FIRST Research Report

Light Management in Greenhouses

I. Daily Light Integral: A useful tool for the U.S. Floriculture industry.

James E. Faust

This project focused on developing a method that commercial growers could use to determine the number of hanging baskets that could be grown in their greenhouses. Several issues needed to be addressed before we could approach the hanging basket issue. First, we needed a unit of light measurement that effectively describes the greenhouse environment, then we needed a method for growers to determine the light levels in their greenhouses using this unit. Finally, we needed to identify how much light greenhouse crops require before we can determine how much light can be intercepted by hanging baskets. We will present the results of this project in a series of reports that deal with each of the issues outline above.

This report discusses the use of daily light integral as a tool for commercial greenhouse growers to effectively discuss light management in greenhouses. Part I provides a framework from which we can discuss greenhouse light management in the following sections. Part II discusses plant responses to daily light integrals which will help growers to relate the daily light integral concept to their production. Finally, Part III discusses the effect of hanging basket production on the daily light integral delivered to the greenhouse bench crops, thus providing a technique for growers to determine how many hanging baskets can be grown in their greenhouses during different times of year while allowing sufficient light to be delivered to the crops below.

Considering the essential nature of light in the process of growing plants, it is really quite amazing how little we consider this topic in the daily process of operating commercial greenhouses. A major limitation to discussing light management issues is that a useful discussion requires a common starting point. The U.S. Floriculture industry struggles to discuss light issues for two main reasons:

1. The numerous units used to describe light make communication a challenge. (Footcandles is most common unit used, but it has serious limitations.)
2. Useful light measurements are particularly challenging to make inside of greenhouses. As a result, few growers have light sensors, and those that do have sensors rarely use them.

Before discussing methods for managing light in the greenhouse, we need to address the light unit problem. We propose the use of the term, daily light integral, as a method for greenhouse growers to effectively communicate about light. In this report, we will discuss how growers can become more familiar with the use of daily light integrals. We will introduce a technique that allows growers to begin to think about light in terms of daily light integrals, even if the grower owns only a footcandle measurement. This will lay the groundwork for discussing light management techniques in the additional reports.

The Footcandle Problem

There are numerous units used to measure and describe light. Each unit has advantages and disadvantages. Footcandle meters are the most commonly sensor and footcandles is the most common unit, so it is particularly important for growers to understand the limitations associated with this instrument and its measurement unit.

1. The first problem is that footcandle meters are primarily designed for use in photography, thus they are designed to reflect how the human eye perceives light. Plants absorb light differently than the human eye, so this introduces errors in the measure of light.
2. Footcandles is an instantaneous measure of the light intensity. Growers will often report that they are growing a crop with X number of footcandles. The main problem with this is that 3000 footcandles in December has a different meaning than 3000 footcandles in June, i.e., a plant grown under a maximum light intensity of 3000 footcandles in June will receive considerably more light than a plant grown under a maximum light intensity of 3000 footcandles in December simply because the daylength is much longer in June.

The limitations of footcandle meters and measurements does not imply that the measurements are of no value. Footcandle measurements are certainly better than trying to make estimates of light with our eyes (Note: human eyes are so effective at adjusting to low and high light conditions, that they are poor at estimating light intensities). Perhaps the most effective uses of footcandle meters are:

1. Calculating greenhouse light transmission, e.g. making a comparison between the light intensity outside and inside the greenhouse.
2. Determining the amount of shade cloth or white wash to be placed on a greenhouse. This is accomplished by measuring the light intensity at the crop height during the middle of a sunny day.

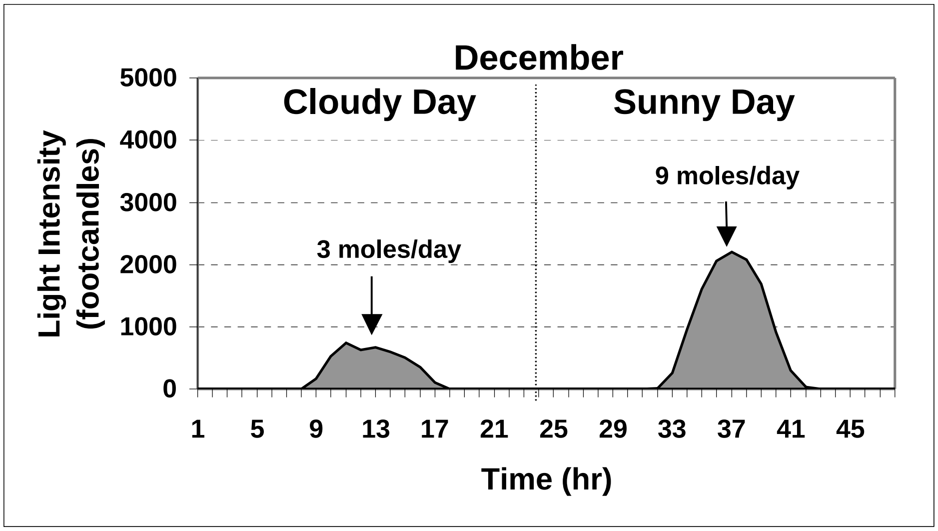
The Daily Light Integral Concept

The term *Daily Light Integral*, or DLI, is used to describe the total quantity of light delivered over the course of an entire day. The daily light integral is reported as the number of moles (particles of light) per day, thus the unit is reported in trade journals as “*moles/day*” or in scientific publications as “$mol \cdot m^{-2} \cdot d^{-1}$”.

The advantage of an integrated measurement over an instantaneous measurement can be demonstrated with an analogy. If you want to know how much rain fell during the course of a day, you would place a bucket outdoors and record the volume of water collected. Whereas, recording the intensity of rainfall at one instant, e.g., the raindrops per second, would be of little value. Similarly, knowing the quantity of light delivered throughout the day is much more useful than making an instantaneous footcandle measurement in the middle of the day. The daily light integral is a relatively new concept for the greenhouse industry but it has some advantages, namely plant growth is often closely correlated to the daily light integral.

Figure 1 demonstrates the effect of the time of year and sky conditions on the light intensity and daily light integral delivered to a greenhouse crop. The maximum light intensity delivered to a greenhouse crop on a cloudy day in December was 900 footcandles, while the daily light integral was 3 moles/day. The maximum light intensity was ~2000 footcandles during both a sunny day in December and a cloudy day in June; however, the daily light integral in December was 9 moles/day compared to 12 moles/day in June. The cloudy summer day has a 25% higher daily light integral than the sunny winter day because the daylength is longer in the summer, so there was more time to accumulate, or absorb, sunlight. An instantaneous footcandle measurement cannot take daylength into account. For this reason, daily light integral is the preferred method of quantifying the amount of light delivered to greenhouse crops. A sunny day in June resulted in a maximum light intensity of 4600 footcandles and a daily light integral of 26 moles/day, more than 8 times the amount of light delivered during the cloudy December day. Although the outside daily light integral during the summer may exceed 50 moles/day, the daily light integral measured inside greenhouses is rarely higher than 25 to 30 moles/day due to interception of light by the greenhouse infrastructure and shade cloth.

A



B

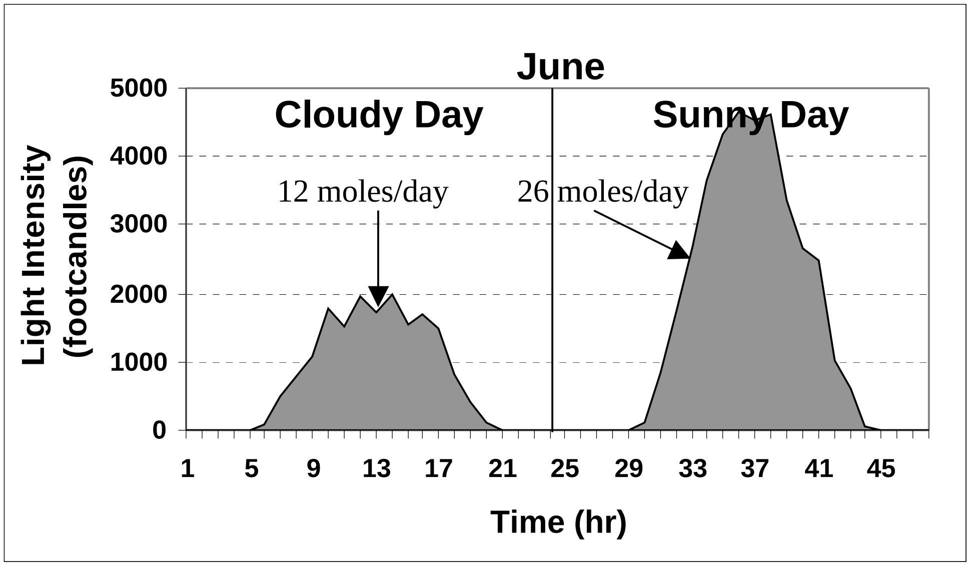


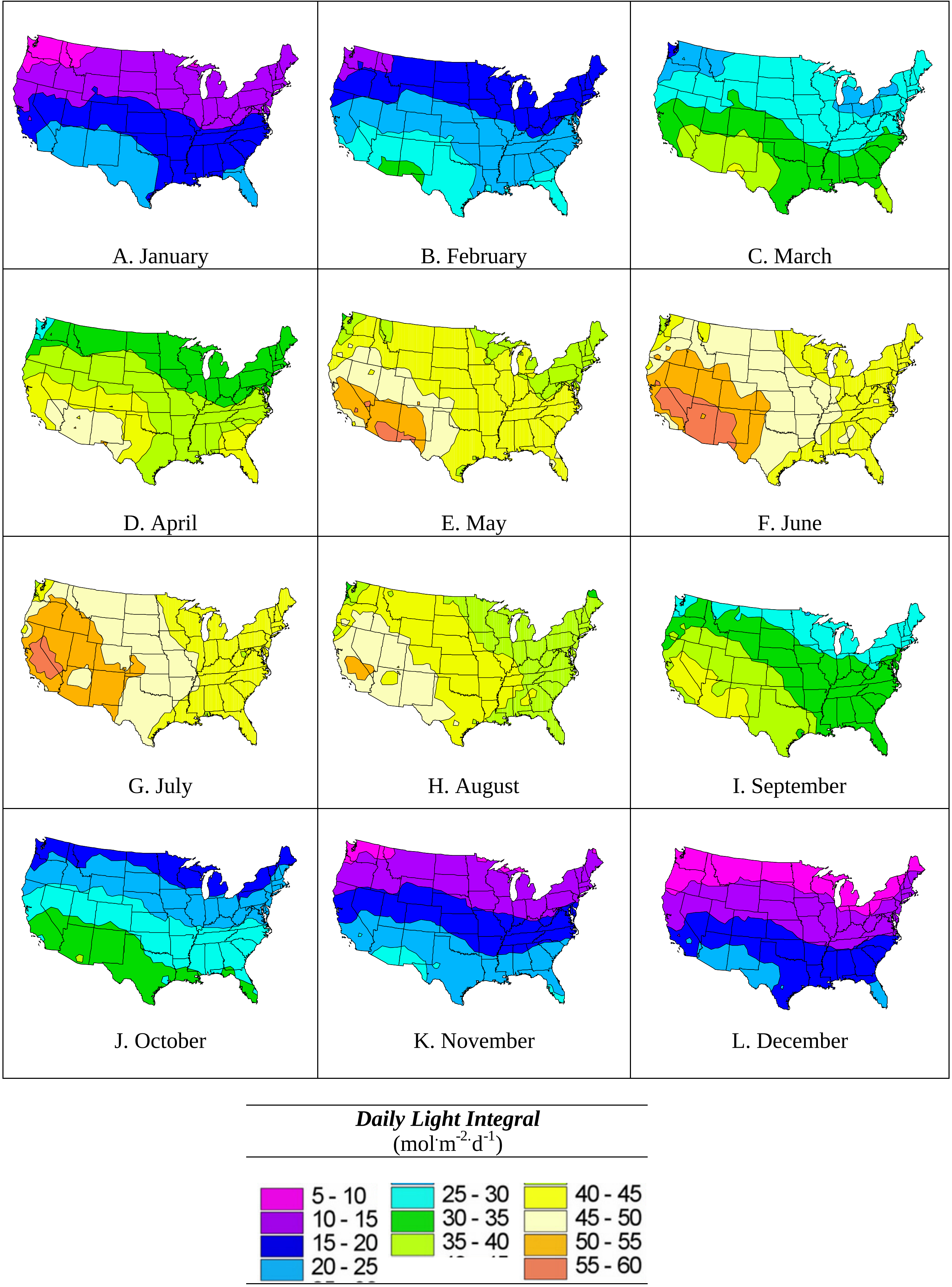
Figure 1. The daily light integral delivered to a greenhouse crop in a greenhouse on a cloudy day and a sunny day in **A.** December and **B.** June.

Estimating Daily Light Integrals across the U.S.

The first goal of this project was to develop a series of daily light integral maps to allow growers to estimate the amount of light being delivered to different locations in the U.S for each month of the year (Figure 2). The mean outdoor daily light integral ranges from 5-10 moles/day across the northern U.S. in December to 55-60 moles per day in the southwestern U.S. in May through July. During the winter months, the differences in daily light integral primarily occur between the northern and southern U.S., while during the summer months the differences in daily light integral primarily occur between the eastern and western U.S.

The daily light integral changes rapidly during the spring and fall. For example, the outdoor daily light integrals for Columbia, Missouri are 28 moles/day in March, 37 moles/day in April, and 42 moles/day in May. Similarly, the daily light integrals change from 42 to 33 to 25 to 16 in August, September, October, and November, respectively. Thus, the light available for plant growth increases dramatically during spring production and decreases dramatically during fall production. These changes have a tremendous impact on plant growth and quality.

Figure 2. The monthly mean daily light integrals (moles/day) delivered across the contiguous U.S.



A. January

B. February

C. March

D. April

E. May

F. June

G. July

H. August

I. September

J. October

K. November

L. December

Note: The daily light integral maps are based on 30 years of solar radiation data at 237 sites across the U.S. Although, this is a considerable amount of data, we can not account for all the microclimates that occur due to localized geography, e.g. local cloud cover due to lake or ocean effects.

Daily Light Integrals inside the Greenhouse

The daily light integral maps only describe the amount of light delivered from the sun to the outside of the greenhouse. The amount of light actually reaching the crop on the greenhouse bench is affected by the greenhouse light transmission.

Light must be transmitted through the greenhouse structure to be delivered to the plants. Surprisingly, only 35 to 70% of light measured outside the greenhouse typically reaches the greenhouse crop. Don’t be fooled by the high transmission percentage of most greenhouse glazing materials when considering greenhouse light transmission. Polyethylene and glass may transmit >90% of the light the hits the material in perpendicular orientation, however, the greenhouse infrastructure (posts, gutters, trusses etc…) allows 0% transmission and sunlight that hits the glazing material at a low angle, such as in the winter or early or late in the day, is often reflected outward, away from the greenhouse. Thus, the actual amount of light transmitted to the greenhouse crop is much less than often expected. Factors such as dust, condensation, hanging baskets and shade cloth will reduce greenhouse light transmission even further. The only way to know the greenhouse light transmission for a particular greenhouse is to make some measurements.

Growers can measure greenhouse transmission by measuring the light intensity outside the greenhouse and then quickly measuring the light intensity inside the greenhouse. These measurements must be made when the light intensity is not changing rapidly, so either clear sky or uniformly overcast conditions are preferred. Overcast conditions have the benefit that the greenhouse light environment is relatively uniform, although the transmission percentage may be slightly higher on cloudy days compared to sunny days. On sunny days, the light intensity measurements recorded in the greenhouse will vary tremendously depending on the placement of the sensor. Also, if the light intensity is changing from moment to moment, it is difficult to make comparable measurements inside and outside the greenhouse, unless you have two sensors and radio communication. Greenhouse light transmission is calculated with the following equation:

*Greenhouse light transmission (%) = (1 –((Light intensity measured outside – Light intensity measured at canopy level) / Light intensity measured outside))*100*

One of the reasons for developing the daily light integral maps was that these are not measurements that are easily made in commercial greenhouses, thus growers can simply calculate the daily light integral delivered to their crops based on their greenhouse light transmission percentage.

Daily light integrals inside the greenhouse can be *estimated* by multiplying the greenhouse light transmission percentage by the daily light integrals indicated on the maps in Figure 2. For example, 25 to 30 moles/day are typically delivered to South Carolina in October. If the greenhouse light transmission is 50%, then we could expect that greenhouse to receive 12.5 to 15 moles/day during October, which is plenty of light to grow a poinsettia crop, but is approaching the lower range of desirable light levels for high-quality pansies. For this reason, outdoor pansy crops are typically superior to greenhouse-grown pansies, assuming outdoor temperatures are not excessively high.

Daily Light Integrals provided by High-Pressure Sodium Lamps

The daily light integral delivered by supplemental lighting, e.g., high-pressure sodium lamps, can be determined rather easily. Measure the light intensity (in footcandles) at the height of the plant canopy while the lights are on and there is no sunlight. Convert footcandle measurements to micromoles/second, then to moles/day.

Example:

At night, a measurement of 300 footcandles is made at canopy height under high-pressure sodium lamps. The lamps burn for 12 hours.*

First: Convert footcandles to micromoles/second:

300 ft-c x 0.127 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ per ft-c = 38.1 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$

Second: Calculate the daily light integral (moles/day) provided by the lamps:

38.1 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ x 3600 seconds/hour / 1000000 µmoles/mol x 12 hours =

1.6 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (or 1.6 moles/day)

*Note: The conversion factor used to convert from footcandles to micromoles is different for sunlight compared to light from high-pressure sodium lamps; therefore, one should not make light measurements while both the sun is shining and the lamps are on and then convert that measurement from one unit to the next.

Measuring Daily Light Integrals

If you want to get actual daily light integral numbers for a specific greenhouse, two options are possible. First, light sensors, preferably a quantum sensor, can be attached to an integrating device that is capable of recording the light measurement on a set interval, e.g. every hour. This equipment is commercially available. Apogee Instruments manufactures a Quantum Integrating Device that can simultaneously measure 8 quantum sensors and report the current light intensity or daily light integral on a digital screen. It is a worthwhile investment for research greenhouses but can be expensive for most growers. Spectrum Technologies produces a single quantum sensor mounted on a mini-datalogger. This unit is highly mobile and user-friendly for commercial greenhouse use. Software is required.

A second option is available for growers that have an outdoor weather station and a climate control computer. Light measurements can be downloaded to a spreadsheet, then the outdoor daily light integrals can be calculated (see spreadsheet example below). The example uses “watts per square meter” since many greenhouse weather stations report this value. Daily light integrals inside the greenhouse can be estimated based on greenhouse light transmission numbers. This can not be easily done if retractable shade curtains are used.

Greenhouse
Trans%
0.60

Time	W/m2 Outside	W/m2 Greenhouse	(multiply outside measurement by GH transmission pct)
5:00	0	0	
6:00	0	0	
7:00	0	0	
8:00	30	18	
9:00	143	86	
10:00	320	192	
11:00	490	294	
12:00	620	372	
13:00	701	421	
14:00	714	428	
15:00	660	396	
16:00	553	332	
17:00	392	235	
18:00	193	116	
19:00	14	8	
20:00	0	0	
21:00	0	0	
		10.4	W/m2 (= sum of third column x 0.0036*)
		20.9	**moles/day** (= W/m2 x 2)

*Note: 0.0036 comes from 60 seconds/min X 60 min/hr / 1000000 micromole/mole

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II. Plant Growth Responses to Daily Light Integrals.
James E. Faust

The amount of light that a plant receives has a tremendous impact on plant quality and marketability. Plants can be thought of a “light counters”, in other words, they count the number of particles of light that they are able to absorb. The intercepted light then fuels photosynthesis and growth. This is the beauty of using Daily Light Integrals (DLI) to describe the greenhouse light environment, since it is a direct measure of the number of particles of light delivered to the plant; therefore, plant growth is closely correlated with DLI.

The purpose of this project was to identify how plants respond to DLI so that growers can more efficiently utilize the light delivered to their greenhouse.

Measuring Plant Growth

Growth can be measured in several ways. One of the simplest measures of growth is fresh weight, which is simply the weight of the growing tissues (roots, shoots, and flowers). Dry weight is the weight of the same tissue minus the water (the water is removed by placing the plant tissue in the oven). Growers don’t sell bedding plants based on their weight, but this is still a reasonable method for describing growth. Additionally, we like to divide the shoot fresh or dry weight by the height of the plant. This provides the weight per unit height, which a good indicator of plant quality, since the higher the weight per inch of height, the “fuller” the plant, and plant quality is closely associated with the “fullness”. Growth can also be quantified by measuring the number of lateral stems, stem diameter, leaf size (area), flower size (diameter), and flower number.

Our results will be presented as a general series of principles that growers will benefit from understanding. Then, we will follow with a discussion of more specific responses to DLI.

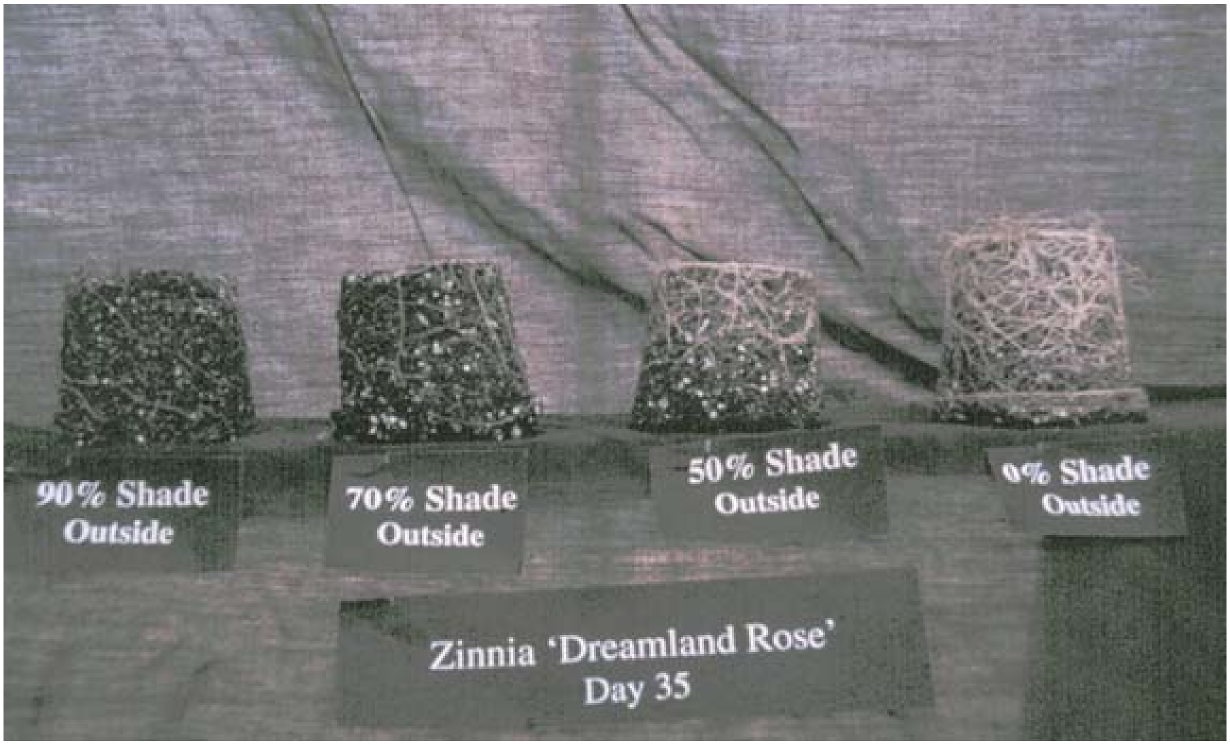
1. Plants partition their resources to the area of greatest need

Under low light conditions, plants try to increase light interception. The best way to do this is by increasing the area of individual leaves. These leaves tend to be very thin and pliable. In contrast, individual leaf size decreases and leaf thickness increases under high light conditions. These leaves are thick and have accumulated a lot of starch. However, under high light conditions, plants will have more leaves. So, even though they are individually smaller leaves, the leaf area of the entire plant increases as DLI increases.

2. Root growth is proportional to shoot growth

Roots are dependent on shoots (leaves and stems) for sugars created during photosynthesis, while shoots are dependent on roots for water and nutrients. So, it should come to no surprise that root and shoot growth are proportional. Shoot growth increases as DLI increases, so root growth also increases as DLI increases. Although this may be common sense, it can be surprising to observe how root growth dramatically increases as DLI increases (Figure 1).

Figure 1. The effect of daily light integral on zinnia root growth. The plants received (*left to right*) 4, 14, 24, and 48 moles/day.



3. Many "shade" crops grow best under moderate to high light levels

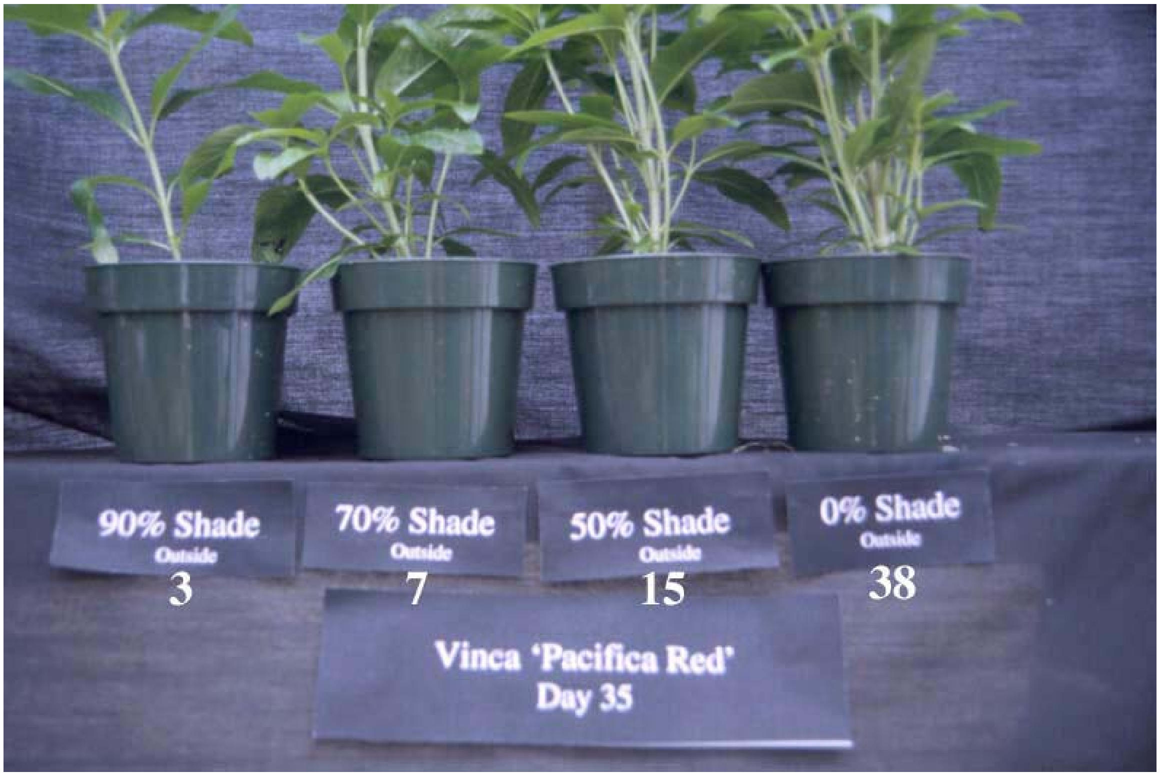
It is probably best to describe shade plants as those species that "tolerate" low light conditions; however, many of these species actually grow best in moderate to high light conditions. For example, begonias produce commercially accepted plants under low DLI conditions (5 moles/day), but the highest quality begonias are produced at a much higher DLI (~20 moles/day). Keep in mind that although the best growth, in terms of plant size, may occur at higher light levels, the leaves may be more attractive under moderate light levels.

Another example is Hosta. Many varieties of hosta grow best outdoors under full sun conditions; however, they require ample water. If drought stress occurs, sunburn will occur under full sunlight.

4. Increasing DLI increases branching

Under low light conditions, there may only be enough energy to support the primary stem. If the light levels increase, more lateral shoots will develop. In other words, the plant will only develop a lateral shoot if there is plenty of food (sugars from photosynthesis) to support those shoots. Therefore, the number of lateral branches increases as DLI increases (Figure 2).

Figure 2. The effect of daily light integral on vinca branching. The plants from left to right received 3, 7, 15, and 38 moles/day.



5. Large plants benefit more from higher DLI than small plants

Individual leaves do not require high light levels to saturate their ability to do photosynthesis. So, small plants do not require high light levels to achieve their maximum growth rate. (“Small” refers to total leaf area of the plant relative to the amount of space occupied by the plant. This is called the Leaf Area Index.). Larger plants benefit from higher light levels because the lower leaves are heavily shaded. Thus, relatively high light levels are required for the lower leaves to reach their full photosynthetic potential.

DLI=Growth=Quality

In most cases, the growth resulting from increasing DLI improves plant quality. More light = more lateral shoots = more flowers = a higher quality plant. The exception occurs with some “shade crops”. For example, impatiens and begonia actually achieve more growth (fresh and dry weight, lateral shoots etc…) in full outdoor sunlight. However, the appearance is inferior, since the leave and flowers often have a faded or bleached appearance in full sun.

Maximizing versus Optimizing

In most cases, there is a “diminishing returns” effect on plant growth as DLI increases. For example, plants grown in a greenhouse may be 2X greater at 20 moles/day versus 10 moles/day; however, plant quality may be commercially acceptable at 10 moles/day. So, 20 moles/day may provide the maximum growth rate, while 10 moles/day is optimal, assuming the other 10 moles/day can be used to grow additional plants, e.g., hanging baskets.

DLI affects growth, Temperature affects timing.

Light and temperature responses are sometimes confused. Light has a large impact on growth, while temperature influences development. Growth refers to plant size, fresh mass, dry mass, branching and flower number. Development refers to leaves or flowers being developed in the meristematic areas of the plant. Thus temperature influence how fast leaves and flowers develop.

The interaction of temperature and light has a big impact on plant quality. The biggest and best quality plants are often grown under high light and cool temperatures. These conditions allow for a lot of energy (sunlight) to be packed into the plant, since the leaves are developing relatively slowly. In contrast, low light and high temperatures are the worst conditions for growing most plants. Under these conditions, very little energy is available, yet the plant is developing leaves and flowers very rapidly. The result is poor quality plant appearance. During summer conditions, growers must be careful not to create these conditions be providing excess shade during the hot summer months.

Low light does not = stretch

It is common perception amongst grower that low light conditions promote plant "stretch". Our data do not support this conclusion. In most situations, low DLI (<5 moles/day) produces shorter plants than moderate DLI environments (10 moles/day). Under low DLI condition, the plants lack sufficient energy to produce a vigorous primary shoot. In nature, no competitive advantage exists for a plant to grow taller after several cloudy days, since increased height will not result in increased light interception. So, why might we perceive that plants stretch under low light conditions. There are several possibilities:

1. The growth that occurs under low DLI is often very poor, thus, the poor quality growth is perceived as "stretch" since low light plants lack lateral branches and have thin stems and leaves (Figure 3)
2. It is possible that flower initiation and/or development is inhibited so that low light plants require more time to flower. As a result, they get taller prior to flowering because more leaves are formed on the stem prior to a flower initiating in the shoot tip.
3. Low light plants dry out slower than high light plants. It is possible that an amply-watered low light plant grows taller than a drought-stressed high light due to the higher humidity and the lack of drought stress.
4. Plants that have a prostrate or low-growing habit may elongate more under low light. In nature, it makes sense that a petunia or pansy would benefit from elongating if the stems and leaves were being shaded by debris, such as dead leaves, on the soil surface. For example, pansy petioles appear to elongate under low light conditions.

Figure 3. The effect of daily light integral on A) Vinca and B) Zinnia height and quality. Vinca received (*left to right*) 3, 7, 15, and 38 moles/day, while zinnia received 4, 14, 24, and 48 moles/day. Note that plant height, branching and flowering increased as DLI increased.

A.


90% Shade
Outside
3
70% Shade
Outside
7
50% Shade
Outside
15
0% Shade
Outside
38
Vinca 'Pacifica Red'
Day 35

B.

Spacing affects the DLI intercepted

If 20 moles/day of light is delivered to a 4” petunia spaciously grown at 8”x8” spacing and to a 4” petunia grown pot-to-pot (4”x4” spacing), the plant grown at wide spacing will likely intercept more light. Wide spacing allows more light to be absorbed by the sides and interior of the plant. Thus, a plant’s light requirement increases as it begins to be shaded by neighboring plants.

Categorizing Plant DLI Requirements

Plants can be categorized into very low light, low light, moderate light, high light, and very high light responses. Following is a generalization of plant responses to different light levels.

Very Low Light

Very low light conditions (<5 moles/day or 500 to 1000 footcandles), typically results in poor quality plant growth and flowering. Under very low light conditions, the plant lacks sufficient energy to produce a high quality plant. The plants often have just one thin primary stem with very little lateral branching. There may be insufficient light to support flowers, so flowering can be delayed, flowers may be very small, few flowers may be produced, or the plants may stay entirely vegetative, i.e., not produce any flowers. Supplemental lighting is very beneficial under these DLI conditions. Only a few crops, such as African violets, can produce acceptable plants under very low light conditions.

Low Light

The quality of the growth that occurs under low light conditions (5-10 moles/day or 1000 to 2000 footcandles), largely depends on the greenhouse temperatures. Under cool growing conditions (<65°F), plant quality can be quite good. For example, northern European growers compensate for low light conditions by growing their crops cool. Crop time is increased but the quality is good. Cool temperatures allow the leaves and flowers to develop slowly which allows the plant more time to accumulate energy from sunlight to produce healthy leaves and flowers. In contrast, high temperatures (>75°F) during low light conditions result in poor quality growth. Under warm temperatures, the plant is developing new leaves and flowers very quickly, but there is insufficient energy from sunlight to produce substantive leaves and flowers. Supplemental lighting is beneficial under these DLI conditions.

Moderate Light

Plant growth is usually commercially acceptable for most greenhouse crops grown under moderate light conditions (10 to 20 moles/day or 2000 to 4000 footcandles). Plants flower normally with acceptable branching and flower number. Most potted flowering plants perform very well under moderate light conditions. It is relatively easy to manage watering under moderate light conditions compared to higher light levels. Once the plant has sufficient light to support flowers, increasing the light level further has little effect on time to flower. The potential benefit of supplemental lighting is limited under moderate DLI conditions.

High Light

The highest quality greenhouse-grown bedding plants, stock plants, and herbaceous perennials are usually produced under high light conditions (20-30 moles/day or 4000-6000 footcandles). These crops often produce commercially acceptable crops at moderate light conditions; however, the quality will improve further under high light conditions. High light conditions provide extremely well-branched (bushy) plants and high flower numbers. Root growth is proportional to shoot growth, so high light conditions also produce excellent root systems. The highest yields of greenhouse-grown cut flower crops and greenhouse vegetables are typically grown under high light levels; however, excessive greenhouse temperatures can limit greenhouse yields even though higher light levels are desirable for these crops. As a result, greenhouse performance and yields of cutflower and vegetables are often less than what can be achieved with outdoor production.

Very High Light

Many species produce superior quality plants outdoors compared to inside greenhouses. This is due to higher light levels (30-60 moles/day or 6000 to 10000 footcandles) and cooler plant temperatures. Plant temperatures can be cooler outdoors due to increased air movement, lower relative humidity and thermal cooling due to the exposure to the open sky.

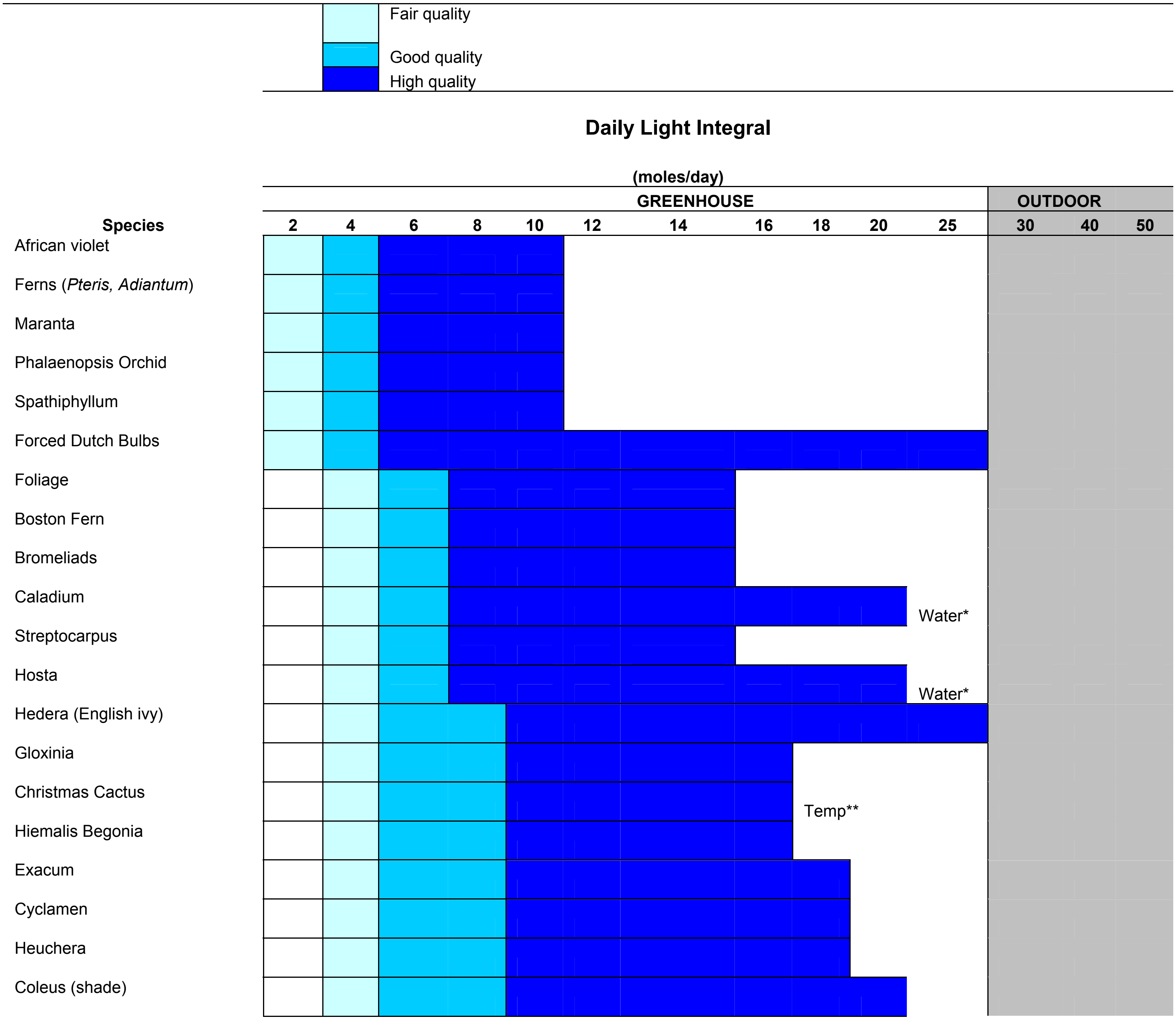
Plants considered shade plants may actually grow very well in full outdoor sunlight provided that ample water is available and temperatures do not become excessive. For example, many hosta varieties grow very well outdoors throughout the summer in the southeastern U.S. as long as the plants are well-watered. Large leaf varieties experience higher leaf temperatures under high light conditions, thus these plants may require shade to prevent sunburn.

Excessively high light may result in a change in leaf orientation and shape. Leaves grown under excessively high light produce a more vertical and curled leaf blade in order to avoid light interception. For example, the leaves of young pansy plants may curl when grown at 40 moles/day (outdoor summer light levels) even if temperatures are cool. Excessive light can also result in heat stress or “sunburn” of some species. Sunburn is most likely to occur when a plant has not been acclimated to high light conditions. Plant water use and evaporation increases as sunlight increases, so water management can be more difficult under high light conditions. Root death can also occur on the south side of dark-colored containers due to excessively high soil temperatures resulting from direct outdoor sunlight.

Table 1 provides a comparison of light requirements for various floriculture crops. Species differ in both the minimum and maximum acceptable light levels. The minimum and maximum ranges can be altered by temperature and water. Cool temperatures will allow plants to be grown at lower light levels, while the minimum light levels are higher at warm temperatures. Similarly, high temperatures can limit the amount of light that “cool” crops can absorb. For example, lobelia and fuchsia tolerate full sunlight if the temperatures are moderate, but require shade when temperatures are warmer. Water can also modify the light requirement. For example, caladiums are typically considered to be a shade crop, while they are grown outdoors in full sunlight in Florida for tuber production. However, ample water is always provided. Drought stress under full sunlight conditions is damaging to many species, since drought forces the stomata on the leaves to close. As a result, transpiration ceases and leaf temperatures begin to increase dramatically.

Table 1 differentiates between the light levels required for minimal acceptable quality, good quality and high quality crops. These are subjective categories, but the intent is to demonstrate that plant quality improves as the daily light integral increases.

Table 1. Generalized responses of various greenhouse crops to daily light integrals.



░ Fair quality

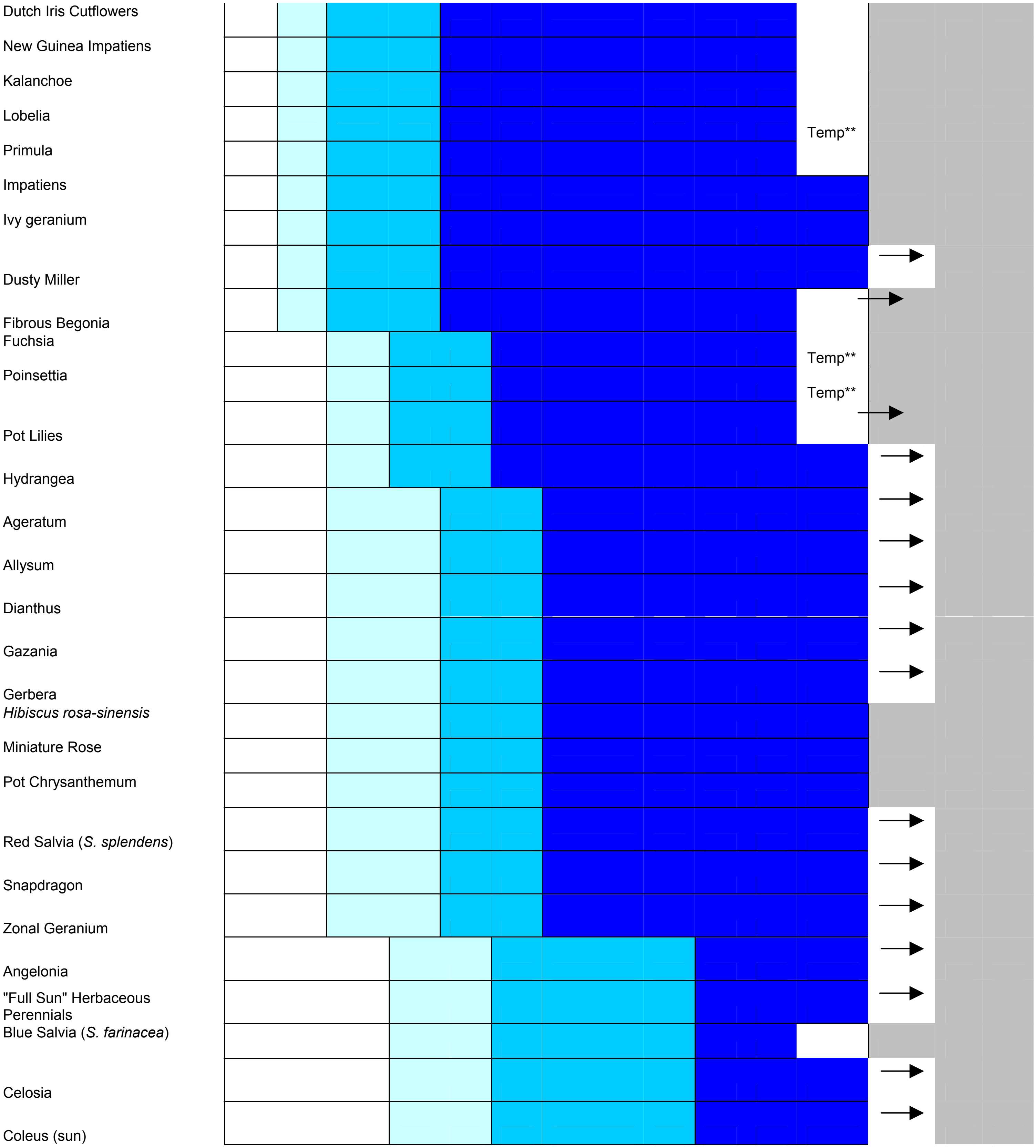
▒ Good quality

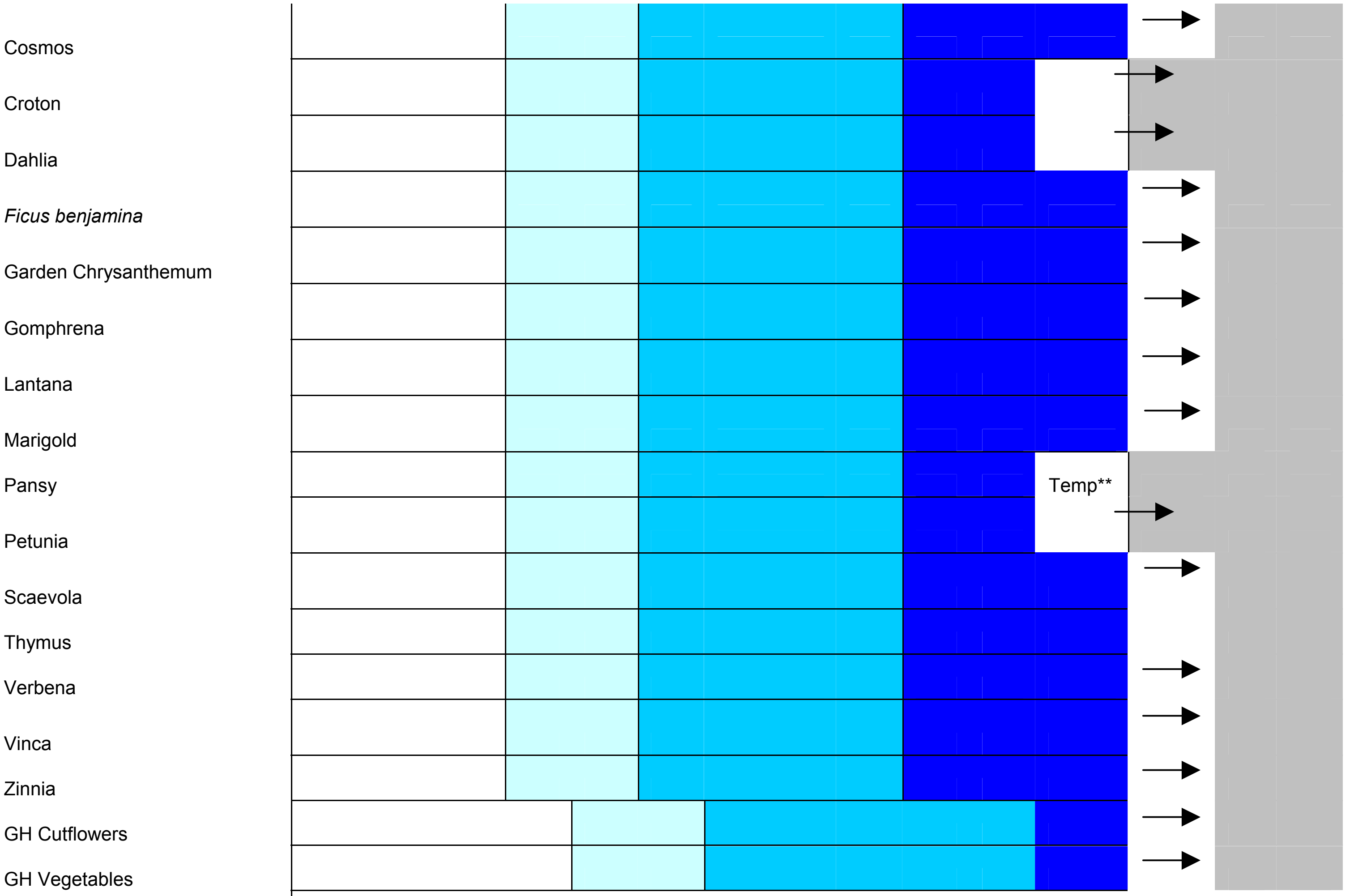
█ High quality

Daily Light Integral

(moles/day)

	GREENHOUSE											**OUTDOOR**		
Species	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**25**	**30**	**40**	**50**
African violet	░	▒	█	█	█									
Ferns (*Pteris, Adiantum*)	░	▒	█	█	█									
Maranta	░	▒	█	█	█									
Phalaenopsis Orchid	░	▒	█	█	█									
Spathiphyllum	░	▒	█	█	█									
Forced Dutch Bulbs	░	▒	█	█	█	█	█	█	█	█	█			
Foliage		░	▒	█	█	█	█							
Boston Fern		░	▒	█	█	█	█							
Bromeliads		░	▒	█	█	█	█							
Caladium		░	▒	█	█	█	█	█	█	█	Water*			
Streptocarpus		░	▒	█	█	█	█							
Hosta		░	▒	█	█	█	█	█	█	█	Water*			
Hedera (English ivy)		░	▒	▒	█	█	█	█	█	█	█			
Gloxinia		░	▒	▒	█	█	█	█						
Christmas Cactus		░	▒	▒	█	█	█	█	Temp**					
Hiemalis Begonia		░	▒	▒	█	█	█	█						
Exacum		░	▒	▒	█	█	█	█	█					
Cyclamen		░	▒	▒	█	█	█	█	█					
Heuchera		░	▒	▒	█	█	█	█	█					
Coleus (shade)		░	▒	▒	█	█	█	█	█	█				


Dutch Iris Cutflowers
New Guinea Impatiens
Kalanchoe
Lobelia
Temp**
Primula
Impatiens
Ivy geranium
Dusty Miller
Fibrous Begonia
Fuchsia
Temp**
Poinsettia
Temp**
Pot Lilies
Hydrangea
Ageratum
Allysum
Dianthus
Gazania
Gerbera
Hibiscus rosa-sinensis
Miniature Rose
Pot Chrysanthemum
Red Salvia (*S. splendens*)
Snapdragon
Zonal Geranium
Angelonia
"Full Sun" Herbaceous Perennials
Blue Salvia (*S. farinacea*)
Celosia
Coleus (sun)



*Water-Requires ample water to perform well at high light levels

**Temperature-Requires cool or moderate temperatures to perform well at high light levels

Arrows indicate that the species continues to perform well in full-sun outdoor conditions

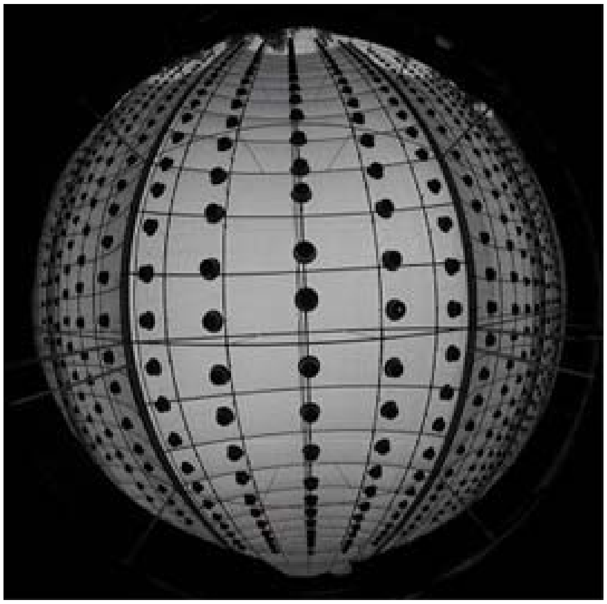
FIRST Research Report

Light Management in Greenhouses

III. The Effect of Hanging Baskets on the Greenhouse Light Environment

James E. Faust

Hanging baskets intercept light that would otherwise be delivered to the bench crop. For example, Figure 1 displays a "plant's eye" view of hanging baskets placed overhead. The hanging baskets in the figure intercepted 10% of the light that would have otherwise reached the bench crop. Too many hanging baskets overhead can obviously reduce plant quality on the bench crops by reducing the daily light integral delivered to those crops.



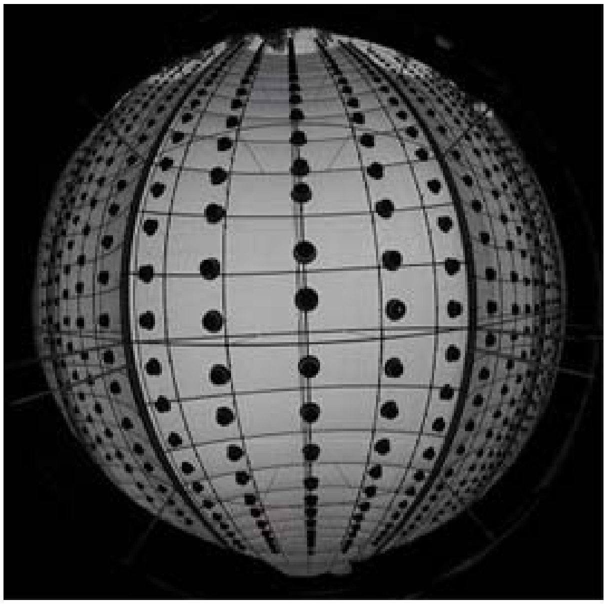
How many hanging baskets can be grown overhead? This question is usually answered through trial and error based on observations of the bench crop; however, a more precise answer can be estimated based on light measurements with a portable daily light integral (DLI) measuring devise (available from Spectrum Technologies) or by using the maps in Part I of this report combined with a greenhouse light transmission measurement. With the DLI datalogger, one can simply place the sensor on the bench to record the DLI reaching the bench crop. The sensor should be moved to several different locations for a few days since the shadow pattern can vary from spot to spot.

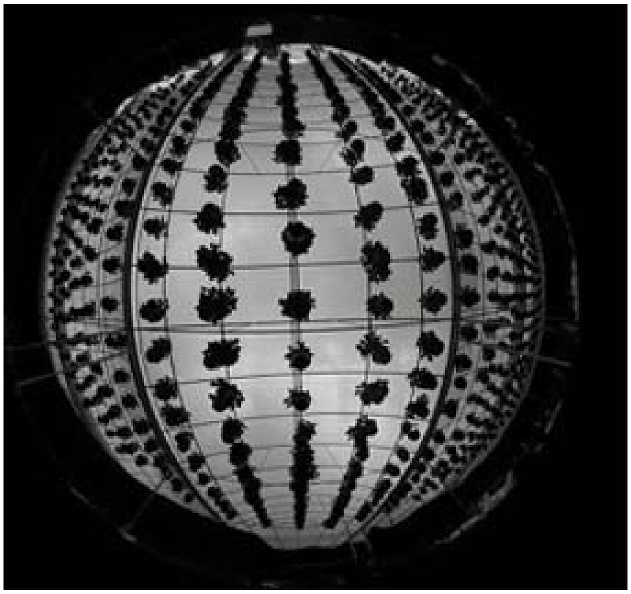
With the DLI maps (Table in Report 1), one can see that Columbus Ohio, for example, the average outdoor DLI for February is 15 to 20 moles/day (we will assume 15 moles/day to account for a below average year). A greenhouse transmission measurement indicates that this particular greenhouse transmits 50% of the outdoor light without any hanging baskets, resulting in 7.5 moles/day delivered to the bench crop during February. If low light crops, like impatiens and begonias, are being grown below the hanging baskets, we can make the assumption 5 moles/day is adequate to grow a commercially acceptable crop. (Note: The baseline daily light integral might be 8 to 10 moles/day for higher light crops, like vinca and marigolds, See Table 1 in Report II for guideline for many crop species). Thus, in February in Columbus, we can place hanging baskets overhead to intercept 33% of the light above the bench, if shade crops are being grown. However, if higher light-requiring crops are being grown, then no hanging baskets can be grown overhead in February. We will have to wait until the daily light integral being delivered to the bench crop exceeds 10 moles/day before considering placing hanging baskets over a high light crop. In this example, this will occur in March.

Factors affecting light interception by hanging baskets

Several factors affect how much light hanging baskets intercepts, including plant size, pot color and hanging basket density.

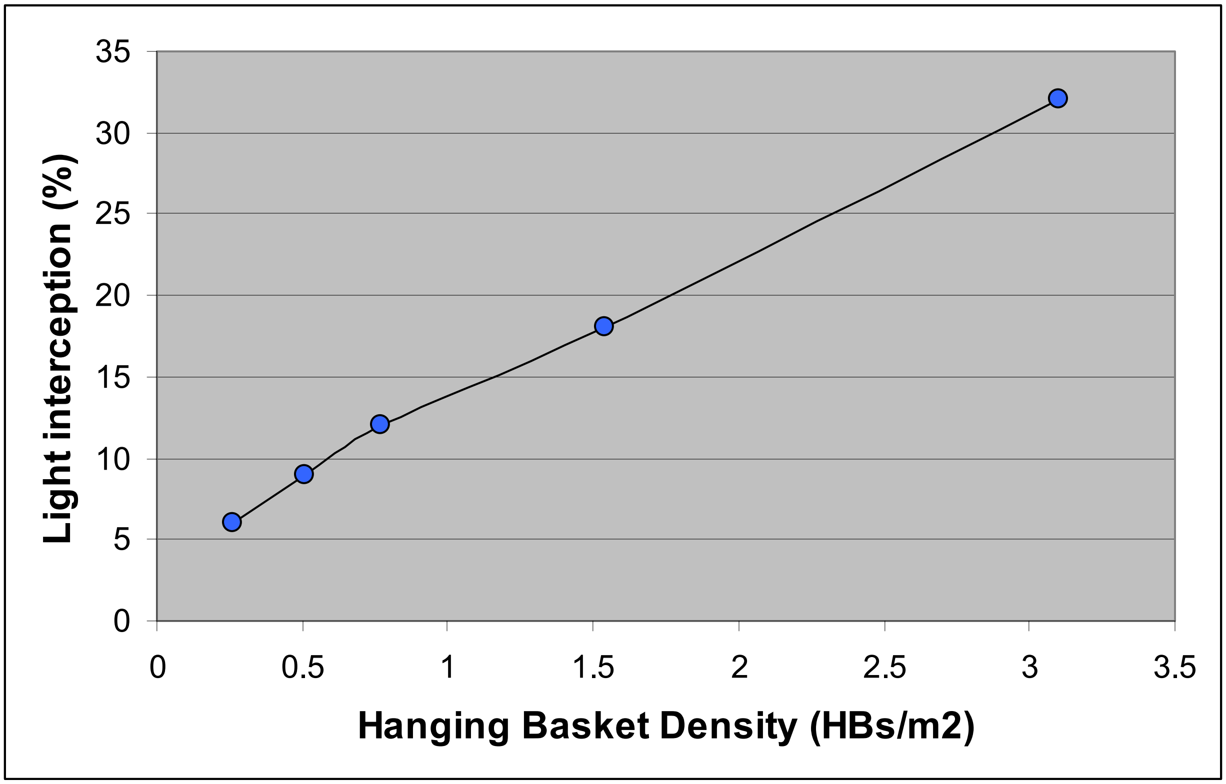
Plant Size. The size of the plant growing in the hanging basket is a very important factor to consider, since a large plant will intercept more light than the basket itself. When hanging baskets are first hung, the plant in the basket is usually smaller than the basket itself. So, the plant doesn’t intercept very much light that would otherwise reach the bench crop. However, as the crop grows, the plant may eventually intercept more light than the containers themselves. Fortunately, hanging baskets are not usually getting large until later in the spring, when the DLI is much higher than in February and March. If the hanging baskets can be marketed at a relatively small size, one can grow a lot more baskets and still allow sufficient light to be delivered to the bench crop. The following photos show green hanging baskets without plants (left) and with plants (right). The density of baskets is 1.5 baskets per m^2 of greenhouse space (10.8 ft^2 per m^2). The empty baskets intercepted 10% of the solar radiation, while the baskets with plants intercepted 27% of the solar radiation.





Container Color. The color of the hanging basket container is also important, since green containers can intercept nearly twice the light compared to white containers. The reflective white surface of hanging baskets can significantly increase light transmission of a crop. This is particularly true early in the hanging basket season when the plants are still small. As the plant in the hanging basket grows bigger, less light reflects off the side of the pot, so the effect of container color on light transmission is diminished. Our measurements indicate that white baskets intercept approximately half the light compared to green baskets. For example, if a particular arrangements of green baskets intercepted 10% of the light, then white baskets would be expected to intercept half that percentage, or 5% of the light.

Hanging Basket Density. Obviously, the more hanging baskets the more light intercepted. We made light measurements under 5 different hanging basket densities. The following graph shows a general response for light interception by green hanging baskets.



Growers can calculate their hanging basket density to estimate the light interception by green hanging baskets. These number reflect the means of treatments with and without plants in the baskets. So, large plants will result in higher interception and smaller plants with less intercept. White containers will also result in less light interception.

Hanging Basket Arrangement. We did not observe any measurable difference in light interception when equal numbers of baskets were hung in one layer versus multiple layers. For example, we placed 6 lines of baskets in a greenhouse that were all hung at the same height. Then, we placed the same number of baskets on just 3 lines using S-hooks on every other basket to create a two-tier crop. Both arrangements intercepted similar amounts of light.

Hanging Basket Line Orientation. Hanging basket lines can be run north-south or east-west. North-south lines are recommended, because the shadow pattern across the benches is constantly changing which results in a more uniform growing environment. East-west lines create relatively constant shadow patterns, especially from September to April. This results in poor uniformity of light delivered to the bench crops, thus some plants can receive much higher light levels than neighboring crops. Poor light uniformity creates a problem with watering, since light interception and water use are closely correlated.

Red-to-Far-Red Light Ratio. Plants in hanging baskets can reflect or filter sunlight before it reaches the greenhouse floor. Since plants intercept red light quite readily, the light that is reflected or filtered from plants in baskets has less red light than far-red light (sunlight has equal amounts of red and far red light). Low red-to-far-red light ratios promote stem elongation, so it has always been a concern that hanging baskets will cause bench crops to elongate more rapidly. Our data suggest that relatively high hanging basket densities (>1.5 baskets per m^2) will lower the red-to-far-red light ratio slightly. However, the change is relatively small, so we are of the opinion that hanging baskets do not have major impact on light quality (red-to-far-red light ratio), so the major issue with baskets is the effect on light quantity (daily light integral).