THE USE OF SUPPLEMENTAL LIGHTING FOR VEGETABLE CROP PRODUCTION: LIGHT INTENSITY, CROP RESPONSE, NUTRITION, CROP MANAGEMENT, CULTURAL PRACTICES

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INTRODUCTION

In general, growth responses to environment are influenced by both quantity (cumulative light or light sum or light integral; light intensity x light period; the number of photons intercepted per m^2 per unit of time) and quality (spectral distribution) of light, as well as interaction with temperature and cultural practices. The quantity of light is affected by a combination of day length, solar angle, atmospheric cover, plant density, canopy structure, and greenhouse structure and cover materials, while the spectral distribution of light received at a given point depends on solar angle, atmosphere, transmission through leaves, and reflection from nearby plants and other objects, including the soil surface (Heuvelink and Dorais, 2003). In order to increase light integral for greenhouse production, an important research program on supplemental lighting of several vegetable crops was initiated fifteen years ago at the Horticultural Research Centre of Laval University, Quebec. The physiological influence of supplemental light intensity and photoperiod on seedling production as well as on vegetable crop production has been well studied. Crop management recommendations were made for Quebec growers and nowadays, almost all lettuce growers use supplemental lighting. Approximately 10% of cucumber growers and 15% of tomato growers are now producing during winter time with supplemental lighting. Considering that daily light integral in greenhouse vary during the year from 1 to 35 mol m^{-2} d^{-1}, and the demand for high quality products year-round by consumers increases, this technology is sustainable for the greenhouse industry.

SUPPLEMENTAL LIGHTING

The efficiency of supplemental lighting decreases when natural photosynthetic photon flux (PPF) is added, but increases when CO_2 concentration is increased. Theoretically, the relative photosynthetic yield of HPS lamps should be 34% higher than that of natural light. The optimal supplemental lighting that should be installed for a vegetable crop would vary according to the daily light integral (variation due to location and time of the year), crop species, lamps costs (Quebec; \$50-60 m^{-2}; 120 µmol m^{-2} s^{-1} HPS 400W), electrical costs (Quebec; \$0.035-0.06 KW/h; \$9-\$11 m^{-2}), and heating requirements (Quebec; around \$20-\$27 m^{-2} per year). It was estimated that heat from supplemental lighting provided between 25 and 41% of the heating requirements of a double-polyethylene greenhouse in Quebec city (46°48' N-71°23' O) (Brault *et al.,* 1989). The contribution of supplemental lighting to the greenhouse heating requirements is dependant on factors such as supplemental light levels, ventilation set points, regional climate, greenhouse energy efficiency and ambient humidity. Under Quebec growing conditions, the real contribution is around 25% when 120 µmol m^{-2} s^{-1} is used for a 16-h photoperiod. Lamps are generally located 1 m higher than the wiring system just above the rows. In Finland, 50% of the lamps are distributed above the rows and 50% between rows because of short natural period during the winter. Lamps are generally turned off when solar radiation reach 240-300 W m^{-2}, and the daily light integral of 1200 J cm^{-2} is reached.

LIGHT QUALITY AND LIGHT SOURCE

Changes in photoperiod and light quality are sensed by plants by photoreceptors such as the phytochrome. The phytochrome system (350-800 nm) within the plant functions regulates metabolic events that result in adaptive responses such as stem length, leaf shape and thickness, and carbon partitioning between plant organs. Cryptochrome (320-500 nm) and UV-B (280-350 nm) receptors are two other kinds of photoreceptors involved the first one in stomatal opening, leaf color and thickness, and stem elongation. The source of supplemental lighting mostly used for crop production is the high-pressure sodium (HPS) lamps, which are the most efficient (26-30%) in converting electric energy into useful light for photosynthesis. High-pressure sodium (HPS) lamps have a high red/far red ratio and a very small portion in blue and violet (6%). Green and yellow light (40% of HPS light) promote internode length and leaf area compared to natural light. It has been shown that red light promoted the keeping quality of cucumber. The newer 600 W HPS lamps have a higher PAR yield, more red light and less blue light compared to 400 W HPS lamps. Thus, for the same light intensity, fewer 600 W lamps are needed. The energy efficiency of metal halide (MH) lamps is not high enough (0.9 µmol per W compared to 1.4-1.6 µmol per W for 400 and 600 W HPS lamps; need 25% more lamps), and their useful life is lower than HPS lamps (±5000 hours compared to 10 000 hours). However, MH lamps have a wider spectrum than HPS.

LIGHT INTENSITY

In Quebec, Ontario and British Columbia daily light integrals from solar radiation vary during the course of a year from 3.9 to 21.0 MJ m^{-2}, 4.7 to 22.5 MJ m^{-2} and 2.3 to 22.8 MJ m^{-2}, respectively. Thus, supplemental lighting can be useful to promote photosynthesis most parts of the year (September to March and during cloudy days). For example, the use of 100 µmol m^{-2} s^{-1} (20 W m^{-2} PAR) of supplemental lighting for 16 hours per day would add up to 1.15 MJ m^{-2} (PAR) of light energy, and would increase the total light energy provided to the plants by 70, 84 and 143% for the Ontario, Quebec and British Columbia regions in December, and by 25, 26 and 33% for the same regions in March, respectively (Papadopoulos *et al.,* 2002). A rule of thumb estimating the effects of light on production and often used in practice, is the one-percent rule, stating that 1% reduction in light will reduce production by 1%. Despite its simplicity, the one-percent rule often gives close estimates of the consequences of light loss on tomato yield (Heuvelink and Dorais, 2003).

Lettuce – Light integral of 12-13 mol m^{-2} d^{-1} or higher are generally needed for lettuce production. Lettuce was found to be very responsive to the use of supplemental lighting. More than 18 growth cycles per year were produced by Quebec growers when using supplemental lighting. The use of 50-100 µmol m^{-2} s^{-1} over a 16-h to 24-h photoperiod during the winter months increased the lettuce biomass by 1.4 to 2.7 times as compared to natural light, and reduced the production cycle by 25% (Gaudreau *et al.*, 1994). Use of supplemental lighting reduced nitrate concentration of lettuce by 10 to 26% during the winter time when natural light was the lowest. It also improved lettuce quality such as heart firmness but increased tip burn incidence. In practice, supplemental light levels of 50-100 µmol m^{-2} s^{-1} are generally used in Quebec.

Cucumber – A cucumber plant produces 3.4 to 4.3 g of dry matter per MJ m^{-2} PAR under 364 and 620 µmol mol^{-1} of CO_2, respectively (Nederhoff, 1994). In general, supplemental lighting increases the fruit relative growth rate, fruit biomass and fruit number harvested, as less fruits are aborted. The installed lighting capacity for cucumber varies from 120 W m^{-2} (Quebec) to 200 W m^{-2} (Finland). In Quebec, supplemental lighting using photosynthetic photon flux (PPF) up to 300 µmol m^{-2} s^{-1} was shown to increase vegetative growth (number of leaves, leaf thickness, stem length, dry matter content) and winter yield up to 3 times after 5 months, and decrease the time to the first harvest by 19 days. Under a high light integral (30 mol m^{-2} d^{-1} or more) the growing period was only 10 days compared to 24 and 17 days under 5.5 and 10 mol m^{-2} d^{-1}, respectively. In year-round production of cucumbers under supplemental lighting, 70 to 80% increase in yield was seen when using PPF at 180 to 200 µmol m^{-2} s^{-1} when compared to natural lighting (Blain *et al.*, 1986). Under higher light levels, more dry matter was transported to the fruits because the fruit load became higher (Marcelis, 1994). Supplemental lighting at 200 µmol m^{-2} s^{-1} increased stomatal conductivity and net photosynthesis when natural light was below 280 µmol m^{-2} s^{-1} (Turcotte *et al.*, 1989). Under Quebec growing conditions, it was calculated that the maximum income would be made with a supplemental lighting of 120-150 µmol m^{-2} s^{-1}.

Sweet pepper – Sweet pepper needs a light integral of at least 12 mol m^{-2} d^{-1} during the winter time for a good control of the production cycles. The light use efficiency (LUE) is 2.1 g MJ^{-1} PAR at 450 µL^{-1} L^{-1} CO_2. The installed lighting capacity for sweet pepper is around 100-120 W m^{-2}. It has been shown that supplemental lighting at 120 µmol m^{-2} s^{-1} (around 13.9 mol m^{-2} d^{-1} in December to 23.5 mol m^{-2} d^{-1} in March) increased total fruit weight harvested by 18 to 33%. In general, 150-175 µmol m^{-2} s^{-1} (photoperiod of 16-h) are used for production.

Tomato – A light requirement equal or higher than 30 mol m^{-2} d^{-1} is reported for a tomato culture, while a light integral of 4.8 to 6.0 mol m^{-2} d^{-1} is generally favorable for tomato seedling production, which correspond to a light intensity of 83 µmol m^{-2} s^{-1} during a photoperiod of 16-20 h. Light levels below 1.5 MJ m^{-2} of solar radiation (3.1 mol m^{-2} d^{-1}) result in an increased incidence of reduced fruit set and poor flower quality. For a single-truss production experiment, a minimum of 4 mol m^{-2} d^{-1} was needed for a positive yield. Approximately 50 MJ m^{-2} of global radiation is required for 1.0 kg fresh mass of tomato fruit; considering 3.1 g dry matter per MJ m^{-2} PAR with 93 % moisture content (9.7 to 12.8 g fresh mass per mol m^{-2} of light). Light use efficiency (LUE) values varying between 2.8 and 4.0 g MJ^{-1} intercepted PAR, in experiments where no CO_2 enrichment was applied, have been reported (Heuvelink and Dorais, 2003).

For tomato, the installed lighting capacity in Quebec is around 120 W m^{-2} (400 W HPS), while in Finland is around 160 W m^{-2} (400 W HPS), and between 94-188 W m^{-2} (600 W HPS) in The Netherlands. Supplemental lighting has been shown to have a beneficial effect on growth and yield. Using supplemental lighting of 120-150 µmol m^{-2} s^{-1} (HPS 400W, 16-h photoperiod) increased the relative growth rate by 5 to 53% according to the physiological stage of the plant and the natural light level (Yelle *et al*, 1987; Dorais *et al.*, 1992). Increasing supplemental lighting of winter tomato crop (seedling in June) from 100 to 150 µmol m^{-2} s^{-1} increased the photosynthetic rate of the fifth leaves by 67% (Dorais *et al.*, 1992). During witer months, the use of supplemental lighting increased yield by 70 to 106 % when compared to natural light, and sustained a minimum weekly yield of 1 kg m^{-2} from November to February. Increasing supplemental lighting from 100 to 150 µmol m^{-2} s^{-1} gave an additional 20-36% yield increase related to a higher number of fruit, not fruit size. In fact, the use of supplemental lighting for greenhouse crops to secure flowering in the winter is successful when there is surplus assimilate after the demand of more competitive organs is met. In The Netherlands, yield increase of 67 to 115% were observed under supplemental lighting of 118 to 235 µmol m^{-2} s^{-1} (8.5 to 16.9 mol m^{-2} d^{-1}) for a 20-h photoperiod and CO_2 enrichment of 1000 µmol mol^{-1}. Recent trials have estimated that 100 J cm^{-2} per cluster and 100 J cm^{-2} for plant maintenance should be provided. Fruit quality may also be affected by supplemental lighting. Increasing the intensity of light from 100 to 150 µmol m^{-2} s^{-1} increased the total percentage of class one fruit from 77 to 81%, increased sugar content with PPF, and decreased total (titratable) acid content. Ripening of fruits of topped plants occurs more rapidly under HPS lighting. Depending upon location in Canada, it has been estimated that the maximum income return would be achieved at supplemental light levels between 100-150 $\mu mol\ m^{-2}\ s^{-1}$ during a progressive photoperiod of 12- to 16-h (i.e. 100 $\mu mol\ m^{-2}\ s^{-1}$ during 16-h results in an additional 5.8 $mol\ m^{-2}\ d^{-1}$).

PHOTOPERIOD

Lettuce - Lettuce is a day neutral or long-day plant, and daylight extension from 16- to 24-h increased the plant biomass by 20% and reduced the growth cycle by 7 days when high light intensity was used. Increasing the photoperiod from 16- to 24-h, did not produce further decrease in nitrate concentration, which might be harmful for human health.

Cucumber – Extending the photoperiod with supplemental lighting to 18-h increased the quantity of CO_2 daily assimilated and reduced the respiration period (Turcotte *et al.*, 1989). Plants had a higher daily carbon balance, which explain their higher growth rate and yields. The leaf thickness also increased with the photoperiod. The optimal photoperiod was between 18- to 20-h. The promoted effects of extended day treatments increased with photoperiod, but were independent of the time of application (Turcotte and Gosselin, 1988). In contrast to tomato, shifting part of the supplemental lighting to the middle of the night (discontinuous night; two short nights) did not affect the daily carbon balance of cucumber (Turcotte *et al.*, 1989). However, as the plant get older, a 4-h dark period should be provided.

Sweet pepper - Sweet pepper could also benefit from an extended light period. Under continuous photoperiod, the photosynthetic rate was higher and more photoassimilates were translocated to the fruit. Diurnal translocation rates were 2 to 3 times higher under 18-h and 24-h photoperiod than 12-h lighting and linear relationship between translocation rate and photosynthetic rate was observed (Dorais *et al.,* 1995). The use of 18-h to 24-h photoperiod increased yield up to 33% compared to natural light. However, continuous lighting did not improve growth and yield of pepper compared to 20-h photoperiod. Foliar chlorophyll content and Chl a/b ratio, however, was negatively correlated to lengthening of the photoperiod.

Tomato – Extended photoperiod to 18- and 24-h by high pressure sodium lamps (HPS, PL 780/N 400, 120 $\mu mol\ m^{-2}\ s^{-1}$) had no significant effect on the leaf area of greenhouse tomato but increased their dry weight (Dorais *et al.,* 1996). Under a high PPF provided by metal halide lamps (GTE-Sylvania 400 W, 350 $\mu mol\ m^{-2}\ s^{-1}$), leaf area of tomato plant grown under 24-h photoperiod was lower than the 14-h lighting treatment, but had a higher specific weight (Demers *et al.,* 1998). In several cases, leaf chlorosis was observed after several days of long photoperiod (over 17-h) and continuous light treatment with supplemental lighting. However, under almost 24-h of natural lighting in Finland, tomato plants do not show negative symptoms. In contrast to sweet pepper, use of an extended photoperiod (over 14 hours at supplemental lighting rate of 120 $\mu mol\ m^{-2}\ s^{-1}$) either had no effect or caused a total yield reduction. Extended photoperiod (18-h and 24-h photoperiod) resulted in a decrease (26-29%) in net photosynthesis than 12-h photoperiod (Dorais *et al.*, 1996). As pepper plants, foliar chlorophyll content and ratio of Chl a/b of tomato leaf was negatively correlated to lengthening of the photoperiod (Dorais *et al*, 1995). In practice, most growers use progressive photoperiod; increasing the photoperiod from 12-h to 17-h with the reduced natural light level and then decreasing the photoperiod with the increase of natural light. Half of the extended photoperiod is provided before the sunrise and the other half after the sunset. Another strategy is to light 30 minutes before sunrise and terminate 1 hour after sunset, for a total of 9- to 12-h photoperiod a day according to the season. For tomato, the dark period should be uninterrupted, since splitting the dark period in two short night periods decreased growth and yield (Vézina *et al,* 1991).

CROP MANAGEMENT

CO_2 **-** CO_2 is the substrate for photosynthesis and higher concentrations increase the rate of diffusion of CO_2 into the leaf and therefore gross leaf and crop photosynthesis. Because of inhibition of photorespiration by CO_2, gross photosynthesis increases with CO_2 concentration, even at low light intensities. For a broad categories of plant species, light use efficiency (LUE), expressed by mol of CO_2 fixed per mol of photons absorbed, can respond to variation in atmospheric CO_2 concentration. For example, LUE of tomato was increased by about 6% to 15% per 100 µmol^{-1} mol^{-1} increase in CO_2 concentration. A combination of CO_2 enrichment and supplemental lighting for greenhouse crops grown under winter in northern regions could have a synergistic effect in increasing LUE, the leaf area index combined with biomass having a great influence on the LUE (Heuvelink and Dorais, 2003). For example, an increase in CO_2 concentration from 350 to 1000 µmol mol^{-1} increased crop photosynthesis by 33% and 43%, at 500 and 1500 µmol m^{-2} s^{-1}, respectively. Using regression equations, the relative increase of photosynthesis (X, % per 100 µmol mol^{-1}) caused by additional CO_2 at certain CO_2 concentration (C, µmol mol^{-1}) can be roughly estimated for greenhouse tomato grown under normal conditions by the following rule of thumb $X = (1000/C)^2 * 1.5$ (Nederhoff, 1994). Under poor light conditions, CO_2 supply increases fruit set of tomato. However, CO_2 concentration had no effect on rate of appearance of leaves and trusses nor on the dry matter allocation; sink strength (assimilate demand) rather than source strength (plant assimilate availability) determines the assimilate partitioning. The estimated relative effect of doubling atmospheric CO_2 concentration on production increase varies between 11% to 32% for fruit vegetable crops. For example, after 4 weeks of high CO_2 concentration (from 330 to 900 µmol mol^{-1}), tomato yield increased by 21%, while an increase of 16% was observed after 20 weeks of harvest of plant grown under 450 µmol mol^{-1} compared to 350 µmol mol^{-1}. In order to take advantage of higher PPF provided by the lamps, CO_2 enrichment is generally maintaind to 700-1000 µmol mol^{-1}.

Temperature - Temperature affects mainly the assimilate demand by sink organs (i.e. tomato fruit) without changing photosynthesis rate in the range of 15°C-25°C. Only under conditions of high light and high CO_2 can gross crop photosynthesis be significantly affected by temperature. Thus, the optimal temperature is higher under high PPF and CO_2 concentrations. High temperature enhances early fruit growth at the expense of vegetative growth. At high temperature, the rate of plant development (increase in number of new leaves and trusses/fruits) is higher. In an indeterminate tomato plant, temperature affect floral initiation, floral development, fruit set and fruit growth simultaneously, and its effect is closely associated to the light condition. For example, the optimum temperature for vegetative growth is 18°C to 25°C, while the flowering rate augment almost linearly when temperature increases from 17°C to 27°C (Heuvelink and Dorais, 2003). Recent studies on tomato have shown that the use of a low pulse of temperature (LPT; 12°C and 15°C for 2-h before the end of the photoperiod) inhibits the appearance of leaf chlorosis under 20-h photoperiod. CO_2 assimilation rate of the 5th developed leaf from the apex grown under LTP of 12°C was higher than LTP of 15°C leaves. Fruit size was not influenced by LPT of 12°C treatment compared to LPT of 15°C for a similar 24-h average temperature (18.3 to 18.7°C). After 20 weeks of treatment, no significant difference could be observed in the total cumulative yield (kg m^{-2}), and fruit quality expressed by BER, cuticle cracking and misshaped fruit (Dorais *et al.,* 2002). For a similar cucumber fruit load, more dry matter was transported to the fruits at 25°C than at 18°C, while for tomato literature data are not conclusive on a possible direct effect of temperature on partitioning. On the other hand, optimal temperature for lettuce is around 18°C and vary with cultivars. High temperatures combined with high light conditions increase leaf width. Too high temperatures, however, result in a high incidence of tipburn, bolting and "puffy" heads.

Plant population **-** Biomass production is primarily driven by photosynthesis, while photosynthesis to a great extent depends on light interception, which furthermore varies with leaf area of the canopy. Consequently, plant population should increases with light intensity. For example, the highest cumulative tomato yield was achieved at 150 µmol m^{-2} s^{-1} and a low density planting of 2.3 plants m^{-2} during the winter, but a high density planting of 3.5 plants m^{-2} was required for the remainder of the year (Dorais *et al.,* 1991). In practice, growers increase their plant population (July/August) from 2.5 plants m^{-2} to 3.3 in January/February. With higher level of supplemental lighting (up to 260 µmol m^{-2} s^{-1}), tomato plant population could increase to around 5 plants m^{-2}. Severe pruning is done under high plant population, keeping only 12-15 leaves per plant. Similarly, cucumber plant population should be adjusted to the PPF, and open crop structure should be maintained for higher fruit quality and shelf life.

Plant balance - For a long season crop, the total yield is determined by the balance between the vegetative and reproductive growth, and consequently, the assimilate partitioning. Light intensity and CO_2 concentration influence source strength, whereas sink strength primarily depends on temperature. The light intensity received by the plant affects the quantity of assimilates available to the plant organs and thus their degree of sink competition. In a tomato plant, assimilate availability (source strength) is generally lower than assimilate demand (sink strength). The estimated total assimilate demand could be 2 to 3 times the assimilate availability, averaged over a whole growing season. Hence, competition between sinks becomes the determinant factor for control of biomass allocation. Competition occurs between vegetative and generative plant organs, among trusses and among fruits within a truss, and can be cultivar dependant. A certain balance between vegetative (future production potential) and generative growth (short-term productivity) should be maintained, as sufficient but not too much new leaf area has to grow for future light interception and biomass production (Heuvelink and Dorais, 2003). Consequently, fruit load should be adjusted (fruit pruning and stem density) to the assimilate supply which fluctuates during the growing period due to the solar radiation. Similarly, a steady fruit load is desirable for cucumber as leaf photosynthesis declined when no fruit are allowed on the plant.

Water and Nutrition **-** Water and nutrient uptake increased with supplemental lighting compared to natural light (Tremblay *et al.*, 1986). As for unlighted crops, water and salinity stress are believed to favor generative development in tomato. Young plants are often stressed to stimulate fruit growth on the first truss.

POLLINATION AND PEST MANAGEMENT

For high fruit quality, successful pollination under supplemental lighting is essential. Pollination is normally done with bumble bees. Hives are generally closed during the afternoon (exit door). Small UV lamps could be installed nearby the hive to facilitate the orientation of bumble bees to their hive after the sunset. Preventive measurements and biological control for pest management should be well established. For example, *Encarsia* needs more time to complete its life cycle in winter and new deleafing strategy should be taken. The use of predator (i.e. *Dicyphus*) without diapause in winter when supplemental lighting is used should be chosen.

CROP SYSTEM

From previous studies, what is the best growing system of supplemental lighting utilization for vegetable crop production. Studies were conducted in tomatoes and cucumber utilizing a v-shaped training system under supplemental lighting of 100 to 150 µmol m^{-2} s^{-1} (Dorais *et al.,* 1991; Gobeil and Gosselin, 1990). For tomato, four crops per year were grown sequentially resulting in a mean weekly yield greater than 1.3 kilogram m^{-2} during the winter months. Maintaining crops in a v-shaped system was found to be very labor intensive. An alternative training system using intercropping on gutters where the level of older plants are adjusted according to the light requirement of the younger ones is recommended. Old plants are topped one or two weeks before the intercrop. Bottom leaves of the old crop are severely pruned and temperature is managed according to the new crop. Both crops share production area for a period of 6-8 weeks. This system optimizes use of both natural and supplemental lighting by the young plants, and facilitates plant maintenance. Tomato yields up to 90 kilograms m^{-2} per year have been achieved with this system using supplemental lighting of 130 to 175 µmol m^{-2} s^{-1}. At the Finnish Research Station an experiment was done recently with 5 tomato intercrops per year, with 10 clusters per crop. Growing short cycles allow longer photoperiods, higher temperatures, higher plant population, and elimination of pest-infested plants. Yields of 100 kg m^{-2} per year was expected.

FUTURE

The use of supplemental lighting for crop production of Northern regions is the future for high quality product and reduced fossil energy use per kg of vegetable produced. In Canada, the energetic needs for greenhouse heating and dehumidifying reach 500 to 1000 kWh per m^2. The use of 80 umol m^{-2} s^{-1} of HPS supplemental lighting during 15-h contributes to around 200 kWh m^{-2} per year. Considering 25% lost of energy by the lamps, 140 000 m^3 of natural gas ha^{-1} per year could be replaced by hydro -electricity. Consequently, a reduction of 252 tons ha^{-1} (Quebec; 324 tons ha^{-1} with 120 umol m^{-2} s^{-1}) of carbon dioxide release could be reached. With the ratification of the Kyoto protocol, both energy consumption per kg of crop produced and carbon dioxide release into the environment will have to be reduced. The intercropping system under supplemental lighting is promising for the year-round production of vegetable. However, for such an energy- and capital-intensive system to be profitable, high yields must be obtained. Several parameters should be adapted according to the crop. The optimal light intensity, adequate crop schedule and plant population, deleafing and truss pruning, climate control, especially daily temperature evolution, and pest management would have to be adjusted.

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CONVERSION FACTORS

Daylight: $1\ \mu mol\ m^{-2}\ s^{-1} = 56$ lux $= 0.217\ W\ m^{-2}$ PAR $= 5.2$ ft-c
HPS light: $1\ \mu mol\ m^{-2}\ s^{-1} = 85$ lux $= 0.2\ W\ m^{-2}$ PAR $= 7.9$ ft-c

$1\ J = 1\ W\ s^{-1}$
1 kWh = 3.6 MJ

$1\ MJ\ m^{-2}$ natural PAR $= 4.6\ mol\ m^{-2} = 71.9$ klxh = 6 640 ft-c
HPS $1\ MJ\ m^{-2}$ PAR $= 5\ mol\ m^{-2} = 118$ klxh = 10 970 ft-c