High Pressure Sodium Irradiation and Infrared Radiation Accelerate *Petunia* Seedling Growth

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Abstract. The increase in photosynthetic photon flux (PPF) and plant temperature associated with supplemental high pressure sodium (HPS) irradiation were investigated during *Petunia* × hybrids Villm. 'Red Flash' seedling development. Seedlings were treated for 14 days following emergence or 5 days after the first true leaf had expanded to 1 mm. Treatments consisted of continuous infrared (IR) radiation (Ambient + IR), ambient conditions with spill-over radiation from adjacent treatments (Ambient - IR), root zone heating to 19.5C (RZ Heat), continuous HPS irradiation at 167 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ PPF (HPS + IR) or continuous HPS irradiation at 167 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ PPF filtered through a water bath to remove IR (HPS - IR). Linear regression of natural log-transformed fresh weights indicated that increasing ambient PPF 53% and elevating plant temperature 4.3C (HPS + IR) increased seedling relative growth rate (RGR) by 45% compared with the control (Ambient - IR). Elevating plant temperature with + IR by 4.8C without supplementing PPF (Ambient + IR) increased RGR by 31% but failed to increase fresh weight (FW) above controls and resulted in etiolated plants that were unsuitable for transplanting. Once plants were removed from supplemental treatment and returned to ambient conditions, RGR for all treatments was similar. The increased FW promoted by IR and HPS treatments was maintained for up to 7 days after treatment. Therefore, the increased seedling growth responses observed with HPS treatment were due primarily to an increase in RGR during HPS treatment that is not sustained beyond treatment.

Accelerating early seedling growth results in increased dry weight (DW) accumulation throughout the development of the crop when compared with treatment at later stages of development. The stimulation of early seedling growth results in earlier flowering and increased yield (Krizek et al., 1968; Lawrence and Calvert, 1953). *Begonia semperflorens* L. exhibited accelerated growth with the application of 27C supplemental root zone heating (Graper and Healy, 1987a). Treatment of *Petunia* with continuous 1000 fc ($\approx 200 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$) supplemental light, 7 days after sowing, using 400-W Lucalux (HPS) for 10 or 15 days, decreased days to flower by up to 18% compared with plants grown under natural short days (Carpenter and Carlson, 1974). *Petunia* seedlings were transplantable 1 to 2 weeks earlier (Wolnick and Mastalerz, 1969) and seed geranium seedlings up to 60 days earlier (Armitage et al., 1978) when grown with supplemental fluorescent light.

Treating *Petunia*, *Ageratum*, and *Tagetes* plants with 2000 to 2500 fc (≈ 320 to $350 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ PPF) from mixed fluorescent and incandescent lighting at 30C resulted in a 12-fold increase in FW accumulation compared with plants grown under natural days in the greenhouse at 24C during January and February (Krizek et al., 1968). Treatment of *Lycopersicon esculentum* Mill., *Cucumis sativus* L., and *Lactuca sativa* L. under 30/24C (day/night) and 2000 $\mu\text{l CO}_2$ /liter compared to 24/18C and 350 $\mu\text{l CO}_2$ /liter resulted in a 7-fold increase in FW (Krizek et al., 1974).

Petunia seedling DW at the six-leaf stage increased 47% and plants reached anthesis 11 days earlier when HPS of 120 to 240 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ was applied continuously to *petunia* during days 10 to 15 after seedling emergence (Graper and Healy, 1987b;

Graper et al., 1990). A HPS treatment applied during the first 10 days or after 20 days post-germination was not as effective as treatment during this critical period of development (Lang and Healy, 1985). A 10-day HPS treatment to *Begonia* × *semperflorens*, using a similar irradiance, increased DW by 20% at transplant if the supplemental irradiance treatments were given during days 5 to 20 post-seedling emergence (Graper and Healy, 1987a, 1990).

Supplemental lighting in the greenhouse often involves the use of HPS lamps as the irradiation source. HPS lamps emit $\approx 27\%$ PPF with the remaining 73% as thermal radiation with further losses due to conduction and convection (Bubenheim et al., 1988). Thus, supplemental lighting can significantly increase plant temperature through radiant heating, especially when high irradiance levels are used.

The purpose of this study was to determine the contribution of supplemental PPF vs. thermal radiation on early *petunia* seedling development. To separate the effects of thermal radiation from PPF, supplemental HPS irradiance was provided with or without thermal radiation, while the ambient PPF occurred with or without supplemental thermal radiation. Effects of elevated leaf and soil temperatures were also studied using root zone heating.

Materials and Methods

Petunia × *hybrida* 'Red Flash' seed was sown into plug flats (cell size $1.4 \times 1.4 \times 2.5$ cm tall; cell vol. = 2.6 cm^3 ; 512 cells per flat) filled with Redi-Earth peat-lite mix (W.R. Grace, Cambridge, Mass.). One seed was sown per cell using an Old Mill Seeder (Old Mill Co., Savage, Md.). The seeds were germinated under intermittent mist in a 21C glasshouse with the medium at 27C. Experiments were conducted from 2 Feb. through 1 Apr. 1988.

Plants were moved to an 18C glasshouse and grown under ambient light conditions until the cotyledons expanded to the horizontal on 80% of the emerging seedlings. Plants were irri-

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Abbreviations: DW, dry weight; FW, fresh weight; HPS, high pressure sodium; IR, infrared; PPF, photosynthetic photon flux; RGR, relative growth rate.

gated as needed, using intermittent overhead mist and fertilized daily with 15–16–17 (15N-7P-14.K) (W.R. Grace, Fogelsville, Pa.). The fertilizer concentration was increased from 50 to 100mg·liter⁻¹ as seedlings grew from the one- to four-leaf stage.

Five treatments were designed to study the effects of continuous supplemental PPF vs. supplemental thermal radiation. Treatments not irradiated with HPS received “spill-over” irradiation from adjacent treatment areas (Table 1). The treatments were as follows: 1) Ambient greenhouse conditions without supplemental IR (Ambient – IR); 2) supplemental IR radiation supplied by a 400-W electrical resistance “cone heater”, mounted in a reflector and suspended ≈75 cm above the plants (Ambient + IR); 3) unfiltered HPS irradiation (167 μmol·s⁻¹·m⁻² supplied by vertically mounted 400-W lamps (HPS + IR); 4) HPS irradiation filtered through a 12-cm-deep plexiglass circulating water bath maintained at ≈15C (HPS – IR); and 5) ambient greenhouse conditions with root zone heating provided by an electrical heating mat controlled at ≈20 C (RZ Heat).

Plants in the supplemental heating treatments RZ Heat and Ambient + IR maintained either a similar leaf or root zone temperature as plants being irradiated with HPS (Table 1). The HPS – IR provided the same PPF level as in the HPS + IR treatment without increasing plant temperature (Fig. 1, Table 1). Root zone temperatures were monitored by using 24-gauge (0.51 mm diam) copper/constantan thermocouples placed in the growing medium ≈1 cm deep. Plant temperatures were monitored by using a 40-gauge (O. 12 mm diam) copper/constantan thermocouple attached to the underside of a fully expanded leaf with paper tape. PPF levels were continuously monitored during the experiments using LI-200SA quantum sensors (LI-COR, Lincoln, Neb.) and compiled using a Campbell Scientific data logger (Campbell Scientific, Logan, Utah).

Ambient PPF measured in the Ambient – IR and Ambient + IR treatments fluctuated between 1 and 7 mol·day⁻¹·m⁻² PPF (Fig. 1). The 24-h supplemental HPS irradiance treatments, HPS + IR and HPS – IR, increased the total daily PPF ≈2.4–fold.

In Expt. 1 sown 2 Feb., seedlings were placed into the treatments 5 days after seeding, when 80% of the cotyledons had expanded and remained under treatment for 14 days. The other experiments were sown 20 Feb., 23 Mar., or 1 Apr., with treatments starting once the first true leaf was 1 mm long on 80% of the seedlings (12 days after seeding). Treatments continued for 5 days. At the end of this period, the plants were removed from the treatment area and grown under ambient light at 21C in the greenhouse to observe subsequent development.

Ten shoots were collected for each sample from each experimental unit, which consisted of one-half of a 512-plug flat.

Plant samples were collected every 24 or 48 h and weighed to determine shoot FW. To maintain consistent samples, flats were thoroughly irrigated and placed on a greenhouse bench to allow the foliage to dry before sampling. The number of leaves unfolded to a horizontal position in each experimental unit was recorded.

The FW was used rather than DW, due to the small size of the plants. Once seedling size had increased, after day 10, DW was used to compare trends observed using FW. The mean percent DW of all treatments was 7.9% ± 0.3% of FW and was similar for all treatments. The relative growth rate, expressed as FW (RGR), was calculated and presented as the slope of the regression lines. Each treatment consisted of four replications and two experimental units. Means were separated using SAS General Linear Models procedure single-degree-of-freedom comparisons (SAS Institute, Cary, N.C.). Data were transformed using natural log to linearize the data before regression analysis.

Results

Experiment 1 was designed to develop a baseline RGR response under continuous treatment. Supplemental HPS and IR treatments significantly accelerated the rate of plant FW accumulation compared with the plants in the Ambient – IR treatment. The greatest increase in seedling FW occurred under unfiltered HPS (HPS + IR). The FW of HPS – IR averaged 12% less than HPS + IR. Although seedlings in the HPS – IR and Ambient + IR treatments had comparable amounts of FW by the end of the experiment, seedlings in the Ambient + IR treatment were etiolated and not acceptable transplants. Daily RGR values were variable but in general the supplementary lighting and IR treatments had 17% higher RGR than the Ambient – IR treatment, as indicated by the slope of each linear regression equation (Fig. 2).

Observations of leaf development indicated that expansion of the first true leaf began during 5 to 8 days post-seedling emergence (data not presented). Higher RGR values also were recorded during this period. Therefore, the development of the first true leaf to 1 mm in length was used as a physiological marker to begin the 5-day supplemental treatments in subsequent experiments.

As observed in Expt. 1, the RGR for Ambient + IR and HPS + IR differed significantly from the Ambient – IR (Fig. 3). The rate of FW accumulation increased dramatically with the HPS + IR and HPS – IR treatments. The FW of HPS + IR and HPS – IR was 88% and 68% higher than Ambient – IR by day 12 post-seedling emergence, respectively, while the FW of the HPS + IR treatment averaged 38% higher than the Ambient – IR treatment (Fig. 3). Regression lines of seedlings

Table 1. Night quantum sensor PPF, Eppley radiometer irradiance (280 to 2800 nm) measurements (&SE) and plant leaf and root zone temperatures (C ± SE) for each of the five treatments: Ambient – IR, continuous supplemental IR heating (Ambient + IR), continuous supplemental HPS that was filtered through a water bath to remove IR (HPS – IR), continuous unfiltered supplemental HPS irradiation (HPS + IR), and supplemental root zone heating (RZ Heat).

Treatment	PPF (μmol·s ⁻¹ ·m ⁻²)	Irradiance (W·m ⁻²)	Temp (°C)	
			Leaf	Root zone
Ambient – IR	6.2 ± 0.8 ^z	1.7 ± 0.4	15.9 ± 2.1	15.8 ± 2.5
Ambient + IR	12.6 ± 4.2	11.1 ± 3.9	20.7 ± 2.1	19.4 ± 1.7
HPS – IR	167.3 ± 5.3	48.4 ± 1.8	18.4 ± 1.8	17.8 ± 1.5
HPS + IR	166.8 ± 6.6	79.6 ± 2.9	20.2 ± 2.6	19.4 ± 1.8
RZ Heat	8.6 ± 0.6	2.6 ± 0.5	18.8 ± 1.2	19.5 ± 1.6

^zEight measurements were made at equal distances from the center of the treatment area at the seedling leaf height in each treatment.

Fig. 1. Total integrated PPF for 6 to 21 Apr. corresponding today's 0 to 15 post-seedling emergence. The treatments were: continuous spill-over irradiation ($\square$, Ambient - IR), continuous supplemental IR heating ($\blacksquare$, Ambient + IR), unfiltered HPS irradiation ($\bullet$, HPS + IR) and HPS irradiation filtered through a water bath to remove IR ($\circ$, HPS - IR).

Fig. 2. Linear regression models of natural log-transformed cumulative FW of *Petunia* 'Red Flash' seedlings. The four treatments were Ambient - IR ($\square$), continuous supplemental IR heating ($\blacksquare$, Ambient + IR), unfiltered HPS irradiation ($\bullet$, HPS + IR), and HPS irradiation filtered through a water bath to remove IR ($\circ$, HPS - IR). Plants were treated days 0 through 14 post-seedling emergence. The linear regression equations are: HPS + IR $2.21 + 0.31$ (Day), $r^2 = 0.95$; HPS - IR $2.22 + 0.29$ (Day), $r^2 = 0.97$; Ambient + IR $1.90 + 0.30$ (Day), $r^2 = 0.96$; Ambient - IR $1.78 + 0.25$ (Day), $r^2 = 0.97$. Lines with different letters were significantly different using single-degree-of-freedom contrasts. Ten plants were sampled at each date with each treatment replicated four times.

treated with RZ Heat and Ambient - IR were parallel and had similar intercepts (data not presented). Supplemental RZ Heat to 20C, therefore, had little impact on seedling development.

The increase in FW described with HPS treatment was sustained only as long as the supplemental irradiance was applied

Fig. 3. Linear regression models of natural log-transformed cumulative FW of *Petunia* 'Red Flash'. The effects of the four treatments are compared during the treatment period of days 7 to 12 post-seedling emergence and following treatment during days 12 to 19. Plants were grown under ambient conditions during days 12 to 19. The treatments were Ambient - IR ($\square$), continuous supplemental IR heating ($\blacksquare$, Ambient + IR), unfiltered HPS irradiation ($\bullet$, HPS + IR), and HPS irradiation filtered through a water bath to remove IR ($\circ$, HPS - IR). Data presented are the combined results from three separate experiments sown 20 Feb., 23 Mar., and 1 Apr. The linear regression equations for the period from day 7 to 12 are: HPS + IR, $1.13 + 0.34$ (Day), $r^2 = 0.90$; HPS - IR, $1.25 + 0.33$ (Day), $r^2 = 0.89$; Ambient + IR $1.67 + 0.27$ (Day), $r^2 = 0.84$; Ambient - IR, $2.03 + 0.21$ (Day), $r^2 = 0.078$, while the regression equations for day 13 to 19 are: HPS + IR, $1.96 + 0.27$ (Day), $r^2 = 0.98$; HPS - IR, $1.83 + 0.27$ (Day), $r^2 = 0.98$; Ambient + IR, $1.65 + 0.27$ (Day), $r^2 = 0.97$; Ambient - IR, $1.37 + 0.27$ (Day), $r^2 = 0.98$. Regression models with different letters are significantly different using single-degree-of-freedom contrasts.

(Fig. 3). Once the treatment period ended on day 12, the increase in FW was similar in all treatments regardless of previous treatment (Fig. 3). However, the FW 7 days after treatment had stopped was 90% higher (based on actual FW) in HPS + IR treated plants than in Ambient - IR as a result of the increased rate of growth during treatment.

An Eppley radiometer was used during the night to determine the total supplemental irradiation from 285 to 2800 nm. Although the range of the Eppley is restricted to relatively short longwave radiation, $\approx 60\%$ of the energy at those wavelengths was absorbed by the plexiglass and 12 cm of water (HPS - IR, Table 1). A recent report by Bubenheim et al. (1988) reported that $\approx 70\%$ of the shortwave radiation (285 to 2800 nm) emitted from HPS lamps was removed by a plexiglass barrier with 4-cm-deep water. They went on to measure the longwave radiation (2800 to 100,000 nm) using a Fritschen net pyradiometer and found that this same plexiglass and water barrier removed 94% of the radiation in those wavelengths. Therefore, the water barrier used in these experiments was effective in limiting the thermal radiation reaching plants in the HPS - IR treatment.

Discussion

Lawrence and Calvert (1953) reported that treatment of tomato seedlings with 500 fc ($\approx 80 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$) cool-white

fluorescent light for 2 weeks resulted in faster growth, flowering 8.5 days earlier, and 27% greater fruit production throughout the life of those plants. The source of this precocious development may have been the result of a sustained increase in RGR or the compounded growth of seedlings that grew more vigorously during treatment. Our results indicated that increased RGR, expressed as FW, was not sustained following treatment with supplemental irradiance or IR, but rather RGR returned to a rate similar to the Ambient – IR treatment (Fig. 3). Therefore, increased RGR can only be achieved when seedlings are exposed to supplemental irradiance or elevated radiant temperatures.

When the FW of plants had increased during the treatment, it remained higher for up to 7 days following the return of the plants to ambient conditions. Thus, the increase in plant size observed after irradiation with HPS supplemental treatments may be the result of an increase in cell size or the number of cells produced during treatment, which then subsequently continued to divide at a relatively constant rate.

Leaf area of *Capsicum annuum* and *Lycopersicon esculentum* increased due to elevated root zone temperatures (Gosselin and Trudel, 1984). Petunia plants had 38% more leaf area and 47% greater DW (Graper et al., 1990; Merritt and Kohl, 1982) when root zone temperatures were 6 to 30C higher than the control. Our RZ Heat treatment increased root zone temperature by 4C and was not an effective means of increasing FW.

Using supplemental IR to increase leaf temperature 5C (Table 1) increased FW by 40% despite the reduction in plant quality. (Figs. 2 and 3). Leaf temperatures were increased to a similar degree by HPS + IR. However, HPS was more effective than supplemental IR in elevating total FW accumulation. HPS produced more vigorous, compact, darker green seedlings than Ambient + IR. When the thermal radiation was filtered from HPS, the IR-induced growth response was diminished but not to the extent observed when only thermal irradiation was used (Ambient + IR). A synergism between supplemental irradiance and leaf temperature was indicated by our results and expands on work by Downs (1985). Our data support his observation that, although plant growth was related to increased supplemental irradiance treatment, there was a clear interaction between supplemental irradiance and substrate/foliage temperature on plant growth. Whereas Downs suggested that the role of supplemental irradiance during the dark period may simply be a leaf and substrate warming response, our results showed that growth rate was more directly influenced by supplemental irradiance than by IR (Fig. 3).

Our work showed that PPF plays a greater role in the ultimate development of petunia seedlings than the increase in plant tem-

perature associated with using HPS or IR irradiation. The role of photoperiod, photosynthetic period, peak and total daily PPF on seedling petunia development and carbohydrate partitioning needs further investigation.

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