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Growth and Development of *Petunia × hybrids* as a Function of Temperature and Irradiance

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Abstract. *Petunia × hybrids* 'Snow Cloud' plants were grown under 25 temperature combinations ranging from 10 to 30C and at photosynthetic photon flux levels of 100 or 200 $\mu mol \cdot s^{-1} \cdot m^{-2}$ (6.5 and 13 $mol \cdot day^{-1} \cdot m^{-2}$, respectively). Days to flower-was a quadratic function of average temperature, with 25C being the optimum temperature for minimal tire-e to flower at 200 $\mu mol \cdot s^{-1} \cdot m^{-2}$. Plant height increased "linearly and average internode length increased quadratically as day temperature increased. The number of lateral shoots decreased quadratically as average temperature increased, and the average length of each shoot decreased quadratically as day temperature increased.

A fundamental objective of most commercial establishments growing bedding plants is to produce a crop that meets the quality standards of the market in the shortest time possible. Growers may manipulate irradiance, photoperiod, temperature, nutrition, and other factors alone or in combination to achieve the desired results. Thus, production time relies heavily on the past experience of the grower and the techniques used to produce the crop. Many times this method results in substandard plant quality or inefficient production methods.

The plant's response to the environment has been used to develop production strategies to increase the efficiency of producing floricultural crops (Grueber et al., 1986; Karlsson et al., 1983, 1988). Much of the research involving irradiance and temperature effects on *Petunia × hybrids,* a popular bedding plant (Lieberth, 1988), was conducted 15 to 30 years ago (Boodley, 1970; Carpenter and Carlson, 1974; Mastalerz, 1965; Seeley, 1955) and many of the suggested production techniques are now outdated. Only recently has interest in this area of petunia research been renewed (Armitage and Kowalski, 1982; Merritt and Kohl, 1982, 1983). The purpose of this study was to determine the influence of irradiance and temperature on the growth and development of petunia so that production strategies could be refined for the crop.

Materials and Methods

'Snow Cloud' petunia seeds were sown in no. 406 plug trays (plug size: 1.5 × 1.5 × 2.0 cm; 3.0-ml capacity) containing a commercial peat-lite mix (Michigan Peat Co., Sandusky, Mich.). Plug trays were covered with clear polyethylene and placed under constant light at 200 $\mu mol \cdot s^{-1} \cdot m^{-2}$ (17.3 $mol \cdot day^{-1} \cdot m^{-2}$) and a constant 23C. The polyethylene was removed after 5 days and the plug trays were placed on capillary matting. Ten days after sowing, the seedlings were transplanted into 9-cm pots (0.34 liter) filled with the same commercial peat-lite mix. Plants were irrigated as necessary to prevent water stress and fertilized with 10.7 mM N and 3.18 mM K from $(CaNO_3)_2$ and KNO_3 at each irrigation.

The seedlings were placed in one of five walk-in 5.85-m^2 growth chambers maintained with air at a constant 10, 15, 20, 25, or 30C. Seedlings were placed at a spacing of 123.5 plants/m^2. Each chamber was maintained at an 18-h photoperiod and divided to provide photosynthetic photon flux (PPF) levels of 100 or 200 $\mu mol \cdot s^{-1} \cdot m^{-2}$ (6.5 and 13 $mol \cdot day^{-1} \cdot m^{-2}$, respectively). Plants were moved among growth chambers to supply a factorial combination of five day temperatures (DT), five night temperatures (NT), and two PPF levels. Changes between NT and DT corresponded with the change in photoperiod.

Leaf temperatures were measured with a Sensortek (Clifton, N. J.) BAT-12R meter and Omega (Stamford, Corm.) copper-constantan thermocouple. The difference between temperature set points and leaf temperature was < 1.5C; temperature set points were used for data analysis. PPF was provided by a mixture of cool-white fluorescent and incandescent bulbs (input wattage 90:10, respectively), and PPF levels were adjusted by raising the lamps to maintain the proper PPF at the canopy top. PPF levels were determined with a LI-COR (Lincoln, Neb.) LI-185A meter and LI-190SB quantum sensor.

Data were collected for each treatment at time of flowering. The experiment was terminated 120 days after sowing the seed,

Table 1. Mean number of days to flower for *Petunia × hybrids* 'Snow Cloud' in response to day and night temperatures between 10 and 30C and high or low irradiances (13 or 6.5 $mol \cdot day^{-1} \cdot m^{-2}$ for an 18-h photoperiod.

Temp (°C)					
	Day				
Night	10	15	20	25	30
		High irradiance			
10	NF[z]	77	60	51	49
15	105	74	57	50	49
20	83	68	56	50	49
25	74	64	53	46	49
30	66	57	51	46	52
		Low irradiance			
10	NF	100	74	58	54
15	NF	89	67	56	54
20	101	81	67	55	52
25	87	69	59	52	51
30	82	66	56	52	51
Significance					
NT		***	NT × DT		***
DT		***	NT × I		***
Irradiance (I)		***	DT × I		***
			NT × DT × I		***

[z]NF = Treatments did not flower within 120 days from snowing.
***Significant at $P = 0.001$.

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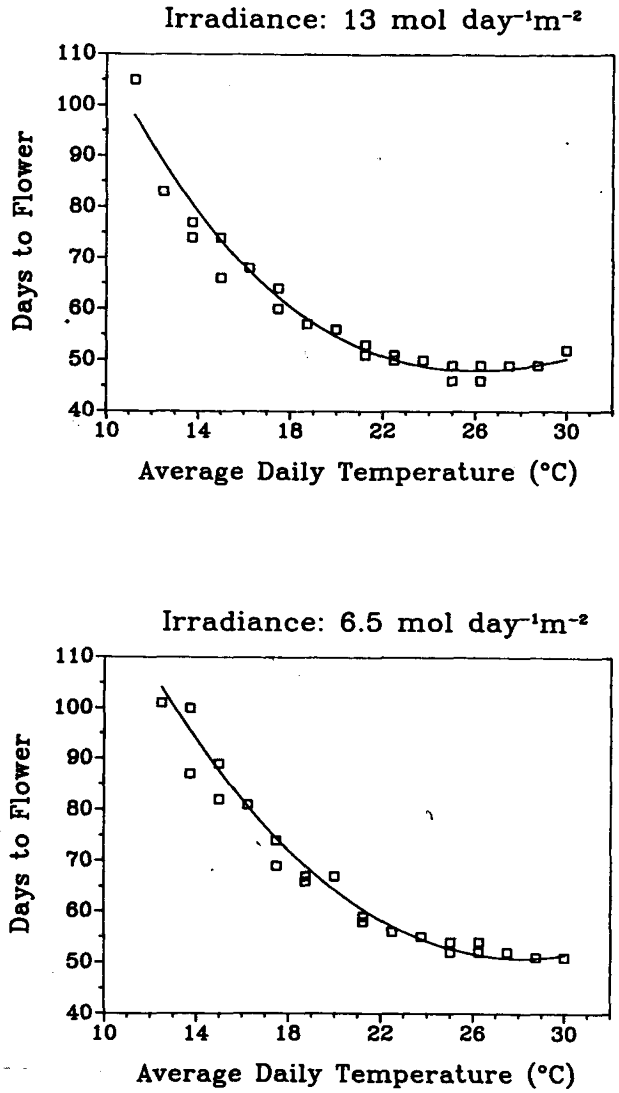

Fig. 1. Days to flower for *Petunia* × *hybrida* 'Snow Cloud' in response to average daily temperature (AVG) between 10 and 30C. **(top)** 13 $mol \cdot day^{-1} \cdot m^{-2}$ [days to flower = 190.205- (11.1917·AVG) + (0.219176·AVG^2)], r^2 = 0.915; **(bottom)** 6.5 $mol \cdot day^{-1} \cdot m^{-2}$ [days to flower = 212.741 – (11.7045·AVG) + (0.211953·AVG^2)], r^2 = 0.937.

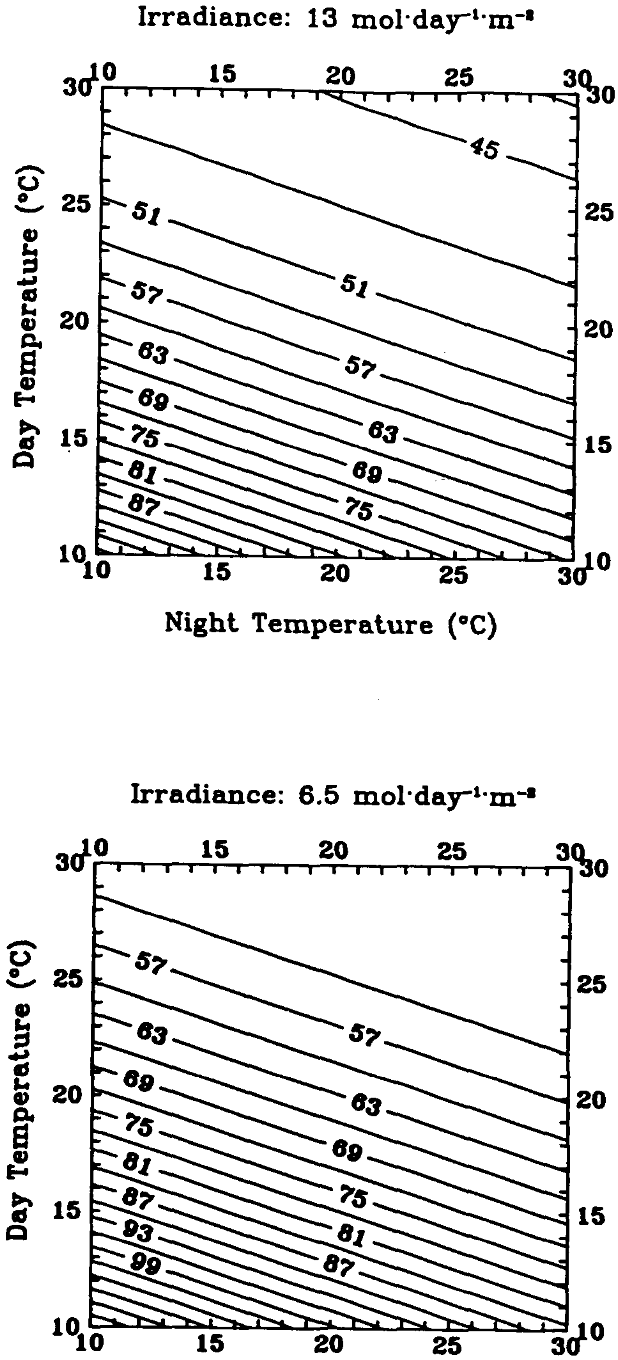

Fig. 2. [sopleth plots of days to flower for varying combinations of night and day temperature between 10 and 36C for *Petunia* × *hybrida* 'Snow Cloud' at: **(top)** 13 $mol \cdot day^{-1} \cdot m^{-2}$ and **(bottom)** 6.5 $mol \cdot day^{-1} \cdot m^{-2}$.

at which time data were collected on remaining plants not yet flowering. Data collected included days from sowing to flower, plant height, average internode length, number of lateral shoots, and average lateral shoot length. A plant was considered in flower when the outer edge of the corolla reflexed perpendicularly to the corolla tube. Plant height was measured from the soil line to the top of the main stem. Average internode length was determined for the internodes on the main stem and did not include any lateral shoots. Lateral shoots that had attained a minimum length of 4 mm were counted and measured from the point of attachment to the main stem to the end of the stem of the shoot.

Results and Discussion

Plants grown at a constant 10C at either irradiance and those grown at 15C NT and 10C DT at 6.5 $mol \cdot day^{-1} \cdot m^{-2}$ did not flower within 120 days from sowing (Table 1). Days to flower was determined to be a quadratic function of average temperature (AVG) for each irradiance (Fig. 1). As AVG increased, days to flower decreased. Plants grown under 13 $mol \cdot day^{-1} \cdot m^{-2}$ flowered 3 to 23 days before their respective counterparts at the lower irradiance, except at the two highest AVG (25C NT/30C DT and constant 30 C), which showed no significant difference in time to flower between the two irradiance levels. Irradiance had more of an effect in reducing time to flower at the lower AVG than at the higher AVG. Isopleth plots were developed from the equations to show the response of time to flower to varying NT and DT at an 18-h photoperiod (Fig. 2).

Table 2. Mean plant height (in centimeters) for *Petunia* x *hybrids* 'Snow Cloud' in response to day and night temperatures between 10 and 30C and high or low irradiances (13 or 6.5 mol·day^{-1}·m^{-2}) for an 18-h photoperiod.

Temp (°C)					
	Day				
Night	10	15	20	25	30
		High irradiance			
10	11.3	12.5	17.5	21.6	21.6
15	11.7	12.2	15.2	19.4	22.9
20	11.2	12.0	25.4	22.1	23.0
25	12.7	14.2	19.1	19.5	20.8
30	13.3	13.8	19.4	21.5	25.3
		Low irradiance			
10	11.8	17.8	20.6	23.3	27.1
15	12.6	17.9	21.3	27.6	26.7
20	14.6	16.9	27.0	25.2	28.6
25	16.6	16.3	21.6	26.1	27.5
30	13.5	16.4	23.3	25.2	37.5
Significance					
NT		***	NT × DT		***
DT		***	NT × I		NS
Irradiance (I)		***	DT × I		***
			NT × DT × I		***

NS,***Nonsignificant or significant at P = 0.001, respectively.

Increasing air temperature has long been known to decrease time to flower in petunia (Seeley, 1955). It has also been shown that increasing the soil temperature while maintaining commercial production air temperatures would produce similar results (Merritt and Kohl, 1982). Plants in this study, grown at 13.5 mol·day^{-1}m^{-2}, showed a significant decrease in flowering time as the average air temperature approached 25C, with higher temperatures slightly delaying the crop. This delay may have been due, at least in part, to the increased bud abortion experienced at the higher average temperature (data not reported). Similar bud abortion was found at the lower irradiance also.

An irradiance of 13 rather than 6.5 mol·day^{-1}·m^{-2} decreased time to flower in petunia (Table 1) by up to 3 weeks. High intensities of fluorescent lights (287 µmol·s^{-1}·m^{-2}) used to supplement natural light conditions when growing petunias were shown to decrease time to flower by up to 12 days when compared to plants receiving low-intensity incandescent lighting to extend the photoperiod (Carpenter and Beck, 1973). In our study, plants flowered in 67 days when grown with air at a mean of 20C and at an irradiance of 6.5 mol·day^{-1}·m^{-2}. However, when the intensity was doubled, the plants flowered in only 56 days. At the higher irradiance, the average temperature could be lowered to 15C and plants still would flower at the same time as those grown at 20C at the lower irradiance. The plants could be held at a high NT with little heating during the day. This procedure would result in fuel savings for commercial applications using heat blankets, since only the small area under the blanket would be raised to the higher temperature at night. Time to flower would not increase.

Plant height (Table 2, Fig. 3) increased as DT increased or as irradiance decreased. Plant height was influenced more by low irradiance at 30C DT than at 10C DT. Plants grown at 10C DT and an irradiance of 13 mol·day^{-1}· m^{-2} were similar in height to those grown at the lower irradiance and corresponding NT. However, as DT increased, the difference in plant height at the same NT/DT combination increased when the two irradiances were compared (Fig. 4). Plants grown under 13 mol·day^{-1}·m^{-2} at 30C DT were up to 6 cm shorter than plants grown under 6.5 mol·day^{-1}·m^{-2} and 30C DT. Plants grown at a constant 20C at either irradiance were much taller than expected, based on the data collected from plants from the other treatments. Since this response could not be reproduced in subsequent trials, we considered it anomalous and data from these treatments were not used in data analysis for plant height or average internode length.

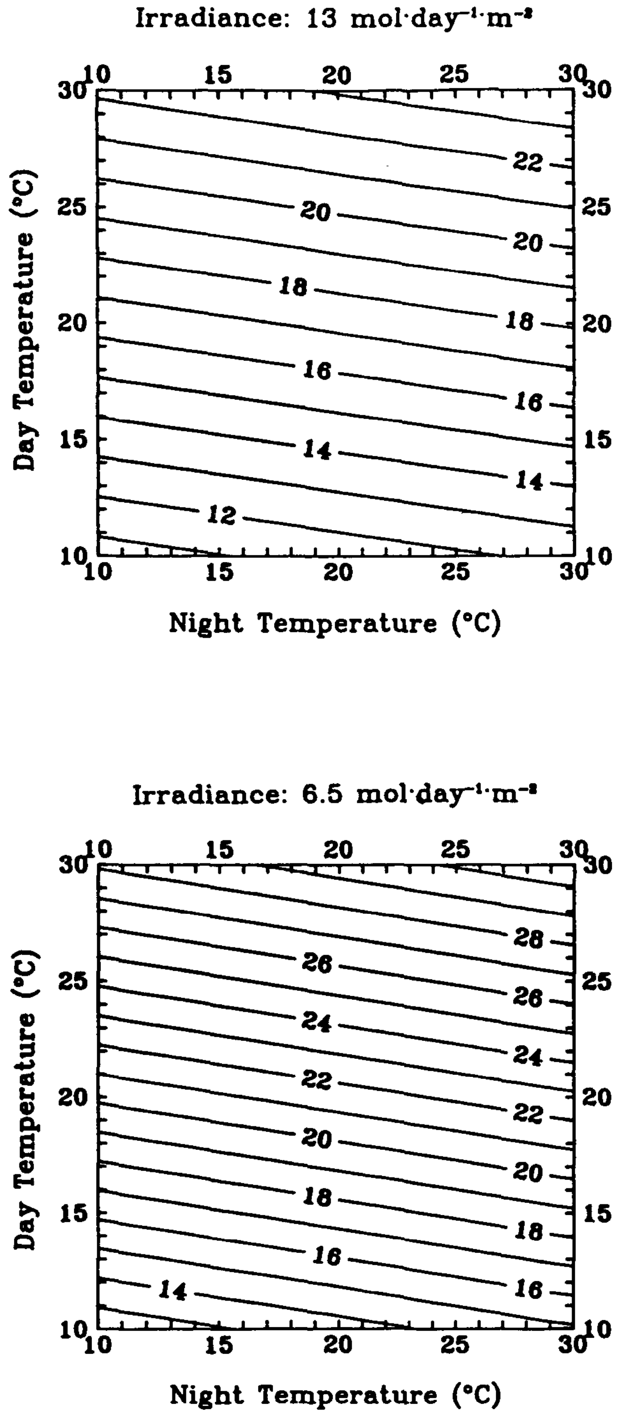

Fig. 3. Isopleth plots of plant height (in centimeters) for varying combinations of night and day temperature between 10 and 30C for *Petunia* × *kybrida* 'Snow Cloud' at: **(top)** 13 mol·day^{-1}·m^{-2} [plant height = 3.78643 + (0.3204·DT) + (0.35232·AVG)], r^2 = 0.750 and **(bottom)** 6.5 mol·day^{-1}· m^{-2} (plant height = 3.01463 + (0.40296·DT) + (0.5216·AVG)], r^2 = 0.810.

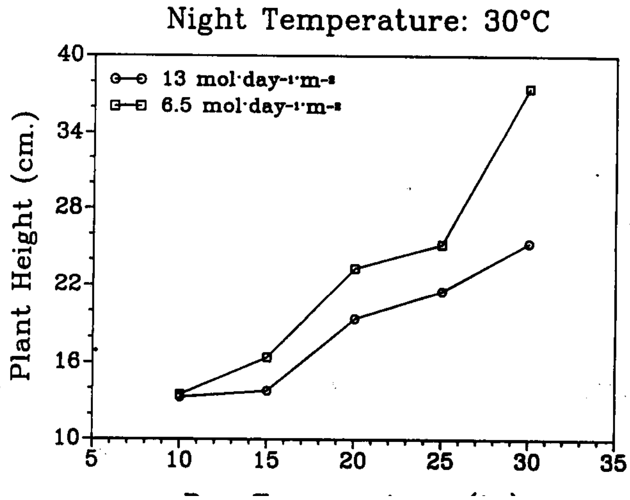

Fig. 4. Plant height for *Petunia* × *hybrids* 'Snow Cloud' at 30C NT and DT between 10 and 30C at irradiances of 13 and 6.5 $mol \cdot day^{-1} \cdot m^{-2}$.

Table 3. Mean average internode length (cm) for *Petunia* × *hybrida* 'Snow Cloud' in response to day and night temperatures between 10 and 30C and high or low irradiances (13 or 6.5 $mol \cdot day^{-1} \cdot m^{-2}$) for an 18-h photoperiod.

	Temp (°C)				
	Day				
Night	10	15	20	25	30
		High irradiance			
10	0.6	0.6	1.0	1.1	1.2
15	0.6	0.9	0.8	1.1	1.3
20	0.6	0.7	1.4	1.2	1.3
25	0.6	0.7	1.0	1.0	1.1
30	0.7	0.7	1.1	1.3	1.2
		Low irradiance			
10	0.7	1.0	1.2	1.4	1.5
15	0.7	1.0	1.3	1.6	1.5
20	0.8	1.0	1.6	1.5	1.5
25	0.9	0.9	1.2	1.5	1.5
30	0.8	0.9	1.4	1.4	1.9
Significance					
NT		*	NT × DT		*
DT		***	NT × I		NS
Irradiance (I)		***	DT × I		***
			NT × DT × I		***

NS,*,***Nonsignificant or significant at $P = 0.05$ or 0.001, respectivelv.

Plant height was dependent on internode length, since all plants flowered with a similar number of nodes on the main stem. The effects of DT and irradiance on average internode length were similar to their effects on plant height. As DT increased, average internode length increased significantly (Table 3). Likewise, plants at the lower irradiance had longer average internode lengths than plants at the higher irradiance. The effect of NT was less significant than either DT or irradiance (Fig. 5).

Krizek et al. (1972) reported that increasing both DT and NT increased plant height in petunia seedlings. However, they only used three temperature regimes in which an increase in NT accompanied an increase in DT. They did not discuss separate effects of NT and DT, just the combined effects.

The difference between day temperature and night temperature (DIF) has been shown to influence internode length and plant height (Erwin et al., 1989). Internode length increases as DIF increases. DIF did not have as great an effect in this experiment as has been seen in other plants. However, the 18-h photoperiod may have decreased the effect of DIF, and DIF might have been more apparent if a shorter photoperiod had been selected.

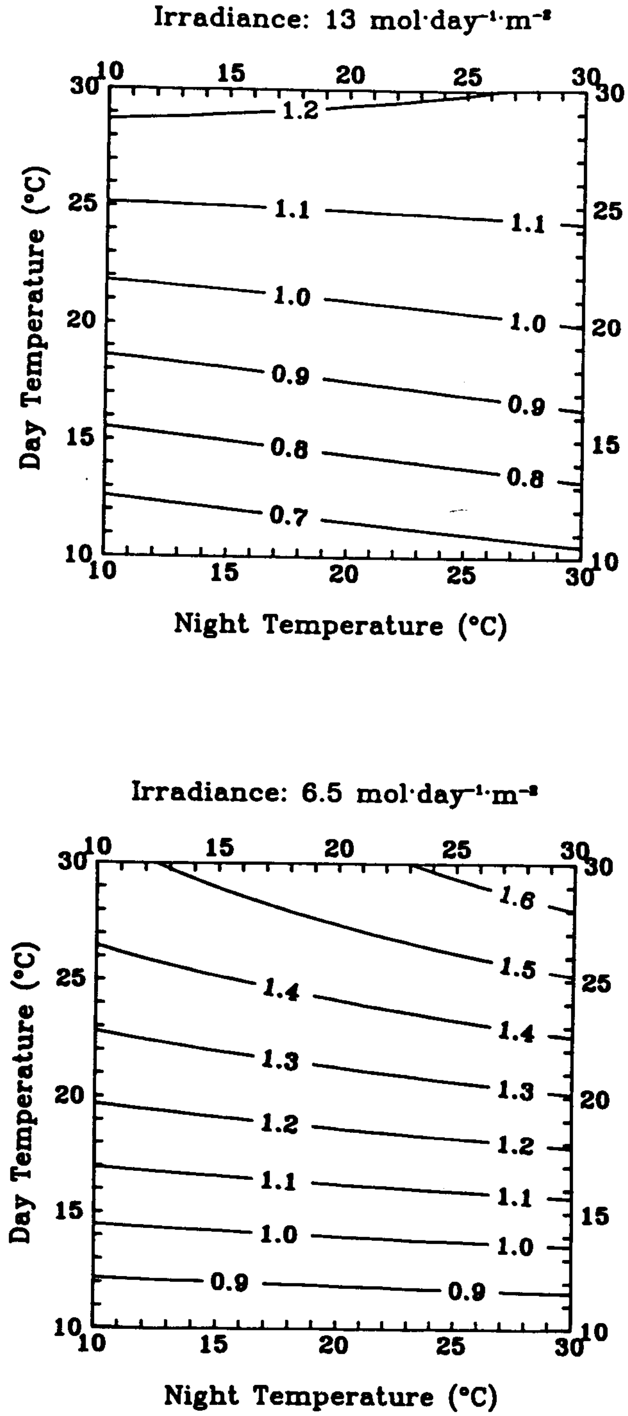

Fig. 5. Isopleth plots of average internode length (in centimeters) for varying combinations of night and day temperatures between 10 and 30C for *Petunia* × *hybrida* 'Snow Cloud' at: **(top)** 13 $mol \cdot day^{-1} \cdot m^{-2}$ [average internode length = $0.143507 + (0.037663 \cdot DT) + (0.00063527 \cdot DT \cdot NT) - (0.000023821 \cdot NT \cdot DT^2)$], $r^2 = 0.733$; **(bottom)** 6.5 $mol \cdot day^{-1} \cdot m^{-2}$ [average internode length = $0.13144 + (0.069617 \cdot DT) - (0.0009204 \cdot DT^2) + (0.000011519 \cdot NT \cdot DT^2)$], $r^2 = 0.809$.

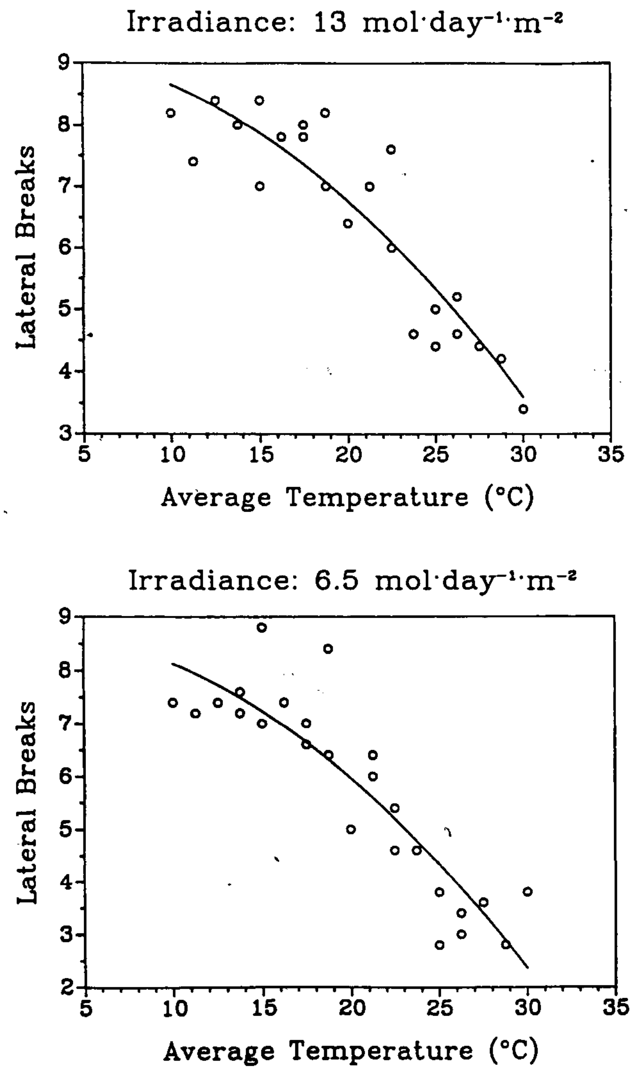

Fig.6. Lateral shoots formed by *Petunia* × *kybrida* 'Snow Cloud' in response to average daily temperature (AVG) between 10 and 30C for **(top)** 13 mol·day^{-1}·m^{-2} [number of shoots = 9.29607 – (0.00634·AVG^2)], r^2 = 0.837; **(bottom)** 6.5 mol·day^{-1}·m^{-2} (number of shoots = 8.85987 – (0.00723·AVG^2)], r^2 = 0.801.

The number of lateral shoots formed by the plants was a function of average temperature (Table 4). Plants formed a similar number of lateral shoots at both irradiances. As average temperature increased, the number of lateral shoots decreased (Fig. 6). The average length of each lateral shoot varied widely within each plant. However, average length was strongly influenced by day temperature (Table 5) —as day temperature increased, the average length decreased. Night temperature had no effect.

Previous work showed that higher temperatures decreased lateral branching in petunia (Carpenter, 1974; Carpenter and Carlson, 1974; Piringer and Cathey, 1960), similar to the results found in this study. Petunia and other crops have also shown increased lateral branching when light intensity increased (Carpenter, 1974; Erickson et al., 1980). An increase in lateral branching under a higher intensity was not evident from our data. However, the higher intensity used in this study (200 µmol·s^{-1}·m^{-2}) was not as high as intensities used in other experiments (533 µmol·s^{-1}·m^{-2}) (Carpenter, 1974).

Plant quality is the main underlying factor to consider when

Table 4. Mean lateral shoot number for *Petunia* × *hybrida* 'Snow Cloud' in response to day and night temperatures between 10 and 30C and high or low irradiances (13 or 6.5 mol·day^{-1}·m^{-2}) for an 18-h photoperiod.

	Temp (°C)				
	Day				
Night	10	15	20	25	30
		High irradiance			
10	8.2	8.0	8.0	7.0	5.0
15	7.4	7.0	7.0	6.0	4.6
20	8.4	7.8	6.4	4.6	4.4
25	8.0	7.8	7.0	4.4	4.2
30	8.4	8.2	7.6	5.2	3.4
		Low irradiance			
10	7.4	7.2	7.2	6.0	3.8
15	7.2	7.0	6.4	5.4	3.0
20	7.4	7.4	5.0	4.6	3.6
25	7.6	7.0	6.4	2.8	2.6
30	8.8	8.4	4.6	3.4	3.8
Significance					
NT		***	NT × DT		***
DT		***	NT × I		NS
Irradiance (I)		***	DT × I		NS
			NT × DT × I		NS

NS,***Nonsignificant or significant at P = 0.001, respectively.

Table 5. Mean lateral shoot length (in centimeters) for *Petunia* × *hybrida* 'Snow Cloud' in response to day and night temperatures between 10 and 30C and high and low irradiances (13 or 6.5 mol·day^{-1}·m^{-2}) for an 18-h photoperiod.

	Temp (°C)				
	Day				
Night	10	15	20	25	30
		High irradiance			
10	8.1	8.2	6.0	2.7	1.3
15	7.7	8.2	7.0	2.4	1.8
20	8.7	7.4	4.1	2.3	0.8
25	8.4	8.3	7.2	2.6	1.2
30	9.7	7.7	6.5	2.0	0.9
		Low irradiance			
10	8.1	8.1	6.5	2.4	0.8
15	7.2	5.6	4.5	1.7	0.6
20	8.1	7.2	3.2	2.1	1.9
25	9.6	7.8	3.7	1.7	1.3
30	7.4	5.6	4.0	3.0	1.0
Significance					
NT		NS	NT × DT		NS
DT		***	NT × I		NS
Irradiance (I)		*	DT × I		NS
			NT × DT × I		NS

NS,*,***Nonsignificant or significant at P = 0.005 or 0.001, respectively.

selecting combinations of irradiance, day temperatures, and night temperatures for forming plant production strategies for petunia. Plant growth can be increased by raising temperatures (Krizek et al,, 1972), but this increased growth rate will also result in lower plant quality by increasing plant height and reducing lateral branching (Merritt and Kohl, 1982; Piringer and Cathey, 1960). Lateral branching and reduced plant height, resulting in increased quality, can be obtained by lowering the growing temperatures. However, this strategy will result in a corresponding delay in time to flower and an extended production period.

Individual growers must first determine the quality their particular market will demand. Only then can a proper selection of combinations of temperature and irradiance be made to produce petunias of desired quality in the shortest time.

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