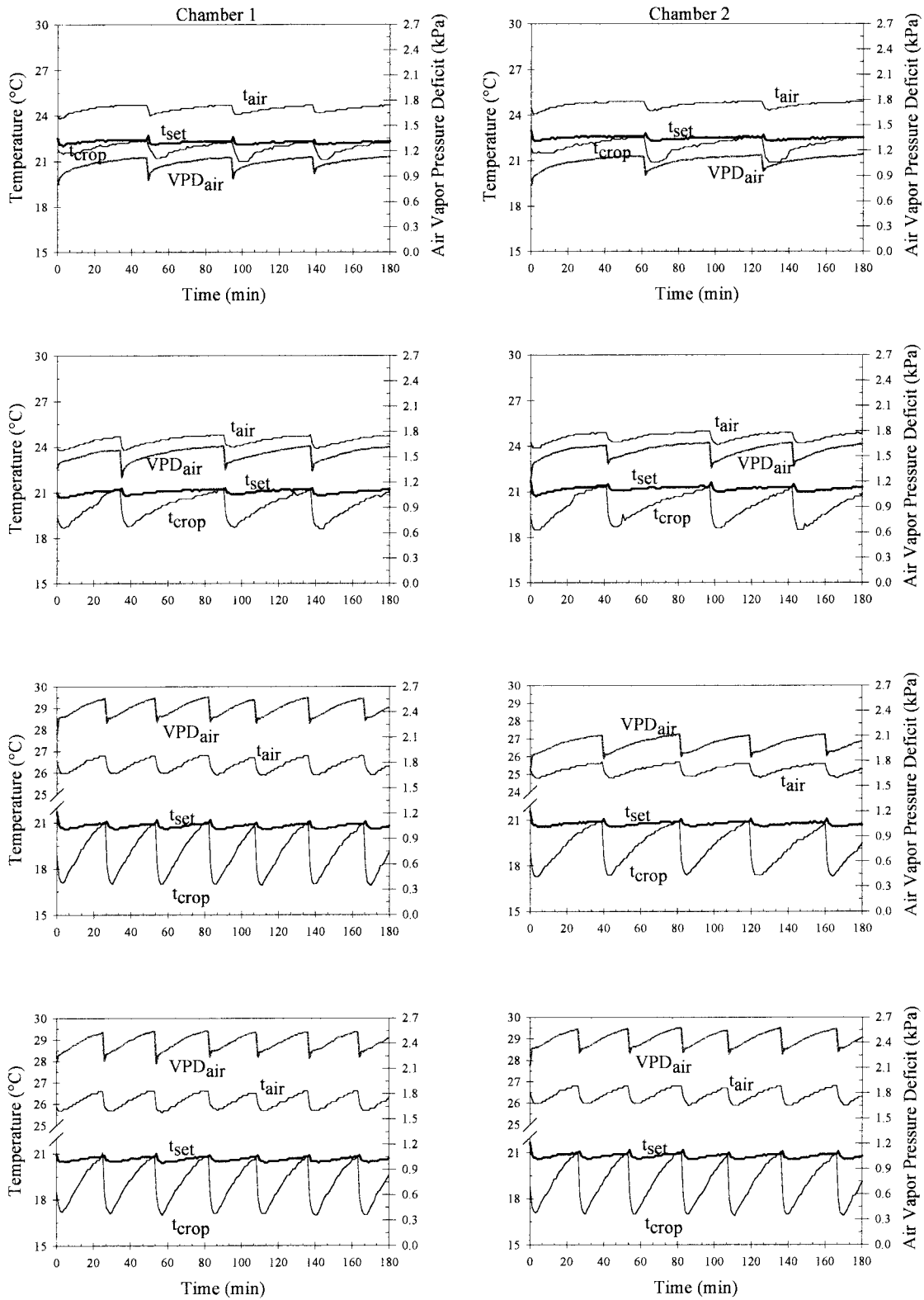
γ = "psychrometric constant" (Pa °C^{-1})

Figure 3. Crop, air, and setpoint temperatures under dark conditions. Measurements of the canopy temperature were performed on unrooted cuttings, which were subjected to four ranges of VPD_{air} (0.8 – 1.1; 1.3 – 1.6; 1.8 – 2.1, and 2.3 – 2.6 kPa).
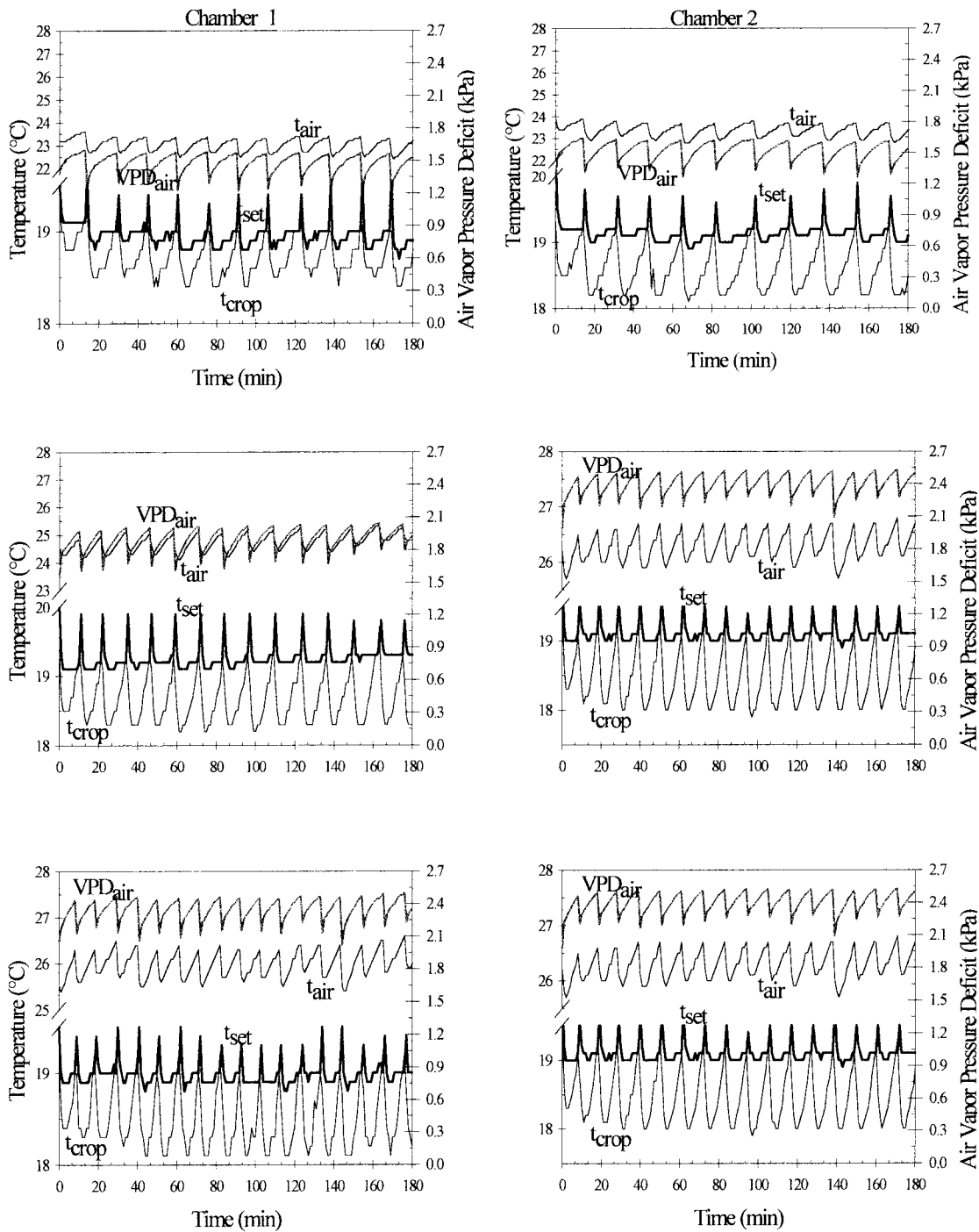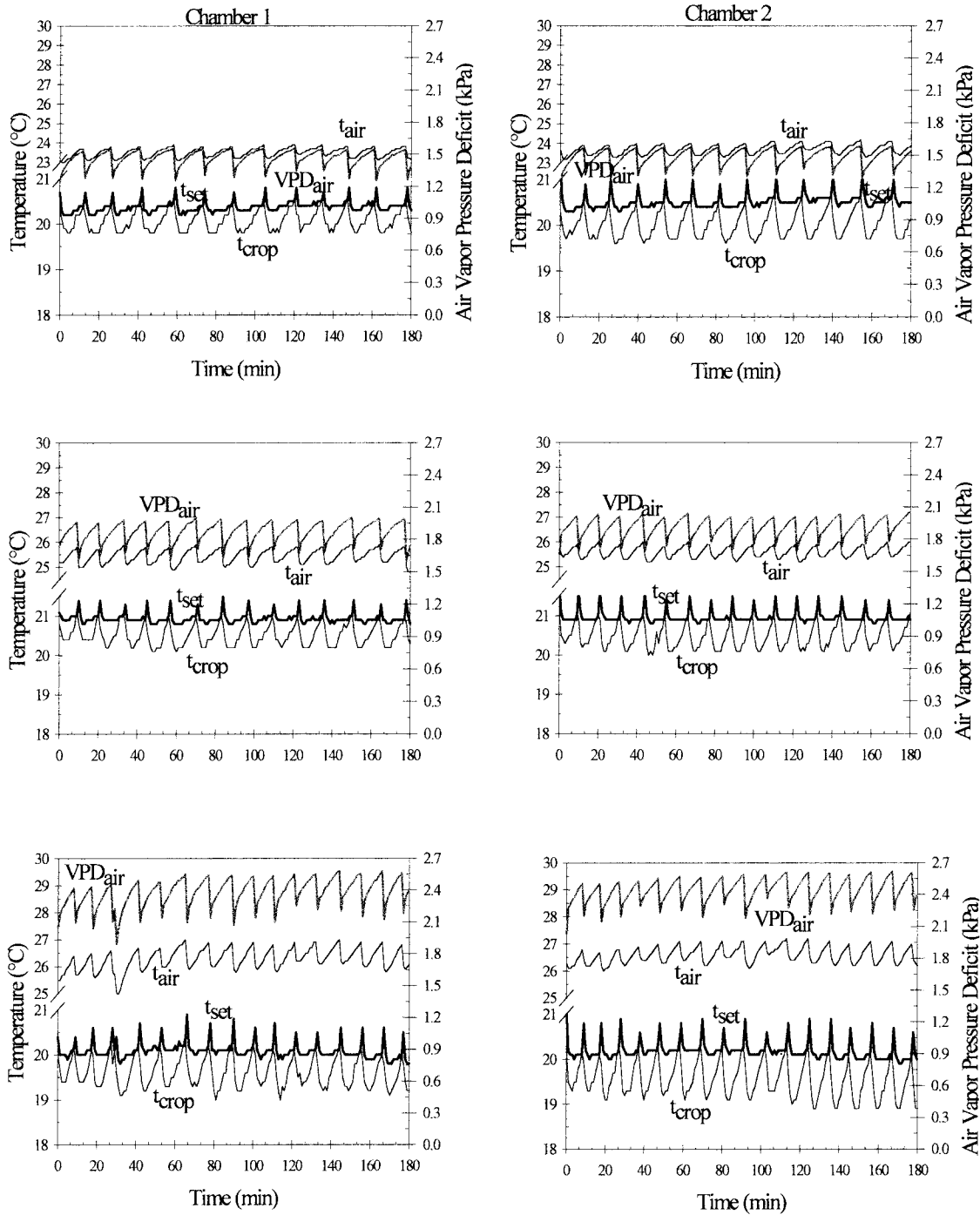
Figure 4. Crop, air, and setpoint temperatures under light conditions. Measurements of the canopy temperature were performed on unrooted cuttings, which were subjected to three ranges of VPD_{air} (1.3 – 1.6; 1.8 – 2.1, and 2.3 – 2.6 kPa). Incident radiation was maintained at 100 W m^{-2}.

Figure 5. Crop, air, and setpoint temperatures under light conditions. Measurements of the canopy temperature were performed on unrooted cuttings, which were subjected to three ranges of VPD$_{air}$ (1.3 – 1.6; 1.8 – 2.1, and 2.3 – 2.6 kPa). Incident radiation was maintained at 200 W m^{-2}.
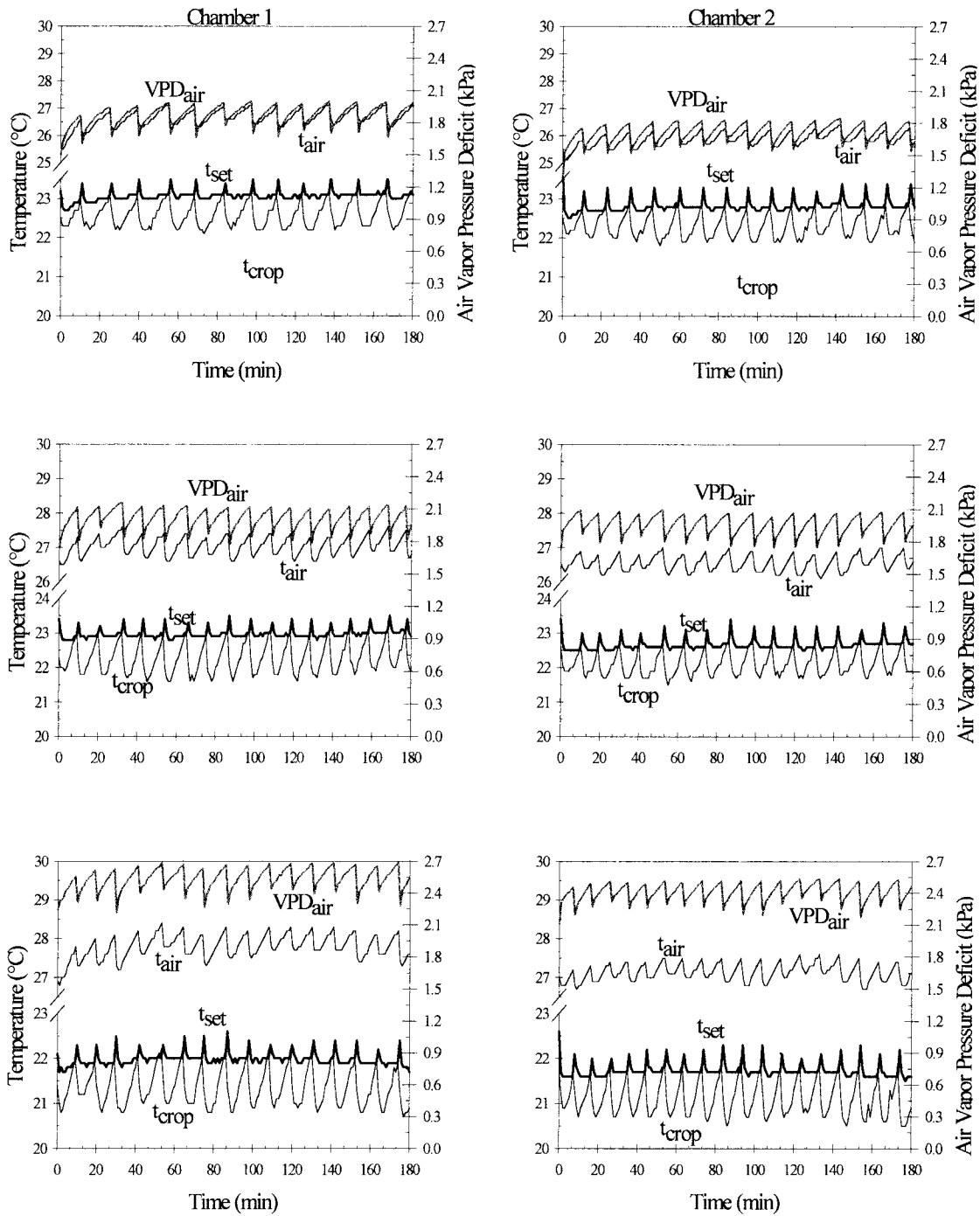
Figure 6. Crop, air, and setpoint temperatures under light conditions. Measurements of the canopy temperature were performed on unrooted cuttings, which were subjected to three ranges of VPD$_{air}$ (1.5 – 1.9; 1.8 – 2.1, and 2.3 – 2.6 kPa). Incident radiation was maintained at 300 W m^{-2}.