INTRACANOPY LIGHTING AS A SOLE SOURCE OF IRRADIATION FOR PLANOPHILE CROP CANOPIES IN CONTROLLED ENVIRONMENTS

J. M. Frantz*, C. Chun, R. J. Joly, and C. A. Mitchell**

Department of Horticulture and Landscape Architecture, Purdue University, West Lafayette, Indiana 47907-1165, USA

*Present Address: Department of Plants, Soils, and Biometeorology, Utah State University, Logan, Utah 84322-4820, USA

**Present Address: Laboratory of Environmental Control Engineering, Chiba University, 648 Matsudo, Chiba 271-8510, JAPAN.

Abstract

Mutual shading attenuates photosynthetic photon flux (PPF) below the light-compensation point within closed canopies of overhead-lighted crop stands. This causes loss of productivity and senescence of lower leaves in dense stands of planophile crops (leaves aligned perpendicular to the plane of incident light). The usual attenuation of blue and red wavelengths in the understory of overhead-lighted canopies is absent in intracanopy-lighted canopies. Deployment of low-intensity light sources within foliar canopies permits leaves to remain physiologically active because they do not need to adapt to a changing light environment. As a result, senescence of lower leaves can be significantly delayed within cowpea (*Vigna unguiculata* L. Walp) crop stands lighted by 15-W fluorescent lamps arrayed within the canopy. Lamina and petioles re-oriented so that adaxial leaf surfaces faced the nearest tubular lamp. Intracanopy lighting with low-PPF photosynthetically-active radiation (PAR) yielded half as much crop biomass as did overhead lighting with high-PPF PAR, but did so consuming only 10% as much electrical energy for lighting. The heat load associated with low-irradiance intracanopy lighting raised leaf temperature no more than 2°C above ambient air temperature without activating the air-conditioning/heat-rejection system, which ran constantly with high-irradiance overhead lighting. Intracanopy lighting with relatively cool light sources that are low in mass, volume, and power requirement and which have an emission spectrum that matches absorption maxima of major pigment systems have a promising future for controlled environment agriculture on Earth and in

Introduction

Traditional designs for plant-growth lighting in controlled environments have lamps positioned overhead (Knight and Mitchell 1988, Salisbury and Bugbee 1985, Tibbitts et al., 1983). Once foliar canopies of planophile crops close, upper leaf layers “mutually shade” the lower leaf canopy and drastically limit the photosynthetically active radiation (PAR) reaching the understory of the crop stand (Ohler and Mitchell 1995). The inner leaves of closed-canopy, overhead-lighted crop stands experience drastic loss of photosynthetic productivity, and leaf senescence and abscission occur with canopy closure (Frantz et al. 1998).

Experimental

An alternative plant-growth-lighting strategy for controlled environments is "intracanopy" lighting, which avoids mutual shading within closed crop canopies by deploying electrical lamps within the canopy and allows plants to grow around the lamps (Fig. 1). Fluorescent lamps were suspended by fish line in three-dimensional space, remote from their ballasts and switches to

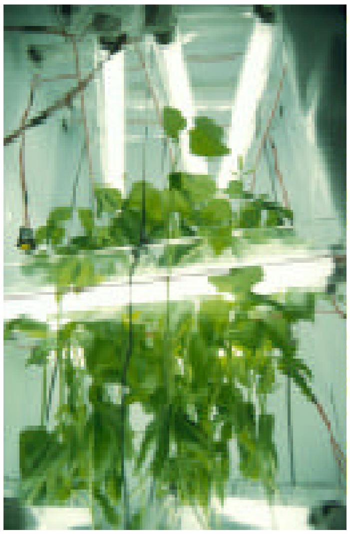

Figure 1. A stand of cowpea plants growing within a three-tiered array of horizontal fluorescent lamps.

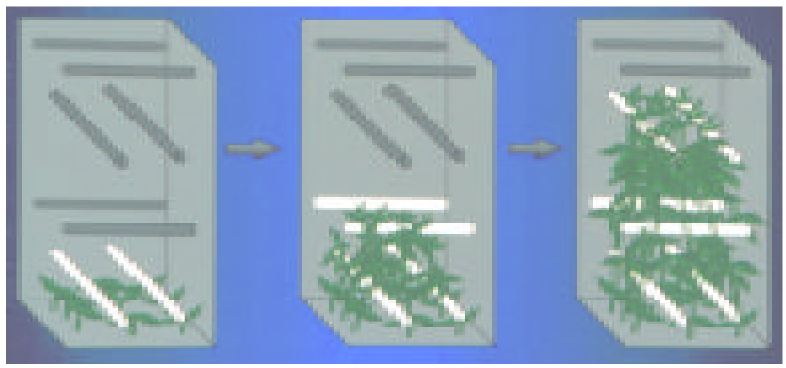

Figure 2. Schematic of a crop stand at three different stages of development with sequential energizing of horizontal intracanopy lamps.

reduce heat load and dead volume within the canopy. Heat load is further reduced by using short, low-voltage lamps and sleeving the tubes with transparent mylar film. An additional energy-saving feature of intracanopy lighting when lamps are arrayed horizontally within different vertical planes is that not all lamps need to be energized at once (Fig. 2). Groups of lamps can be energized sequentially upward to keep pace with increasing height of the crop stand. When cowpea (*Vigna unguiculata* L. Walp) was used as a test crop, both primary and trifoliate leaves reoriented so that the adaxial side of each leaf faced the nearest lamp or the brightest zone of diffuse light (Fig. 3).

Figure 3. Primary leaves of cowpea (top) under above-canopy lighting or (bottom) within intracanopy-lighted space, where leaves curl, fold, or align the adaxial surface toward the closest lamps (Frantz et al. 2001).

Harvest parameters for intracanopy-lighted cowpea stands were significantly greater than those for overhead lighted stands even though total lighting energy was equivalent for both treatments (Table 1). The results indicate that the availability of light within the leaf canopy made the difference in stand productivity.

Table 1. Average harvest-parameter totals for intracanopy (IC)-lighted and overhead (OH)-lighted cowpea stands (Frantz et al. 2000)

Harvest parameter	IC	OH	P^z
Leaf dry mass ($g \cdot m^{-2}$)	149.2	78.1	<0.0001
Stem dry mass ($g \cdot m^{-2}$)	124.9	104.8	<0.001
Root dry mass ($g \cdot m^{-2}$)	20.7	14.5	<0.02
Energy use (MJ/m^2)	11.3	12.2	NS^y

[z] Each treatment was replicated three times (n=3). *P* obtained from *t* test of means between the two treatments.
[y] Nonsignificant.
Note: 1 MJ = 3.6 kW-h

Compared to traditional overhead crop lighting, spectral energy distribution within intracanopy-lighted cowpea stands was relatively stable as the canopy aged (Fig. 4).

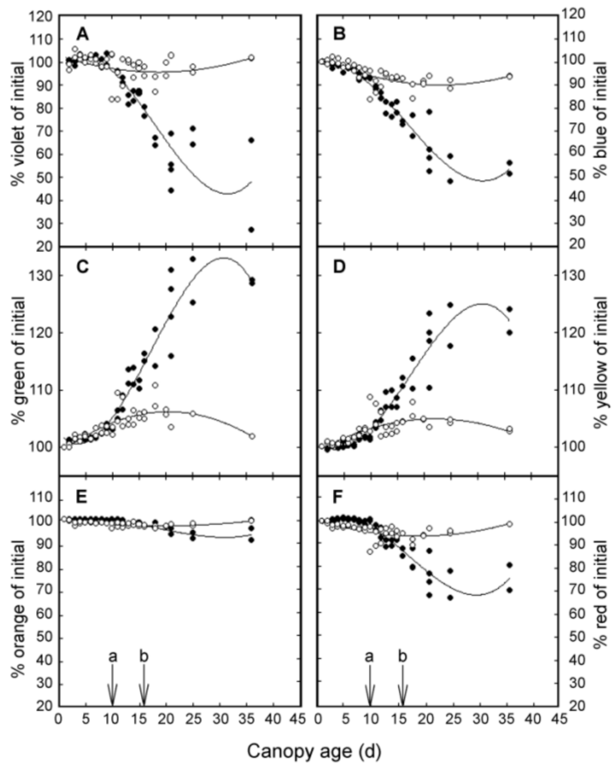

Figure 4. Relative spectral energy distribution over time for radiation incident upon cowpea primary leaves within canopies either overhead lighted (closed symbols) or intracanopy lighted (open symbols). Wavebands are (A) violet, (B) blue, (C) green, (D) yellow, (E) orange, and (F) red (Frantz et al. 2000).

For overhead-lighted canopies, however, wavebands typically absorbed by photosynthetic pigments (violet, blue, red), rapidly declined in radiation within the interior canopy, and the decline continued as the canopy aged. There was a relative increase in the green and yellow components of ambient light in the interior of overhead-lighted canopies, which were depleted of more useful wavebands by the upper leaf layers. In contrast, the spectral composition of white light was quite stable in the understory of intracanopy-lighted cowpea stands. This stability delayed leaf senescence 27 days beyond when interior leaves of overhead-lighted cowpeas began to turn yellow, which was on day 16 of crop growth.

Tubular fluorescent lamps can be arrayed within growth-compartment volume in many different geometric orientations. An inverted-pyramid configuration (A) and a horizontal configuration of lamps (B) gave contrasting PAR light maps for the same number of lamps (8) within two similar growth compartments (Fig. 5). PPF was lower in the mid-compartment volume and more diffuse throughout for the pyramid configuration than for the stacked horizontal one. Light concentrated vertically in the center core of the latter compartment but decreased gradually in all directions toward the walls and corners. Cowpea canopies yielded the same regardless of lamp configuration (Table 2). The horizontal lamp configuration was slightly more efficient utilizing light energy because tiers of horizontal lamps were energized in four different stages, keeping pace with increasing height of the crop canopy, whereas there were only two tiers of pyramidal lamps, and the far ends of the lamps were beyond the top of the canopy when they were first switched on. Although the plasticity of leaf development and orientation permits cowpea foliar

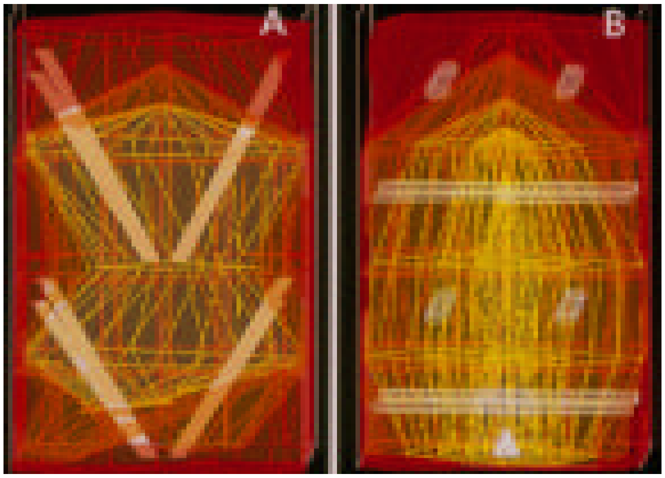

Figure 5. Light maps for (A) an inverted two-tier pyramid intracanopy-lighting configuration versus (B) a four-tier horizontal intracanopy-lighting configuration consisting of the same total numbers of lamps (8) (Frantz et al. 2001).

canopies to adapt to different lamp configurations in terms of similar overall photosynthetic productivity, configurations are preferred that permit sequential energizing of lamps to keep pace with canopy growth without wasting electrical or photon energy.

Table 2. Yield parameters for a comparison between two lamp geometries

Parameters	Pyramidal	Horizontal	Significance[z]
Yield (edible g dm m^{-2})	129.40	130.99	NS
Harvest index (HI) (g edible dm g total $biomass^{-1}$)	60.3	58.3	NS
Edible yield rate (EYR) (g edible dm m^{-2} day^{-1} g $inedible^{-1}$)	2.59	2.62	NS
Yield efficiency rate (YER) (mg edible dm m^{-2} day^{-1} g $inedible^{-1}$)	81.6	75.5	NS
Energy conversion efficiency (ECE) (kg edible dm m^{-2} day^{-1} MJ^{-1})	105.1	117.4	0.05
Energy partition efficiency (EPE) (g edible dm m^{-2} day^{-1} g $inedible^{-1}$ MJ^{-1})	33.2	33.8	NS
Biomass conversion efficiency (BCE) (g edible dm MJ^{-1})	1.94	2.16	0.05
Energy (MJ m^{-2})	8.6	7.8	0.001

[z] Based on two-way *t*-test of means.

Note: 1 MJ = 3.6 kW-h

Traditional expression of PPF on a 2-dimensional area basis is not meaningful at any given point within a closed foliar canopy when incident radiation is received from all directions, as with intracanopy lighting (Fig. 6). Thus, 3-dimensional “light maps” indicating zones of equivalent global PPF predict where leaves will cluster and where zones of highest photosynthetic activity will occur within the canopy.

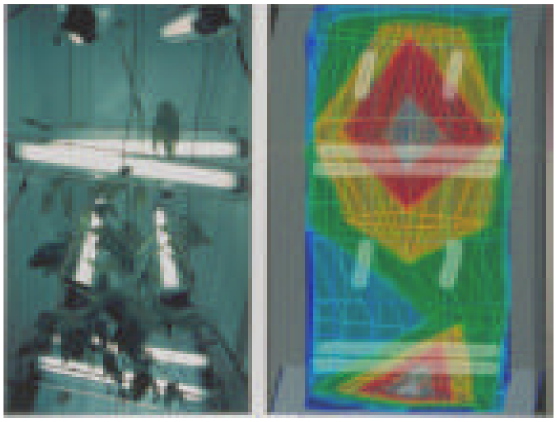

Figure 6. Cowpea canopy (left) and light map (right) showing brighter light intensities near and dimmer light intensities farther from tiered, horizontal fluorescent lamps (Frantz et al. 2001).

Conclusion

Optimization of intracanopy lighting for irradiance, spectral composition, and source will substantially reduce power and energy burdens for crop production in controlled environments and will contribute to the future profitability of controlled environment agriculture on Earth and in space.

Literature Cited

Frantz, J.M., Chun, C., Joly, R.J., and Mitchell, C.A. (1998) Intracanopy lighting of cowpea canopies in controlled environments. *Life Support and Biosphere Science* 5, 183-189.

Frantz, J.M., Joly, R.J., and Mitchell, C.A. (2000) Intracanopy lighting influences radiation capture, productivity, and leaf senescence in cowpea canopies. *Journal of the American Society of Horticultural Science*. 125(6), 694-701.

Frantz, J.M., Joly, R.J., and Mitchell, C.A. (2001) Intracanopy lighting reduces electrical energy utilization by closed cowpea stands. *Life Support & Biosphere Science* 7, 283-290.

Knight, S.L. and Mitchell, C.A. (1988) Effects of CO_2 and photosynthetic photon flux on yield, gas exchange, and growth rate of *Lactuca sativa* L. 'Waldman's Green'. *Journal of Experimental Botany* 39(200), 317-328.

Ohler, T. A. and C. A. Mitchell. (1995) Effects of carbon dioxide and plant density on cowpea canopy productivity for a bioregenerative life support system. *Life Support & Biosphere Science* 2, 3-9.

Salisbury, F.B. and Bugbee, B.G. (1985) Wheat farming in a lunar base. In: *Lunar Bases & Space Activities of the 21st Century*. pp. 635-645.

Tibbitts, T.W., Morgan, D.C., and Warrington, J.J. (1983) Growth of lettuce, spinach, mustard, and wheat plants under four combinations of high-pressure sodium, metal halide, and tungsten halogen lamps at equal PPFD. *Journal of the American Society of Horticultural Science* 108, 622-630.