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Effect of Blue Light and Temperature on Leaf Expansion, Stem Elongation, and Growth

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EFFECT OF BLUE LIGHT AND TEMPERATURE ON LEAF EXPANSION, STEM ELONGATION, AND GROWTH

by

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ABSTRACT

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by

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Utah State University, 1999

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Short height and high yield per unit energy in controlled environments are essential to the success of a food production system for spaceflight. Temperature and light quality can be manipulated in controlled environments to reduce plant height and increase yield. Although the effects of temperature on height and yield are well studied at ambient CO_2, temperature effects at elevated CO_2 with a hydroponic root zone are not well characterized. We studied soybean yield and height under two lamp types over a broad range of temperatures. Temperature had little effect on yield or height, but lamp type had a significant effect on canopy height. This first study highlighted the importance of understanding spectral quality in controlling plant growth, especially canopy height.

Numerous studies have compared lamp types and suggested that profound differences in leaf area, canopy height, yield, and total dry mass responses were due to blue light differences. Unfortunately, the most energy-efficient light sources have the least

blue light. We have a poor understanding of the specific morphological and histological effects of blue light on leaves and stems. Three species, soybeans, wheat, and lettuce, were grown at five blue light fractions (0, 2, 6, 12, and 26%) and two light levels (200 and 500 μmol m^{-2} s^{-1}). Phytochrome photoequilibria were constant among treatments. Blue light responses were species dependent. Wheat leaf area, dry mass, and stem length were insensitive to blue light fraction. Increasing blue light to 26% decreased soybean stem length, but leaf area was greatest at 6% blue. Lettuce leaf area, stem length, and dry mass were highly sensitive to blue light fraction between 0% and 6% under high pressure sodium lamps, but were insensitive between 6% and 26% under metal halide lamps. These results may be complicated by sensitivity to other wavelengths. The decrease in soybean stem length with increasing blue light was caused by an inhibition of cell division, while the decrease in leaf area was caused primarily by a decrease in cell expansion. Increased lettuce leaf area with increasing blue light fraction was caused by both cell division and expansion. This research indicates that lamps high in blue photons are not only energetically wasteful, but do not benefit, and in some cases reduce, plant growth. However, some blue light is necessary for controlling plant height in soybean and even required for proper growth and development in lettuce.

(197 pages)

For my amazing families,
the Ohlers and the Doughers.

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Tracy A. Ohler Dougher

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ABBREVIATIONS

PPF = Photosynthetic Photon Flux

PPE = Phytochrome Photoequilibrium

LED = Light Emitting Diode

MH = Metal Halide

HPS = High Pressure Sodium

DIF = Difference between day temperature and night temperature

PAR = Photosynthetically Active Radiation

YPF = Yield Photon Flux

PE = Photosynthetic Efficiency

RWC = Relative Water Content

CHAPTER 1

INTRODUCTION

This research, funded by the NASA Advanced Life Support (ALS) program, sought to improve production efficiency of crop plants in controlled environments. Astronauts in an ALS system depend on plants for food, air revitalization, and water purification. Plants are grown under controlled conditions so that light intensity, spectral quality, CO_2, plant nutrients, and temperature can be altered to optimize yield per unit of input energy. Growth volume is limited, so plant height needs to be minimized. There is considerable potential to manipulate temperature and light quality to reduce height without reducing yield.

Temperature

Temperature affects both yield and height in many species. Most of these results are from studies done in the field or growth chambers at ambient CO_2 and in soil. In controlled environments, the reduced plant water potential usually associated with high temperatures can be minimized by growing plants hydroponically at high humidity and elevated CO_2. Elevated CO_2 reduces photorespiration, which generally increases with temperature. Thus crops grown in controlled environments should have higher temperature optima than field-grown plants. Optimal field temperatures for many species have been characterized, but the results may be affected by reduced plant water potential and increased photorespiration.

Light

ALS systems will rely on electric lamps or filtered sunlight for plant growth lighting, which provides an opportunity to alter light quality relative to sunlight. Light quality is known to affect plant morphology. High pressure sodium (HPS) lamps and more recently, red light emitting diodes (LEDs) are widely used to improve energy efficiency, but they have little to no blue light. Lamps with a higher blue content such as metal halide (MH) and cool white fluorescent are less energy efficient. Blue photons are energetically expensive to generate. In spite of several decades of research, the mechanisms underlying the effects of blue light on leaf and stem morphology are still poorly understood. Small amounts of blue light appear to be important for normal development of some species; however, too much blue light may be detrimental.

CHAPTER 2

LITERATURE REVIEW

Temperature

Stem morphogenesis

High temperatures increase the elongation of soybean stems. Thomas and Raper (1978) found that at day temperatures of 14 to 18°C stems were relatively short. Increasing temperature from 18 to 30°C at ambient CO_2 increased stem length by at least 20 cm for each 4°C. Increasing night temperature had a much smaller effect on stem elongation than increasing day temperature. A maximum stem length occurred at 30/26°C and a minimum at 14/10°C.

Elevating CO_2 can alter temperature optima. Sionit et al. (1987a) compared CO_2 levels from 350 to 1000 μmol mol^{-1} and found that stem height increased with increasing CO_2, but height was more responsive to temperature. Previous studies on soybeans at the Utah State University Crop Physiology Lab showed that increasing CO_2 level from 350 to 1000 μmol mol^{-1} increased canopy height from 28.5 to 39.5 cm when grown at 26/22°C day/night temperature.

Erwin and Heins (1995) showed that plant height could be affected by the difference between day and night temperatures (DIF). The typical condition of warm days and cool nights results in a positive DIF. Controlled environments and greenhouses can be controlled to maintain cool days and warmer nights, which results in what is called negative DIF. The more positive the DIF, the taller the plant. However, some large-

seeded species and legumes show little sensitivity to DIF (Erwin, 1991; Erwin and Heins, 1995) . Thomas and Raper (1978) examined several combinations of day/night temperatures in ambient CO_2. A reexamination of their data indicated that holding day temperature constant and increasing night temperature from 10 to 26°C (decreasing DIF) increased stem length in soybean. This result is opposite that of Erwin (1991) and Erwin and Heins (1995). However, increasing night temperature only increased stem length by 20 cm. In the same study, increasing day temperature and holding night temperature constant (increasing DIF) more significantly increased stem elongation. This result agrees with Erwin (1991) and Erwin and Heins (1995).

Leaf morphogenesis

Thomas and Raper (1978) found that warm night temperatures and cool day temperatures reduced soybean leaf area. Maximum and minimum leaf areas were achieved at 26/10°C and 14/26°C, respectively. Increasing CO_2 from 330 to 740 μmol mol^{-1} can also increase leaf area but the response appears to be temperature dependent (Baker et al., 1989; Sionit et al., 1987a; Ziska and Bunce, 1995).

Effect of temperature on yield

Temperature affects soybean yield, yield components, and harvest index (Thomas and Raper, 1978; Sionit et al., 1987b). A day/night temperature of 26/20°C appears to be optimal for soybean growth and yield in the field (Raper and Kramer, 1987) and controlled environment at ambient CO_2 (Gibson and Mullen, 1996). High CO_2 typically increases temperature optima, and yield is more responsive to CO_2 at higher temperatures

(Campbell et al., 1990; Ziska and Bunce, 1995; Sionit et al., 1987b; Baker et al., 1989).

Interaction of temperature and light quality

Numerous studies of temperature have been conducted in controlled environments, each under different lamp types (Thomas and Raper, 1978; Downs and Thomas, 1990; Bunce, 1991; Gibson and Mullen, 1996). However, the interaction of light quality and temperature on morphogenesis and growth is not well characterized.

Light Quality

Stem morphogenesis

Internode elongation may be controlled by both phytochrome balance and blue light (Ritter et al., 1981). Changes in the red to far red ratio (R:FR), specifically wavelengths affecting phytochrome 660:730nm, caused by neighbor detection, shading, and end-of-day light quality are well documented (Pausch et al., 1991; Smith, 1982; Ballare et al., 1995). The typical phytochrome response associated with low R:FR is an increase in apical dominance and increased internode elongation.

Blue light appears to profoundly influence stem elongation in many species, such as soybeans (Wheeler et al., 1991; Hunt et al., 1989; Britz and Sager, 1990); chrysanthemum (Rajapakse et al., 1992); white clover (Gautier et al., 1997); sorghum (Britz and Sager, 1990; Warrington and Mitchell, 1976); mustard, spinach, and lettuce (Tibbitts et al., 1983); potato (Yorio et al., 1995); and pepper (Brown et al., 1995). A threshold intensity, above which blue light has no further effect, has been reported for

soybean at a photosynthetic photon flux (PPF) of 30 μmol m^{-2} s^{-1} (Wheeler et al., 1991) and for lettuce at 15 μmol m^{-2} s^{-1} (Hoenecke et al., 1992). Beyond these thresholds, stem and hypocotyl elongation, respectively, did not decrease significantly. Both studies were at moderate (500 μmol m^{-2} s^{-1}) to low (100 μmol m^{-2} s^{-1}) light levels but reports claim that these thresholds may be PPF independent (Wheeler et al., 1991; Hoenecke et al., 1992; Tibbitts et al., 1983).

Other studies have attempted to explain unusual results by suggesting that a balance between red and blue light regulates stem length (Drumm-Herrel and Mohr, 1984; Mohr, 1987; Britz and Sager, 1990). Casal and Smith (1989) suggest a high phytochrome photoequilibrium (PPE) is necessary to trigger blue light effects, but PPE does not interact with blue light once triggered. No conclusive studies have been completed.

Leaf morphogenesis

Leaf morphology under differing lamp types is less well studied. Leaf morphology is here defined as the ratio of leaf area to leaf mass (specific leaf area, m^2 kg^{-1}). Specific leaf area (SLA) can be affected by cell size and number. The effects that are apparently related to blue light may also be attributed to other wavelengths associated with the type of lamps compared. Hoenecke et al. (1992) found that addition of blue light to red LEDs increased leaf area of lettuce, but the lamps in this study completely lacked FR. Brown et al. (1995) later found these same results in pepper plants, but also found a combination of red and far red LEDs still had a leaf area less than metal halide, which has spectral qualities similar to sunlight. Under filtered and unfiltered broad-spectrum metallic iodure

lamps, Gautier et al. (1997) saw no change in total leaf area of white clover with decreased blue light. However, area of leaves on the main stolon was increased.

Morphology can also be altered by leaf number, which affects total leaf area. Yanagi et al. (1996) found that leaf number of lettuce was greater under red than under blue LEDs. Leaf length was similar under these two light sources, but leaf width was less under red LEDs. A combination of red and blue LEDs produced the highest leaf widths and lengths.

Total PPF can interact with the effects of light quality. Tibbitts et al. (1983) found that mustard, lettuce, and spinach tended to have larger leaves under HPS than MH at low PPF (320 μmol m^{-2} s^{-1}) but results were mixed at high PPF (700 μmol m^{-2} s^{-1}). Wheat showed no response to lamp type in these studies. However, Barnes and Bugbee (1992) found reduced leaf length in wheat with increasing blue light at a PPF of 200 μmol m^{-2} s^{-1}. At low R:FR and low blue light, as in shade settings, reduced leaf expansion occurs in shade-avoiding species (Dale, 1988). In this setting, however, R:FR and blue light effects are not separable. In soybean, specific leaf mass (mass per unit area) was significantly less under low pressure sodium lamps than under daylight fluorescent lamps, suggesting broader, thinner leaves (Britz and Sager, 1990).

Effects of morphology on light interception and yield

Wells et al. (1993) found that leaf and stem morphology altered light interception, growth, and, ultimately, yield in field-grown soybeans. PPF interception increased with increasing plant height. Cultivars with narrow leaves also had reduced light interception

and seed yield (Wells et al., 1993). In field grown wheat, light interception and yield of dwarf isolines were reduced by 13% compared to tall isolines (Gent, 1995).

Blue light effects on stem cells

The phototropism and elongation of stems is well studied under blue light. Blue light rapidly suppresses elongation in dark grown seedlings of many species (Cosgrove, 1981; Kigel and Cosgrove, 1991; Liscum et al., 1992). Dark-grown (etiolated) soybean seedlings had downregulated levels of β-tubulin compared to light-grown seedlings (Bustos et al., 1989). This downregulation was correlated with cell elongation because β-tubulin is a building block of microtubules. The effect of light quality, if any, on the regulation of β-tubulin production is not known. Blue light affects the orientation of the microtubules. In stem tissue, microtubules align longitudinally rather than transversely under blue light, but the importance of this response is not clear (Short and Briggs, 1994). Longitudinal alignment may inhibit cell elongation. Blue light may cause changes similar to a stress response, protecting cells from invasion by changing the properties of the cell wall (Horwitz and Gressel, 1987; Voigt and Munzner, 1994). Possible blue light photoreceptor precursor genes affecting stem elongation have been elucidated (Ahmad and Cashmore, 1993; Short and Briggs, 1994).

Blue light effects on leaf cells

Blue light effects on leaf expansion may be caused by changes in cell number and/or cell size. Leaf size is mostly determined by cell number (Dale and Milthorpe, 1983; Wenzel et al., 1997). However, there is no clear evidence that blue light affects cell

division more than cell expansion. Blue light delays cell division in *Chlamydomonas reinhardtii* (Munzner and Voigt, 1992). Blue light increased leaf epidermal cell area in birch plantlets *in vitro* over red light (Saebo et al., 1995). In *Phaseolus vulgaris*, blue light did not decrease cell number for primary leaves but accounted for most of the increase in leaf area of trifoliates (Dale, 1988). This was true for various fluence rates. In the primary leaves of *P. vulgaris*, cell division is complete before most cell expansion begins (Van Volkenburgh et al., 1985), so cell expansion can be studied without cell division affecting results. Using this technique, Van Volkenburgh et al. (1985) found cell elongation was due to a proton efflux associated with the acid growth hypothesis. Staal et al. (1994) found that red and blue light stimulated a proton efflux in pea epidermal cells, also agreeing with the acid growth hypothesis. However, these tests were done on a mutant strain and *in vitro* cells. In wheat, Guerra et al. (1985) found that the lignin precursors phenylalanine ammonia lyase and tyrosine ammonia lyase were lowest under LPS lamps, which contain no blue light. A decrease in these lignin precursors suggests a decrease in lignin synthesis, which would decrease cell wall rigidity and allow for more cell expansion. Blue light is known to affect turgor pressure in soybean pulvini (Donahue et al., 1990) and leaf stomata (Short and Briggs, 1994), probably via a potassium shift. It is unlikely, though, that continuous blue light could sustain a lower turgor pressure.

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CHAPTER 3

EFFECT OF LAMP TYPE AND TEMPERATURE ON DEVELOPMENT, CARBON PARTITIONING, AND YIELD OF SOYBEAN[1]

ABSTRACT

Soybeans grown in controlled environments are commonly taller than field-grown plants. We studied canopy height, carbon partitioning, and yield of soybeans under two lamp types and a range of temperatures. In controlled environments, including liquid hydroponics, height of the dwarf cultivar 'Hoyt' was reduced from 46 to 33 cm when plants were grown under metal halide lamps compared to high pressure sodium lamps at the same photosynthetic photon flux. Metal halide lamps reduced total biomass 14% but did not significantly reduce seed yield. Neither increasing temperature nor altering the difference between day/night temperature affected plant height. Increasing temperature from 21 to 27°C increased yield 32%. High temperature significantly increased carbon partitioning to stems and increased harvest index.

INTRODUCTION

Short-stature, high yielding cultivars are desirable in controlled environments because space is often limited. However, soybeans grown in controlled environments are taller than field-grown plants (Downs and Thomas, 1990). Red:far red ratios, specifically phytochrome 660:730 nm, have been implicated as the cause of internode elongation

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(Pausch *et al.*, 1991), although soybeans may also respond to a balance of red and blue light (Britz and Sager, 1990). Wheeler *et al.* (1991) reported that there was a threshold intensity of blue light (30 μmol m^{-2} s^{-1}) necessary to reduce stem elongation. However, elongation is also dependent upon the total photosynthetic photon flux (PPF) from lamps (Tibbitts *et al.*, 1983). Differences in the spectral quality of high pressure sodium (HPS) and metal halide (MH) lamps could alter the stem length and thus alter carbon partitioning of soybeans.

Another factor affecting stem length is temperature, which is easily manipulated in a controlled environment. The reduced plant water potential usually associated with high temperatures can be minimized by growing plants hydroponically at high humidity and elevated CO_2. Elevated CO_2 reduces photorespiration, which generally increases with temperature. Thus crops grown in controlled environments should have higher temperature optima than field-grown plants. Optimum field temperatures for soybean have been characterized (Raper and Kramer, 1987), but the results may be affected by reduced plant water potential and increased photorespiration.

Our objective was to study soybean canopy height, carbon partitioning, and yield under HPS versus MH lamps at varied and constant day/night temperatures in a CO_2-enriched, hydroponic, controlled environment.

MATERIALS AND METHODS

Dwarf soybean cv. 'Hoyt' (maturity group 2.5) canopies were grown in Plexiglas chambers (0.47 x 0.36 x 0.61 m) at a density of 36 plants m^{-2} (6 plants per chamber). This

choice of density was based on preliminary trials, which indicated that higher densities increased stem elongation and lower densities increased time to canopy closure. An extensive controlled environment screening showed 'Hoyt', a determinate cultivar, to be the shortest and highest yielding. All indeterminate cultivars were unacceptably tall. Chambers were positively pressurized for an open gas exchange system as described by Bugbee (1992). Seeds were germinated in moist diatomaceous earth (Isolite) and transplanted when the hypocotyls had elongated to at least 4 cm (about 6 days). Plants were transferred to an aerated nutrient solution, 21 cm deep, in a 30 L tub. Closed cell foam plugs in a blue Styrofoam lid supported the plants. Nutrient solution was replenished to maintain solution level. Nutrient solution electrical conductivity (14 ± 4.4 mS m^{-1}) and pH (5.6 ± 0.6) were monitored and controlled as necessary. Ammonium sulfate was added as needed to counteract the rise in pH caused by nitrate uptake.

Five day/night temperature regimes were used to test a range of temperatures typically utilized in controlled environments: 29/25, 26/22, 24/24, 23/19, and 21/21°C. Root temperatures were kept constant at the average daily temperature of the shoot: 27, 24, 24, 21, and 21°C, respectively. Shoot air and root-zone temperatures were measured with thermocouples and maintained by computer-controlled heaters. Each set of temperature treatments (5 chambers) was placed under either MH or HPS lamps. All chambers were in a single growth room with light treatments separated by a heavy Mylar sheet. A photosynthetic photon flux of 450 μmol m^{-2} s^{-1} was maintained at the top of the canopy. This supplied approximately 40 and 140 μmol m^{-2} s^{-1} of blue light in HPS and MH lamps, respectively. Intensity was maintained within 4% by shading each chamber

with neutral density filters. Aluminized Mylar around the chamber was maintained at canopy height to minimize the edge effect caused by side lighting. The photoperiod was 12 hours. Carbon dioxide concentration was enriched to 1100 μmol mol^{-1} based on known optimum enrichment levels for controlled environments.

Days to first flower was recorded as appearance of visible flower color. Plants were harvested at physiological maturity as indicated by loss of green color from the pods (Gbikpi and Crookston, 1981). At harvest, canopy height, from stem base to the top of the leaves, was measured *in situ*. Then plants were extended to their full height and measured to the growing tip of the main stem and longest branch. These different length measures were used as a more specific indication of internode elongation. Plants were separated into leaves, stems, pods, and roots, dried at 80°C for 48 hours, and weighed. Seed and pod number were recorded. Yield parameters and carbon partitioning (organ DW / total DW) were calculated from the harvest data. Main effects were tested using the light by temperature interaction error term with SAS ANOVA (SAS Institute, NC) (Appendix D). Net canopy photosynthesis (P_{net}) was calculated from the measured change in CO_2 (infrared gas analyzer in differential mode) times air flow rate through the chamber divided by chamber ground area (Bugbee, 1992).

RESULTS

Effect of Lamp Type

MH lamps significantly reduced canopy height but slightly increased relative branch length compared with HPS lamps (Table 3.1). The main stem of HPS plants was

87% the length of the longest branch while MH main stem was 75% of the longest branch. MH canopy height was greater than the longest branch length because canopy height included petiole lengths. Although not measured, petioles appeared to contribute more to height in MH canopies. Plants grown under MH lamps had 14% less biomass compared to plants under HPS lamps (Table 3.1). Reduced stem mass in MH plants was associated with an increase in harvest index (HI) (Table 3.2). All other component partitioning was similar. MH lamps also had 7% less seed yield than HPS lamps (Table 3.1). Lower pod number and seeds per pod accounted for the lower in seed yield under MH than HPS. P_{net} measurements were consistent with the yield differences between lamp types (Figure 3.1a).

Effect of Temperature

Higher temperatures increased seed yield via increased number of pods per square meter and seeds per pod (Table 3.3). We were surprised to find that cooler temperatures reduced the duration of the seed fill period. Higher temperatures increased P_{net} early in the life cycle (Figure 3.1b) but no trend was apparent after 35d. Total biomass (Table 3.3) and HI (Table 3.4) tended to decrease with lower temperatures.

Percent leaf mass decreased with increasing temperatures probably because of hastened leaf senescence. Warm temperatures also tended to decrease percent root mass.

The day/night temperature scheme did not affect canopy height. Erwin and Heins (1995) showed that altering the difference (DIF) between day/night temperature changed plant height for some species but larger-seeded species showed little response to DIF

(Erwin, 1991). In our experiment, the canopies at +4 DIF (42 cm at 26/22°C, 41 cm at 23/19°C) were not significantly taller than at zero DIF (38 cm at 24/24°C, 36 cm at 21/21°C).

DISCUSSION

While short-stature canopies are desired in controlled environments, high yield is also a priority. The mechanism underlying biomass differences with spectral quality, specifically orange bias (HPS) versus a balanced spectrum (MH), is unknown. However, a 14% biomass difference generated only a 7% difference in yield. Because plant height and seed yield commonly are positively correlated (Wells *et al.*, 1993), a slight difference in yield was to be expected. Taller plants under HPS lamps may have had better light interception.

Higher P_{net}, longer internodes, larger leaves (data not shown), and more rapid canopy closure (data not shown) suggest that there is better light distribution and capture in the HPS canopy. Increasing plant density under MH lamps might overcome canopy closure differences but this would probably increase stem elongation after canopy closure, which would reduce the height advantage for conserving space in a controlled environment.

A lack of significant effect on plant height indicates temperature can be manipulated to some extent to maximize yield without increasing canopy height. The high temperatures increased yield by increasing pod and seed number. Rapid canopy closure and higher photosynthesis contributed to the yield differences. High temperatures also

hastened development as evidenced by shorter time to final vegetative-stage (data not shown) and decreasing time to first flower. We are currently testing temperatures above 29°C (Appendix A).

Measurement of P_{net} is important for calculating oxygen production for a bioregenerative life support system. Regardless of treatment, there was a broad peak in P_{net} between days 25 and 45. Early life cycle rate of increase in P_{net} was caused by rate of canopy closure and radiation capture. Differences between lamp types and between temperatures were apparent during this part of the life cycle. The decrease in P_{net} was due to senescence and treatment had no effect on the rate of decrease. Therefore we are focusing on environmental changes early in the life cycle to increase canopy closure.

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Table 3.1. Three plant length measures, seed yield, and yield components of soybeans grown under two lamp types. Each parameter is an average of the five chambers with different temperature regimes.

lamp type	canopy height (cm)	main stem length (cm)	longest branch length (cm)	seed yield ($g\ m^{-2}\ d^{-1}$)	photo-synthetic efficiency† ($g\ mol^{-1}$)	total biomass ($g\ m^{-2}\ d^{-1}$)	pods per m^2	seeds per pod	mass per seed (mg)
HPS	46.4	41.2	47.1	4.99	0.257	13.7	1486	1.91	159
MH	33.2	19.9	26.6	4.62	0.238	12.0	1385	1.85	167
p-value	<0.01	<0.01	<0.01	0.24	0.24	0.04	<0.01	0.10	0.42

†grams of seed per mol of PPF

Table 3.2. Carbon partitioning of soybeans under two lamp types. Measures are a percent of total dry mass. Sum of the five components equals 100%.

lamp type	seed (harvest index)	stem	leaves	pod	root
HPS	36.4	14.7	27.9	12.8	8.2
MH	37.7	12.2	28.6	12.2	9.3
p-value	0.18	<0.01	0.14	0.19	0.18

Table 3.3. A comparison of yield and yield components for soybeans grown under five temperature regimes. Each parameter is an average of the two chambers of differing lamp type*.

day/night temperature	seed yield ($g\ m^{-2}\ d^{-1}$)	PE† ($g\ mol^{-1}$)	total biomass ($g\ m^{-2}\ d^{-1}$)	pods per m^2	seeds per pod	mass per seed (mg)	days to first flower	days to harvest	seed fill (days)
29/25	5.46	0.281	13.6	1483b	1.96ab	167	19c	87	68
26/22	5.43	0.280	13.1	1550ab	2.03a	153	24b	87	63
24/24	5.02	0.258	12.9	1594a	1.89bc	160	27b	90	63
23/19	4.13	0.213	12.6	1321c	1.79cd	167	32a	90	58
21/21	3.98	0.205	11.9	1230d	1.73d	169	33a	90	57
p-value	0.06	0.06	0.46	<0.01	0.01	0.74	<0.01	0.67	

†PE = photosynthetic efficiency

*Letters within a column indicate significant differences using least significant difference mean separation test at α=0.05

Table 3.4. Carbon partitioning of soybeans under five temperature regimes*. Data are a percent of total dry mass. Sum of the five components equals 100%.

day/night temperature	seed (harvest index)	stem	leaves	pod	root
29/25	40.0a	15.8a	24.3ab	13.0	7.1
26/22	40.9a	12.9b	25.5a	13.8	6.9
24/24	38.9a	12.5b	27.1b	12.9	8.5
23/19	32.6b	13.5b	32.3c	11.2	10.4
21/21	33.0b	12.5b	32.1c	11.5	10.9
p-value	<0.01	0.03	<0.01	0.07	0.06

*Letters within a column indicate significant differences using least significant difference mean separation test at α=0.05

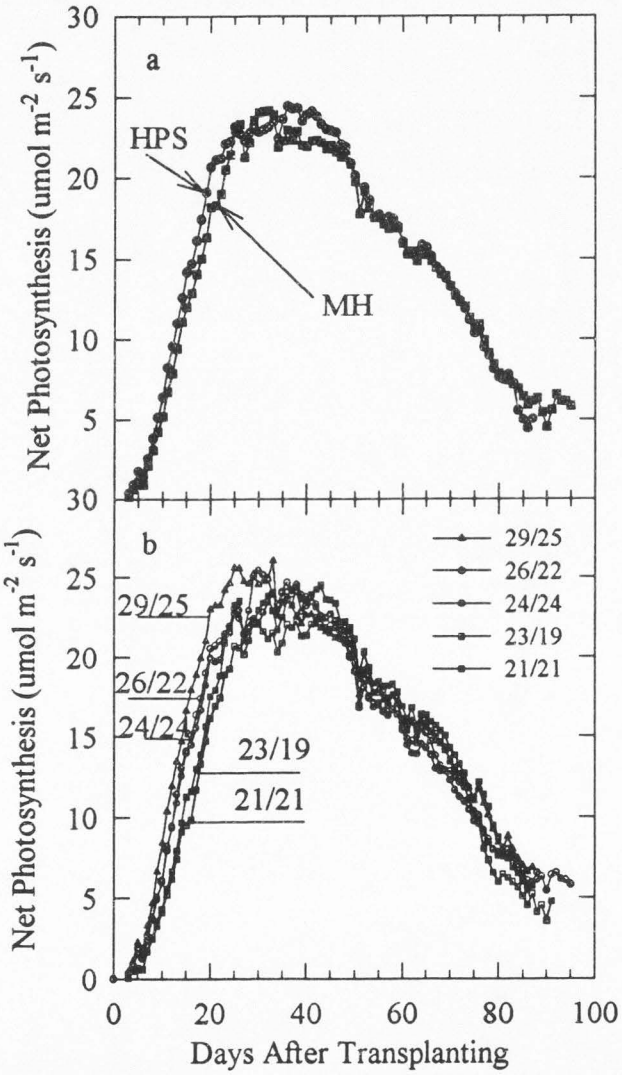

Fig. 3.1. Net photosynthesis (CO_2 uptake) of soybean canopies. Endpoints are an average day of harvest. a) Comparison of lamp types. Measurements are an average of the five chambers of different temperatures. b) Comparison of temperatures. Measurements are an average of the two chambers of differing lamp types.

CHAPTER 4

EFFECT OF BLUE LIGHT ON LEAF EXPANSION, STEM ELONGATION, AND GROWTH

Abstract

Blue photons are energetically expensive so the most energy-efficient lamps contain the least blue light. Blue photons are not used efficiently in photosynthesis, but blue light has dramatic effects on plant development. We studied the growth and development of soybean, wheat, and lettuce plants under high pressure sodium and metal halide lamps with yellow filters creating 5 fractions of blue light (< 0.1%, 2%, 6%, 12%, and 26%) at 200 and 500 μmol m^{-2} s^{-1}. The response was species dependent. Soybean responses were attributable to blue light fraction, whereas lettuce responses were attributable to absolute blue light. Lettuce was highly sensitive to blue light fraction between 0% and 6% blue, but results were complicated by sensitivity to lamp type. For all parameters tested, wheat did not respond to blue light. Soybean stem length decreased with increasing blue light fraction and leaf area was greatest at 6% blue, but total dry mass was unchanged. The data suggest that lettuce growth and development requires some added blue light, but soybean and wheat may not.

Introduction

Energy efficiency of electric lamps has always been important in Earth-based research and it plays an even larger role in space-based life support systems. Photons at

short wavelengths are more energetically expensive than longer wavelengths so the most efficient lamps have reduced blue light. Recent studies have utilized high pressure sodium (HPS) and red light emitting diodes (LEDs). This raises the question of how critical blue light is to plant growth and development.

Blue light has been shown to reduce cell expansion (Cosgrove, 1981) and long-term exposure to blue light could thus reduce leaf area and stem elongation, altering canopy architecture. This, in turn, would affect radiation capture, photosynthesis, and, ultimately, yield (Board et al., 1992; Gent, 1995). Indeed, several studies have shown that reducing blue light can have a positive effect. A decrease in blue light can increase specific leaf area (SLA) (Britz and Sager, 1990; Dougher and Bugbee 1997). Soybeans grown under HPS had more biomass yield than those grown under metal halide (MH) (Dougher and Bugbee, 1997). Increase in total dry mass under HPS versus MH has also been reported for potato (Yorio et al., 1995) and lettuce (Wheeler et al., 1994).

Several studies indicate that blue light does not alter growth. Tibbitts et al. (1983) found that lettuce, spinach, and mustard tended to have increased leaf area under lamps with less blue light, but there were no consistent changes in dry mass of these species under different lamp types. Barnes and Bugbee (1992) also found that blue light did not affect dry matter accumulation, but low blue light increased leaf length in wheat. Goins et al. (1997) also found no change in wheat dry matter accumulation when blue fluorescents were added to red LEDs. White clover grown under orange-filtered (<0.1% blue) metallic iodure lamps had similar total biomass as plants under unfiltered lamps (23% blue)

(Gautier et al., 1997). However, non-photosynthetic thermal radiation was not filtered in this experiment.

By the same token, reducing blue light has been shown to have a negative effect. Wheat tended to have decreased leaf area under lamps with less blue light (Tibbitts et al., 1983). A decrease in blue light greatly elongates stems of soybean (Wheeler et al., 1991) and lettuce (Hoenecke et al., 1992). Brown et al. (1995) found that supplementing with blue light increased pepper plant biomass when plants were grown under red LEDs.

Some studies compared lamp types and the authors suggested that differences were due to blue radiation (Sager and McFarlane, 1997). Other studies added blue fluorescents but the treatments did not have identical non-blue wavelengths (Brown et al., 1995; Hoenecke et al., 1992; Yorio et al., 1998). Due to lamp limitations, these studies have only been conducted at low light levels. Our objective was to test multiple blue light fractions at high and low light. We compared six levels of blue light by filtering blue from two lamp types. We also compared unfiltered HPS and filtered MH lamps at the same blue light level to test if other wavelengths alter blue light effects.

Materials and Methods

Lettuce (*Lactuca sativa*, cv. 'Grand Rapids'), soybean (*Glycine max*, cv. 'Hoyt'), and wheat (*Triticum aestivum*, cv. 'USU-Apogee') were grown in six blue light treatments comprising five blue light fractions (Table 4.1) at a photosynthetic photon flux (PPF) of 500 μmol m^{-2} s^{-1} and 200 μmol m^{-2} s^{-1}. A single growth room was divided into six compartments for the light treatments. Each of the six light banks was filtered with

tempered glass and had a chilled, circulating water barrier to minimize non-photosynthetic thermal radiation. Canary yellow acetate film (Roscolux #312, Oasis Stage Werks, Salt Lake City, UT) was used to reduce the amount of blue light of a given source (transmission curve, Figure 4.1). A comparison of HPS and MH 6% blue was used to determine if any parameter differences were caused by other wavelengths. Spectral output of the lamps was measured with a spectroradiometer (LI-1800, LICOR, Lincoln, NE). All treatments were shaded with neutral density fiberglass screening to obtain the desired PPF.

Definition of blue light

We defined blue light as ranging from 320 to 496 nm. UVA wavelengths (320-400 nm) are present in many lamps and are known to be involved in photomorphogenic responses (Salisbury and Ross, 1992; Munzner and Voigt, 1992; Baskin and Iino, 1987). The UVA wavelengths increase the blue light fraction in HPS lamps by only 0.2% and in MH lamps by 3.6% (Table 4.2). Wavelengths from 496-500 nm were not included in the blue fraction because HPS lamps have a spectral peak from 494-502 nm and photomorphogenic responses rapidly decrease above about 490 nm (Salisbury and Ross, 1992). Including the 496-500 nm wavelengths tends to exaggerate the effective blue from HPS by 20% (Table 4.2).

Phytochrome photoequilibrium differences

Plant morphology and growth are known to respond to the balance of active phytochrome to total phytochrome, measured as phytochrome photoequilibrium (PPE) (Sager and McFarlane, 1997; Barnes and Bugbee, 1991). PPE estimates the balance of

active and inactive phytochromes from response curves of the purified phytochrome *in vitro*. There is still controversy as to the *in vivo* role of chlorophyll altering the radiation absorbed and thus PPE (Sager and McFarlane, 1997). However, measuring the phytochrome response *in vivo* has not yet been achieved and researchers rely on the use of PPE as an estimate. The PPE in these experiments, calculated from spectroradiometric data, ranged from 0.81 at the highest blue light fraction to 0.86 at the lowest blue light fraction. While phytochrome response cannot entirely be ruled out, the magnitude of the responses observed was likely too large to be elicited by such a small change in PPE.

Plant culture and harvest

Germination. Blue light treatments began at imbibition. Plants were given light 2 h at a PPF of 200 μmol m^{-2} s^{-1} or 1 h at a PPF of 500 μmol m^{-2} s^{-1} for the first 4 days. At the end of 4 days, lettuce and wheat were at emergence and with soybean was fit for transplanting. Temperature was maintained at 24/22°C day/night during the germination period. Lettuce seeds were sown directly in Ethafoam plugs with a diatomaceous earth (Isolite) core. Lettuce plugs were kept in a shallow pan of nutrient solution until emergence, 4 days after planting, and then they were transferred to the aerated hydroponic system. Wheat seeds were stratified at 4°C in moist paper towels for 48 h prior to planting. Wheat seeds were also planted in Ethafoam plugs with an Isolite core. Wheat plugs were placed directly in the system. Soybean seeds were germinated in trays of moist Isolite. Seedlings were transferred to Ethafoam plugs and into the system when the hypocotyl was at least 2 cm long, 4 days after planting.

Plant Growth. Plants were grown in an aerated hydroponics system under a 16-h photoperiod. The environment was maintained at 26/22 °C day/night ± 0.3/0.2 between sections within a trial and 68% relative humidity. CO_2 was elevated to 860 μmol mol^{-1}. All sections were connected to a common air conditioning system via a manifold, so carbon dioxide, humidity, and temperature differences between sections was minimal.

Measurements and Harvest. Chlorophyll measurements were made 2 days before harvest with a chlorophyll meter (SPAD-502, Minolta Corp., Ramsey, NJ). Meter readings were in SPAD units, which is based on the ratio of chlorophyll absorbance at 650 nm to nonchlorophyll absorbance at 940 nm. SPAD units are linearly related to measurement made colorimetrically (Monje and Bugbee, 1992). An average of three chlorophyll readings was taken on the middle leaflet of the first trifoliate of soybean, the second true leaf of lettuce, and the second leaf of wheat. Plants were harvested at canopy closure (Appendix B) to test blue light effects without complicating changes in spectral quality caused by canopy closure. Lettuce and soybean were harvested 18 and 17 days after transplanting, respectively. Wheat was harvested 17 days after emergence. Fresh mass and leaf area were taken immediately upon harvest and branch/tiller number and stem length determined. Roots were blotted dry and then weighed for fresh mass. Plant material was dried for 48 h at 80°C and dry mass determined. Specific leaf area was calculated as total leaf area divided by mass of the leaves. Carbon partitioning to each plant part was calculated as dry mass of plant part divided by the total dry mass (times 100 to give percentage). Relative water content (RWC), a potential indicator of cell size, was

calculated for each plant part as fresh mass minus dry mass all divided by fresh mass (times 100 to give percentage).

Statistical procedures

Six plants (pseudo-replicates) of each species were grown under each blue light fraction. Each PPF level was replicated twice in time. Differences between blue light fractions were tested using analysis of variance using a split-plot design with lamp type as the main plot (Appendix D). Mean comparisons were made using LSD at α=0.05 (SAS Institute, NC). To compare relative and absolute blue light, the data were fit using regression analysis (Sigma Plot 4.0, SPSS Inc., Chicago, IL).

Results

Sensitivity to lamp type with constant blue light fraction

MH lamps were filtered to 6% blue to compare with unfiltered HPS lamps at the same blue light fraction. None of the plant responses for wheat and soybean were significantly different between HPS and MH at 6% blue, suggesting that their blue light responses are not affected by the remaining spectral composition (Table 4.3). Wheat and soybean blue light effects were thus considered to be continuous between lamp types over the five blue light fractions.

In contrast to wheat and soybean, lettuce blue light response may be affected by non-blue wavelengths. Chlorophyll concentration, dry mass, leaf area, and specific leaf area of lettuce were significantly different for plants grown under 6% HPS blue and 6%

MH blue (Table 4.3). This indicates that caution must be used in claiming a blue light response when other parts of the spectrum vary. Blue light effects on lettuce chlorophyll concentration, dry mass accumulation, leaf area, and specific leaf area were graphed separately for each lamp type, but other parameters were not significantly different between lamp types and blue light fraction responses were considered continuous.

Dry mass accumulation and partitioning

Wheat dry mass tended to decrease with increasing blue light fraction, but means were not significantly different (Figure 4.2). Wheat carbon partitioning was similar under all blue light treatments (Figure 4.3). Because plants were harvested early, small differences could become larger as the plants matured. However, Barnes and Bugbee (1992) also found no significant difference between 1% and 25% blue light for mature wheat dry mass. Goins et al. (1997) did see a reduction in wheat shoot dry matter between 31% and 0.85% blue, but grain yield was not affected.

Soybean leaf and total dry mass were not responsive to blue light fraction (Figure 4.4a,d). Stem dry mass decreased with increasing blue light fraction (Figure 4.4b). Root dry mass was significantly less at high (26%) and low (0%) blue light fraction (Figure 4.4c). Carbon partitioning to stems at lower blue light fraction was mostly at the expense of the roots (Figure 4.5).

Although lettuce dry mass could not be graphed continuously due to significant differences caused by lamp type at 6% blue, there was a trend for increasing dry mass with blue light fraction under each lamp type (Figure 4.6). More carbon was partitioned to the

stem at low blue at the expense of the leaves (Figure 4.7). Both stem and leaf carbon partitioning changed drastically between 0% and 2% blue. Leaf carbon partitioning recovered by 2% blue, but carbon partitioning to the stem was still significantly higher at 2% blue than 6% blue or above. Some of the carbon partitioning compensation came from the roots, but the change in percent root dry mass with blue light fraction was not statistically significant.

Stem length

Stem length of wheat decreased by only 11% as blue light fraction increased from 0% to 26%, but this response was not significant (Figure 4.8a). Increasing blue light from 0% to 2% decreased soybean stem length only 7%, but a further increase to 6% decreased stem length by 44% (Figure 4.8b). Overall, increasing blue light fraction to 26% decreased soybean stem length 67% from 0% blue. Lettuce stem length decreased 72% between 0% and 2% blue and a further 13% from 2% to 6% blue (Figure 4.8c). Overall, lettuce stem length decreased 88% from 0% to 26% blue.

Leaf area and specific leaf area

Wheat leaf area and SLA were constant under all blue light treatments (Figure 4.9). Soybean leaf area was highest between 2% and 12% blue and decreased at extreme low (0%) and high (26%) blue (Figure 4.10a). Contrary to the findings of Britz and Sager (1990), soybean SLA was not significantly affected by blue light fraction (Figure 4.10b).

Both leaf area and SLA of lettuce were affected by lamp type and could not be drawn as a continuous response curve for blue light fraction. However, there was a

drastic increase in leaf area from 0% to 6% blue under HPS (Figure 4.11a). There was little response to blue light fraction under the MH treatments. SLA decreased with increasing blue light fraction under each lamp type (Figure 4.11b). There was a 54% decrease in SLA between 0% and 2% blue. The mean SLA of 152 $m^2 kg^{-1}$ at 0% blue is extremely high, reflecting the thin, almost transparent, leaves.

Chlorophyll concentration

Wheat chlorophyll was not affected by blue light fraction (Figure 4.12a). Soybean chlorophyll increased 13% between 0% and 2% blue, but was constant from 2% to 26% blue (Figure 4.12b). Although lettuce chlorophyll was significantly different between the two 6% blues, the chlorophyll concentration increased significantly under each lamp type with increasing blue light fraction (Figure 4.12c).

Tillering/branching

Although wheat tiller number tended to decrease with increasing blue light fraction, differences were not significant (Figure 4.13). This is contrary to Barnes and Bugbee (1992), who found that tillering increased 25% between 1% and 25% blue, and Goins et al. (1997), who found no increase in tillering between 0% and 0.85% blue, but a 71% increase between 0.85% and 8.5% blue. Differences in soybean branch numbers were statistically significant (data not shown), but means ranged only from 5.25 to 5.95, which is not physiologically important to light interception and canopy closure.

Relative water content

RWC of wheat leaves, stems, and roots was not affected by blue light fraction (Figure 4.14). RWC of soybean leaves and stems increased significantly with increasing blue light fraction, but root RWC was not significantly affected (Figure 4.15). Lettuce leaf RWC decreased with increasing blue light fraction (Figure 4.16a). Most of the change in leaf RWC occurred between 0% and 2% blue. Lettuce stem and root RWC did not change significantly (Figure 4.16b,c).

Discussion

Species differences

Blue light effects were species dependent and the differences may be associated with differences in plant morphology. Wheat, whose meristematic leaves and stems are sheltered from direct light by upper leaves and leaf sheathes, showed no response to blue light. Both lettuce and soybean have exposed meristematic cells in expanding leaves and stems and both responded to blue light fraction. Interestingly, the response of lettuce was more pronounced than soybean (Figure 4.17).

The many planophile species tested have shown a response to blue light (Brown et al., 1995; Hoenecke et al., 1992; Tibbitts et al., 1983; Yorio et al., 1995). Ryegrass, whose growth habit is erectophile and whose expanding tissues are also shielded, leaf area and shoot length did not respond to red- versus blue-biased lamps (Warrington and Mitchell, 1976). Under similar treatment, however, sorghum, also erectophile in growth habit, did respond. Although indicative that some erectophile species may not be blue

light insensitive, Warrington and Mitchell (1976) only tested lamp type and not blue light response. Direct blue light investigation of these and other grass (erectophile) species is needed to test if a generalization can be made between erectophile and planophile plants.

Inconsistencies with other research

Although Barnes and Bugbee (1992) saw a longer wheat leaf length with low blue, only the longest fully extended leaf was measured and there was no significant difference in dry matter accumulation. Contradiction of our tillering data with Barnes and Bugbee (1992) may be genetic differences in cultivars, as their experiments utilized 'Fielder', an extremely high-tillering cultivar compared to 'Apogee'. Goins et al. (1997) used a low tillering cultivar, but tillering differences were also evident and may be due to the short-duration of our experiments, which did not allow time for blue light effects to be manifested. Goins et al. (1997) saw an increase in wheat dry mass with increased blue light, but compared narrow band red LEDs (0% blue) with broad spectrum white light. It is important to point out that our lowest blue treatment was not truly zero blue and our lamp sources also contained far red. However, the phytochrome photoequilbrium of red LEDs is 0.88, similar to our treatments. Therefore, interactions with phytochrome are probably not responsible for the difference seen between our 0.1% blue and red LEDs.

Results for soybean and lettuce were mostly consistent with previous reports, especially under the <0.1% blue treatment compared to red LEDs (0% blue) (Hoenecke et al., 1992). Surprisingly, soybean SLA did not decrease with increasing blue light as seen previously in a comparison of daylight fluorescent and blue-deficient low pressure sodium

(Britz and Sager, 1990). Although blue light between these lamps does vary considerably, non-blue wavelengths also vary.

Consideration of yield photon flux

The most widely used definition of measurement of photosynthetically active radiation (PAR) is the photosynthetic photon flux, which weights each photon between 400 and 700 nm equally. In reality, the photosynthetic efficiency of blue photons is 30% less than that of red photons and the range extends beyond 400-700 nm (McCree, 1972). A more precise definition of PAR is called the yield photon flux (YPF) (Barnes et al., 1993). YPF is a weighting of each photon according to the "average leaf" photosynthetic efficiency curve elucidated by McCree (1972). In these experiments PPF was equivalent between blue light treatments, but YPF declined by as much as 10% as blue light fraction increased (Table 4.4). Considering that photosynthetic efficiency directly affects plant dry mass, caution must be used when claiming blue light effects on dry mass accumulation. YPF is a more theoretically exact definition of the trends for total dry mass in wheat and soybean. The graph of YPF distributes points across quantum flux (μmol m^{-2} s^{-1}) more accurately (Figure 4.18) and may explain the response better than blue light fraction does (Figure 4.2, 4.4).

Accurate measurements of YPF can only be made with a spectroradiometer. Under these lamp types, a commercial YPF sensor can have substantial errors (Barnes et al., 1993).

YPF differences do not explain the difference in dry mass between the two 6%

blue treatments in lettuce. Indeed, 6% blue MH has 3% lower YPF than 6% blue HPS. However, the 3% difference in YPF is not enough to account for the 81% difference in total dry mass.

Morphology and carbon partitioning

Although total dry mass is better explained by YPF, the dry mass partitioning of soybean is attributable to the morphological changes caused by altering blue light fraction. The change in stem elongation at low blue came at the expense of the roots and to a lesser extent, the leaves. It is difficult to ascertain whether these shifts in carbon partitioning, although not affecting total biomass yield, would affect seed yield. Where small differences occur early on, large differences in yield could result, especially when dry mass accumulation is affected (Board et al., 1992; Gent, 1995).

Relative versus absolute blue light

Blue light can be described two ways, the absolute amount of blue light or the fraction of blue light relative to the photosynthetically active radiation. It is not clear which definition best describes physiological responses. Hoenecke et al. (1992) found that lettuce hypocotyl extension responded to absolute rather than relative blue light. Similarly, Wheeler et al. (1991) suggested that soybean stem elongation was responsive to absolute rather than relative blue light. We conducted studies using two PPF levels so we could quantify relative versus absolute blue light effects (Table 4.4). If absolute blue light determines plant response, the blue light fraction response curves at the two PPF levels should overlap when graphed on an absolute blue light axis.

Indeed, our data for lettuce agree with Hoenecke et al. (1992), where the data better fit on an absolute blue light axis (Figure 4.19a). Soybean stem length, on the other hand, is better fit with a relative blue light axis (Figure 4.19b,c). This discrepancy in the soybean data may lie with the fact that Wheeler et al. (1991) only tested 6% to 26% blue light where stem length is less responsive to blue light.

Because means for wheat response to blue light were not significantly different, it is a moot point to make comparisons between relative and absolute. Because of the complicating factors in other lettuce parameters, we were unable to evaluate the effects of relative versus absolute blue light. For soybean, using stem dry mass and leaf area as typical examples, there is a response to blue light fraction, but the responses are different at the two PPFs (Figure 4.4b, 4.10a). However, graphing the data as absolute blue light does not cause the two PPF levels to overlap (Figure 4.20a,c). The responses do overlap when graphed with blue light fraction and as a percent of maximum (Figure 4.20b,d). This also holds true for leaf, root, and total dry mass and SLA. Although the percent of maximum response can be predicted by blue light fraction, the absolute magnitude of the response is determined by PPF.

Other wavelengths affecting lettuce growth

As mentioned previously, we included two 6% blue treatments, one with HPS, one with filtered MH. For soybean and wheat, the means of these treatments were statistically similar, but for lettuce the two 6% blue treatments produced significantly different chlorophyll concentrations, dry masses, leaf areas, and SLAs (Table 4.3). This

phenomenon was apparent in each trial in this experiment and in trials before this experiment (Dougher and Bugbee, 1998). It is extremely unlikely that these differences were caused by differences between compartments because: i) treatments were randomized each time and ii) atmospheric differences between compartments were minimized by the use of a common air conditioning system. Apparently in lettuce, some wavelength(s) acts in conjunction with blue to affect plant growth. Using data for chlorophyll concentration at a PPF of 200 μmol m^{-2} s^{-1} as an example (Figure 4.21a) (results for the other parameters and PPF of 500 μmol m^{-2} s^{-1} are similar), I will discuss the other wavelengths we have considered.

Absolute blue light. Absolute blue light could be more important than blue light fraction, but the 6% blue treatments of the two lamp types have the same absolute blue light at each PPF: 12 μmol m^{-2} s^{-1} blue at 200 μmol m^{-2} s^{-1} or 30 μmol m^{-2} s^{-1} blue at 500 μmol m^{-2} s^{-1} (Table 4.4). Graphically, data points for 6% blue between PPF levels shift apart, but the two data points within PPF levels are still not separated (Figure 4.21b).

Phototropic blue. Considering that our cutoff points for "blue light" may not be accurate, we tried using the blue response curve for phototropism, developed by Baskin and Iino (1987). Weighting our data with this curve yielded blue levels that were also similar as our 6% blue treatments (Table 4.4). So the curves look very similar to the absolute blue light curves (Figure 4.21c).

Absolute UV. Although MH emits much more UV (300-400nm) than HPS lamps, our system had a water and tempered glass barrier that greatly reduced the UV from either source. However, not all UV was filtered out and the MH treatments still had 3 to 4 times

more UV (Table 4.4). While there is a UV difference between the two 6% blue treatments, it only serves to further separate the data (Figure 4.21d).

UV as a percent of blue. We considered UV-A (320-400nm) as part of the blue range, but MH attains more of its "blue light" from the UV range. Indeed at 6% blue UV as a percent of blue is different for HPS and MH (Table 4.4). However, graphing the data this way also separates the data in the wrong direction (Figure 4.21e).

Phytochrome photoequilibrium. The PPE for all treatments ranged from 0.82 to 0.86 (Table 4.4). This range is too small to elicit a phytochrome effect and also tends to separate the data (Figure 4.21f).

Blue to red and blue to far red ratios. Other researchers have suggested the blue response could be altered by the blue and red (B:R) or blue and far red (B:FR) interaction (Goins et al., 1997). Once again, there is a difference between 6% blue HPS and MH values for B:R and B:FR (Table 4.4), but these ratios also tend to separate the data (Figure 4.21g,h).

Red to far-red ratio. Although we should be able to more accurately calculate PPE utilizing the spectroradiometer, perhaps the response is to R:FR but not a phytochrome response. There is a difference in R:FR of the two 6% blue treatments (Table 4.4), but again graphing on a R:FR axis only separates the data (Figure 4.21i).

Yellow-green wavelengths. At a loss for a known physiological response to explain the difference at 6% blue, we graphed the output of the treatments to find which wavelengths could shift the data to fit their significance (Figure 4.22). We were looking for a shift in lamp output that would make the 6% MH roughly equivalent to the 2% HPS,

because their means are not statistically different. At 570-610 nm we see an overlap of the middle range blue treatments (2, 6, 12%). Using this range, we not only achieved 6% MH equivalent to 2% HPS, but also 12% MH shifts to about 6% HPS (Table 4.4). While these wavelengths fit the response (Figure 4.21j), there is no physiological explanation for it. Green light from 545 to 555 nm has been shown to repress growth, but repression was not seen beyond this range (Klein, 1992).

Thermal radiation. Although the thermal radiation emitted by unfiltered HPS and MH lamps is considerable and different for the two lamp types, the thermal radiation in these experiments was filtered out by water barriers.

Predicting cell expansion using relative water content and dry mass

The change in leaf area and stem length with blue light fraction raises the question of which cellular process is being altered by blue light to achieve these changes: cell division, cell expansion, or both. Without directly measuring the cells, we hypothesized that an increase in RWC without a change in dry mass predicts that cell expansion is primarily responsible for the increase in area or length. For lettuce, leaf area increased from 0% to 6% blue, leaf RWC decreased, but the leaf dry mass increased. This suggests that the increase in leaf area is primarily caused by an increase in cell division. For soybean, leaf area decreased with increasing blue light fraction from 6% to 26% blue and leaf RWC increased, while leaf dry mass was constant. This would suggest that the decrease in soybean leaf area was also caused by a decrease in cell division. For soybean stems, length decreased with increasing blue light fraction, stem RWC increased, but stem

dry mass decreased. This suggests that cell division may be primarily responsible for the change in stem length with blue light fraction.

Conclusions

Blue light effects were species dependent. When considering dry mass and leaf area, soybean and wheat do not benefit from added blue light. However, in an Advanced Life Support system where plant height is important, well-known effects on stem elongation (Britz and Sager, 1990; Dougher and Bugbee, 1997; Wheeler et al., 1991) do not have the same optimum blue light fraction. Lettuce dry mass and leaf area, on the other hand, benefitted from as little as 2% blue, which is also beneficial for suppressing excessive stem elongation (Hoenecke et al., 1992). For some plant growth parameters, blue light responses were small, but the crops were harvested early in the life cycle and effects may not have fully manifested. This research indicates that lamps high in blue photons, such as MH, are not only energetically wasteful, but do not benefit and, in some cases reduce, plant growth.

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Table 4.1. Blue light fractions used in our experiments. Two lamp types were used for the blue light treatments, high pressure sodium (HPS, Sylvania Lumalux) and metal halide (MH, Sylvania Metalarc).

Lamp Type	Blue Light Fraction (%)		
MH	26*	12	6
HPS	0.1	1.7	6*

*blue fraction from the lamp filtered only with tempered glass and water

Table 4.2. Blue light fractions (%) calculated for the six blue light treatments with and without UVA (320-400 nm) and with the HPS 496-500 nm spike. The 320-496 nm range was used in this study. Data are based on quantum flux (moles), not energy flux (watts).

		Lamp Type						
Blue Range		HPS High filter	HPS Low filter	Unfiltered HPS	MH High filter	MH Low filter	Unfiltered MH	total range
- UVA	400-496	0.49	3.41	5.5	5.3	15.5	22.7	400-700
+ UVA	**320-496**	**0.49**	**3.56**	**5.7**	**6.0**	**18.7**	**26.3**	**320-700**
	320-500	0.93	4.52	7.1	6.5	19.4	27.2	320-700

Table 4.3. Effect of lamp type at the same blue light fraction (6%) on dry weight, carbon partitioning, leaf area, specific leaf area, chlorophyll, stem length, and relative water content. Means were tested using an LSD test at $\alpha = 0.05$.

	Wheat		Soybean		Lettuce		
Parameter	HPS[◇]	MH[†]	HPS[◇]	MH[†]	HPS[◇]	MH[†]	HPS/MH
leaf dry weight (g)	0.28	0.23	1.34	1.29	0.52	0.29*	1.79
stem dry weight (g)	0.13	0.10	0.48	0.47	0.028	0.015*	1.87
root dry weight (g)	0.18	0.16	0.49	0.47	0.088	0.050*	1.76
total dry weight (g)	0.59	0.50	2.32	2.22	00.63	0.35*	1.80
leaf as % of total	47.3	46.9	58.0	57.8	81.6	81.2ns	1.00
stem as % of total	21.6	20.5	20.8	20.9	4.6	4.2ns	1.10
root as % of total	31.4	32.6	21.2	21.2	13.8	14.6ns	0.95
leaf area (cm^2)	67.5	59.0	497	492	258	181*	1.43
specific leaf area ($m^2\ kg^{-1}$)	27.1	27.2	37.7	39.2	54.6	66.7*	0.82
chlorophyll (SPAD)	52.3	52.3	36.3	34.2	7.9	4.2*	1.88
stem length (mm)	74.4	72.5	159	154	18.3	15.6ns	1.17
leaf RWC (%)	84.5	84.2	84.7	85.0	93.6	94.0ns	1.00
stem RWC (%)	89.3	88.9	90.4	90.1	92.1	93.2ns	0.99
root RWC (%)	92.9	92.8	94.1	94.2	95.3	95.5ns	1.00

[◇] unfiltered High Pressure Sodium lamp (6% blue), [†] Metal Halide lamp filtered with canary yellow acetate film (6% blue)
* significant at $\alpha = 0.05$, ns = not significant

Table 4.4 Ratios of radiation for the blue light fractions in these studies.

PPF*	Blue Light Fraction (% of total)	Absolute Blue Light* (320-496 nm)	Yield Photon Flux* (300-800 nm)	Photo-tropic Blue* (300-520 nm)	Absolute UV* (320-400 nm)	UV (% of blue)	PPE (P_{fr}/P_{total})	R:FR (600-700nm 700-800nm)	B:R (320-496 nm 600-700 nm)	B:FR (320-496 nm 700-800 nm)	570-610 nm* (% of total)
200	0.1	0.2	194	0.1	0.0005	0.25	0.86	2.80	0.003	0.012	32
	1.5	3	192	1.8	0.05	1.7	0.85	2.71	0.033	0.155	26
	6	12	190	6.8	0.22	1.8	0.86	2.86	0.133	0.661	25
	6	12	184	6.3	0.72	6.0	0.84	4.39	0.220	1.306	27
	12	24	182	13	1.99	8.3	0.83	4.13	0.453	2.593	25
	26	52	177	29	3.88	7.5	0.82	5.11	1.209	7.818	19
500	0.1	0.5	484	0.3	0.0005	0.1	0.86	2.80	0.003	0.012	32
	1.5	7.5	480	4.1	0.05	0.7	0.85	2.71	0.033	0.155	26
	6	30	474	17	0.22	0.7	0.85	2.86	0.133	0.661	25
	6	30	458	16	0.71	2.4	0.85	4.39	0.220	1.306	27
	12	60	454	31	1.97	3.3	0.84	4.13	0.453	2.593	25
	26	130	441	71	3.61	2.8	0.82	5.11	1.209	7.818	19

* in (μmol m^{-2} s^{-1}), PPF = Photosynthetic Photon Flux, PPE = Phytochrome Photoequilibrium

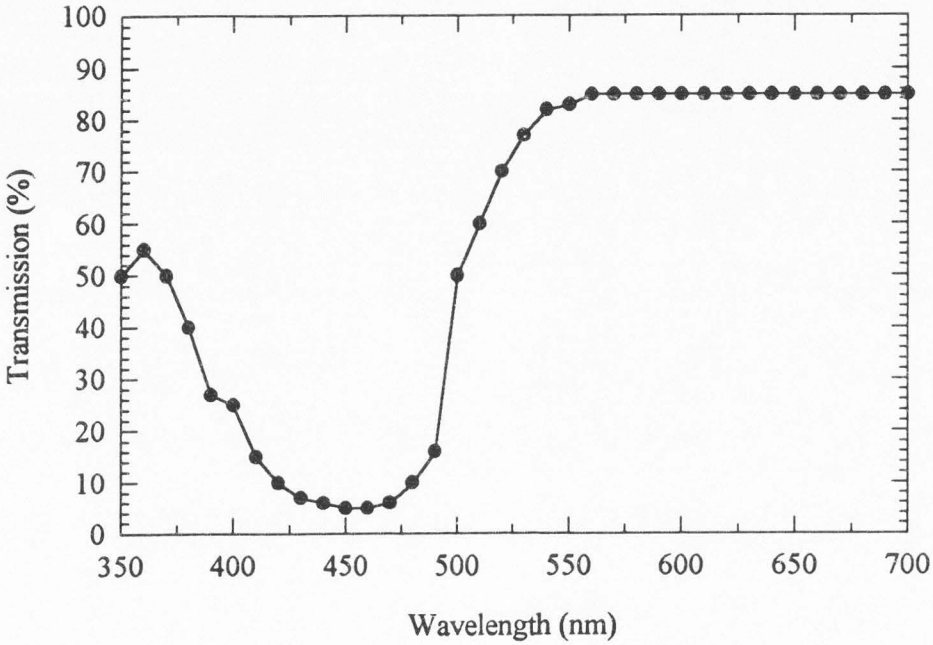

Figure 4.1. Transmission curve for canary yellow cellulose acetate film (#312, Roscolux, Oasis Stage Werks, UT) obtained from Roscolux.

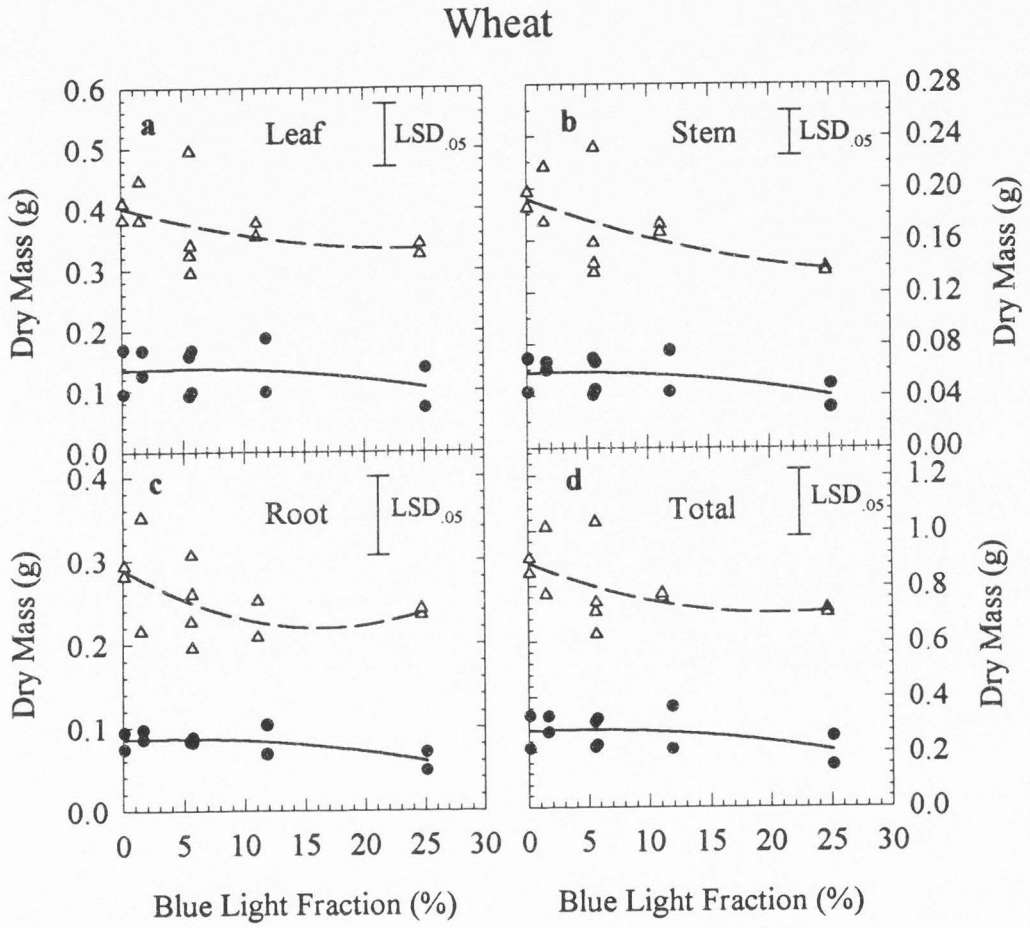

Figure 4.2. Effect of blue light fraction on wheat (a) leaf, (b) stem, (c) root, and (d) total dry mass. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

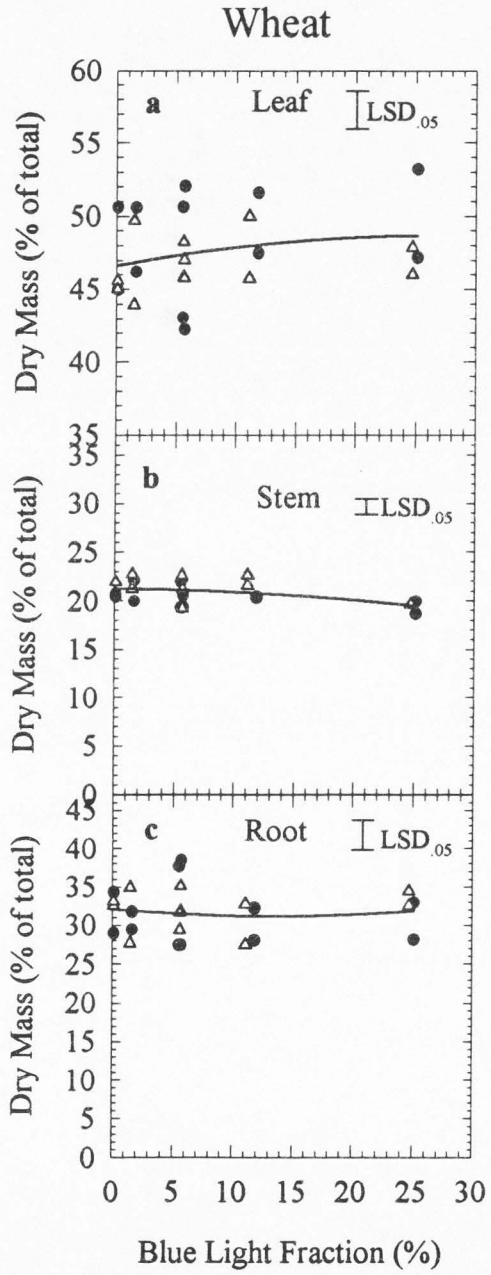

Figure 4.3. Effect of blue light fraction on wheat (a) leaf, (b) stem, and (c) root dry mass as a percent of total dry mass. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

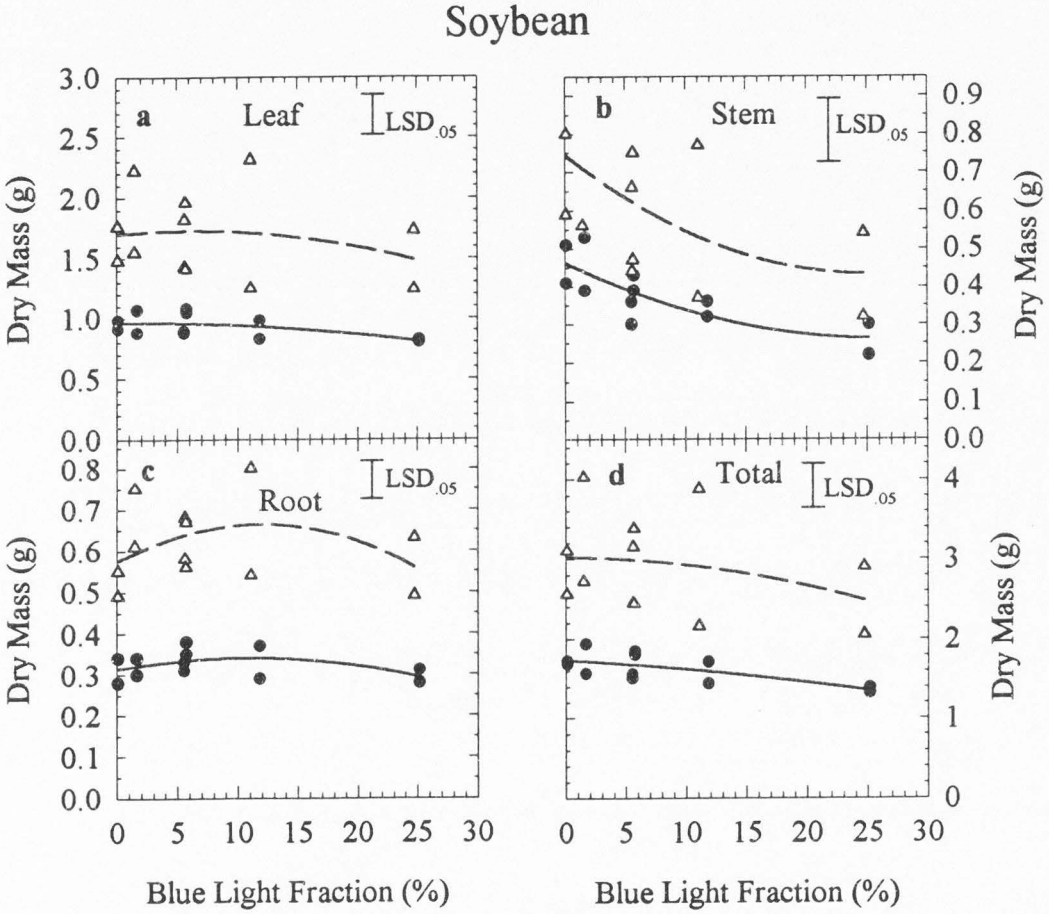

Figure 4.4. Effect of blue light fraction on soybean (a) leaf, (b) stem, (c) root, and (d) total dry mass. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

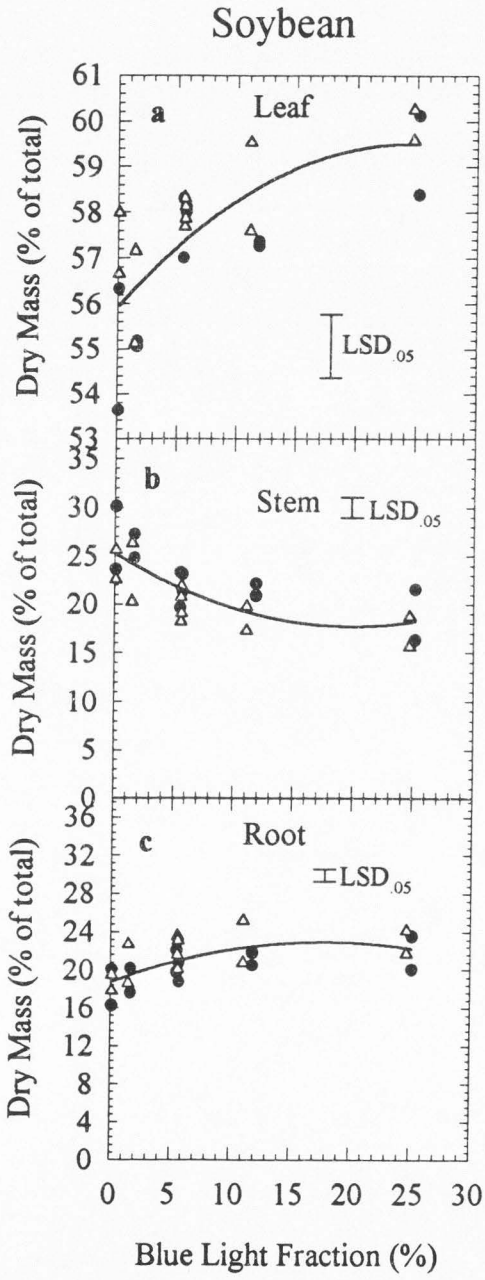

Figure 4.5. Effect of blue light fraction on soybean (a) leaf, (b) stem, and (c) root dry mass as a percent of total dry mass. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

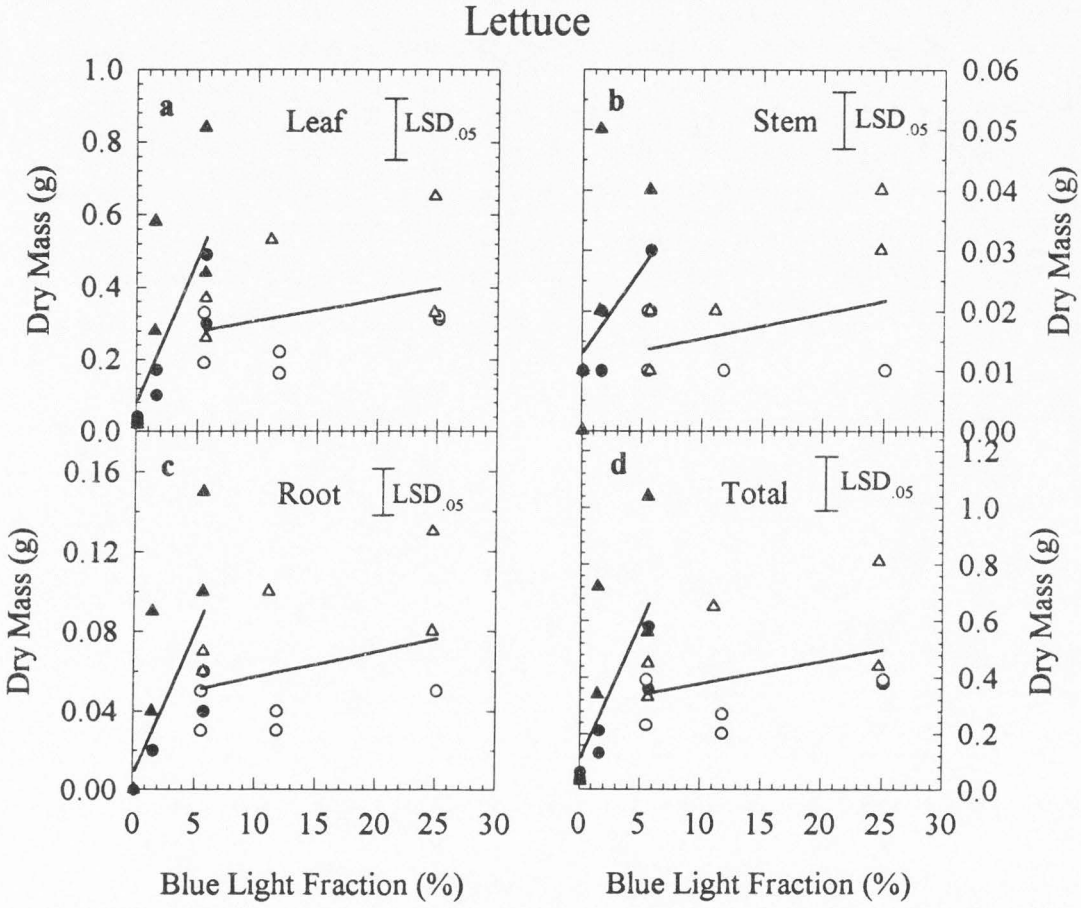

Figure 4.6. Effect of blue light fraction on lettuce (a) leaf, (b) stem, (c) root, and (d) total dry mass. Closed symbols represent blue light fractions created under HPS and open symbols represent blue light fractions created under MH. Triangles represent PPF of 500 μmol m^{-2} s^{-1} and circles represent PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

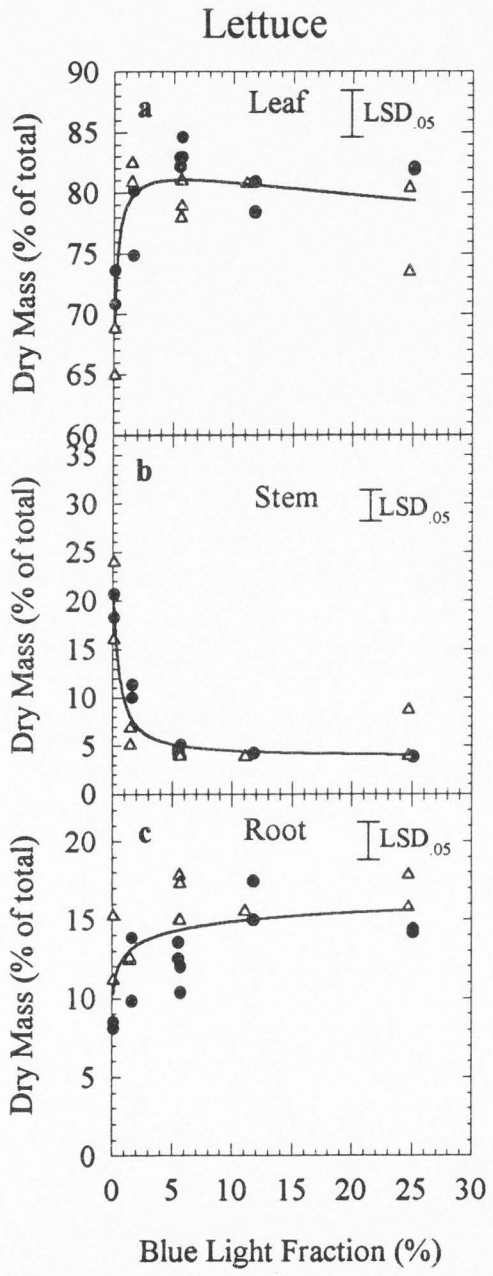

Figure 4.7. Effect of blue light fraction on lettuce (a) leaf, (b) stem, and (c) root dry mass as a percent of total dry mass. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

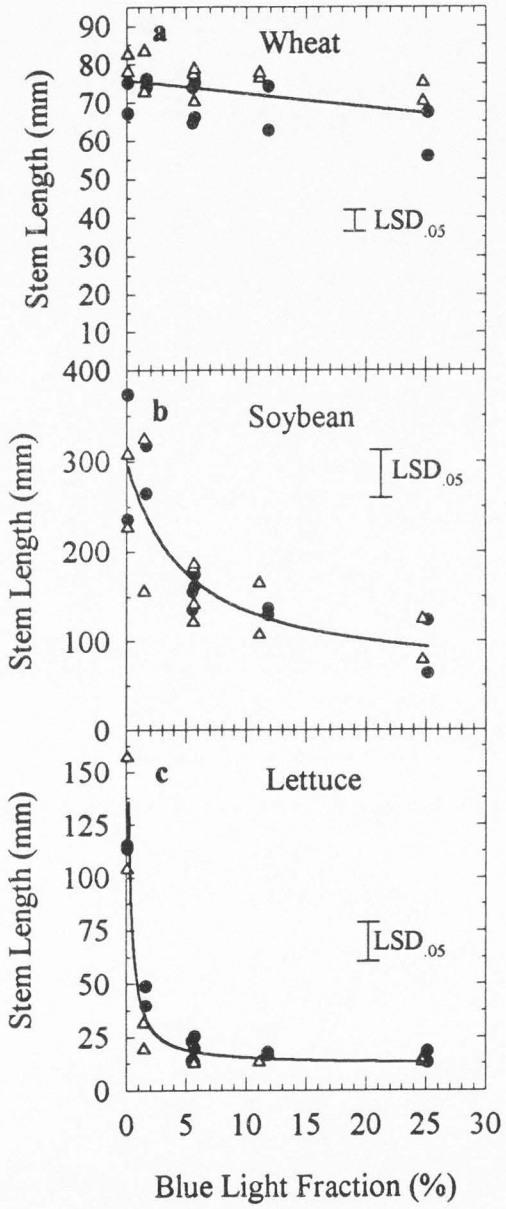

Figure 4.8. Effect of blue light fraction on (a) wheat, (b) soybean, and (c) lettuce stem length. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

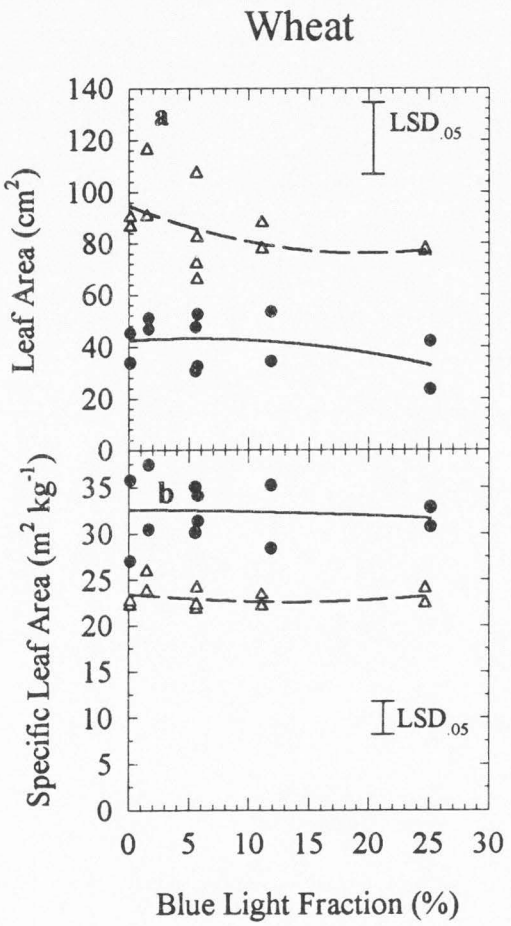

Figure 4.9. Effect of blue light fraction on wheat (a) leaf area and (b) specific leaf area. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

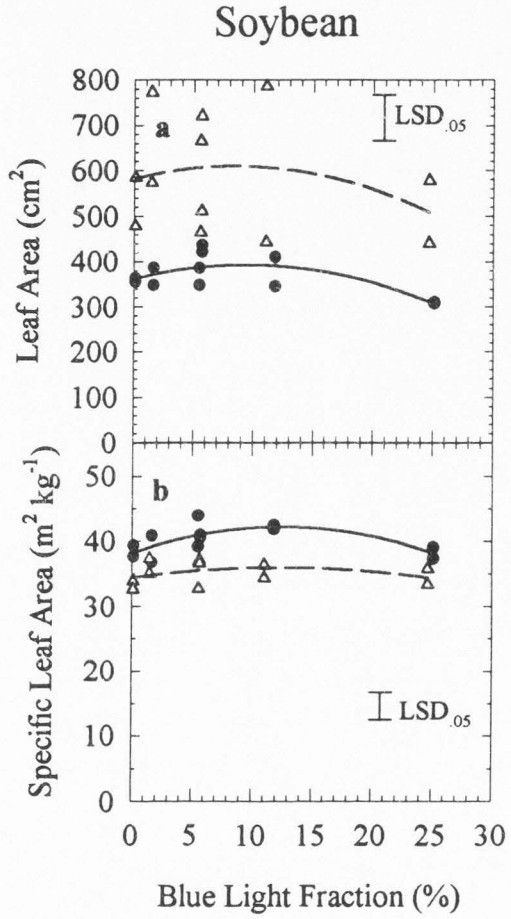

Figure 4.10. Effect of blue light fraction on soybean (a) leaf area and (b) specific leaf area. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

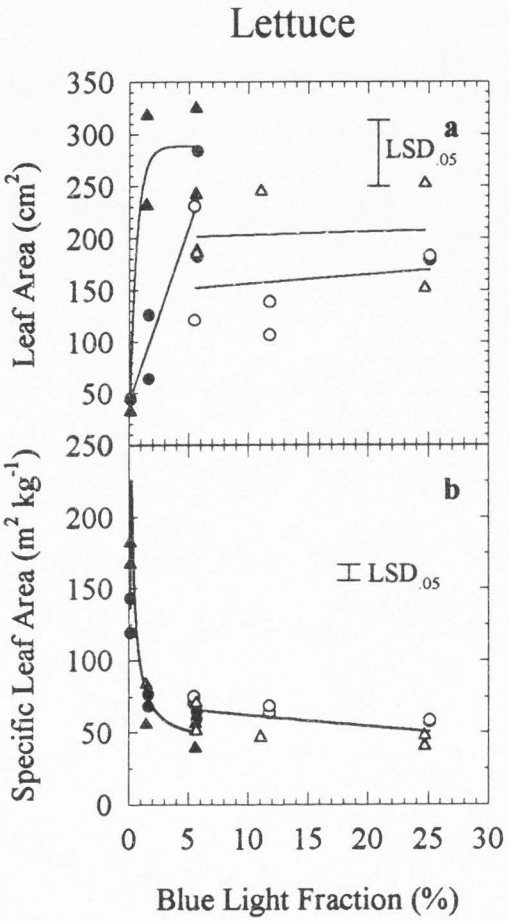

Figure 4.11. Effect of blue light fraction on lettuce (a) leaf area and (b) specific leaf area. Closed symbols represent blue light fractions created under HPS and open symbols represent blue light fractions created under MH. Triangles represent PPF of 500 μmol m^{-2} s^{-1} and circles represent PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions (within a PPF for figure (a)).

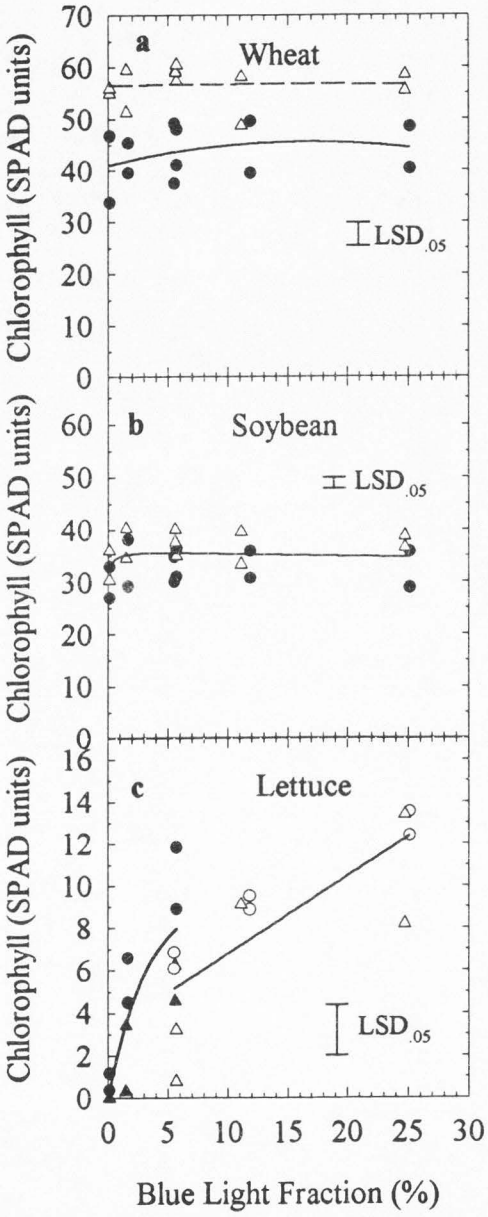

Figure 4.12. Effect of blue light fraction on (a) wheat, (b) soybean, and (c) lettuce chlorophyll concentration. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions (within a PPF for wheat). For wheat and soybeans: Δ represents PPF of 500 μmol m^{-2} s^{-1} and $\bullet$ represents PPF of 200 μmol m^{-2} s^{-1}. For lettuce: Closed symbols represent blue light fractions created under HPS and open symbols represent blue light fractions created under MH. Triangles represent PPF of 500 μmol m^{-2} s^{-1} and circles represent PPF of 200 μmol m^{-2} s^{-1}.

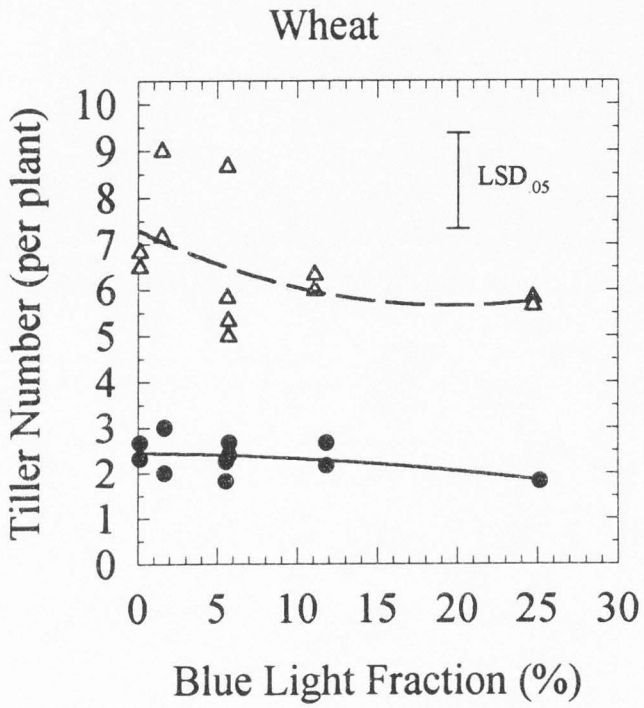

Figure 4.13. Effect of blue light fraction on wheat tiller number. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

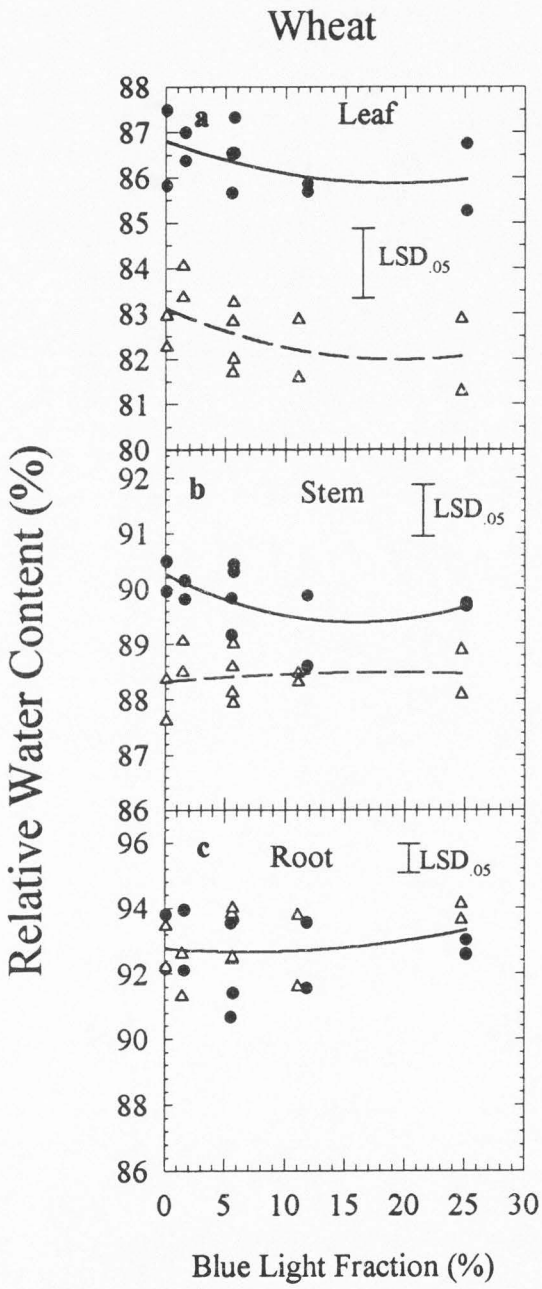

Figure 4.14. Effect of blue light fraction on wheat (a) leaf, (b) stem, and (c) root relative water content. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

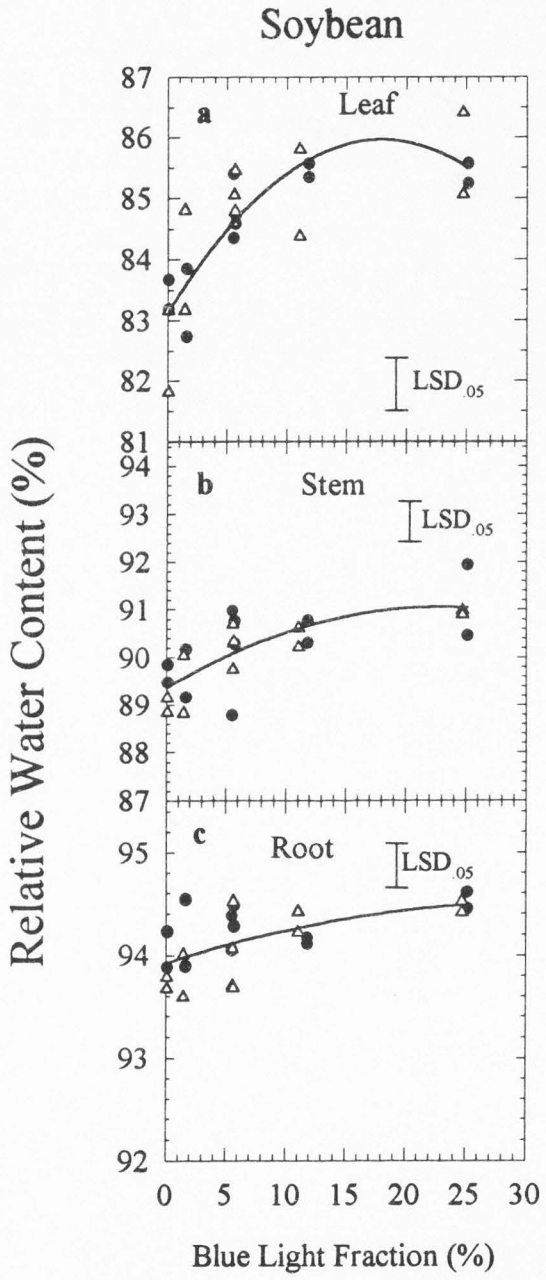

Figure 4.15. Effect of blue light fraction on soybean (a) leaf, (b) stem, and (c) root relative water content. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

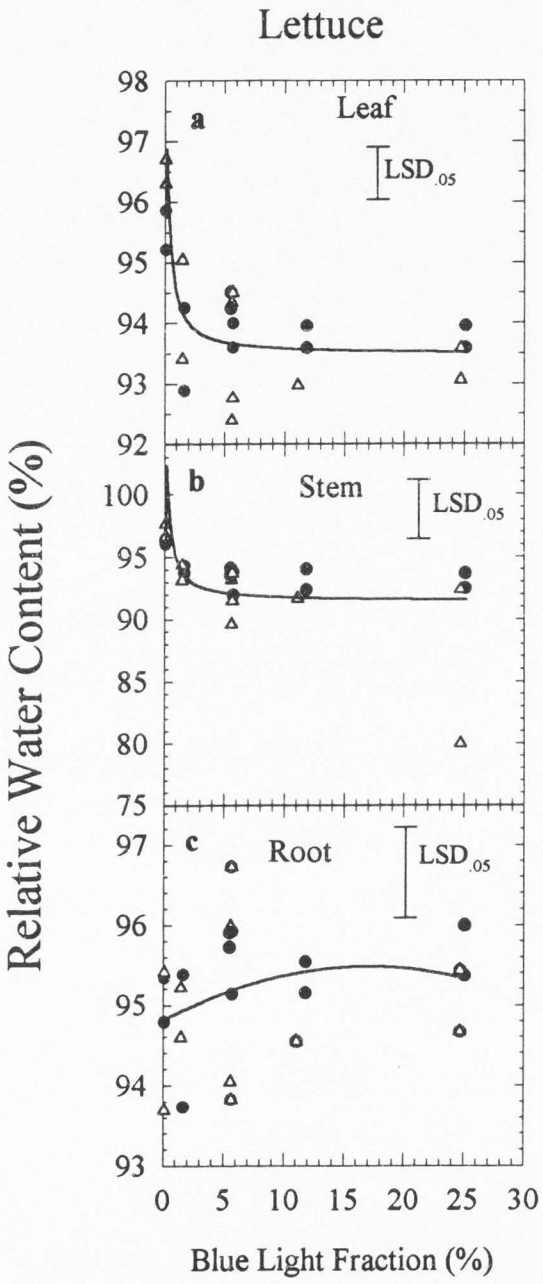

Figure 4.16. Effect of blue light fraction on lettuce (a) leaf, (b) stem, and (c) root relative water content. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions.

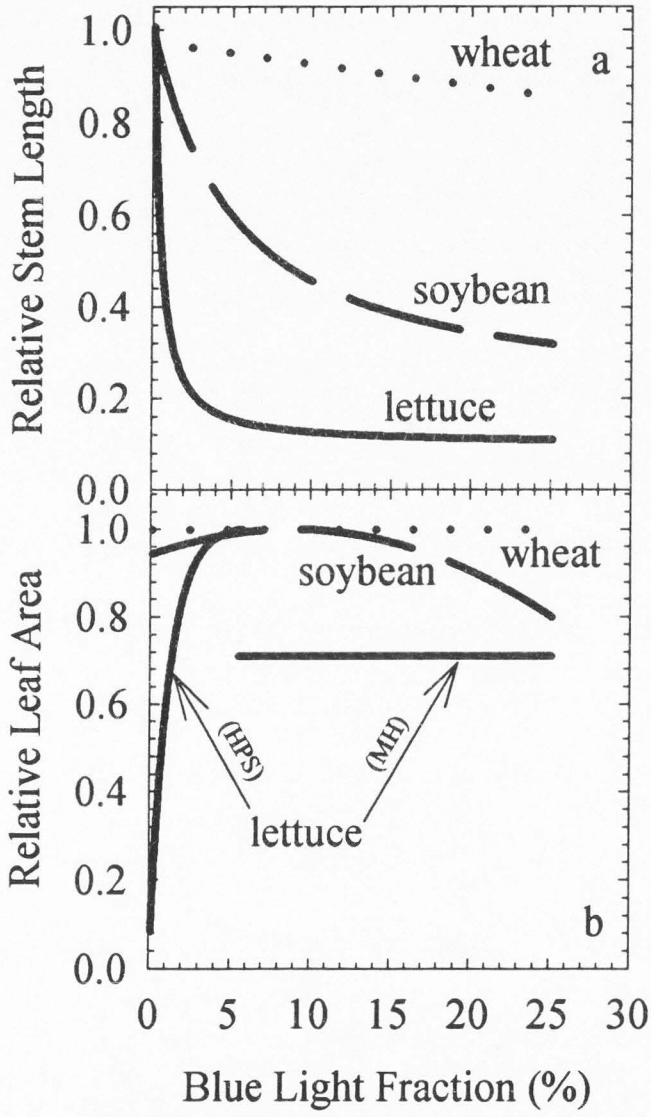

Figure 4.17. Effect of blue light fraction on the relative (a) stem length and (b) leaf area of wheat, soybean, and lettuce. Lines are regressions of means.

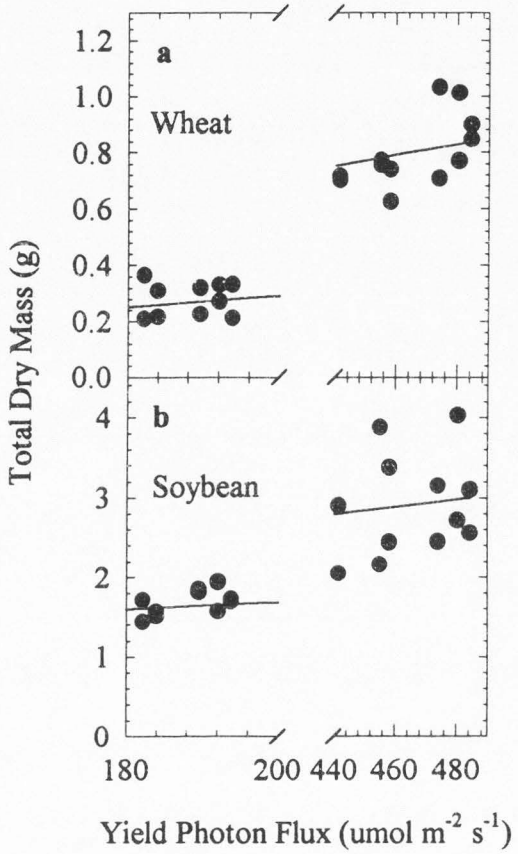

Figure 4.18. Effect of yield photon flux on (a) wheat and (b) soybean total dry mass. Lines are a linear regressions of means.

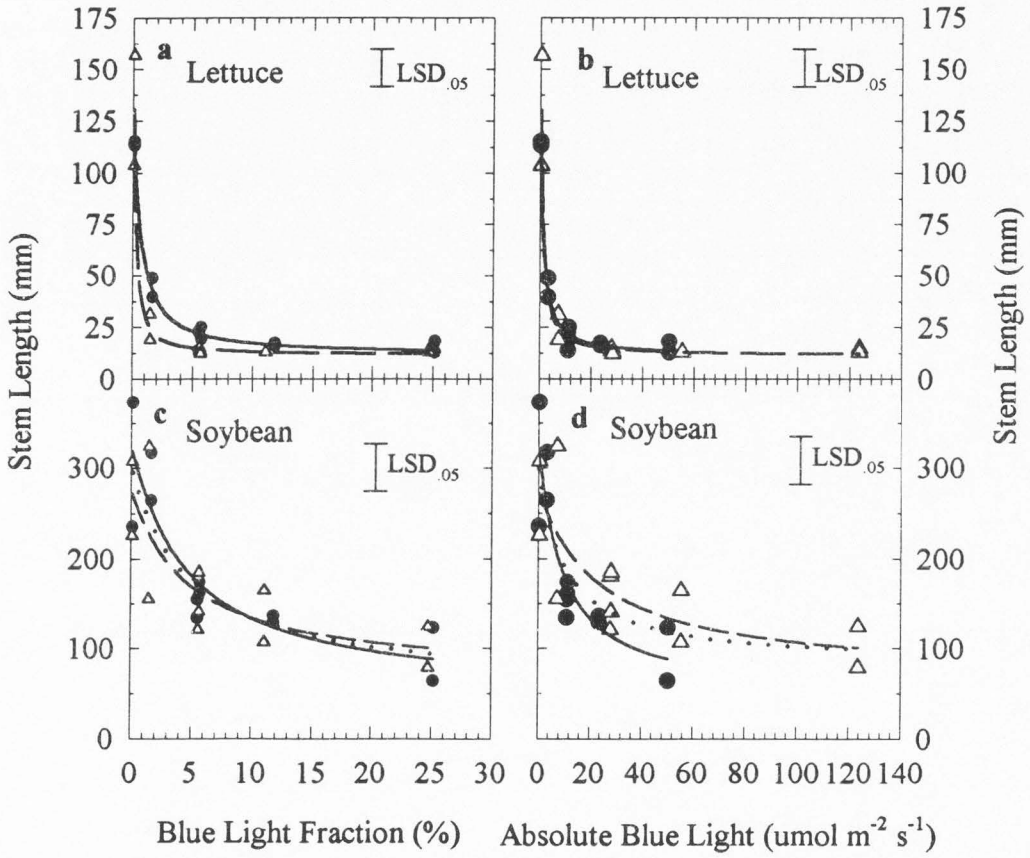

Figure 4.19. A comparison of blue light fraction and absolute blue light to describe (a,b) lettuce and (c,d) soybean stem length response to blue light. Δ and ---- represent PPF of 500 μmol m^{-2} s^{-1}, ● and — represent PPF of 200 μmol m^{-2} s^{-1}, and ····· represents regression of the combined data. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

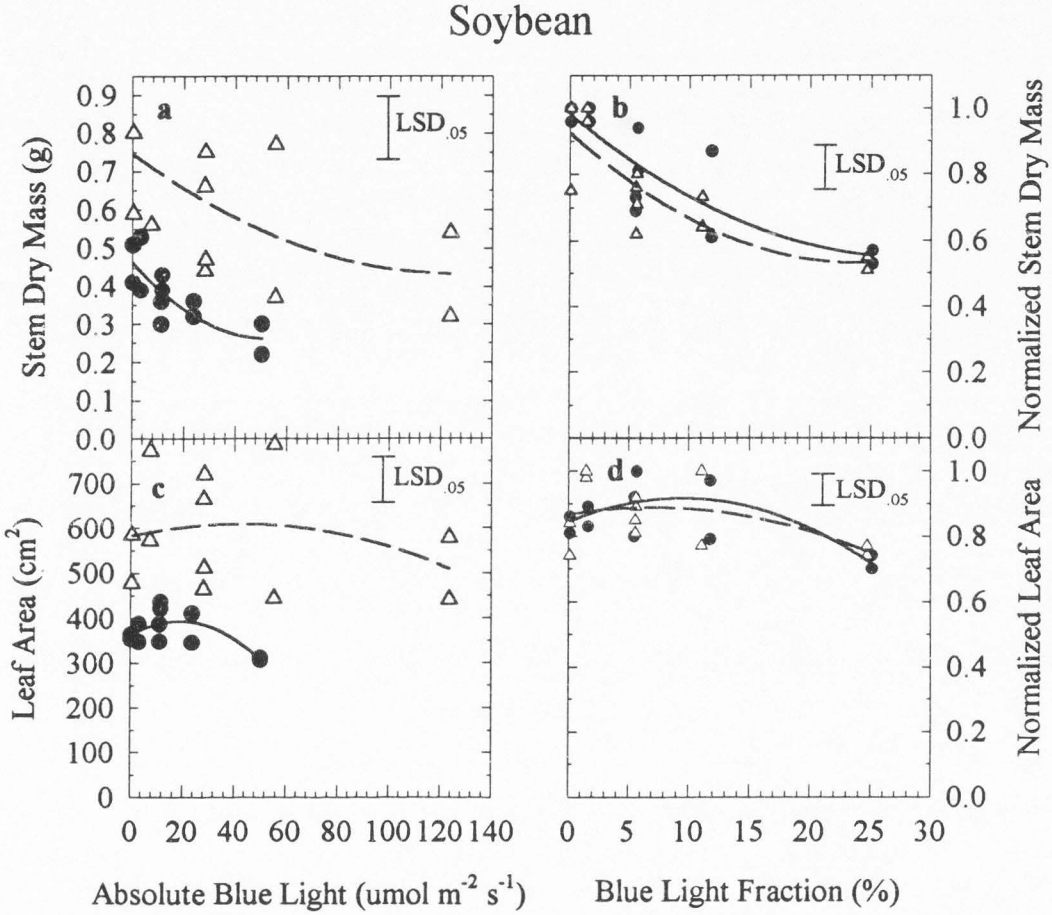

Figure 4.20. A comparison of absolute blue light and blue light fraction to describe soybean (a) stem dry mass, (b) relative stem dry mass, (c) leaf area, and (d) relative leaf area. Δ represents PPF of 500 μmol m^{-2} s^{-1} and ● represents PPF of 200 μmol m^{-2} s^{-1}. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Error bars represent the least significant difference at the α=0.05 level between blue light fractions within a PPF.

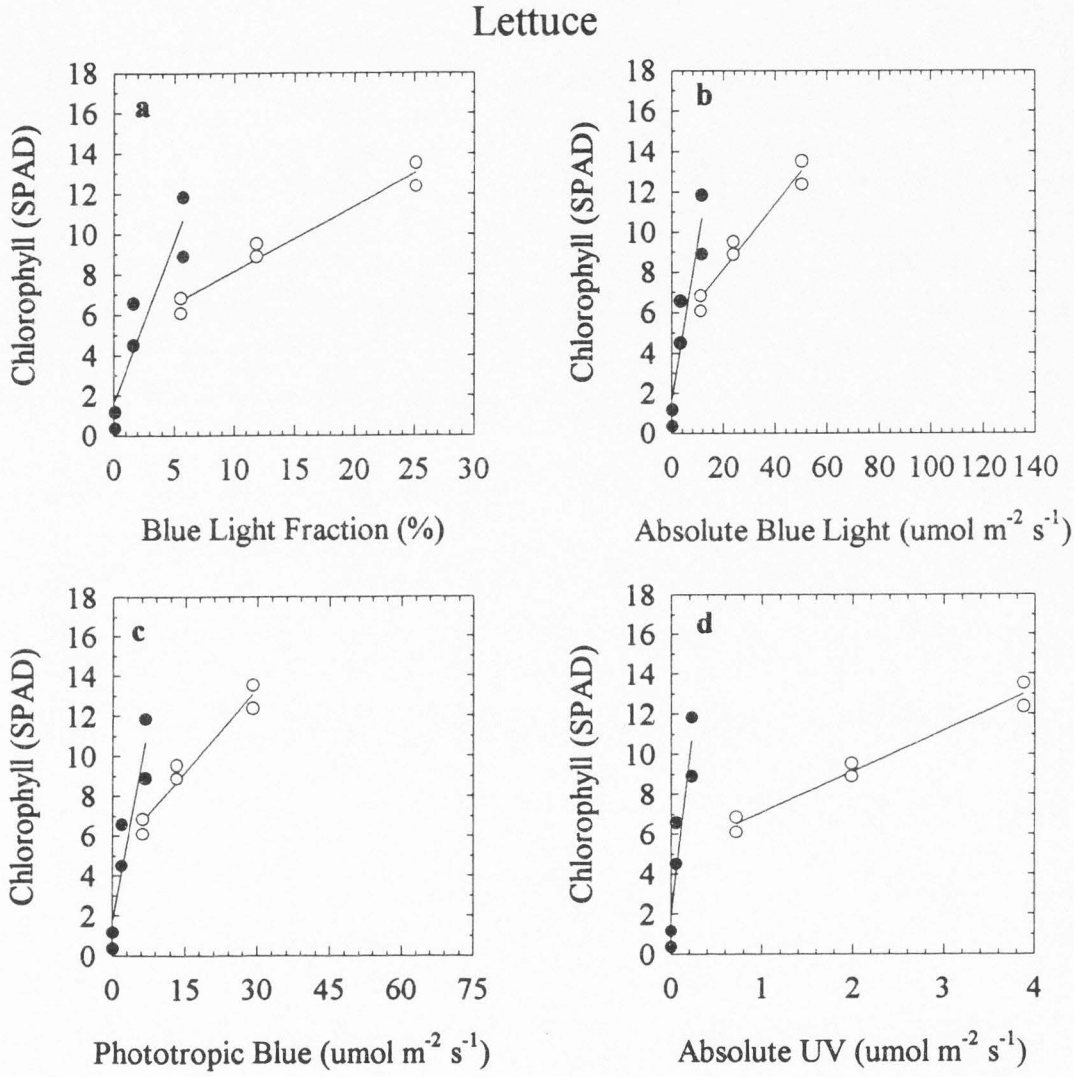

Figure 4.21. A comparison of (a) blue light fraction, (b) absolute blue light, (c) phototropic blue, (d) absolute UV, (e) UV as a percent of blue, (f) phytochrome photoequilibrium, (g) blue to red ratio, (h) blue to far-red ratio, (i) red to far-red ratio, and (j) yellow light as a percent of total, to describe lettuce chlorophyll response to varied light environment. Data are only presented for PPF of 200 μmol m^{-2} s^{-1}. ● represents treatments created under HPS lamps and ○ represents treatments created under MH lamps. Each point is an average of six plants (pseudo replicates). Replicate data points at each blue light fraction represent replicate trials in time. Lines are linear regressions of the means for each lamp type.

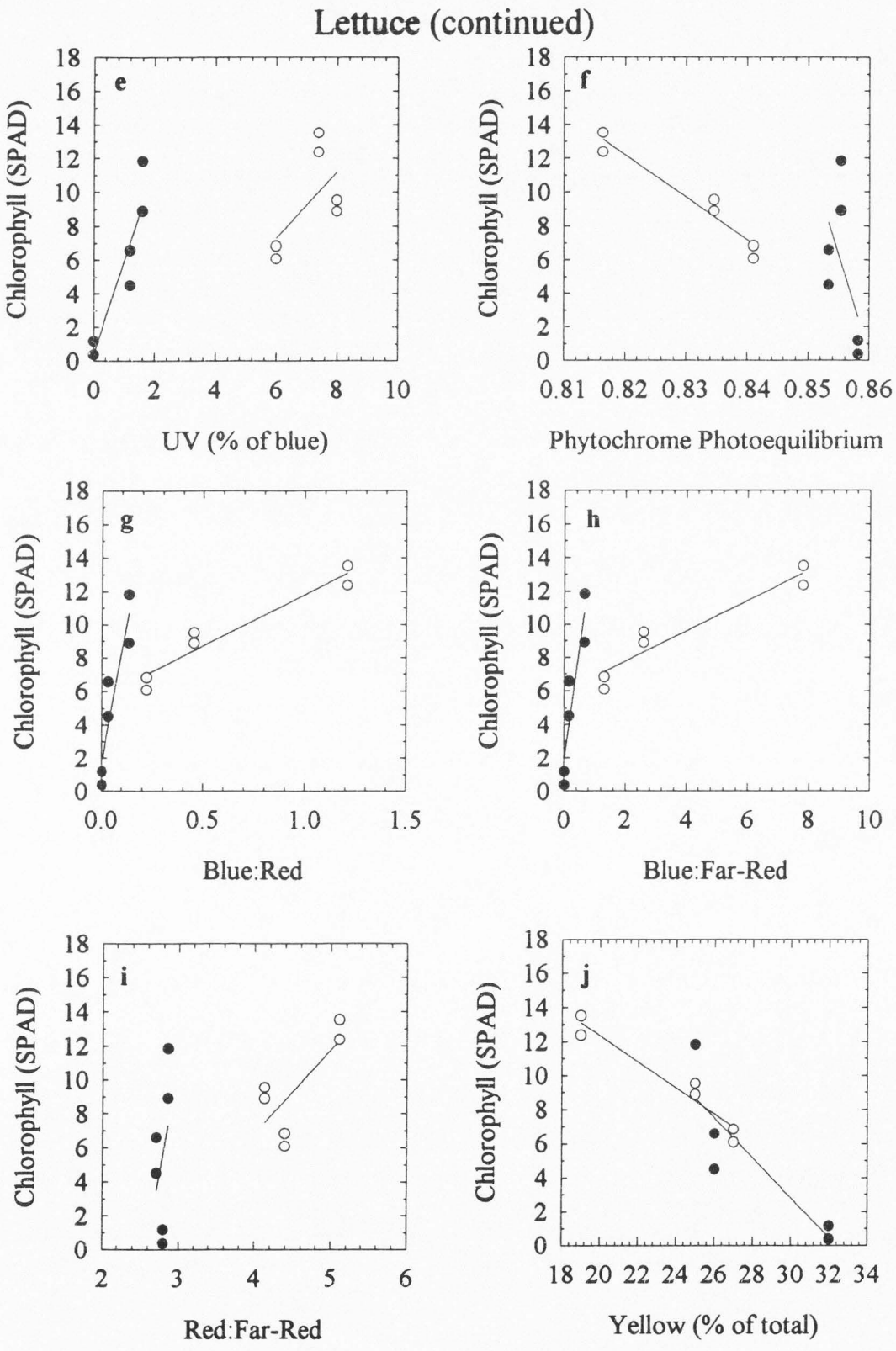

Figure 4.21. Continued

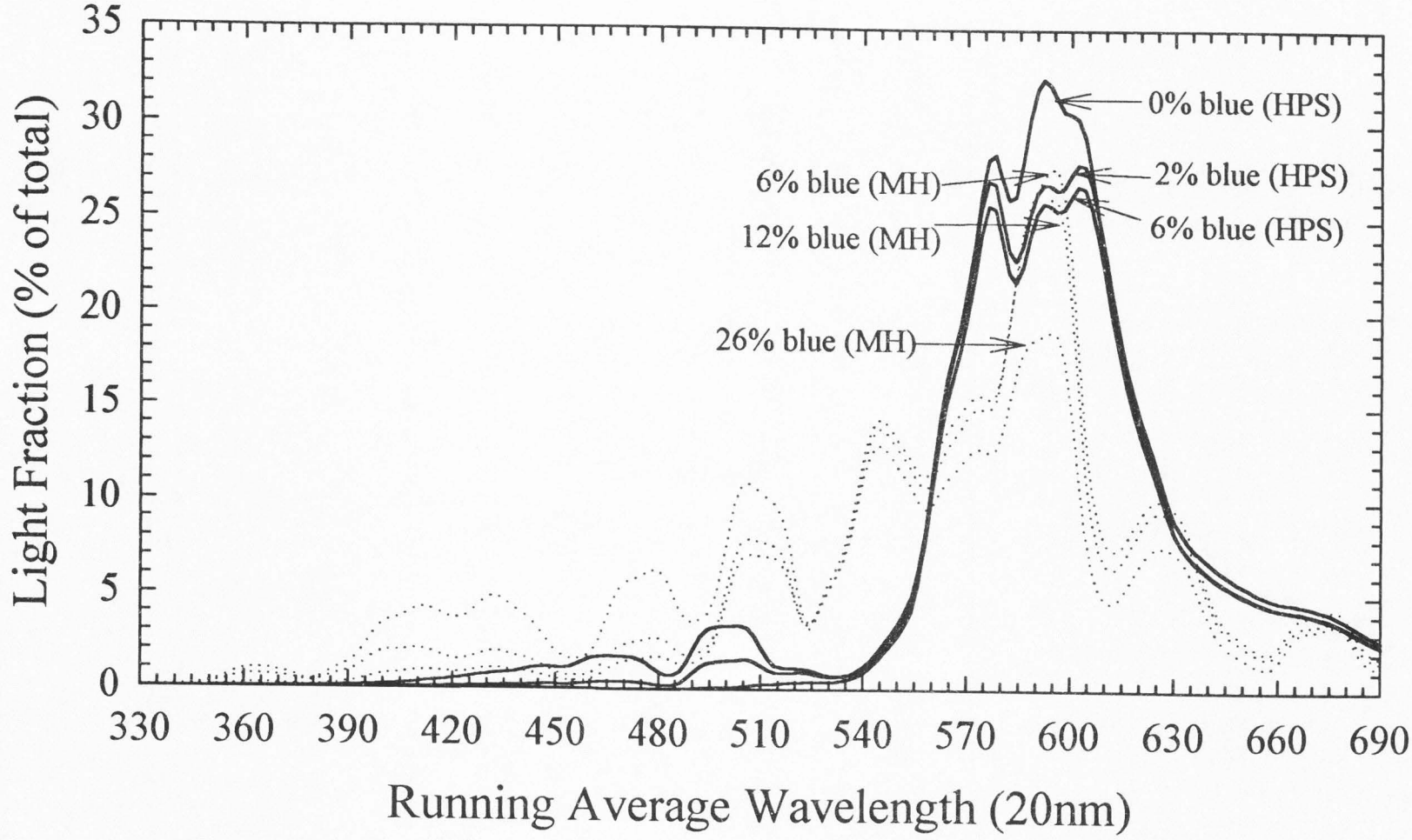

Figure 4.22 - The light fraction as a percent of total for 20 nm running average increments from 300 to 700 nm for the blue light treatments in our experiment. — represents treatments created under HPS lamps and ····· represents treatments created under MH lamps.

CHAPTER 5

BLUE LIGHT EFFECTS ON THE HISTOLOGY OF LEAVES AND STEMS

Abstract

Cell division, cell expansion, or both processes may be affected by blue light. Most studies on changes in cell expansion or division with altered light quality are short-term, cell-level experiments. Long-term, whole-plant effects are not well characterized. We measured cell size and number for stems of soybean, and leaves of soybean and lettuce, at two blue light fractions. Stem cell expansion is known to be rapidly inhibited by blue light when switched from darkness, but we found that decreased soybean stem length over the long term was caused by an inhibition of cell division. Leaf area, on the other hand, was altered by a change in cell expansion for soybean and by a change in both cell expansion and division for lettuce.

Introduction

Blue light effects on leaf expansion and stem elongation at the cellular level are still controversial as to whether cell division or expansion is primarily altered. Blue light-mediated inhibition of stem elongation is often assumed to be caused by changes in cell expansion. However, three key studies measured only hypocotyl elongation and cell wall properties and did not measure cell size (Shinkle and Jones, 1988; Cosgrove, 1981; Kigel and Cosgrove, 1991). Blue light does appear to regulate cell division in *Chlamydomonas*

reinhardtii (Munzner and Voigt, 1992; Voigt and Munzner, 1994). In *Phaseolus vulgaris* leaves, blue light stimulated cell expansion (Van Volkenburgh et al., 1990). However, these studies were short-term hypocotyl or leaf disc experiments. In a longer-term study, Rahim and Fordham (1991) found shade versus sun conditions altered garlic leaf area primarily by changes in cell expansion.

Leaf expansion, however, characteristically has a larger change in cell number than cell size (Dale and Milthorpe, 1983). One would then predict that in response to long-term light exposure, changes in leaf size could be more readily mediated by altered cell division. Based on the current view that the epidermis limits stem and leaf expansion (Dale, 1988; Kutschera, 1992), we measured epidermal cell size and number to account for differences in stem length of soybean and leaf area of soybean and lettuce at two blue light fractions.

Material and Methods

Soybeans and lettuce were cultured in the same system described in Chapter 4. Plants were grown at a photosynthetic photon flux of 500 μmol m^{-2} s^{-1}, 530 μmol CO_2 mol^{-1}, 25/22°C day/night temperature, and 73% relative humidity. Plants grown for stem sections were treated with a 16-h photoperiod and plants grown for leaf impressions were treated with a 12-h photoperiod. While these conditions varied from those described in Chapter 4, the blue light response was the same, namely: soybean leaf area decreased between 6% and 26% blue, lettuce leaf area increased between 0% and 6% blue, and soybean stem length decreased between 0% and 26% blue. Blue light treatments were as follows: soybean stem sections 0% (HPS) and 26% (MH), soybean leaf impressions 6%

(HPS) and 26% (MH), and lettuce leaf impressions 0% (HPS) and 6% (HPS). Six plants were sampled under each blue light fraction and blue light fractions were repeated in another location. Leaf and internode samples were taken when expansion was complete. Change in expansion was tested by measuring internode length and leaf length and width every day until three consecutive days of measurements were the same.

Microscopic examination and measurement. Both stem sections and leaf impressions were viewed under a microscope (Leitz, Laborlux 12 Pol, Wetzal, Germany) and photographed using an attached microcamera (WILD, Heerbrugg, Switzerland). A stage micrometer was photographed separately at the same magnification and used for calibration of the analysis software (ArcView, ESRI, Redlands, CA). The analysis software determined cell areas from tracings of the cells. Stem cell number was determined by dividing the internode length by the average longitudinal cell length. Leaf cell number was determined by dividing leaf area by the average cell area.

Stem sections. Eighteen days after transplanting, soybean plants were transferred to single bottles, two at a time, one from each blue light treatment, to be moved to the lab. Stems were sectioned in the internode just above the cotyledonary leaves. The fresh sections were cut on glass slides in water and the epidermis was peeled away from the section. Samples were covered with a cover slip and immediately viewed at 25X and photographed.

Leaf impressions. The middle leaflet of the soybean first trifoliate and the second true leaf of lettuce were sampled in the middle of the leaf(let) 18 and 17 days after transplanting, respectively. A 4% (w:v) solution of Formvar resin in chloroform

(polyvinyl-formaldehyde) was painted in a thin layer on each leaf. The solution was allowed to dry for at least 30 seconds. Samples were then covered with cellophane tape, peeled off the leaf, and mounted on a glass microscope slide. The sampled leaf was then measured with a leaf area meter (LI-COR, Lincoln, NE). Leaf impressions were viewed and photographed at 40X. All sampling, viewing and photographing took place within 2 h (see Appendix C).

Results and Discussion

The effect of blue light treatments on soybean stem epidermal cells was visually apparent in microscope photographs (Figure 5.1). Plant and cell measurement revealed a 4.7-fold increase in soybean stem length (Figure 5.2a) was associated with a 4.5-fold increase in cell number (Figure 5.2c). This suggests that blue light fraction alters cell division to elicit the inhibition of soybean stem length. Blue light suppression of cell expansion in etiolated seedlings (Cosgrove, 1981; Kigel and Cosgrove, 1991) explains dark to light inhibition of growth, but does not explain the blue light effects of light-grown soybeans.

Microscope photographs did not reveal, to the human eye, any difference in soybean leaf epidermal cells between blue light treatments (Figure 5.3). The 23% decrease in soybean leaf area (Figure 5.4a) caused by changing blue light fraction from 6% to 26% was associated with a 15% decrease in cell area and an 11% decrease in cell number (Figure 5.4b,c). However, only the differences in cell area were statistically significant. This suggests that changes in cell expansion may be the primary driver for

changes in leaf area, but cell division may aid in the change. It is important to note that leaf expansion in soybean is greatest at 6% blue and that blue light enhances leaf expansion from 0% to 6% blue (Chapter 4). According to Van Volkenburgh et al. (1990), blue light is as effective as red light at stimulating cell expansion in *P. vulgaris* leaf discs, but the effectiveness of red light is suppressed by far-red light. The curvilinear response of leaf area to an increase in blue light fraction suggests that this hypothesis may not be true. In our experiments, there were changes in red to far-red ratio with increasing blue light fraction (Table 4.4), but the changes in the ratio do not coincide with the variations in leaf area. More directly, the decrease in cell size with increased blue light fraction between 6% and 26% blue more strongly suggests that, in the long term, blue light at high levels may not be as effective as red light in affecting cell expansion.

An increase in lettuce leaf epidermal cell size was visually apparent in microscope photographs (Figure 5.5). Indeed, the 4.4-fold increase in lettuce leaf area between 0% and 6% blue (Figure 5.6a) was caused by a 3.1-fold increase in cell area and a 1.6-fold increase in cell number (Figure 5.6b,c). The change in lettuce leaf cell expansion, although opposite that of soybean, also raises the question of the effectiveness of blue light compared to red in stimulating cell expansion. For lettuce leaves, both blue and red light may be necessary to trigger the expansion responses. Even so, it appears that blue light is more effective at eliciting the expansion response. These discrepancies in cell expansion may be due to the fact that our plants were started from imbibition under their respective treatments, whereas Van Volkenburgh et al. (1990) used leaf discs from plants that were grown first under white fluorescents and were only treated under red or blue lights for a

short time.

While blue light signal transduction pathways for phototropism have been elucidated (Short and Briggs, 1994), the pathways for blue-light-induced cell expansion and cell division have not, and are likely separate pathways due to the very different kinetics (Short and Briggs, 1994; Liscum et al., 1992). The most likely mechanism suggested for blue light to alter cell expansion is a photoreceptor. A blue light photoreceptor may act to stimulate proton efflux, thus affecting calcium channels (Staal et al., 1994), calcium-calmodulin signaling (Elzenga et al., 1997), and auxin-binding (Jones et al., 1998) .

In cell division, the formation of a new cell wall is mediated by Golgi vesicles, which are guided by microtubules. Two light mechanisms known to alter microtubules may also be mechanisms for blue light to alter cell division. β-tubulin, a building block of microtubules, is known to be downregulated in dark versus light-grown soybean seedlings (Bustos et al., 1989). More specifically, blue light causes microtubules to align longitudinally rather than transversely (Short and Briggs, 1994). The recent elucidation of the HY4 gene, believed to code for a blue-light receptor (Ahmad and Cashmore, 1993), may shed light on how blue light might alter microtubule formation or orientation to affect cell division.

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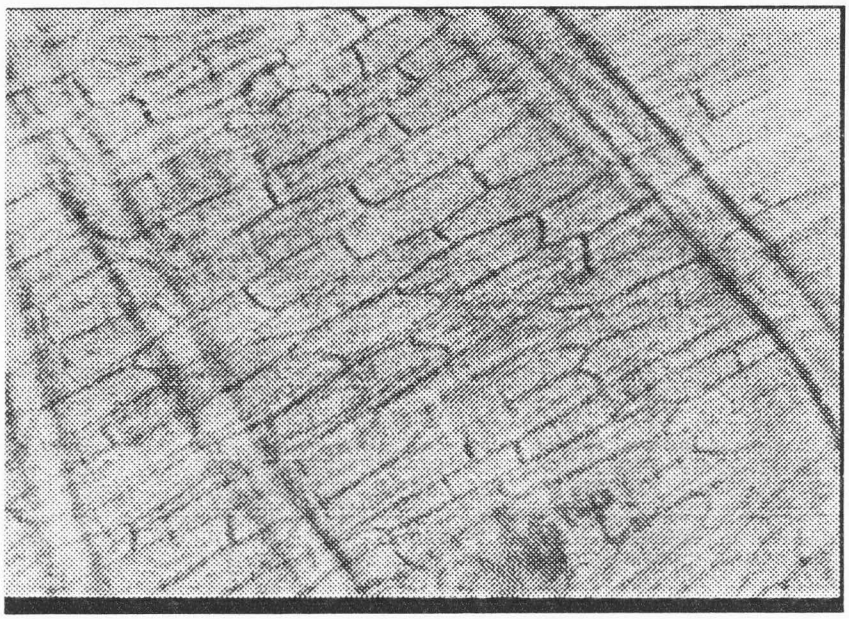
0% blue



26% blue

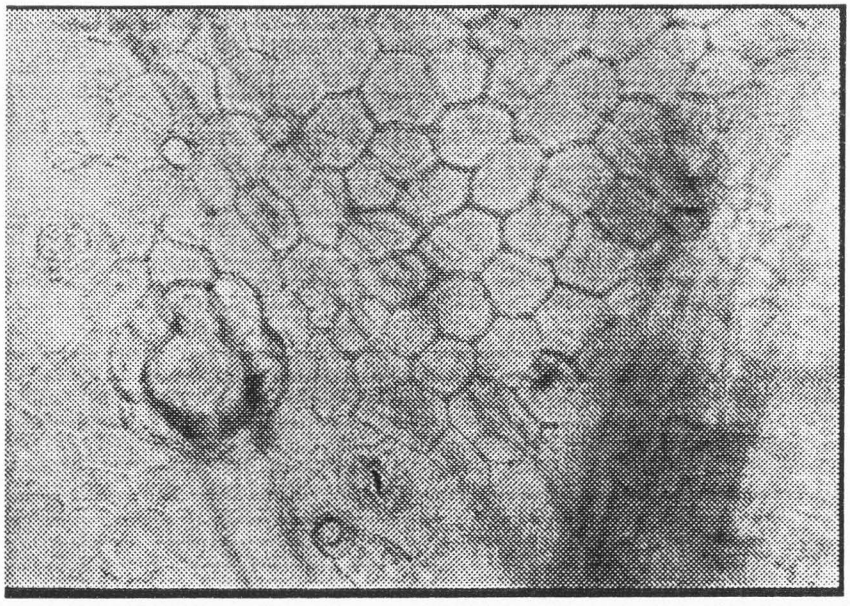


Figure 5.1. Microscope photographs of soybean stem epidermal cells at 0% and 26% blue. Photographs were taken at 25X.

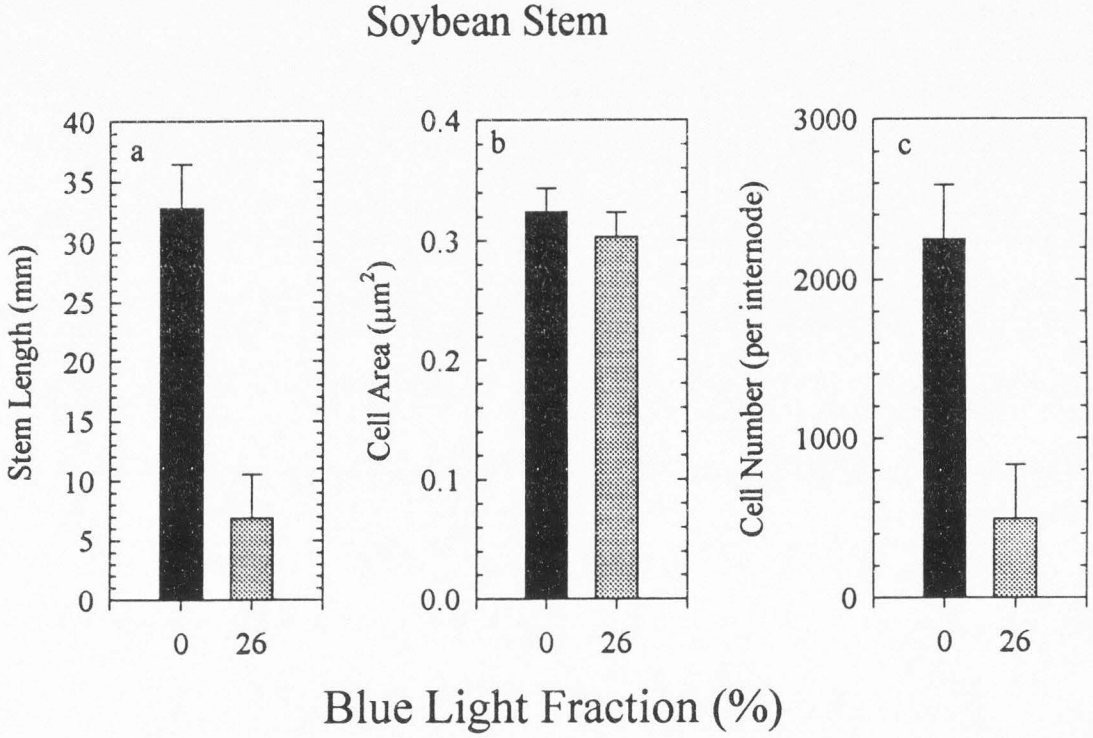
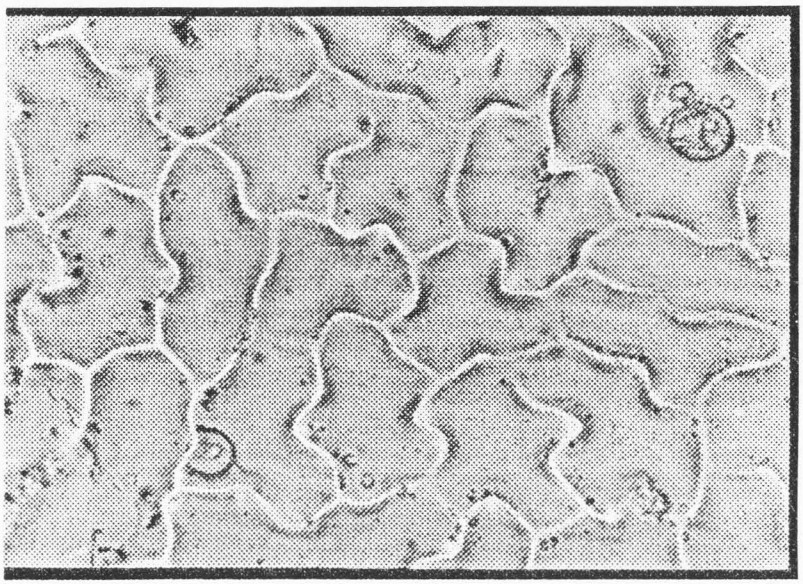


Figure 5.2. Effect of 0% and 26% blue light on soybean stem length, stem epidermal cell area, and stem epidermal cell number per internode. Error bars represent the least significant difference at $\alpha = 0.05$.

Soybean Leaf

6% blue



26% blue

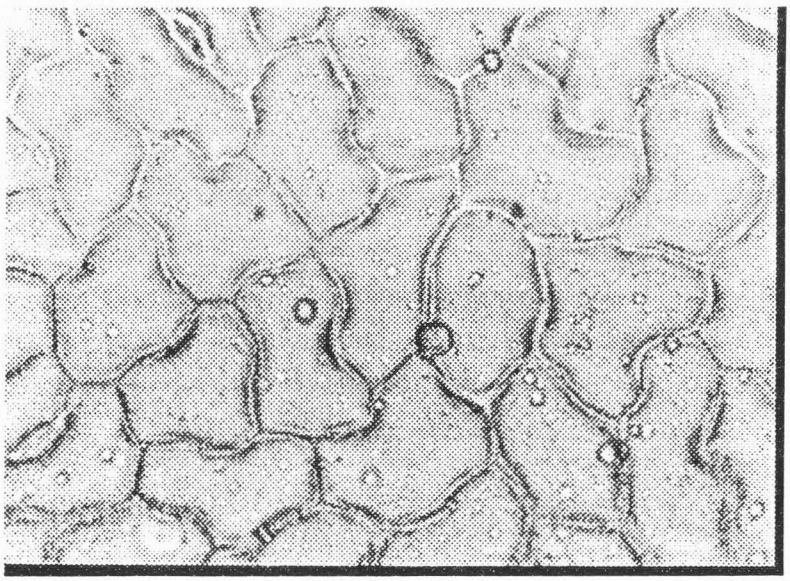


Figure 5.3. Microscope photographs of soybean leaf epidermal cells at 6% and 26% blue. Photographs were taken at 40X.

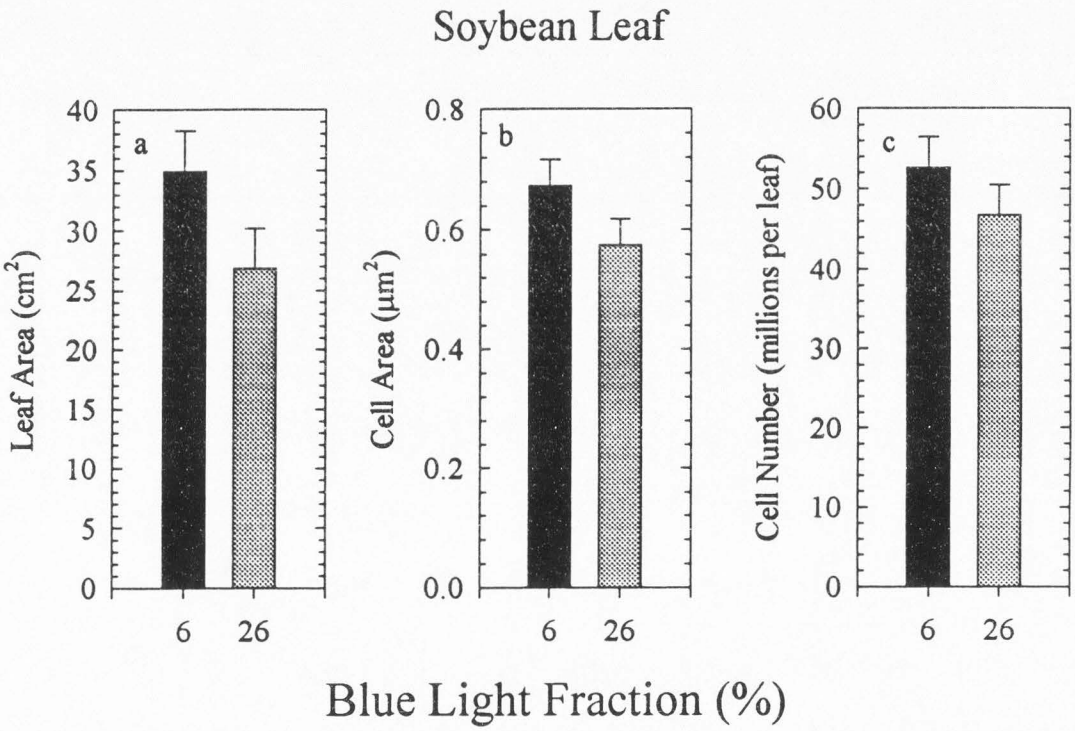
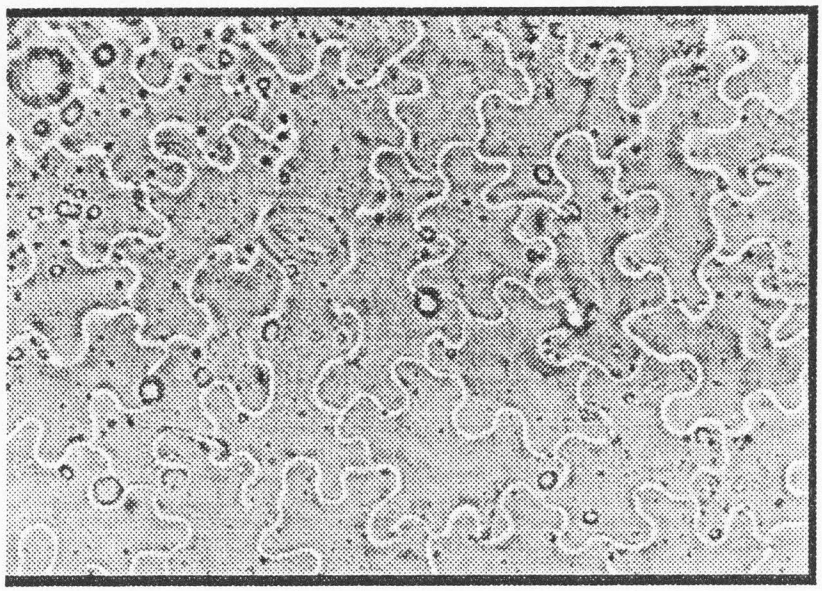


Figure 5.4. Effect of 6% and 26% blue light on soybean leaf area, leaf epidermal cell area, and leaf epidermal cell number. Error bars represent the least significant difference at $\alpha = 0.05$.

Lettuce Leaf

0% blue



6% blue

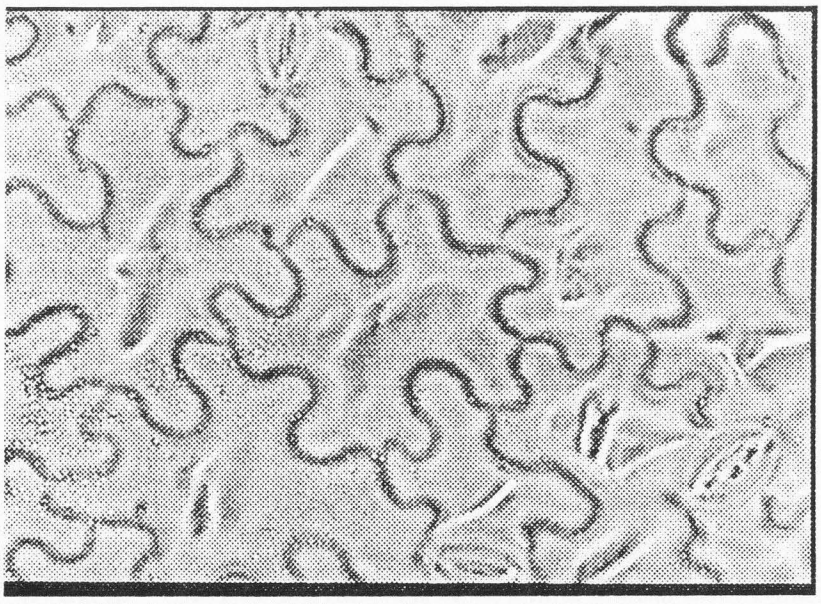


Figure 5.5. Microscope photographs of lettuce leaf epidermal cells at 0% and 6% blue. Photographs were taken at 40X.

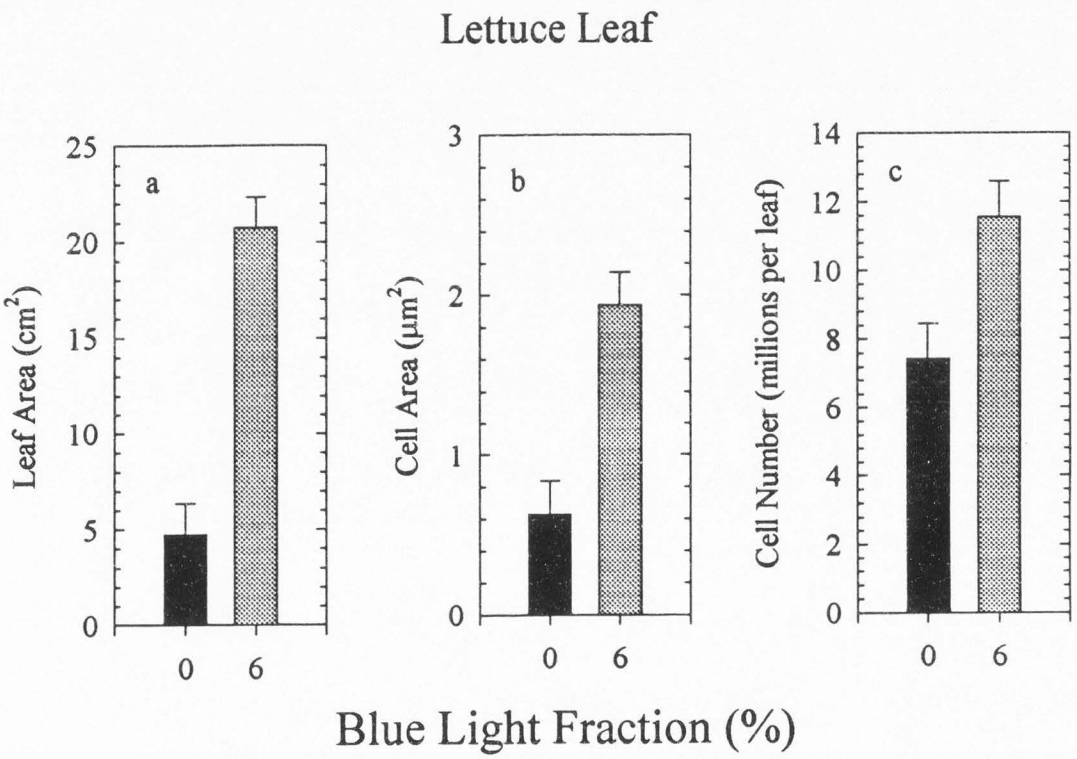


Figure 5.6. Effect of 0% and 6% blue light on lettuce leaf area, leaf epidermal cell area, and leaf epidermal cell number. Error bars represent the least significant difference at $\alpha = 0.05$.

CHAPTER 6

CONCLUSIONS

Growing plants in controlled environments, such as for an Advanced Life Support system, provides an opportunity to manipulate environmental conditions without complicating plant stress factors. Ultimately, all environmental factors could be manipulated to optimize system efficiency. We know that high carbon dioxide (excluding super-elevated carbon dioxide), high relative humidity, and direct nutrient delivery (hydroponics) provide a luxury environment for plant water potential and growth. Soybean canopy height responded minimally to temperature changes under these luxury conditions. A lack of elongation sensitivity means that temperature can be manipulated to optimize other productivity parameters such as yield and harvest index without drastically altering plant height.

The manipulation of light quality under these same luxury conditions causes greater differences in plant height and affects productivity depending on species. Although red light is the least energetically expensive to make, exclusively or narrow-range red light sources greatly enhance stem elongation and, in some cases, compromise productivity. In our experiments, soybeans grown under HPS lamps had more elongated stems, but higher total biomass than under MH lamps. Because phytochrome photoequilibrium was nearly identical for the two light sources, the differences in leaf expansion and stem elongation were hypothesized to be caused by blue light. Specifically examining blue light effects in further experiments, we found the effect of blue light was

very much species dependent. Wheat, which has an erectophile habit where expanding leaves and stems are shaded from light, showed little to no sensitivity to blue light. The small decrease in total dry mass with increasing blue light fraction could better be accounted for by differences in yield photon flux rather than blue light. To this end, wheat can be grown without blue light provided no other life cycle processes are affected by the lack of blue light. Soybean, which has a planophile habit where expanding leaves and stems are exposed to light, was much more sensitive to blue light. Differences in soybean dry mass could not be entirely explained by yield photon flux differences. Our data also indicated that soybean stem elongation responded to blue light fraction rather than absolute blue light. Soybean can be grown without blue light, but where canopy height is a concern, as in Advanced Life Support, some blue light may need to be added to control the height. The general division of species blue light sensitivity by plant growth habit, erectophile versus planophile, requires further investigation using other cultivars and species.

The leafy crop, lettuce, was even more sensitive to blue light fraction and required blue light to develop properly. The fact that lettuce, grown under equivalent phytochrome photoequilibrium and blue light fraction but variable "green" wavelengths, had differing yields suggests lettuce is very sensitive to spectral quality. This raises further questions of which wavelengths also affect lettuce growth and whether other leafy crops have a similar response.

The blue light effect at the cellular level was dependent on both species and plant part. A decrease in soybean stem length was effected by altered cell division while a

decrease in soybean leaf area was effected primarily by altered cell expansion. The fact that blue light affects cell division or expansion, depending on location, suggests sites of perception and/or signal transduction are different for stems and leaves. However, in lettuce leaves, both cell division and expansion were altered by blue light. In some species, the signal perception may not be separate.

Lastly, because we harvested our plants early in the life cycle, our results are only an indication of what might happen to yield. Our early soybean experiments indicated that there may be a change in total biomass and carbon partitioning such that edible yield is not affected. The long-term effects of stem and leaf morphological changes need to be investigated further.

APPENDICES

APPENDIX A. SUPPLEMENTARY EXPERIMENT TO: EFFECT OF LAMP TYPE AND TEMPERATURE ON DEVELOPMENT, CARBON PARTITIONING, AND YIELD OF SOYBEAN

Abstract

Parameters sensitive to lamp type in Chapter 3 retained their sensitivity at higher temperatures. Increasing the temperature to 32/28°C was significantly detrimental to total biomass but did not affect seed yield and photosynthetic efficiency. Lowering root zone temperature did not aid in reducing dark respiration and increasing carbon partitioning to the shoot.

Materials and Methods

Soybeans were grown as described in Chapter 1 except only three day/night temperature regimes were used: 32/28, 29/25, and 26/22°C. Root temperatures were kept constant at the average daily temperature of the shoot: 30, 27, and 24°C, respectively. Two additional shoot chambers were treated at 29/25 and 26/22°C but root zone temperatures were kept constant at 23 and 20°C, respectively. These comprised the five temperature treatments for each lamp type.

Results

Effect of lamp type

The results of this experiment confirm the results of Chapter 3. Even at higher temperatures, a significant difference in canopy height, stem and branch length, and total biomass occur between HPS and MH (Table A.1). The trend of reduced stem mass in MH plants associated with an increase in HI was also apparent, but not significant (Table

A.2). There was a greater and significant change in partitioning to the leaves. Although a trend for decreased seed yield under MH was apparent, once again this trend was not significant (Table A.1). No single yield parameter could account for the trend. No significant changes between treatments were noted in photosynthetic efficiency. Canopy P_{net} measurements were consistent with yield differences between lamp types (Figure A.1a).

Effect of temperature

Extreme high temperature of 32/28°C was detrimental to total biomass production but had a small non-significant effect on seed yield and photosynthetic efficiency (Table A.3). We confirmed that cooler temperatures reduced the seed fill period. The higher temperatures also increased P_{net} early in the life cycle (Fig. A.1b).

At these temperatures there was no difference in carbon partitioning (Table A.4), but the trend for decreased percent root mass with warm temperatures was apparent again. The day/night temperature scheme did not affect canopy height.

We hypothesized that a cooler root zone would have less dark respiration thus making more carbon available for biomass and seed production. However, there was no significant change in biomass or seed production at either shoot temperature regime (29/25, 26/22°C) (Table A.3) and carbon partitioning was not significantly affected (Table A.4).

Table A.1. Supplementary data: Three plant length measures, seed yield, and yield components of soybeans grown under two lamp types. Each parameter is an average of the five chambers with different temperature regimes.

lamp type	canopy height (cm)	main stem length (cm)	longest branch length (cm)	seed yield ($g \cdot m^{-2} \cdot d^{-1}$)	photo-synthetic efficiency† ($g \cdot mol^{-1}$)	total biomass ($g \cdot m^{-2} \cdot d^{-1}$)	pods per m^2	seeds per pod	mass per seed (mg)
HPS	48.6	42.2	51.2	5.04	0.232	14.8	1402	1.82	158
MH	42.2	22.0	29.2	4.97	0.236	13.0	1410	1.90	152
p-value	0.04	0.02	<0.01	0.84	0.84	<0.01	0.93	0.17	0.34

†grams of seed per mol of PPF

Table A.2. Supplementary data: Carbon partitioning of soybeans under two lamp types. Measures are a percent of total dry mass. Sum of the five components equals 100%.

lamp type	seed (harvest index)	stem	leaves	pod	root
HPS	34.1	17.6	25.9	13.0	9.4
MH	38.2	15.4	22.5	14.2	9.8
p-value	0.14	0.12	0.03	0.19	0.70

Table A.3. Supplementary data: A comparison of yield and yield components for soybeans grown under five temperature regimes. Each parameter is an average of the two chambers of differing lamp type.[z]

day/night temperature	seed yield ($g\ m^{-2}\ d^{-1}$)	PE[†] ($g\ mol^{-1}$)	total biomass ($g\ m^{-2}\ d^{-1}$)	pods per m^2	seeds per pod	mass per seed (mg)	days to first flower	days to harvest	seed fill (days)
32/28	4.73	0.219	12.9c	1520	1.85	135	19d	81	62
29/25	5.20	0.244	14.4a	1441	1.90	154	19d	81	62
29/25*	5.22	0.247	14.3a	1473	1.83	158	21c	81	60
26/22	5.16	0.240	13.6b	1344	1.90	164	23b	81	58
26/22*	4.70	0.221	14.2a	1253	1.84	164	26a	81	55
p-value	0.73	0.69	<0.01	0.42	0.72	0.15	<0.01	1.00	

[†]PE = photosynthetic efficiency *reduced root zone temperature

[z]different letters within a column indicate significant differences using a mean separation test of LSD at α=0.05

Table A.4. Supplementary data: Carbon partitioning of soybeans under five temperature regimes. Data are a percent of total dry mass. Sum of the five components equals 100%.

day/night temperature	seed (harvest index)	stem	leaves	pod	root
32/28	36.7	17.4	24.2	13.9	7.8
29/25	36.1	18.2	24.6	12.6	8.6
29/25*	36.5	15.9	23.7	14.2	9.8
26/22	38.1	14.1	24.6	13.5	9.8
26/22*	33.4	17.0	23.8	13.9	11.9
p-value	0.77	0.33	0.96	0.66	0.25

*reduced root zone temperature

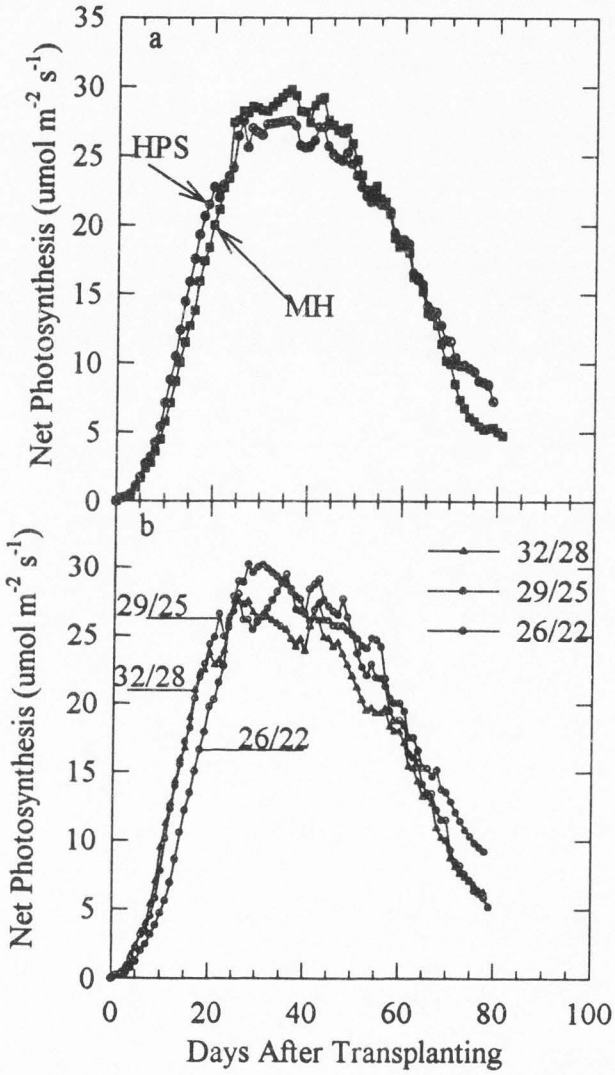


Fig. A.1. Supplementary data: Net photosynthesis (CO_2 uptake) of soybean canopies. a) Comparison of lamp types. Measurements are an average of the five chambers of different temperatures. b) Comparison of temperatures. Measurements are an average of the two chambers of differing lamp types.

APPENDIX B. A COMPARISON OF SEQUENTIAL HARVEST OF SOYBEAN UNDER TWO LAMP TYPES

Purpose

The objective of this experiment was to gain an understanding of when morphological differences between plants grown under high pressure sodium and metal halide become apparent.

Materials and Methods

Soybeans were grown at a density of 36 plants m^{-2} in ten Plexiglas chambers (see system description in Chapter 3). HPS or MH lamps were placed over five chambers each. Mylar sheets around the chambers were maintained at canopy height to minimize edge effect. Plants were grown in aerated nutrient solution (pH=5.6, EC=70 mS m^{-1}), replenished as necessary to maintain solution level. Shoot (26/22°C) and root-zone (24°C) temperatures were measured with thermocouples and maintained by computer-controlled heaters. A photosynthetic photon flux (PPF) of 550 ± 15 μmol m^{-2} s^{-1} was maintained at the top of the canopy. This supplied 49 and 170 μmol m^{-2} s^{-1} of blue light (400-500nm) from HPS and MH lamps, respectively. Photoperiod was 12-h. Carbon dioxide concentration was enriched to 1100 μmol mol^{-1}. Canopy height, percent PPF absorption, and top of the canopy PPF were measured every other day.

Absorption was measured with a line sensor integrating 10 quantum sensors. Light was measured above the canopy (incident), below the canopy (transmitted), upside down above the canopy (reflected), and upside down below the canopy (reflected-transmitted). Absorption was then calculated as incident minus transmitted plus reflected

plus reflected-transmitted all divided by incident.

One chamber from each lamp type was harvested every six days starting 7 days after transplanting. The following were measured at harvest: node, branch, and leaf number; main stem, branch and internode lengths; and leaf area. Plants were separated into leaves, stems, and roots, dried at 80°C for 48 hours, and weighed. Growth rates were calculated as the first derivative of length measurements versus time.

Results

Stem elongation. HPS stems elongate rapidly so the canopy quickly becomes taller than the MH canopy (Figure B.1a). The growth rate under HPS increased quickly to a maximum of 1.5 cm d^{-1} by day 17 (Figure B.1b). MH had a shallower but broader peak at 0.5 cm d^{-1}. The calculated ratio of main stem length:branch length is an indicator of apical dominance. A phytochrome-mediated response, such as elongation due to competition, would have a high apical dominance ratio (>>1) (Ballare et al., 1995). The apical dominance of plants under HPS and MH lamps were not significantly different from one (Figure B.2). This suggests differences in elongation were not phytochrome related. Individual internode lengths were consistently 2-3 times greater under HPS than MH lamps (Figure B.3).

Leaf expansion. More rapid leaf expansion under HPS than MH was apparent by day 13 (Figure B.4a). However, by day 18 HPS leaf growth was only 10% greater than MH (Figure B.4b). Increased leaf area was not caused by an increase in leaf number (Figure B.5). A more rapid leaf expansion allowed for faster canopy closure and increased

light capture (Figure B.6). A 5.4% increase in absorbed light under HPS corresponded to a 5.2% increase in total dry mass as compared to MH (Figure B.7a). Carbon partitioning to the stems accounted for most of the difference in total dry mass with a disparity of 32.5% between lamp types (Figure B.7b).

Literature Cited

Ballare, C.L., A.L. Scopel, and R.A. Sanchez. 1995. Plant photomorphogenesis in canopies, crop growth, and yield. HortScience 30:1172-1181.

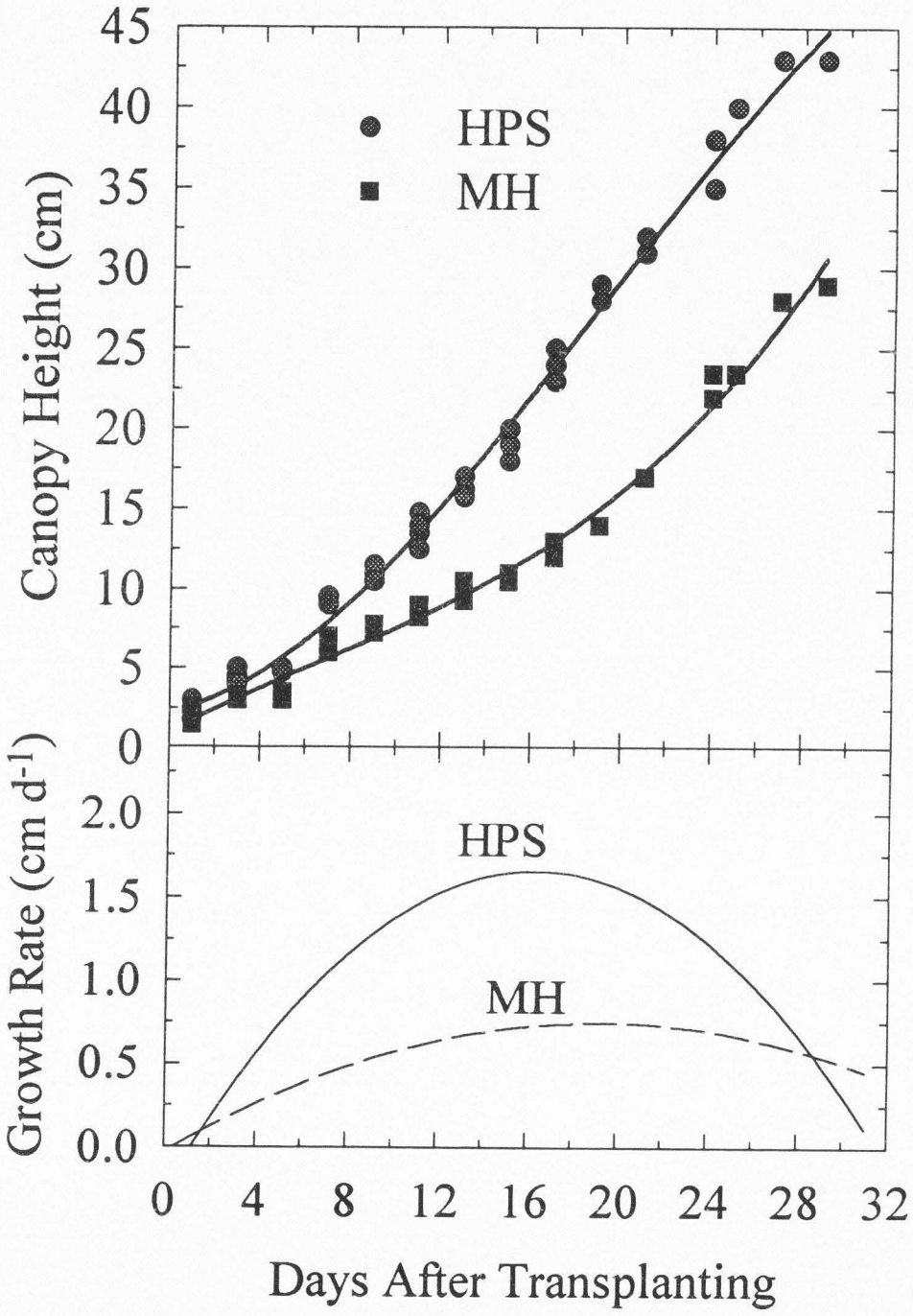


Figure B.1 - The change in (a) canopy height and (b) main stem growth rate with time for soybeans grown under HPS and MH lamps. Each point is a chamber.

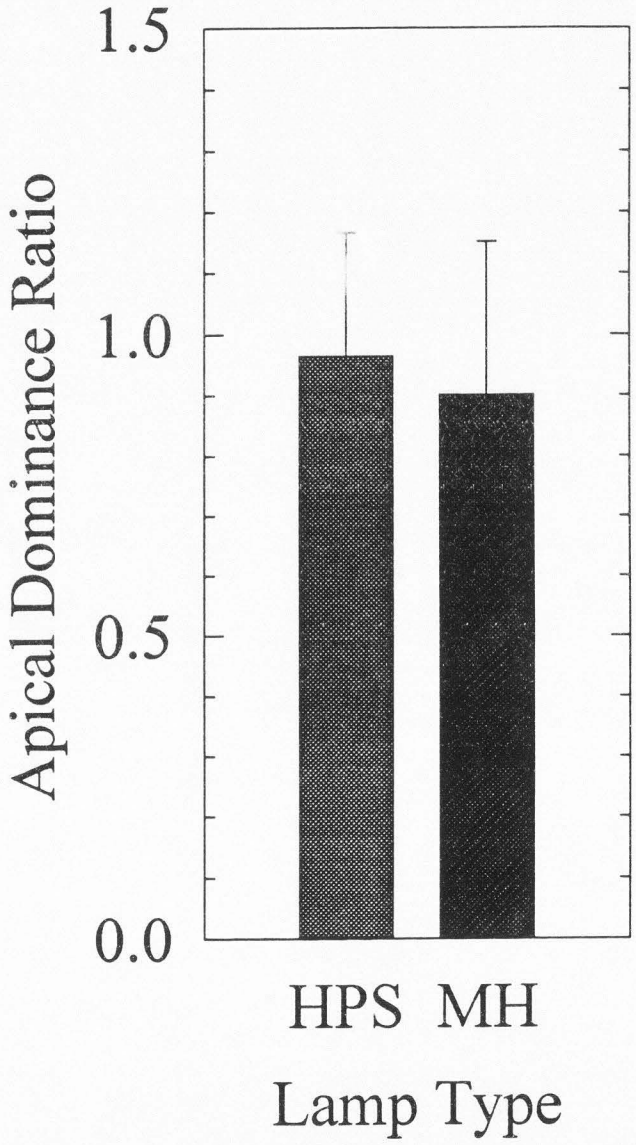


Figure B.2 - The apical dominance ratio (main stem length:branch length) for soybeans grown under HPS and MH lamps.

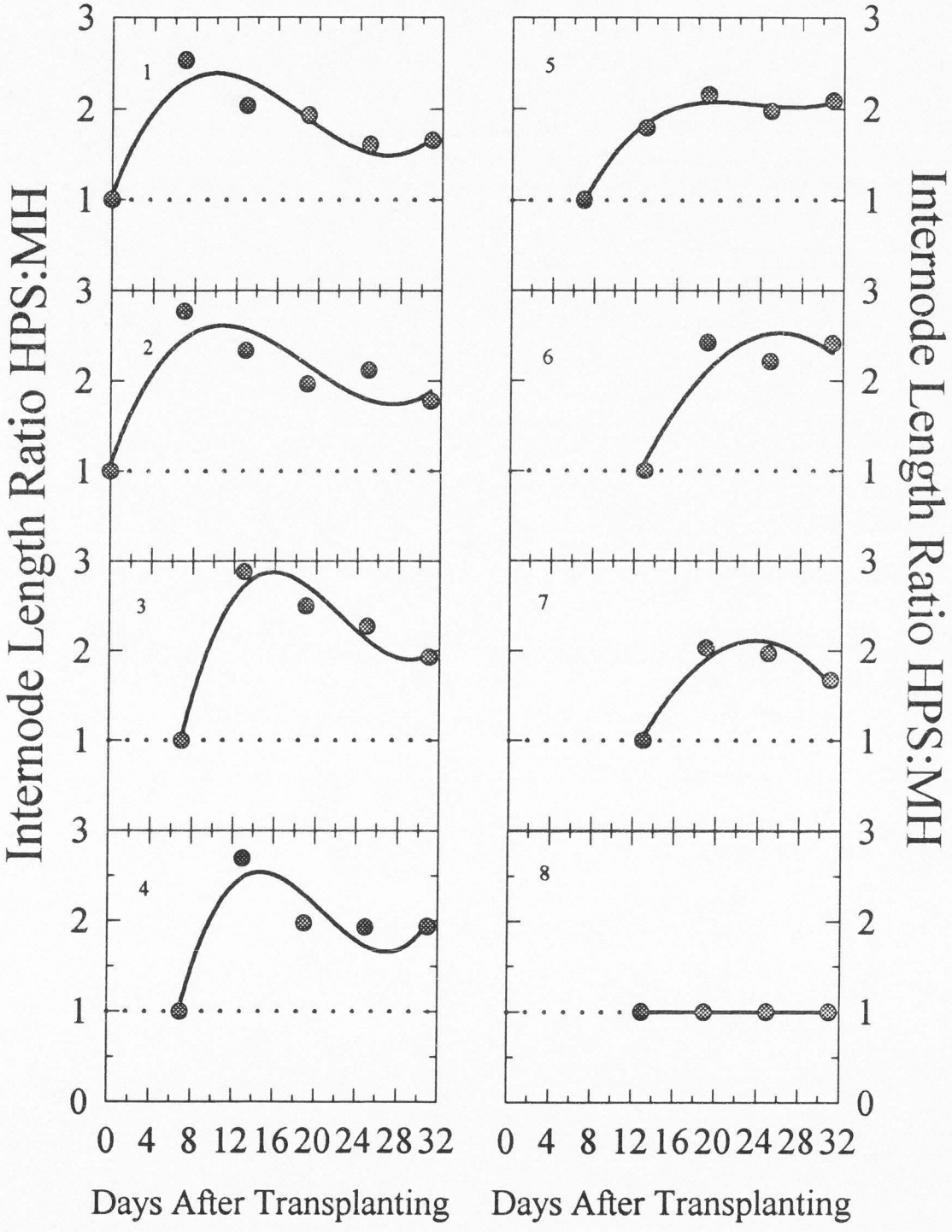


Figure B.3 - The change in the ratio of HPS to MH soybean internode length with time. Each point is an average of six plants. Numbers in the upper left of each graph indicate the internode number starting from the internode above the cotyledons.

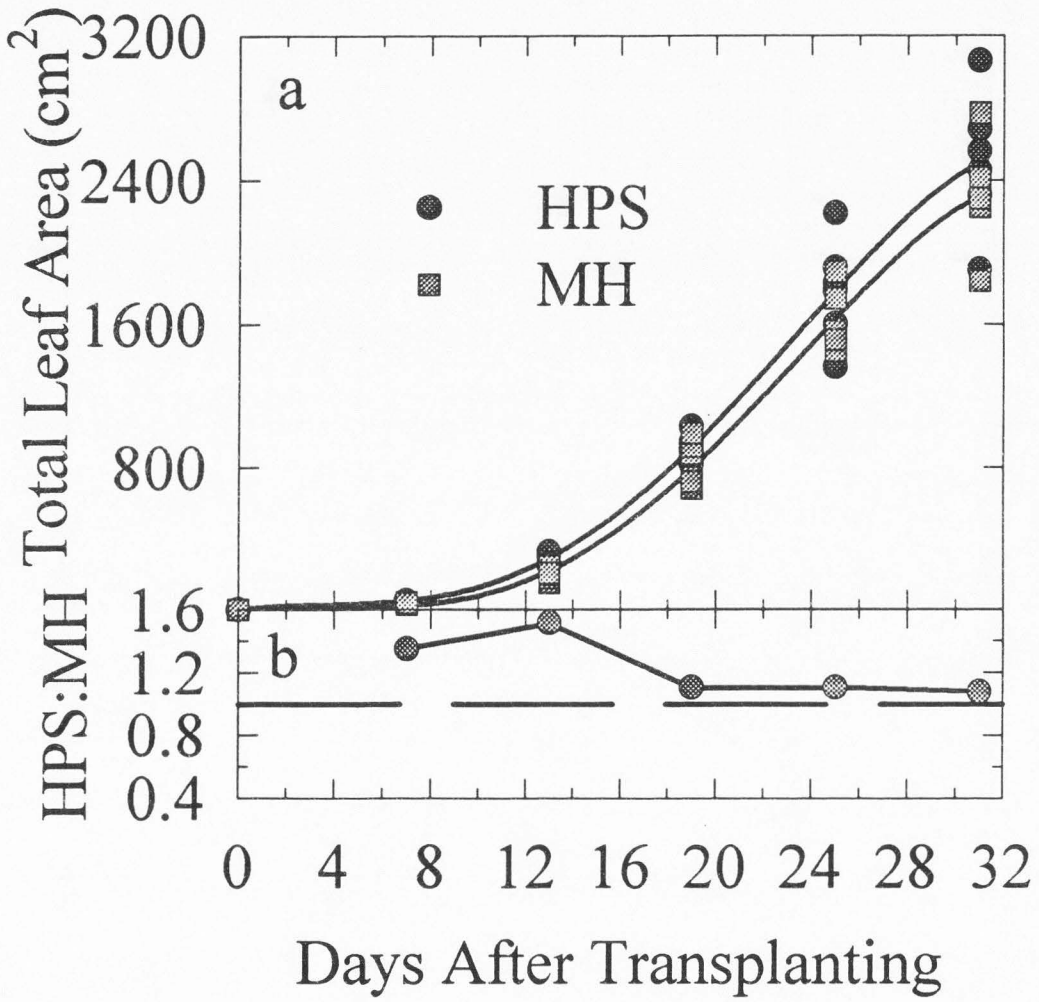


Figure B.4 - The change in (a) total leaf area and (b) ratio of HPS to MH leaf area with time. Each point is an average of six plants.

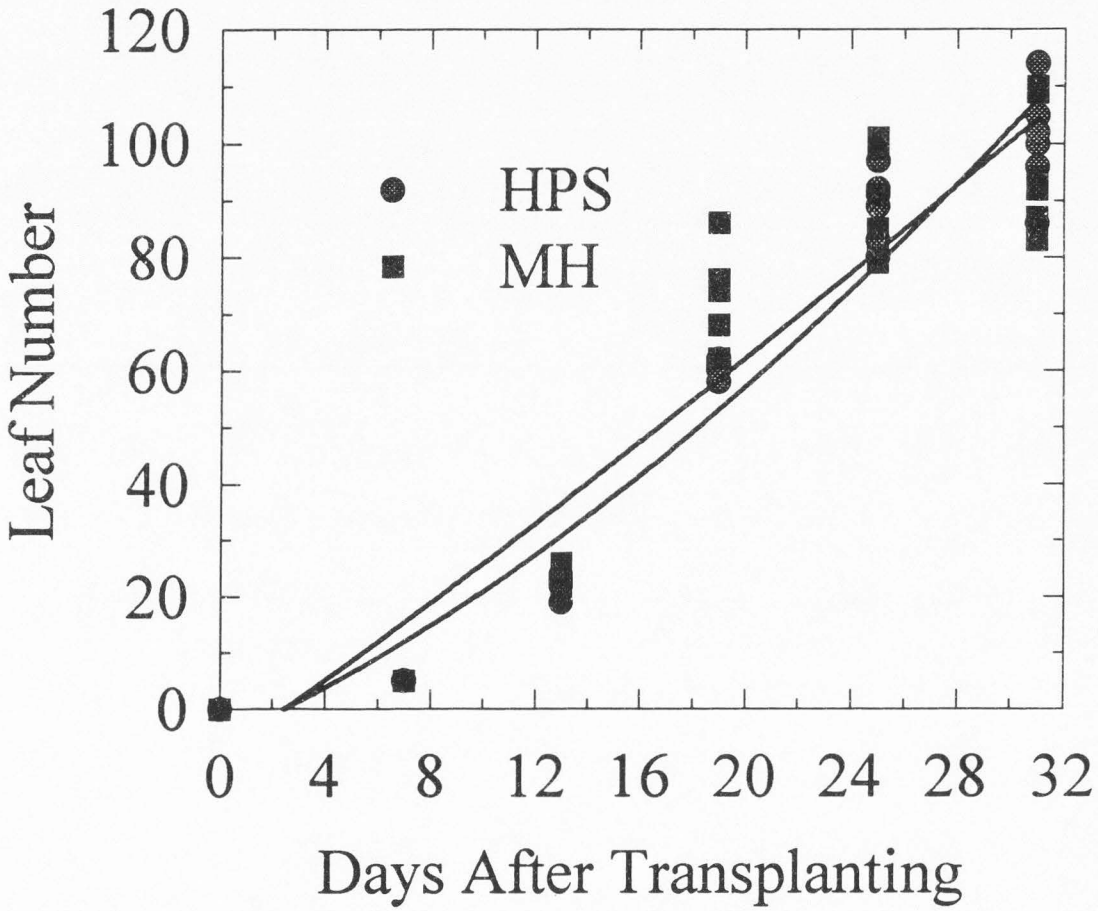


Figure B.5 - The change in leaf number with time for soybeans grown under HPS and MH lamps. Each point is a plant.

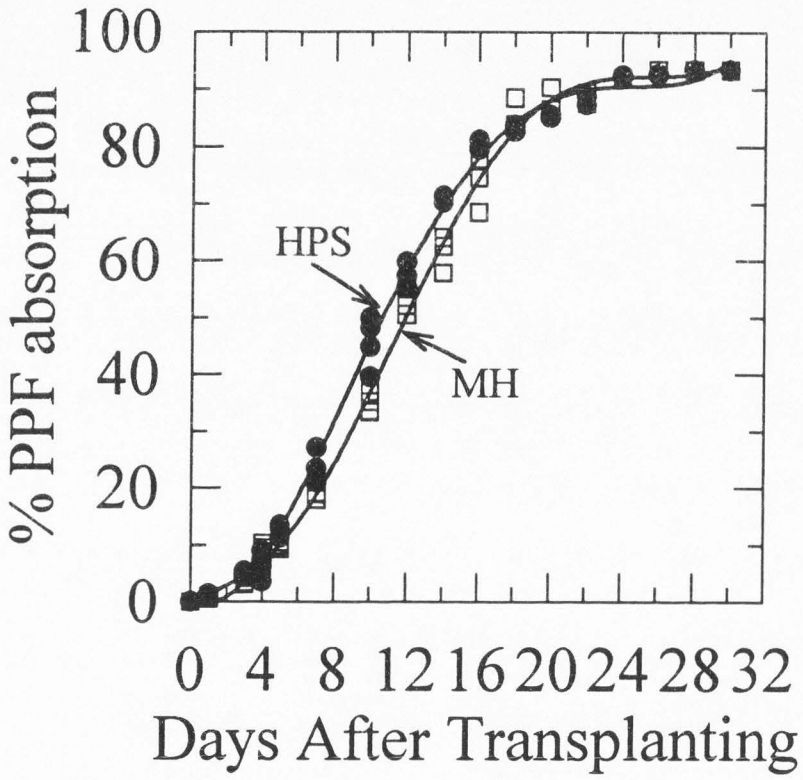


Figure B.6 - The change in percent light absorption with time for soybeans grown under HPS and MH lamps. Each point is a chamber.

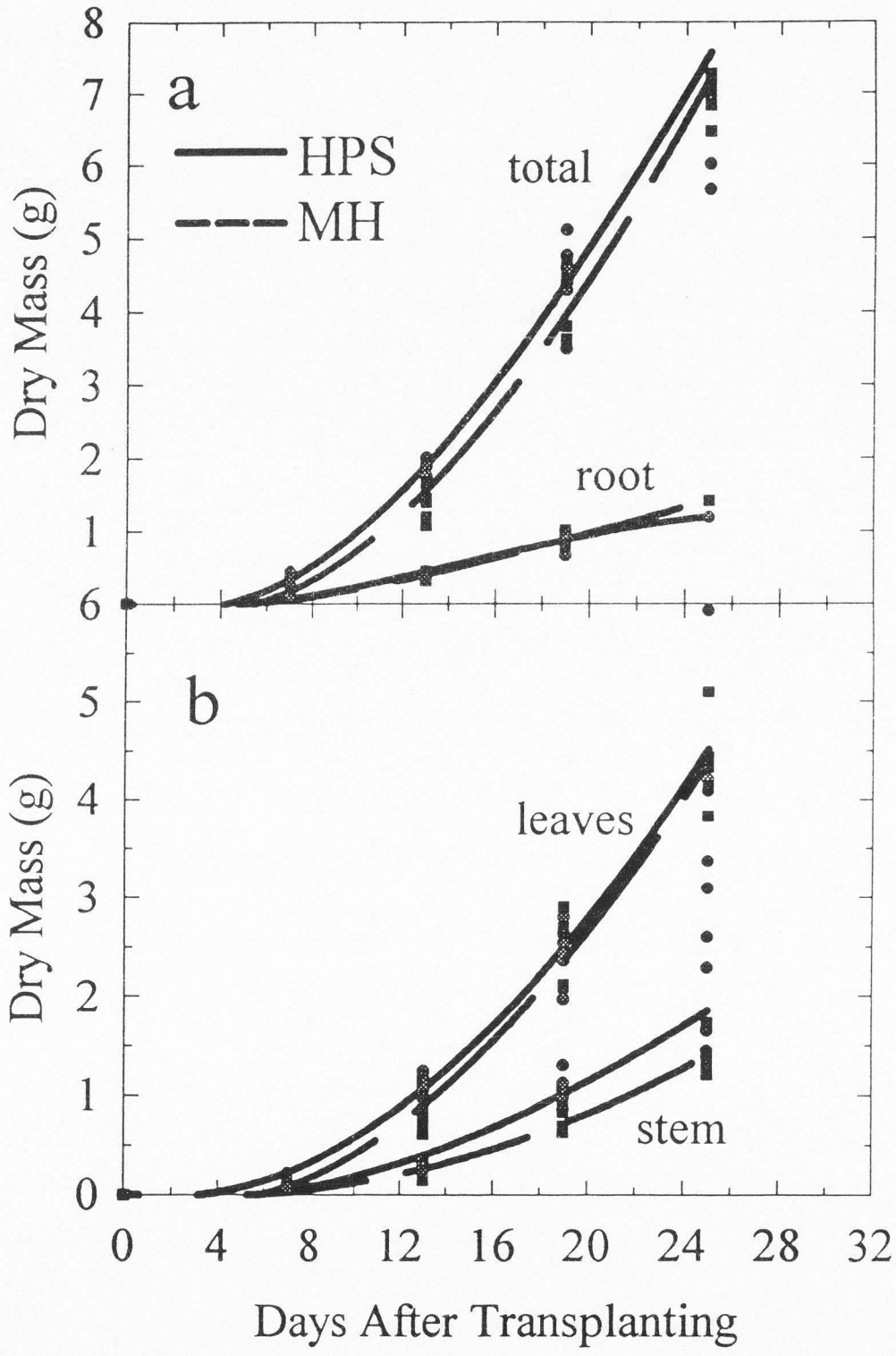


Figure B.7 - The change in (a) total dry mass and (b) carbon partitioning with time for soybeans grown under HPS and MH lamps. Each point is a plant.

APPENDIX C. A COMPARISON OF FOUR LEAF IMPRESSION METHODS

Introduction

Leaf impressions have been used to measure cell size and cell number in grasses (Hilu and Randall, 1984; Rahim and Fordham, 1991) and pea leaves (Lecoeur *et al*, 1995). Cellulose acetate has long been used as the casting compound. However, these impressions tend to shrink and cloud making them useless for measuring cell size (Hilu and Randall, 1984; Rahim and Fordham, 1991). Hilu and Randall (1984) used nail polish as the casting compound to prevent shrinkage. A film of clear nail polish is brushed on the leaves, dried for 2 to 4 hours, and then carefully removed. This impression provides an outline of individual cells because it dissolves some of the waxes that may obscure cell outlines. Tests indicate a commercially available casting compound, Formvar (polyvinylformaldehyde), may work better (Schaefer and Harter, 1942). A simpler method, similar to cellulose acetate, using cellulose triacetate film is available but has not been previously referenced. Four methods, nail polish, Formvar, Hartopane (a butyrate film), and cellulose triacetate film, were compared to test for durability and ease of use.

Materials and Methods

Soybeans were grown under high pressure sodium lamps in conditions described in Chapter 4. Eighteen days after transplanting, four leaf impression methods were tested: nail polish (Strong Nail, Cutex, New York, NY), Formvar (Ted Pella Inc., Redding, CA), Hartopane (Hartwig-Hartoglass, Woodstock, IL), and cellulose triacetate. All four methods were tested simultaneously on the middle leaflet of the first trifoliate of 12

soybean plants. The middle region of the leaf was sampled to obtain a distribution of cell size closest to the mean cell size of the entire leaf (Wenzel *et al*, 1997). Nail polish and Formvar (4% Formvar resin in chloroform) were painted on the leaf and allowed to dry. Nail polish took at least 30 seconds to dry and Formvar took only 10-20 seconds to dry. Samples were then peeled off with cellophane tape and mounted on a glass microscope slide. Immediately after the leaf was treated with a drop of acetone, pieces (1 x 2 cm) cellulose triacetate and Hartopane were pressed into the leaf for 10 seconds. The pieces were then taped to a glass microscope slide. All four method samples were immediately viewed under a microscope at 40X and photographed. Cells were traced and areas calculated in ArcView (ESRI, Redlands, CA) calibrated with a photograph of a stage micrometer at 40X. The same cells were photographed and measured again after 6 days to determine if sample shrinkage had occurred.

Results

Both cellulose triacetate and Hartopane curled severely in six days, compromising the plane of focus. Samples had to be re-taped in order to be photographed again after 6 days. Nail polish impressions were easy to view provided the polish was spread thinly enough, which was difficult to do. Formvar was the easiest method to use and produced the best impressions, but the active ingredient (polyvinylformaldehyde) is a relatively hazardous chemical. None of the methods tested appeared to cloud within 6 days. All methods shrank significantly in six days, except Formvar (Figure C.1). However, the variance in shrinkage was much less than the variance caused by differences in sample cell

size. Because of the simplicity of its use and minimal shrinkage, Formvar was used for all leaf impressions.

Literature Cited

Hilu, K. W., and J. L. Randall. 1984. Convenient method for studying grass leaf epidermis. Taxon 33:413-415.

Lecoeur, J., et al. 1995. Expansion of pea leaves subjected to short water deficit: cell number and cell size are sensitive to stress at different periods of leaf development. J. of Exp. Bot. 46:1093-1101.

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Schaefer, V.J. and D. Harker. 1942. Surface replicas for use in the electron microscope. J. of Applied Physics 13:427-433.

Wenzel, C.L., P.M. Chandler, R.B. Cunningham, and J. B. Passioura. 1997. Comparative leaf epidermal anatomy of mutants of barley (*Hordeum vulgare* L. 'Himalaya') which differ in leaf length. Annals of Bot. 79:47-52.

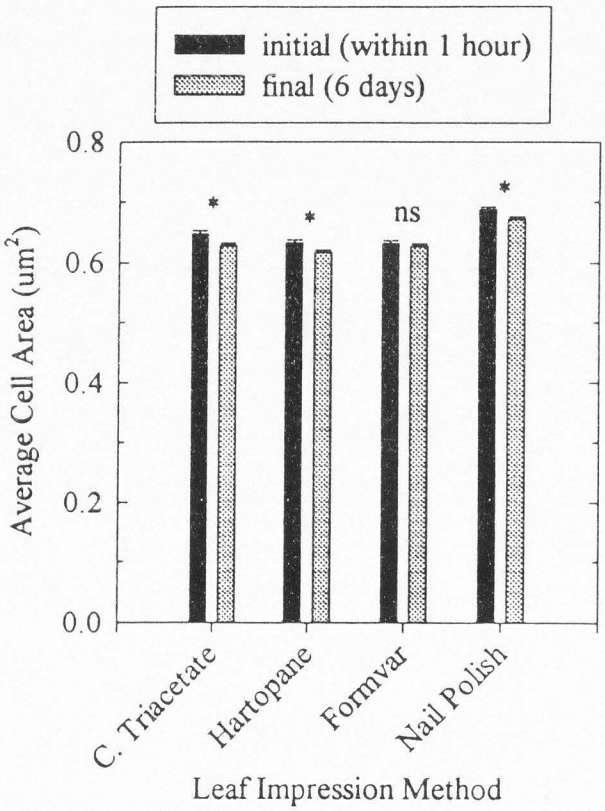

Figure C.1 - Shrinkage over time of four leaf impression methods. Each bar is an average of 12 leaves. Asterisks indicate significant differences at α=0.05.

APPENDIX D. ANOVA TABLES

Table D.1 - ANOVA tables for parameters cited in Chapter 3.

Analysis of Variance Procedure
Dependent Variable: Main Shoot Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	1266.3200	253.2640	12.3300	0.0153
Error	4	82.1840	20.5460		
Corrected Total	9	1348.5040			
	R-Square	C.V.	Root MSE	Mean	
	0.939055	14.83236	4.5328	30.5600	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	1132.0960	1132.0960	55.1000	0.0018
TEMP	4	134.2240	33.5560	1.6300	0.3231

Analysis of Variance Procedure
Dependent Variable: Longest Branch Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	1162.4190	232.4838	43.7300	0.0014
Error	4	21.2660	5.3165		
Corrected Total	9	1183.6850			
	R-Square	C.V.	Root MSE	Mean	
	0.982034	6.257133	2.3058	36.8500	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	1054.7290	1054.7290	198.3900	0.0001
TEMP	4	107.6900	26.9225	5.0600	0.0726

Analysis of Variance Procedure
Dependent Variable: Percent Stem

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	29.9976	5.9995	13.5300	0.0129
Error	4	1.7739	0.4435		
Corrected Total	9	31.7714			
	R-Square	C.V.	Root MSE	Mean	
	0.944168	4.957062	0.6659	13.4340	
Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	15.1782	15.1782	34.2300	0.0043
TEMP	4	14.8193	3.7048	8.3500	0.0318

Table D.1 - continued

Analysis of Variance Procedure
Dependent Variable: Percent Leaf

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	112.5158	22.5032	63.1700	0.0007
Error	4	1.4249	0.3562		
Corrected Total	9	113.9408			

R-Square	C.V.	Root MSE	Mean
0.987494	2.112160	0.5969	28.2580

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	1.1972	1.1972	3.3600	0.1407
TEMP	4	111.3187	27.8297	78.1200	0.0005

Analysis of Variance Procedure
Dependent Variable: Percent Pod

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	10.2200	2.0440	4.8100	0.0766
Error	4	1.6992	0.4248		
Corrected Total	9	11.9192			

R-Square	C.V.	Root MSE	Mean
0.857437	5.221297	0.6518	12.4830

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	1.0304	1.0304	2.4300	0.1944
TEMP	4	9.1896	2.2974	5.4100	0.0655

Analysis of Variance Procedure
Dependent Variable: Percent Seed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	127.9173	25.5835	16.2200	0.0092
Error	4	6.3101	1.5775		
Corrected Total	9	134.2274			

R-Square	C.V.	Root MSE	Mean
0.952989	3.388823	1.2560	37.0630

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	4.1088	4.1088	2.6000	0.1819
TEMP	4	123.8085	30.9521	19.6200	0.0068

Table D.1 - continued

Analysis of Variance Procedure
Dependent Variable: Percent Root

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	29.5312	5.9062	4.9300	0.0738
Error	4	4.7954	1.1989		
Corrected Total	9	34.3266			

R-Square	C.V.	Root MSE	Mean
0.860300	12.49914	1.0949	8.7600

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	3.2036	3.2036	2.6700	0.1775
TEMP	4	26.3276	6.5819	5.4900	0.0639

Analysis of Variance Procedure
Dependent Variable: Pods per Square Meter

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	217707.1000	43541.4200	53.4700	0.0009
Error	4	3257.0000	814.2500		
Corrected Total	9	220964.1000			

R-Square	C.V.	Root MSE	Mean
0.985260	1.988091	28.5351	1435.3000

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	25502.5000	25502.5000	31.3200	0.0050
TEMP	4	192204.6000	48051.1500	59.0100	0.0008

Analysis of Variance Procedure
Dependent Variable: Mass per Seed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	507.4000	101.4800	0.5600	0.7302
Error	4	722.6000	180.6500		
Corrected Total	9	1230.0000			

R-Square	C.V.	Root MSE	Mean
0.412520	8.245773	13.4406	163.0000

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	144.4000	144.4000	0.8000	0.4218
TEMP	4	363.0000	90.7500	0.5000	0.7393

Table D.1 - continued

Analysis of Variance Procedure
Dependent Variable: Seeds per Pod

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.1202	0.0240	13.1000	0.0137
Error	4	0.0073	0.0018		
Corrected Total	9	0.1275			

R-Square	C.V.	Root MSE	Mean
0.942427	2.279771	0.0428	1.8790

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	0.0084	0.0084	4.5800	0.0990
TEMP	4	0.1117	0.0279	15.2200	0.0109

Analysis of Variance Procedure
Dependent Variable: Effective Canopy Height

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	484.2000	96.8400	25.1500	0.0040
Error	4	15.4000	3.8500		
Corrected Total	9	499.6000			

R-Square	C.V.	Root MSE	Mean
0.969175	4.930004	1.9621	39.8000

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	435.6000	435.6000	113.1400	0.0004
TEMP	4	48.6000	12.1500	3.1600	0.1458

Analysis of Variance Procedure
Dependent Variable: First Flower

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	260.9000	58.1800	29.0900	0.0031
Error	4	8.0000	2.0000		
Corrected Total	9	298.9000			

R-Square	C.V.	Root MSE	Mean
0.9732	5.2573	1.4142	26.9000

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	22.5000	22.5000	11.2500	0.0285
TEMP	4	268.4000	67.1000	33.5500	0.0025

Table D.1 - continued

Analysis of Variance Procedure
Dependent Variable: Days to Harvest

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	91.0000	18.2000	1.9500	0.2692
Error	4	37.4000	9.3500		
Corrected Total	9	128.4000			

R-Square	C.V.	Root MSE	Mean
0.708723	3.412698	3.0578	89.6000

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	67.6000	67.6000	7.2300	0.0547
TEMP	4	23.4000	5.8500	0.6300	0.6696

Analysis of Variance Procedure
Dependent Variable: Seed Yield Rate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	4.5704	0.9141	4.4700	0.0859
Error	4	0.8177	0.2044		
Corrected Total	9	5.3882			

R-Square	C.V.	Root MSE	Mean
0.848234	9.4829	0.4521	4.7680

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.5954	0.5954	2.9100	0.1631
TEMP	4	3.9751	0.9938	4.8600	0.0774

Analysis of Variance Procedure
Dependent Variable: Photosynthetic Efficiency

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.0114	0.0023	4.7400	0.0785
Error	4	0.0019	0.0005		
Corrected Total	9	0.0133			

R-Square	C.V.	Root MSE	Mean
0.855514	8.8826	0.0219	0.2471

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.0009	0.0009	1.8700	0.2429
TEMP	4	0.0105	0.0026	5.4500	0.0646

Table D.1 - continued

Analysis of Variance Procedure

Dependent Variable: Total Biomass Rate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	10.3809	2.0762	2.8100	0.1690
Error	4	2.9513	0.7378		
Corrected Total	9	13.3322			

R-Square	C.V.	Root MSE	Mean
0.778634	6.6971	0.8590	12.8260

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	7.0560	7.0560	9.5600	0.0365
TEMP	4	3.3249	0.8312	1.1300	0.4554

Table D.2 - General linear model tables for lettuce parameters in Chapter 4.

General Linear Models Procedure

Dependent Variable: Chlorophyll Concentration

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	2615.5529	118.8888	44.96	0.0001
Error	115	304.1033	2.6444		
Corrected Total	137	2919.6562			

R-Square	C.V.	Root MSE	Mean
0.895843	26.7664	1.6262	6.0754

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	48.0438	48.0438	18.17	0.0001
PPF	1	297.0943	297.0943	112.35	0.0001
LAMP	1	561.9551	561.9551	212.51	0.0001
PPF*LAMP	1	0.5807	0.5807	0.22	0.6402
BLF(LAMP)	4	1379.5035	344.8759	130.42	0.0001
PPF*BLF(LAMP)	4	76.4115	19.1029	7.22	0.0001
REP*PPF	1	63.6865	63.6865	24.08	0.0001
REP*PPF*LAMP	2	18.2682	9.1341	3.45	0.0349
REP*PPF*BLF(LAMP)	7	72.2565	10.3224	3.90	0.0007

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	297.0943	297.0943	4.66	0.2760

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	561.9551	561.9551	61.52	0.0159

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.5807	0.5807	0.06	0.8245

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	1379.5035	344.8759	33.41	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	76.4115	19.1029	1.85	0.2240

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	1028177.7066	46735.3503	9.08	0.0001
Error	115	592044.3672	5148.2119		
Corrected Total	137	1620222.0738			

R-Square	C.V.	Root MSE	Mean
0.634591	42.1250	71.7510	170.3288

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	91423.6506	91423.6506	17.76	0.0001
PPF	1	106742.7372	106742.7372	20.73	0.0001
LAMP	1	11059.6895	11059.6895	2.15	0.1455
PPF*LAMP	1	10684.7803	10684.7803	2.08	0.1524
BLF(LAMP)	4	588804.7873	147201.1968	28.59	0.0001
PPF*BLF(LAMP)	4	125865.3489	31466.3372	6.11	0.0002
REP*PPF	1	323.3359	323.3359	0.06	0.8026
REP*PPF*LAMP	2	556.4908	278.2454	0.05	0.9474
REP*PPF*BLF(LAMP)	7	60864.4551	8694.9222	1.69	0.1185

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	106742.7372	106742.7372	330.13	0.0350

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	11059.6895	11059.6895	39.75	0.0242

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	10684.7803	10684.7803	38.40	0.0251

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	588804.7873	147201.1968	16.93	0.0011

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	125865.3489	31466.3372	3.62	0.0664

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Leaf Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	6.0200	0.2736	12.41	0.0001
Error	115	2.5353	0.0220		
Corrected Total	137	8.5553			

R-Square	C.V.	Root MSE	Mean
0.703654	48.9024	0.1485	0.3036

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.7342	0.7342	33.30	0.0001
PPF	1	0.8770	0.8770	39.78	0.0001
LAMP	1	0.0945	0.0945	4.29	0.0407
PPF*LAMP	1	0.0069	0.0069	0.31	0.5775
BLF(LAMP)	4	3.0468	0.7617	34.55	0.0001
PPF*BLF(LAMP)	4	0.4084	0.1021	4.63	0.0017
REP*PPF	1	0.1924	0.1924	8.73	0.0038
REP*PPF*LAMP	2	0.0040	0.0020	0.09	0.9126
REP*PPF*BLF(LAMP)	7	0.4238	0.0605	2.75	0.0113

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	0.8770	0.8770	4.56	0.2789

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.0945	0.0945	46.80	0.0207

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0069	0.0069	3.41	0.2061

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	3.0468	0.7617	12.58	0.0026

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.4084	0.1021	1.69	0.2561

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Stem Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	0.0165	0.0007	5.15	0.0001
Error	115	0.0167	0.0001		
Corrected Total	137	0.0332			

R-Square	C.V.	Root MSE	Mean
0.496185	62.7105	0.0121	0.0192

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.0017	0.0017	11.61	0.0009
PPF	1	0.0029	0.0029	19.75	0.0001
LAMP	1	0.0001	0.0001	0.89	0.3464
PPF*LAMP	1	0.0001	0.0001	0.81	0.3693
BLF(LAMP)	4	0.0065	0.0016	11.22	0.0001
PPF*BLF(LAMP)	4	0.0020	0.0005	3.35	0.0124
REP*PPF	1	0.0002	0.0002	1.64	0.2023
REP*PPF*LAMP	2	0.0010	0.0005	3.34	0.0390
REP*PPF*BLF(LAMP)	7	0.0013	0.0002	1.26	0.2788

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	0.0029	0.0029	12.01	0.1788

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.0001	0.0001	0.27	0.6563

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0001	0.0001	0.24	0.6706

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.0065	0.0016	8.94	0.0070

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0020	0.0005	2.67	0.1218

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Root Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	0.2120	0.0096	15.13	0.0001
Error	115	0.0732	0.0006		
Corrected Total	137	0.2853			

R-Square	C.V.	Root MSE	Mean
0.743222	47.5144	0.0252	0.0531

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.0122	0.0122	19.22	0.0001
PPF	1	0.0541	0.0541	85.00	0.0001
LAMP	1	0.0103	0.0103	16.23	0.0001
PPF*LAMP	1	0.0000	0.0000	0.05	0.8276
BLF(LAMP)	4	0.0958	0.0239	37.59	0.0001
PPF*BLF(LAMP)	4	0.0204	0.0051	7.99	0.0001
REP*PPF	1	0.0041	0.0041	6.36	0.0130
REP*PPF*LAMP	2	0.0003	0.0001	0.22	0.8028
REP*PPF*BLF(LAMP)	7	0.0080	0.0011	1.80	0.0943

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	0.0541	0.0541	13.36	0.1700

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.0103	0.0103	73.77	0.0133

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0000	0.0000	0.22	0.6874

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.0958	0.0239	20.91	0.0005

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0204	0.0051	4.44	0.0421

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Total Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	9.0539	0.4115	12.87	0.0001
Error	115	3.6777	0.0320		
Corrected Total	137	12.7316			

R-Square	C.V.	Root MSE	Mean
0.711138	47.5626	0.1788	0.3760

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	1.0173	1.0173	31.81	0.0001
PPF	1	1.4953	1.4953	46.76	0.0001
LAMP	1	0.1581	0.1581	4.94	0.0281
PPF*LAMP	1	0.0060	0.0060	0.19	0.6652
BLF(LAMP)	4	4.5337	1.1334	35.44	0.0001
PPF*BLF(LAMP)	4	0.6432	0.1608	5.03	0.0009
REP*PPF	1	0.2681	0.2681	8.38	0.0045
REP*PPF*LAMP	2	0.0087	0.0044	0.14	0.8724
REP*PPF*BLF(LAMP)	7	0.5771	0.0824	2.58	0.0166

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	1.4953	1.4953	5.58	0.2550

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.1581	0.1581	36.19	0.0265

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0060	0.0060	1.38	0.3613

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	4.5337	1.1334	13.75	0.0020

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.6432	0.1608	1.95	0.2069

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Percent Leaf

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	3384.7205	153.8509	17.10	0.0001
Error	115	1034.6408	8.9969		
Corrected Total	137	4419.3613			

R-Square	C.V.	Root MSE	Mean
0.765885	3.8209	2.9995	78.5025

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	34.0889	34.0889	3.79	0.0540
PPF	1	185.3436	185.3436	20.60	0.0001
LAMP	1	305.9006	305.9006	34.00	0.0001
PPF*LAMP	1	9.8418	9.8418	1.09	0.2978
BLF(LAMP)	4	2071.5034	517.8759	57.56	0.0001
PPF*BLF(LAMP)	4	361.0678	90.2670	10.03	0.0001
REP*PPF	1	14.3079	14.3079	1.59	0.2098
REP*PPF*LAMP	2	118.6777	59.3388	6.60	0.0019
REP*PPF*BLF(LAMP)	7	225.1564	32.1652	3.58	0.0016

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	185.3436	185.3436	12.95	0.1725

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	305.9006	305.9006	5.16	0.1512

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	9.8418	9.8418	0.17	0.7233

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	2071.5034	517.8759	16.10	0.0012

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	361.0678	90.2670	2.81	0.1108

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Percent Stem

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	4873.3968	221.5180	23.99	0.0001
Error	115	1061.7103	9.2323		
Corrected Total	137	5935.1071			

R-Square	C.V.	Root MSE	Mean
0.821114	38.8785	3.0385	7.8153

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	5.4471	5.4471	0.59	0.4440
PPF	1	7.4945	7.4945	0.81	0.3695
LAMP	1	1341.2497	1341.2497	145.28	0.0001
PPF*LAMP	1	52.7208	52.7208	5.71	0.0185
BLF(LAMP)	4	2985.0023	746.2506	80.83	0.0001
PPF*BLF(LAMP)	4	114.0869	28.5217	3.09	0.0186
REP*PPF	1	1.0616	1.0616	0.11	0.7352
REP*PPF*LAMP	2	106.4027	53.2014	5.76	0.0041
REP*PPF*BLF(LAMP)	7	169.3837	24.1977	2.62	0.0151

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	7.4945	7.4945	7.06	0.2292

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	1341.2497	1341.2497	25.21	0.0375

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	52.7208	52.7208	0.99	0.4244

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	2985.0023	746.2506	30.84	0.0002

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	114.0869	28.5217	1.18	0.3972

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Percent Root

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	1045.8156	47.5371	8.43	0.0001
Error	115	648.3264	5.6376		
Corrected Total	137	1694.1419			

R-Square	C.V.	Root MSE	Mean
0.617313	17.3536	2.3744	13.6822

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	66.7892	66.7892	11.85	0.0008
PPF	1	267.3784	267.3784	47.43	0.0001
LAMP	1	366.0740	366.0740	64.93	0.0001
PPF*LAMP	1	17.0053	17.0053	3.02	0.0851
BLF(LAMP)	4	147.6967	36.9242	6.55	0.0001
PPF*BLF(LAMP)	4	95.7401	23.9350	4.25	0.0031
REP*PPF	1	23.1643	23.1643	4.11	0.0450
REP*PPF*LAMP	2	23.6482	11.8241	2.10	0.1275
REP*PPF*BLF(LAMP)	7	72.8575	10.4082	1.85	0.0850

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	267.3784	267.3784	11.54	0.1822

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	366.0740	366.0740	30.96	0.0308

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	17.0053	17.0053	1.44	0.3532

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	147.6967	36.9242	3.55	0.0693

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	95.7401	23.9350	2.30	0.1585

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Specific Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	198012.4487	9000.5659	76.50	0.0001
Error	115	13529.3901	117.6469		
Corrected Total	137	211541.8388			

R-Square	C.V.	Root MSE	Mean
0.936044	14.1704	10.8465	76.5433

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	1533.4103	1533.4103	13.03	0.0005
PPF	1	148.5769	148.5769	1.26	0.2634
LAMP	1	37654.4270	37654.4270	320.06	0.0001
PPF*LAMP	1	3693.6400	3693.6400	31.40	0.0001
BLF(LAMP)	4	135420.0067	33855.0017	287.77	0.0001
PPF*BLF(LAMP)	4	11123.4320	2780.8580	23.64	0.0001
REP*PPF	1	3138.3091	3138.3091	26.68	0.0001
REP*PPF*LAMP	2	866.6295	433.3147	3.68	0.0282
REP*PPF*BLF(LAMP)	7	1821.6285	260.2326	2.21	0.0381

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	148.5769	148.5769	0.05	0.8636

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	37654.4270	37654.4270	86.90	0.0113

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	3693.6400	3693.6400	8.52	0.1000

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	135420.0067	33855.0017	130.10	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	11123.4320	2780.8580	10.69	0.0042

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Stem Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	228459.4348	10384.5198	110.81	0.0001
Error	115	10777.6667	93.7188		
Corrected Total	137	239237.1014			

R-Square	C.V.	Root MSE	Mean
0.954950	25.6029	9.6808	37.8116

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	2377.0396	2377.0396	25.36	0.0001
PPF	1	553.9830	553.9830	5.91	0.0166
LAMP	1	63676.1248	63676.1248	679.44	0.0001
PPF*LAMP	1	3.3201	3.3201	0.04	0.8510
BLF(LAMP)	4	150317.2810	37579.3203	400.98	0.0001
PPF*BLF(LAMP)	4	3855.0185	963.7546	10.28	0.0001
REP*PPF	1	357.1012	357.1012	3.81	0.0534
REP*PPF*LAMP	2	1440.8889	720.4444	7.69	0.0007
REP*PPF*BLF(LAMP)	7	5021.3889	717.3413	7.65	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	553.9830	553.9830	1.55	0.4307

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	63676.1248	63676.1248	88.38	0.0111

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	3.3201	3.3201	0.00	0.9521

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	150317.2810	37579.3203	52.39	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	3855.0185	963.7546	1.34	0.3431

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Leaf Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	164.0490	7.4568	23.76	0.0001
Error	115	36.0933	0.3139		
Corrected Total	137	200.1423			

R-Square	C.V.	Root MSE	Mean
0.819662	0.5953	0.5602	94.1151

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	8.5939	8.5939	27.38	0.0001
PPF	1	0.0811	0.0811	0.26	0.6122
LAMP	1	19.4906	19.4906	62.10	0.0001
PPF*LAMP	1	6.4259	6.4259	20.47	0.0001
BLF(LAMP)	4	86.9469	21.7367	69.26	0.0001
PPF*BLF(LAMP)	4	7.1279	1.7820	5.68	0.0003
REP*PPF	1	16.4739	16.4739	52.49	0.0001
REP*PPF*LAMP	2	2.2700	1.1350	3.62	0.0300
REP*PPF*BLF(LAMP)	7	11.6806	1.6687	5.32	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	0.0811	0.0811	0.00	0.9554

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	19.4906	19.4906	17.17	0.0536

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	6.4259	6.4259	5.66	0.1404

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	86.9469	21.7367	13.03	0.0023

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	7.1279	1.7820	1.07	0.4391

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Stem Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	1506.8955	68.4952	1.78	0.0273
Error	115	4436.1847	38.5755		
Corrected Total	137	5943.0802			

R-Square	C.V.	Root MSE	Mean
0.253555	6.6752	6.2109	93.0444

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	3.2681	3.2681	0.08	0.7715
PPF	1	141.2977	141.2977	3.66	0.0581
LAMP	1	262.3557	262.3557	6.80	0.0103
PPF*LAMP	1	105.3606	105.3606	2.73	0.1011
BLF(LAMP)	4	409.0566	102.2642	2.65	0.0367
PPF*BLF(LAMP)	4	112.8530	28.2132	0.73	0.5723
REP*PPF	1	34.7292	34.7292	0.90	0.3447
REP*PPF*LAMP	2	179.8305	89.9152	2.33	0.1018
REP*PPF*BLF(LAMP)	7	345.0543	49.2935	1.28	0.2674

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	141.2977	141.2977	4.07	0.2930

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	262.3557	262.3557	2.92	0.2297

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	105.3606	105.3606	1.17	0.3922

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	409.0566	102.2642	2.07	0.1878

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	112.8530	28.2132	0.57	0.6918

Table D.2 - Continued

General Linear Models Procedure

Dependent Variable: Root Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	22	83.8420	3.8110	3.26	0.0001
Error	115	134.3240	1.1680		
Corrected Total	137	218.1660			

R-Square	C.V.	Root MSE	Mean
0.384304	1.1361	1.0808	95.1315

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	19.8207	19.8207	16.97	0.0001
PPF	1	3.3579	3.3579	2.87	0.0927
LAMP	1	7.6872	7.6872	6.58	0.0116
PPF*LAMP	1	0.2185	0.2185	0.19	0.6662
BLF(LAMP)	4	4.6028	1.1507	0.99	0.4186
PPF*BLF(LAMP)	4	4.3599	1.0900	0.93	0.4474
REP*PPF	1	22.1804	22.1804	18.99	0.0001
REP*PPF*LAMP	2	4.0730	2.0365	1.74	0.1795
REP*PPF*BLF(LAMP)	7	18.9812	2.7116	2.32	0.0298

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	3.3579	3.3579	0.15	0.7638

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	7.6872	7.6872	3.77	0.1915

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.2185	0.2185	0.11	0.7744

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	4.6028	1.1507	0.42	0.7872

Tests of Hypotheses using the Type III MS for REP*PPF*BLF (LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	4.3599	1.0900	0.40	0.8020

Table D.3 - ANOVA tables for soybean parameters in Chapter 4

Analysis of Variance Procedure

Dependent Variable: Chlorophyll

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	2029.7675	88.2507	13.59	0.0001
Error	120	779.2100	6.4934		
Corrected Total	143	2808.9775			

R-Square	C.V.	Root MSE	Mean
0.7226	7.3656	2.5482	34.5958

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	39.9002	39.9003	6.14	0.0146
PPF	1	594.5469	594.5469	91.56	0.0001
LAMP	1	1.6044	1.6044	0.25	0.6200
PPF*LAMP	1	0.0100	0.0100	0.00	0.9688
BLF(LAMP)	4	311.5372	77.8843	11.99	0.0001
PPF*BLF(LAMP)	4	27.8706	6.9676	1.07	0.3730
REP*PPF	1	957.9025	957.9025	147.52	0.0001
REP*PPF*LAMP	2	10.2444	5.1222	0.79	0.4567
REP*PPF*BLF(LAMP)	8	86.1511	10.7689	1.66	0.1156

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	594.5469	594.5469	0.62	0.5752

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	1.6044	1.6044	0.31	0.6320

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0100	0.0100	0.00	0.9688

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	311.5372	77.8843	7.23	0.0091

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	27.8706	6.9676	0.65	0.6446

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	2824428.2469	122801.2281	14.49	0.0001
Error	120	1016736.2341	8472.8020		
Corrected Total	143	3841164.4811			

R-Square	C.V.	Root MSE	Mean
0.7353	19.3168	92.0478	476.5160

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	395110.7211	395110.7211	46.63	0.0001
PPF	1	1676429.3529	1676429.3529	197.86	0.0001
LAMP	1	16844.5788	16844.5788	1.99	0.1611
PPF*LAMP	1	5300.0827	5300.0827	0.63	0.4306
BLF(LAMP)	4	186310.2714	46577.5678	5.50	0.0004
PPF*BLF(LAMP)	4	102767.4795	25691.8699	3.03	0.0202
REP*PPF	1	321273.5761	321273.5761	37.92	0.0001
REP*PPF*LAMP	2	28171.8094	14085.9047	1.66	0.1940
REP*PPF*BLF(LAMP)	8	92220.3751	11527.5469	1.36	0.2208

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	1676429.3529	1676429.3529	5.22	0.2627

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	16844.5788	16844.5788	1.20	0.3883

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	5300.0827	5300.0827	0.38	0.6021

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	186310.2714	46577.5678	4.04	0.0442

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	102767.4795	25691.8699	2.23	0.1555

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Leaf Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	29.0927	1.2649	14.91	0.0001
Error	120	10.1833	0.0849		
Corrected Total	143	39.2760			

R-Square	C.V.	Root MSE	Mean
0.7407	22.3403	0.2913	1.3040

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	2.9237	2.9237	34.45	0.0001
PPF	1	20.1972	20.1972	238.00	0.0001
LAMP	1	0.3253	0.3253	3.83	0.0526
PPF*LAMP	1	0.0435	0.0435	0.51	0.4752
BLF(LAMP)	4	0.7602	0.1900	2.24	0.0688
PPF*BLF(LAMP)	4	0.5142	0.1286	1.51	0.2021
REP*PPF	1	3.0106	3.0106	35.48	0.0001
REP*PPF*LAMP	2	0.3377	0.1688	1.99	0.1412
REP*PPF*BLF(LAMP)	8	0.9802	0.1225	1.44	0.1853

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	20.1972	20.1972	6.71	0.2346

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	0.3253	0.3253	1.93	0.2995

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0435	0.0435	0.26	0.6620

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.7602	0.1900	1.55	0.2764

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.5142	0.1286	1.05	0.4398

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Stem Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	5.3676	0.2334	14.29	0.0001
Error	120	1.9601	0.0163		
Corrected Total	143	7.3278			

R-Square	C.V.	Root MSE	Mean
0.7325	25.9084	0.1278	0.4933

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	0.5201	0.5201	31.84	0.0001
PPF	1	1.9939	1.9939	122.07	0.0001
LAMP	1	0.6981	0.6981	42.74	0.0001
PPF*LAMP	1	0.0016	0.0016	0.10	0.7540
BLF(LAMP)	4	0.5221	0.1305	7.99	0.0001
PPF*BLF(LAMP)	4	0.1614	0.0404	2.47	0.0482
REP*PPF	1	1.2090	1.2090	74.02	0.0001
REP*PPF*LAMP	2	0.0139	0.0070	0.43	0.6539
REP*PPF*BLF(LAMP)	8	0.2475	0.0309	1.89	0.0669

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	1.9939	1.9939	1.65	0.4212

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	0.6981	0.6981	100.25	0.0098

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0016	0.0016	0.23	0.6780

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.5221	0.1305	4.22	0.0397

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.1614	0.0404	1.30	0.3462

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Root Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	3.7202	0.1617	16.66	0.0001
Error	120	1.1648	0.0097		
Corrected Total	143	4.8850			

R-Square	C.V.	Root MSE	Mean
0.7615	21.0591	0.0985	0.4678

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	0.2482	0.2482	25.57	0.0001
PPF	1	3.0150	3.0150	310.60	0.0001
LAMP	1	0.0005	0.0005	0.05	0.8296
PPF*LAMP	1	0.0034	0.0034	0.35	0.5541
BLF(LAMP)	4	0.1740	0.0435	4.48	0.0021
PPF*BLF(LAMP)	4	0.0863	0.0216	2.22	0.0707
REP*PPF	1	0.0949	0.0949	9.78	0.0022
REP*PPF*LAMP	2	0.0251	0.0126	1.29	0.2782
REP*PPF*BLF(LAMP)	8	0.0728	0.0091	0.94	0.4882

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	3.0150	3.0150	31.77	0.1118

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	0.0005	0.0005	0.04	0.8670

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0034	0.0034	0.27	0.6538

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.1740	0.0435	4.78	0.0290

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0863	0.0216	2.37	0.1392

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Total Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	87.2863	3.7951	15.04	0.0001
Error	120	30.2805	0.2523		
Corrected Total	143	117.5668			

R-Square	C.V.	Root MSE	Mean
0.7424	22.1770	0.5023	2.2651

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	8.5803	8.5803	34.00	0.0001
PPF	1	58.4088	58.4088	231.47	0.0001
LAMP	1	2.0367	2.0367	8.07	0.0053
PPF*LAMP	1	0.0515	0.0515	0.20	0.6522
BLF(LAMP)	4	3.1447	0.7862	3.12	0.0177
PPF*BLF(LAMP)	4	1.7820	0.4455	1.77	0.1403
REP*PPF	1	9.8768	9.8768	39.14	0.0001
REP*PPF*LAMP	2	0.5985	0.2993	1.19	0.3090
REP*PPF*BLF(LAMP)	8	2.8070	0.3509	1.39	0.2074

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	58.4088	58.4088	5.91	0.2484

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	2.0367	2.0367	6.81	0.1209

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0515	0.0515	0.17	0.7185

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	3.1447	0.7862	2.24	0.1540

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	1.7820	0.4455	1.27	0.3574

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Percent Leaf

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	365.8129	15.9049	5.33	0.0001
Error	120	358.2880	2.9857		
Corrected Total	143	724.1009			

R-Square	C.V.	Root MSE	Mean
0.5052	3.0039	1.7279	57.5232

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	2.1833	2.1833	0.73	0.3942
PPF	1	30.5479	30.5479	10.23	0.0018
LAMP	1	123.0568	123.0568	41.21	0.0001
PPF*LAMP	1	1.0940	1.0940	0.37	0.5461
BLF(LAMP)	4	123.3096	30.8274	10.32	0.0001
PPF*BLF(LAMP)	4	19.7581	4.9395	1.65	0.1651
REP*PPF	1	15.5226	15.5226	5.20	0.0244
REP*PPF*LAMP	2	15.4555	7.7278	2.59	0.0793
REP*PPF*BLF(LAMP)	8	34.8849	4.3606	1.46	0.1788

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	30.5479	30.5479	1.97	0.3943

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	123.0568	123.0568	15.92	0.0574

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	1.0940	1.0940	0.14	0.7429

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	123.3096	30.8274	7.07	0.0097

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	19.7581	4.9395	1.13	0.4064

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Percent Stem

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1696.0549	73.7415	22.29	0.0001
Error	120	396.9207	3.3077		
Corrected Total	143	2092.9757			

R-Square	C.V.	Root MSE	Mean
0.8104	8.3979	1.8187	21.6567

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	0.1869	0.1869	0.06	0.8125
PPF	1	197.6523	197.6523	59.76	0.0001
LAMP	1	567.6235	567.6235	171.61	0.0001
PPF*LAMP	1	6.4000	6.4000	1.93	0.1668
BLF(LAMP)	4	401.8607	100.4652	30.37	0.0001
PPF*BLF(LAMP)	4	12.4462	3.1115	0.94	0.4430
REP*PPF	1	419.0011	419.0011	126.68	0.0001
REP*PPF*LAMP	2	5.6382	2.8191	0.85	0.4290
REP*PPF*BLF(LAMP)	8	85.2460	10.6557	3.22	0.0024

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	197.6523	197.6523	0.47	0.6169

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	567.6235	567.6235	201.35	0.0049

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	6.4000	6.4000	2.27	0.2709

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	401.8607	100.4652	9.43	0.0040

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	12.4462	3.1115	0.29	0.8752

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Percent Root

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	673.3762	29.2772	8.20	0.0001
Error	120	428.6502	3.5721		
Corrected Total	143	1102.0264			

R-Square	C.V.	Root MSE	Mean
0.6110	9.0778	1.8900	20.8200

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	1.0925	1.0925	0.31	0.5813
PPF	1	72.7929	72.7929	20.38	0.0001
LAMP	1	162.0976	162.0976	45.38	0.0001
PPF*LAMP	1	2.2018	2.2018	0.62	0.4339
BLF(LAMP)	4	109.4111	27.3528	7.66	0.0001
PPF*BLF(LAMP)	4	20.3998	5.1000	1.43	0.2289
REP*PPF	1	273.2291	273.2291	76.49	0.0001
REP*PPF*LAMP	2	3.2243	1.6122	0.45	0.6379
REP*PPF*BLF(LAMP)	8	28.9271	3.6159	1.01	0.4305

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	72.7929	72.7929	0.27	0.6967

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	162.0976	162.0976	100.55	0.0098

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	2.2018	2.2018	1.37	0.3630

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	109.4111	27.3528	7.56	0.0080

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	20.3998	5.1000	1.41	0.3139

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Specific Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1356.1913	58.9648	4.40	0.0001
Error	120	1609.0444	13.4087		
Corrected Total	143	2965.2358			

R-Square	C.V.	Root MSE	Mean
0.4574	9.7524	3.6618	37.5478

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	17.2721	17.2721	1.29	0.2587
PPF	1	848.8364	848.8364	63.30	0.0001
LAMP	1	41.5256	41.5256	3.10	0.0810
PPF*LAMP	1	1.8111	1.8111	0.14	0.7139
BLF(LAMP)	4	155.6552	38.9138	2.90	0.0247
PPF*BLF(LAMP)	4	70.3708	17.5927	1.31	0.2694
REP*PPF	1	22.6297	22.6297	1.69	0.1964
REP*PPF*LAMP	2	36.6656	18.3328	1.37	0.2588
REP*PPF*BLF(LAMP)	8	161.4247	20.1781	1.50	0.1625

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	848.8364	848.8364	37.51	0.1030

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	41.5256	41.5256	2.27	0.2712

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	1.8111	1.8111	0.10	0.7830

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	155.6552	38.9138	1.93	0.1991

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	70.3708	17.5927	0.87	0.5208

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Stem Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	927038.6597	40306.0287	11.77	0.0001
Error	120	411048.1667	3425.4014		
Corrected Total	143	1338086.8264			

R-Square	C.V.	Root MSE	Mean
0.6928	32.0537	58.5269	182.5903

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	8296.1736	8296.1736	2.42	0.1223
PPF	1	6019.1736	6019.1736	1.76	0.1875
LAMP	1	421742.0069	421742.0069	123.12	0.0001
PPF*LAMP	1	18112.6736	18112.6736	5.29	0.0232
BLF(LAMP)	4	260261.1111	65065.2778	18.99	0.0001
PPF*BLF(LAMP)	4	4373.7778	1093.4444	0.32	0.8646
REP*PPF	1	134995.0069	134995.0069	39.41	0.0001
REP*PPF*LAMP	2	21892.1806	10946.0903	3.20	0.0445
REP*PPF*BLF(LAMP)	8	51346.5556	6418.3194	1.87	0.0703

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	6019.1736	6019.1736	0.04	0.8675

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	421742.0069	421742.0069	38.53	0.0250

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	18112.6736	18112.6736	1.65	0.3271

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	260261.1111	65065.2778	10.14	0.0032

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	4373.7778	1093.4444	0.17	0.9475

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Branch Number

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	132.7500	5.7717	6.86	0.0001
Error	120	101.0000	0.8417		
Corrected Total	143	233.7500			

R-Square	C.V.	Root MSE	Mean
0.5679	16.5550	0.9174	5.5417

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	72.2500	72.2500	85.84	0.0001
PPF	1	8.0278	8.0278	9.54	0.0025
LAMP	1	0.1111	0.1111	0.13	0.7170
PPF*LAMP	1	0.0000	0.0000	0.00	1.0000
BLF(LAMP)	4	9.3889	2.3472	2.79	0.0295
PPF*BLF(LAMP)	4	22.2222	5.5556	6.60	0.0001
REP*PPF	1	17.3611	17.3611	20.63	0.0001
REP*PPF*LAMP	2	1.0000	0.5000	0.59	0.5537
REP*PPF*BLF(LAMP)	8	2.3889	0.2986	0.35	0.9420

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	8.0278	8.0278	0.46	0.6198

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	0.1111	0.1111	0.22	0.6838

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0000	0.0000	0.00	1.0000

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	9.3889	2.3472	7.86	0.0071

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	22.2222	5.5556	18.60	0.0004

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Leaf Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	168.9639	7.3463	4.02	0.0001
Error	120	219.0910	1.8258		
Corrected Total	143	388.0548			

R-Square	C.V.	Root MSE	Mean
0.4354	1.5985	1.3512	84.5285

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	2.7840	2.7840	1.52	0.2193
PPF	1	0.0137	0.0137	0.01	0.9311
LAMP	1	80.7845	80.7845	44.25	0.0001
PPF*LAMP	1	0.0714	0.0714	0.04	0.8435
BLF(LAMP)	4	42.7713	10.6928	5.86	0.0002
PPF*BLF(LAMP)	4	10.1511	2.5378	1.39	0.2415
REP*PPF	1	18.4968	18.4968	10.13	0.0019
REP*PPF*LAMP	2	0.4476	0.2238	0.12	0.8847
REP*PPF*BLF(LAMP)	8	13.4434	1.6804	0.92	0.5023

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	0.0137	0.0137	0.00	0.9827

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	80.7845	80.7845	360.98	0.0028

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0714	0.0714	0.32	0.6290

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	42.7713	10.6928	6.36	0.0132

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	10.1511	2.5378	1.51	0.2868

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Stem Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	87.4775	3.8034	4.60	0.0001
Error	120	99.2927	0.8274		
Corrected Total	143	186.7701			

R-Square	C.V.	Root MSE	Mean
0.4684	1.0091	0.9096	90.1429

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	8.5597	8.5597	10.34	0.0017
PPF	1	1.3994	1.3994	1.69	0.1959
LAMP	1	22.7158	22.7158	27.45	0.0001
PPF*LAMP	1	1.5684	1.5684	1.90	0.1711
BLF(LAMP)	4	25.8577	6.4644	7.81	0.0001
PPF*BLF(LAMP)	4	2.2345	0.5586	0.68	0.6105
REP*PPF	1	9.3235	9.3235	11.27	0.0011
REP*PPF*LAMP	2	3.1490	1.5745	1.90	0.1536
REP*PPF*BLF(LAMP)	8	12.6694	1.5837	1.91	0.0639

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	1.3994	1.3994	0.15	0.7647

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	22.7158	22.7158	14.43	0.0629

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	1.5684	1.5684	1.00	0.4234

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	25.8577	6.4644	4.08	0.0431

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	2.2345	0.5586	0.35	0.8353

Table D.3 - Continued

Analysis of Variance Procedure

Dependent Variable: Root Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	14.0861	0.6124	2.75	0.0002
Error	120	26.6772	0.2223		
Corrected Total	143	40.7632			

R-Square	C.V.	Root MSE	Mean
0.3456	0.5008	0.4715	94.1517

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	1	1.0805	1.0805	4.86	0.0294
PPF	1	1.5879	1.5879	7.14	0.0086
LAMP	1	2.9832	2.9832	13.42	0.0004
PPF*LAMP	1	1.5793	1.5793	7.10	0.0088
BLF(LAMP)	4	2.2396	0.5599	2.52	0.0448
PPF*BLF(LAMP)	4	0.3721	0.0930	0.42	0.7950
REP*PPF	1	0.5823	0.5823	2.62	0.1082
REP*PPF*LAMP	2	0.3811	0.1905	0.86	0.4270
REP*PPF*BLF(LAMP)	8	3.2801	0.4100	1.84	0.0753

Tests of Hypotheses using the Anova MS for REP*PPF as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF	1	1.5879	1.5879	2.73	0.3467

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LAMP	1	2.9832	2.9832	15.66	0.0583

Tests of Hypotheses using the Anova MS for REP*PPF*LAMP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	1.5793	1.5793	8.29	0.1024

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	2.2396	0.5599	1.37	0.3271

Tests of Hypotheses using the Anova MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.3721	0.0930	0.23	0.9158

Table D.4 - General linear model tables for wheat parameters in Chapter 4.

General Linear Models Procedure
Dependent Variable: Chlorophyll

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	8612.0795	374.4382	11.49	0.0001
Error	117	3813.3728	32.5929		
Corrected Total	140	12425.4523			
	R-Square	C.V.	Root MSE	Mean	
	0.693100	11.3837	5.7090	50.151	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	241.5683	241.5683	7.41	0.0075
PPF	1	6169.6192	6169.6192	189.29	0.0001
LAMP	1	18.4638	18.4638	0.57	0.4532
PPF*LAMP	1	31.4862	31.4862	0.97	0.3277
BLF(LAMP)	4	259.6953	64.9238	1.99	0.1002
PPF*BLF(LAMP)	4	142.5690	35.6423	1.09	0.3631
REP*PPF	1	1554.7206	1554.7206	47.70	0.0001
REP*PPF*LAMP	2	30.8628	15.4314	0.47	0.6240
REP*PPF*BLF(LAMP)	8	304.7154	38.0894	1.17	0.3239

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	6169.6192	6169.6192	3.97	0.2962

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	18.4638	18.4638	1.20	0.3882

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	31.4862	31.4862	2.04	0.2894

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	259.6953	64.9238	1.70	0.2413

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	142.5690	35.6423	0.94	0.4900

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	88839.5500	3862.5890	18.23	0.0001
Error	117	24783.9320	211.8280		
Corrected Total	140	113623.4820			
	R-Square	C.V.	Root MSE	Mean	
	0.781877	22.6730	14.5540	64.192	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	2241.3480	2241.3480	10.58	0.0015
PPF	1	70150.0640	70150.0640	331.16	0.0001
LAMP	1	3769.0750	3769.0750	17.79	0.0001
PPF*LAMP	1	1003.7050	1003.7050	4.74	0.0315
BLF(LAMP)	4	2977.0620	744.2660	3.51	0.0095
PPF*BLF(LAMP)	4	445.9270	111.4820	0.53	0.7166
REP*PPF	1	1724.3620	1724.3620	8.14	0.0051
REP*PPF*LAMP	2	372.0000	186.0000	0.88	0.4183
REP*PPF*BLF(LAMP)	8	6963.3200	870.4150	4.11	0.0002

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	70150.0640	70150.0640	40.68	0.0990

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	3769.0747	3769.0747	20.26	0.0460

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	1003.7049	1003.7049	5.40	0.1458

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	2977.0620	744.2655	0.86	0.5293

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	445.9271	111.4818	0.13	0.9679

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Leaf Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	2.3313	0.1014	34.69	0.0001
Error	117	0.3419	0.0029		
Corrected Total	140	2.6731			
	R-Square	C.V.	Root MSE	Mean	
	0.872104	21.1877	0.0541	0.2551	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.0689	0.0689	23.58	0.0001
PPF	1	2.0400	2.0400	698.14	0.0001
LAMP	1	0.0557	0.0557	19.04	0.0001
PPF*LAMP	1	0.0254	0.0254	8.70	0.0038
BLF(LAMP)	4	0.0219	0.0055	1.87	0.1198
PPF*BLF(LAMP)	4	0.0049	0.0012	0.42	0.7968
REP*PPF	1	0.0185	0.0185	6.31	0.0133
REP*PPF*LAMP	2	0.0100	0.0050	1.72	0.1841
REP*PPF*BLF(LAMP)	8	0.0967	0.0121	4.14	0.0002

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	2.0400	2.0400	110.57	0.0604

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.0557	0.0557	11.09	0.0795

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0254	0.0254	5.07	0.1532

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.0219	0.0055	0.45	0.7684

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0049	0.0012	0.10	0.9792

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Stem Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	0.5515	0.0240	32.50	0.0001
Error	117	0.0863	0.0007		
Corrected Total	140	0.6378			
	R-Square	C.V.	Root MSE	Mean	
	0.864657	23.7524	0.0272	0.1144	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.0077	0.0077	10.39	0.0016
PPF	1	0.4734	0.4734	641.62	0.0001
LAMP	1	0.0236	0.0236	31.94	0.0001
PPF*LAMP	1	0.0126	0.0126	17.09	0.0001
BLF(LAMP)	4	0.0083	0.0021	2.81	0.0285
PPF*BLF(LAMP)	4	0.0022	0.0005	0.73	0.5725
REP*PPF	1	0.0018	0.0018	2.42	0.1224
REP*PPF*LAMP	2	0.0012	0.0006	0.81	0.4454
REP*PPF*BLF(LAMP)	8	0.0208	0.0026	3.53	0.0011

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	0.4734	0.4734	264.94	0.0391

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.0236	0.0236	39.22	0.0246

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0126	0.0126	20.98	0.0445

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.0083	0.0021	0.80	0.5596

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0022	0.0005	0.21	0.9274

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Root Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1.2146	0.0528	30.54	0.0001
Error	117	0.2023	0.0017		
Corrected Total	140	1.4169			
	R-Square	C.V.	Root MSE	Mean	
	0.857213	24.4491	0.0416	0.1701	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.0010	0.0010	0.59	0.4436
PPF	1	1.0550	1.0550	610.11	0.0001
LAMP	1	0.0295	0.0295	17.06	0.0001
PPF*LAMP	1	0.0116	0.0116	6.69	0.0109
BLF(LAMP)	4	0.0029	0.0007	0.42	0.7931
PPF*BLF(LAMP)	4	0.0059	0.0015	0.86	0.4909
REP*PPF	1	0.0151	0.0151	8.74	0.0038
REP*PPF*LAMP	2	0.0026	0.0013	0.75	0.4745
REP*PPF*BLF(LAMP)	8	0.0800	0.0100	5.79	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	1.0550	1.0550	69.84	0.0758

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.0295	0.0295	22.74	0.0413

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.0116	0.0116	8.92	0.0962

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.0029	0.0007	0.07	0.9885

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0059	0.0015	0.15	0.9585

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Total Dry Mass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	11.1912	0.4866	38.31	0.0001
Error	117	1.4861	0.0127		
Corrected Total	140	12.6773			
	R-Square	C.V.	Root MSE	Mean	
	0.882772	20.8876	0.1127	0.5396	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.1012	0.1012	7.97	0.0056
PPF	1	9.8813	9.8813	777.93	0.0001
LAMP	1	0.3149	0.3149	24.79	0.0001
PPF*LAMP	1	0.1439	0.1439	11.33	0.0010
BLF(LAMP)	4	0.0721	0.0180	1.42	0.2319
PPF*BLF(LAMP)	4	0.0216	0.0054	0.42	0.7903
REP*PPF	1	0.0906	0.0906	7.13	0.0086
REP*PPF*LAMP	2	0.0341	0.0170	1.34	0.2655
REP*PPF*BLF(LAMP)	8	0.5215	0.0652	5.13	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	9.8813	9.8813	109.06	0.0608

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.3149	0.3149	18.49	0.0501

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.1439	0.1439	8.45	0.1008

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	0.0721	0.0180	0.28	0.8851

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	0.0216	0.0054	0.08	0.9854

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Percent Leaf

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1128.2406	49.0539	7.14	0.0001
Error	117	804.3016	6.8744		
Corrected Total	140	1932.5422			
	R-Square	C.V.	Root MSE	Mean	
	0.583812	5.5065	2.6219	47.614	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	695.5703	695.5703	101.18	0.0001
PPF	1	88.7210	88.7210	12.91	0.0005
LAMP	1	27.3764	27.3764	3.98	0.0483
PPF*LAMP	1	1.3411	1.3411	0.20	0.6595
BLF(LAMP)	4	74.2083	18.5521	2.70	0.0340
PPF*BLF(LAMP)	4	39.2121	9.8030	1.43	0.2297
REP*PPF	1	111.5252	111.5252	16.22	0.0001
REP*PPF*LAMP	2	2.9435	1.4718	0.21	0.8076
REP*PPF*BLF(LAMP)	8	118.0829	14.7604	2.15	0.0366

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	88.7210	88.7210	0.80	0.5363

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	27.3764	27.3764	18.60	0.0498

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	1.3411	1.3411	0.91	0.4405

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	74.2083	18.5521	1.26	0.3617

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	39.2121	9.8030	0.66	0.6343

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Percent Stem

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	203.4762	8.8468	1.84	0.0186
Error	117	562.0872	4.8042		
Corrected Total	140	765.5633			
	R-Square	C.V.	Root MSE	Mean	
	0.265786	10.5098	2.1918	20.855	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	4.9750	4.9750	1.04	0.3110
PPF	1	40.6299	40.6299	8.46	0.0044
LAMP	1	32.6308	32.6308	6.79	0.0103
PPF*LAMP	1	10.2001	10.2001	2.12	0.1478
BLF(LAMP)	4	37.9782	9.4946	1.98	0.1026
PPF*BLF(LAMP)	4	22.1161	5.5290	1.15	0.3362
REP*PPF	1	3.9275	3.9275	0.82	0.3678
REP*PPF*LAMP	2	4.9201	2.4600	0.51	0.6006
REP*PPF*BLF(LAMP)	8	45.6776	5.7097	1.19	0.3118

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	40.6299	40.6299	10.34	0.1919

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	32.6308	32.6308	13.26	0.0678

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	10.2001	10.2001	4.15	0.1787

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	37.9782	9.4946	1.66	0.2503

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	22.1161	5.5290	0.97	0.4750

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Percent Root

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1296.2155	56.3572	3.70	0.0001
Error	117	1781.5174	15.2266		
Corrected Total	140	3077.7328			
	R-Square	C.V.	Root MSE	Mean	
	0.421159	12.3758	3.9021	31.530	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	818.1966	818.1966	53.73	0.0001
PPF	1	9.2722	9.2722	0.61	0.4368
LAMP	1	0.2305	0.2305	0.02	0.9023
PPF*LAMP	1	18.9382	18.9382	1.24	0.2670
BLF(LAMP)	4	120.0547	30.0137	1.97	0.1034
PPF*BLF(LAMP)	4	71.6637	17.9159	1.18	0.3247
REP*PPF	1	73.5949	73.5949	4.83	0.0299
REP*PPF*LAMP	2	0.2525	0.1263	0.01	0.9917
REP*PPF*BLF(LAMP)	8	255.3636	31.9204	2.10	0.0414

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	9.2722	9.2722	0.13	0.7829

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.2305	0.2305	1.83	0.3092

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	18.9382	18.9382	149.99	0.0066

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	120.0547	30.0137	0.94	0.4879

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	71.6636	17.9159	0.56	0.6977

Table D.4 - Continued

General Linear Models
Procedure
Dependent Variable: Specific Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	3735.7062	162.4220	46.78	0.0001
Error	117	406.2622	3.4723		
Corrected Total	140	4141.9684			
	R-Square	C.V.	Root MSE	Mean	
	0.901916	6.7656	1.8634	27.542	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	343.9440	343.9440	99.05	0.0001
PPF	1	3028.1775	3028.1775	872.09	0.0001
LAMP	1	4.4718	4.4718	1.29	0.2588
PPF*LAMP	1	2.9786	2.9786	0.86	0.3563
BLF(LAMP)	4	87.9490	21.9873	6.33	0.0001
PPF*BLF(LAMP)	4	12.4365	3.1091	0.90	0.4691
REP*PPF	1	174.3310	174.3310	50.21	0.0001
REP*PPF*LAMP	2	10.7476	5.3738	1.55	0.2171
REP*PPF*BLF(LAMP)	8	111.8238	13.9780	4.03	0.0003

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	3028.1775	3028.1775	17.37	0.1499

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	4.4718	4.4718	0.83	0.4579

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	2.9786	2.9786	0.55	0.5342

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	87.9490	21.9873	1.57	0.2711

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	12.4365	3.1091	0.22	0.9184

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Stem Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	5570.9149	242.2137	5.64	0.0001
Error	117	5024.3333	42.9430		
Corrected Total	140	10595.2482			
	R-Square	C.V.	Root MSE	Mean	
	0.525794	8.9568	6.5531	73.163	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	251.3428	251.3428	5.85	0.0171
PPF	1	1874.0148	1874.0148	43.64	0.0001
LAMP	1	840.8165	840.8165	19.58	0.0001
PPF*LAMP	1	34.0148	34.0148	0.79	0.3753
BLF(LAMP)	4	498.8828	124.7207	2.90	0.0247
PPF*BLF(LAMP)	4	214.2684	53.5671	1.25	0.2948
REP*PPF	1	1230.2901	1230.2901	28.65	0.0001
REP*PPF*LAMP	2	128.1897	64.0949	1.49	0.2290
REP*PPF*BLF(LAMP)	8	551.7968	68.9746	1.61	0.1303

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	1874.0148	1874.0148	1.52	0.4335

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	840.8165	840.8165	13.12	0.0685

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	34.0148	34.0148	0.53	0.5421

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	498.8828	124.7207	1.81	0.2206

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	214.2684	53.5671	0.78	0.5704

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Tiller Number

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	736.1670	32.0073	36.43	0.0001
Error	117	102.7833	0.8785		
Corrected Total	140	838.9504			
	R-Square	C.V.	Root MSE	Mean	
	0.877486	21.0440	0.9373	4.4539	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	0.0082	0.0082	0.01	0.9234
PPF	1	619.9029	619.9029	705.65	0.0001
LAMP	1	36.8503	36.8503	41.95	0.0001
PPF*LAMP	1	13.1229	13.1229	14.94	0.0002
BLF(LAMP)	4	11.8803	2.9701	3.38	0.0117
PPF*BLF(LAMP)	4	8.0538	2.0134	2.29	0.0636
REP*PPF	1	1.9272	1.9272	2.19	0.1413
REP*PPF*LAMP	2	0.1400	0.0700	0.08	0.9235
REP*PPF*BLF(LAMP)	8	37.8754	4.7344	5.39	0.0001

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	619.9029	619.9029	321.66	0.0355

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	36.8503	36.8503	526.42	0.0019

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	13.1229	13.1229	187.46	0.0053

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	11.8803	2.9701	0.63	0.6565

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	8.0538	2.0134	0.43	0.7868

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Leaf Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	573.8760	24.9511	29.63	0.0001
Error	117	98.5207	0.8421		
Corrected Total	140	672.3968			
	R-Square	C.V.	Root MSE	Mean	
	0.853478	1.0871	0.9176	84.415	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	21.1394	21.1394	25.10	0.0001
PPF	1	498.7506	498.7506	592.30	0.0001
LAMP	1	15.9113	15.9113	18.90	0.0001
PPF*LAMP	1	0.5262	0.5262	0.62	0.4308
BLF(LAMP)	4	7.0679	1.7670	2.10	0.0854
PPF*BLF(LAMP)	4	9.1263	2.2816	2.71	0.0335
REP*PPF	1	0.3510	0.3510	0.42	0.5198
REP*PPF*LAMP	2	0.7894	0.3947	0.47	0.6270
REP*PPF*BLF(LAMP)	8	21.1581	2.6448	3.14	0.0030

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	498.7506	498.7506	1421.15	0.0169

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	15.9113	15.9113	40.31	0.0239

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	0.5262	0.5262	1.33	0.3676

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	7.0679	1.7670	0.67	0.6320

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	9.1263	2.2816	0.86	0.5254

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Stem Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	102.6964	4.4651	11.18	0.0001
Error	117	46.7422	0.3995		
Corrected Total	140	149.4386			
	R-Square	C.V.	Root MSE	Mean	
	0.687214	0.7094	0.6321	89.1040	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	2.9518	2.9518	7.39	0.0076
PPF	1	71.8970	71.8970	179.96	0.0001
LAMP	1	3.5527	3.5527	8.89	0.0035
PPF*LAMP	1	5.4439	5.4439	13.63	0.0003
BLF(LAMP)	4	2.0330	0.5082	1.27	0.2849
PPF*BLF(LAMP)	4	3.9311	0.9828	2.46	0.0492
REP*PPF	1	4.1219	4.1219	10.32	0.0017
REP*PPF*LAMP	2	0.4958	0.2479	0.62	0.5394
REP*PPF*BLF(LAMP)	8	7.9295	0.9912	2.48	0.0160

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	71.8970	71.8970	17.44	0.1496

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	3.5527	3.5527	14.33	0.0632

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	5.4439	5.4439	21.96	0.0426

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	2.0330	0.5082	0.51	0.7289

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	3.9311	0.9828	0.99	0.4646

Table D.4 - Continued

General Linear Models Procedure
Dependent Variable: Root Relative Water Content

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	131.0041	5.6958	6.94	0.0001
Error	117	96.0658	0.8211		
Corrected Total	140	227.0698			
	R-Square	C.V.	Root MSE	Mean	
	0.576933	0.9760	0.9061	92.8410	
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	1	2.0858	2.0858	2.54	0.1137
PPF	1	2.8035	2.8035	3.41	0.0672
LAMP	1	0.6785	0.6785	0.83	0.3652
PPF*LAMP	1	8.5095	8.5095	10.36	0.0017
BLF(LAMP)	4	9.9248	2.4812	3.02	0.0206
PPF*BLF(LAMP)	4	11.9899	2.9975	3.65	0.0077
REP*PPF	1	88.7927	88.7927	108.14	0.0001
REP*PPF*LAMP	2	0.1065	0.0533	0.06	0.9372
REP*PPF*BLF(LAMP)	8	13.2452	1.6557	2.02	0.0502

Tests of Hypotheses using the Type III MS for REP*PPF as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF	1	2.8035	2.8035	0.03	0.8880

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LAMP	1	0.6785	0.6785	12.74	0.0703

Tests of Hypotheses using the Type III MS for REP*PPF*LAMP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*LAMP	1	8.5095	8.5095	159.74	0.0062

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP)as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLF(LAMP)	4	9.9248	2.4812	1.50	0.2898

Tests of Hypotheses using the Type III MS for REP*PPF*BLF(LAMP) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PPF*BLF(LAMP)	4	11.9899	2.9975	1.81	0.2201

Table D.5 - General linear model tables for lettuce leaf parameters in Chapter 5.

General Linear Models Procedure

Dependent Variable: Cell Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	1680.7063	93.3726	20.22	0.0050
Error	4	18.4720	4.6180		
Corrected Total	22	1699.1783			

R-Square	C.V.	Root MSE	Mean
0.989129	16.41512	2.1490	13.091

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	5	101.7820	20.3564	4.41	0.0878
BLUE	1	1267.7627	1267.7627	274.53	0.0001
BLUE*REP	5	44.7062	8.9412	1.94	0.2709
LOCALE	1	0.7605	0.7605	0.16	0.7057
LOCALE*REP	5	25.6195	5.1239	1.11	0.4731
BLUE*LOCALE	1	10.6580	10.6580	2.31	0.2033

Tests of Hypotheses using the Type III MS for BLUE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLUE	1	1267.7627	1267.7627	141.79	0.0001

Tests of Hypotheses using the Type III MS for BLUE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	5	101.78200	20.35640	2.28	0.1938

Tests of Hypotheses using the Type III MS for LOCALE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LOCALE	1	0.7605000	0.7605000	0.15	0.7159

General Linear Models Procedure

Dependent Variable: Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	12.603956	0.700220	4.78	0.0701
Error	4	0.586148	0.146537		
Corrected Total	22	13.190104			

R-Square	C.V.	Root MSE	Mean
0.955562	29.16535	0.3828	1.3125

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	5	0.3154296	0.0630859	0.43	0.8099
BLUE	1	8.5012107	8.5012107	58.01	0.0016
BLUE*REP	5	0.7470651	0.1494130	1.02	0.5066
LOCALE	1	0.4305156	0.4305156	2.94	0.1617
LOCALE*REP	5	0.6584938	0.1316988	0.90	0.5567
BLUE*LOCALE	1	0.3312738	0.3312738	2.26	0.2071

Tests of Hypotheses using the Type III MS for BLUE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLUE	1	8.5012107	8.5012107	56.90	0.0006

Tests of Hypotheses using the Type III MS for BLUE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	5	0.3154296	0.0630859	0.42	0.8171

Tests of Hypotheses using the Type III MS for LOCALE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LOCALE	1	0.4305156	0.4305156	3.27	0.1304

Table D.5 - Continued

General Linear Models Procedure
Dependent Variable: Number of Cells

Source	DF		Sum of Squares	Mean Square	F Value	Pr > F
Model	18		3.462E+14	1.923E+13	3.21	0.1334
Error	4		2.395E+13	5.988E+12		
Corrected Total	22		3.702E+14			
		R-Square	C.V.	Root MSE	Mean	
		0.935291	25.52937	2447093	9585403	
Source	DF		Type III SS	Mean Square	F Value	Pr > F
REP	5		1.071E+14	2.141E+13	3.58	0.1204
BLUE	1		8.176E+13	8.176E+13	13.65	0.0209
BLUE*REP	5		1.866E+13	3.731E+12	0.62	0.6949
LOCALE	1		1.635E+13	1.635E+13	2.73	0.1738
LOCALE*REP	5		9.491E+13	1.898E+13	3.17	0.1433
BLUE*LOCALE	1		1.874E+11	1.874E+11	0.03	0.8682

Tests of Hypotheses using the Type III MS for BLUE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BLUE	1	8.176E+13	8.176E+13	21.91	0.0054

Tests of Hypotheses using the Type III MS for BLUE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	5	1.071E+14	2.141E+13	5.74	0.0390

Tests of Hypotheses using the Type III MS for LOCALE*REP as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LOCALE	1	1.635E+13	1.635E+13	0.86	0.3959

Table D.6 - ANOVA tables for soybean leaf parameters in Chapter 5.

Analysis of Variance Procedure

Dependent Variable: Cell Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	0.1625687	0.0090316	0.95	0.5842
Error	5	0.0477351	0.0095470		
Corrected Total	23	0.2103038			

R-SquareC.V.	Root MSE	Mean
0.77301815.63488	0.0977	0.6249

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	0.0333438	0.0066688	0.70	0.6483
BLUE	1	0.0581938	0.0581938	6.10	0.0566
BLUE*REP	5	0.0329357	0.0065871	0.69	0.6531
LOCALE	1	0.0102424	0.0102424	1.07	0.3478
LOCALE*REP	5	0.0165082	0.0033016	0.35	0.8656
BLUE*LOCALE	1	0.0113448	0.0113448	1.19	0.3254

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLUE	1	0.0581938	0.0581938	8.83	0.0311

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	0.0333438	0.0066688	1.01	0.4948

Tests of Hypotheses using the Anova MS for LOCALE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LOCALE	1	0.0102424	0.0102424	3.10	0.1385

Analysis of Variance Procedure

Dependent Variable: Leaf Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	806.33000	44.79611	0.99	0.5610
Error	5	226.79000	45.35800		
Corrected Total	23	1033.12000			

R-SquareC.V.	Root MSE	Mean
0.78048021.79558	6.7348	30.900

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	111.44000	22.28800	0.49	0.7729
BLUE	1	396.90667	396.90667	8.75	0.0316
BLUE*REP	5	207.13333	41.42667	0.91	0.5384
LOCALE	1	6.82667	6.82667	0.15	0.7140
LOCALE*REP	5	75.38333	15.07667	0.33	0.8740
BLUE*LOCALE	1	8.64000	8.64000	0.19	0.6807

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLUE	1	396.90667	396.90667	9.58	0.0270

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	111.44000	22.28800	0.54	0.7436

Tests of Hypotheses using the Anova MS for LOCALE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LOCALE	1	6.8266667	6.8266667	0.45	0.5309

Table D.6 - Continued

Analysis of Variance Procedure
Dependent Variable: Number of Cells

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	1.252E+15	6.953E+13	0.34	0.9594
Error	5	1.027E+15	2.053E+14		
Corrected Total	23	2.278E+15			

R-Square	C.V.	Root MSE	Mean
0.549365	28.82168	14329120	49716466

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	3.047E+14	6.093E+13	0.30	0.8957
BLUE	1	2.073E+14	2.073E+14	1.01	0.3611
BLUE*REP	5	2.544E+14	5.088E+13	0.25	0.9240
LOCALE	1	1.749E+13	1.749E+13	0.09	0.7821
LOCALE*REP	5	2.740E+14	5.479E+13	0.27	0.9133
BLUE*LOCALE	1	1.937E+14	1.937E+14	0.94	0.3760

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLUE	1	2.073E+14	2.073E+14	4.07	0.0996

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	3.047E+14	6.093E+13	1.20	0.4240

Tests of Hypotheses using the Anova MS for LOCALE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LOCALE	1	1.749E+13	1.749E+13	0.32	0.5965

Table D.7 - ANOVA tables of soybean stem parameters in Chapter 5.

Analysis of Variance Procedure

Dependent Variable: Cell Area

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	0.0375165	0.0020843	1.01	0.5513
Error	5	0.0103633	0.0020727		
Corrected Total	23	0.0478798			

R-Square	C.V.	Root MSE	Mean
0.783555	14.51817	0.0455	0.3136

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	0.0133808	0.0026762	1.29	0.3930
BLUE	1	0.0024402	0.0024402	1.18	0.3274
BLUE*REP	5	0.0072888	0.0014578	0.70	0.6456
LOCALE	1	0.0001127	0.0001127	0.05	0.8249
LOCALE*REP	5	0.0118133	0.0023627	1.14	0.4446
BLUE*LOCALE	1	0.0024807	0.0024807	1.20	0.3238

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLUE	1	0.0024402	0.0024402	1.67	0.2523

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	0.0133808	0.0026762	1.84	0.2605

Tests of Hypotheses using the Anova MS for LOCALE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LOCALE	1	0.0001127	0.0001127	0.05	0.8358

Analysis of Variance Procedure

Dependent Variable: Number of Cells

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	26179466	1454415	4.91	0.0432
Error	5	1480135	296027		
Corrected Total	23	27659601			

R-Square	C.V.	Root MSE	Mean
0.946487	39.56133	544.08	1375.3

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	1736887	347377	1.17	0.4325
BLUE	1	18474885	18474885	62.41	0.0005
BLUE*REP	5	2049327	409865	1.38	0.3649
LOCALE	1	1249897	1249897	4.22	0.0951
LOCALE*REP	5	1540502	308100	1.04	0.4830
BLUE*LOCALE	1	1127967	1127967	3.81	0.1084

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLUE	1	18474885	18474885	45.08	0.0011

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	1736887.2	347377.4	0.85	0.5698

Tests of Hypotheses using the Anova MS for LOCALE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LOCALE	1	1249897.0	1249897.0	4.06	0.1001

Table D.7 - Continued

Analysis of Variance Procedure
Dependent Variable: Internode Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	18	5226.9167	290.3843	3.07	0.1094
Error	5	473.7083	94.7417		
Corrected Total	23	5700.6250			

R-Square	C.V.	Root MSE	Mean
0.916902	48.97375	9.7335	19.875

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	158.3750	31.6750	0.33	0.8728
BLUE	1	4030.0417	4030.0417	42.54	0.0013
BLUE*REP	5	239.7083	47.9417	0.51	0.7637
LOCALE	1	247.0417	247.0417	2.61	0.1673
LOCALE*REP	5	364.7083	72.9417	0.77	0.6094
BLUE*LOCALE	1	187.0417	187.0417	1.97	0.2190

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLUE	1	4030.0417	4030.0417	84.06	0.0003

Tests of Hypotheses using the Anova MS for BLUE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
REP	5	158.37500	31.67500	0.66	0.6698

Tests of Hypotheses using the Anova MS for LOCALE*REP as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LOCALE	1	247.04167	247.04167	3.39	0.1251

Table D.8 - ANOVA tables for parameters in Appendix A.

Analysis of Variance Procedure
Dependent Variable: Main Stem Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	560.5000	186.8333	10.83	0.0217
Error	4	69.0000	17.2500		
Corrected Total	7	629.5000			

R-Square	C.V.	Root MSE	Mean
0.890389	13.7300	4.1533	30.2500

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	512.0000	512.0000	29.68	0.0055
TEMP	1	40.5000	40.5000	2.35	0.2002
LIGHT*TEMP	1	8.0000	8.0000	0.46	0.5333

Analysis of Variance Procedure
Dependent Variable: Longest Branch Length

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	773.0000	257.6667	14.12	0.0136
Error	4	73.0000	18.2500		
Corrected Total	7	846.0000			

R-Square	C.V.	Root MSE	Mean
0.913712	10.9539	4.2720	39.0000

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	760.5000	760.5000	41.67	0.0030
TEMP	1	12.5000	12.5000	0.68	0.4544
LIGHT*TEMP	1	0.0000	0.0000	0.00	1.0000

Analysis of Variance Procedure
Dependent Variable: Percent Leaf

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	33.5830	11.1943	7.13	0.0441
Error	4	6.2837	1.5709		
Corrected Total	7	39.8667			

R-Square	C.V.	Root MSE	Mean
0.842383	5.1880	1.2534	24.1588

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	28.9941	28.9941	18.46	0.0127
TEMP	1	0.0136	0.0136	0.01	0.9303
LIGHT*TEMP	1	4.5753	4.5753	2.91	0.1631

Table D.8 - Continued

Analysis of Variance Procedure
Dependent Variable: Percent Stem

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	21.6526	7.2175	1.52	0.3390
Error	4	19.0162	4.7540		
Corrected Total	7	40.6688			

R-Square	C.V.	Root MSE	Mean
0.532414	13.3653	2.1804	16.3138

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	9.4830	9.4830	1.99	0.2307
TEMP	1	4.5451	4.5451	0.96	0.3835
LIGHT*TEMP	1	7.6245	7.6245	1.60	0.2741

Analysis of Variance Procedure
Dependent Variable: Percent Seed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	83.6587	27.8862	4.08	0.1041
Error	4	27.3633	6.8408		
Corrected Total	7	111.0220			

R-Square	C.V.	Root MSE	Mean
0.753533	7.2617	2.6155	36.0175

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	39.4272	39.4272	5.76	0.0743
TEMP	1	0.5202	0.5202	0.08	0.7964
LIGHT*TEMP	1	43.7113	43.7113	6.39	0.0648

Analysis of Variance Procedure
Dependent Variable: Percent Pod

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	4.3407	1.4469	0.94	0.4997
Error	4	6.1485	1.5371		
Corrected Total	7	10.4892			

R-Square	C.V.	Root MSE	Mean
0.413823	9.1685	1.2398	13.5225

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	2.8322	2.8322	1.84	0.2462
TEMP	1	0.1800	0.1800	0.12	0.7494
LIGHT*TEMP	1	1.3285	1.3285	0.86	0.4052

Table D.8 - Continued

Analysis of Variance Procedure
Dependent Variable: Percent Root

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	13.8734	4.6245	2.80	0.1725
Error	4	6.6025	1.6506		
Corrected Total	7	20.4759			

R-Square	C.V.	Root MSE	Mean
0.677550	12.8589	1.2848	9.9913

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.2485	0.2485	0.15	0.7178
TEMP	1	5.3628	5.3628	3.25	0.1458
LIGHT*TEMP	1	8.2621	8.2621	5.01	0.0889

Analysis of Variance Procedure
Dependent Variable: Mass Per Seed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	292.3750	97.4583	1.32	0.3837
Error	4	294.5000	73.6250		
Corrected Total	7	586.8750			

R-Square	C.V.	Root MSE	Mean
0.498190	5.3586	8.5805	160.1250

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	171.1250	171.1250	2.32	0.2021
TEMP	1	120.1250	120.1250	1.63	0.2706
LIGHT*TEMP	1	1.1250	1.1250	0.02	0.9076

Analysis of Variance Procedure
Dependent Variable: Seeds per Pod

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.0164	0.0055	0.91	0.5122
Error	4	0.0242	0.0060		
Corrected Total	7	0.0406			

R-Square	C.V.	Root MSE	Mean
0.404989	4.1691	0.0777	1.8638

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.0153	0.0153	2.54	0.1865
TEMP	1	0.0001	0.0001	0.02	0.8980
LIGHT*TEMP	1	0.0010	0.0010	0.17	0.7031

Table D.8 - Continued

Analysis of Variance Procedure
Dependent Variable: Pods Per Meter Squared

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	104722.3750	34907.4583	7.13	0.0440
Error	4	19572.5000	4893.1250		
Corrected Total	7	124294.8750			

R-Square	C.V.	Root MSE	Mean
0.842532	5.0767	69.9509	1377.8750

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	3916.1250	3916.1250	0.80	0.4216
TEMP	1	50403.1250	50403.1250	10.30	0.0326
LIGHT*TEMP	1	50403.1250	50403.1250	10.30	0.0326

Analysis of Variance Procedure
Dependent Variable: Photosynthetic Efficiency

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.0025	0.0008	5.26	0.0712
Error	4	0.0006	0.0002		
Corrected Total	7	0.0031			

R-Square	C.V.	Root MSE	Mean
0.797925	5.2988	0.0126	0.2379

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.0002	0.0002	0.96	0.3818
TEMP	1	0.0005	0.0005	2.93	0.1622
LIGHT*TEMP	1	0.0019	0.0019	11.90	0.0261

Analysis of Variance Procedure
Dependent Variable: Seed Yield Rate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1.0112	0.3371	3.60	0.1237
Error	4	0.3741	0.0935		
Corrected Total	7	1.3853			

R-Square	C.V.	Root MSE	Mean
0.729984	6.0300	0.3058	5.0713

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.0001	0.0001	0.00	0.9740
TEMP	1	0.1596	0.1596	1.71	0.2614
LIGHT*TEMP	1	0.8515	0.8515	9.11	0.0393

Table D.8 - Continued

Analysis of Variance Procedure
Dependent Variable: First Flower

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	36.3750	12.1250	4.62	0.0867
Error	4	10.5000	2.6250		
Corrected Total	7	46.8750			

R-Square	C.V.	Root MSE	Mean
0.776000	7.3229	1.6202	22.1250

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	0.1250	0.1250	0.05	0.8379
TEMP	1	36.1250	36.1250	13.76	0.0207
LIGHT*TEMP	1	0.1250	0.1250	0.05	0.8379

Analysis of Variance Procedure
Dependent Variable: Days to Harvest

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	16.3750	5.4583	3.36	0.1362
Error	4	6.5000	1.6250		
Corrected Total	7	22.8750			

R-Square	C.V.	Root MSE	Mean
0.715847	1.5762	1.2748	80.8750

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	6.1250	6.1250	3.77	0.1242
TEMP	1	0.1250	0.1250	0.08	0.7953
LIGHT*TEMP	1	10.1250	10.1250	6.23	0.0670

Analysis of Variance Procedure
Dependent Variable: Total Biomass Yield Rate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	6.2080	2.0693	21.01	0.0065
Error	4	0.3940	0.0985		
Corrected Total	7	6.6020			

R-Square	C.V.	Root MSE	Mean
0.940329	2.2184	0.3138	14.1463

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	5.7970	5.7970	58.86	0.0016
TEMP	1	0.4095	0.4095	4.16	0.1111
LIGHT*TEMP	1	0.0015	0.0015	0.02	0.9074

Table D.8 - Continued

Analysis of Variance Procedure
Dependent Variable: EffectiveCanopy Height

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	221.8000	44.3600	4.17	0.0958
Error	4	42.6000	10.6500		
Corrected Total	9	264.4000			

R-Square	C.V.	Root MSE	Mean
0.838880	7.188180	3.2634	45.400

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LIGHT	1	102.4000	102.4000	9.62	0.0362
TEMP	4	119.4000	29.8500	2.80	0.1711

Table D.9 - ANOVA table for Appendix C.

Analysis of Variance Procedure
Dependent Variable: Cell Area

Source	DF		Sum of Squares	Mean Square	F Value	Pr > F
Model	62		0.7621834	0.0122933	107.33	0.0001
Error	33		0.0037797	0.0001145		
Corrected Total	95		0.7659631			
		R-Square	C.V.	Root MSE	Mean	
		0.995065	1.664804	0.0107	0.6429	
Source	DF		Anova SS	Mean Square	F Value	Pr > F
BLOCK	11		0.3989239	0.0362658	316.63	0.0001
METHOD	3		0.0452033	0.0150678	131.55	0.0001
METHOD*BLOCK	33		0.3114385	0.0094375	82.40	0.0001
TIME	1		0.0046802	0.0046802	40.86	0.0001
TIME*BLOCK	11		0.0011738	0.0001067	0.93	0.5233
TIME*METHOD	3		0.0007636	0.0002545	2.22	0.1040

Tests of Hypotheses using the Anova MS for METHOD*BLOCK as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
METHOD	3	0.0452033	0.0150678	1.60	0.2089

Tests of Hypotheses using the Anova MS for TIME*BLOCK as an error term

Source	DF	Anova SS	Mean Square	F Value	Pr > F
TIME	1	0.0046802	0.0046802	43.86	0.0001

APPENDIX E. COPYRIGHT AND PERMISSION INFORMATION

30 SEP 1998

23 September 1998

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To Permissions Editor

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CURRICULUM VITAE

Education

1999 PhD, Utah State University GPA 4.0/4
Major: Plant Science, Crop Physiology
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Major Professor: Bruce G. Bugbee

1994 MS, Purdue University GPA 3.82/4
Major: Horticulture
Thesis Title: Evaluation of Cowpea as a Candidate Species for Inclusion in Controlled Ecological Life-Support Systems
Major Professor: Cary A. Mitchell

1991 BA, Southern Illinois University-Carbondale GPA 3.83/4
Major: Mathematics, *magna cum laude*
Minor: Computer Science

Experience

1994- Graduate Assistant, Crop Physiology Lab, Dept. of Plants, Soils, and Biometeorology, Utah State University

1991-1994 Graduate Assistant, NASA Specialized Center of Research and Training for Bioregenerative Life Support, Dept. of Horticulture, Purdue University

1991 Self-Employed Mathematics Tutor

1990-91 Remedial Algebra Instructor, Dept. of Mathematics, Southern Illinois University

1987-90 Student Secretary, Department of Geography and the Universities Council on Water Resources, Southern Illinois University at Carbondale

1988 Tennis Instructor, Mt. Pulaski Park District

1987-88 Summer internship program with the State Treasurer of Illinois

Teaching Experience

Sp 95-98 **Crop Physiology Teaching Assistant**, USU, Set up lab materials, demonstrated and supervised lab procedures, graded tests and homeworks from class and lab, prepared and gave guest lectures, wrote test questions for guest lectures

F 1997 **Plant Nutrition, Guest Lecturer**, USU, Lectured on the role of mycorrhizae in plant nutrition

Sp 1997 **Greenhouse Design and Management, Guest Lecturer**, USU, Lectured on the role of carbon dioxide in greenhouse management.

Sp 1993	**Plant Propagation Laboratory Instructor**, Purdue University, Organized lab equipment, prepared and gave lectures, wrote and graded quizzes.
F 90, Sp 91	**Remedial Algebra Instructor**, SIU-C, Wrote and graded quizzes and tests, organized and gave lectures, and provided individual tutoring.

Academic Achievements

1998	Crop Science Society of America, Gerald O. Mott Scholarship
1998	CSSA, G.O. Mott Meritorious Graduate Student Award
1998	Women and Gender Research Institute Research Award
1998	National Council of State Garden Clubs, Hazel Dillingham Scholarship
1998	Utah Associated Garden Clubs Scholarship
1997	College of Agriculture Tuition Waiver
1996-97	John E. and Ruth M. Osguthorpe Scholarship
1995	Research Vice-President's Fellowship
1995	CSSA, G.O. Mott Meritorious Graduate Student Award
1994	Space Shuttle Memorial Scholarship
1993	Honorable Mention ASGSB Student Poster Competition
1992	2nd Place ASGSB Student Presentation Competition
1991	Carl G. Townsend Outstanding Senior in Mathematics
1990-91	ABWA-Stephen Buffington Educational Fund Grant
1987-90	American Business Womans Association, Kickapoo Chapter, Scholarship
1990-	Phi Kappa Phi, Honors Fraternity
1990	Liberal Arts & Sciences Honors Society
1987-91	Deans List

Professional Memberships

1998-	American Association for the Advancement of Science
1995-	American Society of Agronomy/Crop Science Society of America
1995-	Utah State University Plant Physiology Club
1993-94	American Society of Horticultural Sciences
1992-94	American Society of Gravitational and Space Biology (ASGSB)
1992-93	Hydroponics Society of America

Activities

1997-	Graduate Student Senate, Plants, Soils, and Biometeorology Rep.
1996-	Tutor, Bridgerland Literacy, Logan, UT
1994	Moderator, Mt. Pulaski Scholastic Bowl Tournament
1993	Student representative, School of Ag, Grade Appeals Committee, Purdue
1993	4-H Science Workshop, Tissue Culture Instructor
1993	4-H Round-up, Tissue Culture Demonstrator
1993	Indiana Junior Horticulture State Convention, Judge
1992-93	City Science Fair, Judge, West Lafayette, IN

1991-94	Horticulture Organization of Research and Teaching Assistants, Purdue University, 1992 social chair, 1993 president
1991-93	Purdue Ballroom Dance Club, 1992-93 treasurer, teaching assistant
1990	SIU-C Basketball Pep Band
1988	SIU-C Student Life Advisor

Publications

T.A.O. Dougher and B.G. Bugbee (1998) Is blue light good or bad for plants? *Life Support and Biosphere Science* 5(2):129-136.

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T.A. Ohler, S.S. Nielsen, and C.A. Mitchell (1996) Manipulation of plant density and harvest time to optimize vegetative yield and proximate composition of cowpea leaves. *HortScience* 31(2):193-197.

T.A. Ohler and C.A. Mitchell (1995) Effect of carbon dioxide level and plant density on cowpea canopy photosynthesis and yield in a controlled environment. *Life Support and Biosphere Science* 2:3-9.

Presentations

T.A.O. Dougher and B.G. Bugbee (1998) Toward an Understand of Blue Light Effects on Diverse Species. Annual meeting of the American Society of Agronomy (oral presentation).

T.A.O. Dougher and B.G. Bugbee (1998) Is blue light good or bad for plants? Third International Conference on Life Support and Biosphere Science (oral presentation).

T.A.O. Dougher and B.G. Bugbee (1997) Effect of Blue Light on Leaf Expansion and Stem Elongation. Annual meeting of the American Society of Agronomy (oral presentation).

T.A.O. Dougher and B.G. Bugbee (1997) Blue light inhibits internode elongation, growth, and yield in soybeans. Annual meeting of COSPAR (poster presentation).

T.A.O. Dougher and B.G. Bugbee (1995) Blue light dose response of soybean growth and development. Annual meeting of the American Society of Agronomy (poster presentation).

T.A. Ohler and C.A. Mitchell (1994) Effect of CO_2 level on cowpea canopy photosynthesis and growth. Annual meeting of the American Society of Horticultural Sciences (poster presentation).

T.A. Ohler and C.A. Mitchell (1993) Manipulation of harvest parameters to optimize yield rate and harvest index of cowpea for use in a bioregenerative life-support system. Annual meeting of the American Society of Gravitational and Space Biology (poster presentation).

T.A. Ohler and C.A. Mitchell (1993) Evaluation of harvest scenarios for cowpea (*Vigna unguiculata* L. Walp), a candidate species for controlled ecological life-support systems. Annual meeting of the American Society of Horticultural Sciences (poster presentation).

T.A. Ohler and C.A. Mitchell (1992) Evaluation of cowpea (*Vigna unguiculata* L. Walp) as a candidate species for inclusion in bioregenerative life-support systems (oral presentation).