CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 18-011
UILU-ENG-2018-2011
ISSN: 0197-9191

ROADWAY LIGHTING'S IMPACT ON ALTERING SOYBEAN GROWTH – VOLUME 2:

LED versus HPS COLOR SPECTRAL IMPACT

Prepared By
Mr. Matthew Palmer
Dr. Ronald Gibbons
Dr. Rajaram Bhagavathula
Virginia Tech Transportation Institute

Dr. David Holshouser
Virginia Tech Tidewater AREC

Research Report No. FHWA-ICT-18-009

A report of the findings of

ICT PROJECT R27-172
Roadway Lighting's Impact on Altering Soybean Growth

Illinois Center for Transportation

June 2018

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-ICT-18-009	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Roadway Lighting's Impact on Altering Soybean Growth – Volume 2: LED versus HPS Color Spectral Impact		**5. Report Date** June 2018 **6. Performing Organization Code** N/A
7. Author(s) Mr. Matthew Palmer, Dr. Ronald Gibbons, Dr. Rajaram Bhagavathula, and Dr. David Holshouser		**8. Performing Organization Report No.** ICT-18-011 UILU-ENG-2018-2011
9. Performing Organization Name and Address Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24060		**10. Work Unit No.** N/A **11. Contract or Grant No.** R27-172
12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Research 126 East Ash Street Springfield, IL 62704		**13. Type of Report and Period Covered** Final Report: 6/17/17 – 6/30/18 **14. Sponsoring Agency Code** FHWA
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		
16. Abstract The impact of roadway lighting on soybean plant growth and development, was measured in situ at three locations in the state of Illinois. These locations were situated in close proximity of each other for the purpose of evaluating whether there was a difference in the soy response to HPS roadway lighting, versus soy lit by a specific model of 4,000K LED roadway lighting. The plant data collection included the reproductive-stage, the plant moisture content, and the dried seed weight after harvest. The impact of the type of roadway lighting on the reproduction stage and normalized yield was within the modeling confidence limits at a level of 90%. Modifications are recommended to the specification for roadway lighting trespass. This will minimize the impact on soybean plants based on the two roadway luminaire designs included in this study.		
17. Key Words lighting trespass, soybean, growth, lighting, lighting systems, street lighting, highway lighting, roadway lighting, lighting specifications, soybean development	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 55 pp + appendices **22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-172, Roadway Lighting's Impact on Altering Soybean Growth.** ICT-R27-172 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review panel were the following:

Mark Seppelt, TRP Chair, IDOT

Carl Bloomfield, Intertek

Norman Bowman, UIUC

Tom Brooks, IDOT

Mike Irwin, IDOT

Michael Jorgenson, Iowa DOT

Philip Kaufmann, IDOT

Dean Mentjes, FHWA

Steven White, IDOC

EXECUTIVE SUMMARY

This effort was an addendum to the original project (Palmer et al. 2017), which was developed to investigate the relationship between roadway lighting and the growth and maturation of the soybean. This project (volume 2) evaluated the difference in soybean response to light trespass into soybean fields in situ between two roadway lighting types with different spectral power distributions (SPD). The two lighting types are high pressure sodium (HPS) and a 4000 K correlated color temperature (CCT) light emitting diode (LED). The light levels measured in illuminance and were converted to photosynthetic photon flux density (PPFD), which is typically used in the research of plant growth. Both lighting measurements were then compared to the development, and yield, of the soybeans planted in the field.

PROBLEM STATEMENT

This project addendum aimed to provide an initial assessment of the effects of an LED roadway light—which has a different SPD than traditional high pressure sodium (HPS) roadway light—on soybean growth.

The results of the proposed work are expected to answer the following questions:

- What is the impact of light level for an LED roadway illuminance on soybean growth and maturity versus an HPS roadway illuminance?
- What impact does light levels have on soybean growth as measured in PPFD?
- Can these measurements be used to extrapolate to roadway lights with SPD differing from the two studied types of luminaires?

FINDINGS

Little difference was found between the 4,000 K LED and HPS lighted soybeans with regard to maturity (R-Stage) and Yield. The differences were smaller than the confidence limits in the models of the responses of the plants regardless of whether the lighting was represented in illuminance or PPFD.

Based on the results and to add a margin of safety the limits should be revised slightly to reflect the additional data as shown in the table below. However, these results are not universally applicable to all LED luminaires even if the CCT is the same as the 4,000 K LED used in this study. The spectral power distribution (SPD) can differ significantly between LED sources with identical CCTs, so these recommendations are only appropriate for the 4,000 K LED and the HPS lighting included in this study. In addition, alternative approaches to limiting the impact such as adaptive lighting identified volume 1 of this report are still viable approaches.

Trespass Illuminance Specifications to Minimize Soybean Impact for HPS and the 4,000K LED Used in this Study for Continuous Nighttime Lighting

Illuminance	Maximum, lx
Horizontal	2.2
Vertical	1.8

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Of the approximately 148,000 miles of roadway lighting in Illinois, an estimated 25,000 miles are adjacent to soybean fields (USDA, 2001). As indicated by the distribution shown in Figure 1, soybean fields in Illinois closely border urban areas—such as Chicago and Springfield—generating a high potential for roadway lighting and sky glow to affect the soybean crop.

Figure 5. Distribution of soybean fields in Illinois.

Lighting can essentially be broken down into two characteristics: lighting level and spectral (color) distribution. Roadway lighting characteristics are often chosen to maximize the benefit to the roadway user while minimizing energy use. However, light that extends beyond the roadway, which is typically called light trespass, can have unintended and/or undesirable effects on plant growth and development during the plant's night cycle.

Artificial lighting may especially impact plant photoperiodicity, which describes the developmental responses (e.g., flowering and ripening) of plants to light and dark cycles. The amount of uninterrupted darkness determines the formation of flowers in most plants. Soybeans are classified as "short day" plants, meaning that they form flowers only after day length decreases (or night length increases) to a certain number of hours, which is defined by the genetic makeup of a particular variety. Thus, the presence of artificial light may delay flowering, and eventually maturation, in soybean plants.

Two factors should be taken into account when considering the effect of roadway lighting on soybean plants: The first factor deals with the light level and the output spectral distribution of the light source (the wavelength composition of the produced light). The spectral distribution is of interest because photosynthesis, photoperiodicity and photomorphology are dependent on wavelength. The second factor is that both chlorophyll a and chlorophyll b exhibit higher activities in the lower (blue) and higher (red) wavelength ranges. This means that sources that output light in these wavelength regions are more likely to impact photosynthesis.

In addition to light trespass from roadside lighting, the light emitted from vehicle headlamps may also affect roadside plants. Due to the sporadic nature of artificial light from headlamps, that light source is unlikely to have a significant impact on plants. However, it could be an issue in fields adjacent to roads with high nighttime traffic volumes.

1.1 OVERVIEW OF RESEARCH APPROACH

This effort was an addendum to the original project (Palmer et al. 2017), which was developed to investigate the relationship between roadway lighting and the growth and maturation of the soybean. This project (volume 2) evaluated the difference in soybean response to light trespass into soybean fields in situ between two roadway lighting types with different spectral power distributions (SPD). The two lighting types are high pressure sodium (HPS) and a 4000K light emitting diode (LED). The light levels measured in illuminance and were converted to photosynthetic photon flux density (PPFD), which is typically used in the research of plant growth. Both lighting measurements were then compared to the development, and yield, of the soybeans planted in the field.

1.2 PROBLEM STATEMENT

This project addendum aimed to provide an initial assessment of the effects of an LED roadway light—which has a different SPD than a traditional high pressure sodium (HPS) roadway light—on soybean growth.

The results of the proposed work are expected to answer the following questions:

- What is the impact of light level for an LED roadway illuminance on soybean growth and maturity versus an HPS roadway illuminance?
- What impact does light levels have on soybean growth as measured in PPFD?
- Can these measurements be used to extrapolate to roadway lights with SPD differing from the two studied types of luminaires?

CHAPTER 2: LITERATURE REVIEW

It was deemed necessary to provide this literature review which somewhat overlaps the literature review provided in volume 1 (Palmer et al. 2017) of the project report in order for this, volume 2, to be a standalone document. This review expands upon the photoperiodicity and photomorphogenesis of plants including soy and expounds upon the definition of photosynthetically active radiation (PAR) and photosynthetic photon flux density (PPFD) and the reasons for using those measurements in the analysis of the field data.

2.1 ECOLOGICAL EFFECTS OF ROADWAY LIGHTING

Roadway lighting increases visibility for all road users and increases safety by reducing crashes. However, it also has some unanticipated side effects. Roadway lighting affects the growth and maturity of plants, as well as the behavior of animals (Spellerberg, 1998). With respect to animals, roadway lighting could potentially extend feeding times of some species of birds (Hill, 1992), for example.

2.2 PHOTOPERIODICITY AND PHOTOMORPHOGENESIS OF PLANTS INCLUDING SOY

The effect of lighting on plants has been documented extensively. Plants such as the soybean and rice require a dark cycle to begin reproductive development, and are significantly affected by light trespass from roadway lights. The phenomenon in plants that requires darkness to mature is called photoperiod sensitivity. Photoperiod sensitivity is the mechanism by which certain chemicals in the plant are converted from an inactive state to an active state in order to induce flowering or maturity. Photoperiodicity and photomorphogenesis are two aspects of photoperiod sensitivity. Photoperiodicity is the variation in response of a plant to the 24 hour day/night cycle in terms of reproduction or growth and is also referred to as circadian rhythm. Photomorphogenesis is plant development controlled by the spectral content of the light.

The Photoperiodicity and photomorphogenesis in plants is driven primarily by two photoreceptors: phytochrome and cryptochrome. Phytochrome is has the most influence on photomorphology and is sensitive to longer wavelengths in the red and infrared range. Cryptochrome is sensitive to shorter wavelengths and absorbs in the blue and near UV ranges.

Phytochromes are plant photoreceptors that are part of the circadian regulation in plants. Phytochrome has two isoforms that exhibit two different photochromicities and change photochromicity upon light absorption. The ground state (P_R) has a narrow absorption with a peak at 650-670 nm.(Devlin, 1969) Absorption of red light transforms the phytochrome to the P_{FR} state, which has a peak absorption in the far red and near infrared, most sensitive to the range of 705–740 nm with a much broader absorption that partially overlaps the P_R range (Devlin, 1969).

Cryptochromes are flavoprotiens that act as another photoreceptor in plants. Cryptochromes absorb in the blue range with peaks near 450 nm and UV with peaks near 380 nm. Cryptochromes seem to partially regulate growth and circadian clocks in certain conditions, such as exposure to light with low red spectral content (Pedmale et al. 2016).

2.3 EFFECTS OF STREET LIGHTING ON SOYBEAN PLANTS

Plants such as the soybean require a dark cycle to begin reproductive development, and are significantly affected by light trespass from roadway lights. Stray light from roadway lighting fixtures could keep the plants in a vegetative state for a longer period of time by rendering the flowering/reproductive mechanisms inactive (Brown Jasa, 1997). One of the earliest studies that reported the relationship between length of day and time of flowering for the soybean was conducted by Garner and Allard (1920). They reported that, in the absence of a suitable length of day, the plant could go into a vegetative state, leading to gigantism.

Two studies reported that artificial lights significantly affected the growth and maturity of the soybean (Briggs, 2006) and maize crops alongside roadways (Sinnadurai, 1981). Species that are more sensitive to the length of the day are significantly affected (fewer flower heads) by artificial lights that simulate roadway lighting (Bennie et al. 2015; Kostuik et al. 2014). Studies conducted in China have also shown that street lights delay the maturity of the soybean in the summer and decrease yield (Zong-Ming, 2007).

2.4 EFFECT OF LIGHT SPECTRUM ON SOYBEAN GROWTH AND MATURITY

Typically, light from a source is measured in lumens. However, the definition of the lumen is based on human visual response—and cannot be used to measure the quality of light for plants. Light energy incident on the plant is measured as photosynthetically active radiation (PAR). PAR is the amount of light available for photosynthesis in the 400 to 700 nm (nanometer) wavelength range.

Photosynthetic photon flux density (PPFD) is the measurement of the total amount of PAR that is produced by the light source each second. PPFD for a light source can be calculated if the spectral power distribution of the light source is known (Ashdown, 2016). If $W_{rel}(\lambda)$ is the relative spectral power distribution of the light source and $V(\lambda)$ is the luminous efficiency function at wavelength λ, then t*he spectral radiant flux ($\Phi(\lambda)$) incident on the plants can be calculated as follows:

$$\Phi(\lambda)/\text{lumen} = [W_{rel}(\lambda)] / [683 * \Sigma(400\text{-}700)\ [V(\lambda)\ W_{rel}(\lambda)\ \Delta\lambda]] \qquad \text{(Equation 1)}$$

From this, the photosynthetic photon flux (PPF) per nm in micromoles per second per nm can be calculated as follows:

$$\text{PPF /nm} = (10^{-3}) * [\lambda * \Phi(\lambda)] / (N_a * h * c) \qquad \text{(Equation 2)}$$

where

N_a = Avogadro’s constant, 6.023×10^{23}
h = Planck’s constant (6.626×10^{-34} joule-seconds)
c = speed of light, 2.998×10^{8} m/s
λ = wavelength in meters

The PPF per lumen for the given light source can be obtained by summing over the wavelength range of 400 to 700 nm:

$$\text{PPF} = 8.359 * 10^{-3} * \Sigma(400\text{-}700)\ [\lambda * \Phi(\lambda) * \Delta\lambda] \qquad \text{(Equation 3)}$$

The unit of PPF is micromoles per second (µmol/s) per lumen and all the photons are weighted equally from 400 to 700 nm, irrespective of the photosynthetic response. PPFD is the summation of the all of the photons falling on a surface for a given time and has units of mol/(sec-m^2). HPS lighting typically has a PPFD of 11.7 µmol/sec-m^2 per lm while a 4000K light-emitting diode (LED) PPFD might be 14.2 µmol/sec-m^2 per lx(CIE, 2004). Based on PAR, a 4000K LED could impact the plant more.

Figure 2 shows the normalized spectrum of a typical roadway HPS and roadway LED spectrum along with the PAR weighting versus wavelength. The 4000K LED has significantly less red (600–700 nm) and less infrared spectral content (700–800 nm) than the HPS lighting, but has a large blue spike at 442 nm.

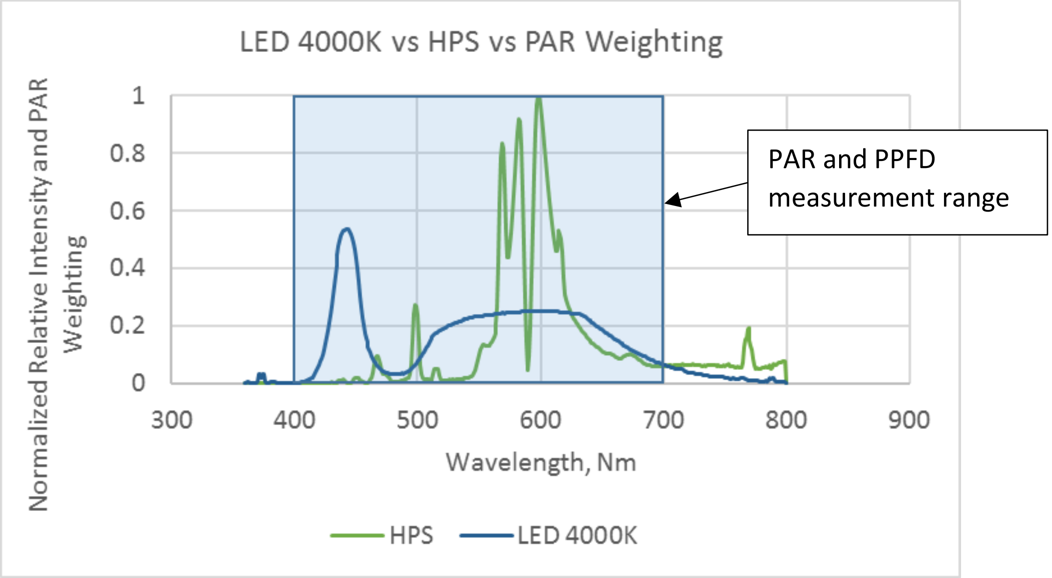


Figure 6. PAR weighting curve versus normalized typical HPS and 4000K LED spectrum. The highlighted area is the PAR and PPFD measured range.

Artificial light (e.g., incandescent lamps) has also been used to delay flowering and reproductive development in soybean plants. Lawrence and Fehr (1981) reported that plants exposed to light treatments every night, experienced more delayed reproductive development than those exposed to light treatments every other night. Nissly et al. (1981) exposed several hundred strains of soybean to natural day length and an extended photoperiod of continuous 5-hour nighttime interruption. The soybean strains that were exposed to the extended nighttime photoperiod experienced a delay in flowering.

The spectrum of the light source also plays a significant role in the reproductive developments of plants such as the soybean. Artificial light elicited enhanced or suppressed growth depending on the plant species. This response was greatest in light sources with higher amounts of red lights and a higher red/far-red ratio—such as those used in conventional roadway lighting types (HPS) (Cathey & Campbell, 1975a, 1975b). Parker et al. (1946) first studied the spectra that prevented the flowering of soybean plants and reported that the wavelengths between 600 and 680 nm effectively prevent flowering. This prevention of flowering ends at the red end of the visible spectrum (~720 nm; Figure 3). The phenomenon of the red spectrum preventing flowering in soybean plants was also reported by Downs (1956). Downs also suggested the effects of the red spectrum on the flowering of soybean plants could be reversed by brief exposures (2 to 5 minutes) to the far-red spectrum (>735 nm). Han et al. (2006) also reported that the soybean flowering responses to red spectrum (658 nm) were reversible by far-red spectrum (730 nm) exposure.

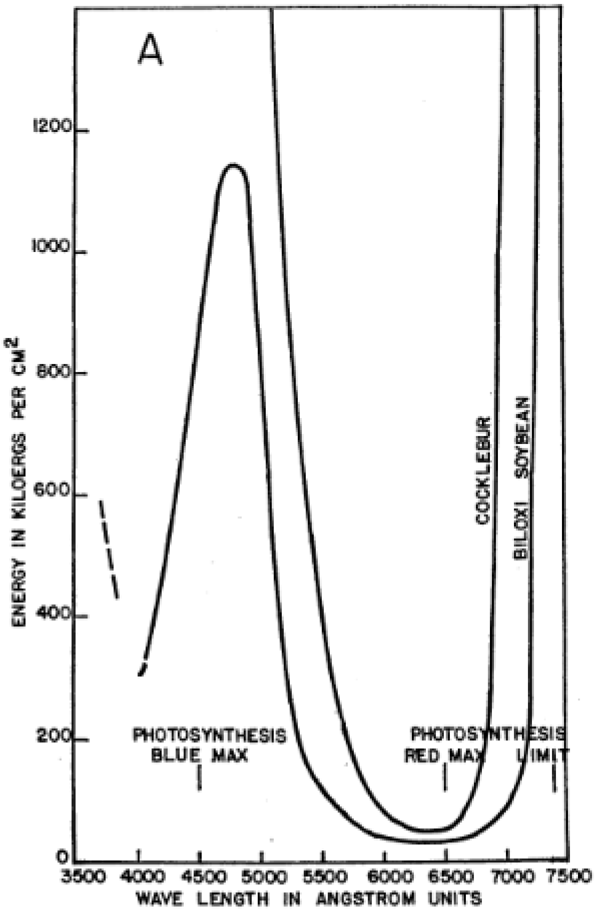


Figure 7. Action spectra of soybean and cocklebur that suppresses floral initiation (Parker et al., 1946).

As previously mentioned, HPS lights are popular for road lighting because of their luminous efficiencies. The HPS spectrum has very little blue content that could cause undesirable morphological responses, such as stem elongation, in soybean plants. Wheeler et al. (1991) reported that HPS light sources that have lower blue light content may result in shorter stems. In that study, soybean plants were grown in the presence and absence of HPS lights with and without the presence of blue content. Total photosynthetic photon flux was maintained at 300 or 500 µmol/m^2/s. The results of this study showed that the phenomenon of elongated stems in presence of HPS lighting could be prevented by adding blue light to the spectrum of the light source (up to 30 µmol/m^2/s; Figure 4). The Wheeler et al. (1991) study also found that plant reproductive development is affected by HPS light sources. Although the plants in that study—which were exposed to blue light—did not have elongated stems, it remains to be seen whether blue light could also affect later stages of plant growth and reproductive development. A different study showed that cool white fluorescent light could also result in a delay in the maturity of the soybean (Buzzell, 1971).

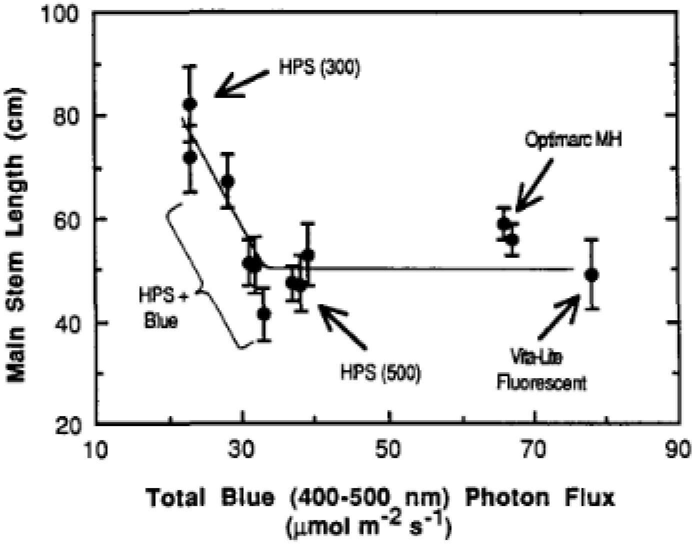


Figure 8. Effect on the soybean stem length of adding blue light (400 to 500 nm) to the HPS spectrum. Blue light was added by supplementing HPS lights with blue fluorescent lamps (Wheeler et al., 1991).

Recently, a study conducted by Cope and Bugbee (2013) examined the effect of three colors of LEDs (different levels of blue content in the light spectrum) on the growth and development of the soybean. The results showed that although the blue light did not affect the plant's total dry weight, it did affect the plant's development. Similar to the results of Parker et al. (1946), LEDs with higher blue content were found to result in soybean plants with shorter stems (Figure 5). The biggest differences in plant development was observed in low light conditions (PPF = 200 µmol/m^2/s). The results of the study showed that the amount of blue content in light required to cause an effect, could depend on the plant's age—and that light quality and level could significantly affect a plant's growth and development.

Figure 9. The effect of blue light on soybean stem length 9 days after emergence. Stem elongation decreased with an increase in blue light (Cope & Bugbee, 2013).

The spectral regions that affect growth, as found during the literature review, are shown in Figure 6 versus the same example HPS and LED spectrums presented in Figure 2. The spectral ranges that delay development are shown in red areas, while the infrared region that research shows may help the plants recover is shown in yellow. As illustrated, HPS lighting has more flowering-preventing output in the 600–730 nm range than 4000K LED lighting. However, the LED has more blue content (400–500 nm) than the HPS and almost no infrared.

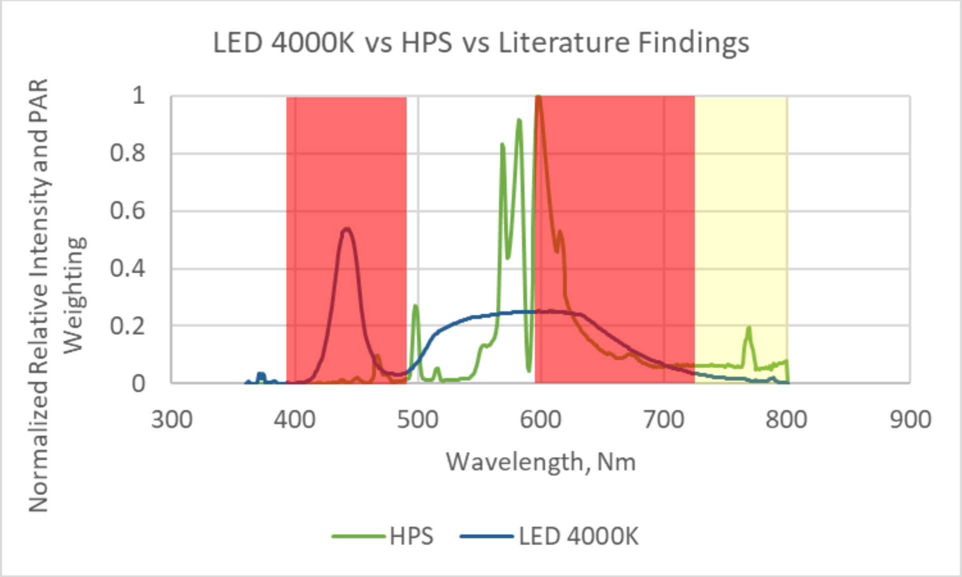


Figure 10. Spectral regions that likely affect soybean development. The darker areas (red) represent the wavelengths that delay development, while the lighter area (yellow) represents wavelengths that help the soybean recover.

2.5 RESEARCH GAPS

There is overwhelming evidence that light affects the growth and maturity of soybean plants. The original project performed research that addressed the effect of roadway lighting on the maturity of soybean plants in an actual field adjacent to a lighted roadway. However, it included only HPS lighting because no suitable field could be identified with LED lighting and soybeans. With the shift in luminaire types on roadways from narrow-spectrum (HPS) to broad spectrum-light sources (LEDs), it makes it even more important to understand the influence of spectrum on the maturity of the soybean.

CHAPTER 3: PROJECT PROCESS

This project was undertaken in a series of tasks. A group of three sites were selected for the addendum to the study. At each site, a group of GPS points were selected as evaluation points during harvest. The beans at each test point were hand-harvested and evaluated for growth characteristics. The lighting levels were measured after the harvesting of the soybean through the use of a semi-automated lighting measurement robot.

3.1 SITE SELECTION

Virginia Tech and Illinois Department of Transportation (IDOT) personnel provided 5 additional potential sites for data collection, all fairly close to Springfield, Illinois. These 5 sites were selected based on proximity of fields to lighting and streets as well as type of lighting. These sites were visited by IDOT personnel for potential inclusion in the study. After the farmers were contacted, the researchers selected three sites for the lighting study. The three sites were in close proximity to each other and Springfield in order to minimize the effect of latitude on the growth of the soy plants (Table 1). The sites also included a field at the intersection of IL-125 and IL-123, which was upgraded to 4,000K LED lighting in early 2017.

Table 1. Selected Soybean Field Sites with Encroaching Lighting

Site	Intersection/ Interchange	Light Type	CCT	Type	Town	AADT*	Variety	Time in Field, days
Pleasant Plains 2	NW of IL-125 and IL-123	LED	4000K	Highway	Pleasant Plains	4,800		
Hazlett	I-97 and Hazlett Rd.	HPS	2100K	Highway	Springfield	11,900	Asgrow AG36X6	172
Washington	W. Washington St. and Meadowbrook Rd.	HPS	2100K	Highway	Springfield	3,100	Asgrow AG36X6	172

*Annual average daily traffic

The farmers at each of the sites were informed of the experimental process and were provided with a land-use agreement clarifying any questions. The farmers were compensated for the use of their field and the soybeans taken for analysis.

3.2 SAMPLE TEST POINTS SELECTION

For each field, sample test points were selected as the test locations for the lighting and growth evaluations. The sample points were selected based on the roadway lighting fixture locations and the approximate maturity of the soy plants in the fields—and extending into the field perpendicular to the nearest roadway. In the Pleasant Plains field, 42 points were sampled. In the two HPS fields, another 45 points were sampled. The locations were detected by use of a handheld GPS receiver, which means that the error in the precision of the location of each sample is larger than the light measurement—and is approximated to be ± 6.6 ft. (± 2 m).

Figure 7 shows the harvest locations and lighting data collected in the Pleasant Plains 2 field near the intersection of IL-123 and IL-125. The harvest locations are indicated by the pink circles, while the robot path is indicated by the other colored trace. The sample points were aligned with 3 luminaires and included 2 samples in between each pair of luminaires. Points were also distributed in the direction perpendicular to the roadway. The first row harvested was the second row from the roadway. The next three rows moving away from the roadway were distributed across the light affect zone. Two additional sample rows were taken farther from the lights to make sure sufficient data was collected—where the lighting was low and the plants were mature. Figure 8 illustrates one of the samples taken from the Pleasant Plains site showing incomplete maturity.

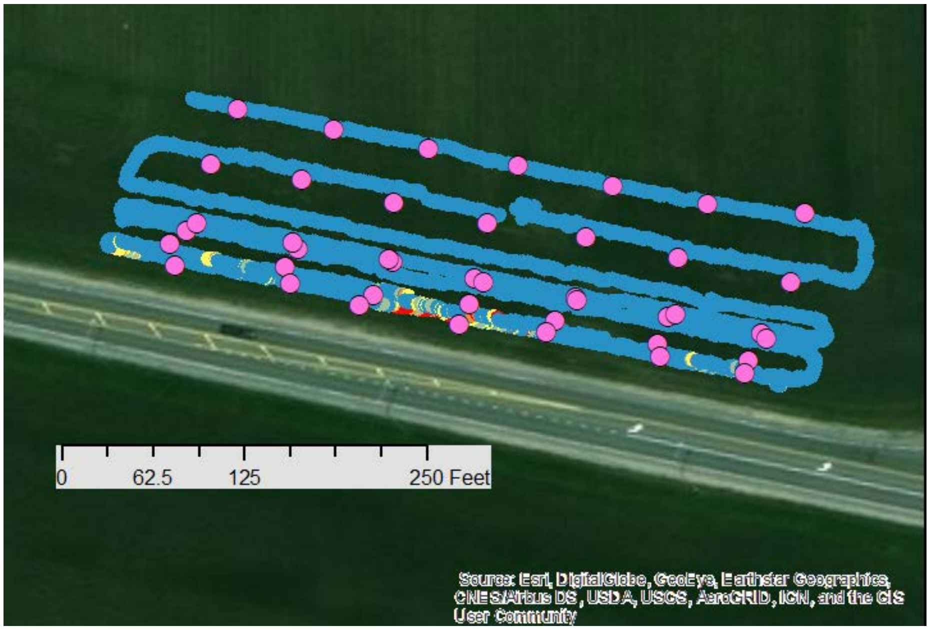


Figure 11. Pleasant Plains 2 Field with LED lighting.

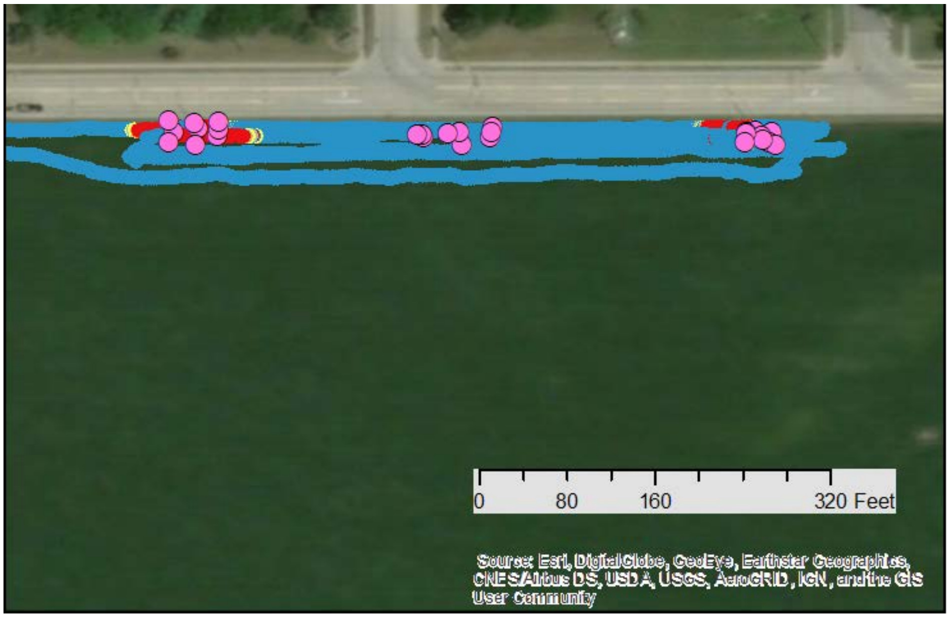
Figure 12. Example sample collected from the Pleasant Plains 2 field.

The Hazlett field was lighted by only two HPS luminaires. One was located near the SE corner of the field shown in Figure 9 near the 60 foot marker of the scale. The other one was located on the other side of Hazlett to the east and outside of the view shown. The samples were closer together in this field than in the others due to the presence of only one luminaire.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 13. Hazlett Field and Sample Points.

The sampling points for the Washington site (Figure 10) was more difficult to visualize on a map because the luminaires were installed in an alternating pattern. The sample points were distributed around three light poles on the south side of Washington St.—where the farmer had left plants standing for this study. During the hand harvest, the sample sites were selected to try to capture plants with an even distribution of maturity, including a few that were fully mature in appearance.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 14. HPS lighted field at Washington St. and Meadowbrook Rd.

3.3 PLANT MEASUREMENTS

The soybean plants were hand-harvested on September 26th and 27th. At harvest time, photos were taken of each sample so that R-stage measurements could be completed. One meter of plants were harvested from 89 sample locations. The soybean plants were transported in a van to Virginia Tech's Tidewater Agricultural Research and Extension Center in Suffolk, Virginia, for a maturity and yield analysis.

The plants were cut within 2-3 cm of the soil during the hand harvest. Plant height was measured with a meter/yard stick from the where the plants were cut, to the top growing point on the main stem.

Plants were weighed and then dried in a forced-air drier for 24 hours. After drying, the plants were again weighed, the number of nodes and pods were determined, and then pods were removed from the plant and weighed. Seeds of samples representing varying weights and development stages were shelled from pods and weighed to estimate seed yield.

The reproductive stage was determined by examining the stem of three different plants and staging each plant—employing a standardized system used by soybean agronomists—and originally developed by Iowa State University (Fehr and Caviness, 1977). To improve the granularity of the measurements, the estimate of R-stage for plants with maturity levels in between the standard levels, included an additional number after the decimal (Table 2). For example, a plant between stage R3 and R4 might have been labeled 3.5 if half of the flowers had developed pods.

Table 2. R-Stage Maturity Rating

R-Stage	Abbreviated Stage Title	Description
1.0	Beginning bloom	Flower appearing anywhere on the plant
2.0	Full bloom	Flowers at the top 2 nodes of the main stem
2.5		Halfway to R3
3.0	Beginning pod	Pod 3/16 inch long at one of the four uppermost nodes on the main stem with a fully developed leaf
3.3		30% pods greater than ¾ inch long on the main stem
3.5		50% of pods greater than ¾ inch long on the main stem
4.0	Full pod	Pod ¾ inch long at one of the four uppermost nodes on the main stem with a fully developed leaf
4.5		Half of the pods forming seed 1/8 inch long in pods on the main stem
5.0	Beginning seed	Seed 1/8 inch long in a pod at one of the four uppermost nodes on the main stem with a fully developed leaf
5.5		50% of the pods with seed filling half of the pod cavity
6.0	Full seed	seedpod containing green seed that fills the pod cavity at one of the four uppermost nodes on the main stem with a fully developed leaf
6.5		Halfway to R7
7.0	Physiological maturity	One normal pod on the main stem that has reached its mature pod color
8.0	Full maturity	Ninety-five percent of the pods have reached their mature pod color

3.4 LIGHTING MEASUREMENTS

The lighting data was collected using the Robotic Roving Lighting Mobile Measurement System (RRLMMS) and a temporary home station. The RRLMMS is a semi-automated light measurement system for indoor spaces, sidewalks, and other off-highway roadway lighting. The instrument collected four horizontal and four vertical illuminance measurements, as well as the location of the measurements. For the horizontal illuminance data collection, the robot had four arms extending 31 in. from its base. Each arm housed an upward-facing sensor head from a Konica Minolta T-10A illuminance meter. For the vertical illuminance data collection, four more sensor heads were mounted on a vertical post extending up from the robot's base. They were mounted facing forward, backward, and to each side of the robot. Figure 11 shows the RRLMMS.

Figure 15. Robotic Roadway Lighting Mobile Measurement System (RRLMMS).

The RRLMMS was equipped with mapping technology that could be used to determine the robot's position using a combination of a global positioning system (GPS), inertial measurement, wheel encoders, and electronic compass measurement. The differential GPS (DGPS) system used a rover and base DGPS concept. This approach reduced the positional precision error from ± 32.8 ft. (± 10 m) to ± 4 in. (0.10 m). The DGPS positioning precision was deemed necessary based on descriptions of the depth of the lighting effect into the field.

The system collected three horizontal (there is a redundant front and rear measurement on the device) and four vertical illumination measurements. Data was collected at 4 Hz. The robot forward speed was approximately 4 ft. per second (fps). This resulted in a data point on approximately a 1-ft. spacing. The row spacing for the robot path followed the plant sampling locations in order to minimize interpolation errors—but was approximately 10-ft. of spacing perpendicular to the roadway, for three or four rows. The remainder of the rows of lighting data were collected on approximately 20-ft. of spacing perpendicular to the roadway. The spacing was increased because the rate of change of the lighting levels decreases as the distance from the source (light) increases. (Figure 12).

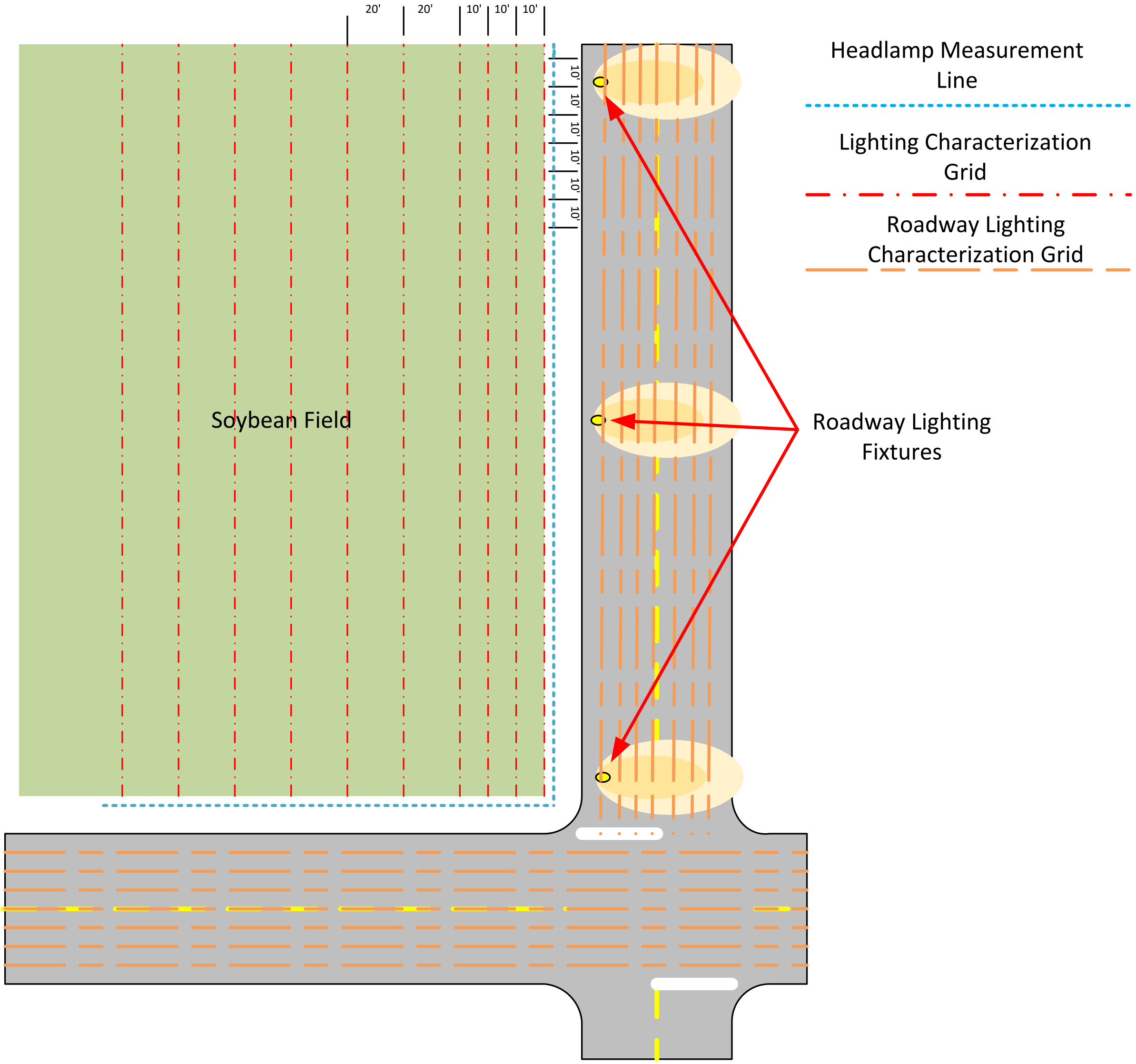


Figure 16. Schematic showing the lighting characterization strategy.

3.5 ANALYSIS

The data was analyzed by first reducing the lighting data to the specific levels at each sample point, followed by reducing the growth and plant data, and then performing statistical analyses.

3.5.1 Lighting Data Reduction

The noise in the lighting measurements required that additional post-processing be performed before analysis with respect to the plant characteristics. The lighting in the fields was characterized after harvesting, and two of the fields had already been tilled to add fertilizer, and were very rough.

The roughness of the field caused the RRLMMS robot to bounce and rock back and forth, adding noise to the data. Custom software written for the original project was again used to streamline the selection and interpolation of the lighting data—to enable the lighting levels to be determined at the sample points. The lighting data were digitally filtered with a fourth-order Butterworth filter. Figure 13 shows the horizontal illuminance sampled at each coordinate for a field from the light characterization from the original project.

The data shows rapid level changes (represented as color changes in the figure), especially in the first and second measurement rows from the top of the chart (close to the luminaires), and in the rows farthest from the top (farthest from the luminaires). Figure 14 shows the same horizontal illuminance after filtering. This filtering approach significantly reduced noise in the data and allowed for a more consistent analysis of the lighting.

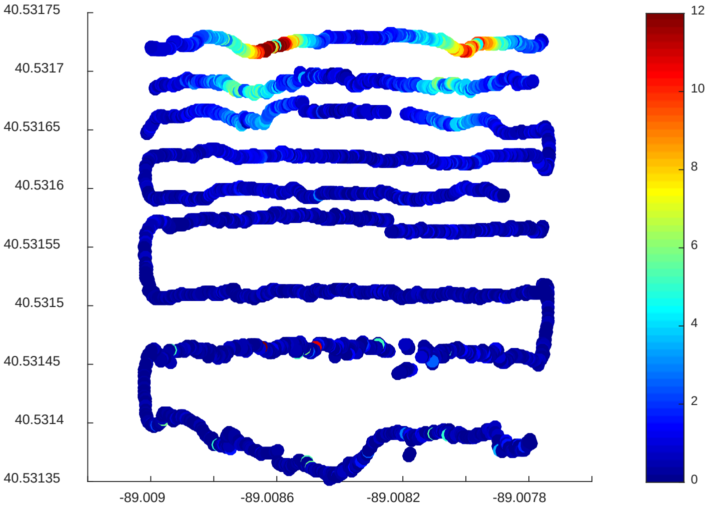


Figure 17. Horizontal illuminance for a 2016 field (Normal1) before digital filtering. The horizontal illuminance is represented by the color. The y and x axes are latitude and longitude in degrees.

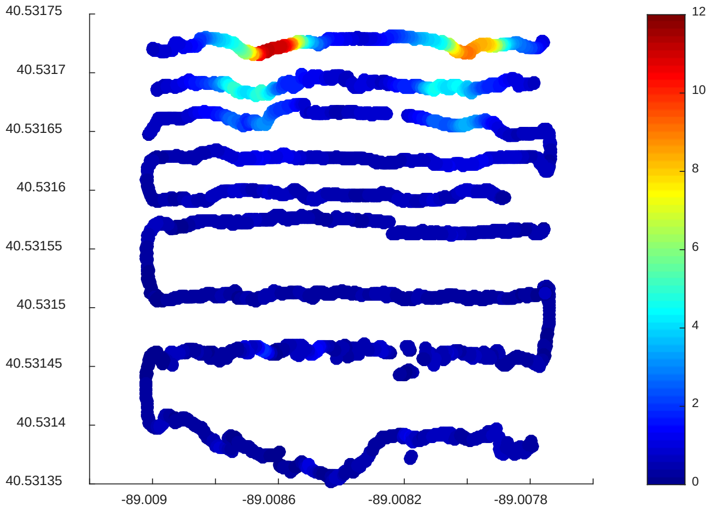


Figure 18. Horizontal illuminance for a 2016 field (Normal1) illustrating the smoothing of the data with digital filtering. The horizontal illuminance is represented by the color. The y and x axes are latitude and longitude in degrees.

After filtering, the data was interpolated into a two-dimensional space (latitude and longitude) in order to obtain the lighting values for the plant sample and harvest points. "Nearest neighbor" was used for the interpolation.

3.5.2 PAR / PPFD Calculation

The PAR-based lighting value PPFD was calculated for the HPS and LED spectra—and used in the analyses along with illuminance—to determine whether it was a good indicator of the impact of the SPD for each light type on the soybean plants. The theory postulated that using PPFD would allow one model for the response of each of the affected plant physiology measures, independent from the light type.

There is considerable overlap between the wavelength range for photosynthesis and the wavelength range for the photoreceptors responsible for the photomorphogenesis of plants. PPFD, it was theorized, would be a better measure of the soy plant sensitivity to roadway lighting than illuminance, which is based on what humans can see. In addition, PAR and PPFD measurement devices are commercially available.

Utilizing PPFD should shift the lighting measurements for the two light types relative to the plant responses in directions that result in similar soy plant responses (maturity and yield) at the similar PPFD values. In other words, utilizing PPFD would combine the impact of irradiance and SPD into one measurement independent of light type. In addition, a statistical analysis of the plant response data versus lighting in PPFD and lighting Type (LED or HPS), would find no significance to the difference in type. This would allow for writing a single specification for lighting trespass levels that is easily measureable and would work for a variety lighting types and SPDs.

SPD values published by the manufacturer of the 4000K LED utilized at the Springfield2 field were utilized along with previously captured HPS SPD for the PPFD calculation. The normalized SPDs for those lights are shown in Figure 15. The LED luminaires have a peak emission in the blue at approximately 450 nm, and the phosphor coating created a broad emission with another peak at about 580 nm. The HPS emission spectrum had multiple narrower peaks with the primary peak at 579 nm. The majority of the emission was between 575 and 625 nm.

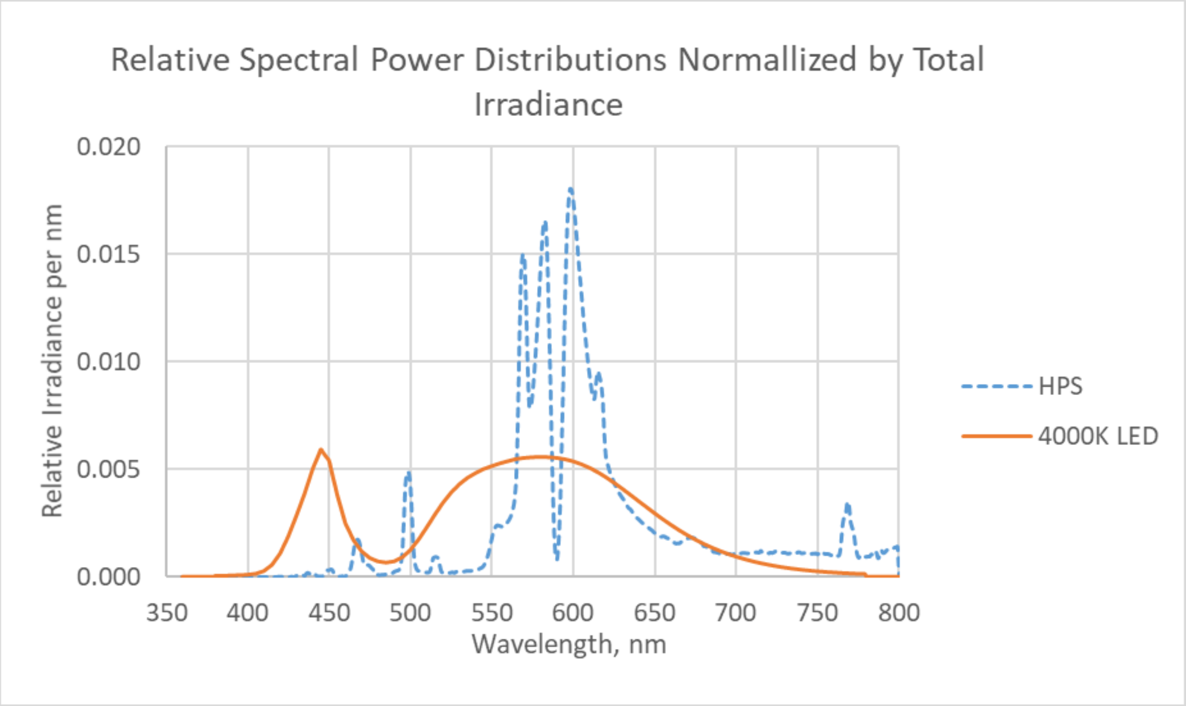


Figure 19. Typical spectral power distributions (SPD) for the LED and HPS lights used in this study.

3.5.3 Plant Analysis

Plant moisture was calculated from the plant weights before and after drying. Estimated seed yield was determined from all samples by a non-linear relationship of seed weight with pod + seed weight from the shelled samples. Average values were then calculated for all of the plants harvested from each sample location.

3.5.4 Statistical Analysis

A statistical analysis was performed first for all fields, and then for the growth and development measurements. Each of these analyses also considered the impact on varietals. Some data normalization was required to remove the impact of field variations for the analysis as well.

3.5.4.1 Normalization

During the statistical analysis, the growth, harvest, and lighting data was combined into a database for analysis. A new factor, total illuminance, was introduced to combine the vertical and horizontal measurements. The total illuminance was calculated by taking the square root of the sum of the squares of the vertical and horizontal measurements. This was performed to account for all of the lighting flux falling on the plants that might affect the growth, maturity, and yield. The formula used was the magnitude of vector addition:

$$Magnitude = \sqrt{x^2 + y^2} \qquad \text{(Equation 4)}$$

Measurements varied within the field and may be attributed to a number of factors, including but not limited to, variety, soil differences, and general crop management. To account for these variables, the data was normalized by field. To account for this variation by field, plant maturity, calculated as percent mass (y_i), was normalized by field by dividing by the yield (y_0) of the plants farthest from the light source, as shown in (Equation 5).

$$y_n = y_i/y_0 \qquad \text{(Equation 5)}$$

3.5.4.2 Modeling

Modeling of plant yield was performed in an off the shelf software package which enables entry of a wide range of model equations to be entered in a non-linear regression fit function. The fitting function outputs the model coefficients, the confidence limits, and the fit parameters when utilized. The fit function also enables either a random start point or initial guesses for the parameters, entry of the confidence interval, and entry of other parameters.

Several models were tried including multiple versions of the logistic function and polynomials with orders from two to five. Ultimately, a 3rd order polynomial resulted in the best r-squared values for normalized yield (see Equation 6).

$$Normalized\_yield = d*x3 + c*x2 + b*x \qquad \text{(Equation 6)}$$

The maturity measurement (R-stage) was not normalized since all fields had R-Stage 8 samples. A logistic function was used to model the R-Stage for since it is the most likely fit to plant growth and/or maturity (Equation 7)—where *LL* was the light level measurement, and b and c were fit parameters found using a nonlinear least squares methodology. The constant *6* and the multiplier of *2* were used to limit the model to exist between the asymptotes of R-Stages of 6 and 8. The lower limit was based on observing that the R-Stage of the harvested plants was never lower than 6, and had a concave upward trend with increasing lighting levels.

$$R - Stage = 6 + 2\left(\frac{1}{1 + e^{b(LL-c)}}\right) \qquad \text{(Equation 7)}$$

3.5.4.3 Analysis

An analysis was performed using statistical analysis software. Generalized linear models relating to the lighting levels, the field, and the interaction of lighting and field were also generated.

The lighting values were binned into groups in order to perform multiple ANOVAs (Analysis Of Variance) and pairwise comparisons between the lighting conditions and the plant characteristics. The bins are shown in Table 3.

Table 3. Table of Bins for the Illuminance Data

Bin Level	Min Limit (lx)	Max Limit (lx)
01	0.0	1.0
02	1.0	2.0
03	2.0	3.0
04	3.0	4.0
05	4.0	5.0
06	5.0	6.0
07	6.0	7.0
08	7.0	8.0
09	8.0	9.0
10	9.0	10.0
11	10.0	11.0
12	11.0	12.0
99	12.0	n/a

Additional ANOVAs were calculated using horizontal illuminance, vertical illuminance, and light type, as those relationships would be necessary for writing a roadway lighting trespass specification for minimal impact on the soybean. A confidence interval of 90% was used to assess significance due to the number of uncontrolled variables.

After conversion of the illuminance to PPFD, the data was again binned to enable analysis with ANOVAs. The binning utilized a spacing of 12 μmoles$\cdot$s$^{-1}\cdot$lum^{-1} in order have the same number of bins as the illuminance analyses for the HPS lighting. This would allow the graphical representation of the HPS model to remain a constant shape and location—and emphasize the differences in the models for the LED lighting response enabled by the use of PPFD. This would allow direct comparison of the use of PPFD and illuminance. The binning values for PPFD are shown in Table 4.

Table 4. Table of Bins for the PPFD Data

Bin Level	Min Limit (µmoles·s^{-1}·lum^{-1})	Max Limit (µmoles·s^{-1}·lum^{-1})
012	0	12
024	12	24
036	24	36
048	36	48
060	48	60
072	60	72
084	72	84
096	84	96
108	96	108
120	108	120
132	120	132

Lower limits from the original project for the plant physiology were used in the interpretation of the results. At an R-Stage of 7, the plants have stopped producing dry material and have begun to dry out—and will be harvestable after a few days. A normalized yield limit of 85% was selected for interpretation of yield.

CHAPTER 4: RESULTS

The results of the lighting measurements, plant measurements, and analysis are presented below.

4.1 LIGHTING RESULTS

4.1.1 Light Trespass from Roadway Lighting

The average values for each field are shown in Table 5. As the table shows, the LED-lighted field has the lowest average trespass lighting illuminance value of the three fields sampled in 2017.

Table 5. Light Trespass Field Summary Values

	Horizontal Illuminance			Vertical Illuminance		
Site	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**
Pleasant Plains 2	1.22	0.04	5.26	1.26	0.32	3.48
Hazlett	3.32	0.17	8.45	1.82	0.59	3.63
Washington	2.74	0.88	5.26	1.85	1.32	2.36

Two of the fields had already been rip plowed and were extremely rough, so the robot path varied from the desired straight-line path. The lighting data was made smooth with a fourth-order Butterworth digital filter in order to remove the noise in the data caused by the rough fields.

Figure 16 shows the smoothed horizontal illuminance of the field NW of the IL-125 and IL-123 intersection, where the new LED luminaires were installed. The lighting was installed on the southern shoulder of IL-125, on the opposite side of the road from this field.

The horizontal lighting data from the field NW of IL-97 and Hazlett, and the horizontal illuminance from the field SW of Washington and Meadowbrook (Washington), are shown in Figure 17 and Figure 18 respectively. The horizontal illuminance levels in these fields were higher than in the LED field.

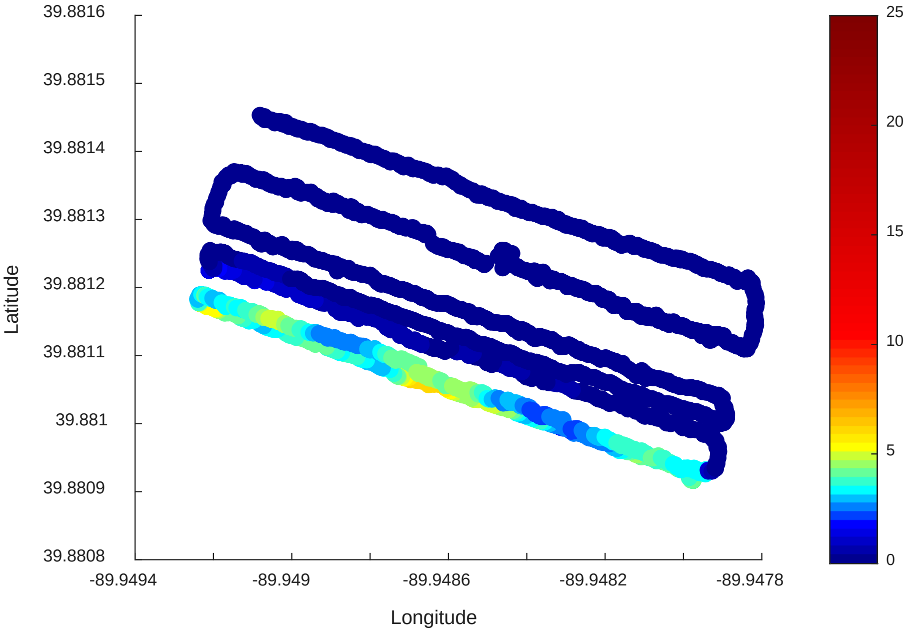


Figure 20. Horizontal illuminance levels after smoothing from the field NW of the intersection of IL-125 and IL-123. The color scale is in lux.

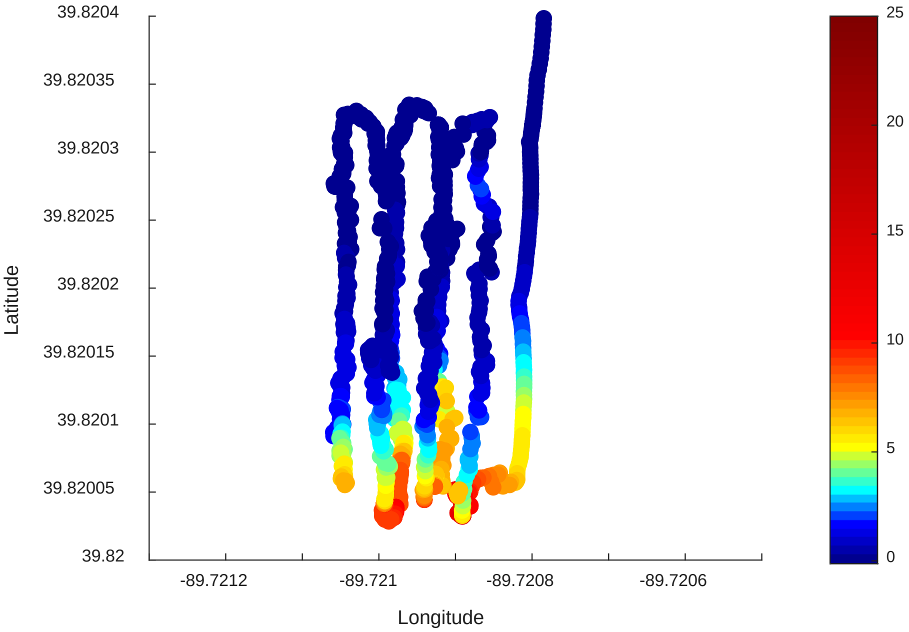


Figure 21. Horizontal illuminance levels after smoothing from the field NW of the intersection of IL-97 and Hazlett. The color scale is in lux.

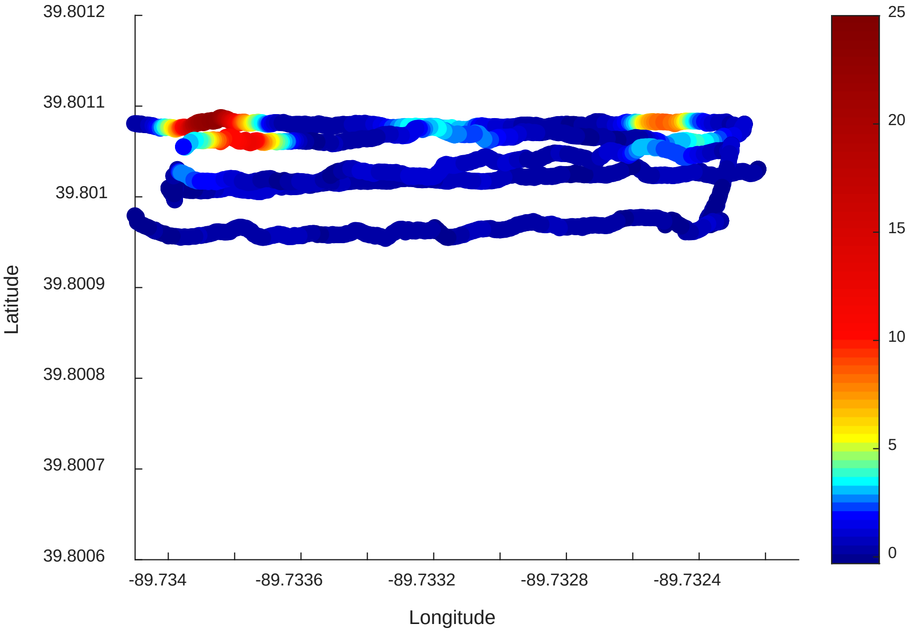


Figure 22. Horizontal illuminance levels after smoothing from the field NW of the intersection of Washington St. and Meadowbrook Rd. The color scale is in lux.

4.1.2 PPFD

PPFD was calculated using example spectral power distribution (SPD) of each lighting type. The SPD for each source contained lighting levels with a 1 nm resolution. These SPDs were normalized by the total area under the curve. This produced SPDs that would result from measuring a 1-Watt luminaire of each type. Multiplicative factors were calculated for converting illuminance measurements into PPFD for each lighting type using the equations in the literature review (Table 6).

Note that while the HPS lighting factor is driven by physics and is thus the same for the majority of HPS lights, LED SPDs can vary significantly, even for similar or identical correlated color temperature (CCT). Therefore, the LED conversion factor cannot be universally applied to 4,000K LED luminaires.

Table 6. Illuminance to PPFD Conversion Factors for Each Luminaire Type

Light Type	Conversion Factor: μmoles$\cdot$s$^{-1}\cdot$lum^{-1}
HPS	12.305
4,000K LED	13.716

4.1.3 Ambient Lighting Levels

Ambient lighting levels were also measured at a point in the field far from the influence of street lighting. The horizontal illuminance from ambient lighting varied from 0.05 to 0.17 lx in the fields sampled, with an average of 0.1 lx. The ambient vertical illuminance averaged 0.46 lx. The ambient measurement included skyglow and the light from the moon.

4.2 RELATIONSHIP TO SPD

There were two primary interests for the analysis: (1) soybean maturity (R-Stage); and (2) yield effects. R-Stage measurements contributed to the estimate of the amount of time that the lighting delays plant development.

4.2.1 Analysis of Plant Characteristics at Harvest versus Lighting and Light Type

The ultimate impact on the farmer is at harvest. Maturation delays impact the farmer because the green plants, which have a high moisture content, will jam the combine, requiring the farmer to stop and remove the jam by hand. The ideal seed moisture is 13%, but as little as 16% moisture (23% increase) can cause harvesting and threshing issues. High moisture seed content also lowers the price per bushel that the farmer can obtain for the crop due to the buyer's drying costs. Maturation, however, is a better way to measure of the ability to harvest. Therefore, maturity and yield affect the money a farmer can make from the field and is analyzed in detail.

4.2.1.1 General Overview

Based on the original project (Palmer et al. 2017), it was known that the plants seemed to be affected by either horizontal illuminance or vertical illuminance, or a combination of the two. Therefore, the total illuminance was included in the analysis. The vector sum of the vertical and horizontal illuminance was used to calculate the total illuminance at each plant location.

As shown in Figure 19, the yield estimate had significant variance versus total illuminance. This chart includes both light types. The normalized yield decreases versus increasing illuminance and the slope appears to become more negative as the illuminance increases.

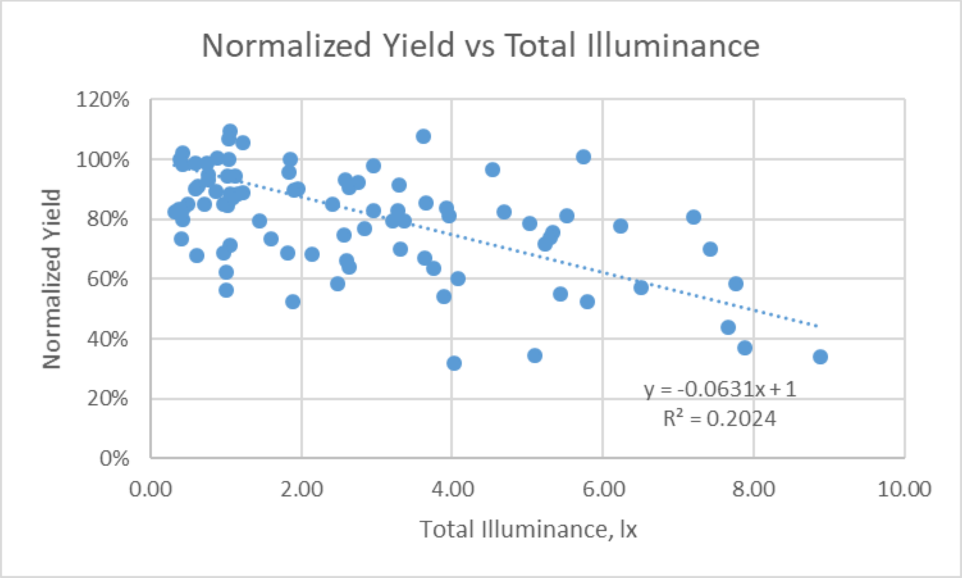


Figure 23. Yield estimate vs. total illuminance.

Similarly, Figure 20 shows the R-Stage variance versus the total illuminance, again including both light types. R-Stage also decreases relative to increasing illuminance. Unlike normalized-yield, the slope of R-Stage versus illuminance appears to become less negative as illuminance increases. Due to the variance in the data, it is difficult to tell without a model.

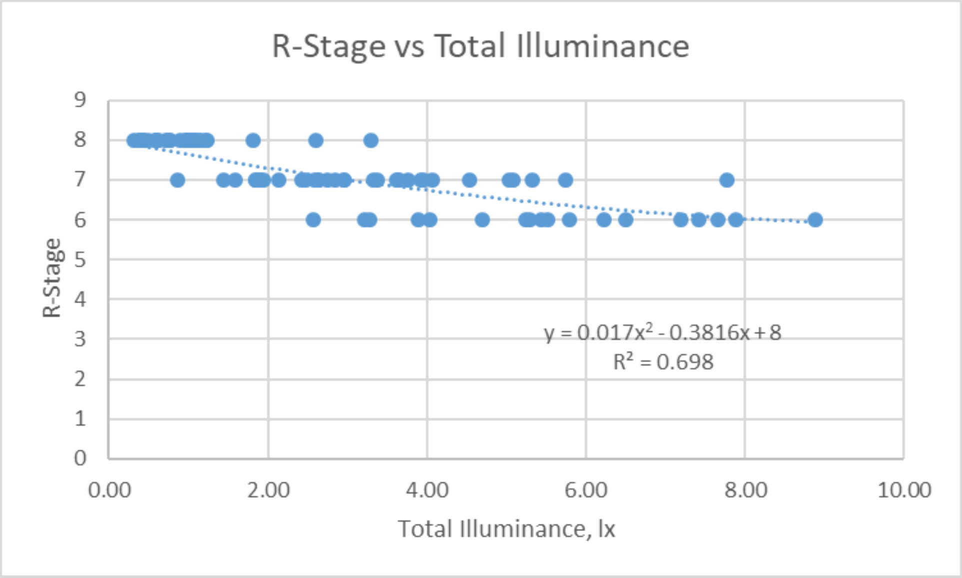


Figure 24. R-Stage vs. total illuminance.

4.2.1.2 Statistical Analysis

As mentioned, the two most critical aspects of the plants at harvest—maturity and yield—were analyzed statistically.

4.2.1.2.1 Maturity (R-Stage) at Harvest

Dry matter accumulation ceases once the soybean plant reaches R7, causing the crop to eventually dry down and be harvested. Although most leaves have fallen by the beginning of R7, the seeds still contain about 60 percent moisture, which is well beyond the marketable seed moisture of 13% (Pedersen, 2004). Excess plant and seed moisture will not allow the crop to be harvested until the soybean reaches R8 (full maturity), 15 to 20 days later. Even after R8 is reached, it may take an additional 5 to 10 days before the seed dries to less than the harvestable 15% moisture.

The ANOVA results of the relationship of maturity (R-Stage) with total PPFD and lighting type are shown in Table 7. The results indicate that total PPFD is very significant in describing the variation in the R-Stage. Lighting type was not statistically significant, while the interaction of Type and total PPFD was significant. Total PPFD was expected to be significant, but not the interaction.

Table 8, which shows that total illuminance was very significant, while Type and the interaction were not. The lack of significance indicates that the difference in lighting Type is within the realm of experimental uncertainty.

Table 7. ANOVA of R-Stage to Total PPFD and Lighting Type

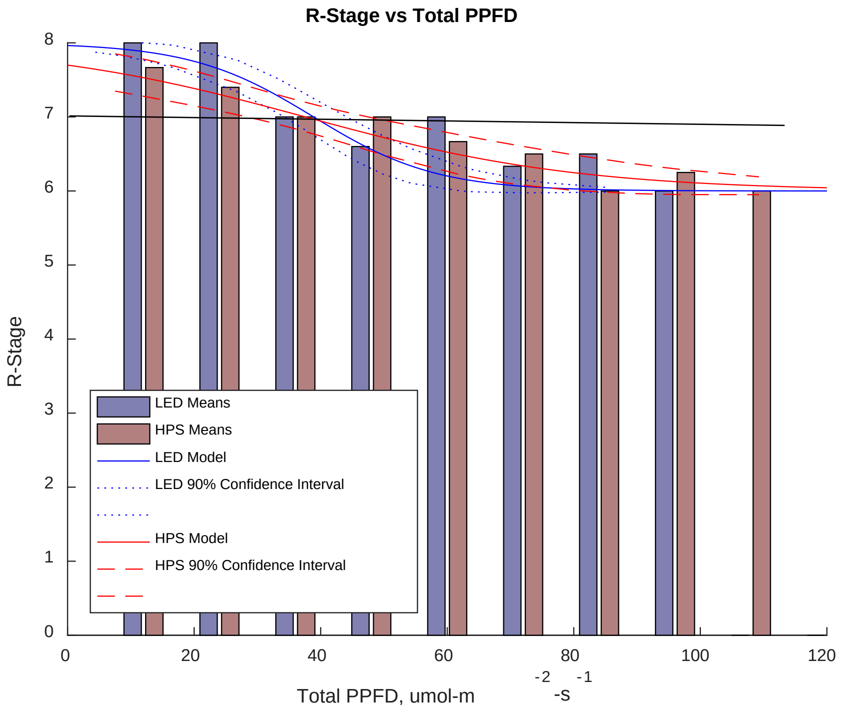
Source	DF	Type III SS	Mean Square	F Value	Pr > F
Total PPFD	9	25.15866996	2.79540777	15.84	<.0001
Type	1	0.16047449	0.16047449	0.91	0.3435
Total PPFD*Type	7	2.62648873	0.37521268	2.13	0.0518

Table 8. ANOVA of R-Stage to Total Illuminance and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Total Illuminance	8	24.32497280	3.04062160	16.65	<.0001
Type	1	0.01651968	0.01651968	0.09	0.7645
Total Illuminance*Type	6	1.98051666	0.33008611	1.81	0.1097

Figure 21 shows the results for the R-Stage versus the total PPFD and total illuminance, separated by lighting type and with 90% confidence limits. The bars in the figure indicate the binned means, a solid line represents the fitted model, and the 90% confidence limits appear as dotted and dashed lines. The models were fit to the raw data, but the ANOVA utilized the binned means, so the model is shown versus the binned means for interpretation. The tightening of the confidence levels near the higher lighting levels is an artifact of the sample distribution. There were fewer plant samples at the higher light levels. The R-Stage data variance resulted in confidence limits that are relatively small for these models. The r-squared value was 0.81 for the LED data and 0.51 for the HPS model. For comparison, the 2016 R-Stage data vs illuminance was reanalyzed using the same modeling approach as the 2017 data. Figure 22 shows the binned means and model of the 2016 data which had an r-squared of 0.11. Figure 22 illustrates the year and possibly field differences between the 2016 and 2017 HPS data sets. All of the model coefficients and r-squared values are shown in Appendix A.

As stated in the Analysis section, the bins were selected to minimize the graphical difference in the HPS response models. In addition, axes limits of the graphs in Figure 21 were likewise chosen to normalize the graphical representation of the HPS model to allow direct comparison of the PPFD and Illuminance models. In other words, the shape and location of the model for HPS response is nearly identical in both graphs, as expected since the conversion to PPFD is based on a single multiplier calculated from the SPD, which was constant. This selection of axes also emphasizes the difference in the LED model between the two lighting measurements since the HPS model curve doesn’t change.



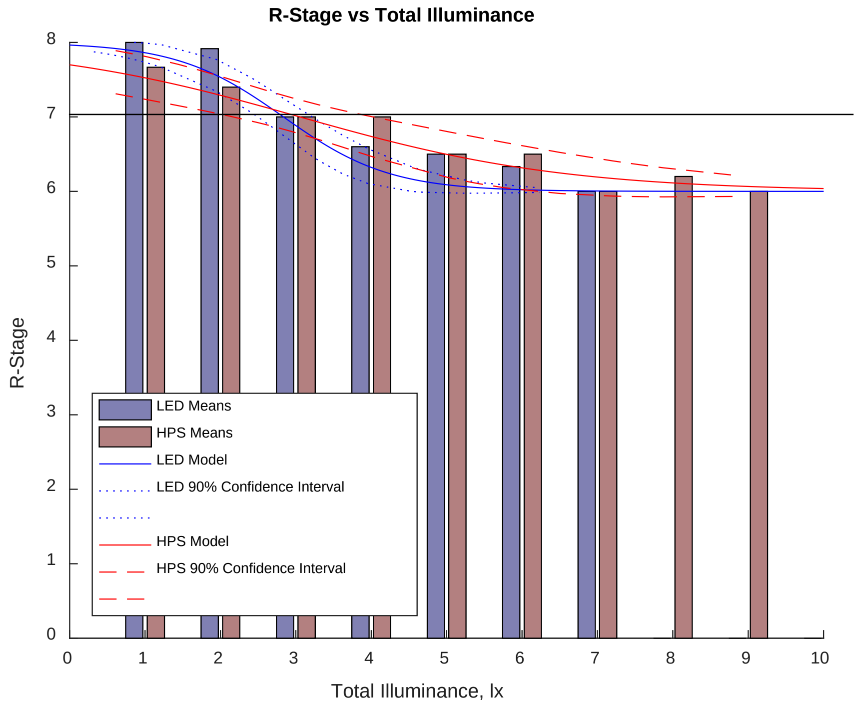


Figure 25. R-Stage versus total PPFD in µmoles·m^{-2}·s^{-1} (top) and total illuminance in lx (bottom). The horizontal line indicates the maturity limit.

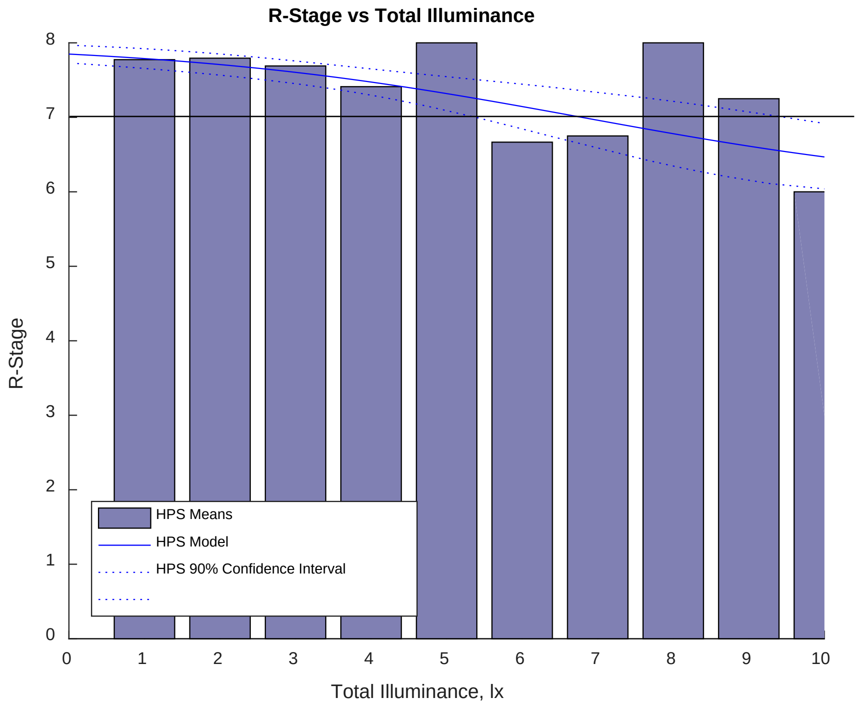


Figure 26. R-Stage vs total illuminance from 2016 study showing trespass lighting had less of an effect than 2017. The horizontal line indicates the maturity limit.

What's immediately clear from the two models in the two charts from 2017, is that there was a practical difference in the soy plant maturity with respect to the different light types in this study, regardless of the lighting measurement used, whether illuminance or PPFD. While both models have asymptotic R-Stage limits of 6 minimum and 8 maximum, the model of soy response to LED lighting has a steeper slope in maturity versus lighting level than the model for the HPS lighted plants. The models demonstrate that the plants are not as affected by the LED lighting at lower values of illuminance or PPFD, but seem to be more affected once the total PPFD passes 42 umol-m^{-2}-s^{-1}. Both models cross R-Stage 7 at approximately 42 umol-m^{-2}-s^{-1}.

Utilizing PPFD as the lighting measurement (Figure 21, top) spreads the data for the LED lighted plants out along the light level axis relative to the HPS model, but does not change the distribution in the y axis. This results in a subtle change in the slope, but not enough to result in the same model parameters. The R-Stage values relative to total illuminance for HPS and LED lighted plants (Figure 21, bottom) indicate a similar trend where the LED light has less impact on the maturity of the soybeans than the HPS lighting up to 3 lx, but then has a greater effect above 3 lx. The LED model shows the plants are limited to R-Stage 7 at 2.8 +/-1 lx while the HPS model crosses R-Stage 7 at 3.0 +/-1.5 lx, which is smaller than the uncertainty. This result is different from the 2016 result as seen in Figure 22, where the limit for R-stage 7 plant maturity was found to be 6.8 lx +/- 2.5 lx.

The non-linear regression of the models to the plant characteristics (R-Stage) take into account the number of samples at each light level. It is worth noting that most of the samples are below 5 lx total illuminance as shown in Figure 23. This is illustrated to some extent by the 90% confidence limits shown in Figures 20 through 22. However the number of samples at each lighting level is particularly important considering the sample locations were chosen to sample the highest density of plants in the transition from no effect to most effect. Considering just the histogram, this would tend to indicate the maximum lighting level should be between 1 and 4 lx.

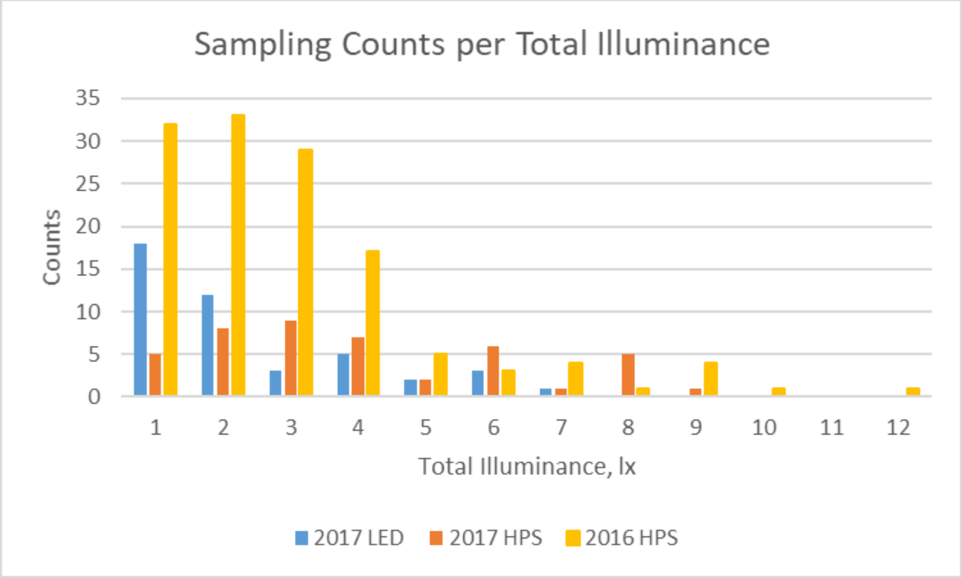


Figure 27. Histogram of the plant samples versus lighting level.

Table 9 and Table 10 show the ANOVA results for the R-Stage correlation to Type and the horizontal and vertical components of PPFD, respectively. Similarly, Table 11 and Table 12 show the results of the ANOVA for the variance of the R-Stage with respect to Type and horizontal and vertical illuminances, respectively. The horizontal and vertical lighting, whether measured in PPFD or illuminance, shows strong correlation to the R-stage, while Type is not statistically significant. In addition, the interaction of horizontal PPFD and Type is statistically significant, while the interactions of Type with the horizontal and vertical components of illuminance are not. The statistical significance of the interaction of Type with horizontal PPFD likely indicates that, for these lights, illuminance is a better way to measure how the lighting affects the plant's maturity.

Table 9. R-Stage versus Average Horizontal PPFD and Light Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Horizontal PPFD	8	25.95100957	3.2438762	22.76	<.0001
Type	1	0.03660851	0.03660851	0.26	0.6138
Horizontal PPFD*Type	6	1.71673531	0.28612255	2.01	0.0757

Table 10. R-Stage versus Average Vertical PPFD and Light Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vertical PPFD	3	20.48432177	6.82810726	30.63	<.0001
Type	1	0.25236741	0.25236741	1.13	0.2906
Type*Vertical PPFD	3	1.37840809	0.45946936	2.06	0.112

Table 11. R-Stage versus Average Horizontal Illuminance and Light Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Horizontal	8	25.16521832	3.14565229	19.24	<.0001
Type	1	0.23411956	0.23411956	1.43	0.2353
Horizontal*Type	5	1.40194806	0.28038961	1.71	0.1419

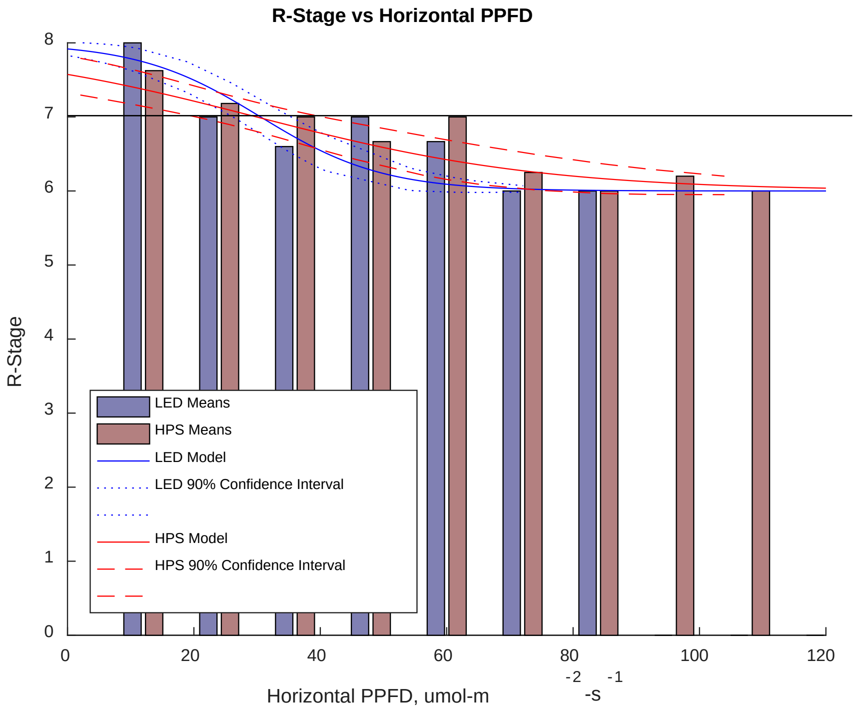
Table 12. R-Stage versus Average Vertical Illuminance, and Light Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vertical	3	21.39797166	7.13265722	30.86	<.0001
Type	1	0.19720225	0.19720225	0.85	0.3584
Type*Vertical	3	0.47384857	0.15794952	0.68	0.5648

Figure 24 and Figure 25 show the R-Stage versus horizontal and vertical components of the PPFD and illuminance, respectively—also with 90% confidence limits. The model for soy maturity versus the horizontal component of the PPFD (Figure 24) shows that the soy plants were affected more by the LED light at higher lighting levels similar to the analysis of the total PPFD, although the crossover occurs at a lower lighting level (24 umol-m^{-2}-s^{-1}). The maturity reached R7 at a horizontal PPFD of 30 umol-m^{-2}-s^{-1} for both the HPS and LED lighted plants.

However, the use of PPFD did not collapse the two models into one for the different lighting types. The models for maturity for both HPS and LED illuminated cross R7 at 2.2 lx horizontal.

In Figure 25, the R-Stage versus the vertical component of PPFD and Illuminance are plotted relative to the lighting types. For the LED lighted plants, R7 is reached at 24 umol-m^{-2}-s^{-1} and 20 umol-m^{-2}-s^{-1} for the HPS. Using vector addition, the total PPFD from the horizontal and vertical R-Stage limits is 38 umol-m^{-2}-s^{-1}, nearly identical to the finding from the total PPFD analysis. LED lighted both LED and HPS models cross R7 at 1.8 lux. Again, there are only small differences in the curves relative to the two lighting measurements. Using PPFD did not collapse the two models into one for the different lighting types.



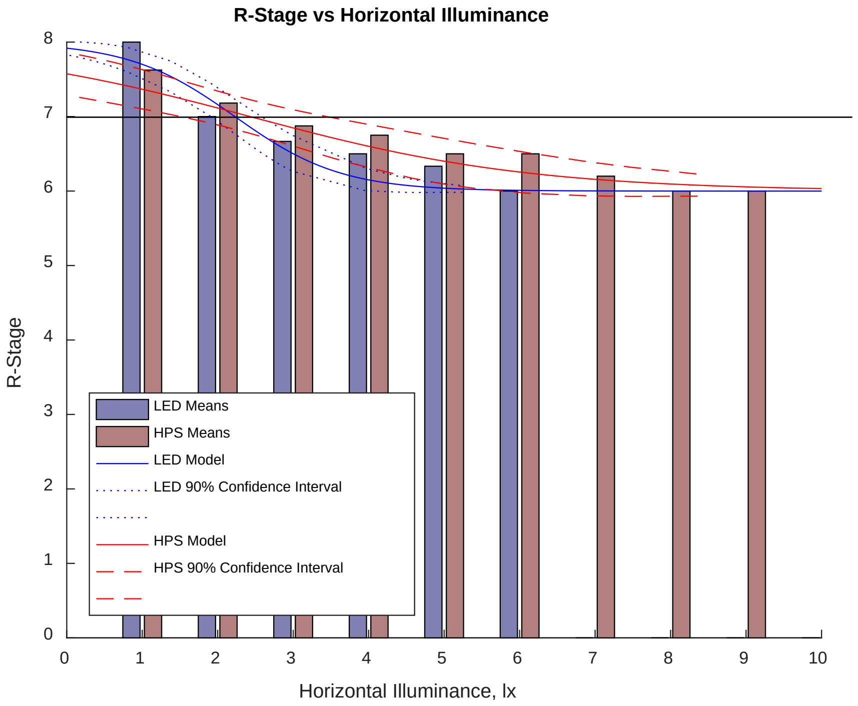
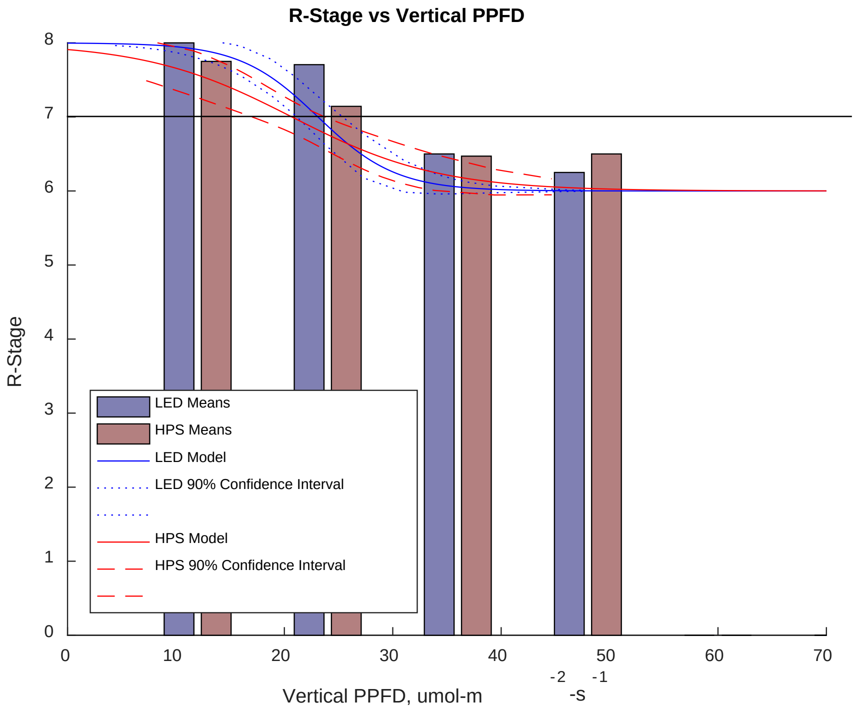


Figure 28. R-Stage versus horizontal PPFD in µmoles·m^{-2}·s^{-1} (top) and horizontal illuminance in lx (bottom). The horizontal line indicates the maturity limit.



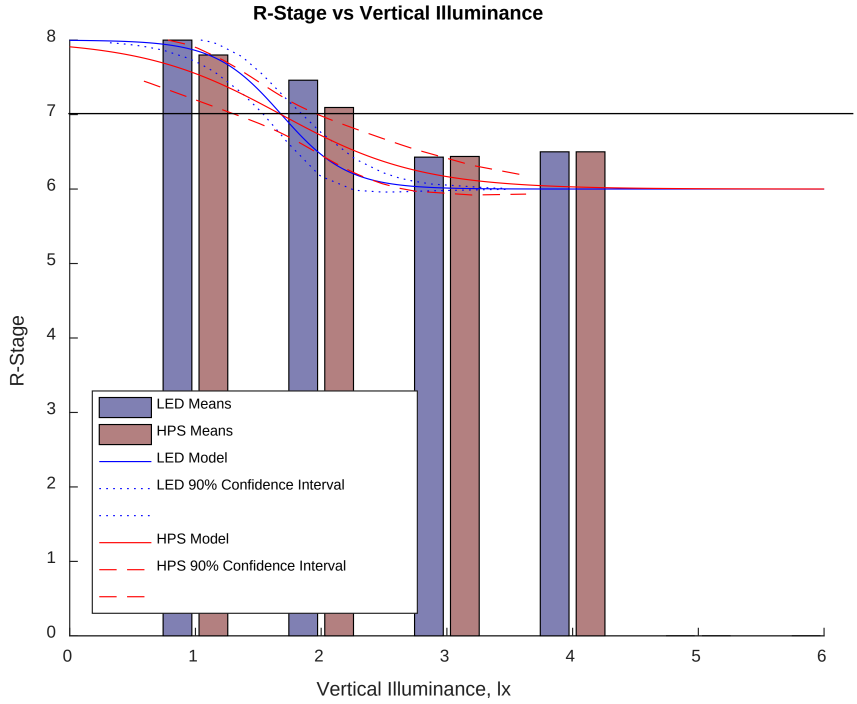


Figure 29. R-Stage versus average vertical PPFD in µmoles·m^{-2}·s^{-1} (top) and average vertical illuminance in lx (bottom). The horizontal line indicates the maturity limit.

4.2.1.2.2 Normalized Yield at Harvest

The ANOVA of the normalized yield (Table 13) found that the total PPFD measurement and the light Type (HPS vs LED) were significant, but the interaction was not. The lighting level significance agrees with the field observations that the presence of lighting affects crop yield. Had PPFD represented the difference of the impact of light type on soy, then Type would not have been significant. The significance of the relationship to lighting type (HPS vs. LED) suggests that PPFD is does not collapse the models for yield versus PPFD into one model independent of the lighting type.

Table 13. ANOVA of Normalized Yield to Total PPFD and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Total PPFD	9	0.51401357	0.05711262	2.76	0.008
Type	1	0.17741141	0.17741141	8.58	0.0046
Total PPFD*Type	7	0.14537211	0.02076744	1.00	0.4359

Table 14 shows the ANOVA results for normalized yield versus binned total illuminance and light Type. All factors are statistically significant. This is a strong indication of the influence of lighting Type on soybean production. The significance of the interaction of the two factors when using illuminance—and the lack of interaction when using PPFD—suggests that there may be a spectral based lighting measurement along the lines of PPFD—that could be developed to collapse or nearly collapse the models for the two light types into one model independent of lighting type.

Table 14. ANOVA of Normalized Yield to Total Illuminance and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Total Illuminance	8	0.42869317	0.05358665	2.73	0.0109
Type	1	0.17999703	0.17999703	9.17	0.0034
Total Illuminance*Type	6	0.24921768	0.04153628	2.12	0.0616

Figure 26 shows the normalized yield versus total PPFD and total illuminance plotted by lighting type: LED or HPS. The bars in the figure indicate the binned means, a solid line represents the fitted model, and the 90% confidence limits appear as dotted and dashed lines. As mentioned in the Analysis section, 3rd order polynomials were utilized to model the normalized yield versus the lighting levels. The soybean yield response to lighting is to initially decrease with light levels as little as 1 lx, and then flatten out before a sharp decrease in the yield versus the largest lighting levels (7-9 lx).

As Figure 26 shows, the confidence limits are broad for the normalized yield versus PPFD or illuminance, which corresponds to a large experimental uncertainty relative to the fit. The r-squared values vary from 0.01 to 0.20, which is also a result of the experimental uncertainty. Accordingly, normalized yield models should be considered carefully, especially near the higher lighting level values, where there were fewer (sometimes only one) sample points.

Again, the 2016 data was modeled using the same approach as the 2017 data. Figure 27 shows the result of the modeling of the normalized yield versus total illuminance and the yield limit. As can be seen, the 90% confidence bounds are large illustrating a similar large variance in the data.

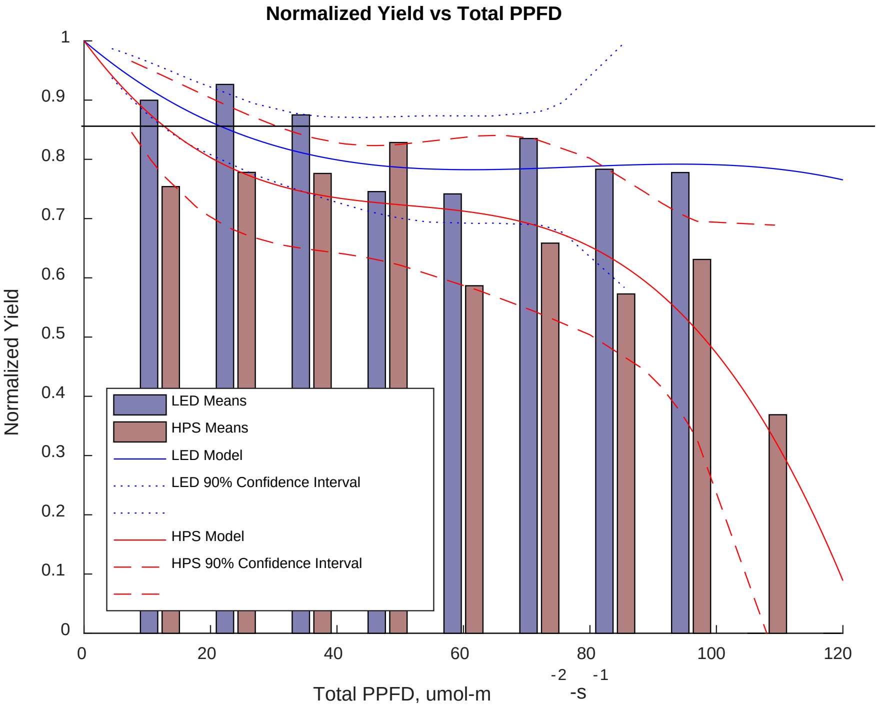
In terms of yield limits, the models predict 85% yield is maintained at a total illuminance of about 1 lx for the HPS lighted field, and 2 lx for the LED lighted field. These values again are smaller than the results from the 2016 analysis of HPS lighted fields where the model doesn't cross 85% yield until approximately 7.5 lx, suggesting that there are complex interactions between the weather and the artificial lighting, or that the beans affected by the lighting continue to mature and will reach maturity later than the rest of the field.

Figure 26 shows several additional results. First, as indicated by the models and means for LED versus HPS, the 4,000K LED lighting has a smaller effect on the soybean yield regardless of whether the lighting is expressed in µmoles$\cdot$m$^{-2}\cdot$s^{-1} or illuminance in lx—at any given total lighting level. This could be because the higher blue content produces more energy in the plants exposed to LED lighting, resulting in more growth and higher bean production.

Second, converting to PPFD does not collapse the models for the LED lighted plant response—and the HPS lighted plant response—into one model independent of light type. This is illustrated by the similarity of the LED and HPS curves using PPFD, to the corresponding HPS and LED curves using illuminance. Converting to PPFD slightly increased the difference between the models representing the normalized yield of the plants to the two light types, which can be seen in Figure 26

Thirdly, the measurement of normalized yield shows large variations for both lighting measurements, as shown by the confidence limits in the figures. For large LED lighting levels, there was considerable variance in the yield measurement. The variance is likely due to the unmeasured variation in field specific parameters such as water distribution and drainage, distribution of fertilizers, and/or soy variety.

However, while difference is statistically significant in the ANOVA which utilized binned data, the difference is much smaller than the uncertainty in the modeling which utilized the raw data (not binned by light level) as shown by the confidence limits in Figure 26. For the HPS lighted field, the uncertainty in yield versus total illuminance is -0.5 to +5.0 lx. The upper confidence limits for the LED lighted plants indicate that the yield may not ever drop below 85%. Therefore, the difference may not be practically significant.



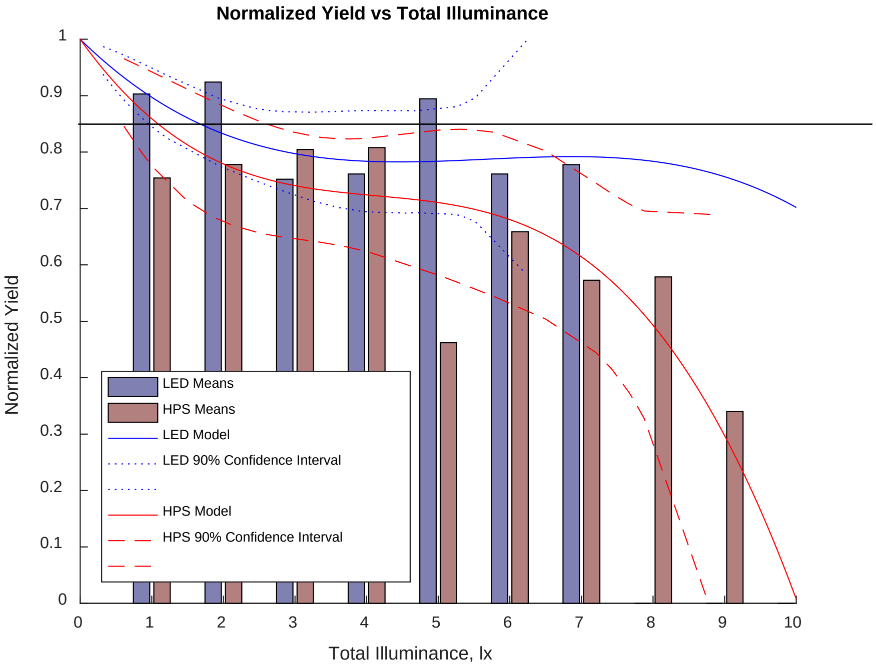


Figure 30. Normalized yield versus total PPFD in µmoles·m^{-2}·s^{-1} (top) and total illuminance in lx (bottom). The horizontal line indicates the yield limit.

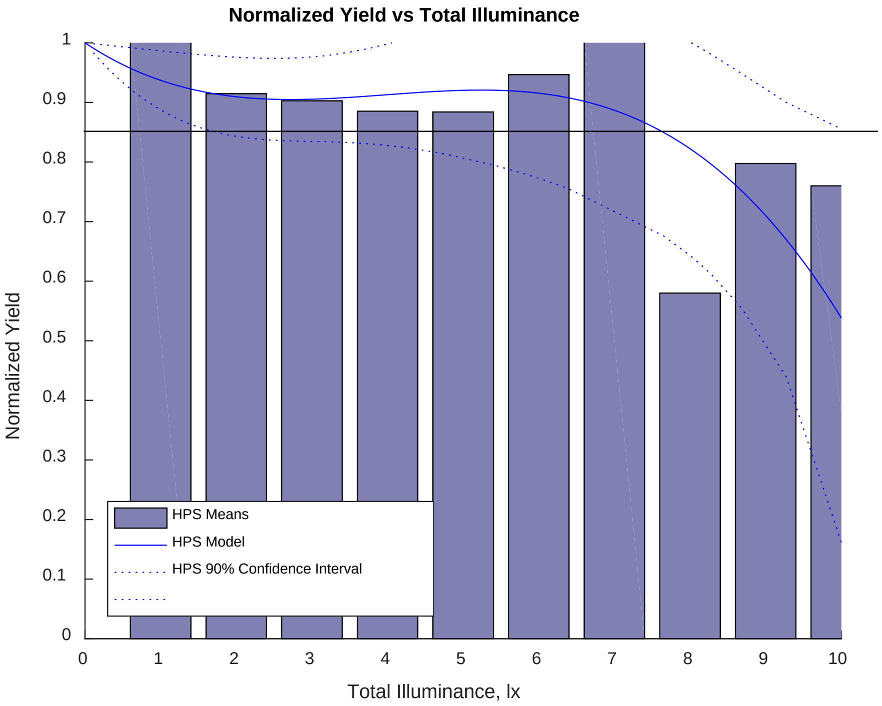


Figure 31. Normalized yield versus total illuminance from the 2016 data for comparison to the 2017 results. The horizontal line indicates the yield limit.

The ANOVA results of the normalized yield versus the horizontal PPFD and Type—as well as vertical PPFD and Type—are shown in Table 15 and Table 16. The ANOVA results, with respect to horizontal and vertical illuminance and Type, are shown in Table 17 and Table 18.

In both analyses, the horizontal component of the lighting measurement was significant, as was the Type. The vertical component of lighting using PPFD was statistically significant (90% confidence), but the vertical illuminance was not significant.

Table 15. ANOVA of Normalized Yield to Horizontal PPFD and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Horizontal PPFD	8	0.47005824	0.05875728	3.02	0.0055
Type	1	0.11132672	0.11132672	5.73	0.0193
Horizontal PPFD*Type	6	0.20004859	0.03334143	1.72	0.1295

Table 16. ANOVA of Normalized Yield to Vertical PPFD (Vertical PPFD) and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vertical PPFD	3	0.19302615	0.06434205	2.63	0.0558
Type	1	0.33448212	0.33448212	13.67	0.0004
Type*Vertical PPFD	3	0.03249957	0.01083319	0.44	0.7230

Table 17. ANOVA of Normalized Yield to Horizontal Illuminance and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Horizontal Illuminance	8	0.44100229	0.05512529	2.73	0.0109
Type	1	0.07319468	0.07319468	3.62	0.0609
Horizontal Illuminance*Type	5	0.16633027	0.03326605	1.65	0.1584

Table 18. ANOVA of Normalized Yield to Vertical Illuminance and Lighting Type

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Vertical Illuminance	3	0.14778474	0.04926158	2.11	0.1057
Type	1	0.28427581	0.28427581	12.17	0.0008
Type*Vertical Illuminance	3	0.10009824	0.03336608	1.43	0.2407

Figure 28 shows the means and the model fit of the nominal normalized yield for the horizontal components of PPFD and illuminance. Again, conversion to PPFD increases the separation between the light type models instead of collapsing them. However, for the horizontal illuminance and horizontal component of PPFD, the models predict essentially the same lighting measurement at an 85% yield: 12 µmoles·m^{-2}·s^{-1} or 1 lx.

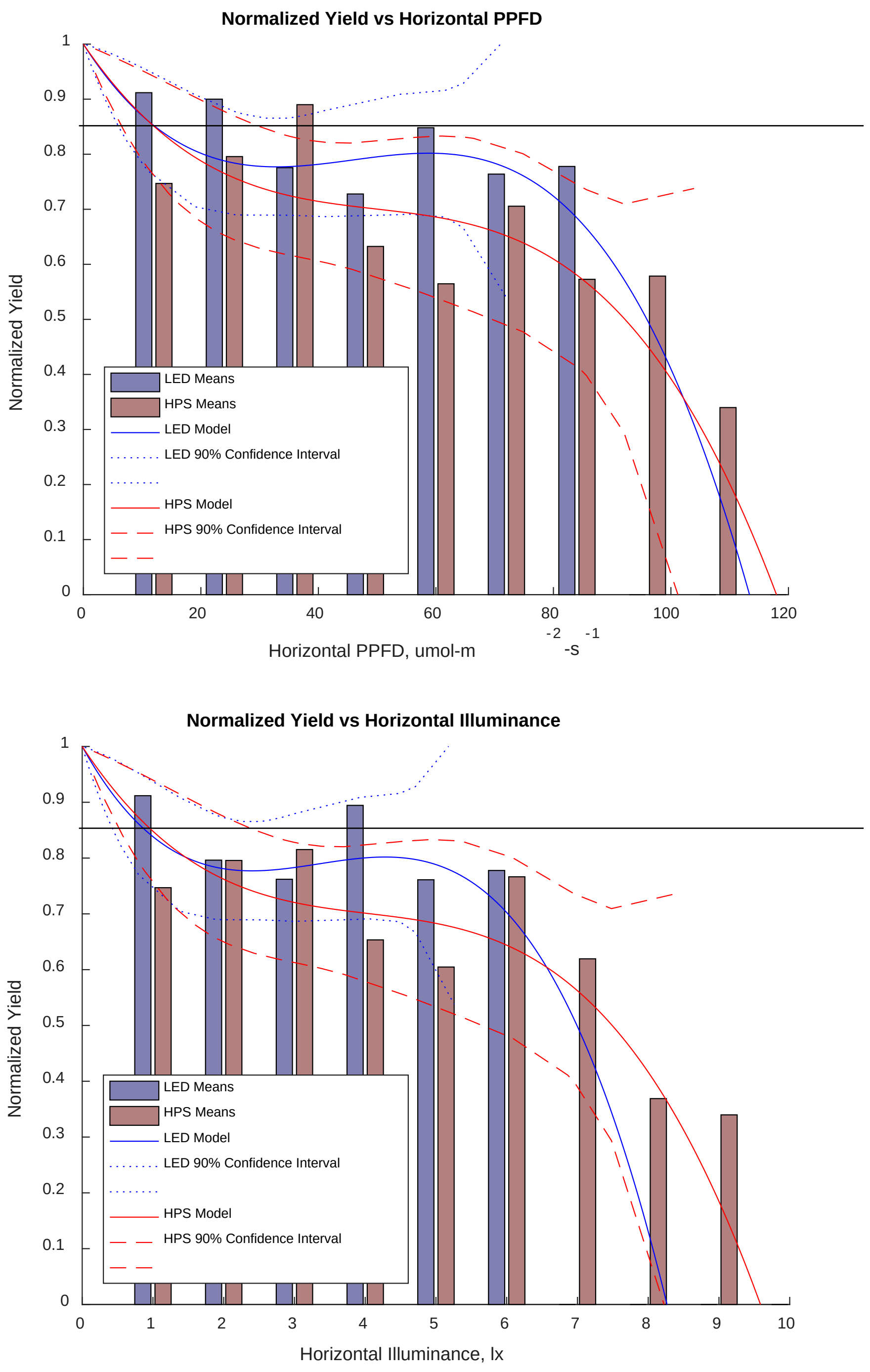
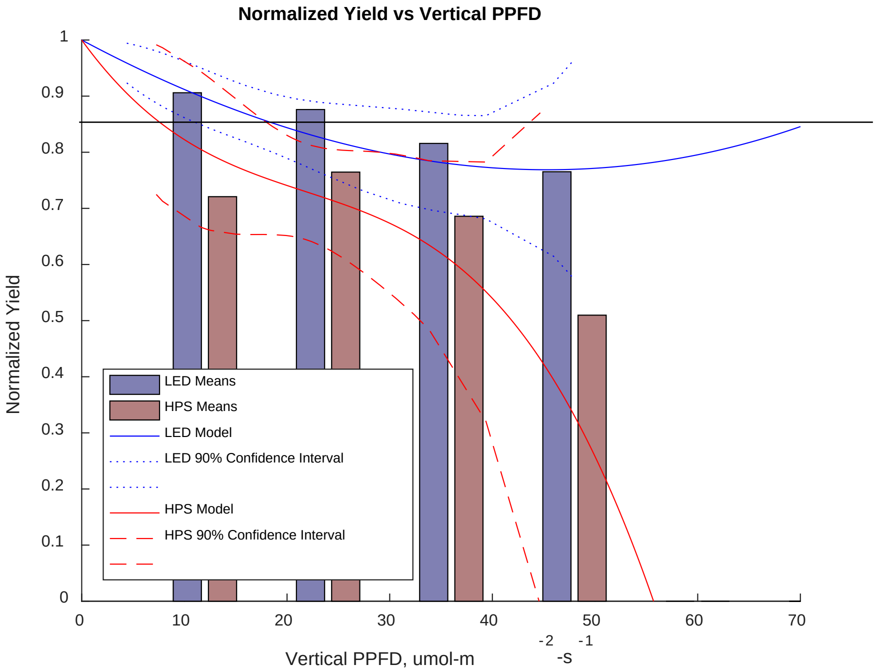


Figure 32. Normalized yield versus horizontal PPFD in µmoles·m^{-2}·s^{-1} (top) and horizontal illuminance in lx (bottom).

Normalized yield versus vertical PPFD and vertical illuminance is shown in Figure 29. Again, the normalized yield versus lighting for LED light type, exceeds the normalized yield versus HPS lighting and light level, regardless of whether light level is expressed in PPFD or illuminance. PPFD increases the separation between the models for the soy response to the LED light type versus the HPS type. In the case of vertical measurements, the HPS model crosses 85% yield at approximately 10 μmoles$\cdot$m$^{-2}\cdot$s^{-1} or approximately 1 lx. The LED model predicts 85% yield at approximately 24 μmoles$\cdot$m$^{-2}\cdot$s^{-1}, or approximately 2 lx. Given that the difference in plant response to the horizontal component of light level was invariant for light type, and that the vertical component lighting measures are nearly identical to the total lighting levels, then the difference in yield is related to only the vertical component of lighting.

Finally, the difference in the soy yield with respect to the light type and the total and vertical components of lighting levels is only 1 lx. This is quite small relative to the findings for HPS lighting from 2016, where 6 lx horizontal and 3 lx vertical were found to be the limits for 85% yield. The confidence limits for the modeled responses to the 2017 data (HPS and LED) are large and the r-squared value for the fits were low. Therefore, the model may not predict the plant responses well. As mentioned for the R-Stage results the plants continue to grow and mature despite being delayed by the artificial lighting as reported in volume 1 (Palmer et al., 2017) in the Peoria field and as determined from the survey and anecdotal conversations with the farmers. There could also be a complex interaction between lighting level and weather in the soy response.



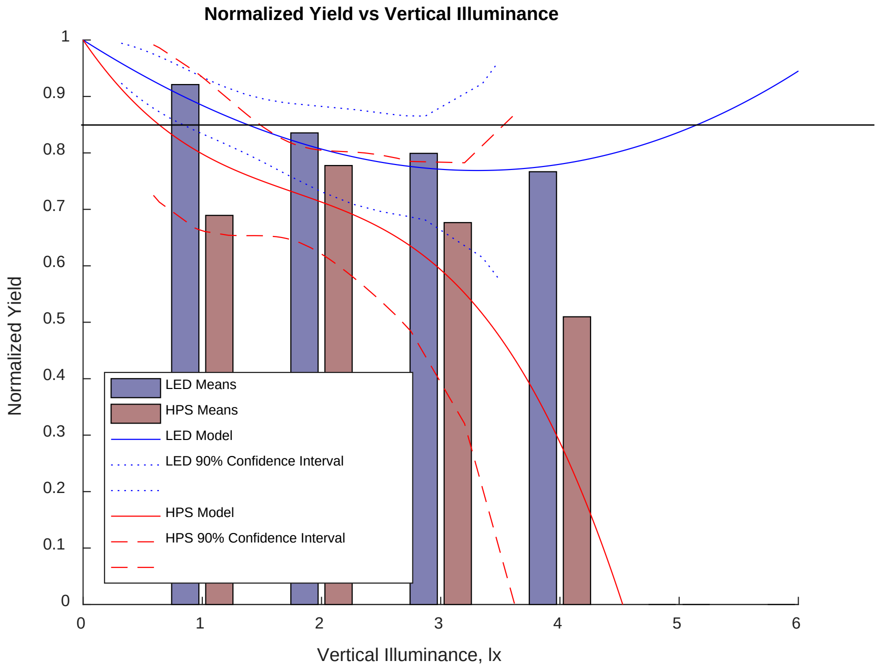


Figure 33. Normalized yield versus average vertical PPFD in µmoles·m^{-2}·s^{-1} (top) and average vertical illuminance in lx (bottom).

4.2.1.2.3. Year to Year Variation in the Plants Not Affected by the Trespass Lighting

In order to understand the difference in the 2016 and 2017 maturity and normalized yield, the plant growth measurements for the plants least affected by the lighting were analyzed. The growth measurement were analyzed with respect to year and type of light at the edge of the field.

Figure 30 shows the average estimate yield, not normalized, from the plants that were not affected by the trespass lighting (R-Stage 8 and total illuminance less than 1.5 lx). As can be seen the yields are almost identical and there is overlap in the error bars (standard error) between the 2016 HPS fields and the 2017 LED fields which is essentially no difference. The 2017 HPS yield is 70% of the yield of 2016 HPS fields and the error bars are separate, so the result is significant. In this graph, there are 7 fields of data in the 2016 HPS mean but only 1 field of data in the 2017 HPS and only 1 field for the 2017 LED means, so difference in HPS data could be seasonal or field related. There were no R-8 samples in the second HPS field that were in lighting less than 1.5 lx.

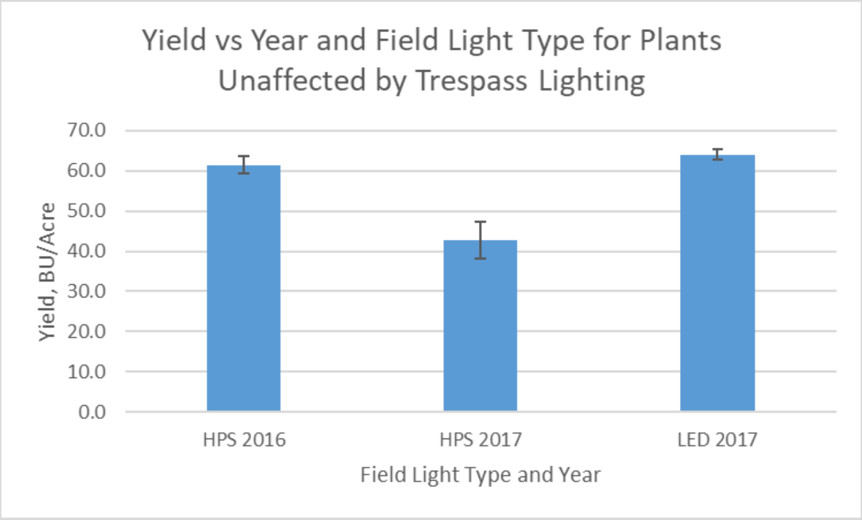


Figure 34. Year to year variation in average yield versus light type at the edge of the field. The error bars represent the standard error.

Other factors such as temperature (Lauer, 2003) and seeding rate (Cherney, 2011) can have an effect on the physiology of the soybean plants while the plants display complex compensatory growth with respect to planting dates, tillage and management approach, as well as variety (cultivar) (Lauer, 2004). This may explain the difference in yield for the unlighted plants in the HPS fields.

Figure 31 shows the year to year variation in height based on light type on the edge of the field for the plants not affected by light. In this chart the differences are shown by limiting the range of the y axis. There is only a five percent difference in the height of the plants between 2016 and 2017 HPS fields. There is an additional 5% reduction in height for the LED field.

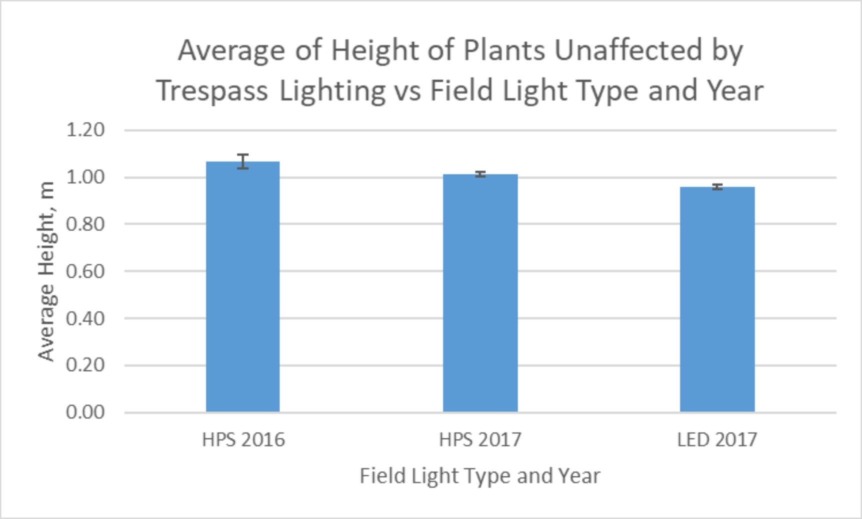


Figure 35. Year to year variation in average plant height versus light type at the edge of the field. The error bars represent the standard error.

Dry and wet masses of the plants are shown year to year and by field light type in Figure 32. As can be seen, the average plant mass, dry and wet, are similar to the yield results with the 2017 HPS lighted fields having plants that were less than half of the average mass of either the 2016 HPS or 2017 LED lighted fields.

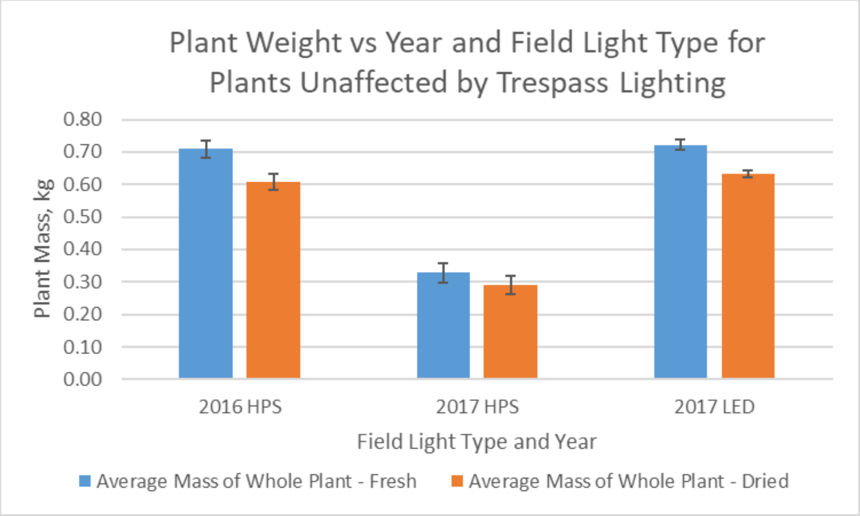


Figure 36. Year to year variation in average plant mass, fresh and dry, versus light type at the edge of the field. The error bars represent the standard error.

Figure 33 shows the year to year variation in plant moisture versus light type at the edge of the field for the plants unaffected by the trespass lighting. In this chart it can be seen that there is neither a significant or practical difference in the plant moisture year to year or versus light type.

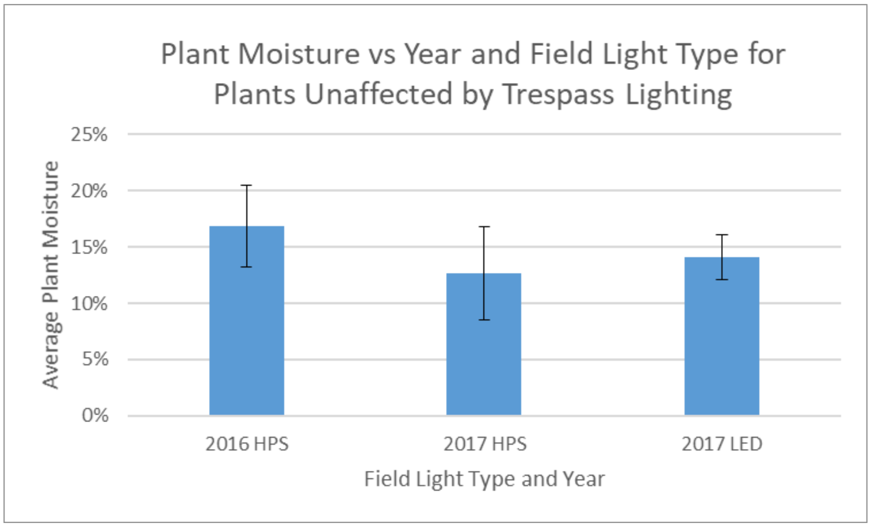


Figure 37. Year to year variation in average plant moisture versus light type at the edge of the field. The error bars represent the standard error.

The year to year variation in plant mass measurements and yield measurements seem to be related to field or farmer differences rather than seasonal differences especially given the lack of differences in the height and plant moisture.

4.3 ANALYSIS SUMMARY

Utilizing PPFD does not provide a universal lighting measurement that normalizes the maturity and yield responses of the soy, independent of lighting type. However, the differences in the responses are small for this study when compared to the confidence levels.

Based on an R-Stage ANOVA, the difference in soy response to the two light types for light levels measured in illuminance is not statistically significant for total, horizontal or vertical illuminance. In addition, the practical difference is less than the uncertainty in models for both light types.

The average maturity of the plants harvested for this project were not below R6. This shows that all of the plants did flower eventually, suggesting that the photoperiodicity of soybeans is related to both the night length, and the total illuminance during the night.

The yield response difference between the LED and HPS lighted plants was on the approximately 1 lx for total and vertical lighting measurements. While the difference between the HPS and LED light types was found to be statistically significant, the confidence limits indicate that the difference may not be practically different.

CHAPTER 5: DISCUSSION

This experiment was largely an observational study with no control over a range of confounding factors. However, the seven sites selected provided sufficiently clear and statistically significant evidence that trespass lighting has an impact on not only soybean plant maturity—but also on the yield of beans from those plants. This study arrived at several key conclusions.

The analysis performed for this study show a statistical, but small practical difference in the normalized yield and no statistically significant differences in the maturity of the soy plants lighted by 4,000K LED street lights used in this study versus the HPS lighted plants. PAR, or more specifically PPFD, was utilized in the analysis as a common measurement of the soy plant's photomorphogenesis. This is due to the fact that there was considerable overlap in the PPFD wavelength range and the phytochrome and cryptochrome sensitivities.

5.1 MATURITY

The difference was small between the light types for the R-Stage—about 1.0 to 1.5 lx total illuminance at an R-Stage of 7—which was also the R-Stage utilized for the previous study. The statistical analyses of illuminance show that lighting Type was not statistically significant. Further, converting the lighting measurement from illuminance to PPFD did not remove the difference in maturity response of the soy plants to the two different lighting types, and appeared to separate the curves more.

The HPS lighted plants were limited to R7 at illuminance levels of 3 lx horizontal and 1.8 lx vertical—compared to the 2016 study—which found plants limited to an R7 at 5.7 lx horizontal and 4.5 lx vertical. This is a fairly large discrepancy between the two years. One possible reason for the discrepancy is the experimental uncertainty in the data. As Figure 24 and Figure 25 show, the model uncertainty for the R-Stage of the HPS lighted field, results in a range of illuminance values ranging from 1.2 to 2.2 lx vertical, and from 2 to 4.2 lx horizontal. The upper values of the confidence ranges for the HPS lighting in this study are starting to approach the values found in the original study for HPS lighting, especially if the uncertainty in the 2016 model for R-Stage was similar.

Many other uncontrolled variables could have affected an offset in maturity for similar lighting levels, including temperature variances between 2016 and 2017 and seeding rate in each field. In addition, the Volume 1 report pointed out that a particular field had mature plants in higher lighting suggesting that the plants are delayed in maturity rather than stopped and continue to mature in the higher lighting. Therefore, the absolute lighting values from the comparison of the LED and HPS light types should be considered carefully, with respect to the 2016 analysis. However, the difference in soy response to lighting values between the HPS and LED plants should be accurate and valid, since all of the plants were within 10 miles of each other and at nearly the same latitude. This ensured that the plants saw similar amounts of sunlight, rainfall, wind, etc.

5.2 YIELD

Utilizing an 85% yield as a limit, the difference in soy response between the LED and HPS illuminated plants was approximately 1 lx total illuminance—with the LED lighted field producing more normalized yield per lx than the HPS field. The difference was marginal at 85% yield versus horizontal illuminance, but again was 1 lx for the difference in vertical illuminance between the LED and HPS models. This suggests that only the vertical component of the LED illuminance affected the yield in a positive manner, and was responsible for the difference in yield with respect to total illumination. This is a small amount of light, and while statistically significant, is within the model confidence limits, and could therefore be attributed to experimental uncertainty.

The SPD from each light type should be identical for the vertical and horizontal components. Therefore, if there is a difference in the plant's response to the SPD in the vertical plane versus the horizontal plane, it is a result of the complex photochemistry and cellular structure of the plant—and would require considerably more samples in a controlled environment to determine. Unfortunately, that relationship cannot be determined from this study's data.

5.3 PPFD

A different lighting calculation may be needed to characterize the lighting level that can be applied to luminaires with SPDs differing from the 4,000K LED, and HPS luminaires used in this study. The results from this study indicate there is minimal, if any, difference on maturity limits between the 4,000K LED used in this study, and HPS lighting. In addition, LED luminaires increase plant yields over HPS luminaires by a small amount.

5.4 YEAR TO YEAR VARIATION

It is not clear why there is a difference between the HPS light effect on the plants between 2016 and 2017, especially for the normalized yield, which was normalized by the plants that were not in the light effective zone. This should have theoretically minimized seasonal variations, field differences, and variety differences.

An analysis of the plants unaffected by the trespass lighting showed significant differences in plant mass and yield for the fields with HPS lighting, but no difference in the yield and mass of the plants between the 2016 HPS lighted fields and the 2017 LED lighted field. There was no significance difference in the plant height and moisture across light type and year in plants unaffected by the lighting.

Since the fields selected for 2017 data collection with HPS lighting were farmed by the same farmer, the differences in yield and mass may be related to an uncontrolled factor in the growth of the soybean plants that is under the control of the farmer such as row spacing, tillage, or amount of fertilizer rather than seasonal.

5.5 DISCUSSION SUMMARY

Based on the above discussion, it is unclear why there is a significant difference between the 2016 results and the 2017 results that is not attributable to the LED vs HPS lighting type. It does not appear to be seasonal due to the similarity in plant height and moisture of the plants unaffected by the trespass lighting.

Based on there being no difference in the plant characteristics that can be attributed to seasonal differences, there may be some complex interaction of the lighting and season variations. This could only be tested by planting the same crop by the same farmer in the same location in multiple years, which would be difficult given the crop rotation needed to keep the land from turning fallow. That being said, the differences could also be farmer or field specific, which would require additional data to isolate.

To add a margin of safety, the limits should be revised to reflect the unknown difference year to year in the lighting level and due to the width of the confidence limits. The team is recommending the lower values of lighting from the 2017 results, but no difference based on the spectra of the sources in this study. The results of averaging the limits together versus year are shown in Table 19 and Table 20. As can be seen the more limiting values are related to keeping the normalized yield above 85%.

Table 19. Average of Total, Horizontal and Vertical Illuminances for both years for an R-Stage of 7

R-Stage 7		
Total Illum.	**Horizontal Illum.**	**Vertical Illum.**
2.9	2.2	1.8

Table 20. Average of Total, Horizontal and Vertical Illuminances for both years for an 85% yield

85% Yield		
Total Illum.	**Horizontal Illum.**	**Vertical Illum.**
1.8	1.0	1.5

However, these results are not universally applicable to all LED luminaires, even if the CCT is the same as the 4,000K LED used in this study. The spectral power distribution can differ significantly between light sources with identical CCTs, so these recommendations are only appropriate for the 4,000K LED in this study.

However, this does not negate the remainder of the findings from Volume 1 of the project report. There is sufficient evidence to suggest that the photoperiodicity is affected by total dose and not the magnitude of the lighting. Therefore, reducing the dose by adapting or turning off of the luminaires after a curfew should also reduce the impact of the lighting on soy. In fact, anecdotal evidence in reported Volume 1 (Palmer et al., 2017) suggested that turning the street lights off for just a weekend or two (4 nights) allowed the soy plants to completely recover.

In addition, the compensatory growth reported in response to late planting dates (Lauer, 2004) includes a photomorphogenesis or photoperiodicity response to light that increases growth rate and maturation rate up to R6. This enables the plants planted later in May to reach maturity and yield on time (relative to the soy planted earlier) despite lower total light dose from a shorter growing period. This supports the theory that the soy plants can compensate for artificial light as well.

Therefore, the trespass lighting could be higher than the limits listed above for part of the night up to perhaps midnight, if they are turned off afterwards. Since the impact on soy appears to be related to dose, the limits could be conservatively increased by a factor of 2 if the lights are turned off for half of the night for the growing season. In other words, the trespass light limits ($L_{cont.}$) could be increased by the inverse of the ratio of time on (T_{on}) to the total time the sun is down (T_{night}) when using adaptation ($L_{adaptive}$). (Equation 8)

$$L_{adaptive} = L_{cont.} * T_{night} / T_{on} \qquad \text{Equation 8}$$

CHAPTER 6: CONCLUSIONS

Little practical difference was found in the maturity of the soy plants lighted by the 4,000 K LED Street lights, versus the HPS street lights used in this study. The use of PAR or PPFD worsened the difference between the two lighting types and, based on the analysis performed for the study, does not capture the differences in plant response to the light sources used in this study.

The difference in lighting type was not statistically significant for maturity when utilizing illuminance as the lighting measure. In addition, there was no difference in the modeled responses of the soy plants to the two lighting types at a maturity R-Stage of 7.

While lighting type was found to be statistically significant with respect to plant yield, the difference in lighting levels between the two light types for the plants to reach an 85% yield was only 1 lx vertical, and 0 lx horizontal based on the response model with the LED producing more yield with a slightly higher vertical illuminance. However, this difference is within the models' uncertainty at 90% confidence, and thus may not represent a practical difference.

However, there was a difference in the 2016 and 2017 results for the lighting levels that could impact maturity and yield. The difference could not be attributed to lighting levels or lighting type. To add a margin of safety, the limits should lowered reflect the values in Table 21.

It is important to note that these results are not universally applicable to all LED luminaires even if the CCT is the same as the 4,000K LED used in this study. The spectral power distribution can differ significantly between light sources with identical CCTs, so these recommendations are only appropriate for the 4,000K LED in this study.

Finally, adaptive lighting using controls can also be used to minimize the impact of lighting trespass on soy as reported in the Volume 1 of this report. The impact of lighting on soy is related to total dose (time and level) so higher trespass lighting levels will have a reduced impact if the levels are dimmed or the lights are turned off for a portion of the night.

Table 21. Revised Trespass Illuminance Limits for the HPS and 4,000K LED Streetlights Used in This Study Continuous Nighttime Lighting

Illuminance	Maximum, lx
Horizontal	2.2
Vertical	1.8

REFERENCES

Ashdown, I. (2016). Photosynthetic Photon Flux Density (PPFD) - Concepts. Retrieved from http://docs.agi32.com/AGi32/Content/adding_calculation_points/PPFD_Concepts.htm

Bennie, J., Davies, T. W., Cruse, D., Inger, R., & Gaston, K. J. (2015). Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 370*(1667), 20140131.

Briggs, W. R. (2006). Physiology of plant responses to artificial lighting. *Ecological consequences of artificial night lighting (C. Rich and T. Longcore, eds.). Island Press, Washington, DC*, 389-411.

Brown Jasa, L. (1997). CropWatch No. 97-24, Oct. 10, 1997.

Buzzell, R. I. (1971). INHERITANCE OF A SOYBEAN FLOWERING RESPONSE TO FLUORESCENT-DAYLENGTH CONDITIONS. *Canadian Journal of Genetics and Cytology, 13*(4), 703-707. doi:10.1139/g71-100

Cathey, H. M., & Campbell, L. E. (1975a). Effectiveness of five vision-lighting sources on photo-regulation of 22 species of ornamental plants. *Journal-American Society for Horticultural Science (USA)*.

Cathey, H. M., & Campbell, L. E. (1975b). Security lighting and its impact on the landscape. *Journal of arboriculture*.

Cherney, W. J. C. a. J. H. (2011). Growth and Yield Responses of Soybean to Row Spacing and Seeding Rate. *Journal of Agronomy, 103*(1), 123-128.

CIE. (2004). *Colorimetry, Third Edition. CIE Technical Report 15:2004*. Retrieved from Vienna, Austria:

Cope, K. R., & Bugbee, B. (2013). Spectral effects of three types of white light-emitting diodes on plant growth and development: absolute versus relative amounts of blue light. *HortScience, 48*(4), 504-509.

Devlin, R. M. (1969). *Plant Physiology 2nd Edition*: Van Nostrand Reinhold Co.

Downs, R. J. (1956). Photoreversibility of Flower Initiation. *Plant Physiology, 31*(4), 279-284.

Fehr, Walter R., Caviness, Charles E. (1977). *Stages of soybean development* (87). Retrieved from Ames, IA: https://lib.dr.iastate.edu/specialreports/87/

Garner, W. W., & Allard, H. A. (1920). EFFECT OF THE RELATIVE LENGTH OF DAY AND NIGHT AND OTHER FACTORS OF THE ENVIRONMENT ON GROWTH AND REPRODUCTION IN PLANTS 1. *Monthly Weather Review, 48*(7), 415-415.

Han, T., Wu, C., Tong, Z., Mentreddy, R. S., Tan, K., & Gai, J. (2006). Postflowering photoperiod regulates vegetative growth and reproductive development of soybean. *Environmental and Experimental Botany, 55*(1–2), 120-129. doi:http://dx.doi.org/10.1016/j.envexpbot.2004.10.006

Hill, D. A. (1992). *The impact of noise and artificial light on waterfowl behaviour: a review and synthesis of available literature*: British Trust for Ornithology.

Kostuik, J., McEachern, S., & Melnychenko, A. (2014). *Western Manitoba Soybean Adaptation Trial*. Retrieved from

Lauer, P. P. a. J. G. (2003). Soybean Agronomic Response to Management Systems in the Upper Midwest. *Journal of Agronomy, 95*, 1146-1151.

Lauer, P. P. a. J. G. (2004). Soybean Growth and Development in Various Management Systems and Planting Dates. *Crop Science, 44*, 508-515.

Lawrence, B., & Fehr, W. (1981). Reproductive response of soybeans to night interruption. *Crop Science, 21*(5), 755-757.

Nissly, C. R., Bernard, R. L., & Hittle, C. N. (1981). Variation in Photoperiod Sensitivity for Time of Flowering and Maturity Among Soybean Strains of Maturity Group III1. *Crop Science, 21*(6). doi:10.2135/cropsci1981.0011183X002100060009x

Palmer, Matthew., Ronald Gibbons, Rajaram Bhagavathula, David Holshouser, and Daniel Davidson. (2017). *ICT PROJECT R27-172: ROADWAY LIGHTING'S IMPACT ON ALTERING SOYBEAN GROWTH: VOLUME 1.* A report of the findings of ICT PROJECT R27-172. Illinois Center for Transportation Series No. 17-014. Research Report No. FHWA-ICT-17-010. Illinois Center for Transportation, Rantoul, IL. Retrieved at https://apps.ict.illinois.edu/projects/getfile.asp?id=5252

Parker, M. W., Hendricks, S. B., Borthwick, H. A., & Scully, N. J. (1946). Action Spectrum for the Photoperiodic Control of Floral Initiation of Short-Day Plants. *Botanical Gazette, 108*(1), 1-26.

Pedersen, P. (2004). *Soybean Growth and Development* (PM 1945). Retrieved from Ames, IA:

Pedmale, U. V., Huang, S.-s. C., Zander, M., Cole, B. J., Hetzel, J., Ljung, K., . . . Chory, J. (2016). Cryptochromes interact directly with PIFs to control plant growth in limiting blue light. *Cell, 164*(0), 233-245. doi:10.1016/j.cell.2015.12.018

Sinnadurai, S. (1981). High pressure sodium street lights affect crops in Ghana. *World crops*.

Spellerberg, I. (1998). Ecological effects of roads and traffic: a literature review. *Global Ecology and Biogeography, 7*(5), 317-333.

USDA. (2001). 2001 Agricultural Statistics Annual. *United States Department of Agriculture - National Agricultural Statistics Service.* Retrieved from https://www.nass.usda.gov/Publications/Ag_Statistics/2001/

Wheeler, R., Mackowiak, C., & Sager, J. (1991). Soybean stem growth under high-pressure sodium with supplemental blue lighting. *Agronomy journal, 83*(5), 903-906.

Zong-Ming, Z. (2007). Influence of Street light illumination on soybean growth and Yield [J]. *Anhui Agricultural Science Bulletin, 20*, 028.

APPENDIX: MODEL FIT COEFFICIENTS

Total Lighting vs R-Stage				
Model	2/(1+exp(b*(x-c)))+6			
		c	b	R squared
2016	HPS Illum.	4.59	0.60	0.11
2017	LED Illum.	1.68	3.79	0.81
2017	HPS Illum.	1.68	1.82	0.40
2017	LED PPFD	25.35	0.25	0.81
2017	HPS PPFD	20.70	0.15	0.40

Horizontal Lighting vs R-Stage				
Model	2/(1+exp(b*(x-c)))+6			
		c	b	R squared
2016	HPS Illum.	4.59	0.60	0.11
2017	LED Illum.	1.68	3.79	0.81
2017	HPS Illum.	1.68	1.82	0.40
2017	LED PPFD	25.35	0.25	0.81
2017	HPS PPFD	20.70	0.15	0.40

Vertical Lighting vs R-Stage				
Model	2/(1+exp(b*(x-c)))+6			
		c	b	R squared
2016	HPS Illum.	4.59	0.60	0.11
2017	LED Illum.	1.68	3.79	0.81
2017	HPS Illum.	1.68	1.82	0.40
2017	LED PPFD	25.35	0.25	0.81
2017	HPS PPFD	20.70	0.15	0.40

Total Lighting vs Norm Yield				
Model	dx^3 + cx^2 + bx + 1			
	d	c	b	R squared
2016 HPS Illum.	-1.98E-03	2.36E-02	-8.46E-02	0.09
2017 LED Illum.	-1.36E-03	2.30E-02	-1.25E-01	0.20
2017 HPS Illum.	3.22E-03	4.01E-02	-1.78E-01	0.16
2017 LED PPFD	-3.98E-07	1.02E-04	-8.27E-03	0.20
2017 HPS PPFD	-1.73E-06	2.65E-04	-1.45E-02	0.16

Horizontal Lighting vs Norm Yield				
Model	dx^3 + cx^2 + bx + 1			
	d	c	b	R squared
2016 HPS Illum.	-1.98E-03	2.36E-02	-8.46E-02	0.09
2017 LED Illum.	-1.36E-03	2.30E-02	-1.25E-01	0.20
2017 HPS Illum.	3.22E-03	4.01E-02	-1.78E-01	0.16
2017 LED PPFD	-3.98E-07	1.02E-04	-8.27E-03	0.20
2017 HPS PPFD	-1.73E-06	2.65E-04	-1.45E-02	0.16

Vertical Lighting vs Norm Yield				
Model	dx^3 + cx^2 + bx + 1			
	d	c	b	R squared
2016 HPS Illum.	-1.98E-03	2.36E-02	-8.46E-02	0.09
2017 LED Illum.	-1.36E-03	2.30E-02	-1.25E-01	0.20
2017 HPS Illum.	3.22E-03	4.01E-02	-1.78E-01	0.16
2017 LED PPFD	-3.98E-07	1.02E-04	-8.27E-03	0.20
2017 HPS PPFD	-1.73E-06	2.65E-04	-1.45E-02	0.16

Illinois Department of Transportation

ILLINOIS