Performance of Various Salad Crops Grown under Candidate Lighting Technologies

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Electric Plant Lighting Systems

ELECTIC POWER

EMF

Conversion Efficiency
mol photons/J

$$E = hc/\lambda$$

PPF

Delivery & PS Efficiency
g /mol photons

EDIBLE BIOMASS

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

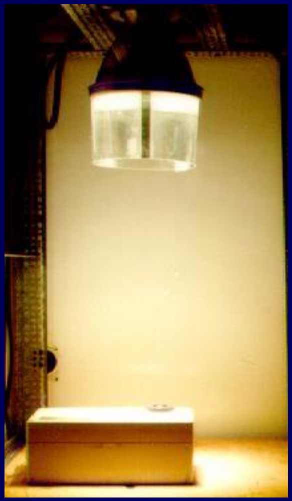
Why Salad-Type Crops?

- 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**

Arabidopsis **grown under Red LEDs alone (no blue light)**

- **Abnormal leaf development under red LEDs alone (without supplemental blue light)**
- **Promotion of vegetative growth and delayed flowering under red LEDs alone**
- **Fewer seed (but viable) produced under red LEDs alone**

Goins, G.D., N.C. Yorio, M.M. Sanwo, and C.S. Brown. 1997. J. Exp. Bot. 48:1407-1413.

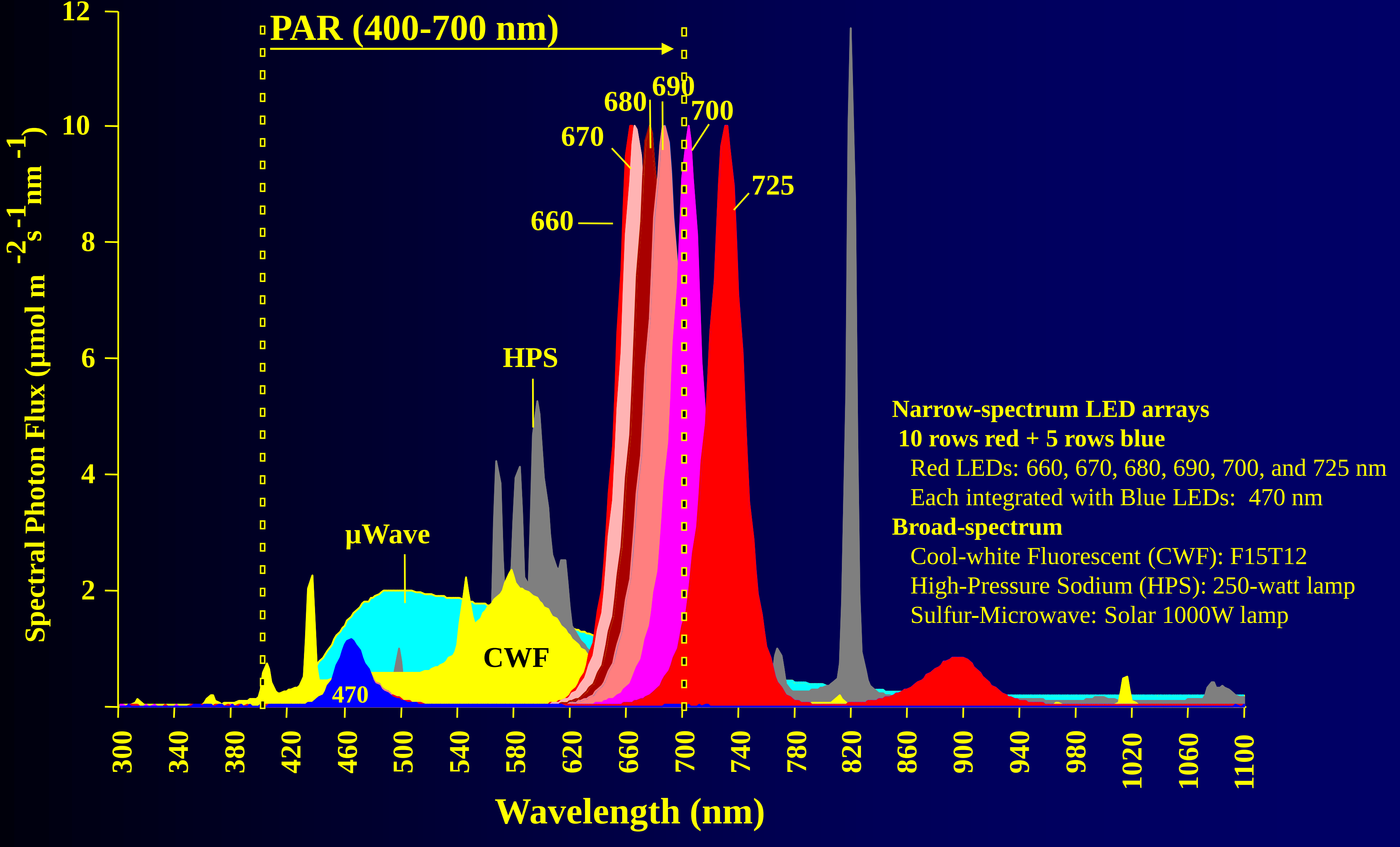
Goins et al., 1998. J. Life Support & Biosphere Science 5:143-149.

Sanwo M.M., G.D. Goins, N.C. Yorio, and C.S. Brown. 2001. J. Exp. Bot. (In review)

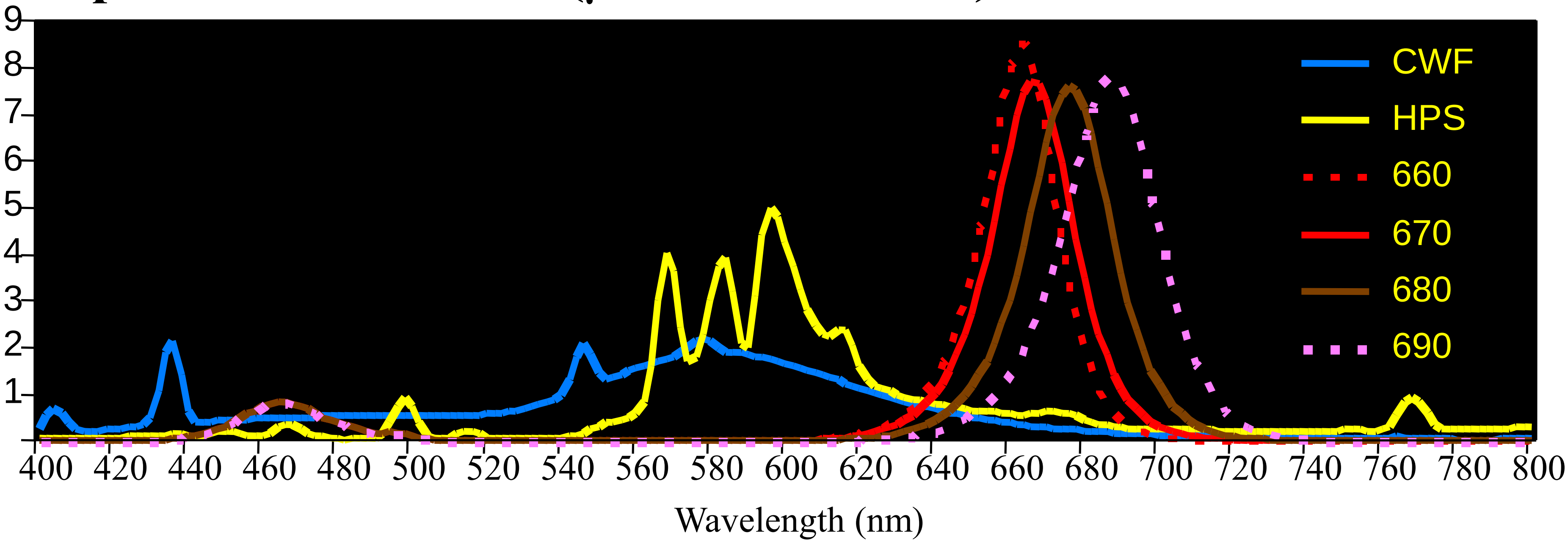
Hypothesis

- Salad-type plant productivity under certain wavelengths of LEDs will challenge levels of productivity achieved with a broad-spectrum lighting sources

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



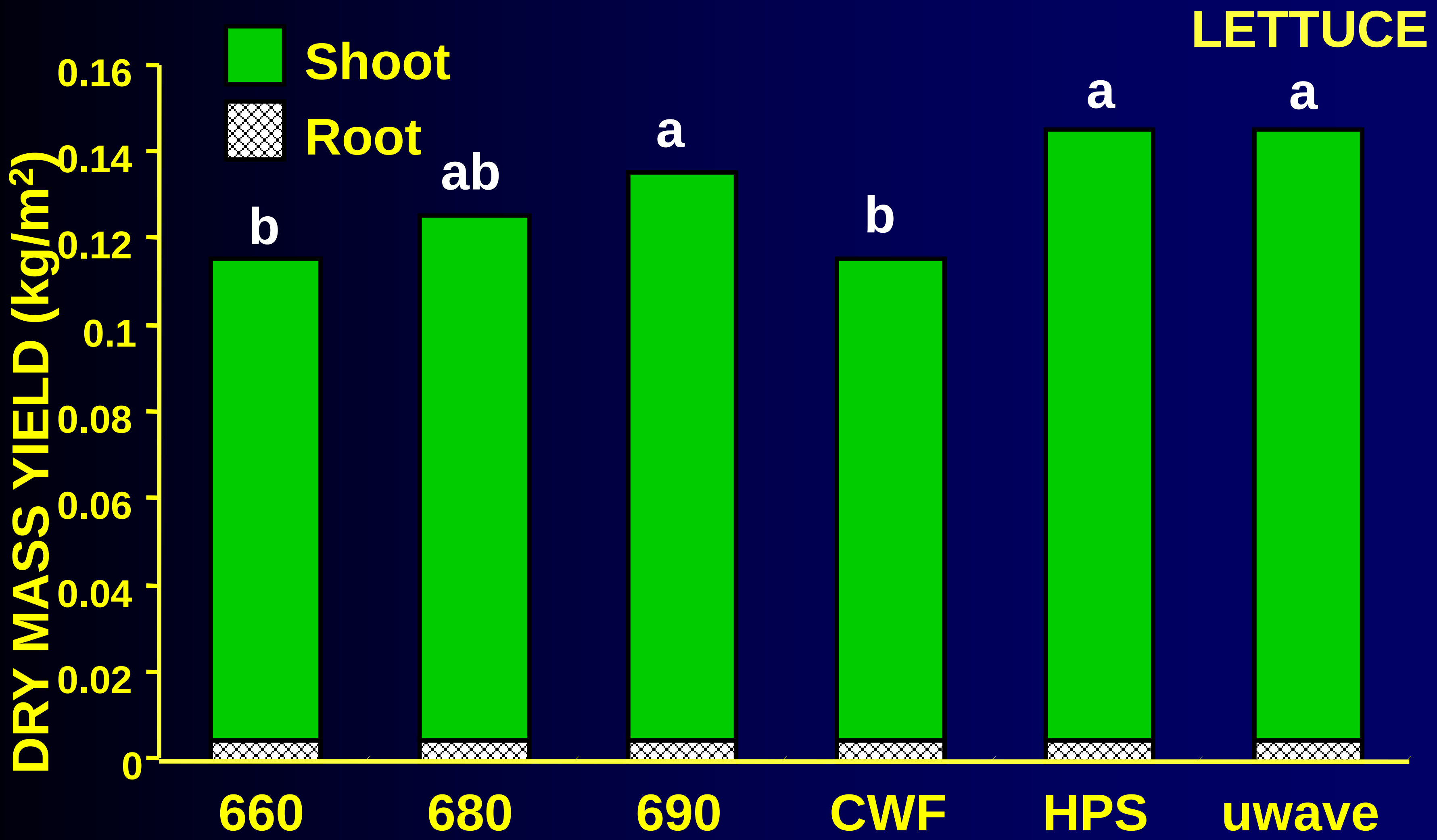
Spectral Photon Flux (µmol m^{-2} s^{-1} nm^{-1})



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
Photon flux (300-1100)	272	401	251	253	264	296
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

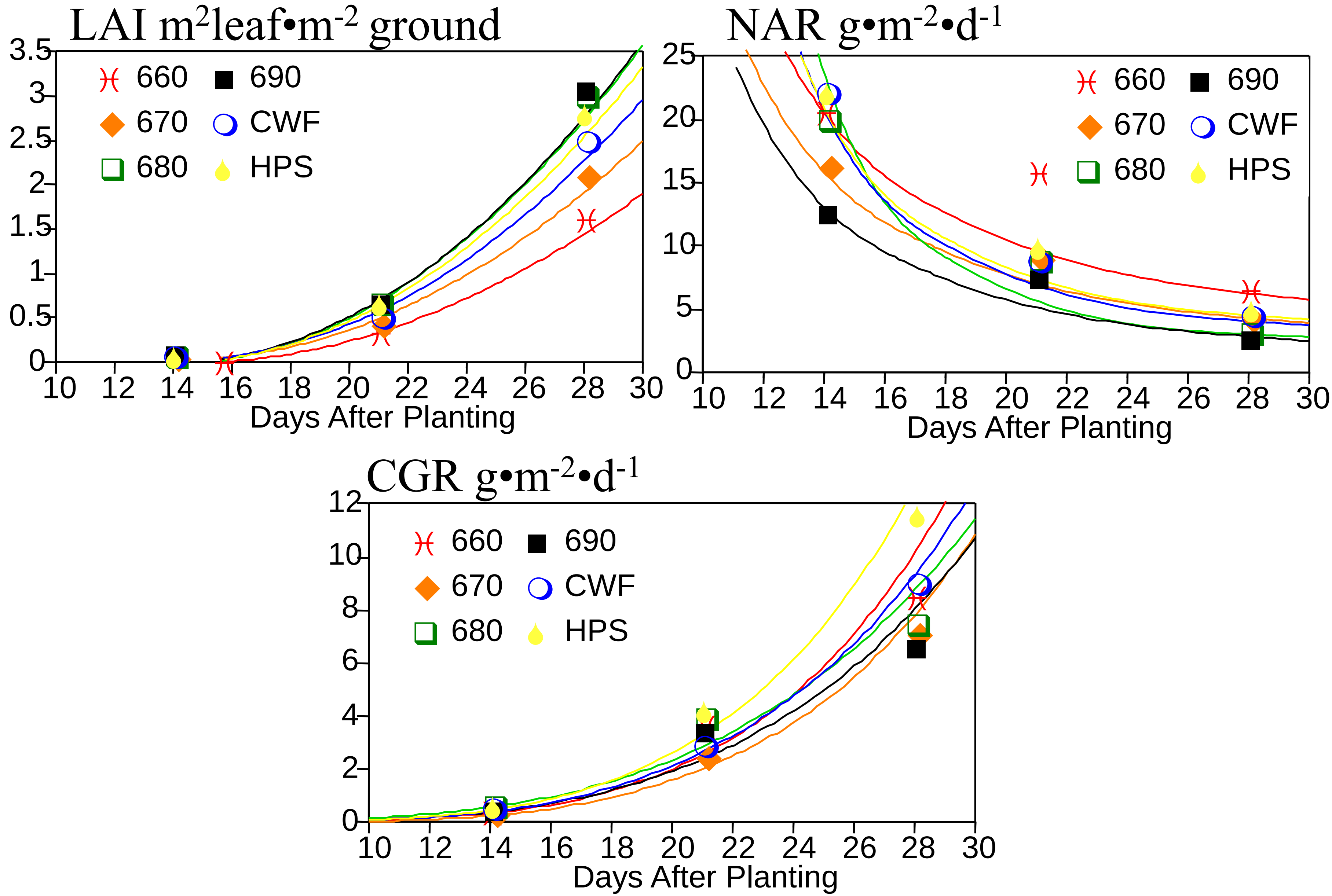
Experimental Details

- Lighting treatments located in 3 Conviron PGW-36 chambers
- 16 (spinach) 18 (lettuce, radish) hour light photoperiod
- Instantaneous irradiance 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PAR
- Daily average irradiance 14-16 $mol \cdot m^{-2} \cdot day^{-1}$
- 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

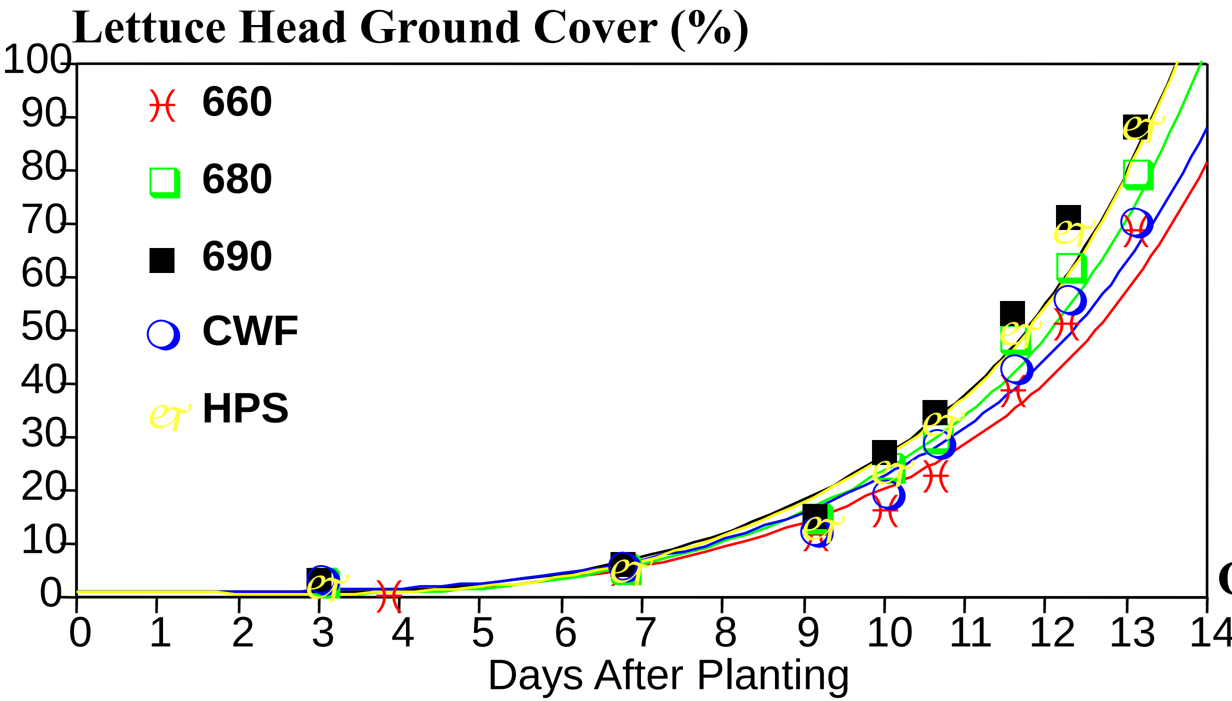


Shoot and root dry mass yield of "Waldmann's Green" lettuce at 28 DAP.

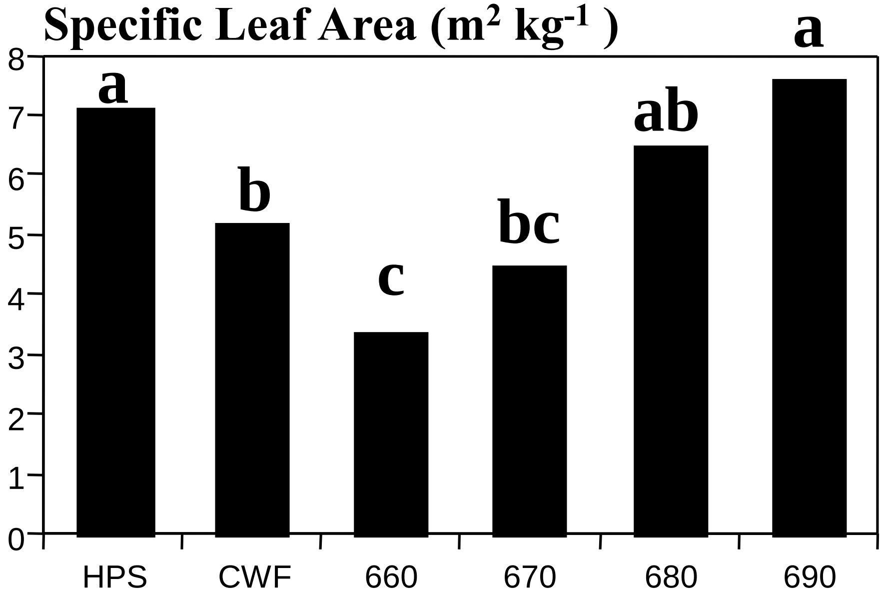
Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test ($P<0.05$).



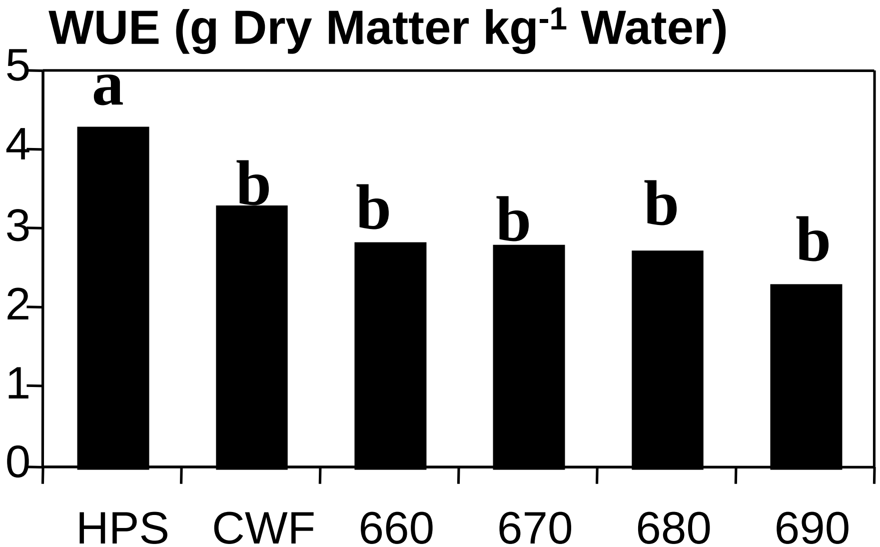
Leaf area index (LAI), net assimilation rates, and crop growth rates of "Waldmann's Green" lettuce plants over 28 day crop cycles in the presence of LED, CWF, or HPS lighting *(see appendices for curve fit functions).*

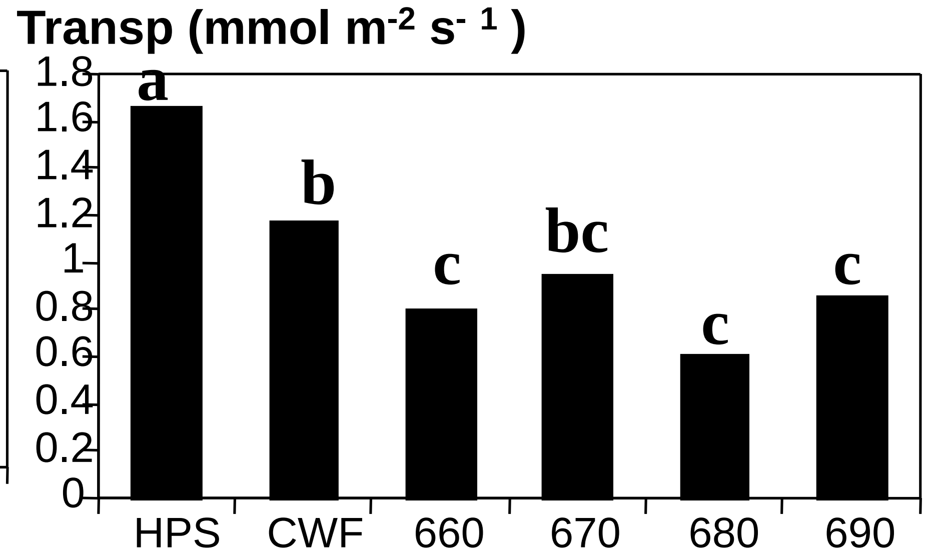


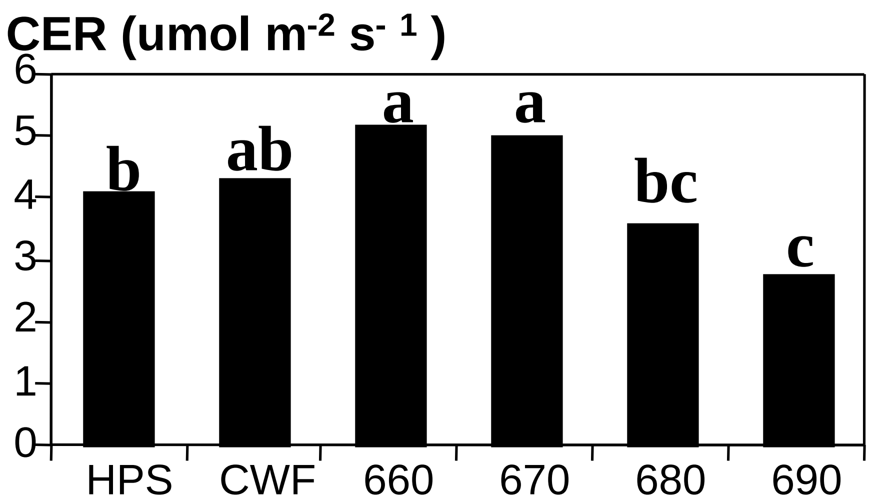
Overhead Digital Photography



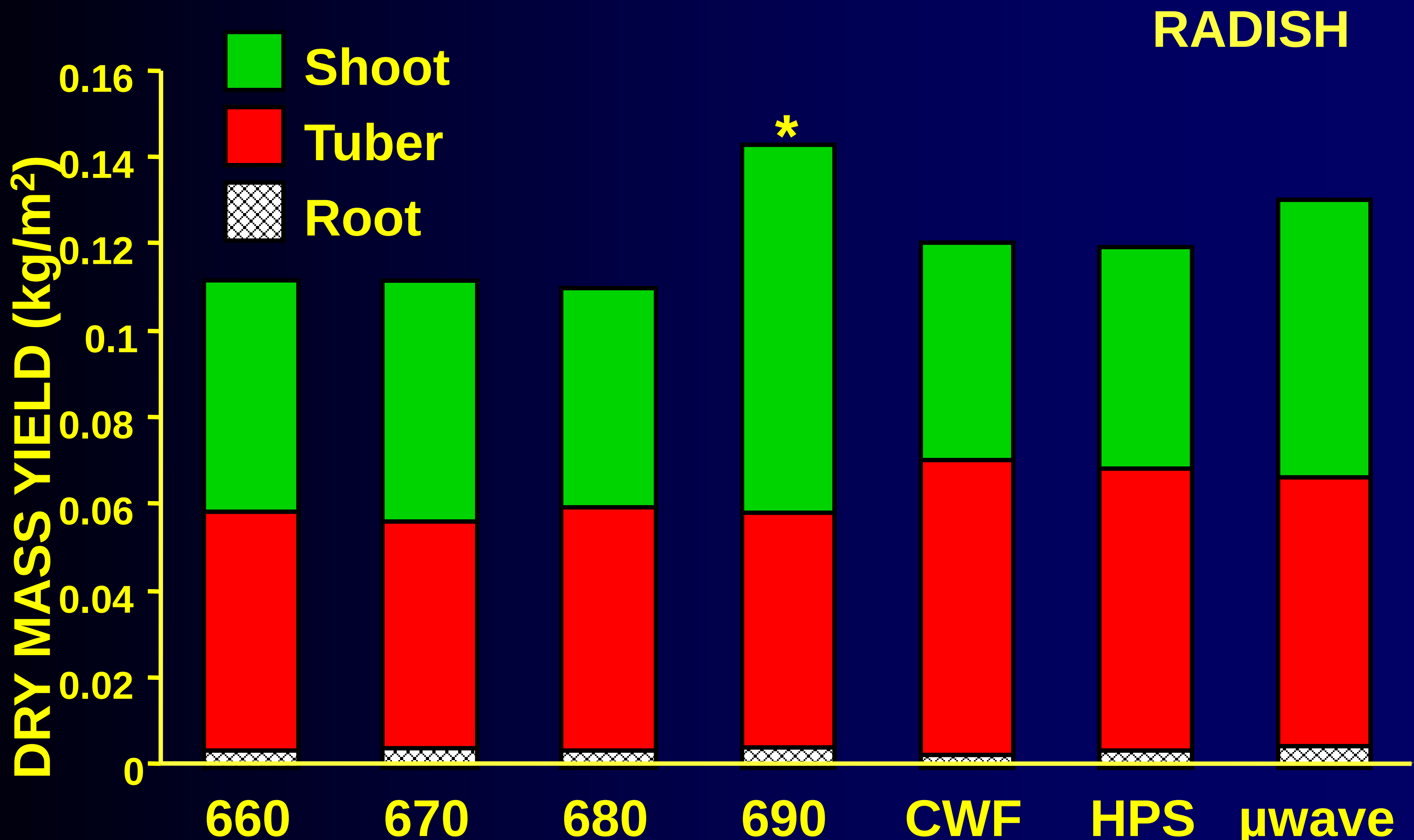
Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test ($P<0.05$)





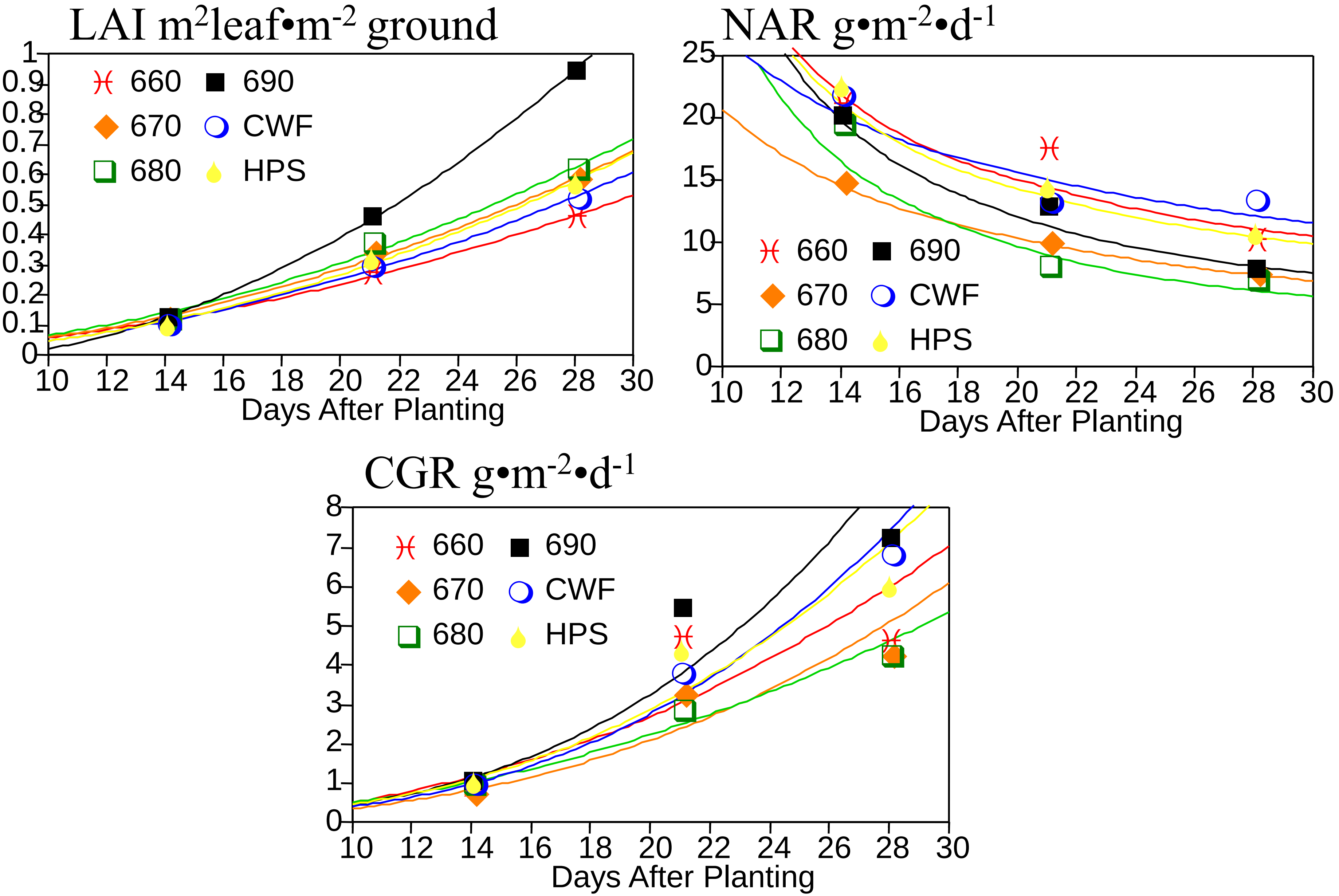


Water use efficiency (WUE), transpiration, and carbon exchange rates of 28 day-old "Waldmann's Green lettuce plants grown in the presence of LED, CWF, or HPS lighting. Different letters above bars indicate significant difference based on ANOVA and Tukey's HSD mean procedure test ($P<0.05$)

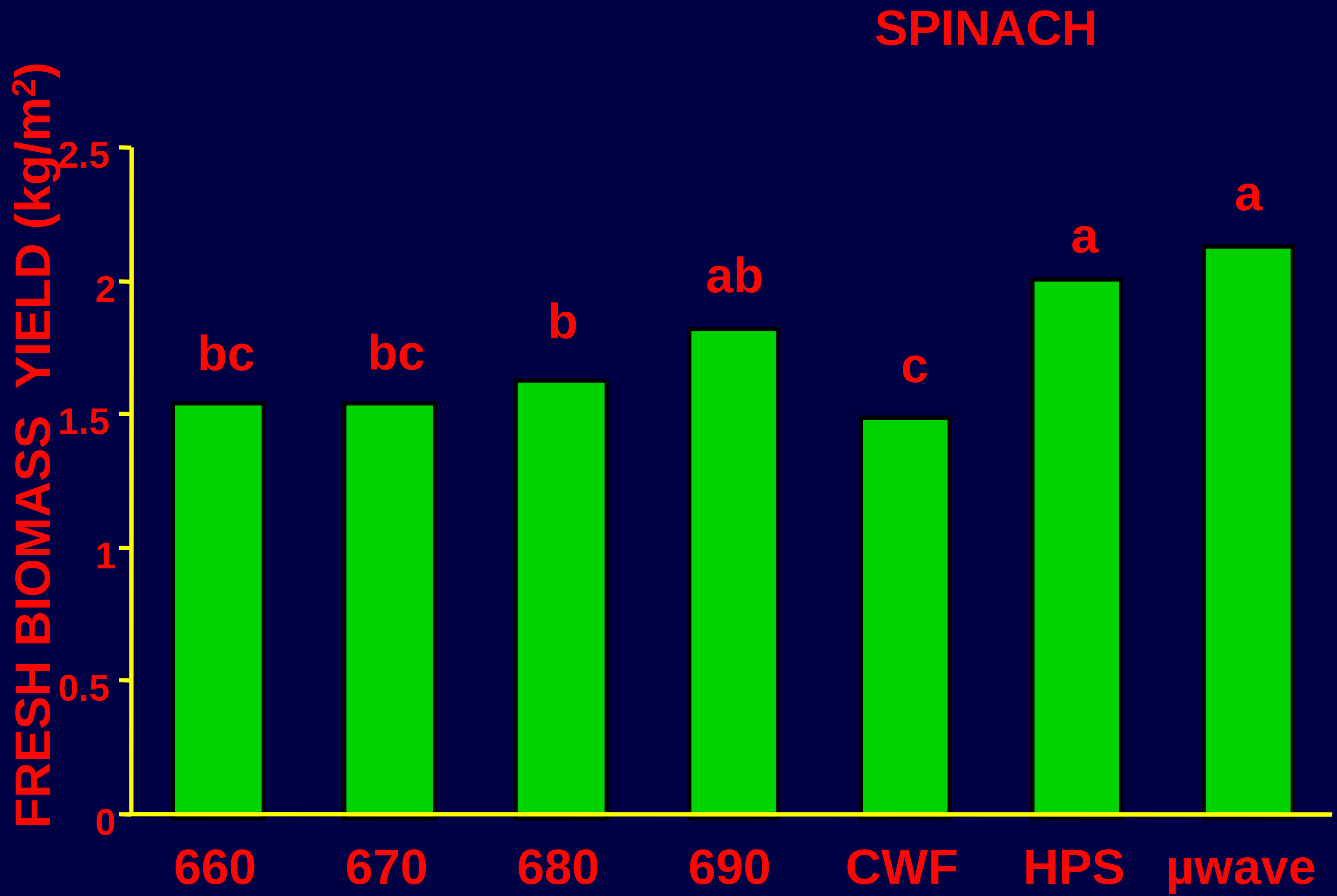


Shoot, tuber, and root dry mass yield of "Cherry Belle" radish plants at 28 DAP.

*** Radish plants grown under 690 nm LEDs showed significantly greater combined total and shoot dry mass as compared to remaining treatments based on ANOVA and Tukey's HSD mean procedure test ($P<0.05$).**

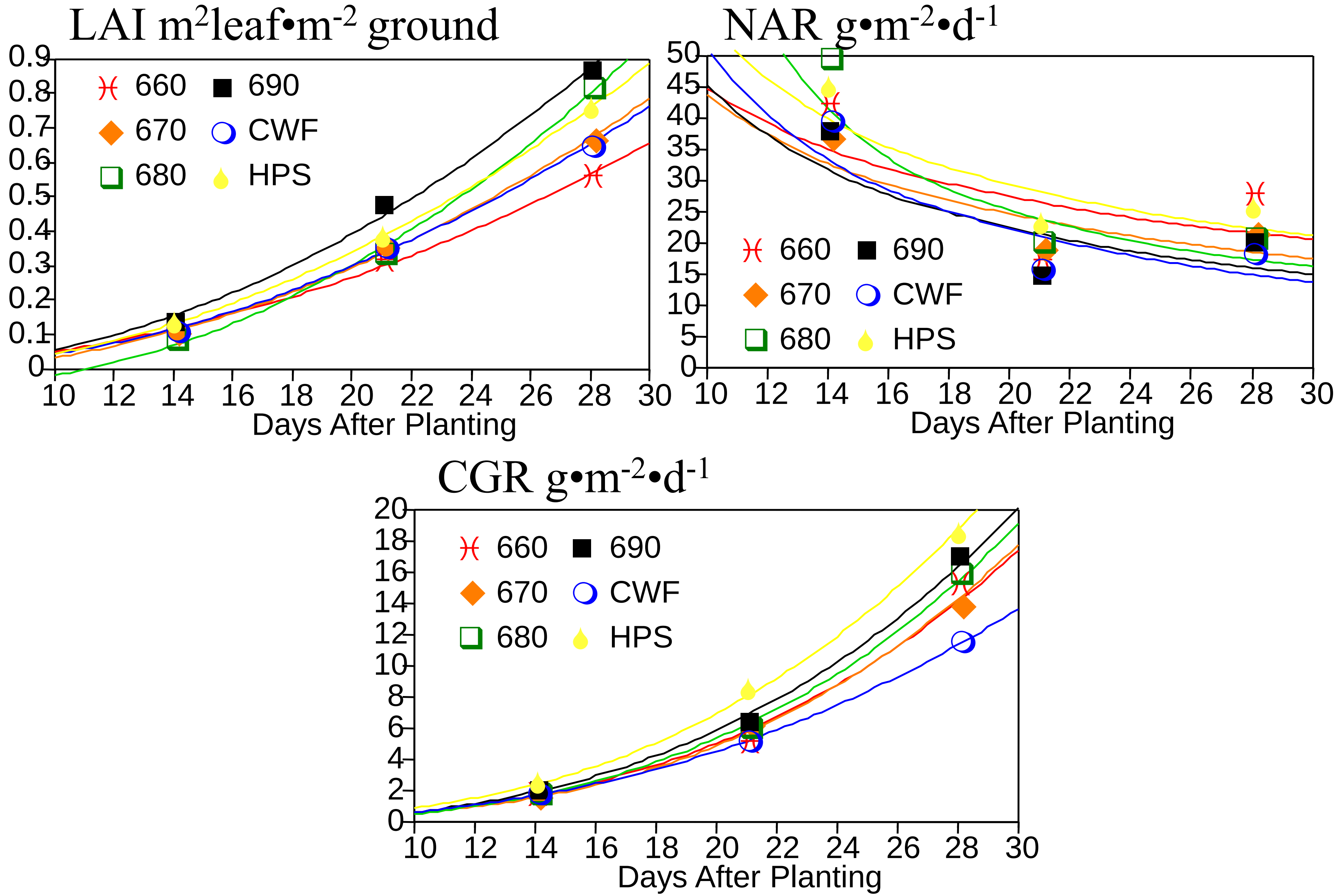


Leaf area index (LAI), net assimilation rates, and crop growth rates of "Cherry Belle" radish plants over 28 day crop cycles in the presence of LED, CWF, or HPS lighting *(see appendices for curve fit functions).*



Shoot fresh mass yield of “Whitney” spinach 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 "Whitney" spinach plants over 28 day crop cycles in the presence of LED, CWF, or HPS lighting *(see appendices for curve fit functions).*

CONCLUSIONS

- **Tests to date confirm that LED lighting technologies (and sulfur-microwave) are plausible alternatives to conventional (HPS, CWF) plant lighting sources**
- **Far-red radiation was observed to promote a higher LAI in each species tested which appeared to enhance photosynthetic assimilation by increasing leaf area**
- **Yield promotion observed in HPS and 680-690 nm LEDs appeared to be partially a consequence of more efficient light interception during early growth as opposed to increased CER on a leaf area basis**

ACKNOWLEDGEMENTS

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    Scott Young

Future Research

- Evaluate other salad crops' (onion, carrot, etc.) responses and photosynthetic conversion efficiencies under microwave, HPS, CWF, and LED lamps
- Expand electrical power requirements and efficiencies database for candidate lighting technologies
- "Salad-machine" integration issues which need address:
  - Comparisons of ISS plant lighting configurations and sources
  - Efficient cropping system for continuous and/or mixed salads
  - Robust low maintenance nutrient delivery system
  - Rapid and straightforward planting and harvesting system
  - Plant spacing schemes that optimize canopy radiation capture

Appendices - Growth Analysis Curve Fit Equations

LETTUCE

```
TRT  LAI
660  f(x) = 4.386370E-3*x^2 + -6.868807E-2*x + 0.000000E+0
     R2^2 = 9.364963E-1,R1^2 = 8.819856E-1,R0^2 = 9.610218E-1
670  f(x) = 5.817356E-3*x^2 + -9.172412E-2*x + 0.000000E+0
     R2^2 = 9.363985E-1,R1^2 = 8.818562E-1,R0^2 = 9.611829E-1
680  f(x) = 8.208201E-3*x^2 + -1.274679E-1*x + 0.000000E+0
     R2^2 = 9.434614E-1,R1^2 = 8.912842E-1,R0^2 = 9.662423E-1
690  f(x) = 8.335405E-3*x^2 + -1.293185E-1*x + 0.000000E+0
     R2^2 = 9.426196E-1,R1^2 = 8.901510E-1,R0^2 = 9.655514E-1
CWF  f(x) = 6.868040E-3*x^2 + -1.078988E-1*x + 0.000000E+0
     R2^2 = 9.391571E-1,R1^2 = 8.855176E-1,R0^2 = 9.632391E-1
HPS  f(x) = 7.569556E-3*x^2 + -1.164198E-1*x + 0.000000E+0
     R2^2 = 9.515682E-1,R1^2 = 9.023471E-1,R0^2 = 9.722370E-1
```

```
TRT  NAR
660  f(x) = a * (x^-1.627310E+0 ),
     where a = exp(7.424944E+0 )
     R^2 = 8.470692E-1
670  f(x) = a * (x^-1.965505E+0 ),
     where a = exp(8.018069E+0 )
     R^2 = 9.689917E-1
680  f(x) = a * (x^-2.714952E+0 ),
     where a = exp(1.022869E+1 )
     R^2 = 9.671102E-1
690  f(x) = a * (x^-2.244467E+0 ),
     where a = exp(8.552496E+0 )
     R^2 = 9.178558E-1
CWF  f(x) = a * (x^-2.350694E+0 ),
     where a = exp(9.302109E+0 )
     R^2 = 9.996359E-1
HPS  f(x) = a * (x^-2.206301E+0 ),
     where a = exp(8.932569E+0 )
     R^2 = 9.958946E-1
```

```
     CGR
660  f(x) = a * (x^4.739158E+0 ),
     where a = exp(-1.347717E+1 )
     R^2 = 9.739419E-1
670  f(x) = a * (x^4.734825E+0 ),
     where a = exp(-1.371935E+1 )
     R^2 = 9.906889E-1
680  f(x) = a * (x^3.865429E+0 ),
     where a = exp(-1.071153E+1 )
     R^2 = 9.648428E-1
690  f(x) = a * (x^4.212977E+0 ),
     where a = exp(-1.196016E+1 )
     R^2 = 9.605018E-1
CWF  f(x) = a * (x^4.357723E+0 ),
     where a = exp(-1.228513E+1 )
     R^2 = 9.983351E-1
HPS  f(x) = a * (x^4.451821E+0 ),
     where a = exp(-1.229503E+1 )
     R^2 = 9.918132E-1
```

RADISH

```
TRT  LAI
660  f(x) = 1.663265E-4*x^2 + 1.825000E-2*x + -1.810000E-1
     R2^2 = 9.952053E-1,R1^2 = 9.992910E-1,R0^2 = 1.000000E+0
670  f(x) = 2.622449E-4*x^2 + 2.217857E-2*x + -2.451000E-1
     R2^2 = 9.959083E-1,R1^2 = 9.989815E-1,R0^2 = 1.000000E+0
680  f(x) = -1.173469E-4*x^2 + 4.016429E-2*x + -4.190000E-1
     R2^2 = 9.880819E-1,R1^2 = 9.998189E-1,R0^2 = 1.000000E+0
690  f(x) = 1.747828E-3*x^2 + -1.512667E-2*x + 0.000000E+0
     R2^2 = 9.999873E-1,R1^2 = 9.901323E-1,R0^2 = 9.995530E-1
CWF  f(x) = 7.740966E-4*x^2 + -2.865727E-3*x + 0.000000E+0
     R2^2 = 9.973126E-1,R1^2 = 9.980594E-1,R0^2 = 9.962632E-1
HPS  f(x) = 8.932691E-4*x^2 + -4.368218E-3*x + 0.000000E+0
     R2^2 = 9.963705E-1,R1^2 = 9.987298E-1,R0^2 = 9.946886E-1
```

```
     NAR
660  f(x) = a * (x^-1.008552E+0 ),
     where a = exp(5.775411E+0 )
     R^2 = 8.709201E-1
670  f(x) = a * (x^-9.896396E-1 ),
     where a = exp(5.303118E+0 )
     R^2 = 9.999311E-1
680  f(x) = a * (x^-1.337797E+0 ),
     where a = exp(6.560377E+0 )
     R^2 = 9.856048E-1
690  f(x) = a * (x^-1.337797E+0 ),
     where a = exp(6.560377E+0 )
     R^2 = 9.856048E-1
CWF  f(x) = a * (x^-7.486222E-1 ),
     where a = exp(4.997517E+0 )
     R^2 = 8.204566E-1
HPS  f(x) = a * (x^-1.075494E+0 ),
     where a = exp(5.946319E+0 )
     R^2 = 9.995859E-1
```

```
CGR
660  f(x) = a * (x^2.382416E+0 ),
     where a = exp(-6.150696E+0 )
     R^2 = 8.173017E-1
670  f(x) = a * (x^2.641070E+0 ),
     where a = exp(-7.178986E+0 )
     R^2 = 9.217385E-1
680  f(x) = a * (x^2.166482E+0 ),
     where a = exp(-5.695778E+0 )
     R^2 = 9.718287E-1
690  f(x) = a * (x^2.899836E+0 ),
     where a = exp(-7.478880E+0 )
     R^2 = 9.167183E-1
CWF  f(x) = a * (x^2.885331E+0 ),
     where a = exp(-7.613889E+0 )
     R^2 = 9.830861E-1
HPS  f(x) = a * (x^2.680184E+0 ),
     where a = exp(-6.972680E+0 )
     R^2 = 9.333589E-1
```

Appendices - Growth Analysis Curve Fit Equations, Continued

SPINACH

```
TRT  LAI
660  f(x) = 8.476877E-4*x^2 + -3.600655E-3*x + 0.000000E+0
     R2^2 = 9.958817E-1,R1^2 = 9.989947E-1,R0^2 = 9.943779E-1
670  f(x) = 1.135443E-3*x^2 + -7.929227E-3*x + 0.000000E+0
     R2^2 = 9.991852E-1,R1^2 = 9.954668E-1,R0^2 = 9.977359E-1
680  f(x) = 1.701582E-3*x^2 + -1.893978E-2*x + 0.000000E+0
     R2^2 = 9.924338E-1,R1^2 = 9.668747E-1,R0^2 = 9.972017E-1
690  f(x) = 1.429732E-3*x^2 + -8.804587E-3*x + 0.000000E+0
     R2^2 = 9.973565E-1,R1^2 = 9.980218E-1,R0^2 = 9.953969E-1
CWF  f(x) = 1.057040E-3*x^2 + -6.313303E-3*x + 0.000000E+0
     R2^2 = 9.977817E-1,R1^2 = 9.976192E-1,R0^2 = 9.960368E-1
HPS  f(x) = 1.253969E-3*x^2 + -8.032045E-3*x + 0.000000E+0
     R2^2 = 9.995950E-1,R1^2 = 9.865915E-1,R0^2 = 9.999910E-1
```

```
     NAR
660  f(x) = a * (x^-7.075977E-1 ),
     where a = exp(5.430680E+0 )
     R^2 = 2.954319E-1
670  f(x) = a * (x^-8.301600E-1 ),
     where a = exp(5.688781E+0 )
     R^2 = 6.706433E-1
680  f(x) = a * (x^-1.313573E+0 ),
     where a = exp(7.253213E+0 )
     R^2 = 7.994498E-1
690  f(x) = a * (x^-1.012098E+0 ),
     where a = exp(6.144640E+0 )
     R^2 = 5.288936E-1
CWF  f(x) = a * (x^-1.192141E+0 ),
     where a = exp(6.688037E+0 )
     R^2 = 6.927851E-1
HPS  f(x) = a * (x^-8.728888E-1 ),
     where a = exp(6.019757E+0 )
     R^2 = 7.195641E-1
```

```
     CGR
660  f(x) = a * (x^3.024974E+0 ),
     where a = exp(-7.433830E+0 )
     R^2 = 9.877079E-1
670  f(x) = a * (x^3.162906E+0 ),
     where a = exp(-7.879642E+0 )
     R^2 = 9.977387E-1
680  f(x) = a * (x^3.130021E+0 ),
     where a = exp(-7.691477E+0 )
     R^2 = 9.986090E-1
690  f(x) = a * (x^3.014519E+0 ),
     where a = exp(-7.247496E+0 )
     R^2 = 9.970763E-1
CWF  f(x) = a * (x^2.694862E+0 ),
     where a = exp(-6.548022E+0 )
     R^2 = 9.996035E-1
HPS  f(x) = a * (x^2.883933E+0 ),
     where a = exp(-6.666987E+0 )
     R^2 = 9.989002E-1
```