Energy Management in Controlled Environment Agriculture
-
Modern Lighting Systems, Temperature and Humidity Control, and "AgriVoltaics"

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Overview of this presentation

- Controlled Environment Agriculture (CEA) Overview
  - Protected cultivation, various structures (greenhouses)
  - CEA with complete control
    - Over: Temperature, Light, Humidity, CO_2,…
    - Hydroponic systems
- Lighting systems – past, present and new technologies
  - HID vs LED lamps
  - Is sunlight free?
- AgriVoltaics: Growing plants in shade of solar
  - PV greenhouse experiment

“Controlled Environment Agriculture” versus “Protected Cultivation”

- “CEA”
  - A system of plant production technologies that enable full control of the environment around the plants: roots, stems, leaves, flower and fruit
  - Greenhouses, growth chambers, in-door production
- “Protected Cultivation”
  - A horticultural system where plants/crops are protected from harmful biotic and abiotic influences
  - Same as above, but also container nurseries, hoop-houses, shade houses, screen houses
- Note: the tools and structures are similar
- CEA goes beyond “protection” and aims at total control over the system.
  - Note: full control has higher input costs.
  - Energy Management is very different between CEA and Protected Cultivation.

CEA

- We want to control (optimize) <u>ALL</u> variables
  - Temperature (air, root zone, tissue…)
  - Relative Humidity
  - CO_2
  - Nutrients
  - Water
- Taking control costs money and generally involves energy
- For each variable, the more we want to change, the more it will cost to do that
- In CEA we eliminate variables that we cannot control:
  - roots are in soilless culture (substrate, liquid hydroponics, aeroponics, etc)

Protected cultivation in horticulture consists of:

- Greenhouses
  - » Enclosures which can completely seal in the interior
  - » Prevent precipitation from falling on plants
  - » Some level of control over interior temperature, etc
    - Vents, fans, heaters, electronic controls

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- Tunnels/Cold-frames
  - » No environmental controls (other than crude venting)
  - » Generally, partially open (with ability to enclose the space)

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  - » Generally, partially open (with ability to enclose the space)
- Shadehouse
  - » Structure for making partial shade at some controlled level
  - » Old technology: lath houses
  - » Newer technology: shade fabric (woven or non-woven)
- Sreenhouse
  - » Screen material of some mesh, generally to exclude pests

CEA – types of structures

- Greenhouses with adequate structure to install lamps, heating, cooling, etc
  - Typically glass and steel
- In-door without sunlight
  - All light is made with lamps
- Structure can be
  - Warehouse-type buildings
  - Converted shipping containers
  - Purpose-built

Indoor Plant Production

- In a building with a conventional roof (not transparent)
  - Growth chambers; Growth rooms
  - All variables are controlled and fully automated
  - Sunlight is not used to provide plants with PAR (Photosynthetically Active Radiation); Instead, lamps are used to make light
- Emerging technology – feasible due to:
  - Advanced lighting technologies
  - Advanced soilless culture methods
  - Advanced tools for air handling (CO_2, humidity,…)

“Vertical production” (stacked) is possible! Some examples:

- Photo: Leafy greens
  - (Note the lights are off in this photo)
- Layers = 6

Growing plants “without sunlight” – real examples

- AeroFarms
- Photo: Layers=7

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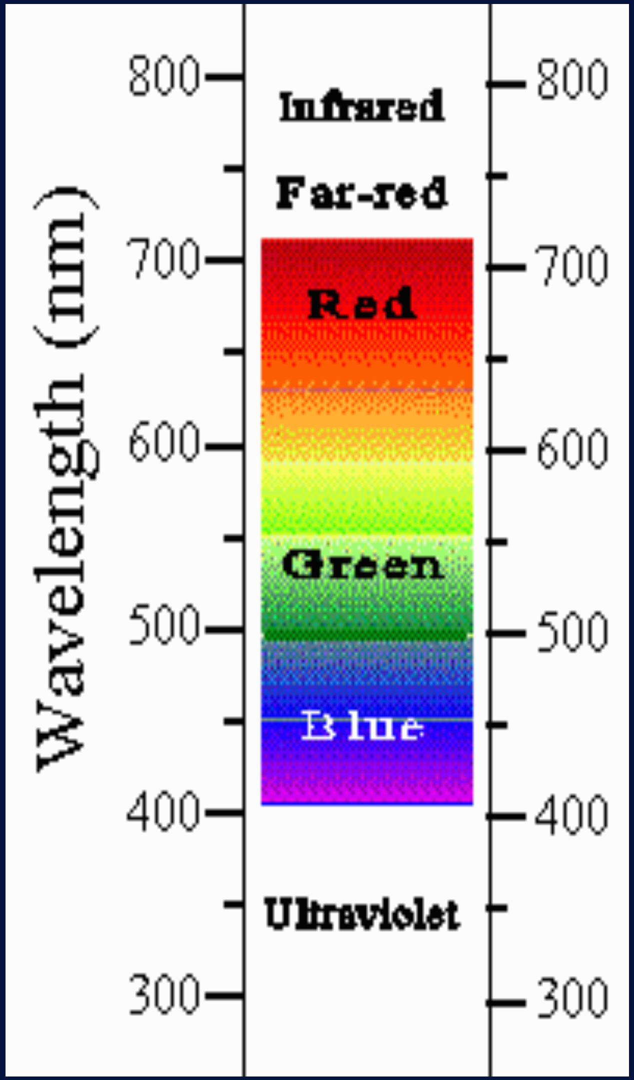
Light

- It is relatively easy to take light away
  - Shade curtains
- It is generally more difficult (expensive) to make light
- Light affects:
  - Photosynthesis
  - Photoperiodic control
  - Stomatal function
  - Other?
- General categories of greenhouse lighting
  - HID lamps: High-pressure sodium, Metal Halide
  - Newer HID technologies: induction lamps, plasma
  - Light Emitting Diode (LED) lamps

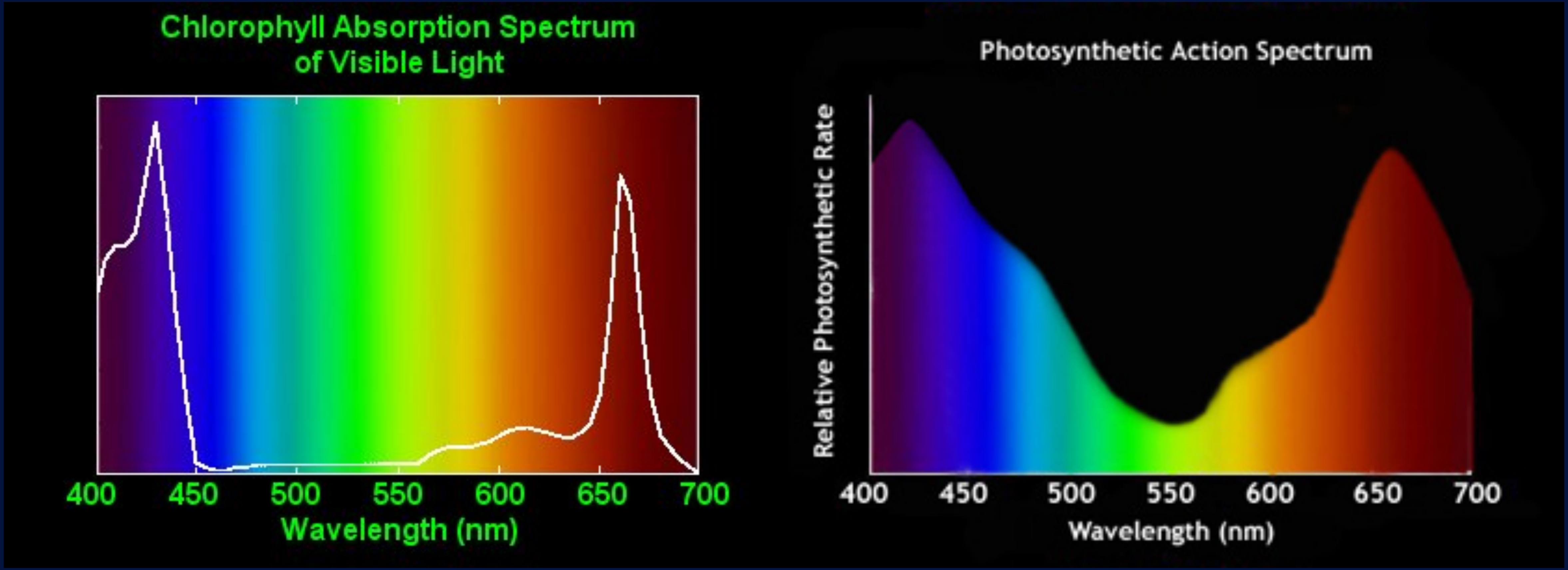
Light

- PAR – Photosynthetically Active Radiation
  - Photons with wavelengths between 400 nm to 700 nm
- Short-wave Radiation (a.k.a. Visible light)
  - Same range
- With new technologies we are interested in making primarily the wavelengths that will return on investment



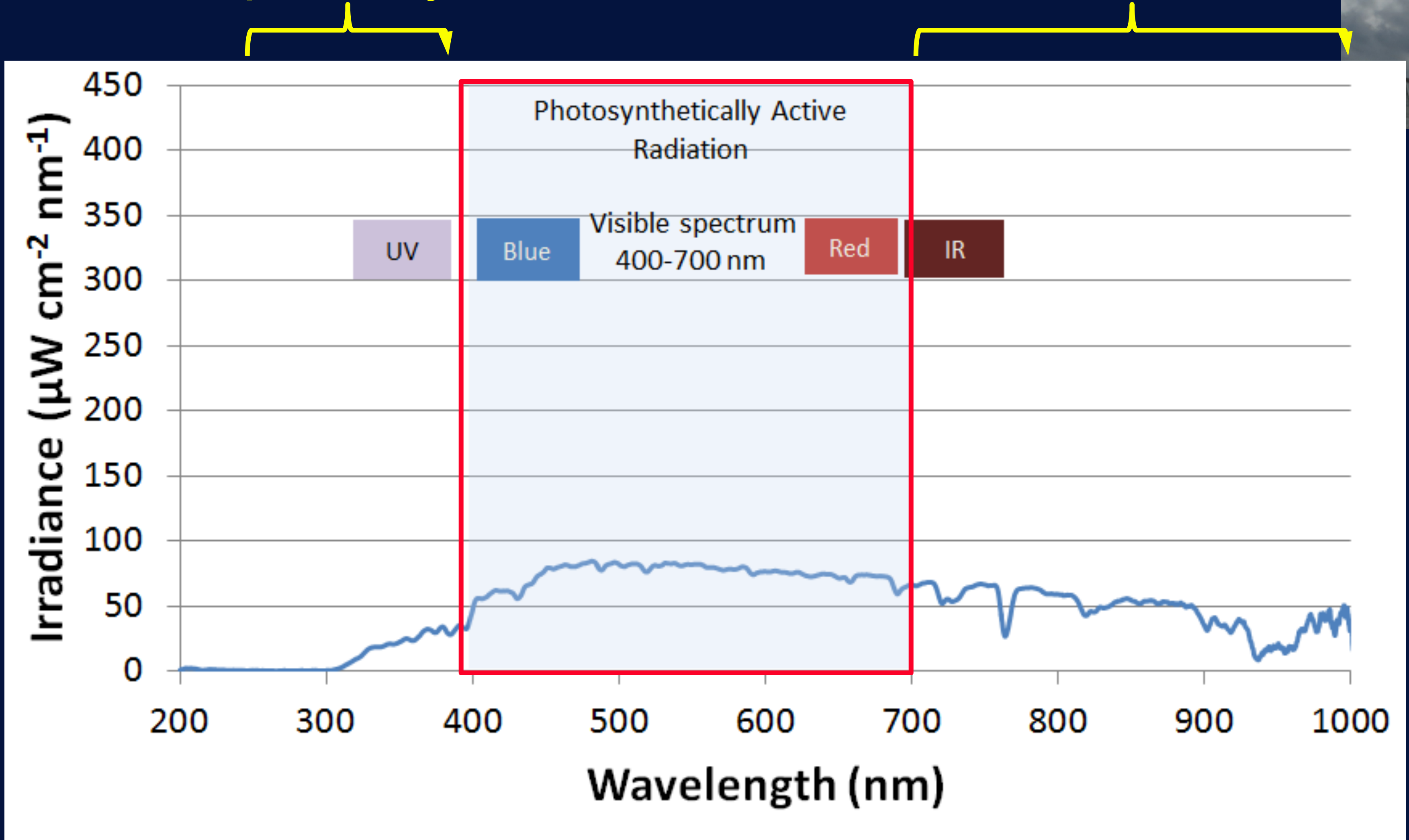
Common wisdom about the needs of plants:

- Searching on-line for information about how photosynthesis responds to PAR you find this:



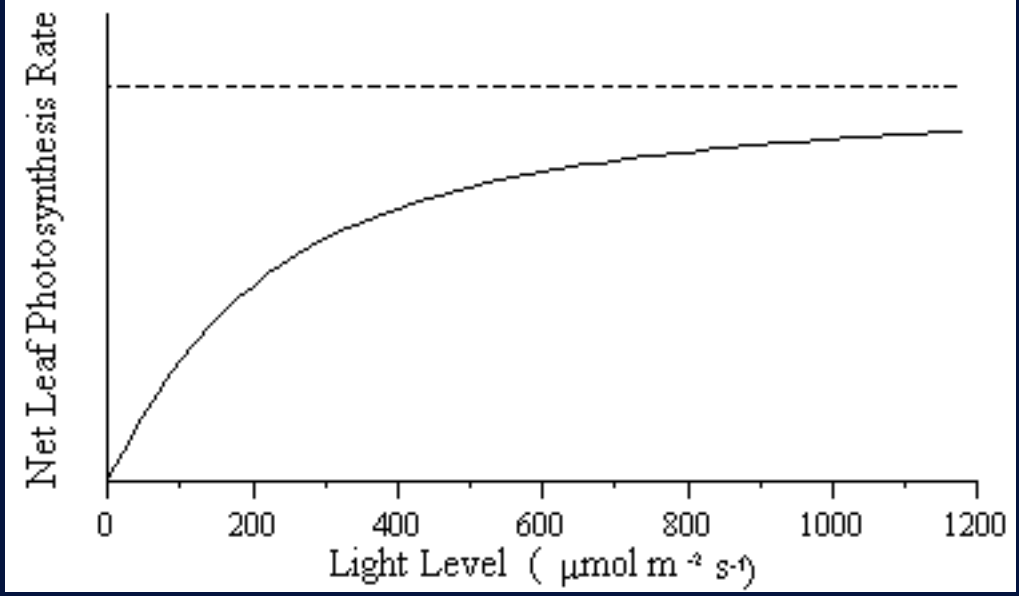
Sunlight outdoors (partly cloudy)

- So, much of spectrum does not result in photosynthesis



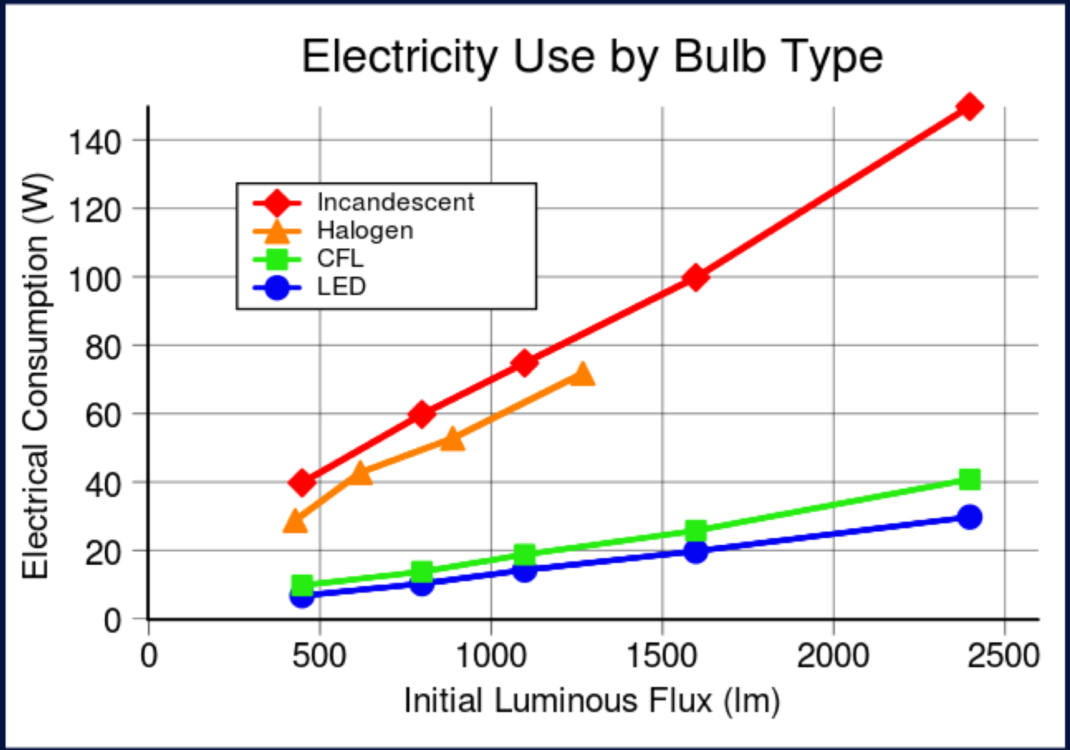
PAR (Photosynthetically Active Radiation)

- Gross Photosynthesis rate vs PAR:
- Note
  - Upper asymptote
  - Note linearity at low light
    - » It makes sense to add light when it is dark; not when light level is high
  - Also: Keep greenhouse covering clean during winter
  - This conventional wisdom does not account for spectrum; all wavelengths between 400 nm and 700 nm are treated the same



Incandescent and Fluorescent lamps

- Efficiency is too low for supplemental lighting in CEA
  - Incandescent: 7%
    - » i.e. of electricity consumed 93% ends up as heat
  - Compact Fluorescent (CLF)



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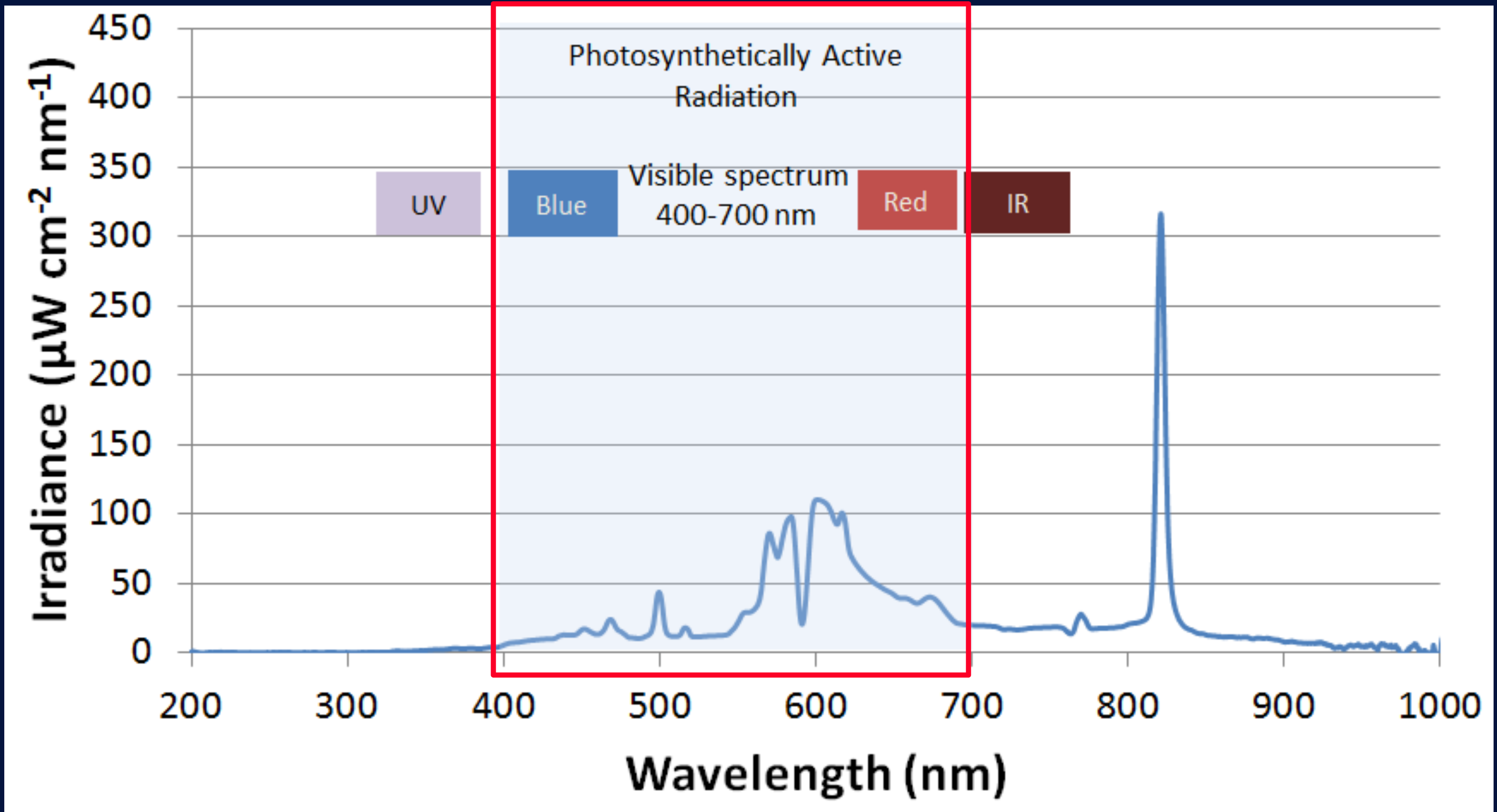
HID (High Intensity Discharge) lamps

- Generally, the various HID systems are similar
  - They differ in how they create light within a glass tube
  - Photons go through various coatings where wavelength is shifted
    - » Eg. Plant growth florescent lamps; same with induction lamps

HID lamp
(Low-pressure sodium)

- Note: lots of light that plants do not use



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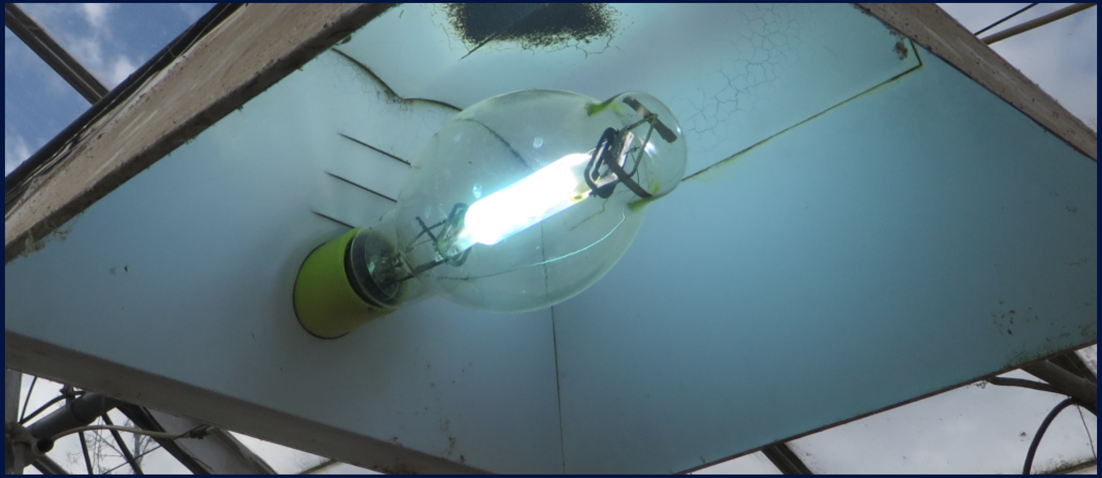
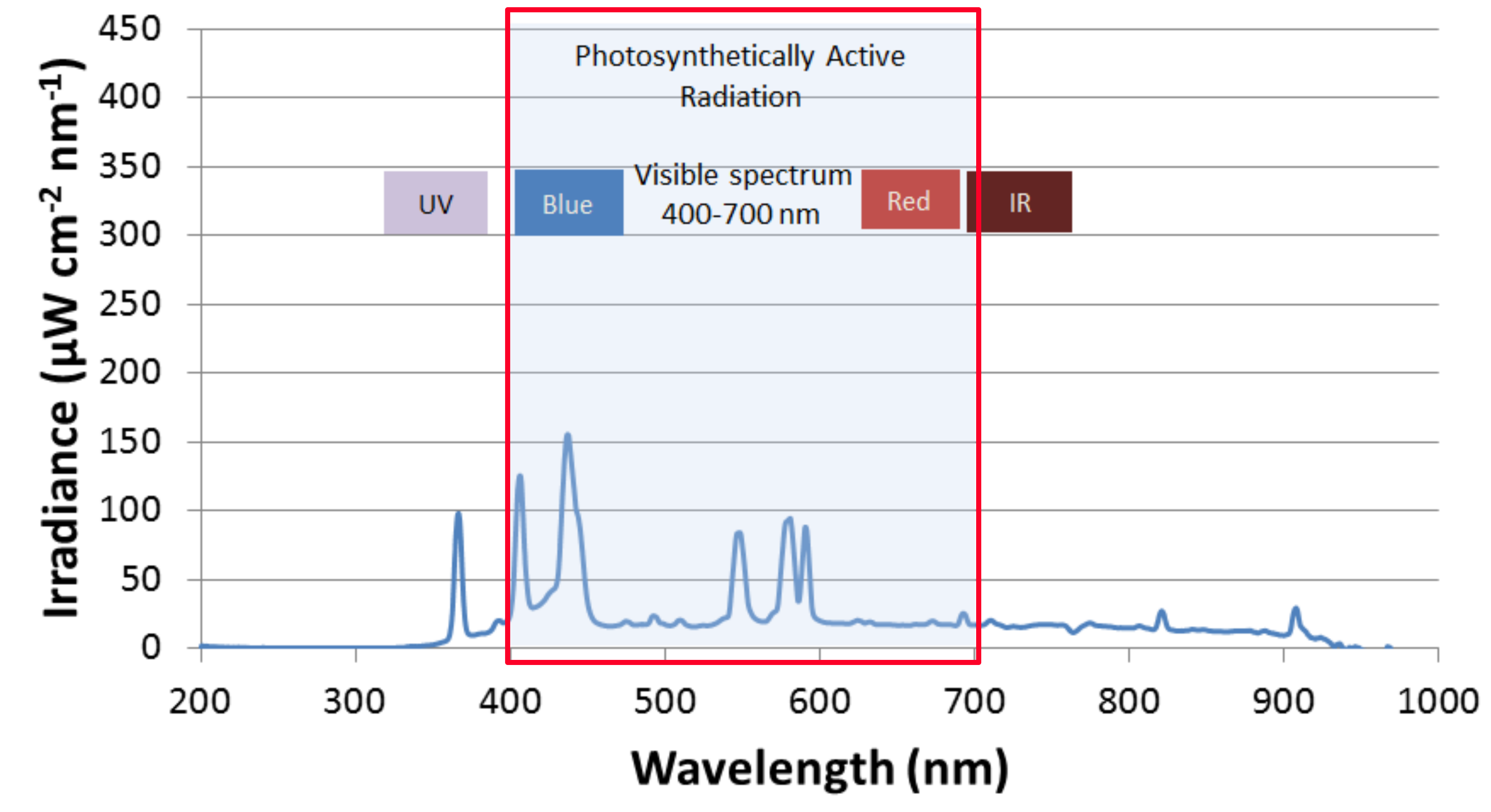
HID lamp (Metal Halide)

- Note: lots of blue light





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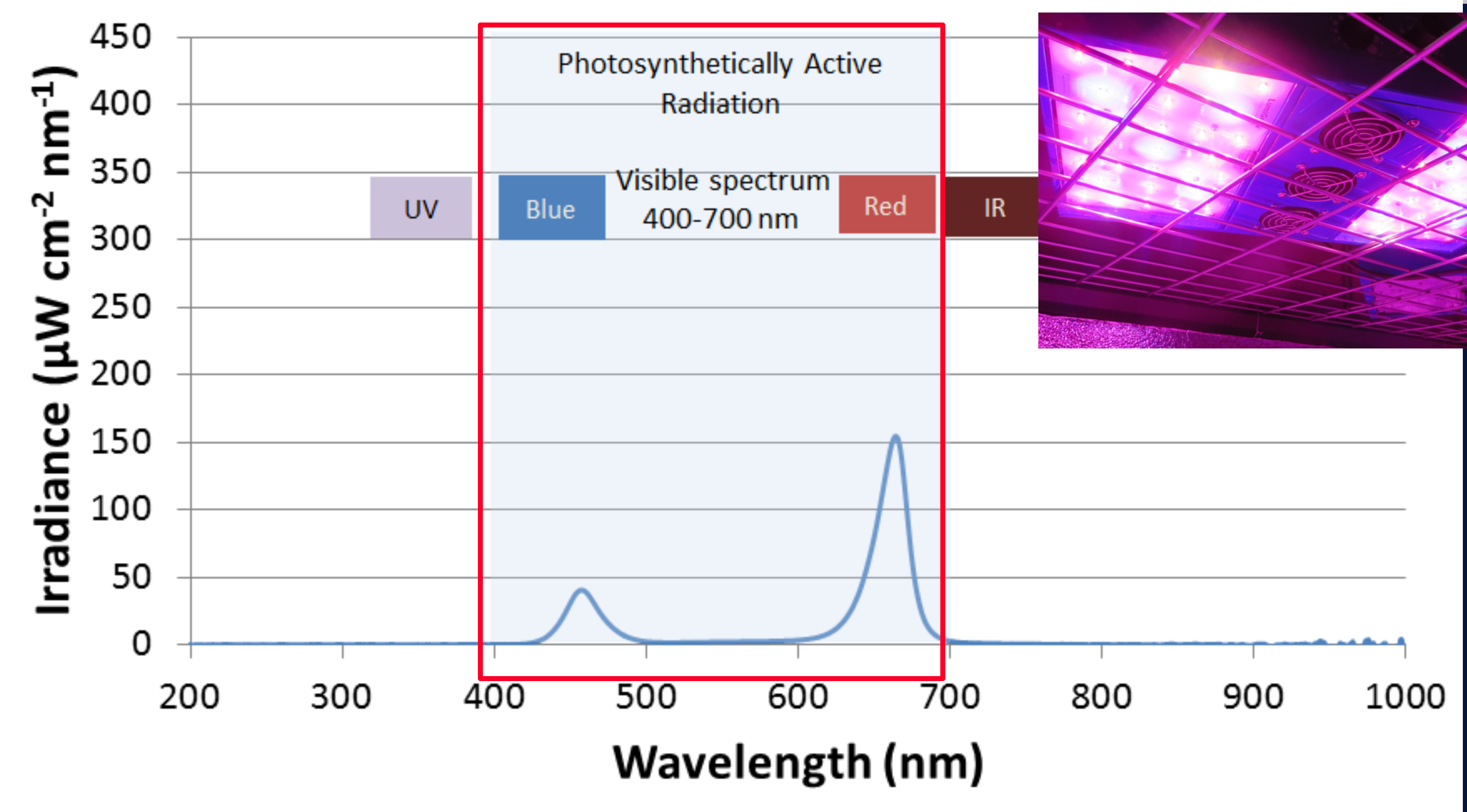
LED lamp (Lumigrow)

- Both blue and red turned up



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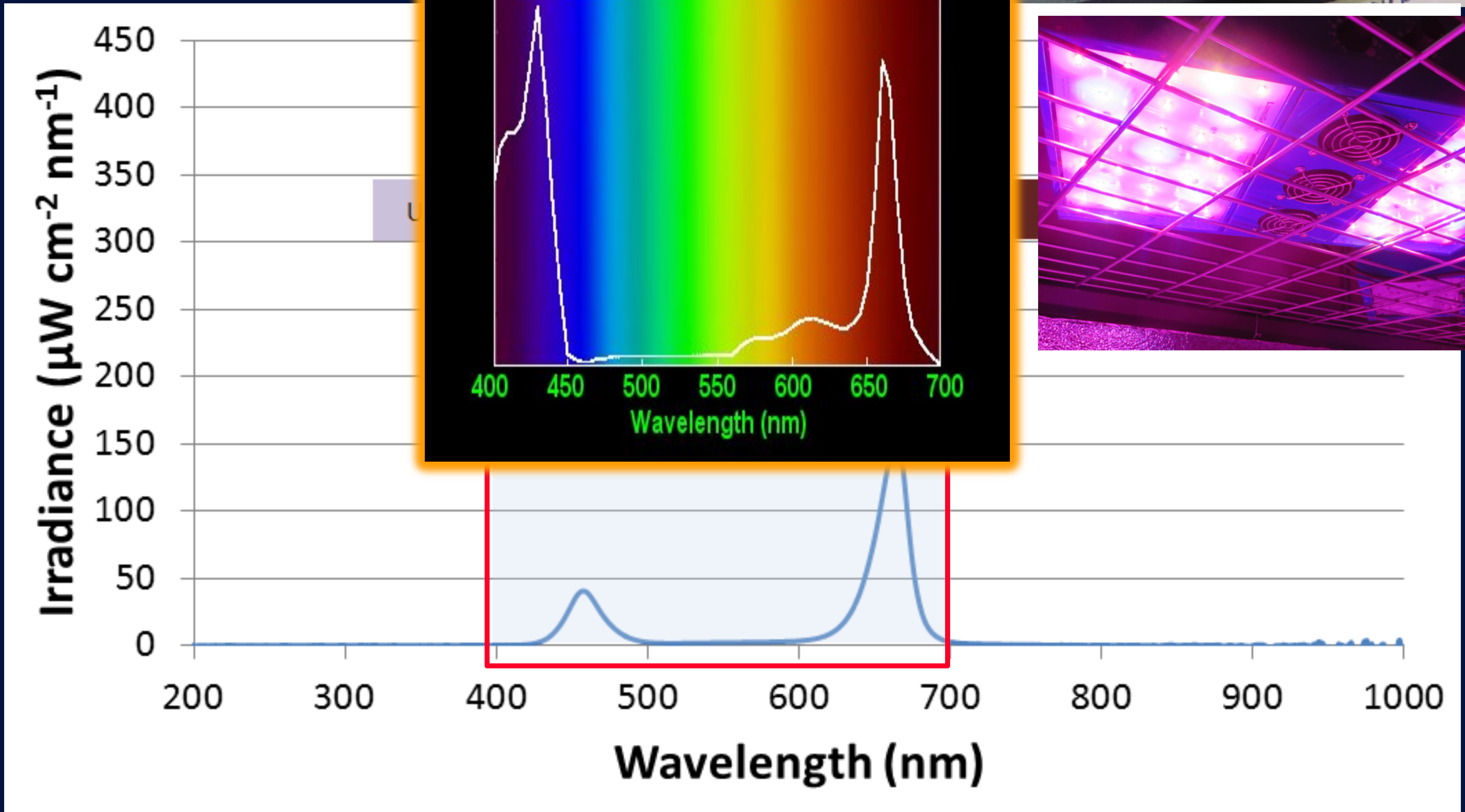
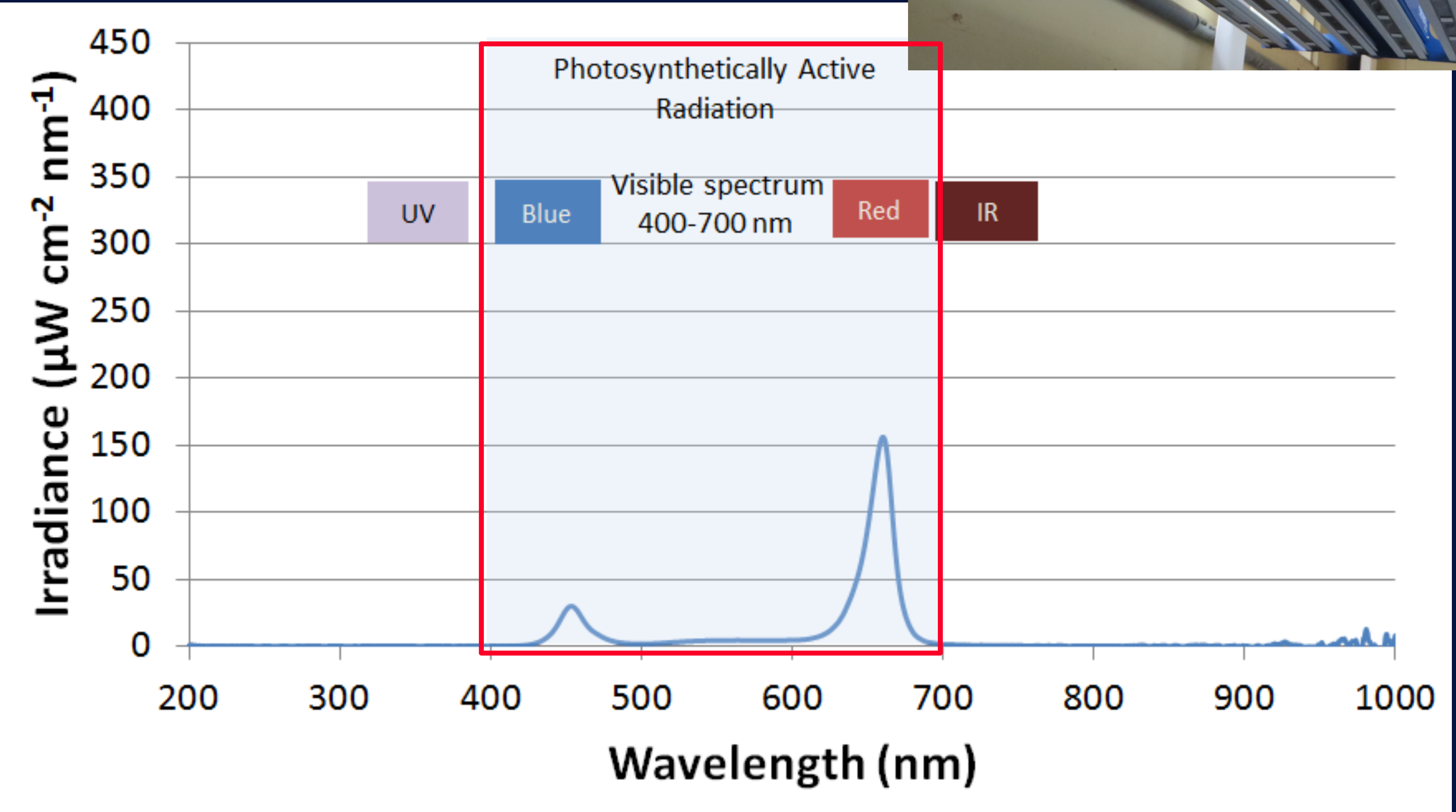


LED lamp (Illumitex 300W)

- Both blue and red turned up



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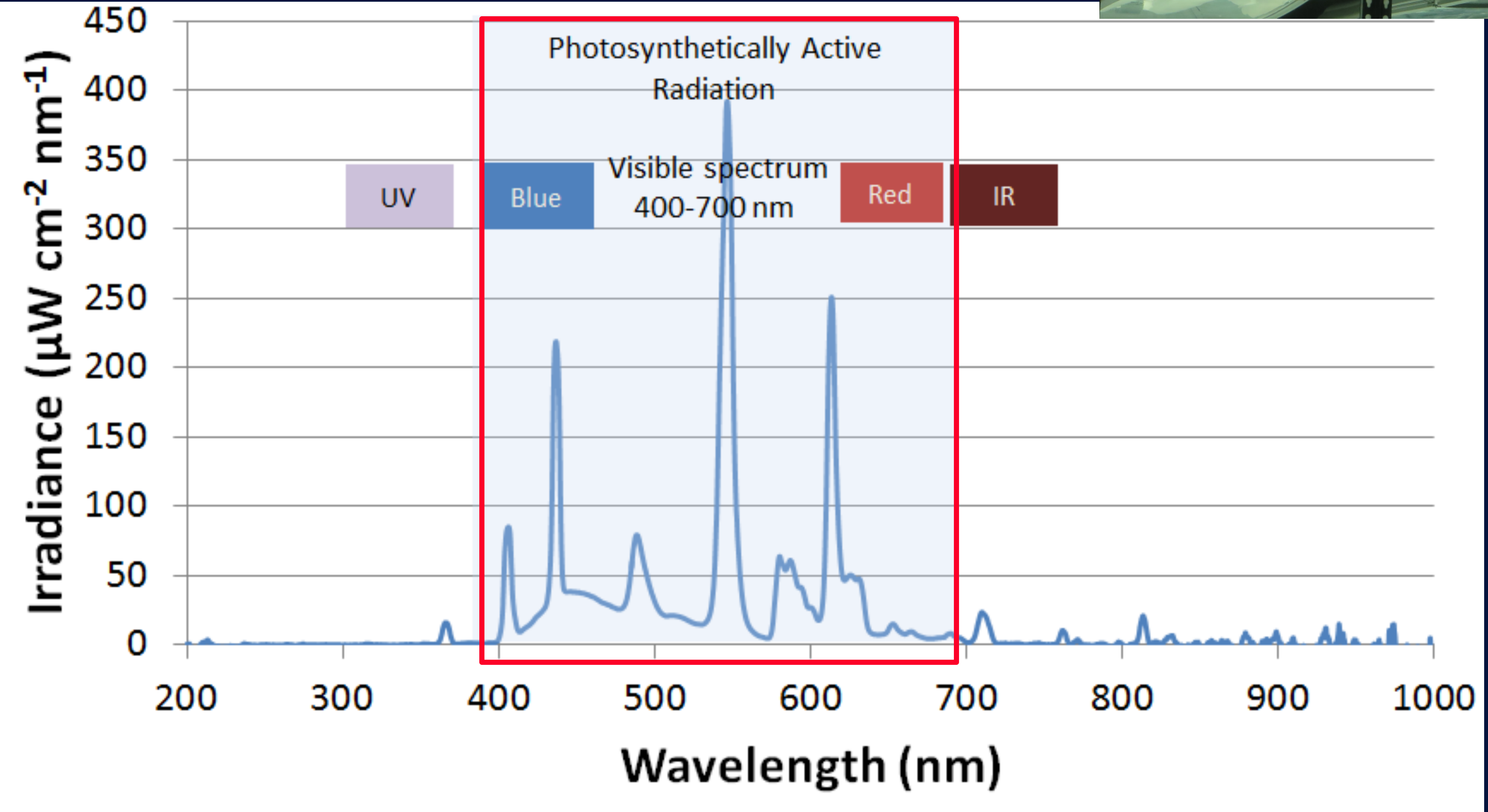
HID lamp: Induction lamp



In-door agriculture

- Note that various technologies have been changing
  - Hydroponics allows us to grow plants faster with more nutrient and water use efficiency
  - Sensors continue to get better and cheaper
  - Computer controls: getting better and cheaper
  - Lamps are becoming more efficient:
    - » Spectra tailored to plant production needs
    - » Efficiency is increasing (Induction and LED technology)
    - » Cost of operations is coming down
    - » Cost of LED lamps (currently relatively high) is coming down.
- Result of these changes:
  - In last 5 years it has become economically feasible to produce high-value vegetable and fresh herb crops in-doors

LED lamps as replacement for HID lamps (in Greenhouse production)

- currently cost significantly more (coming down)
- use less electricity (still improving slowly)
- last much longer (50000 hours with less decline over time)
- Issues when replacing existing HID lamps with LED
  - Cone of light cast down is different – lay-out of lamps needs to be different.
  - HID lamps also irradiate plants with long-wave radiation (warmth)
    - » During winter, energy use of HID lamps is part of heating cost
  - So, in the greenhouse, LED lamps may or may not be an improvement; grower should expect differences
  - Most LED lamp manufacturers have not understood uniformity needed by grower

LEDs in In-door production

- LED lamps have unique advantages for in-door production
  - LED Lamps can be hung very close to plant
  - Air-conditioning is a big cost in in-door production – LED lamps generate less heat
  - In vertical production we need to optimize vertical space utilization. Although most LED lamps are not “thin”, this can easily change. We have shown that a lamp can be built which takes at most 2 inches of vertical space
    - » Using low-output LEDs in large quantities

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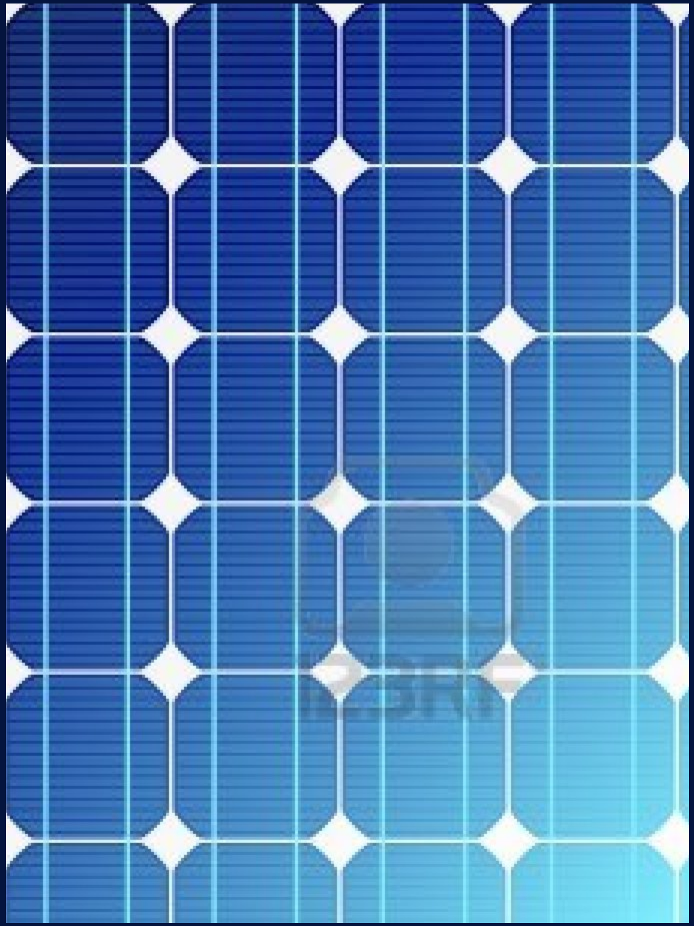
Solar Energy

- The sun's light: radiant energy that can be "harvested"
- Plants are solar collectors that use sunlight for:
  - Photosynthesis to convert light energy into energy stored in carbohydrates
  - Heat to maintain metabolic processes
  - Other processes (photoperiodism,…)
- Human-use of solar power includes:
  - Solar heating of hot water (e.g. solar hot water heater)
  - Concentrated solar energy can heat up water
  - Photovoltaics (PV): direct conversion of light to electricity

Photovoltaic (PV) Technologies



- How does PV work?
  - Some materials generate small amounts of electricity when the photons in light strike it
  - Electrons are moved through thin conductors (wires, traces,…); these connect to cables that attach to other devices to convert or store the energy

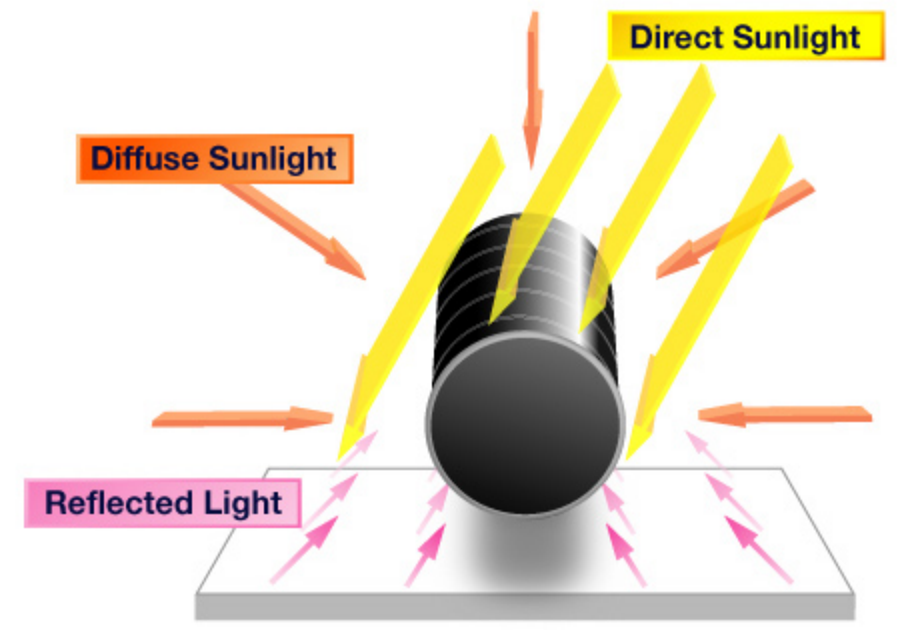
- A solar module generally consists of an array of such “cells”. Solar panel manufacturers combine “modules“ into “panels”
- Conversion rates: up to 20% - usually lower
- Note: a conventional panel generally intercept ALL light that strikes it

Types of PV panels

- Conventional flat panels:
  - Rectangular array of cells, usually in a frame
  - Most panels allow no light to pass through
  - It is typical to maximize light interception for electricity production.
  - Plants in the shadow of such panels have over 90% shade
  - Growing plants under solar panels seems impossible!
- Conventional flat panels on trackers
  - Same as above, but entire set of panels pivot to maximize light interception

Types of PV panels

- Tubular PV technology
- Reflective surface below
- Generally designed for flat roof commercial buildings



Solyndra was a company selling such systems in 2009-2011

- Solyndra panels:
  easy to install and to
  cover more roof area
- These panels do not need to move to track the sun because the tubular design automatically tracks sun if tubes are oriented north-south
- So, despite letting some percent of light through between the tubes, they can achieve greater amount of power production per roof

Photovoltaic Technologies and Plant Production

- PV electricity production is of interest to many businesses - generally to anyone that owns a building or property where panels can be installed
- Shade is generally a good thing – cooler buildings
- But what about plants under this shade:
  - Conventional panels: complete shade (too much for plants)
  - Solyndra panels allow some percent of light to penetrate
  - Omitting the reflective surface below results in a shading system that looks very similar to a lath house

- So, we asked: Can this shading system be used for plant production in outdoor nurseries?

Solyndra Shade House Project at UCDavis

- We set up a test:

Solyndra Shade House Project at UCDavis

- Our focus was only the nursery side of the issue (not electricity generation; not over fields of crops)
- Three treatments:
  - S44: Shade produced by their conventional panel (44 mm tube spacing) – no shade cloth
  - S88: Shade produced by panels where every other tube was omitted – so tube spacing is 88 mm
  - Shade produced by conventional shade cloth at roughly similar shading level as S88

Photovoltaic Shade house

PV Shadehouse research project: S44 (high density)

S44 - note little, if any, shadow patterns

PV Shadehouse research project: S88

S88 - note shadow patterns – distinct shade/direct-light

PV Shadehouse research project: shade "cloth"

Shade cloth – mostly diffuse light

Expectations:

- We <u>expected</u>:
  - Solyndra's standard spacing of modules (S44 – i.e. 44mm - >70% light interception) would be too much shade and would result in reduced growth
  - Shade-tolerant plants would do well in S88 and shade cloth
- We set out to look for
  - Any abnormal growth patterns due to differences in spectral distribution
  - Any observations that would impact nurseries

Results

- Shade under PV is different compared with shade cloth
  - when sun is overhead there is more direct light while earlier and later in the day, all light is diffuse, indirect light
  - Citrus seems to benefit from this
  - Plant growth of young Lemon trees in the three treatments resulted in no differences (even the darkest treatment)
    - » How is this possible ???????

Japanese Boxwood 'Green Beauty'

(*Buxus microphylla japonica*)

All plants grew well; no significant differences in height increases or width increase over 20 weeks

Rather than show you dozens of groups of photos with no difference, let's fast forward

Barberry ‘Crimson Pygmy’

(*Berberis thunbergii*)

Looks like less growth in S44;
Data analysis is pending

Note that these photos in next slides are NOT to same scale

Golden Euonymus

(Euonymus japonicus aureomarginatus)

No significant differences in height increases or width increase over 20 weeks

Observations

- The darkest treatments did result in lesser growth early for some plants; but for many, the plant growth was similar in all treatments.
- We also grew some leafy greens and herbs

Basil

(*Ocimum basilicum*)

Lettuce

(*Lactuca sativa*)

Kale

(*Brassica oleracea acephala*)

Many horticultural trials have been run in this shadehouse

- 4 species: grew best under medium shade (Control, S88)
- 15 species: no differences in growth between the three treatments
- 5 species: plants grew taller, wider and heavier in S44
- 4 species: taller and wider in S44 but not heavier (slightly stretched plants)
- 5 species: taller and wider in S44 but less weight (stretched plants)

After Solyndra went out of business (tubular PV was no longer available), we began to look at other options

- Can we achieve similar success with conventional panels by spacing them further apart or using trackers to favor plants rather than electricity production?

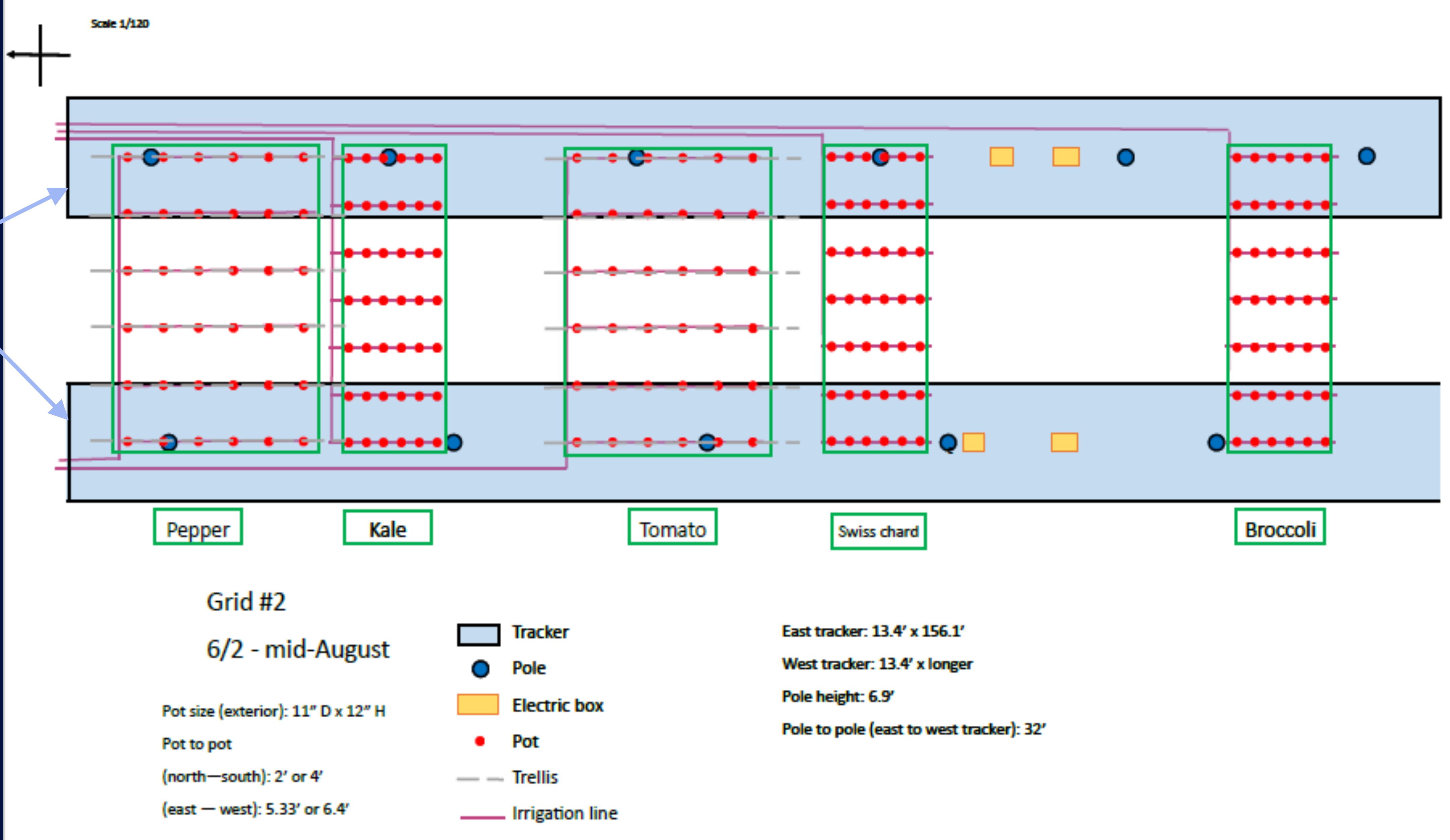
Research collaboration with at SunPower

- In Davis, California (not at UCDavis)
- Growing plants under solar PV system
- This project asks: can we grow agricultural crops between rows of trackers of solar PV panels?

Full Shade	Medium Shade	Low Shade	Full Sun	Low Shade	Medium Shade	Full Shade

Plot Orientation

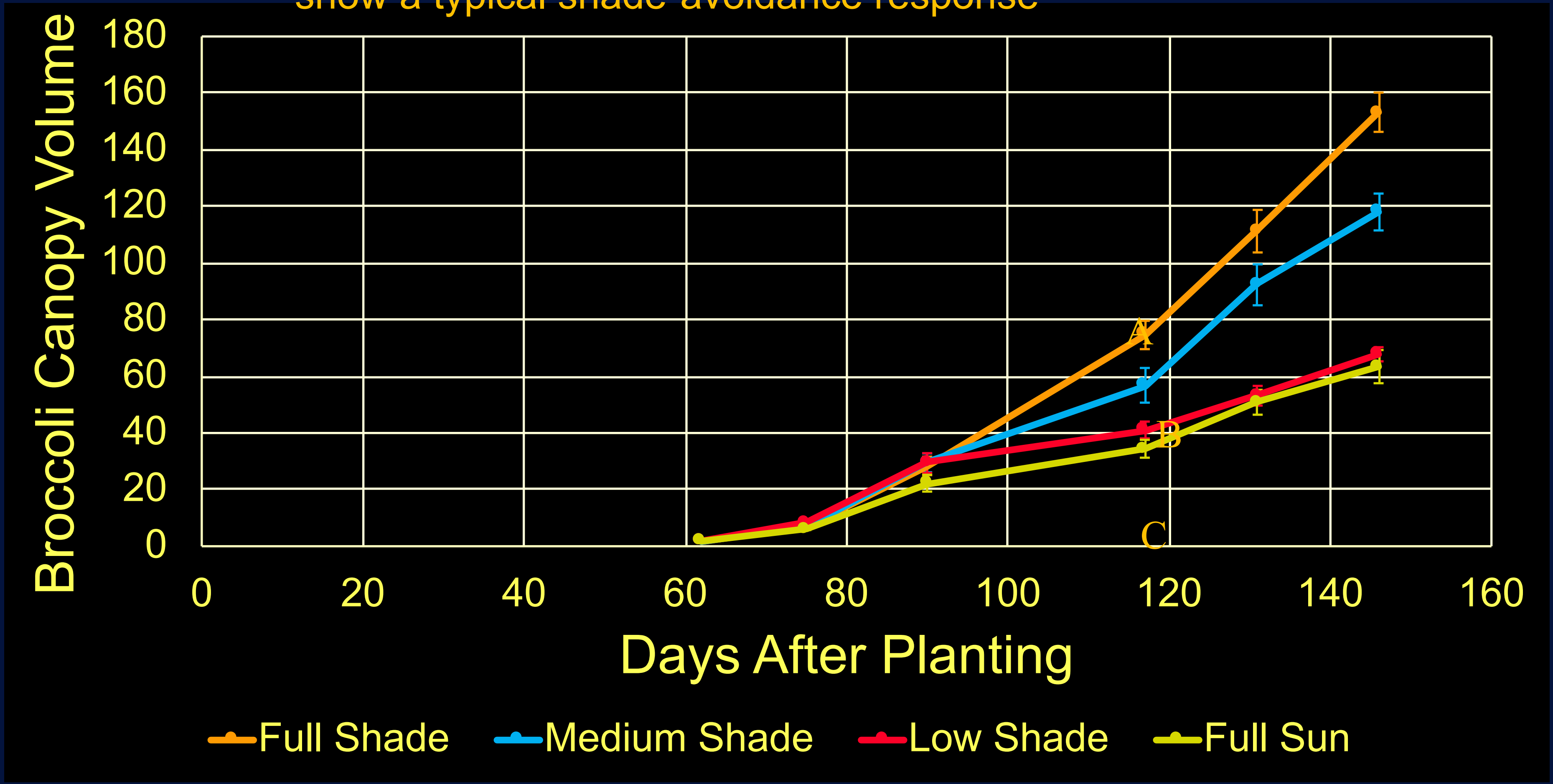
Rows of solar PV on trackers with open space in between the rows



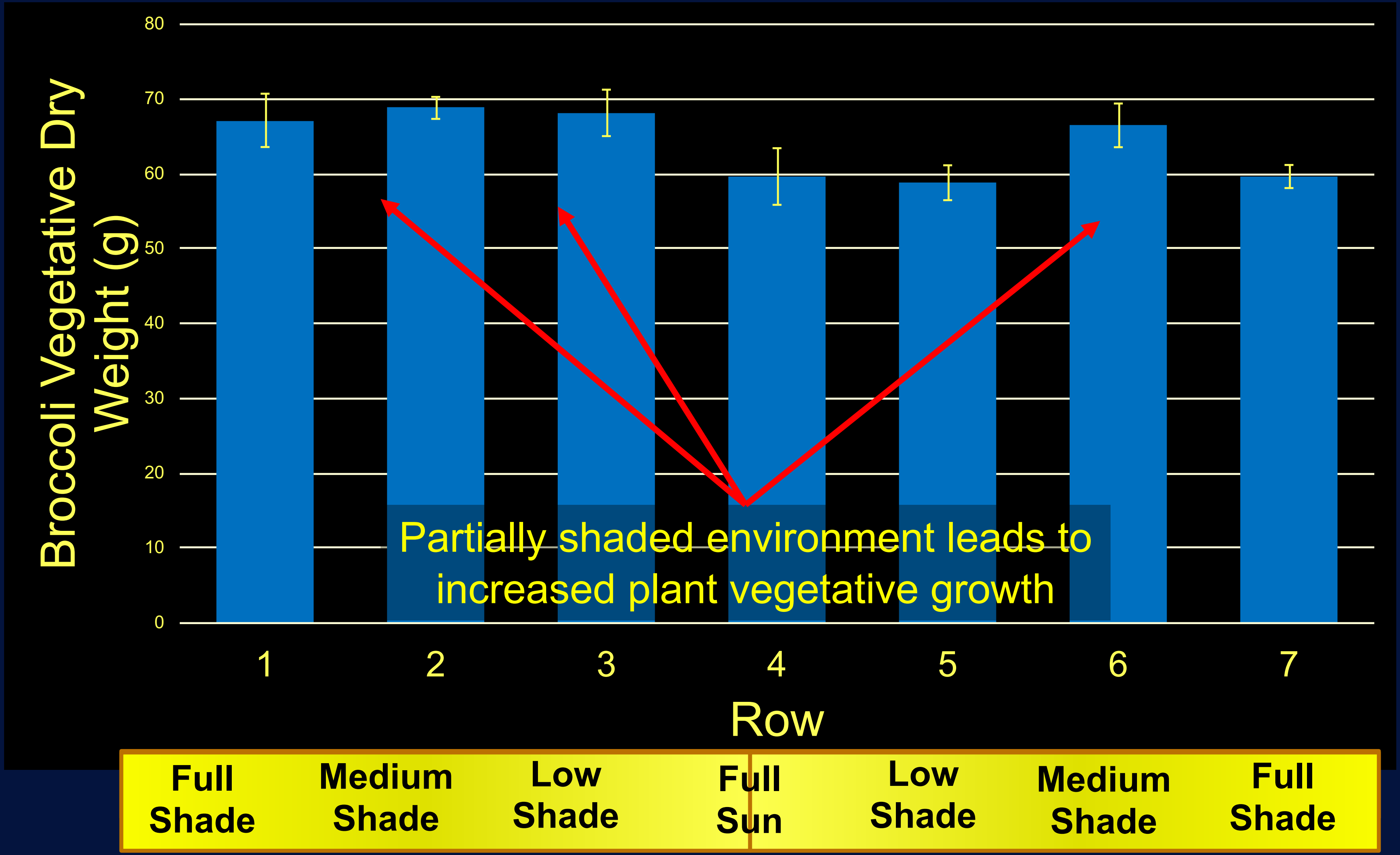
Broccoli

Broccoli Growth Curve – Canopy Volume by Light Treatment

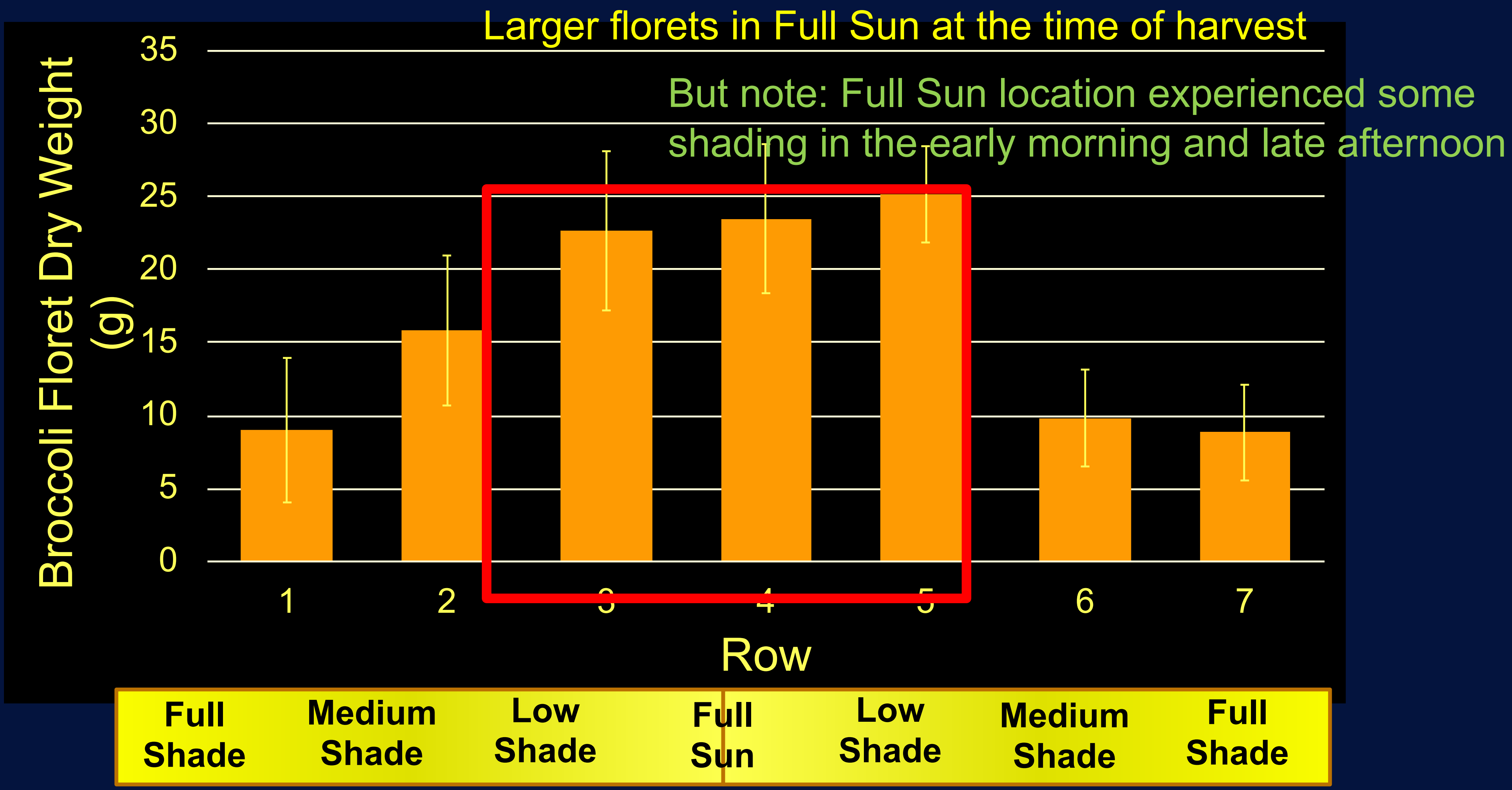
Expansion of the leaves and elongation of the stems/petioles show a typical shade-avoidance response



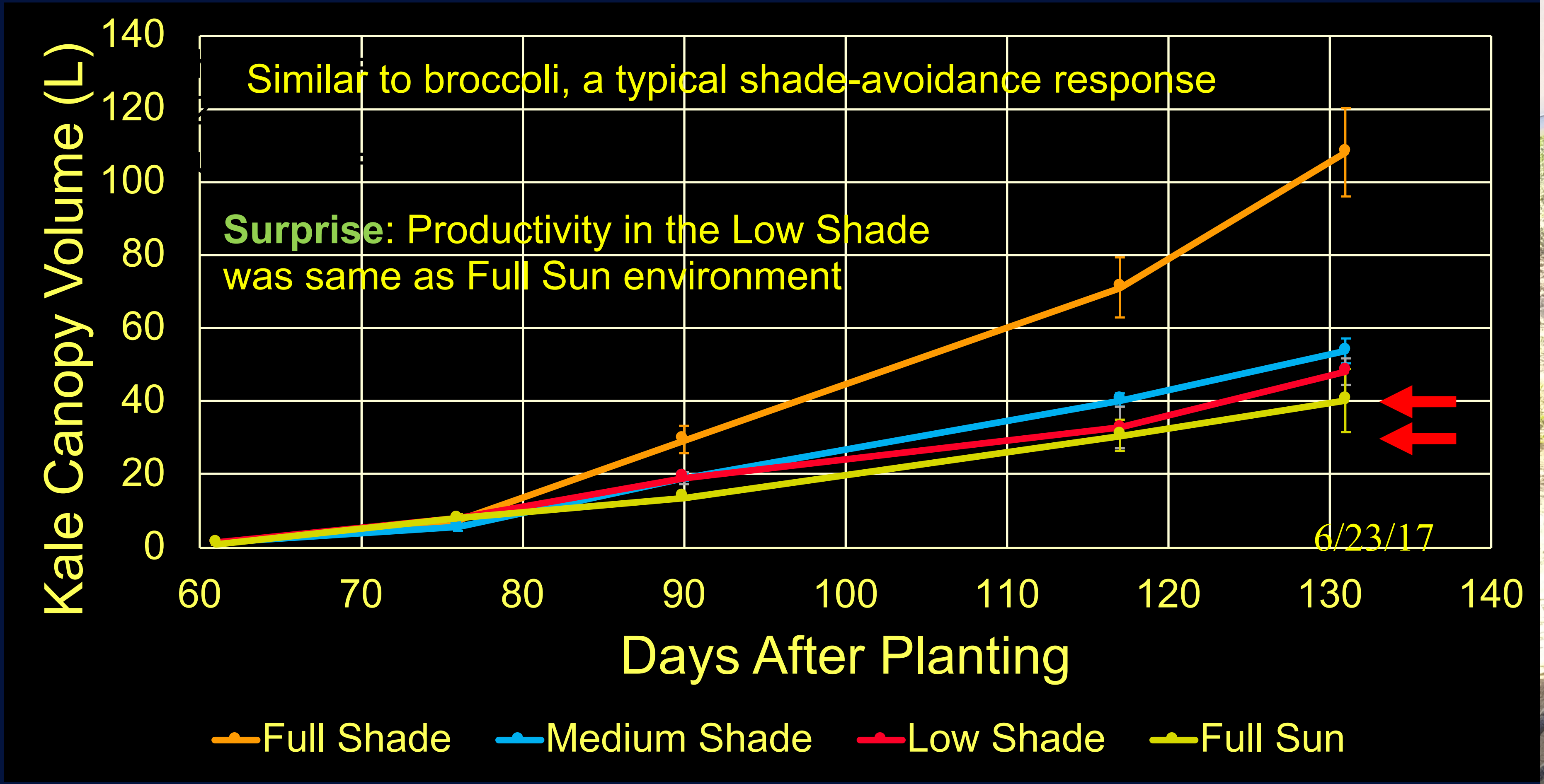
Broccoli Vegetative Shoot DW by Position



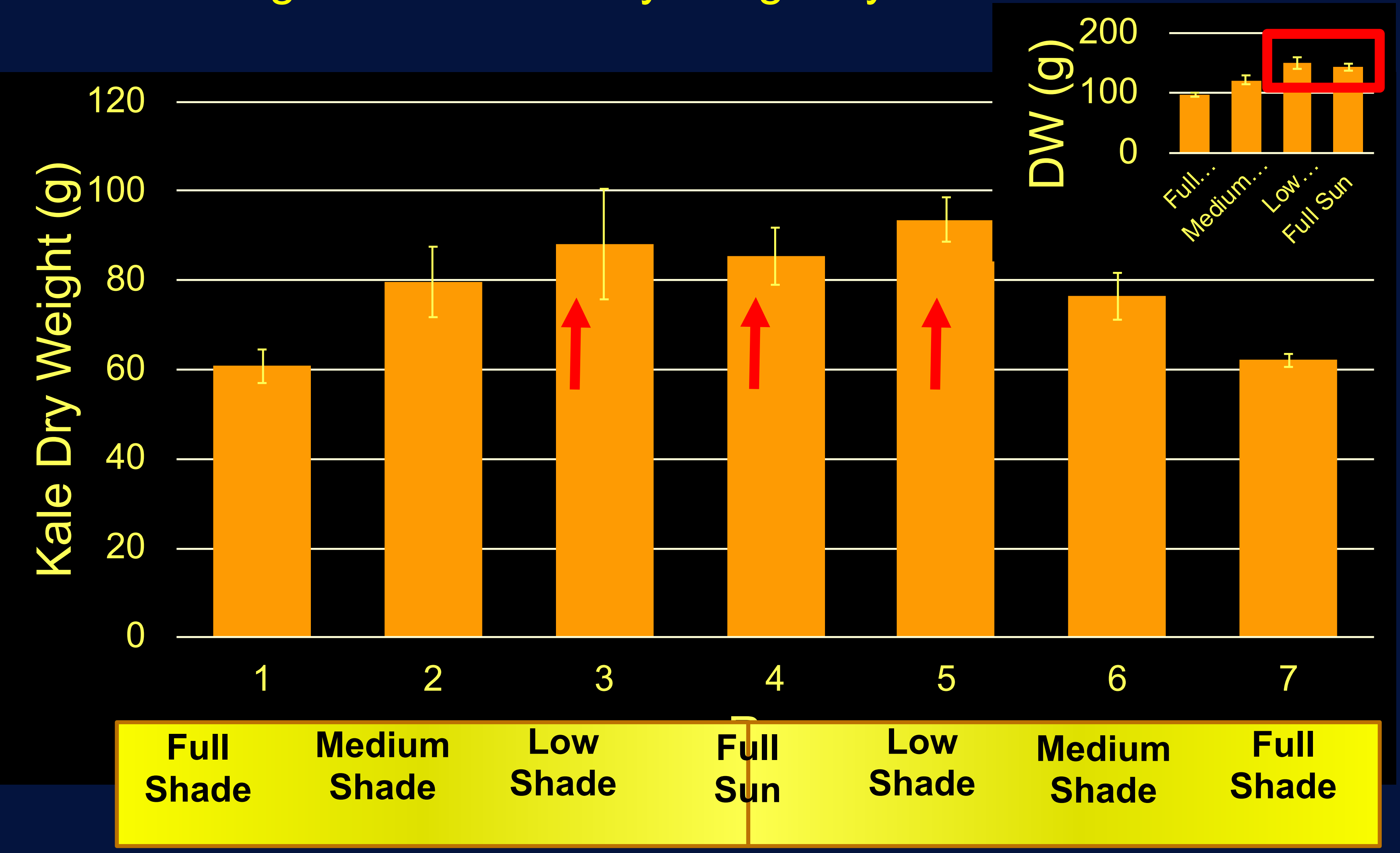
Broccoli Floret Dry Weight by Position



Kale Growth Curve – Canopy Volume by Light Treatment



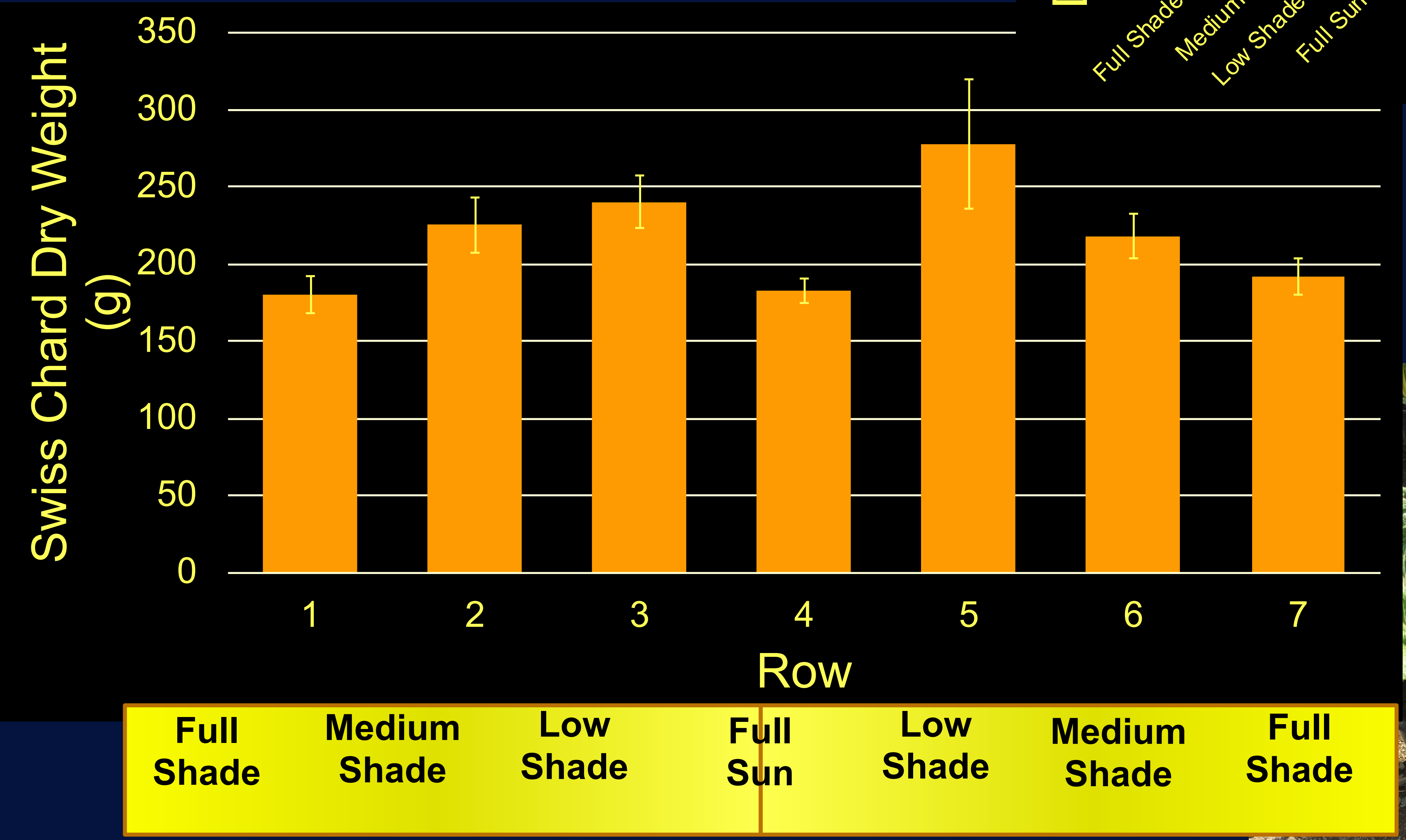
Kale Vegetative Shoot Dry Weight by Position

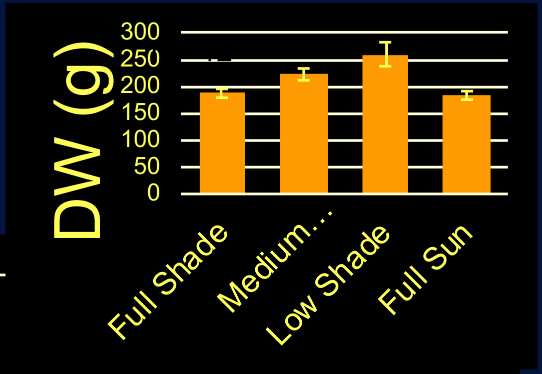


Swiss Chard Growth Curve - Vegetative Shoot DW by Position

Biomass accumulation in Swiss Chard was improved in partially shaded environments early in the growth cycle

Swiss Chard Vegetative Shoot DW

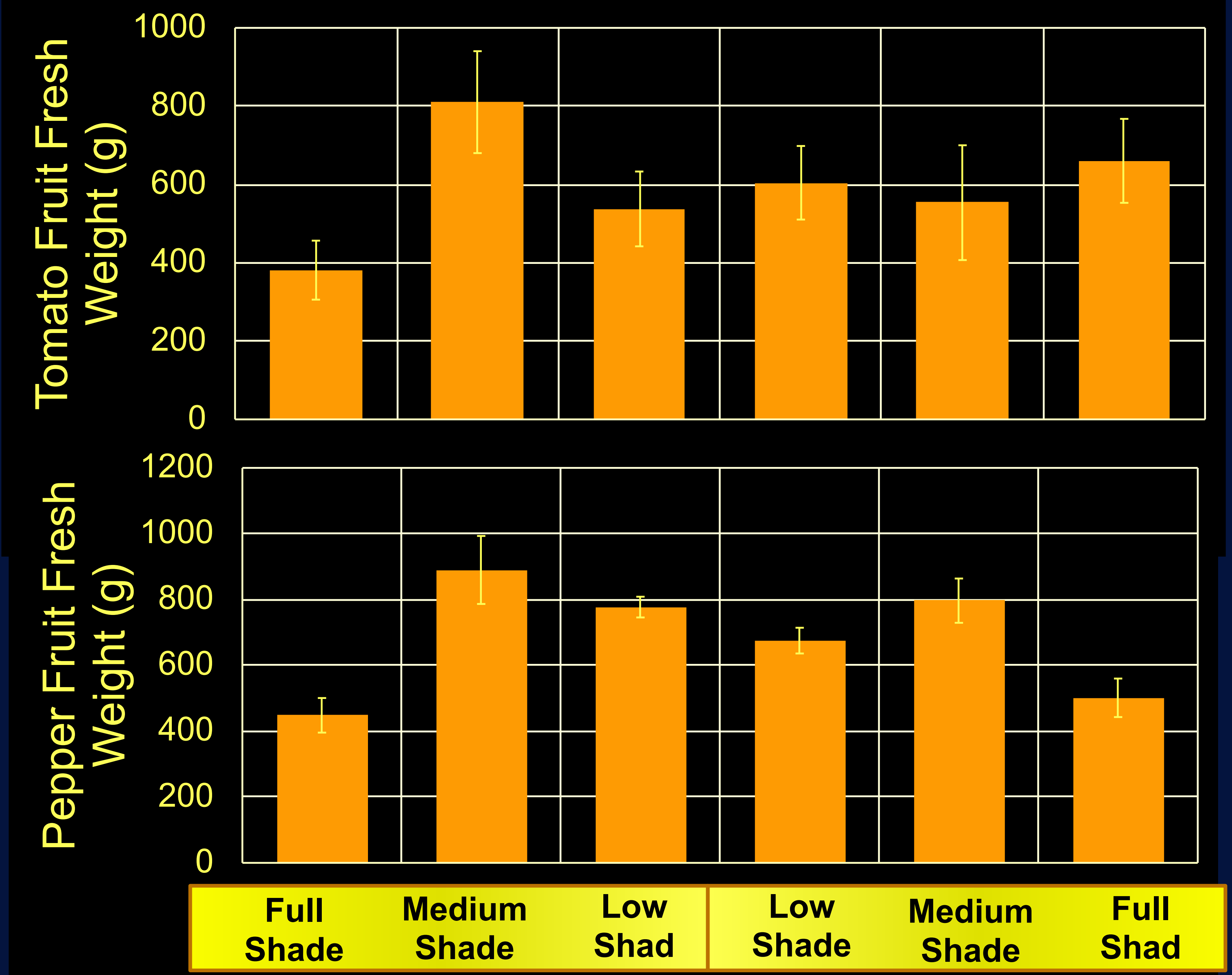




Tomato

and

Pepper



Results and Discussion

- Some crops do OK with partial shade, some do best with full sun
  - Under full shade (directly under panels) is generally not economically feasible for any crops
  - Leafy greens vs Tomato and pepper

Conclusion regarding PV Ag

- It is not a matter of whether PV panels over plants can work; It is a matter of the level of shading
  - if there is ample light, then this WILL work at some shading level X%
- Shadow patterns are important – narrow bands are better then large rectangular blocks
- The key to making it work:
  - Don’t be greedy on the PV side of the energy use – find a compromise
  - ALWAYS install shading so the shadow moves!
    - » Orient rectangular bands of shading system north-south

Important implications for:

- Conventional agriculture:
  - It is possible to integrate solar PV with plant agriculture as long as the PV light interception and PAR interception by plants is "in balance"
    - » the exact balance varies for each crop and geographic location
- Protected cultivation agriculture
  - Access to electricity during daytime is especially relevant for greenhouse cooling – we can grow plants in places where conventional protected cultivation is not feasible!

Important implications

- We anticipate important innovative applications in areas that have excessive sunlight
  - Here plants suffer due to extreme light and temperature
    - » Intercept some of this light to make electricity, leave rest for plants (Research is needed to optimize % of each)
- Use electricity for agricultural uses:
  - Conditioning climate (active evaporative cooling) for plants
  - Pumping water (hydroponic and soilless culture plant production)
  - Sell rest of electricity to utilities (second income stream for farmers)

Photovoltaic Greenhouse – is it possible?

- Can greenhouses be photovoltaic?
  - What if glass could be selective to allow photosynthetic wavelengths through and make electricity with the rest?
- Note the core problem:
  - High investment in intensive production
  - Light is expensive to create (with lamps and electricity)
  - Most greenhouses do not have excess light
- But there are situations where greenhouses use shade systems
  - The problem is that fixed PV will be a problem during winter conditions where light is low
  - Can we make light with PV electricity? Do the numbers add up?
  - The price of installing PV has dropped to where you can calculate your kWh price to be lower than what you pay to your utility

Questions?

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