THE DIURNAL PROGRESSION OF SUBSTRATE TEMPERATURE IN UNSHADED TEMPERATURE-CONTROLLED GREENHOUSES AND ELECTRIC-LIGHTED CONTROLLED-ENVIRONMENT ROOMS

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THE DIURNAL PROGRESSION OF SUBSTRATE TEMPERATURE IN UNSHADED TEMPERATURE-CONTROLLED GREENHOUSES AND ELECTRIC-LIGHTED CONTROLLED-ENVIRONMENT ROOMS*

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DOWNS R. J. *The diurnal progression of substrate temperature in unshaded temperature-controlled greenhouses and electric-lighted controlled-environment rooms.* BIOTRONICS **16**, 57–70, 1987. Maximum substrate temperature was related chiefly to irradiance and, in controlled-environment rooms, to the spectral distribution of the light source. Depth in the substrate and night temperature depression changed the daily time course of substrate temperature but did not alter the maximum attained. The diurnal progression of substrate temperature in the controlled-environment room repeated itself from day to day until the plants became large enough to shade the substrate surface. The shading effect repeated itself between experiments. In the temperature-controlled greenhouse, substrate temperature maximum and time course varied from day to day as well as with time of year, but a reasonable prediction of substrate temperature could be made from the average irradiance per day.

Key words: greenhouse; controlled-environment room; substrate temperature; irradiance.

INTRODUCTION

A recent study (*14*) was undertaken to provide a direct, measured relationship between plant growth and irradiance throughout the year in an unshaded, temperature-controlled greenhouse. As expected, plant growth varied with season, but over the four-year period of the study growth varied severalfold during months that produced virtually the same average irradiance per day. The scatter of the data points about the model curve strongly suggested that some factor other than irradiance was altering growth, despite the fact that air temperature, air flow, position in the greenhouse, substrate, nutrient levels, and water were the same in each monthly test. Preliminary measurements indicated that substrate temperature was a major interacting factor.

Few data could be found that described the diurnal progression of substrate

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temperature in pots located in greenhouses or in controlled-environment rooms. Soil in greenhouse ground beds was reported to be warmer than the air temperature and to be related to air temperature changes in much the same way as field soil (*33*). Generally soil temperature in the field at a depth of 2–4 cm fluctuates less than air temperature and lags behind changes in air temperature, often by several hours (*7*, *9*, *18*, *28*). Seeman (*26*) suggested that substrate temperature in pots also roughly paralleled the diurnal progression of greenhouse air temperature. The results presented by Whittle and Lawrence (*33*) and by Seeman (*26*) seem to have been obtained in unheated, unventilated greenhouses and therefore may not be applicable where air temperature control is available. Matsui *et al.* (*21*) showed that the diurnal progression of soil temperature in containers placed in a 25°C Phytotron greenhouse exhibited a very rapid increase in temperature beginning about 0730 and attained a maximum temperature of 33.6°C after about 3 hours. Substrate temperature in pots is generally conceded to be higher than in greenhouse ground beds with the maximum depending on the pot material as well as air temperature and solar irradiance (*6*). For example, comparative data show that substrate temperature in plastic pots is higher than in clay ones, and containers made of black or green plastic result in higher root zone temperatures than white plastic pots (*1*, *8*, *19*).

Rajan *et al.* (*25*) showed that under a controlled-environment room illuminance of 32 klx (a photosynthetic irradiance of about 95 W m^{-2}) and a fluorescent-incandescent ratio of 2.8: 1 soil temperature in 13 cm plastic pots increased 5°C above air temperature. The rate of temperature rise at the onset of the light period was, like the data obtained in greenhouses (*21*), very rapid. Watts (*32*) reported that soil temperature in 15 cm pots located in controlled-environment rooms that provided a photosynthetic irradiance of 200 W m^{-2} from mercury and fluorescent lamps increased 8°C above the air temperature within 2 hours after the onset of the light period. Unfortunately his data also included an unexplained decrease in the substrate temperature of as much as 5°C about 1 hour after the lamps were turned on and a temporary increase of about the same magnitude about 1 hour after the lamps were turned off.

The few data that are available on substrate-air temperature relationships make it clear that seed germination must often take place under temperature conditions that are drastically different than the air temperature, even in facilities where the environment is otherwise controlled. After the seeds germinate, seedling root temperature also must be considerably different than the air temperature. The many papers on root zone temperature (e.g. *2*, *4*, *13*, *16*, *22*, *23*, *27*) show that substrate temperature affects shoot growth and development as well as the growth of the roots. Thus, an investigator using controlled-environment chambers and greenhouses should at least know how the root temperature relates to the controlled air temperature at various times during the diurnal cycle. Therefore the purpose of this study was to measure and describe the diurnal progression of substrate temperature in unshaded, temperature-controlled greenhouses and in fluorescent-incandescent lighted controlled-environment rooms.

METHODS AND MATERIALS

Green, 15 cm, plastic pots were filled with a commercial soilless substrate composed of peat moss and vermiculite. The substrate was watered to field capacity and the pots placed in a controlled-environment room or in an unshaded, temperature-controlled greenhouse. The controlled-environment room was equipped with 1500 mA cool white fluorescent lamps and incandescent lamps in an installed watt ratio of 2.5: 1. The photosynthetic photon flux density (PPFD) ranged from 620 to 710 μmol s^{-1} m^{-2} depending on lamp temperature and age. A preliminary experiment showed that a 16 hour light period resulted in a substrate temperature only 0.6°C higher than at the close of a nine-hour light period. Therefore, as a matter of convenience most of the data were taken using 9 hours of light per day and a day/night temperature of 22/18°C with the day temperature coincident with the light period. Average air velocity was 0.33 m s^{-1}. Greenhouse air temperatures were maintained by a mechanical refrigeration system at 22°C during the light period and at 18°C during the night with an average air velocity of 0.37 m s^{-1}. To avoid photoperiod perturbations in the greenhouse due to stray light from adjoining buildings and due to season, long photoperiods were maintained by interrupting the night from 2300 to 0200 hours with an irradiance of 12 W m^{-2} (300–1100 nm) from incandescent lamps (*15*).

Substrate temperatures were measured with copper-constantan thermocouples enclosed in stainless steel sheaths. A plexiglass frame was fitted to the side of each pot to insure that the thermocouple was located in the center of the pot at the prescribed depth (Fig. 1). Depth in most of the studies was 32 mm. Other thermocouple positions were used and are described when the data are presented. Thermocouple output was recorded on a Linseis, 0–50°C, multipen, 250 mm stripchart recorder that was given a calibration check every 48 hours, or the outputs were logged as 15 minute averages using a computer and analog connections for eight inputs.

The system was examined to insure that radiant energy did not increase thermo-

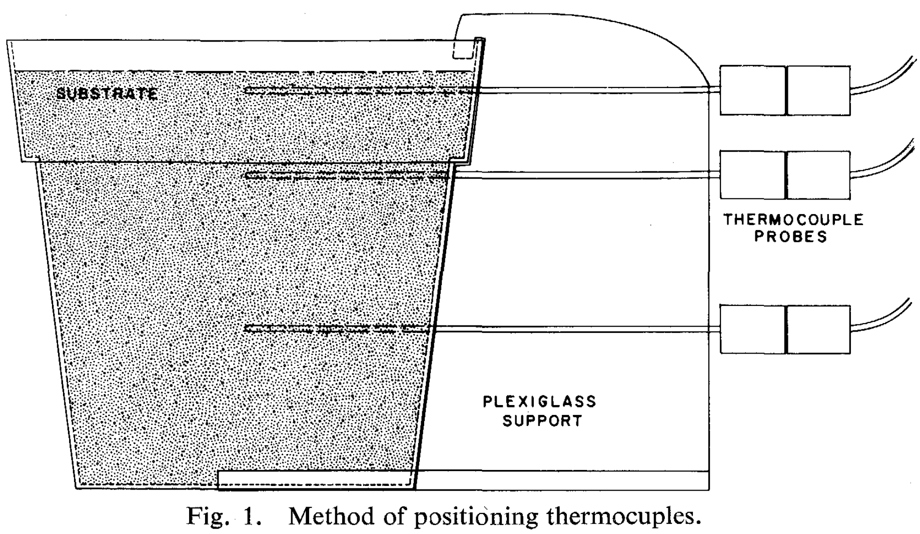

Fig. 1. Method of positioning thermocuples.

couple output except through pot and substrate heating. Irradiating the plexiglass frame and the base of the thermocouple probe with 290 W m^{-2} (300–1100 nm) from an incandescent flood lamp, while shielding the pot and substrate from the radiant energy, resulted in no change in substrate temperature. When the pot and substrate also were irradiated, the substrate temperature increased 7°C in one hour. A preliminary test also showed that pot to pot variation could be held to less than 0.5°C.

RESULTS AND DISCUSSION

Controlled-Environment Rooms

In the absence of radiant energy, substrate temperature responded slowly to a 4°C change in air temperature. Due to evaporative cooling, substrate temperatures remained below the air temperature during the 22°C phase. When a light period coincided with the day/night temperature change, substrate temperature lagged behind the rapid rise in air temperature by about 1 hour but continued to increase to 8–9°C above the air temperature by the end of the 9 hour day. During the night phase of the cycle, substrate temperature required nearly 9 hours to reach the night air temperature, but by the beginning of the next day cycle was 0.5 to 1°C below the air temperature (Fig. 2). The 4°C decrease in air temperature at night had little effect on the maximum temperature attained during the light period (Fig. 3), but the rate of substrate cooling during the dark period was slowed by the lack of a night period temperature depression.

Depth in the substrate, below the upper 10 mm, also had little effect on the

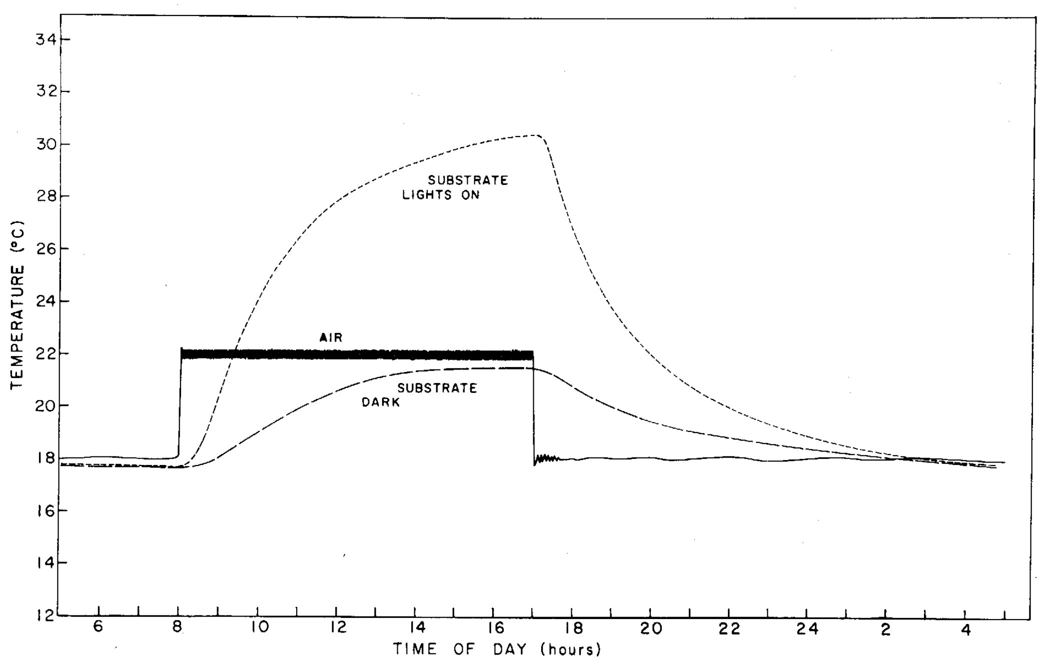

Fig. 2. Time course of substrate temperature in a controlled-environment room with or without a PPFD of 650 μmol s^{-1} m^{-2} from fluorescent and incandescent lamps.

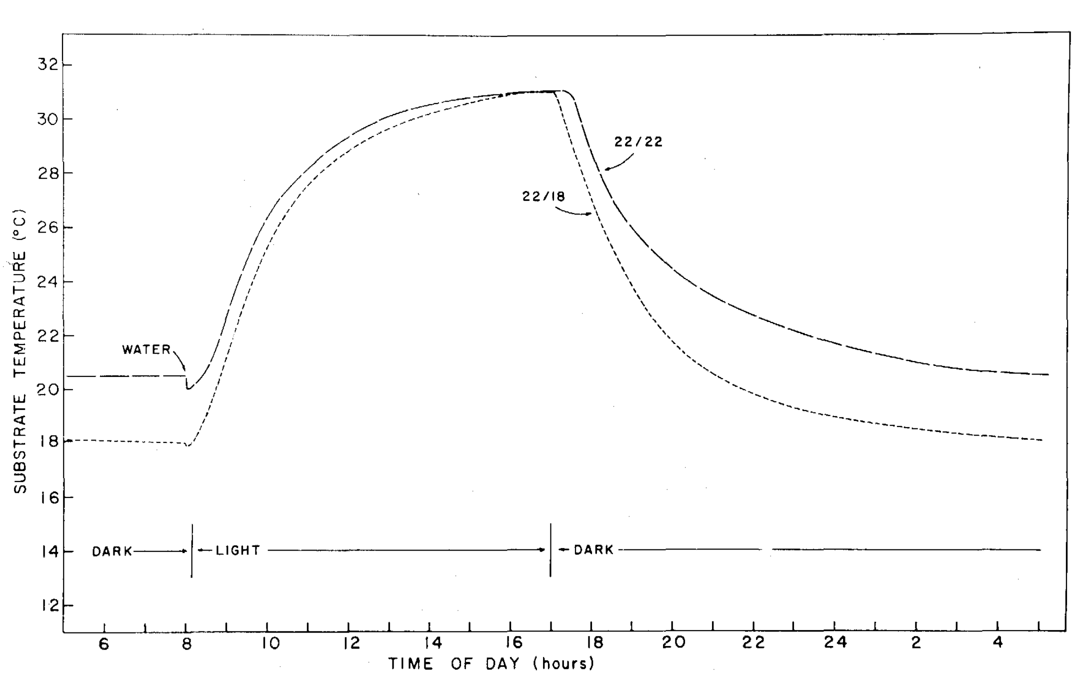

Fig. 3. Time course of substrate temperature with and without a 4°C night period temperature depression.

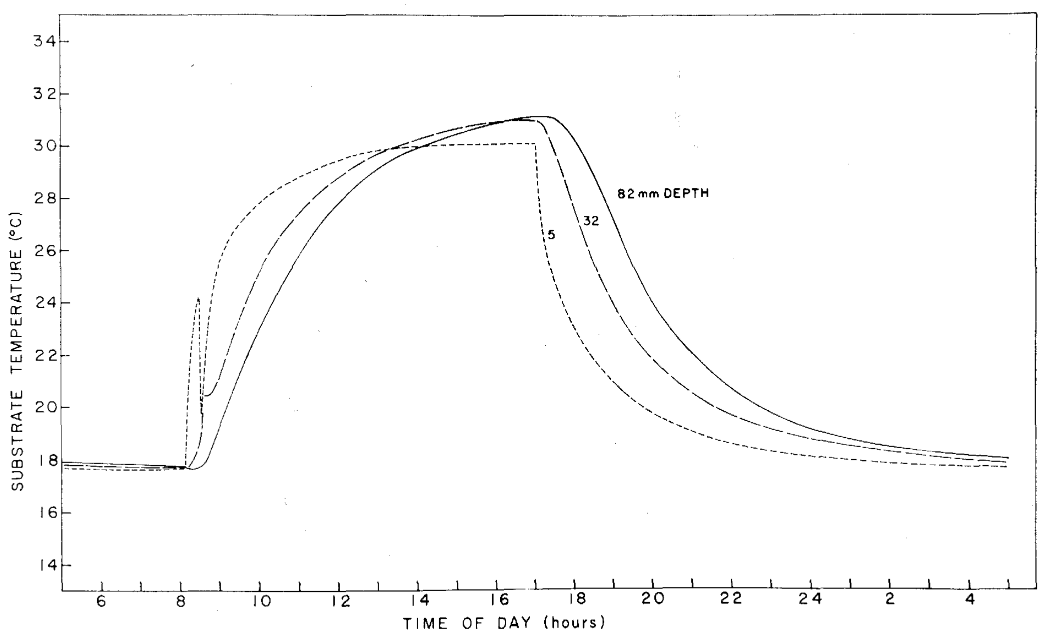

Fig. 4. Time course of substrate temperature at three depths in a fluorescent-incandescent lighted controlled-environment room with a 22/18°C day/night temperature.

maximum temperature attained by the substrate, although the time course was somewhat altered (Fig. 4). The greater the depth in the pot the slower the rise in substrate temperature at the beginning of the light period and the slower it decreased at night. Thus a substantial vertical temperature gradient was present 1 hour after the onset of the light period, but after about 6 hours substrate temperature was nearly the same at all depths except above 10 mm where evaporative cooling reduced the maximum temperature.

A horizontal temperature gradient also existed within the pot. The pot wall responded more rapidly to a change in air temperature and to irradiance than the substrate in the center of the pot (Fig. 5). Thus in the early part of the light period the difference between pot wall and substrate temperature was more than 4°C. This difference decreased slowly until by the end of the light period the gradient between the center of the substrate and the inner wall of the pot was only 0.7–1.0°C.

The temperature of tap water varies with season and in temperate latitudes can be 10°C or less during winter. The first pots watered receive the warmer water that has been standing in the pipes of the building, while later applications draw on colder water from the mains outside the building. Therefore, within a single controlled-environment room, the substrate in the first and last pots watered can exhibit very different temperature changes due to watering. Even when the water had been equilibrated with the room air temperature, watering the substrate in the latter part of the light period caused a sharp decrease in the root zone temperature (Fig. 6). However, watering with room temperature water early in the light period induced a large increase in substrate temperature. Lowering the water temperature to 15°C and watering after the air temperature had reached 22°C still had the peculiar

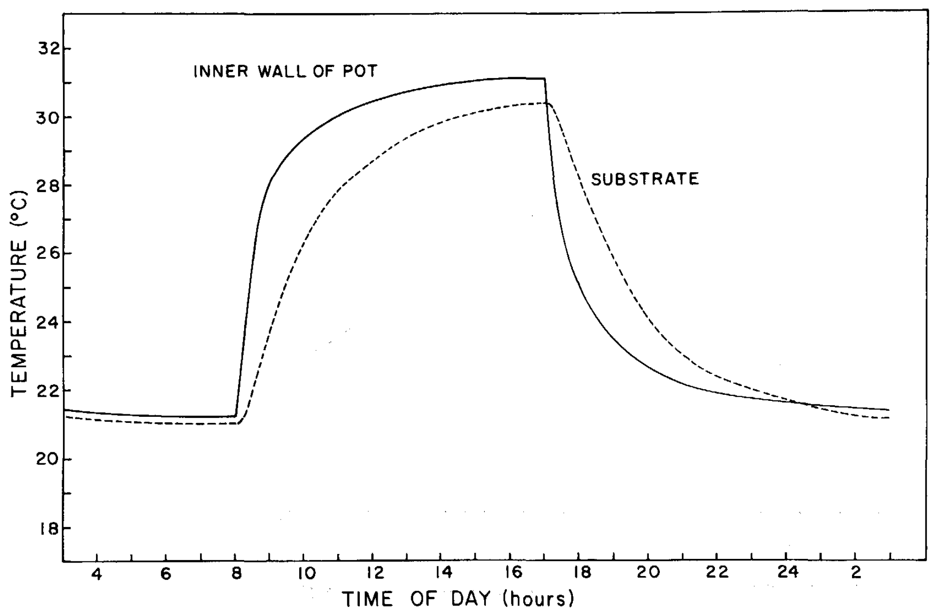

Fig. 5. Comparison of the temperature of the substrate and pot wall at 32 mm depth in a fluorescent-incandescent lighted room with a day/night temperature of 22/18°C.

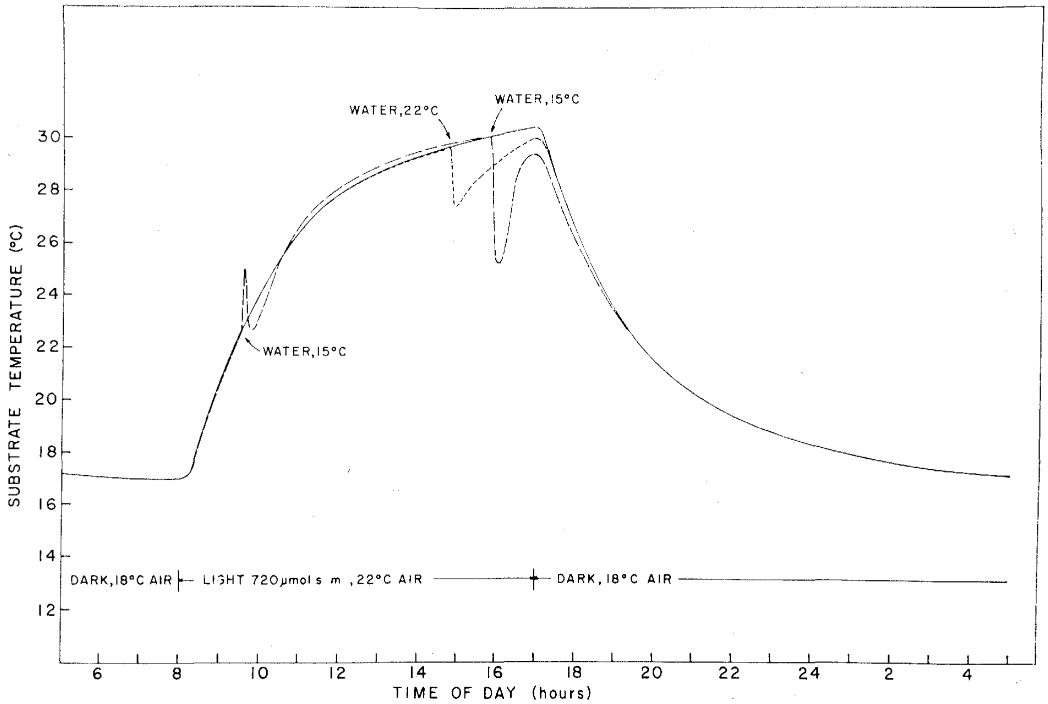

Fig. 6. Effect of water temperature and time of watering on substrate temperature in a fluorecent-incandescent lighted room with a 22/18°C day/night temperature.

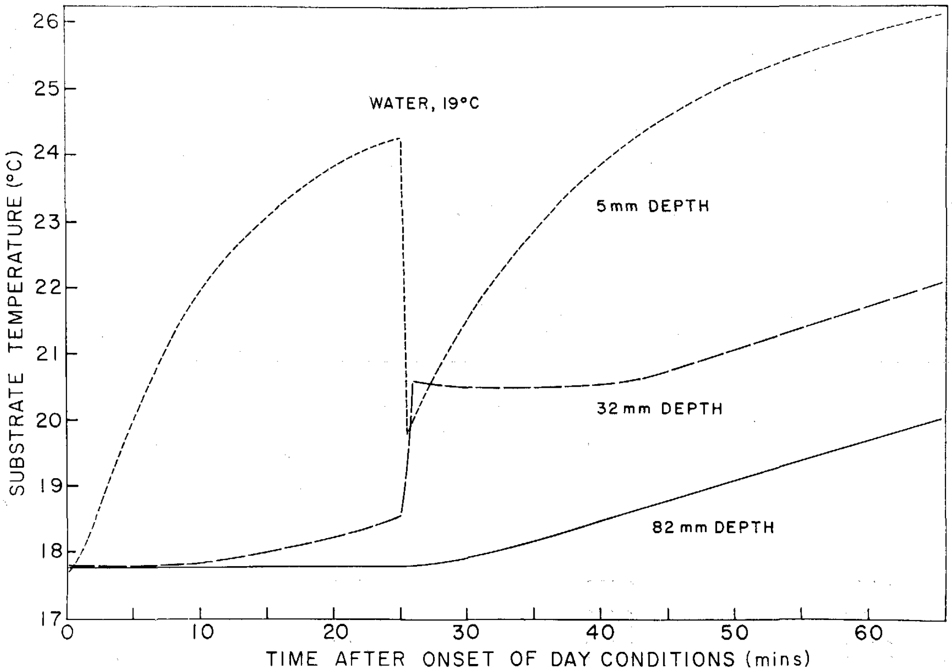

Fig. 7. Effect of watering on substrate temperature at three depths.

effect of raising substrate temperature at 32 mm depth (Fig. 6). Further investigation (Fig. 7) showed that watering early in the light period markedly decreased the temperature of the substrate at 5 mm, increased it at 32 mm, and had little effect at 82 mm depth. The upper 5 mm absorbed heat much more rapidly than the deeper layers of the substrate. This heat was taken up by the water and, as the water passed downward through the substrate, was transferred to the cooler substrate as shown by the increase in temperature at 32 mm. By the time the water reached 82 mm depth, water and substrate temperatures were in equilibrium and little change in temperature was observed. Thus, the concept that application of water or nutrient solution brought to air temperature will prevent sudden changes in root zone temperature is not valid. A change in substrate temperature almost always accompanies the watering process when water is applied during the light period. At best the change can be minimized by using a watering solution brought to the temperature of the substrate, rather than the air, at the time of application.

The maximum temperature reached by the substrate was related to photosynthetic photon flux density and to the spectral energy distribution of the light source, in particular the amount of long wavelength radiation emitted (Table 1). Thus 72 μmol s^{-1} m^{-2} from incandescent lamps which produce 66% of their output power between 850–2700 nm (*29*) resulted in a higher substrate temperature than 578 μmol s^{-1} m^{-2} from fluorescent lamps that produce only 8% in the 850–2700 nm range.

The chief purpose of a transparent barrier between the lamp loft and the growing area is to prevent the lamp temperature, and consequently the PPFD, from decreasing when the experimental conditions call for air temperatures significantly above or below the lamp optimum. As shown in Table 2, the transparent barrier also serves to substantially reduce the rise in substrate temperature due to the light source.

The maximum temperature of the substrate obviously will decrease somewhat as the plants grow and screen the substrate surface from radiant energy. However, the decrease will be relatively small if the pots are spaced well apart, because large amounts of heat are conducted through the pot wall which has a surface area about 3.3 times greater than the substrate surface. Therefore, when the pots are crowded

Table 1. Substrate temperature at 32 mm depth resulting from reducing the PPFD* by decreasing the number of fluorescent lamps

Installed watts		PPFD	Substrate temperature Max. °C
Fluorescent	Incandescent		
0	0	0	21.8
0	2400	72	27.0
6020	0	578	26.2
6020	2400	650	31.1
5160	2400	580	30.5
4300	2400	485	29.6
3440	2400	415	28.9
2580	2400	335	28.5

* Photosynthetic photon flux density, μmol s^{-1} m^{-2}, 400–700 nm.

Table 2. Effect of a barrier between the light source and the growing area on substrate temperature in 22°C air.

Light source*	PPFD μmol s^{-1} m^{-2}	Maximum substrate temperature (°C)
Fluor+Incand no barrier	810	35.8
Fluor+Incand with barrier	700	30.6
Fluor no barrier	730	28.6
Fluor with barrier	705	26.2
Incand, no barrier	65	29.6
Incand, with barrier	63	26.5

* 28, 215 W cool white fluorescent; 24, 100 W incandescent lamps.

Table 3. Maximum substrate temperature after a nine-hour light period at different air temperatures in a fluorescent-incandescent lighted controlled-environment room with a PPFD of 610 μmol s^{-1} m^{-2}.

Air temperature (°C)	Maximum substrate temperature (°C)
30	36.5
26	31.5
22	30.5
18	27.5

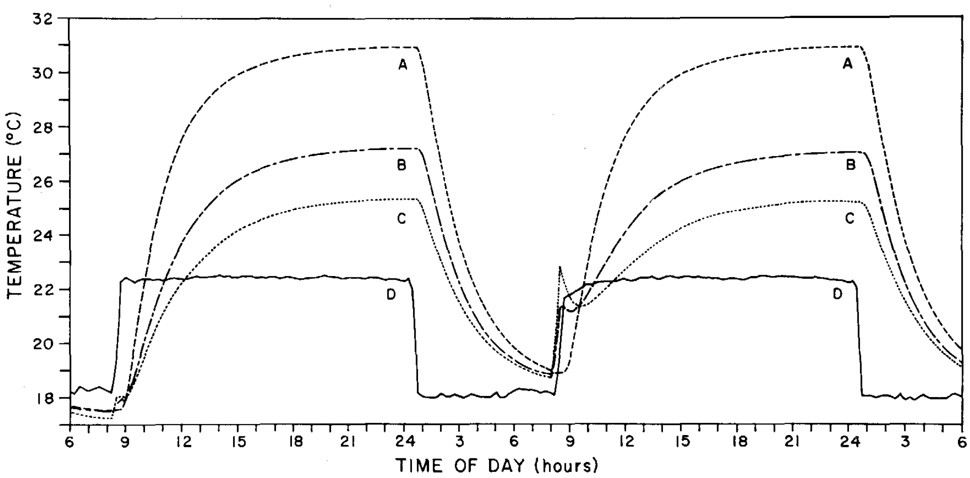

Fig. 8. Effect of shading on the time course of substrate temperature. A) Prior to plant emergence with pots spaced 9 cm apart, B) Pots of cucumber plants with a leaf area of 1700 cm^2 spaced 9 cm apart, C) Five pots of substrate touching the center measured pots, D) Air temperature.

together so that the outer pots screen the inner ones from radiant energy, the inner pots exhibit a smaller increase in substrate temperature than when the substrate surface is shaded (Fig. 8). Under conditions where the canopy becomes continuous and shades the pot walls as well as the substrate surface area, root zone temperature may not rise higher than the air temperature.

Our data suggest that the daily progression of substrate temperature and the maximum attained will vary between controlled-environment rooms operated at the same day/night air temperature and photoperiod chiefly as functions of irradiance and spectral energy distribution of the light source. For each type of controlled-environment room, root zone temperatures will change with different air temperature programs (Table 3), but for each air temperature program substrate temperature follows a consistent daily pattern.

Greenhouses

The diurnal course of substrate temperature in the controlled-environment room consistently repeats itself from day to day until the plants are large enough to shade the substrate, and the progressive decrease in substrate temperature as a result of increased shading as the plants grow repeats itself between experiments. In the unshaded, temperature-controlled greenhouse, however, substrate temperature varied within and between days as well as with time of year. During the day, the chief factor influencing substrate temperature was solar irradiance. Figure 9 shows the relationship between irradiance per day and the maximum substrate temperature attained. Scatter of the data is due to the diurnal variance in irradiance. For example, the maximum substrate temperature would be different on days with intermittent clouds as compared to continuous overcast for several hours preceding or followed by clear skies even though the total daily irradiance might be the same.

The effect of watering is apparent in the first two cycles of Fig. 10. A much lower response of substrate temperature to watering is shown in the third cycle of

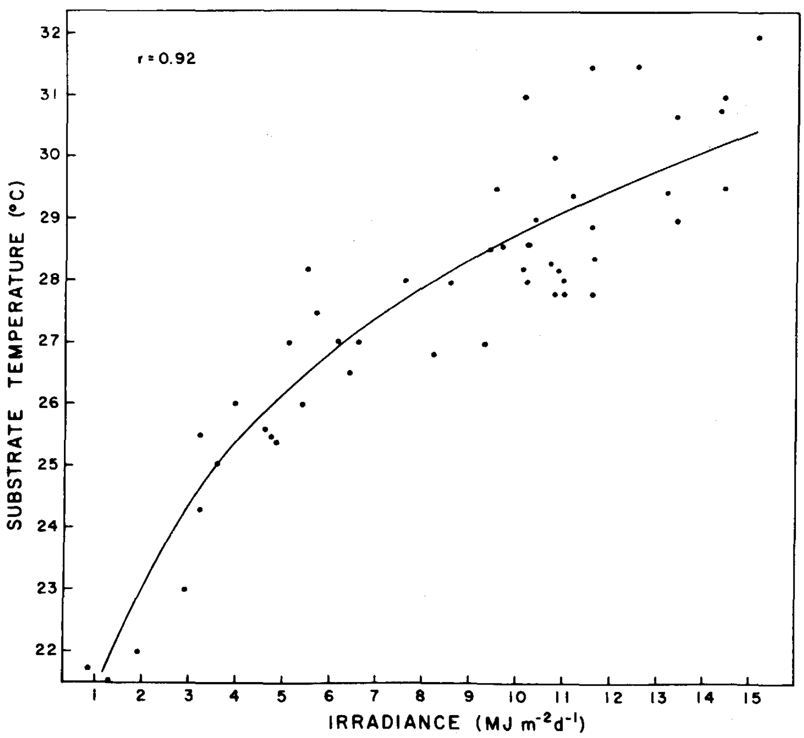

Fig. 9. Maximum daily substrate temperature as a function of the irradiance per day in an unshaded, temperature-controlled greenhouse.

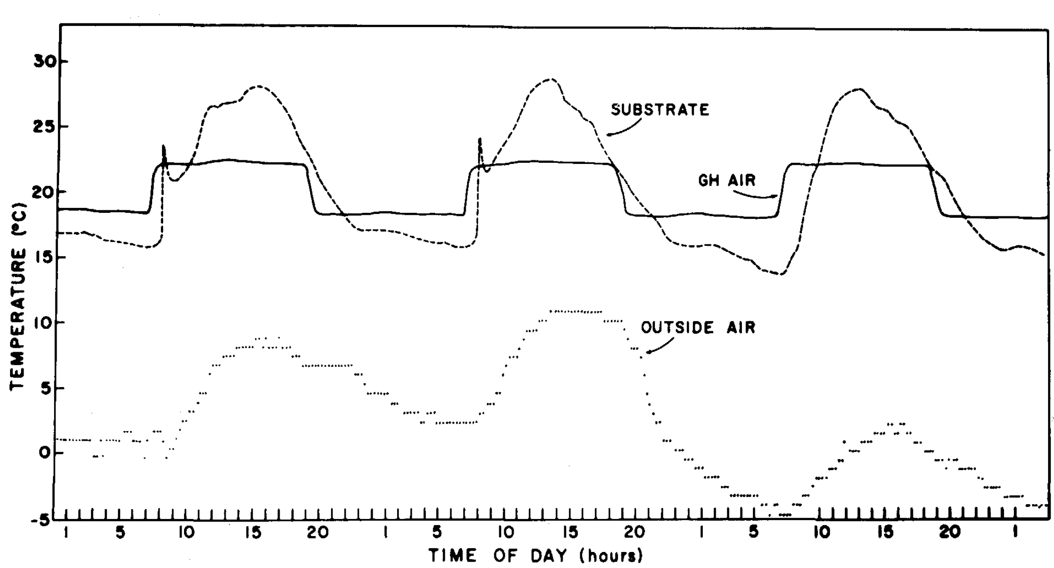

Fig. 10. Relationship between outside air, greenhouse air and substrate temperature in an unshaded, temperature-controlled greenhouse during February.

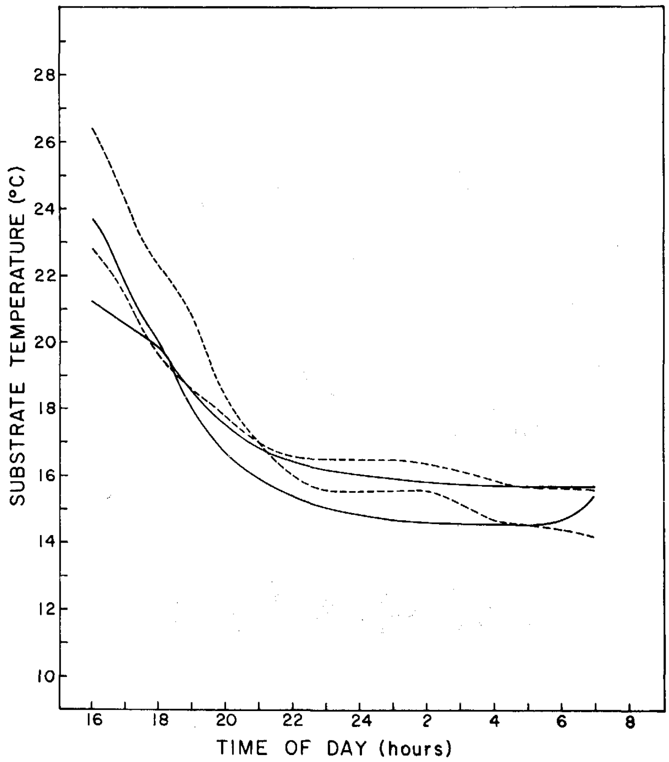

Fig. 11. Time course of substrate temperature on alternating nights with (dotted) and without (solid) a dark period interruption with incandescent lamps in a greenhouse with an 18°C air temperature.

the figure where watering took place before solar radiation became a significant factor and water temperature was adjusted to approximate the substrate temperature at the time of application. At night substrate temperature in the greenhouse often dropped 4–5°C below the greenhouse air temperature (Fig. 10). Measurements suggested that the temperature outside the greenhouse was affecting the temperature of the greenhouse glass and, as the glass temperature decreased below about 10°C, it began to act as a thermal sink to which the substrate radiated. The peculiar flattening of the downward trend of dark period substrate temperature shown in Figure 10 was due to the use of a dark period interruption with incandescent lamps to obtain a long photoperiod effect during winter (Fig. 11). Apparently the incandescent lamps altered the characteristics of the thermal sink since tests in temperature-controlled rooms showed that the irradiance from the incandescent lamps did not supply enough thermal energy to significantly raise the substrate temperature.

The effect of the incandescent photoperiod control lamps on the time course of substrate temperature in the greenhouse raised the question about possible effects on substrate temperature under light from the high intensity discharge (HID) lamps often used to supplement the low natural irradiance of winter. The problem has been that the recommended supplemental irradiance of only 8–12 W m^{-2} (3.3–4.9 klx) (*10–12*, *24*) seems rather low, especially when combined with the fact that higher irradiances, the order of 48 W m^{-2}, often reduce growth and in some cases cause chlorosis (*11*). Moreover, the report that the best results with supplemental light are obtained by using it from 2000 to 0400 hours rather than by including it with the natural light during the day (*12*) is hard to reconcile with the concept that the purpose of supplemental light is to increase the photosynthetic rate. Measure-

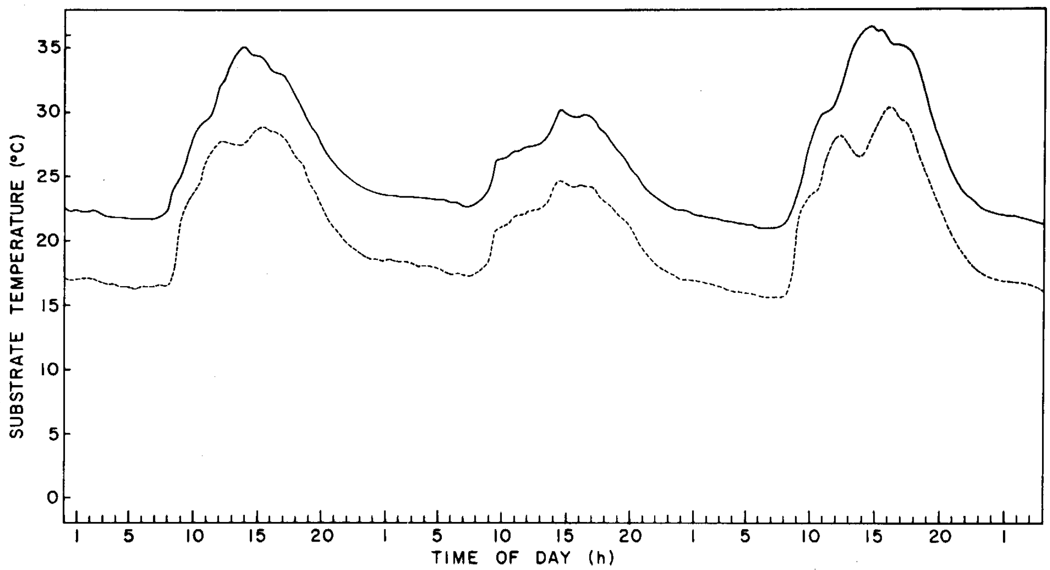

Fig. 12. Substrate temperature with (upper) and without (lower) supplemental light in an unshaded greenhouse with day/night air temperature controlled at 22/18°C. Irradiance per day 10.8, 5.5 and 13.4 MJm^{-2}.

ments showed that substrate temperatures increased significantly under HID lamps, exceeding 35°C on clear days. The substrate temperature also was warmed at night and never dropped below the air temperature (Fig. 12).

In the greenhouse, the biological effects of substrate temperature would appear more severe than in the electric-lighted controlled-environment room. Root growth of a number of plant species stops or is severely reduced at temperatures above 30°C or below 18°C (*3, 4, 20, 30, 31*). Shoot (*17*), hypocotyl growth (*21*), and leaf fresh weight (*5*) also may be reduced when root temperature drops below 18°C. On a clear winter day, the inhibitory maximum level of substrate temperature can be reached in a greenhouse with a 22°C air temperature, and root zone temperatures can decrease significantly below 18°C in an 18°C greenhouse when outside temperatures approach 0°C.

The increased efficiency of the supplemental light at night compared to during the day (*12*) appears to be in part the result of root zone warming which prevents the substrate from reaching inhibitorily low temperatures. The use of supplemental light during the day, however, can raise the substrate temperature to the point where root growth is reduced or roots injured. Increased thermal radiation due to supplemental light, especially on clear days, also can raise the temperature of the leaf and stem (*12*). The reduced growth due to elevated root temperature, higher respiration rate, and thermal effects on leaves thus may nullify the benefits of increased photosynthesis.

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