Performance of Various Salad Crops Grown under Candidate Lighting Technologies

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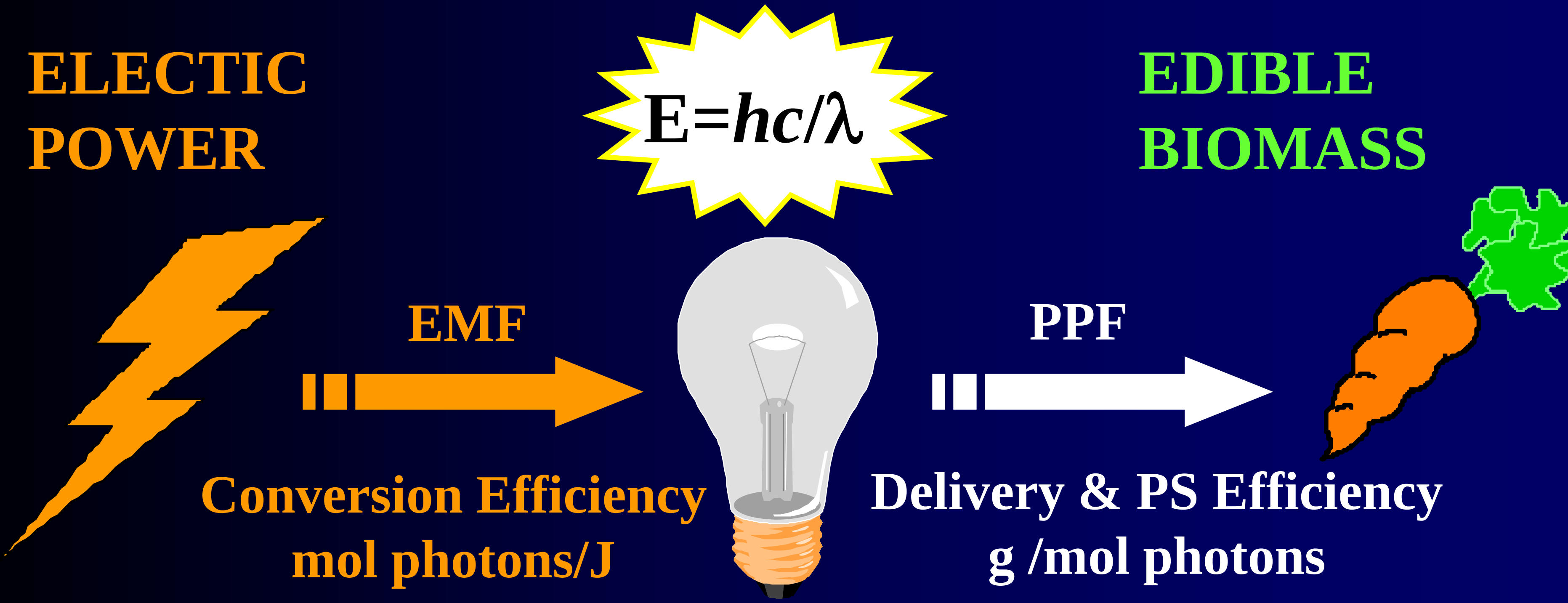
Electric Plant Lighting Systems



System Design

- Power Requirements
- Thermal Exchange/Removal
- Mass and Volume
- Modularity

Source Lamp

- Safety
- Conversion Efficiency
- Spectral Quality
- Spectral Distribution
- Longevity

Crop

- Quantum Efficiency
- Spectral Absorption
- Light Interception
- Photoperiod
- Light Pollution

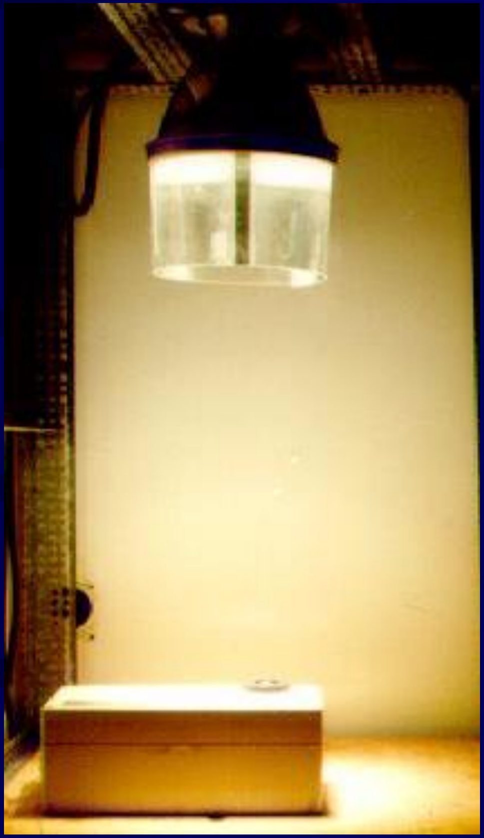
Why Salad-Type Crops?

- Low growth habit with defined shape
- Adaptable to confined controlled environment cultivation
- Short life cycle allows multiple harvests in defined time periods
- Simple post-harvest processing
- Fresh vegetable source with supplemental minerals, vitamins, and fiber

Light-emitting diodes (LEDs)

- Small mass and volume
- Limited thermal radiation projection to plant canopy
- Plants safely grown in close proximity to arrays
- Particularly suited for space transit vehicles

Sulfur-Microwave Lamp



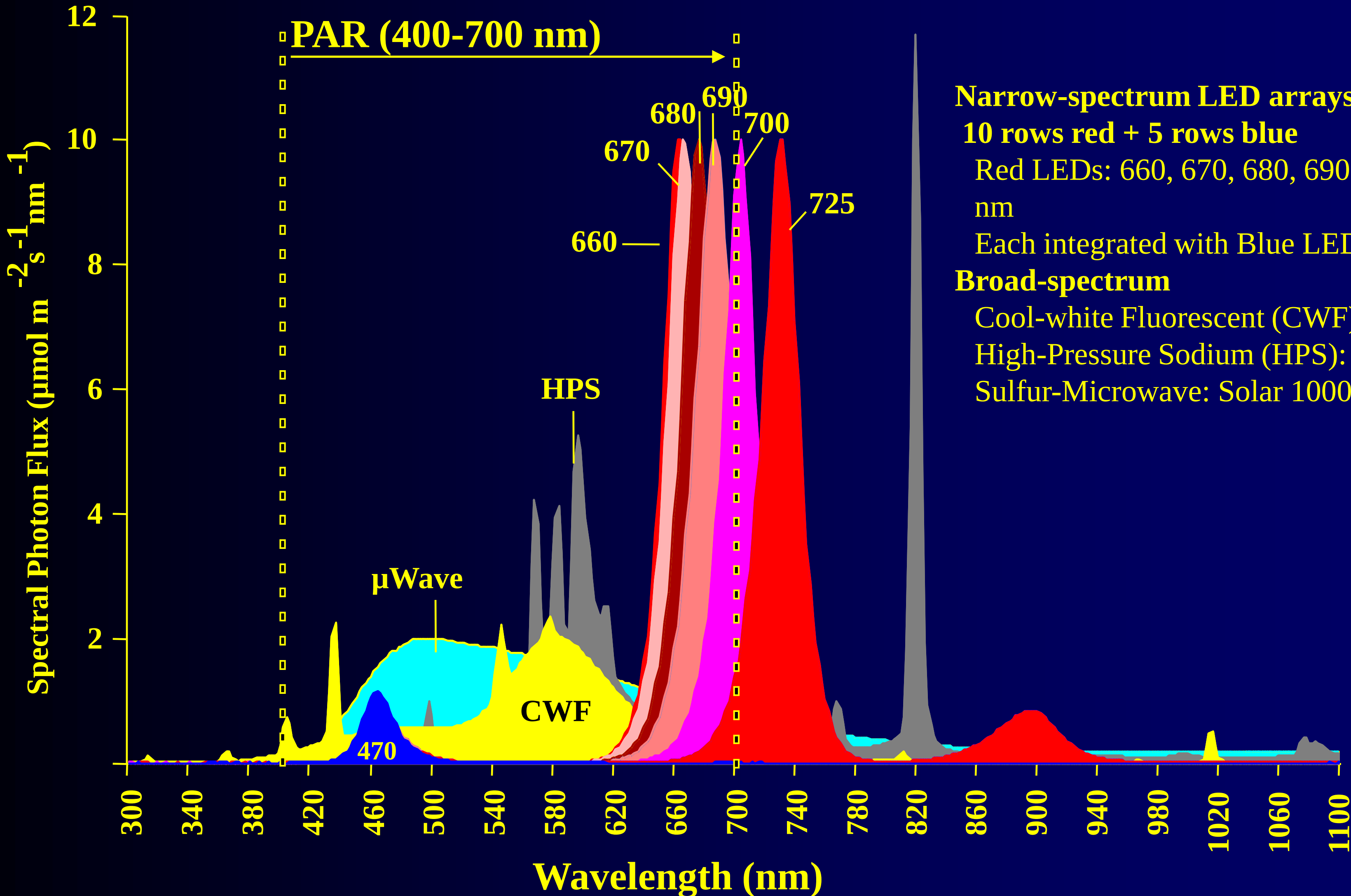
- Good electrical to visible light conversion efficiency
- High visible light output for remote “light pipe” applications
- Uniform broad-spectrum visible light emission
- Output can be dimmed without significant spectral shift

Past experiments with LED lighting at KSC

Wheat grown under Red LEDs alone (no blue light)

- Net positive CER, dry matter, & grain yield decreased
- In leaves during vegetative and pre-anthesis stages
  - sucrose levels decreased
  - Decreased SPS & cytosolic Frc 1,6 Bpase activities
  - starch levels elevated
  - Increased ADP-G activity
  - Given supplemental blue light, plants grown under red LEDs similar to those under broad-spectrum sources

Spectral distribution of light (300-1100nm) from lamp sources in salad crop experiments at KSC



Narrow-spectrum LED arrays

10 rows red + 5 rows blue

Red LEDs: 660, 670, 680, 690, 700, and 725 nm

Each integrated with Blue LEDs: 470 nm

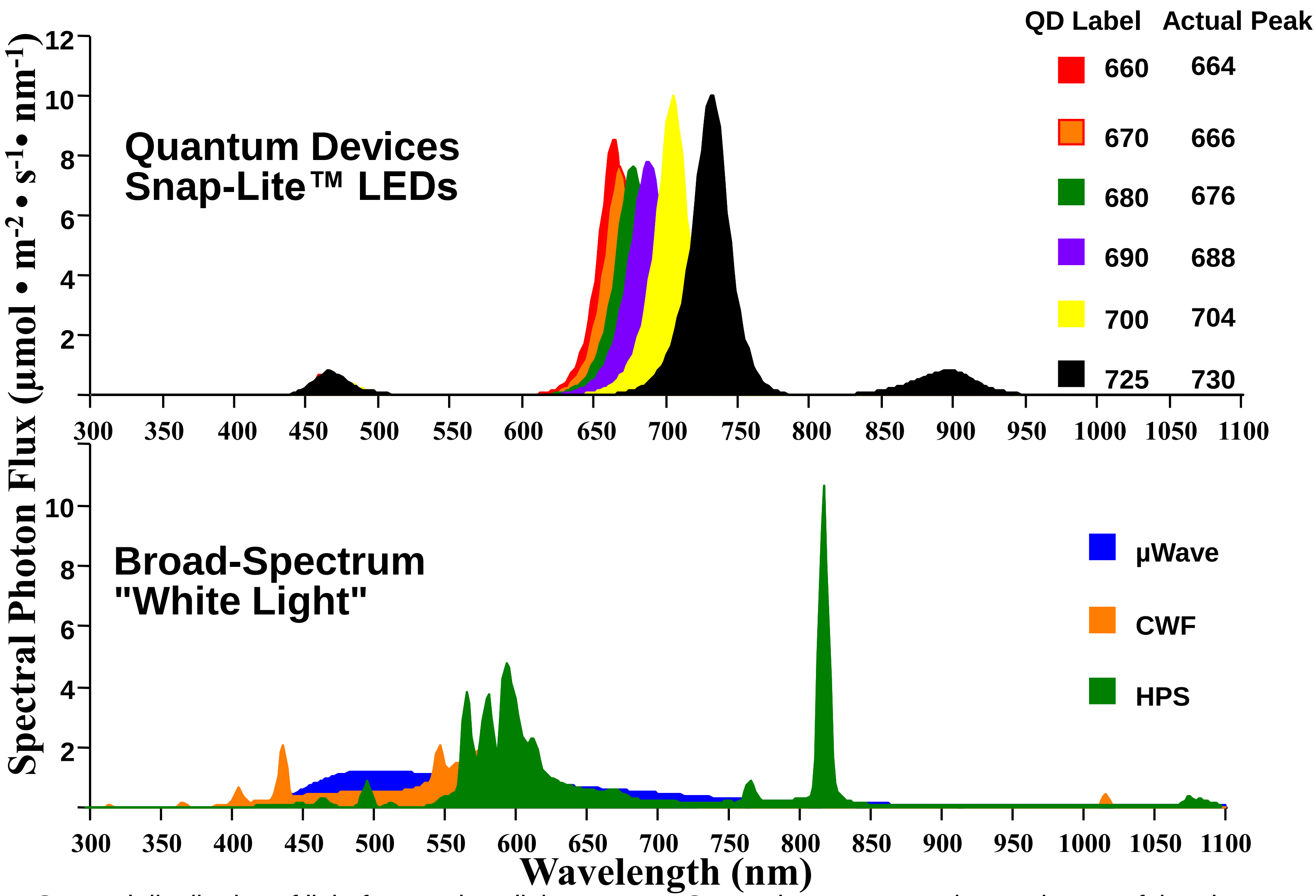
Broad-spectrum

Cool-white Fluorescent (CWF): F15T12

High-Pressure Sodium (HPS): 250-watt lamp

Sulfur-Microwave: Solar 1000W lamp

Spectral scans (300-1100nm) of light sources



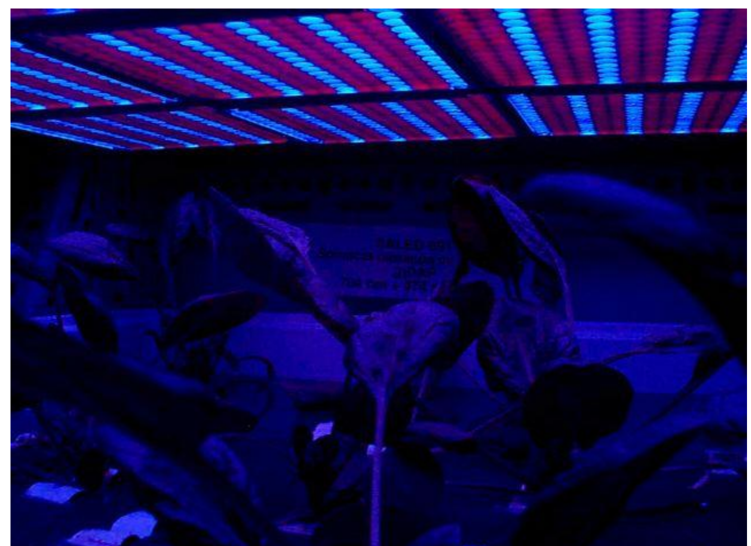
Spectral distribution of light from various light sources. Spectral scans were taken at the top of the plant canopy with a spectroradiometer. Total PPF was approximately 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for all light sources.

Spectral Characteristics of Lighting Sources

	Lamp								
Characteristic	µWave	CWF	HPS	660	670	680	690	700	725
				($\mu mol \cdot m^{-2} \cdot s^{-1}$)					
300-400	1	5	1	0	0	0	0	0	0
400-500	66	54	16	22	22	22	21	23	25
500-600	113	130	129	1	1	1	1	2	2
600-700	72	66	106	227	227	230	228	130	18
700-800	35	7	28	1	3	11	47	188	319
800-900	16	4	100	0	0	0	0	31	0
900-1000	11	2	9	0	0	0	0	13	18
1000-1100	11	5	14	0	0	0	0	0	0
Photon flux (300-1100)	324	272	401	251	253	264	296	378	413
PPF (400-700)	250	250	250	250	250	253	249	154	45
YPF	209	218	229	225	221	212	196	150	82
Blue	66	54	16	22	22	22	21	23	25
R	72	66	106	227	227	230	228	130	18
FR	28	4	15	1	2	7	30	94	160

HPS **CWF**

690 + 470 nm **700 + 470 nm**

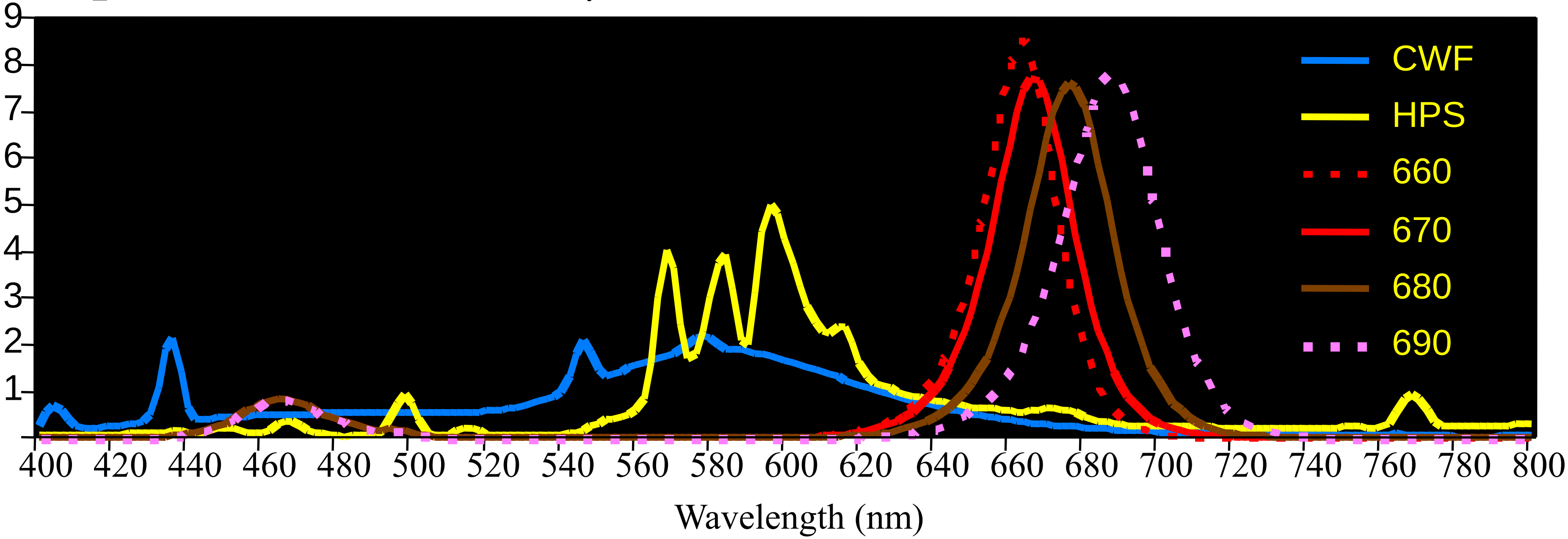


Spinach at 26 dap under different lamp banks

Experimental Details

- Lighting treatments located in 3 Conviron PGW-36 chambers
- 16 (spinach) 18 (lettuce, radish) hour light photoperiod
- Instantaneous irradiance 250 $\mu mol \bullet m^{-2} \bullet s^{-1}$ PAR
- Daily average irradiance 14-16 $mol \bullet m^{-2} \bullet day^{-1}$
- Distance lamp bank to root-shoot barrier: 25 cm
- Plant Trays: 52 cm W x 59 cm L x 10 cm H
- Root-shoot barrier: 52 cm W x 59 cm L (Growth area: 0.3 m^2)
- Harvest 6 plants at 14, 21, and 28 DAP

Spectral Photon Flux ($\mu mol\ m^{-2}\ s^{-1}\ nm^{-1}$)



Characteristic	CWF	HPS	660	670	680	690
300-400	5	1	0	0	0	0
400-500	54	16	22	22	22	21
500-600	130	129	1	1	1	1
600-700	66	106	227	227	230	228
700-800	7	28	1	3	11	47
800-900	4	100	0	0	0	0
900-1000	2	9	0	0	0	0
1000-1100	5	14	0	0	0	0
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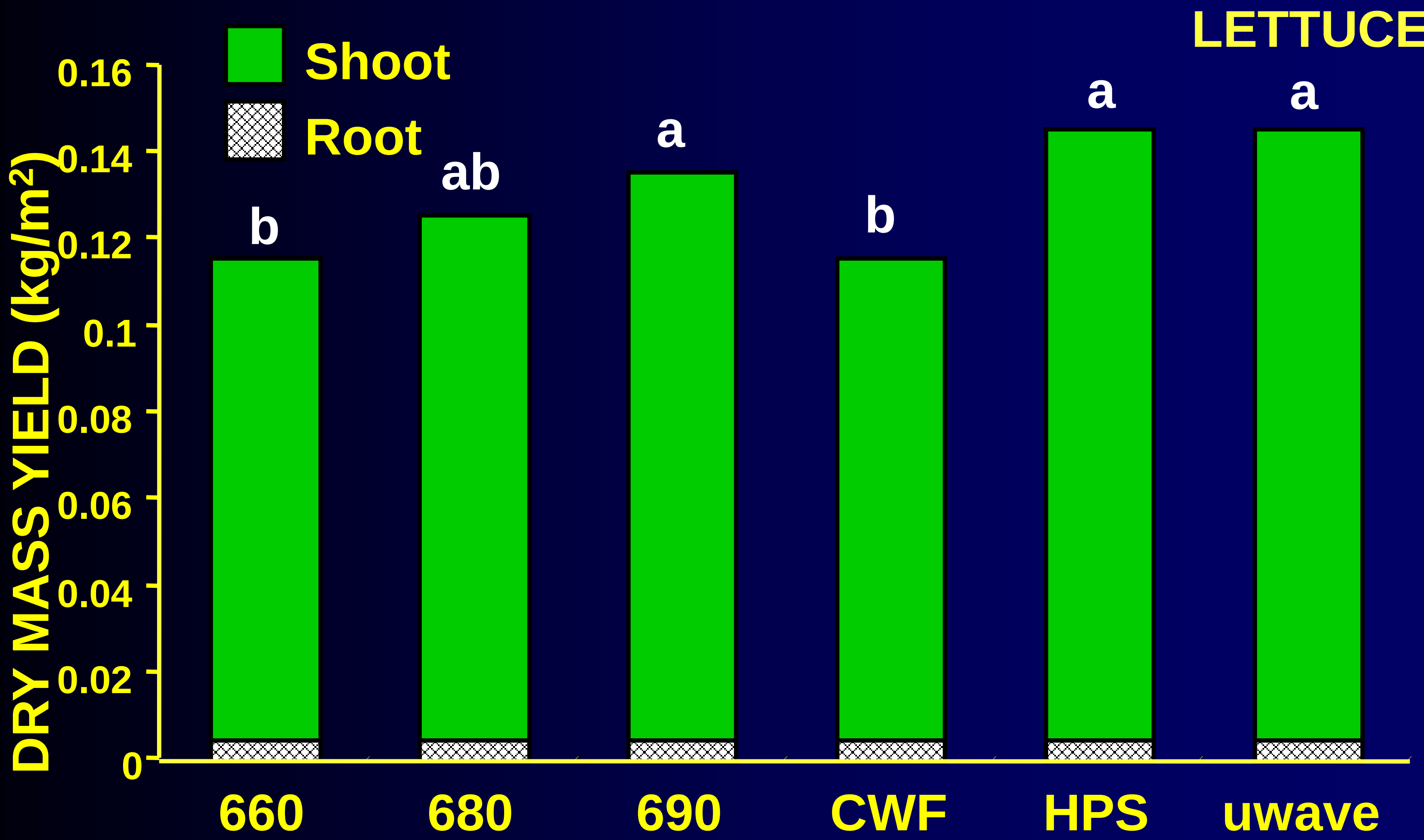
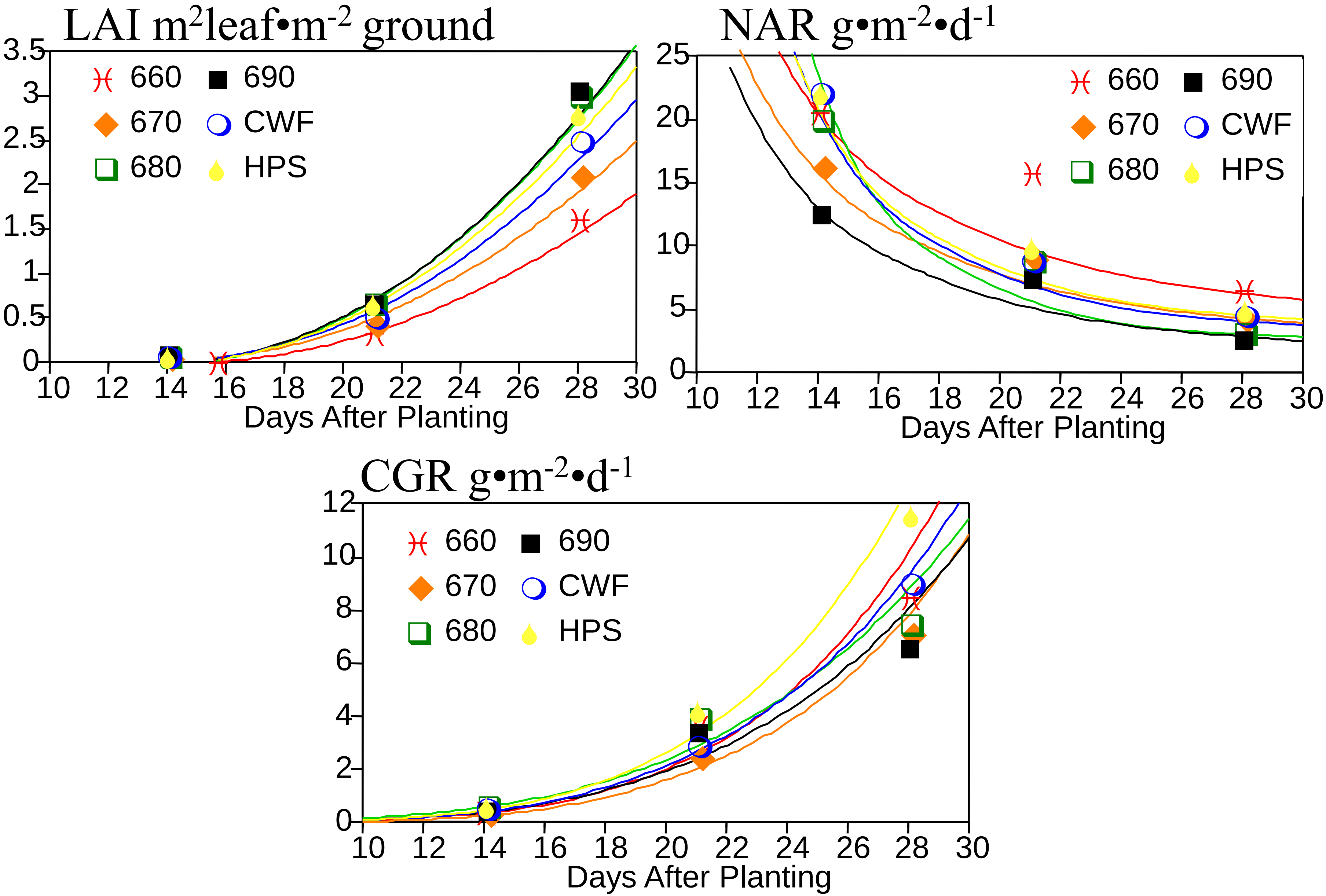
PPF (400-700)	250	250	250	250	253	249
YPF	218	229	225	221	212	196
Blue	54	16	22	22	22	21
R	66	106	227	227	230	228
FR	4	15	1	2	7	30
PSS	0.84	0.85	0.88	0.87	0.84	0.76



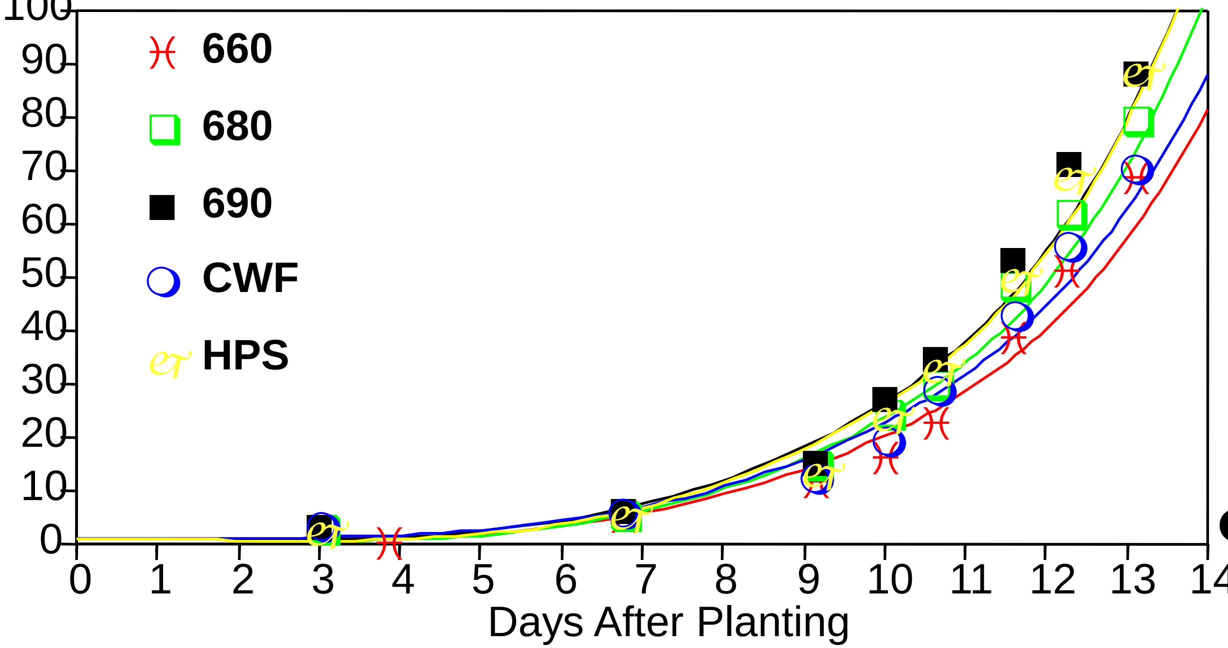
Shoot and root dry mass yield of “Waldmann’s Green” lettuce at 28 DAP.

Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test ($P<0.05$).



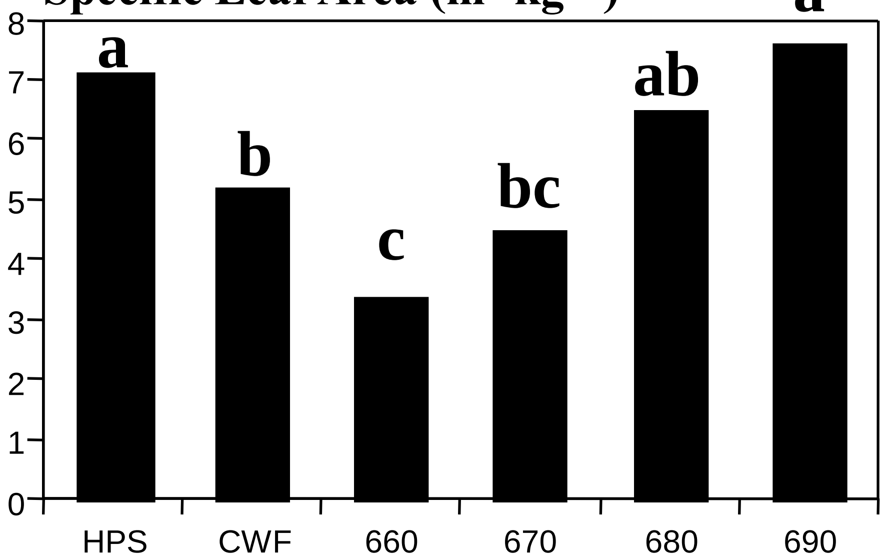
Leaf area index (LAI), net assimilation rates, and crop growth rates of "Waldmann's Green" lettuce plants over 28 day crop cycles in the presence of LED, CWF, or HPS lighting *(see appendices for curve fit functions).*

Lettuce Head Ground Cover (%)

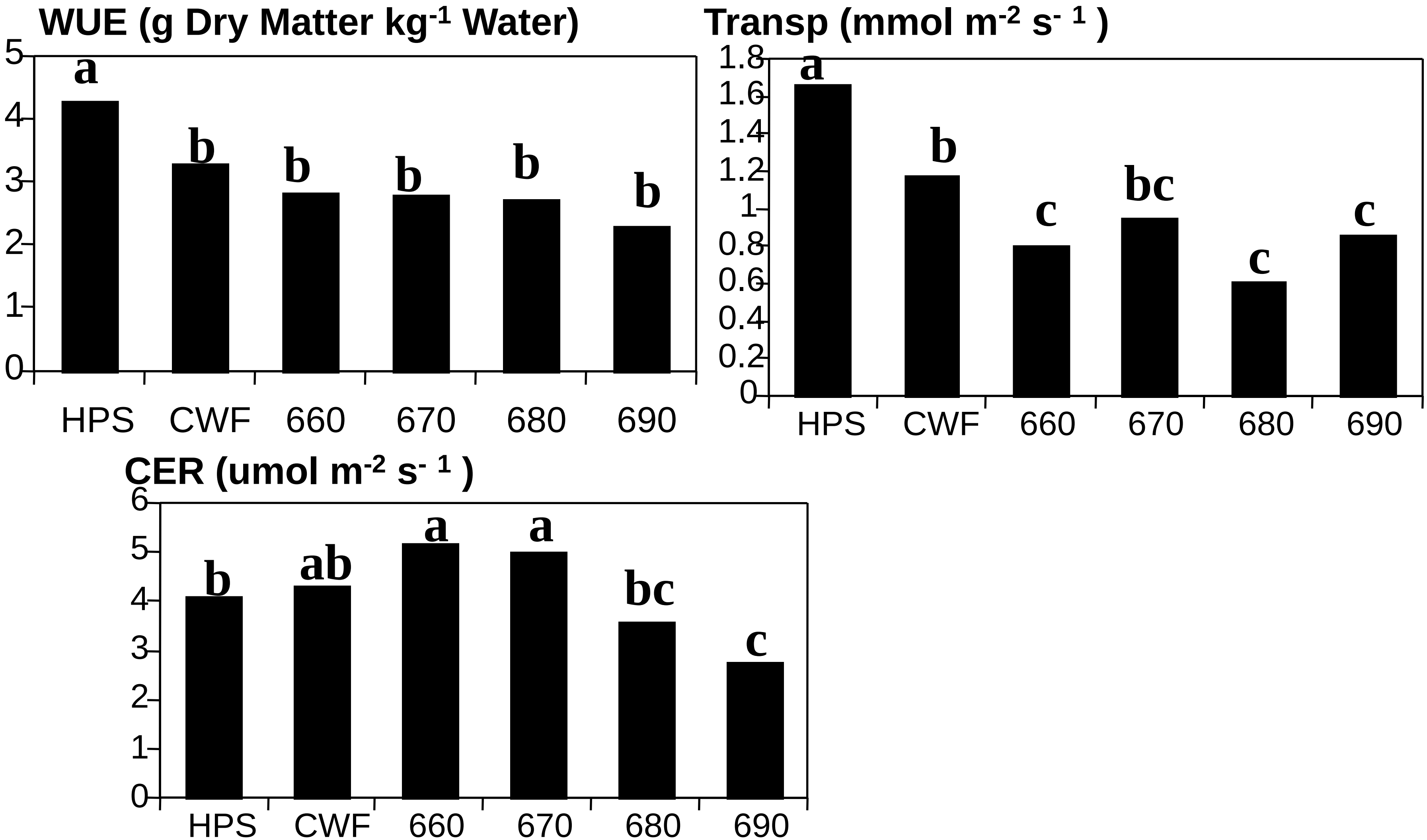


Overhead Digital Photography

Specific Leaf Area (m^2 kg^{-1})

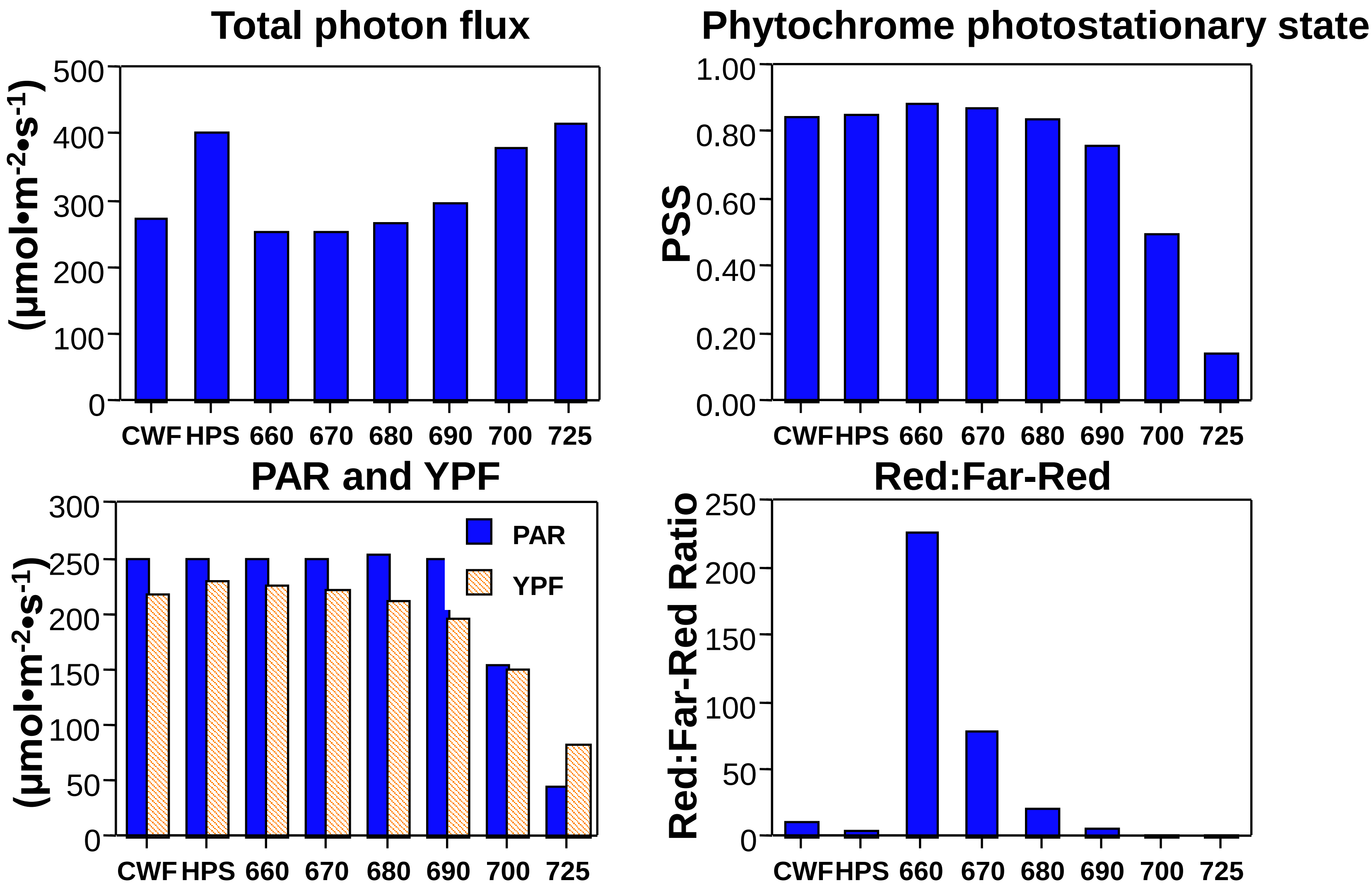


Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test (P<0.05)

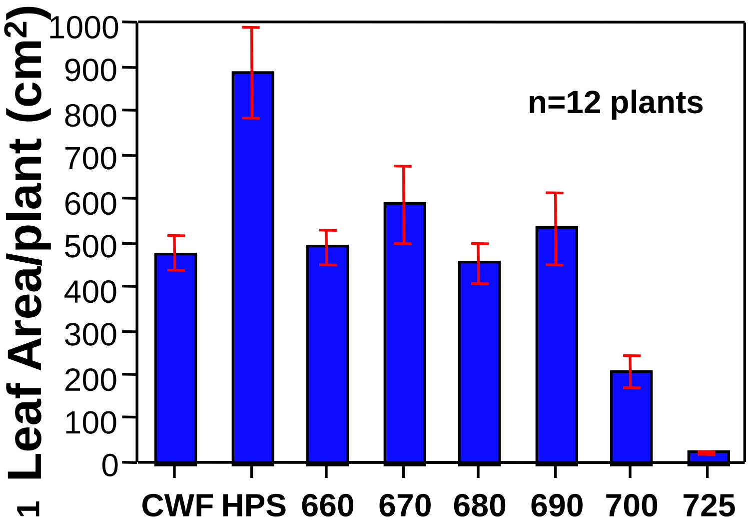


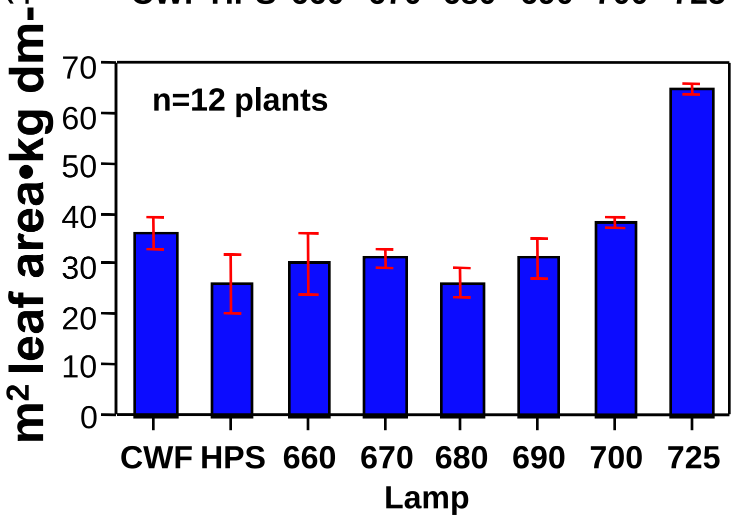
Water use efficiency (WUE), transpiration, and carbon exchange rates of 28 day-old “Waldmann’s Green lettuce plants grown in the presence of LED, CWF, or HPS lighting. Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test ($P<0.05$)

Spectral Characteristics Comparison

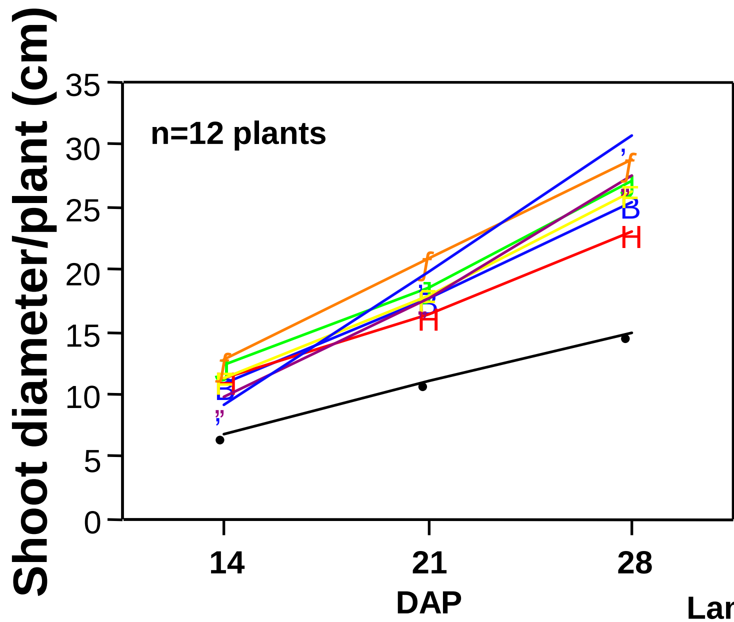


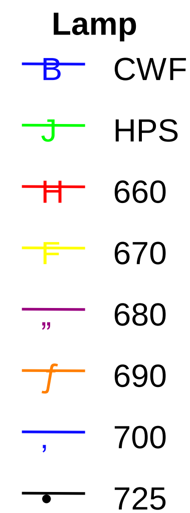
Spinach Leaf Measurements





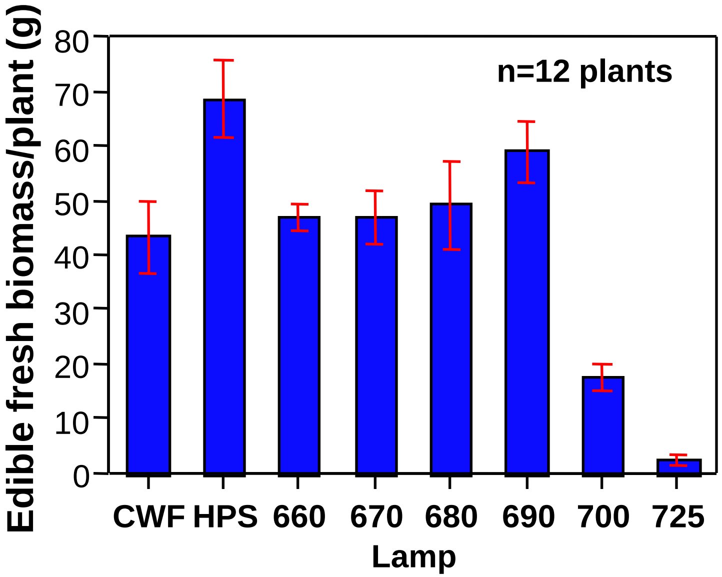
Total leaf area (top) and specific leaf area (bottom) for spinach plants grown under various lighting sources for 28 days.



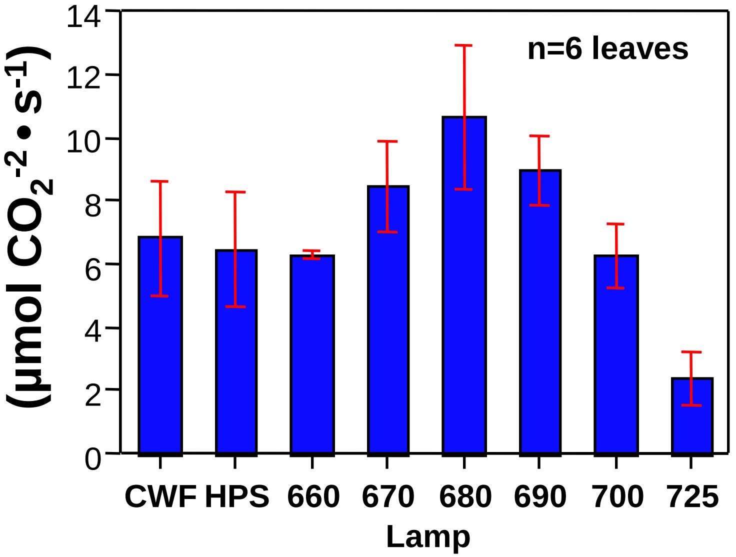


Average shoot diameter for spinach plants grown under various lighting sources for 14, 21, or 28 days after planting.

Spinach edible biomass and net leaf photosynthesis



Edible fresh biomass (leaves + stems) for spinach plants grown 28 days under various lighting sources.



Net rate of leaf photosynthesis for spinach plants (21 DAP) grown under various lighting sources (error bars indicated standard deviation of the treatment mean).

Summary

- Successfully implemented 8 separate light treatments
- Completed spinach growth experiments
- Given equal PAR (with 660-690 nm red LEDs) biomass yields similar
- Shoot diameter tends to increase with red LED wavelength, especially beyond 690 nm
- Many measurements yet to be complete
  - Plant physiological assays
  - Lamp bank electrical power consumption

Supplemental Lighting Strategy for Greenhouse Strawberry Production

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RUTGERS

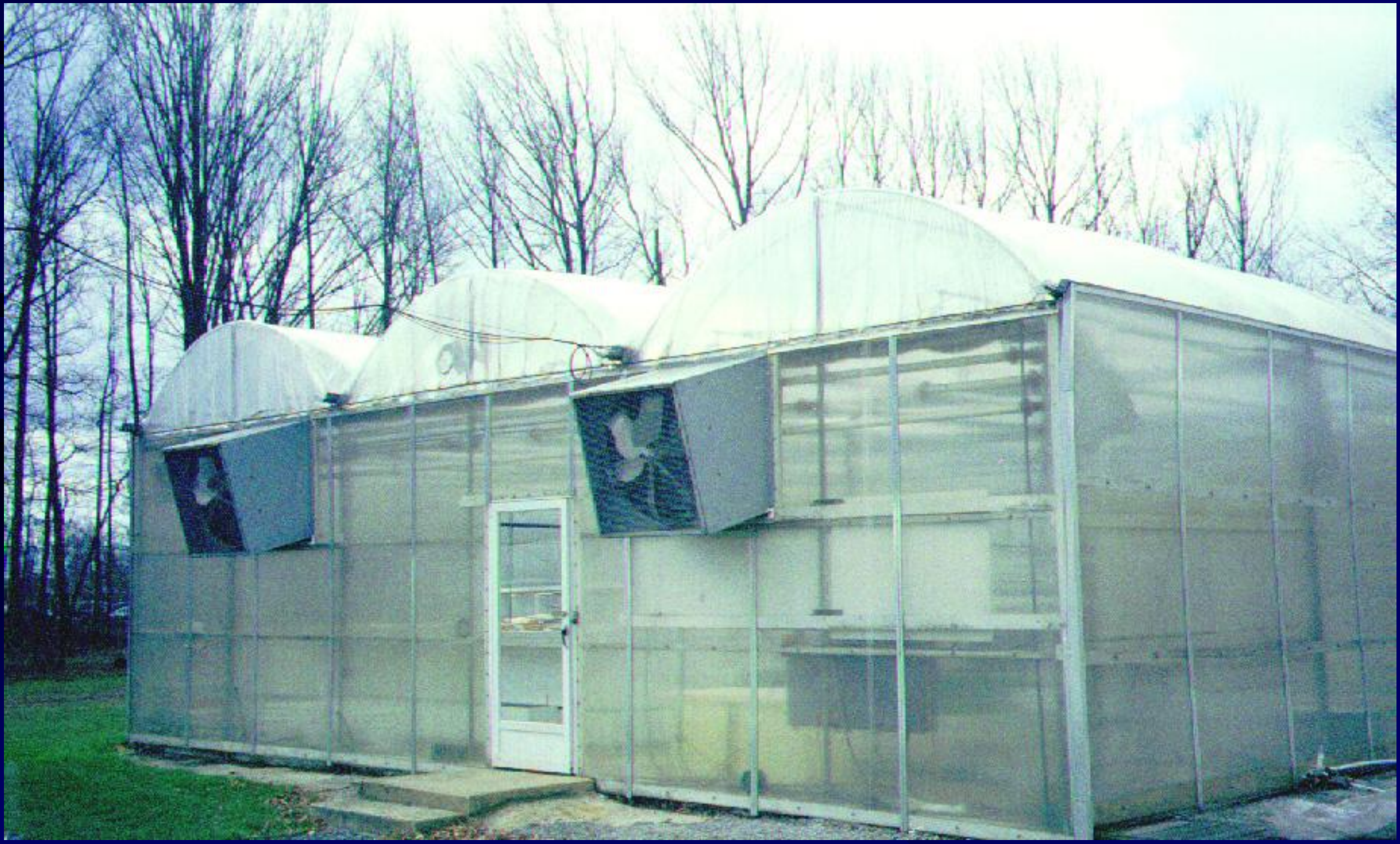
Objectives

- **To test the effects of different Daily Light Integrals (**DLIs**)**

- **To compare the treatment effects:**
  - **Productivity (grams of fresh fruit / plant)**
  - **Economically = ($ / plant)**
    - **Value of Supplemental Light (**SL**)**

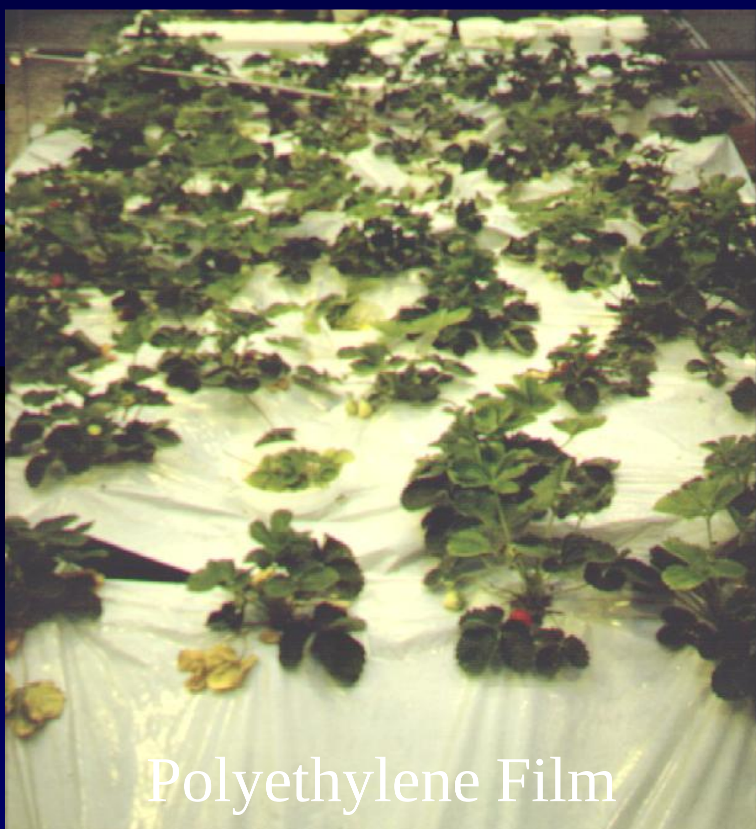
Cultural Practices (cont.)

- **Conditioned plug plants are transplanted into the greenhouse. (September 1, 1999)**

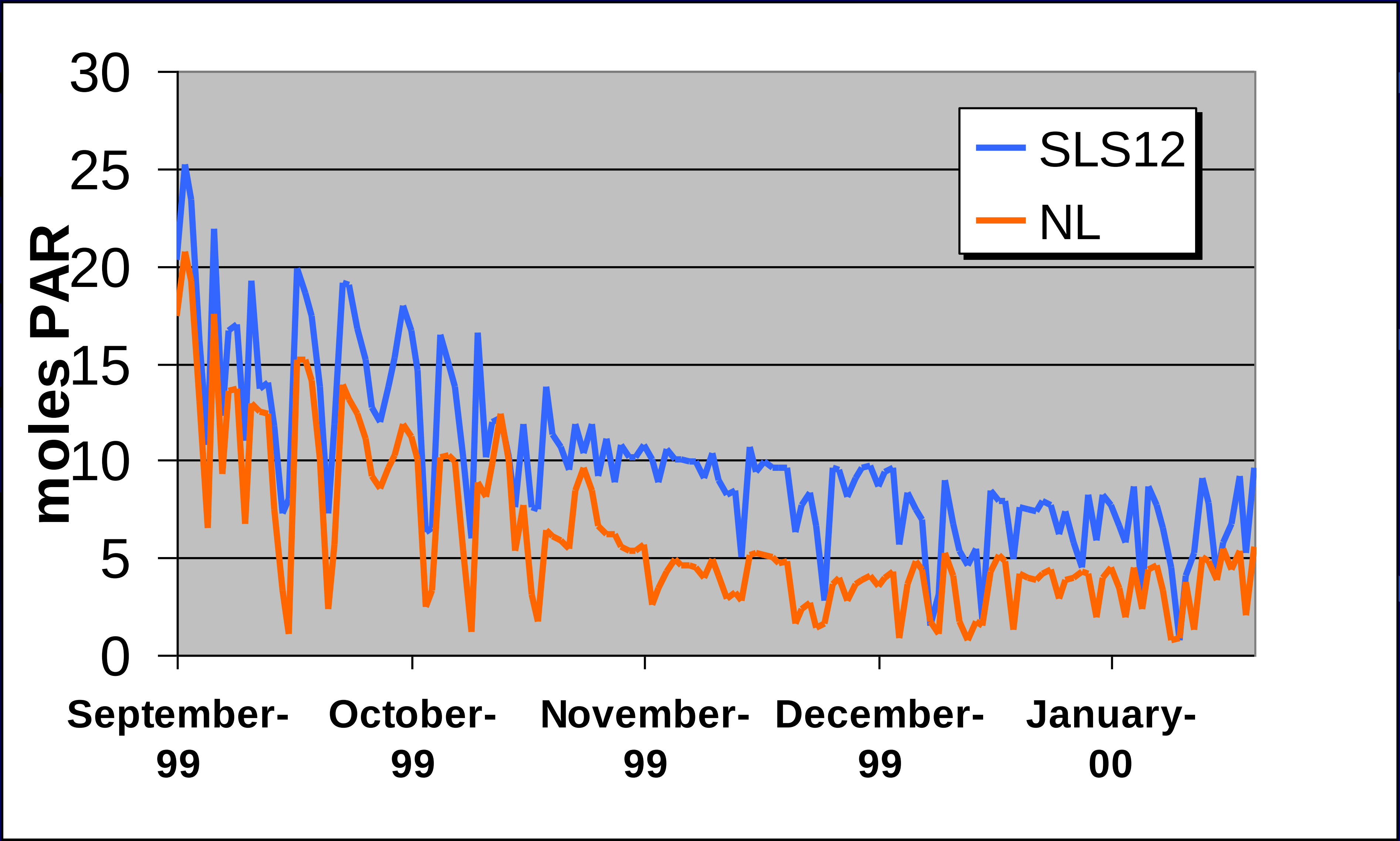


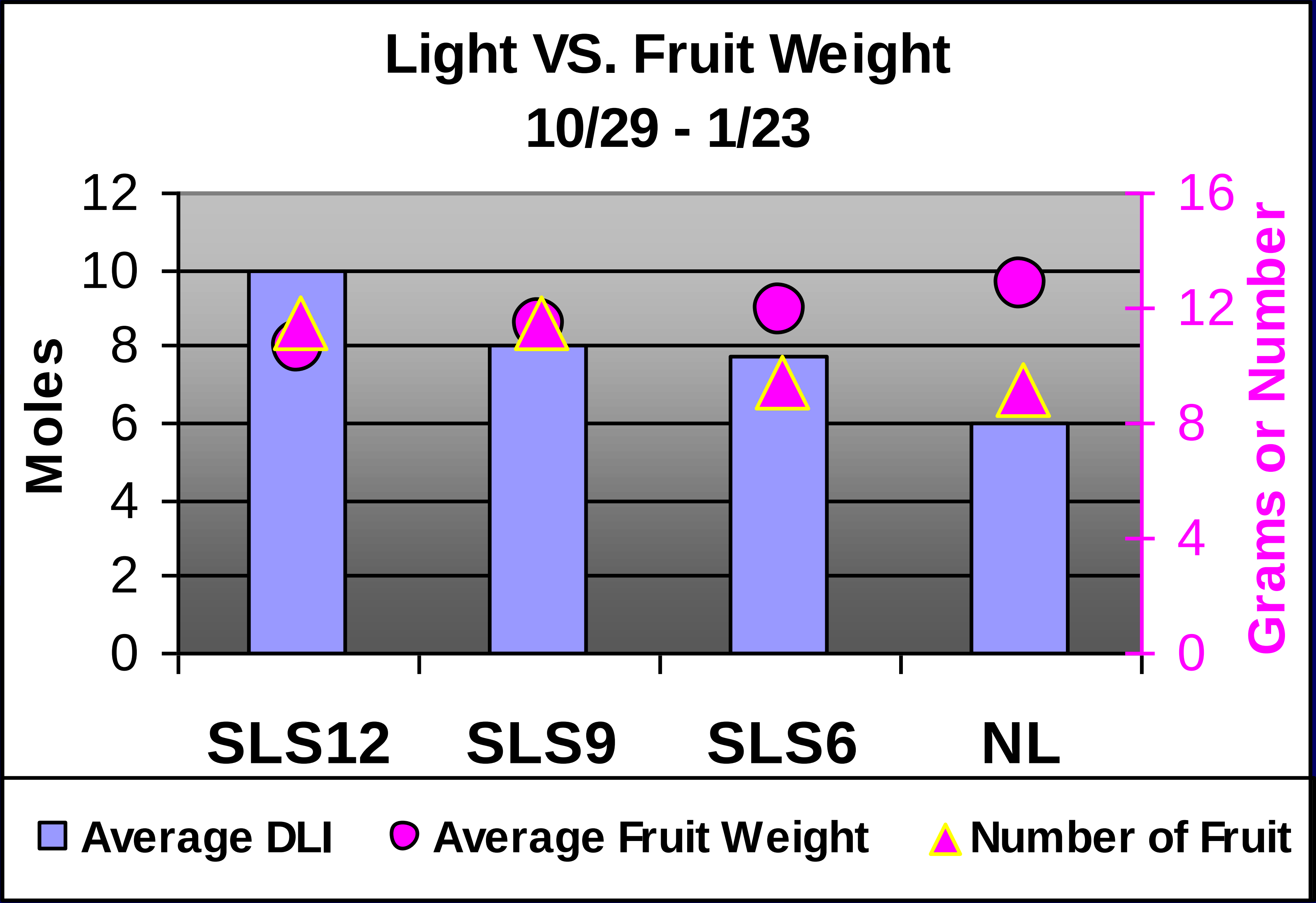
Incandescent Lamps

HPS Lamps



Measured Daily Light Integral




Light VS. Fruit Weight
10/29 - 1/23
Moles
Grams or Number
0
2
4
6
8
10
12
16
12
8
4
0
SLS12
SLS9
SLS6
NL
Average DLI
Average Fruit Weight
Number of Fruit

CO_2 AND MARS GREENHOUSES

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Kennedy Space Center

CO_2 and Mars Greenhouses

- **Why worry about CO_2 for Mars Greenhouses?**

  ⇒ **CO_2 is required for plant photosynthesis**

  ⇒ **CO_2 affects stomatal opening and transpiration**

  ⇒ **CO_2 can affect respiration**

  ⇒ **CO_2 is available from the Martian atmosphere and could serve as a pressurizing gas**

- **Plant Responses to CO_2:**
  - **Photosynthesis increases with increased CO_2***

$$CO_2 + H_2O \xrightarrow{\text{light}} CH_2O + O_2$$

  - **Transpiration decreases with increased CO_2*** ***Stomata Close and Water Use Drops***
  - **Respiration decreases with increased CO_2***

** Typical responses as CO_2 is increased from 0.04 kPa to 0.10 kPa*

Composition of Mars Atmosphere*

Gas	Percent (%)	~Pressure ** (kPa)
CO_2	95.3	0.67
N_2	2.7	0.019
Ar	1.6	0.011
O_2	0.13	0.0009
CO	0.07	0.0004
H_2O	0.03	0.0002

**Owen et al. 1977. J. Geophys. Res.28:4635-4639.*

*** Assuming a total pressure of 0.7 kPa*

Potatoes

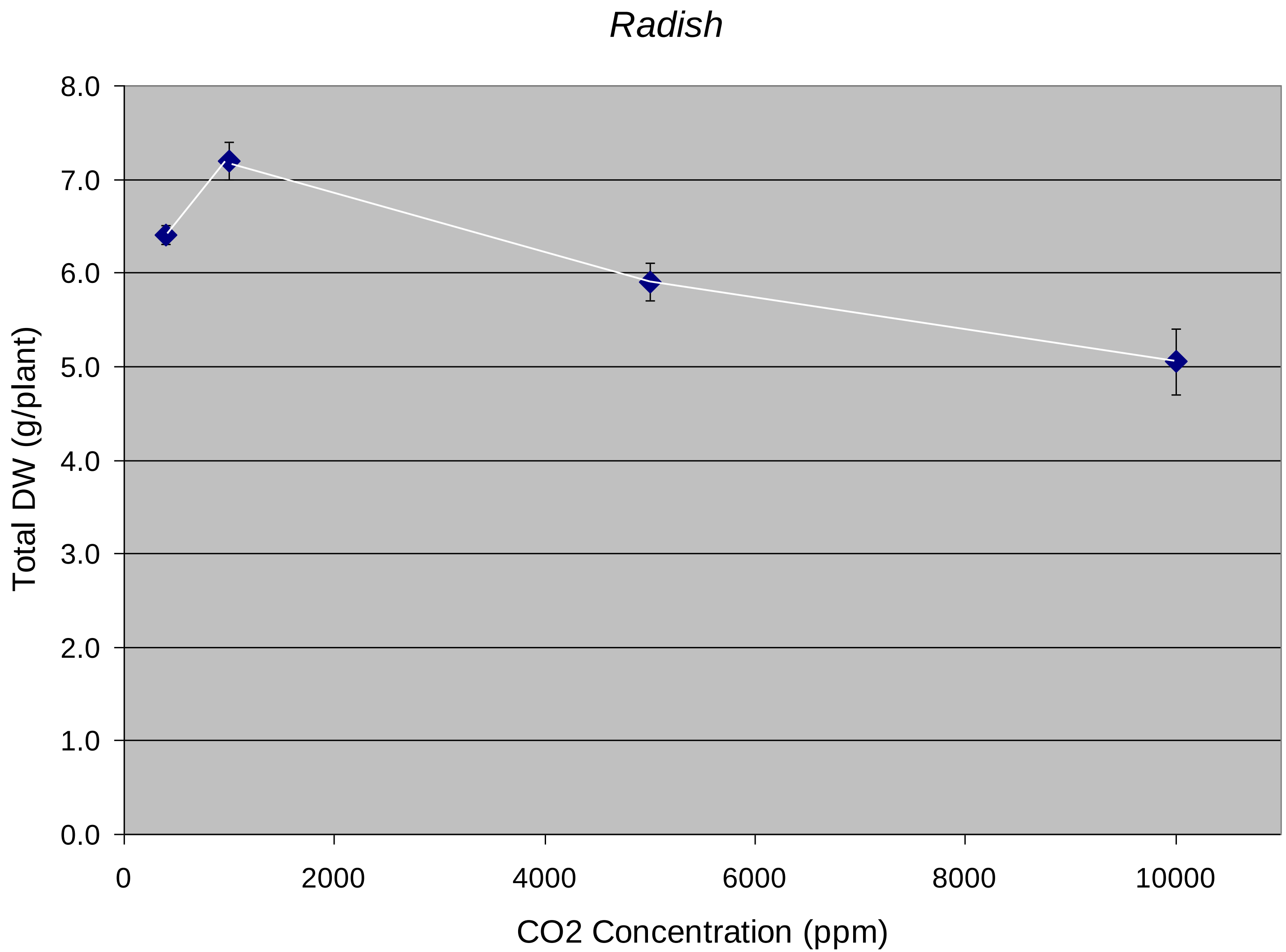
CO_2 and Mars Greenhouses

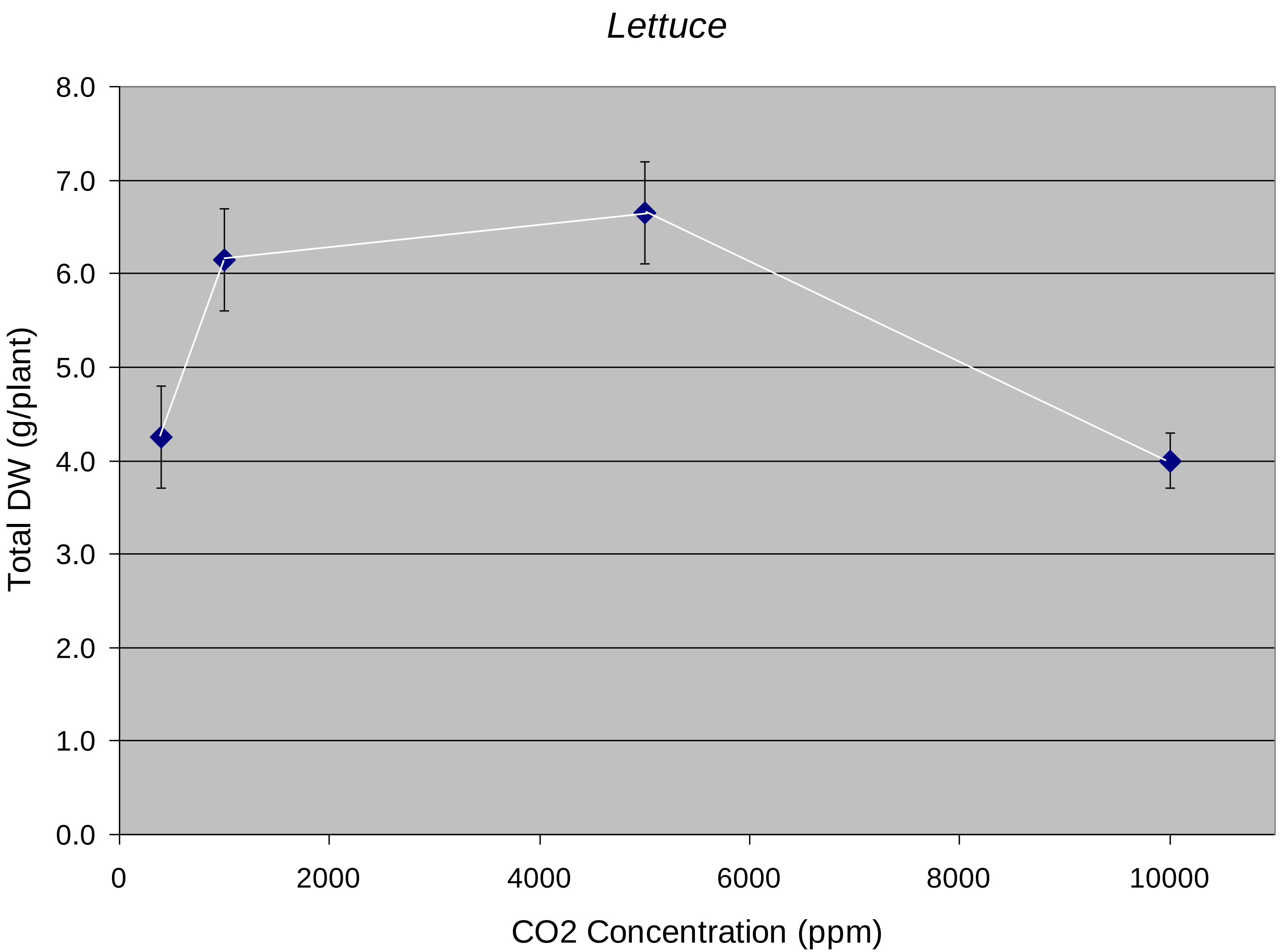
Sweetpotatoes

CO_2 Injury to Leaves

Radish

Soybean


Radish
Total DW (g/plant)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
2000
4000
6000
8000
10000
CO2 Concentration (ppm)



Lettuce
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Total DW (g/plant)
0
2000
4000
6000
8000
10000
CO2 Concentration (ppm)