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# ROADWAY LIGHTING'S IMPACT ON ALTERING SOYBEAN GROWTH: VOLUME 1

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**Roadway Lighting's Impact on Altering Soybean Growth**

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**16. Abstract**

The impact of roadway lighting on soybean plant growth and development was measured in situ at seven locations in the state of Illinois. The plant data collection included periodic height, reproductive-stage, and Normalized Difference Vegetation Index (NDVI), as well as plant moisture content and dried seed weight after harvest. The periodic measurements were made at the same locations over time to determine delays in plant development. The impact of roadway lighting trespass was significant and measurable above thresholds of both horizontal and vertical illuminance as well as a combination of the two. A specification was drafted to minimize the impact of roadway lighting trespass on the soybean, and countermeasures were recommended to control the impact of lighting on the soybean.

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# EXECUTIVE SUMMARY


This project studied roadway lighting's impact on altering growth and development of the soybean. This effort evaluated light spill from roadways (i.e., light trespass) into soybean fields in situ and then compared those levels of light to the development, growth, and yield of soybeans planted in the same field without light trespass.

In the past, there has been overwhelming evidence that artificial light affects the growth and maturity of soybean plants. However, such research has been conducted predominantly in a controlled laboratory setting. The effect of roadway lighting on the maturity of soybean plants in an actual field adjacent to a lighted roadway has never been reported before.

This project aimed to provide an initial assessment of the effects of lighting level on soybean growth for both overhead lighting and vehicle headlamps. The study answered the following questions:

- What is the impact of light level on soybean growth and maturity?
- What is the impact of vehicle headlamps on soybean growth and maturity?
- What is the cost and benefit relationship of modifying or replacing lighting in terms of soybean impact?

Seven farms were selected at various locations in Illinois based on the trespass lighting measured in the unplanted fields, farmer participation, and planned soybean crop. The lighting was surveyed robotically immediately after the fields were planted but before plant emergence in order to minimize soil compaction and to prevent damaging any plants. The lighting data collected included vertical and horizontal illuminance from the roadway edge of the field inward until the lighting levels were minimal. Any moonlight or other lighting trespass, such as sky glow, was measured. Headlamp light trespass into the field and the roadway lighting levels were also characterized.

During the growing season, the plant data collection included minimally invasive, periodic height, reproductive-stage, and Normalized Difference Vegetation Index (NDVI) measurements, performed on site. Just before the farmer harvested, a 1-m (3-ft) strip of plants was collected from rows at 130 sample locations across the seven sites for final analysis. The data measured included final height measurement, plant moisture content, and dried seed weight after harvest.

The study found three main effects of lighting on soybean plants: development delays, yield reduction, and height increase. Based on the data collected, soybean development can be delayed anywhere from 2 to 7 weeks when exposed to light trespass from typical high-pressure sodium (HPS) lighting used on Illinois roadways. Although development was delayed, most of the plants sampled matured (R7 stage, physiological maturity) before the farmer harvested the field.

From a harvesting standpoint, the limits for trespass illuminance are 5.7 lux (lx) horizontal and 4.5 lx vertical to enable mechanical harvesting and threshing. Yield is also limited by horizontal illuminance, which should be kept at no more than 5.7 lx each to keep yield above 87% .

Height and stage of plant maturity are both affected by trespass illuminance values, as shown from periodic measurements during the growing season, but the limit for the effect seemed to be greater than for the yield measurements. The study attempted to determine soybean variety differences, as different varieties were grown in the field, and this did not appear to affect the results obtained.

The project found that house side shields attached to the luminaires could potentially be effective in minimizing the impact of lighting on soybean growth on the house side as observed in one field. Draft specifications were developed for horizontal, vertical, and the combination of the two for lighting trespass maximums for roadway lighting to minimize soybean growth impact.

Trespass light from the roadway luminaire into soybean fields should be limited to the values listed in in the following table. These values are based on the limits found from the analysis of the R-Stage data and from the yield data. These values will ensure that the plants are eventually harvestable and that the yield will be at least 87–88% of the norm for the field.

**Illuminance Specifications to Minimize Soybean Impact**

| Illuminance | Maximum, lx |
|---|---|
| **Horizontal** | 5.7 |
| **Vertical** | 4.5 |

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# CHAPTER 1: INTRODUCTION

Of the approximately 148,000 miles of roadway lighting in Illinois, an estimated 25,000 miles are adjacent to soybean fields (based on the 2001 U.S. Agricultural Survey (USDA 2001) and geographic information system [GIS] mapping). 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 1. Distribution of soybean fields (green) 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 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 photosynthetic sensitivity is dependent on wavelength; 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. Because Illinois currently uses primarily high-pressure sodium (HPS) lighting, an acceptable test site with different lighting technology could not be found. Therefore, the spectral output of the light sources were not considered in this study.

In addition to light trespass from roadside lighting, the light emitted from vehicle headlamps may also affect roadside plants. Owing 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 project was developed to investigate the relationship between roadway lighting and the growth and maturation of the soybean. This project evaluated light trespass into soybean fields in situ and then compared those levels of light to the development, growth, and yield of the soybeans planted in the field.

## 1.2 PROBLEM STATEMENT

This project aimed to provide an initial assessment of the effects of lighting level on soybean growth for both overhead lighting and headlamps.

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

- What is the impact of light level on soybean growth and maturity?
- What is the impact of vehicle headlamps on soybean growth and maturity?
- What is the cost and benefit relationship of modifying or replacing lighting in terms of soybean impact?

# CHAPTER 2: LITERATURE REVIEW

## 2.1 HIGH-PRESSURE SODIUM (HPS) LAMPS AND ROADWAY LIGHTING

HPS lamps have been widely used in the United States and the rest of the world for the purpose of lighting roadways because of their high luminous efficiency (lumens per watt) and longer lamp life. The HPS lamp is a discharge lamp and produces light by creating an electric arc through a sodium-mercury amalgam that is vaporized. It has a distinct yellow color because the spectrum of the lamp is dominated by the emission characteristics of sodium vapor (center on 579 nanometers [nm]), as shown in Figure 2.

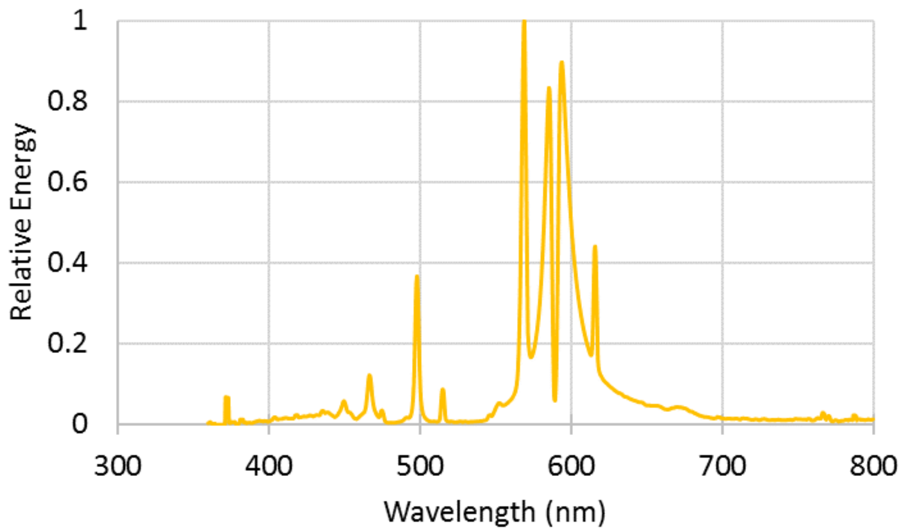



**Figure 2. Spectral power distribution of a 2700 K HPS lamp used for lighting roadways.**

## 2.2 ECOLOGICAL EFFECTS OF ROADWAY LIGHTING

Roadway lighting increases visibility for all road users and increases safety by reducing crashes, but 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.

## 2.3 EFFECTS OF STREET LIGHTING ON SOYBEAN PLANTS

The effect of lighting on plants has been documented extensively. Plants such as the soybean require a dark cycle to begin reproductive development and are significantly affected by light trespass from roadway lights. The phenomenon in plants of requiring 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 to induce flowering or maturity. 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 (Kostuik, McEachern et al. 2014, Bennie, Davies et al. 2015). Studies conducted in China have also shown that street lights delay the maturity of the soybean in 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 wavelength range.

Photosynthetic photon flux density (PPFD) is the measure 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 $\lambda$, then the 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:

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

where

$N_a$ = Avogadro's constant, $6.023 \times 10^{23}$
$h$ = Planck's constant ($6.626 \times 10^{-34}$ joule-seconds)
$c$ = speed of light, $2.998 \times 10^{8}$ m/s
$\lambda$ = 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:

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

The unit of PPF is micromoles per square meter per second (μmol/$m^2$/s) 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 11.7E-3 μmol/sec-$m^2$ per lx while a 4000K light-emitting diode (LED) PPFD might be 14.2E-3 μmol/sec-$m^2$ per lx(CIE 2004). Based on PAR, a 4000K LED could impact the plant more. Figure 3 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 large blue spike at 442nm.

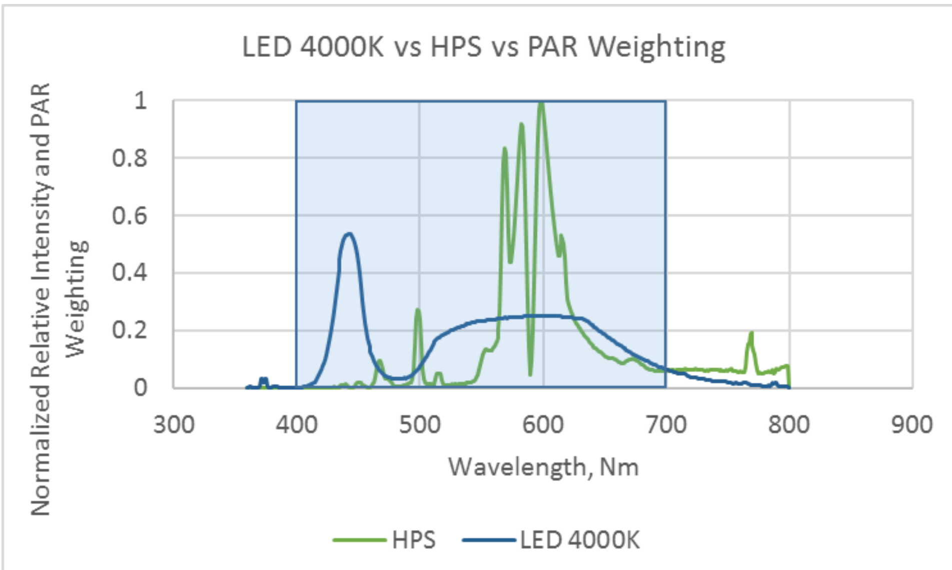



**Figure 3. PAR weighting curve versus normalized typical HPS and 4000K LED spectrum.**

Artificial light (e.g., incandescent lamps) have 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, Bernard et al. (1981) exposed several hundred strains of soybean under natural day length and an extended photoperiod by continuous or 5-hour nighttime interruption. The soybean strains that were exposed to the extended nighttime photoperiod experienced a delay in flowering.

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 and Campbell 1975, Cathey and Campbell 1975). Parker, Hendricks 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 4). 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, Wu et al. (2006) also reported that the soybean flowering responses to red spectrum (658 nm) were reversible by far-red spectrum (730 nm) exposure.

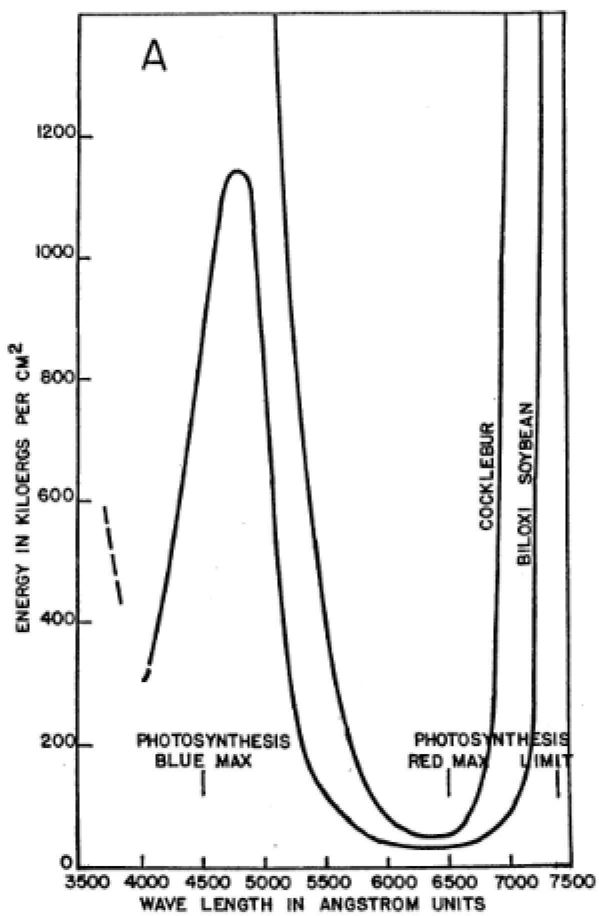



**Figure 4. Action spectra of soybean and cocklebur that suppresses floral initiation (Parker, Hendricks et al. 1946).**

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, Mackowiak 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 5). 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 maturity of the soybean (Buzzell 1971).

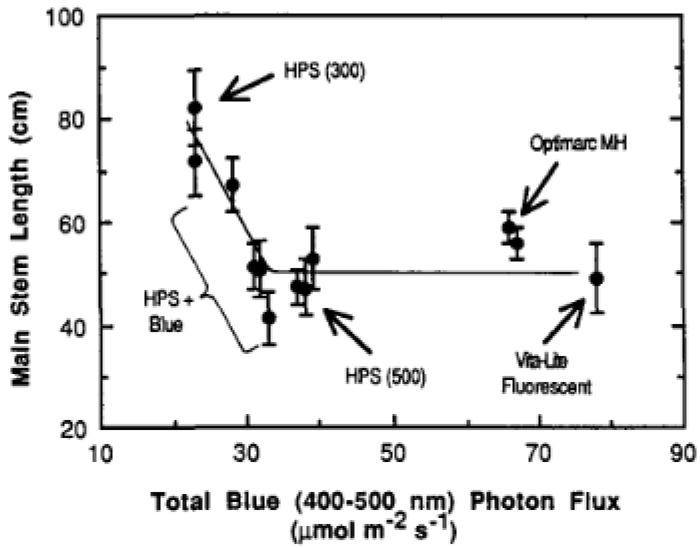



**Figure 5. Effect on the soybean stem length of adding blue light (400 to 500 nm) to the HPS spectrum. Blue light was added by supplementing HPS lights with blue fluorescent lamps (Wheeler, Mackowiak et al. 1991).**

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, Hendricks et al. (1946), LEDs with higher blue content were found to result in soybean plants with shorter stems (Figure 6). The biggest differences in plant development was observed in low light conditions (PPF = 200 µmol/m$^2$/s). The results of 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.

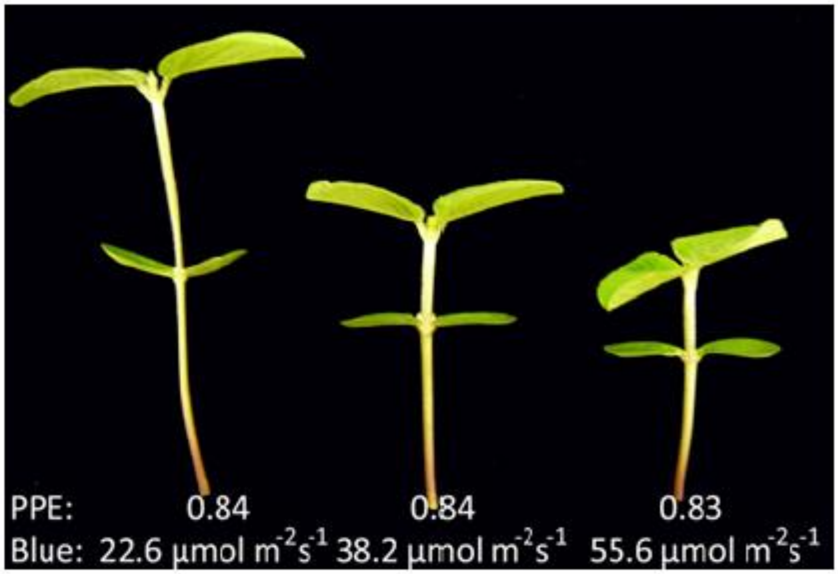



**Figure 6. The effect of blue light on soybean stem length 9 days after emergence. Stem elongation decreased with an increase in blue light (Cope and Bugbee 2013).**

The spectral regions that affect growth, as found during the literature review, are shown in Figure 7 versus the same HPS and LED spectrums presented in Figure 3. 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.

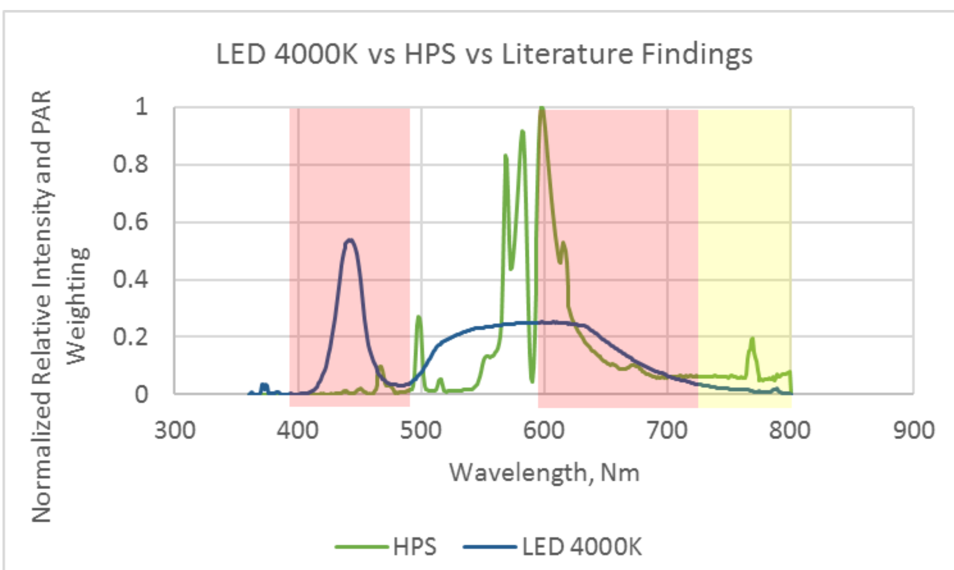



**Figure 7. Spectral regions that likely affect soybean development. The red areas represent the wavelengths that delay development, while the yellow area represents wavelengths that help the soybean recover.**

## 2.5 RESEARCH GAPS

There is overwhelming evidence that light affects the growth and maturity of soybean plants. However, such research has been conducted predominantly in a controlled laboratory setting. The effect of roadway lighting on the maturity of soybean plants in an actual field adjacent to a lighted roadway has never been reported before. There is a need to characterize not only the amount of light that is incident on the soybean adjacent to the roadway but also to measure the extent or the spread of such an effect. Likewise, the effect of headlamps on the growth and maturity of the soybean has never been reported. Furthermore, with the shift in luminaire types on roadways from narrow-spectrum (HPS) to broad spectrum-light sources (LEDs), it is all the 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 sites was selected for the study. Each of these sites was evaluated, and the lighting levels were measured at or before the planting of the soybean. At each site, a group of GPS points were selected as evaluation points. Then, during the growing season, the test points were evaluated for growth and maturity. Finally, the beans at each test point were hand-harvested and evaluated for growth characteristics.

Additionally, a survey of the soybean farmers was conducted as a method to evaluate the impact of lighting on their costs and operations.

Each of these aspects of the process is discussed in the following sections.

## 3.1 SURVEY

The overarching objective of this task was to understand the effect of roadway lighting on the maturity of the soybean from the point of view of soybean farmers. Although the effect of roadway lighting on soybean maturity was well known and documented, the extent or the cost of this issue has never been reported.

A survey was designed to understand the extent, cost, and operational difficulties faced by the farmers whose fields are affected by roadway lighting. The survey was released through a news article in *FarmWeek*, a weekly newsletter of the Illinois Farm Bureau, on November 7 and December 5, 2016.

The survey began with an introduction describing the goal of the project and the goals of the survey. Participation in the survey was entirely voluntary, and the participants' privacy was protected. The survey was approved by the Virginia Tech Institutional Review Board. The survey consisted of 24 multiple-choice questions and was designed to provide an understanding of the following factors:

- Characteristics of the roadways adjacent to the fields
- Factors affecting soybean maturity and the effect of roadway lighting
- Extent of the soybean crop affected
- Effects of late maturity of soybean plants on harvesting and costs of harvesting

## 3.2 SITE SELECTION

Virginia Tech and Illinois Department of Transportation (IDOT) personnel provided 13 potential sites for data collection, all fairly close to Springfield, Illinois. These 13 sites were selected based on proximity of fields to lighting and streets and included a mix of types of roadways (collector, highway, and rural). These sites, plus four more identified while in state, were visited and surveyed for potential inclusion in the study. On-site light level measurements using a light meter provided on loan from IDOT were taken in order to establish the potential for a lighting effect. After the farmers were contacted, the researchers selected seven sites for the lighting study. These sites were selected because soybeans were being planted and there was sufficient light trespass into the fields. The sites selected are listed in Table 1.

**Table 1. Selected Soybean Field Sites with Encroaching Lighting**

| Site | Intersection/ Interchange | Light Type | Type | Town | AADT | Varietal | Lighting Treatment |
|---|---|---|---|---|---|---|---|
| Pleasant Plains | IL-125 and IL-123 | HPS | Highway | Pleasant Plains | 4750 | Beck's 345 | Home side shield |
| Springfield1 | I-72 and MacArthur Blvd | HPS | Interstate | Springfield | 1500 | Pioneer Seed-36T86 | None |
| Assumption | US-51 and E Leafland St | HPS | Highway | Assumption | 4950 | 38R25 | None |
| Normal1 | County Rd 1700 N | HPS | County Road | Normal | 11,600 | Burrus Power Plus 3401 | None |
| Peoria** | IL-150 and Orange Prairie Rd | HPS | Highway | Dunlap | 11,100* | Hughes 555 | None** |
| Normal2 | I-39 / IL-51 and Co Rd 1900 N, southeast corner | HPS | Highway | Normal | 225 | 2915 Stone Seed | None |
| Springfield2 | Prairie Crossing Dr and Old Chatham Rd | HPS | Highway | Springfield | 1000* | Pioneer Seed-36T86 | None |

* Estimated from nearby, similar roadways.

** In previous seasons, the city municipality turned off the roadway lighting on one or two weekends in an attempt to reduce the lighting effect on the soybean maturity.

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.

## 3.3 LIGHTING MEASUREMENTS

The lighting in all selected fields was characterized during the late May 2016 spring quarter. The spring was quite wet, delaying planting a month or so, but the schedule was adjusted to accommodate the delay.

The lighting data were 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 8 shows the RRLMMS.

**Figure 8. 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 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 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 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 were 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 data collection was performed over a distance corresponding to one unit of pole spacing, with a starting location selected while on site. The row spacing was initially 10-ft spacing perpendicular to the roadway, for three or four rows. The remainder of the rows of lighting data were collected on 20-ft spacing perpendicular to the roadway because lighting levels decrease as the square of the distance from the source (Figure 9).

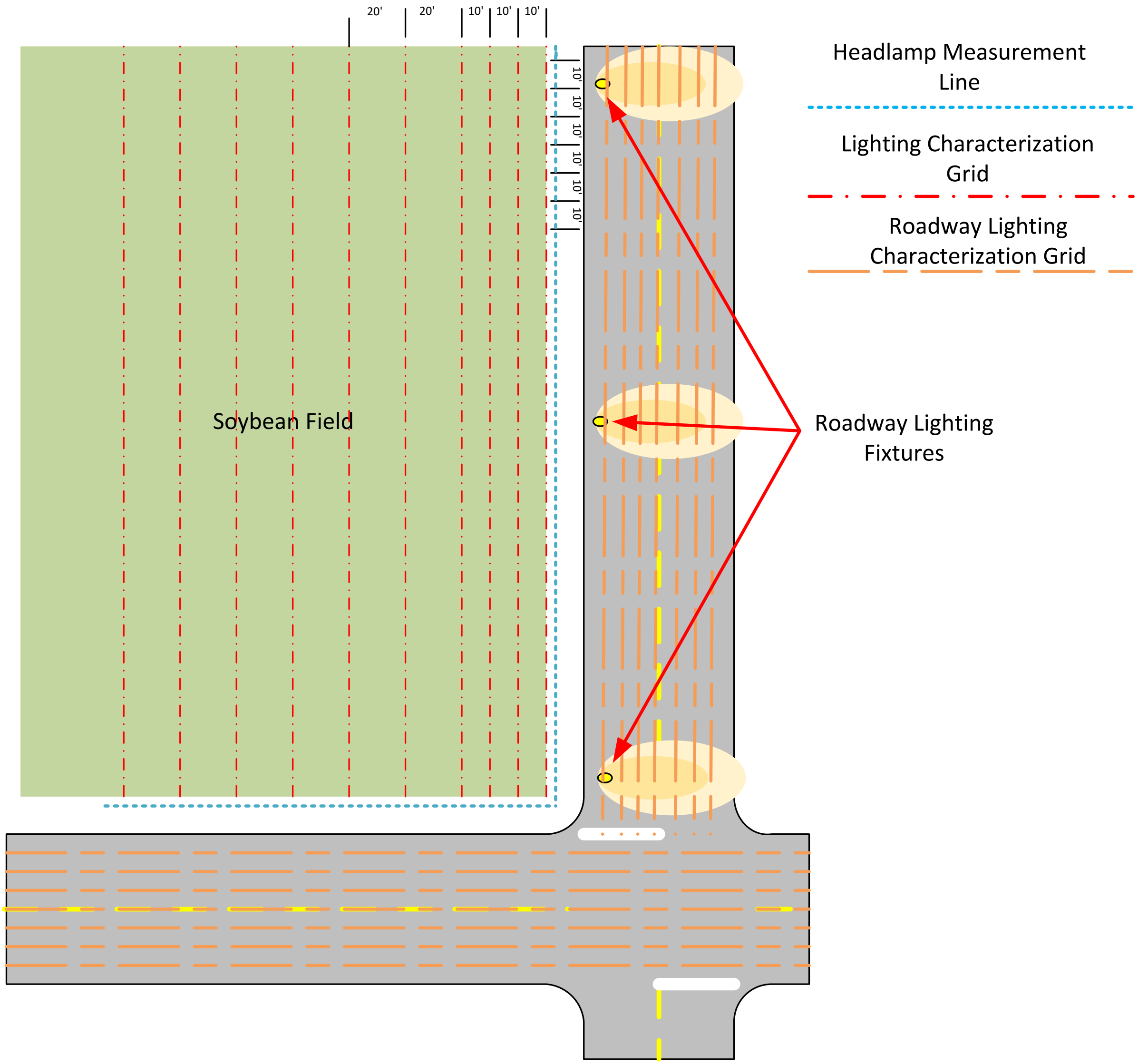



**Figure 9. Schematic showing the lighting characterization strategy.**

In addition to the lighting in the fields, the lighting in the roadway was measured with a trailer-mounted version of the RRLMMS. In the roadway, each lane was measured along each direction of travel and each side of the field. Finally, the light trespass into the field from headlamps was measured along the edge of the field with a vertically held Minolta T10-A.

## 3.4 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 photos of fields, and on the assumption that lighting was the cause of the delay in maturity. The detailed lighting values collected were also used to guide selection of the points. In addition, points were selected to be near the robot collection path so that no interpolation would be required to reduce error sources.

Approximately 20 sample points were selected per field, distributed around the base of the light poles and extending into the field perpendicular to the nearest roadway.

For Normal1, the data were aligned with two luminaires, distributed from one luminaire to another. The sample locations were more concentrated near the two luminaires, but one additional point was sampled in between the luminaires in order to capture any lighting overlap (Figure 10). The luminaire poles can be seen in Figure 10. The two points farthest from the roadway were selected to be within the lighting collection area but at a value lower than 0.5 lx, to be used as the control sample for the field. The other field sample points were similar in distribution.

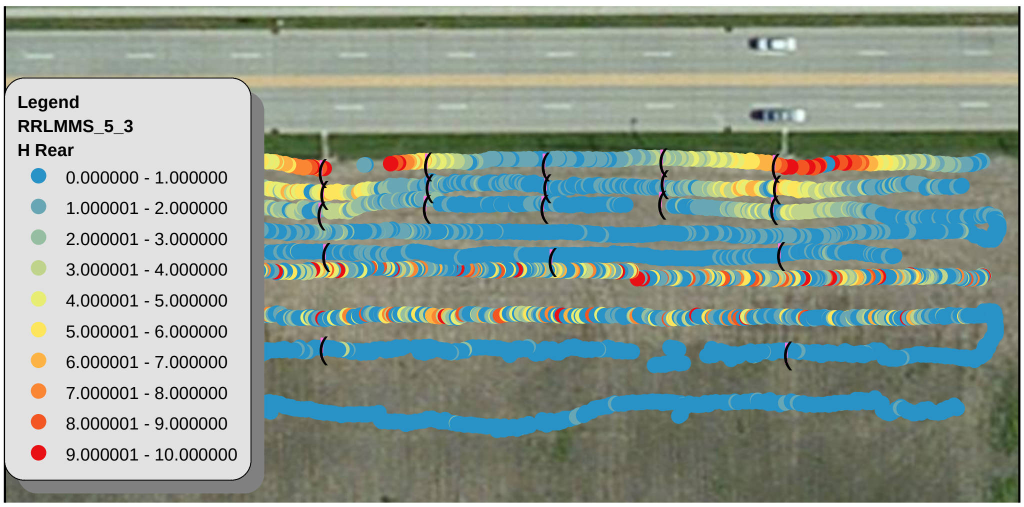



**Figure 10. Normal1 sample locations.**

In Pleasant Plains, the field to the southwest of the intersection of IL-125 and IL-123, the samples were selected away from the intersection, starting at the second luminaire and going to the third luminaire. The sample points were placed close to the measurement points, oriented perpendicular to IL-125, and spanned the space between the poles. The horizontal illumination in this field was affected by shielding placed on these luminaires, causing the light trespass to be brighter between the lighting, so more samples were taken there.

For Springfield1, the sample locations were selected to be more concentrated near the southern luminaire and ran from halfway between two luminaires to halfway between the next two luminaires.

At Assumption, the sample points were aligned with the curving robot data collection path, resulting in a radial arrangement. The nearest luminaire was across the intersection. However, eight sample locations at Assumption were destroyed at some point during the installation of a new power line. The outer edge of the field was trampled or run over by vehicles. Unfortunately, this included the location of most of the higher lighting levels for this field.

For Peoria, the sample locations were aligned similarly to Normal1, spanning from one luminaire to another. The arrangement of the sample points was too different to try to capture any nuances that the samples at other sites might not have, such as overlapping lighting levels farther from the roadway.

The sample locations for Normal2 were centered on the luminaire. These luminaires were fairly far from the field but were high mast, so there was sufficient lighting in the field. Higher vertical illumination was observed in the field near the northern luminaire, so the sample locations were located there.

In Springfield2, the luminaires were spaced more widely than some of the other fields, so the sample locations were arranged from one luminaire through halfway to the next luminaire.

## 3.5 MONITORING

Growth and development measurements were made at each of the test points in the field. Measurements collected were R-stage (flower, pod, seed, and maturity stages), Normalized Difference Vegetation Index (NDVI), and plant height. The first measurements were collected in mid-June, shortly after the summer solstice.

GPS coordinate points were generated for each of 138 sample locations across the seven fields selected based on the robotic measurements. The GPS coordinates for the sample points were uploaded into Trimble-based handheld scouting units, and a database structure was developed for collecting data on plant height, plant stage, and NDVI.

Plant height was measured with a meter/yard rod to a tenth of an inch on three plants from soil level to the top growing point on the main stem.

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). Because staging can be subjective, at the beginning of each sampling period, the agronomist would reacquaint with the visual cues for soybean staging at the Illinois sites by staging several dozen plants inside and outside of the affected area in order to improve the assessment of the light affected plants. 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 |

Three NDVI readings were taken above the crop canopy, at a distance of roughly 24 in. NDVI measurements were taken with Trimble's GreenSeeker™ handheld crop sensor, which is used to estimate plant biomass. When the trigger is pulled, the sensor turns on and emits brief bursts of red and infrared light and then measures the amount of each that is reflected back. NDVI can range from 0.00 to 0.99. Readings were collected in a matter of seconds.

Site visits and growth measurements at the selected sample locations were completed on the dates shown in Table 3. 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). The last visit to the fields before harvest was September 22, 2016. Measurements were not completed that day because of lodging and loss of leaves.

**Table 3. Growth, Maturity, and NDVI Sample Dates**

| Sampling | Date | Weeks After Planting* |
|---|---|---|
| 1 | 07/14/2016 | 7.4 |
| 2 | 07/28/2016 | 9.4 |
| 3 | 08/25/2016 | 13.4 |
| 4 | 09/09/2016 | 15.6 |
| 5, Harvest | 09/26/2016 | 18.0 |

* The field at Pleasant Plains was planted 2 weeks earlier than all the other fields.

For the first four visits (Sampling 1, 2, 3, and 4) three measurements were taken for each parameter at each GPS point. At each field point, data at points along a radial circle around the GPS point were collected. These three data points were averaged into a single point. The fifth sampling was taken just before harvest to look at the maturity of plants at each GPS point and observe whether they were lodged. It was not possible to collect height or NDVI at this advanced stage. During each sampling, field observations were also captured relative to soybean development and plant height as affected spatially by light and not directly measurable by height, stage, or NDVI.

## 3.6 HARVEST

The soybean plants were hand-harvested on September 26 and 27. At harvest, only the height and R-stage measurements were completed. One meter of plants was harvested from 130 of the 138 sample locations. Again, eight sample locations selected did not have plants at the time of harvest.

The soybean plants were transported in a refrigerated trailer to Virginia Tech's Tidewater Agricultural Research and Extension Center in Suffolk, Virginia, for yield analysis (Figure 11). The soybean plants were refrigerated for the trip to minimize moisture loss and prevent mold growth.

**Figure 11. Soybean plants returned for analysis at the Virginia Tech Hampton Roads Research Center.**

## 3.7 ANALYSIS

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

### 3.7.1 Lighting Data Reduction

The noise in the lighting measurements required that additional post-processing be done before analysis with respect to the plant characteristics. Measurements were timed to occur immediately after planting but before plant emergence in order to have the smoothest possible field and to prevent any damage to the plants.

Nonetheless, the fields were still challenging to drive with the RRLMMS. The field roughness caused the robot to bounce and rock back and forth, adding noise to the data. Custom software was written 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 12 shows the horizontal illuminance sampled at each coordinate. 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 13 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.

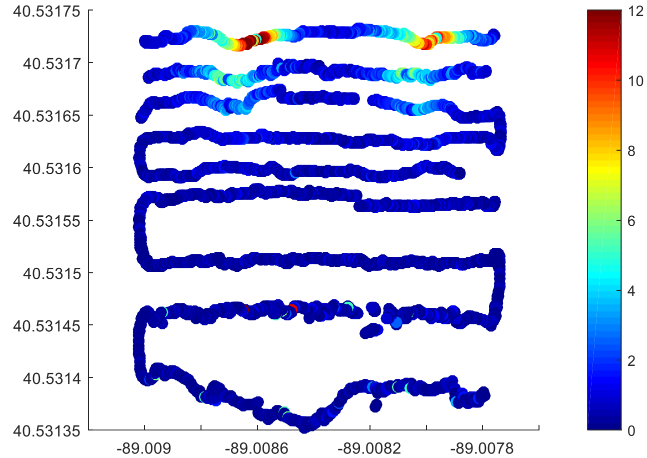



**Figure 12. Horizontal illuminance for Normal1 before digital filtering. The horizontal illuminance is represented by the color. The y and x axes are latitude and longitude in degrees.**

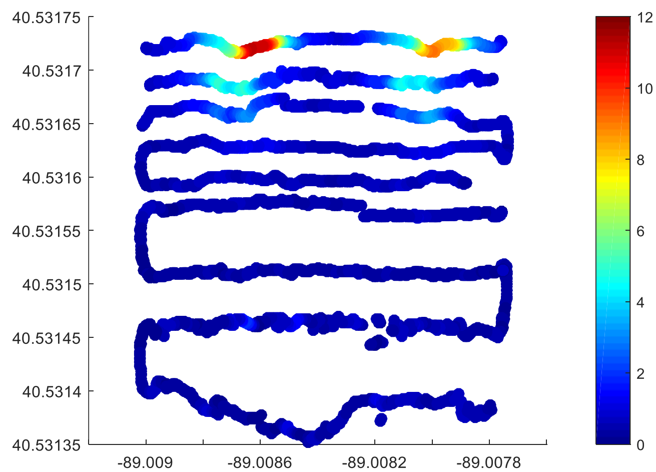



**Figure 13. Horizontal illuminance for Normal1 after digital filtering. The horizontal illuminance is represented by the color. The y and x axes are latitude and longitude in degrees.**

After filtering, the data were interpolated in 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. All of the sites used HPS luminaires; therefore, the lighting data were not converted into PAR-equivalent light levels because doing so would simply be multiplying the illuminance values in lx by a scalar, in this case, 19.3E-3 µmol/(sec-m$^2$)/lx. This can be done for future analysis or comparison; the PAR equivalent can be calculated by convoluting the HPS spectrum and the PAR spectrum. However, the PAR ignores the infrared content, which could be a factor, and does not weight the wavelengths relative to the literature results.

### 3.7.2 Plant Analysis

Plants were weighed within 12 hours after removal from the refrigerated trailer and then dried in a forced-air drier for 24 hours. After drying, plants were weighed, number of nodes and pods were determined, and pods were removed from the plant and weighed. Plant moisture was calculated from the plant weights before and after drying. Seeds of samples representing varying weights and development stages were shelled from pods and weighed to estimate seed yield. Estimated seed yield was determined from all samples by a non-linear relationship of seed weight with pod + seed weight from the shelled samples.

### 3.7.3 Statistical Analysis

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.

#### *3.7.3.1 Normalization*

During the statistical analysis, the growth, harvest, and lighting data were 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 were normalized by field. For height data, the normalization was performed by dividing by the height of the plant sample farthest from the light source ($h_0$), as shown in (Equation 5).

$$h_n = h_i / h_0 \qquad \text{(Equation 5)}$$

The height of each sample in time during the growth period was also normalized by the samples farthest from the lighting, by field.

Because the plant samples were hand-harvested before the farmer harvested the field, the moisture content of soybean seeds farthest from the light source had not yet reached the ideal 13%. To account for this variation by field, plant moisture content, calculated as percent mass ($m_i$), was normalized by field by dividing by the moisture percentage ($m_0$) of the plants farthest from the light source, as shown in (Equation 6).

$$m_n = m_i/m_0 \qquad \text{(Equation 6)}$$

Similarly, the weight of the seeds and pods (together) and the yield were normalized by the values from the plant farthest from the light sources. The maturity measurement (R-stage) was not normalized since all fields had R-Stage 8 samples, and NDVI was not normalized because there were no harvest time measurements.

After normalization, there still existed a significant amount of scatter in some of the measurements. Therefore, it was decided to analyze the growth and development measurements individually by field. Sigmoid functions were used to model the data because there appeared to be upper and lower bounds to most of the measurements (Equation 7).

$$y = \alpha / (\delta + e^{-x}) \qquad \text{(Equation 7)}$$

In the sigmoid equation, $y$ is the measurement of the plant (such as height), $x$ is the lighting value (horizontal illuminance), and $\alpha$ and $\delta$ are fitted constants. Nonlinear regression was used to determine optimal values for $\alpha$ and $\delta$ for each measurement in each field.

### *3.7.3.2 Analysis*

Analysis was performed with statistical analysis software (SAS) and generalized linear models relating the lighting levels, the field, and the interaction of lighting and field were generated. For lighting levels, total illuminance, as stated previously, was used for the lighting level in the assessment because it was assumed the direction of light hitting the plant did not matter.

The lighting values were binned into groups in order to perform multiple ANOVA (Analysis Of Variance) and pairwise comparisons between the lighting conditions and the plant characteristics. The bins are shown in Table 4.

**Table 4. Table of Bins for the Lighting 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 and vertical illuminance, 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.

# CHAPTER 4: RESULTS

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

## 4.1 SURVEY RESULTS

Overall, only six people responded to the questionnaire. Of those six, one person did not complete the survey; thus, the survey had only five completed responses. The main results from the survey are summarized as follows.

### 4.1.1 Road Characteristics

All the respondents had a public roadway adjacent to their farm. Four of five respondents planted their crop 5 to 10 ft away from the road, while one planted their crop more than 15 ft away from the roadway. All the roads adjacent to the respondent's farms were paved; four of the roads were paved with asphalt while the remaining road was paved with concrete. A majority (3) of the roads were treated in winter. All of the roads had two lanes of traffic. Two of the respondents had an intersection close to the farm, and both intersections were stop controlled. A majority (3) of the respondents indicated that there was lighting present on the road or intersection adjacent to the farm.

### 4.1.2 Factors Affecting Soybean Maturity and the Effect of Roadway Lighting

Of the factors that influence soybean production, four of the respondents indicated that temperature, air quality, and length of day played an important role. A majority (3) of the respondents reported that location of the plant influenced maturity; the remaining two responded that length of the day affected maturity.

A strong majority (4) of the respondents indicated that proximity to a road affected soybean production. Similarly, four of the respondents reported that proximity of the road affected soybean maturity, yield, and quality. All of the respondents reported that plant locations closest to the roadway experienced a delay in crop maturity; in addition, one of the respondents also indicated that areas with bad drainage experienced a delay in maturity. Two of the respondents reported that proximity to roads affected other crop production (i.e., crops other than soybean), while another two reported that it did not; the remaining one did not know.

All respondents reported that artificial lighting from street lights affected soybean maturity.

### 4.1.3 Extent of the Soybean Crop Affected

A majority (3 to 4) of the respondents reported that less than 10% of the crop adjacent to the roadway experienced quality issues, delayed maturity, and delayed yield (Figure 14). One respondent reported that between 10% and 30% of the crop adjacent to a roadway had quality issues, delayed maturity, and delayed yield. The remaining one respondent reported that the quality issues, delayed maturity, and reduced yield were greater than 20%.

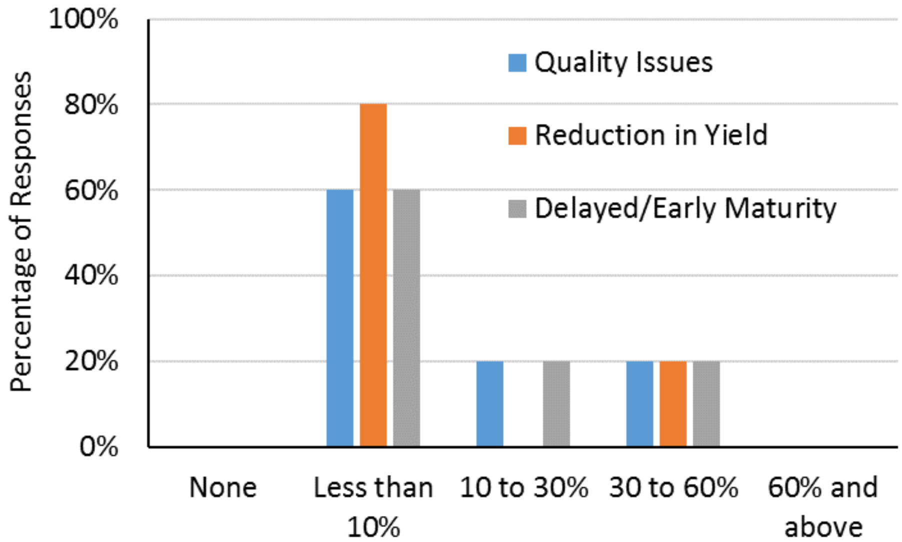



**Figure 14. Percentage of responses, of the five total respondents, for reduction in soybean quality, yield, and percentage of crop that experiences a delayed/early maturity as a result of the proximity of the roadway to the soybean farm.**

### 4.1.4 Effects of Late Maturity of Soybean Plant on Harvesting and Costs of Harvesting

A majority (3 of 5) of the respondents performed a second harvest for the soybeans adjacent to the road, while two did not. Four of six of the respondents reported that the reharvesting costs were between 1% and 2% of the overall harvesting budget, and two said it cost 5% or more.

A strong majority (4 of 5) of the respondents indicated that late harvesting did not affect the planting of late-season crops.

### 4.1.5 Survey Conclusions

The goal of this survey was to understand the extent, cost, and operational difficulties that are caused by the delayed maturity of the soybean as a result of roadway lighting. Five major findings were evident:

- First, a multitude of factors such as temperature, air quality, and, most important, the length of the day, play an important role in the maturity of the soybean plant.
- Second, there is strong agreement (4 of 5) among respondents that proximity to a roadway and the presence of roadway lighting significantly affect the maturity of the soybean.
- Third, a majority (3 of 5) of the respondents reported that less than 10% of the soybean crop adjacent to the roadway experienced a delay in maturity or a reduction in yield.
- Fourth, while a majority (4 of 5) of respondents performed a second harvest on the soybean whose maturity was delayed, the cost of the second harvesting was less than 2% of the overall harvesting budget.

- Finally, a strong majority (4 of 5) of the respondents reported that the late harvesting of the soybean plants that experienced delayed maturity did not affect the planting of late-season crops.

## 4.2 LIGHTING RESULTS

### 4.2.1 Light Trespass from Roadway Lighting

The lighting trespass summaries for each site are shown in Table 5. As the table shows, the fields had a broad range of lighting levels. Pleasant Plains and Assumption had the lowest lighting levels, while Springfield2, Peoria, and Normal1 had the highest values.

**Table 5. Light Trespass Field Summary Values**

| | Horizontal Illuminance | | | Vertical Illuminance | | |
|---|---|---|---|---|---|---|
| **Site** | **Avg.** | **Min.** | **Max.** | **Avg.** | **Min.** | **Max.** |
| **Pleasant Plains** | 0.37 | 0.01 | 1.37 | 0.64 | 0.14 | 1.58 |
| **Springfield1** | 0.75 | 0.01 | 3.52 | 2.06 | 0.11 | 5.47 |
| **Assumption** | 0.40 | 0.08 | 0.95 | 1.46 | 0.30 | 3.90 |
| **Normal1** | 2.50 | 0.33 | 9.81 | 2.51 | 0.77 | 5.22 |
| **Peoria** | 2.86 | 0.12 | 7.33 | 2.31 | 0.37 | 5.19 |
| **Normal2** | 0.63 | 0.23 | 1.39 | 1.93 | 0.50 | 3.22 |
| **Springfield2** | 1.63 | 0.28 | 6.69 | 2.09 | 0.81 | 4.40 |

As the figures that follow illustrate (Figure 15 through Figure 18), there was significant light propagation into the fields, with the exception of the intersection of IL-125 and IL-123 (Figure 15). All of the diagrams in Figure 15 through Figure 18 are oriented with north at the top.

At the IL-125 and IL-123 intersection, IDOT had installed shields to reduce the light trespass back into the field. This field was the first field characterized and was difficult to traverse with the robot. This farmer used a no-till approach to planting. Therefore, there was significant corn stubble in the field, and the field was a bit rougher than expected. The best way to provide markers in the field was still being optimized to guide the robot; hence, there is a less uniform path for that field, as evidenced in the following figures.

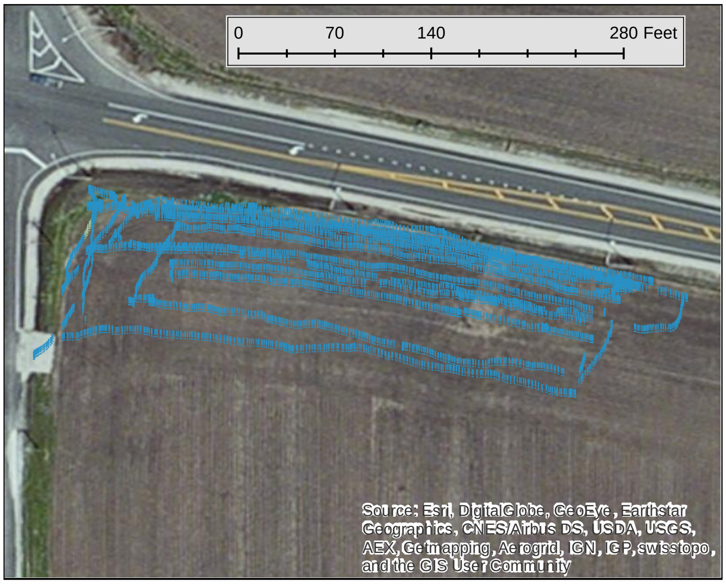



**Figure 15. IL-125 and IL-123 intersection, west of Springfield.**

In Figure 16. , the lighting can be seen to illuminate farther into the field; with a more uniform, lobe-like pattern. The robot tended to follow the furrows and tractor tire tracks in the fields, so guidance was less accurate where there were intersecting tractor tire tracks. The guidance issues can also be seen in Figure 17, where the robot tended to either follow the rows or cross at an angle close to perpendicular when the path was not aligned with the rows past the headlands.

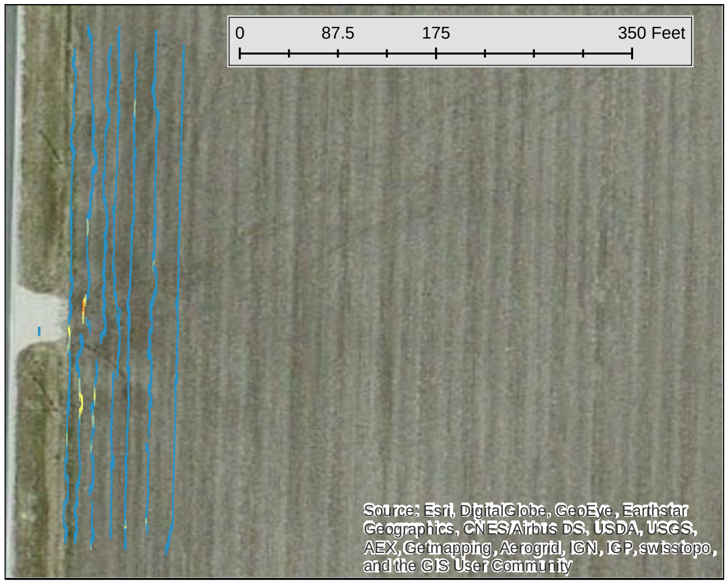
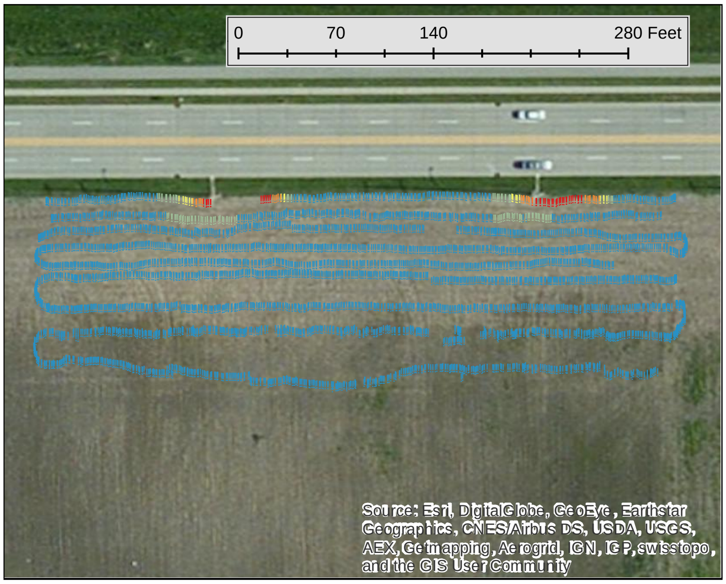




**Figure 16. Recreation drive near the intersection of MacArthur Boulevard and I-72 (top) and east of the intersection of Prairie Crossing Drive and Old Chatham Road (bottom).**



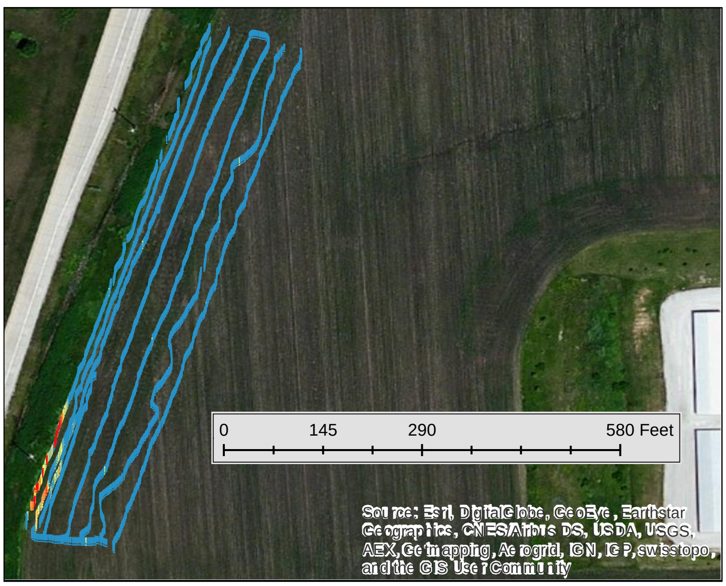




**Figure 17. County Road 1700 N, Normal (top), and the exit from I-39 north to Business 51, north of Normal (bottom).**

In Figure 18 (top), data are shown from the field west of Orange Prairie Road north of Peoria. The background map from ARCMAP (GIS software) was photographed before the road was expanded. The rightmost, long north-south run west of the short run is approximately 5 ft inside the existing field.

Finally, an additional field, over the proposed six, was selected in case of the loss of one of the other field sites. This field (Figure 18, right) was recently tilled but not planted when the lighting was characterized. The tilling left the field soft, but still with rows in the field. Laying in the field, just north of the intersection and east of IL-51, was a power line pole that was not yet installed. The farmer had adjusted his headlands to go around this pole, creating almost semi-circular rows where the robot was run. These rows made guiding the robot very challenging, but the data collected should be sufficient for this study.


**Figure 18. Orange Prairie Road north of IL-150, Peoria (left), and northeast of the intersection of IL-51 and East Leafland St., east of Assumption (right).**

Figure 19 shows the relative horizontal illumination levels versus latitude and longitude at each sample location at Pleasant Plains. The area of the circles represents the level of illumination. The average horizontal illuminance was 0.37 lx.

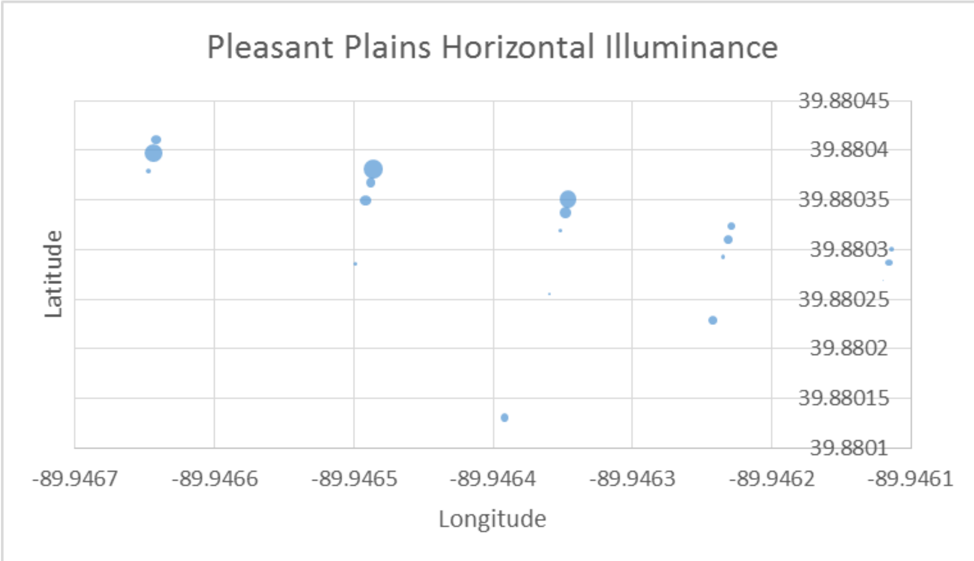



**Figure 19. Horizontal illuminance at Pleasant Plains.**

The following charts (Figure 20 through Figure 30) show the horizontal and vertical illuminance levels at each sample point for the other fields. Again, the area of the circles in the graph represent the relative illuminance levels and are scaled the same as in Figure 19. As Figure 20 shows, the vertical illuminance was similar to the horizontal illuminance at Pleasant Plains.

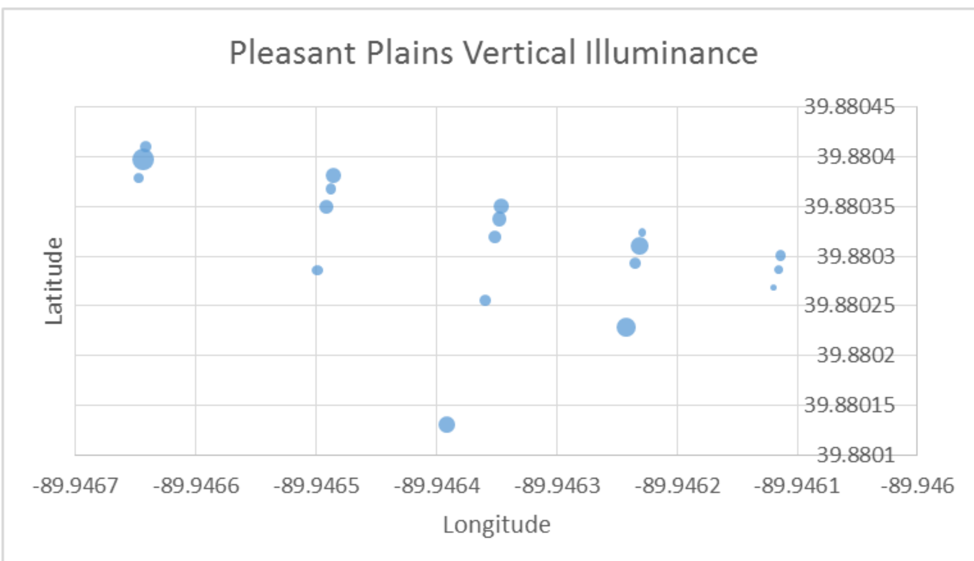



**Figure 20. Vertical illuminance at Pleasant Plains.**

As the figures show (Figure 19, Figure 23, and Figure 29), the Pleasant Plains, Assumption, and Normal2 sites had the lowest average horizontal illuminances. The Springfield1, Normal1, and Springfield2 sites all had similar horizontal illuminances, with peak values near 10 lx (Figure 21, Figure 25, and Figure 31, respectively).

Figure 21 and Figure 22 show the lighting levels from Springfield1. The vertical illuminance in that field was higher than the horizontal illuminance. This can also be seen in the Assumption and Normal2 fields (Figure 23, Figure 24, Figure 29, and Figure 30).

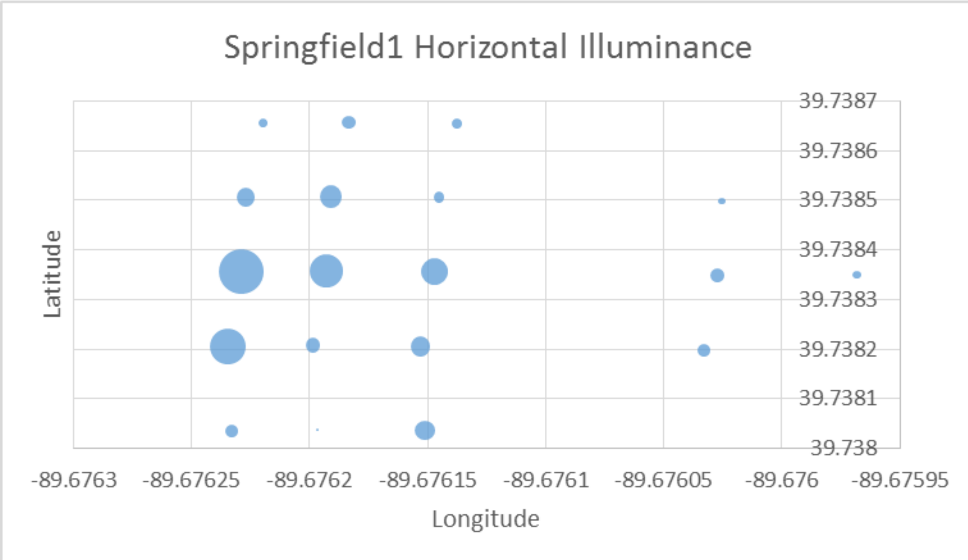



**Figure 21. Horizontal illuminance at Springfield1.**

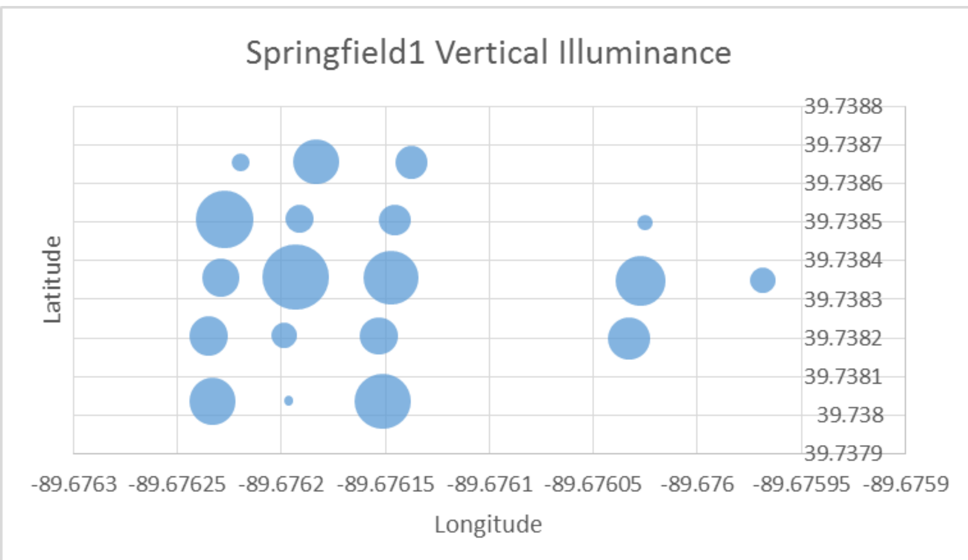



**Figure 22. Vertical illuminance at Springfield1.**

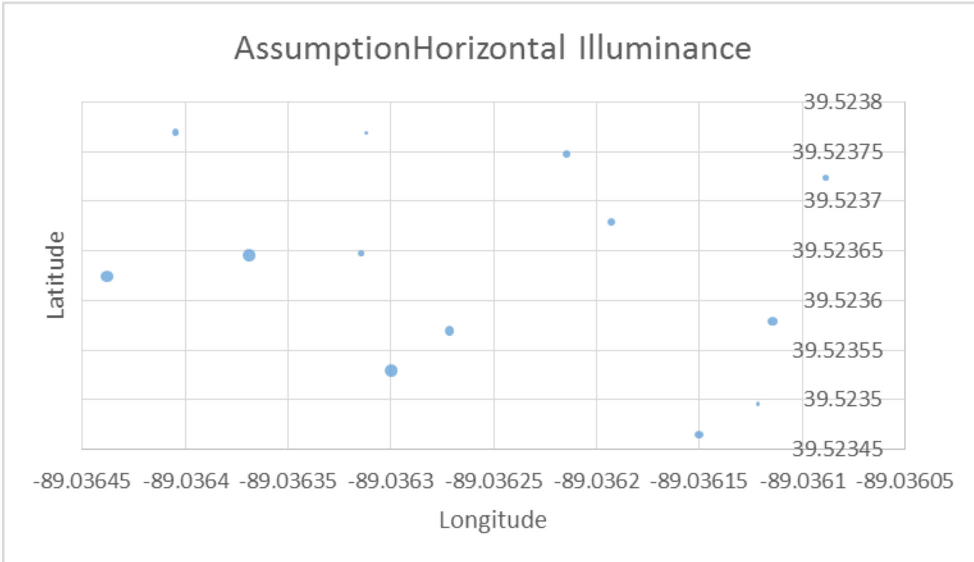



**Figure 23. Horizontal illuminance at Assumption.**

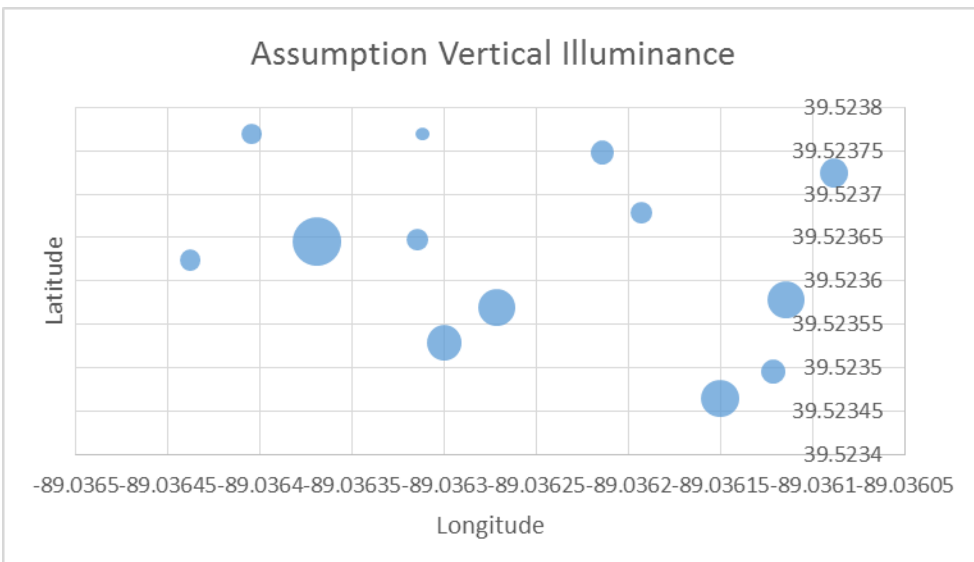



**Figure 24. Vertical illuminance at Assumption.**

However, at the fields with higher levels of horizontal illuminance, the vertical illuminance was lower than the horizontal and was slightly more uniform (Figure 25 and Figure 26).

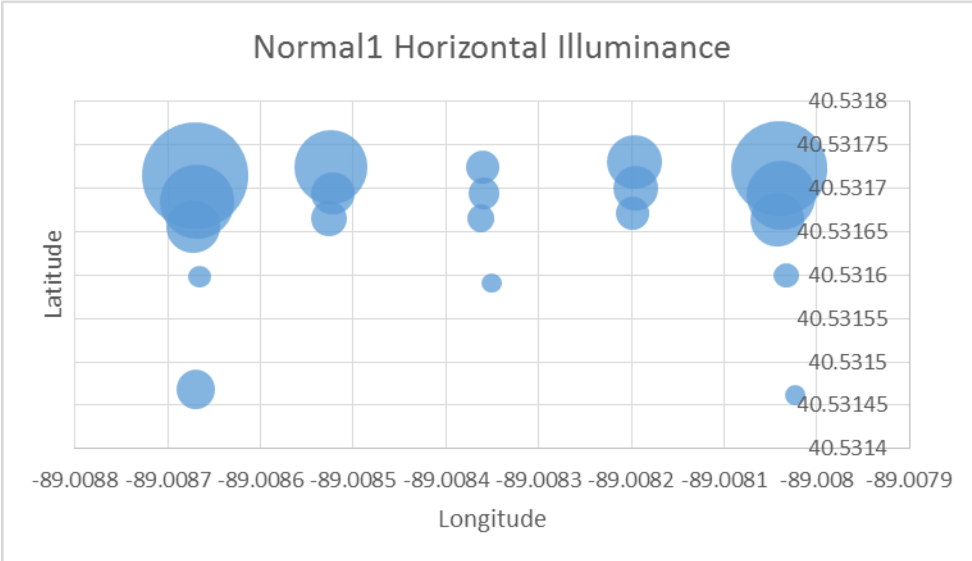



**Figure 25. Horizontal illuminance at Normal1.**

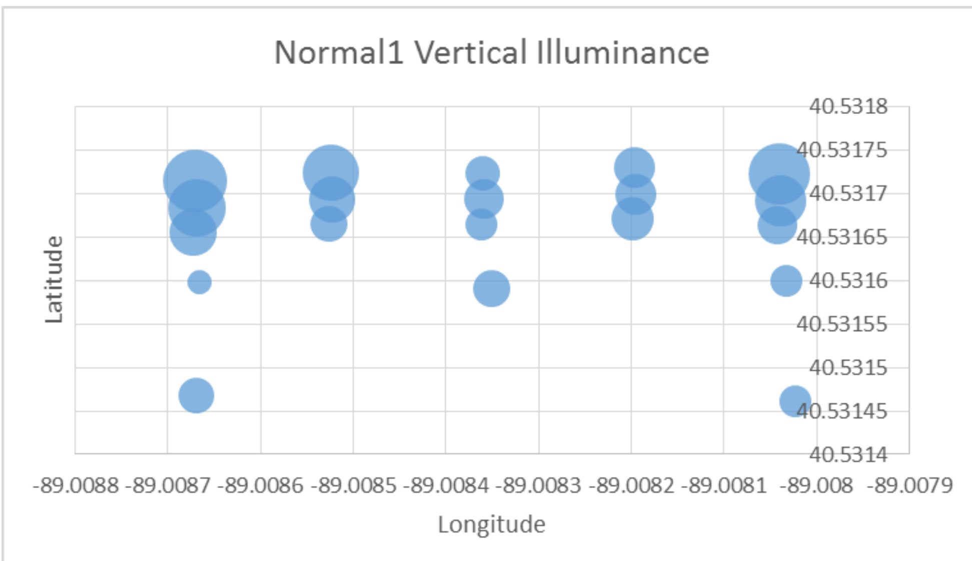



**Figure 26. Vertical illuminance at Normal1.**

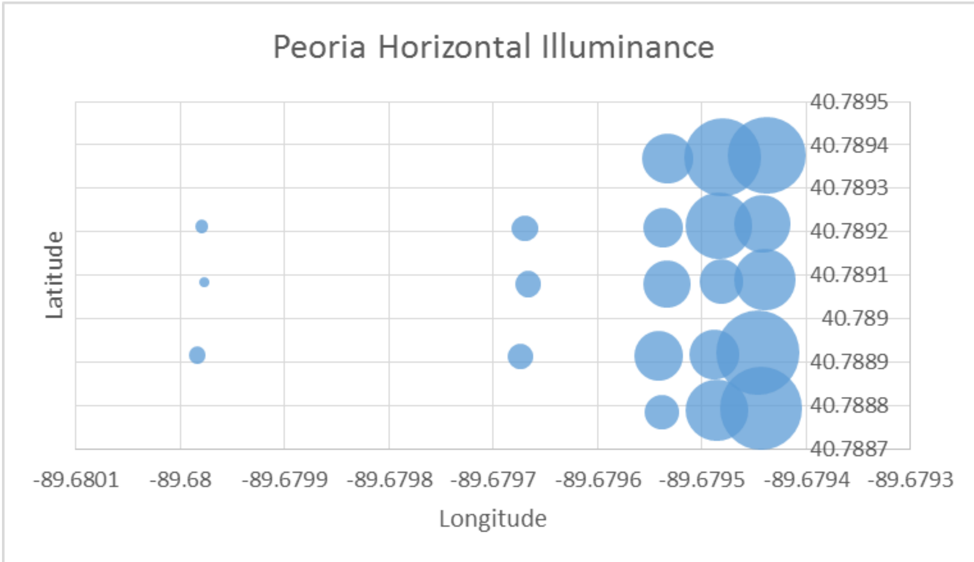



**Figure 27. Horizontal illuminance at Peoria.**

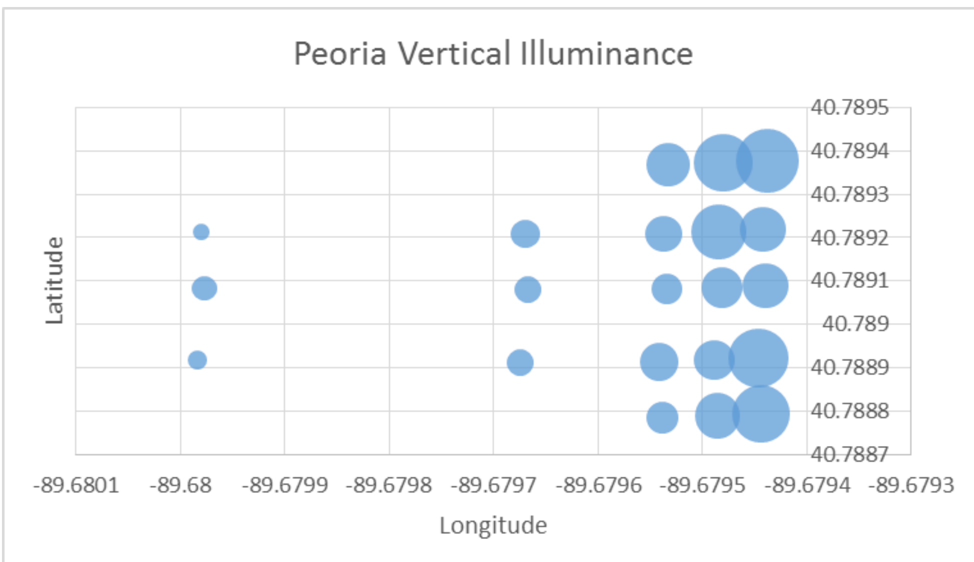



**Figure 28. Vertical illuminance at Peoria.**

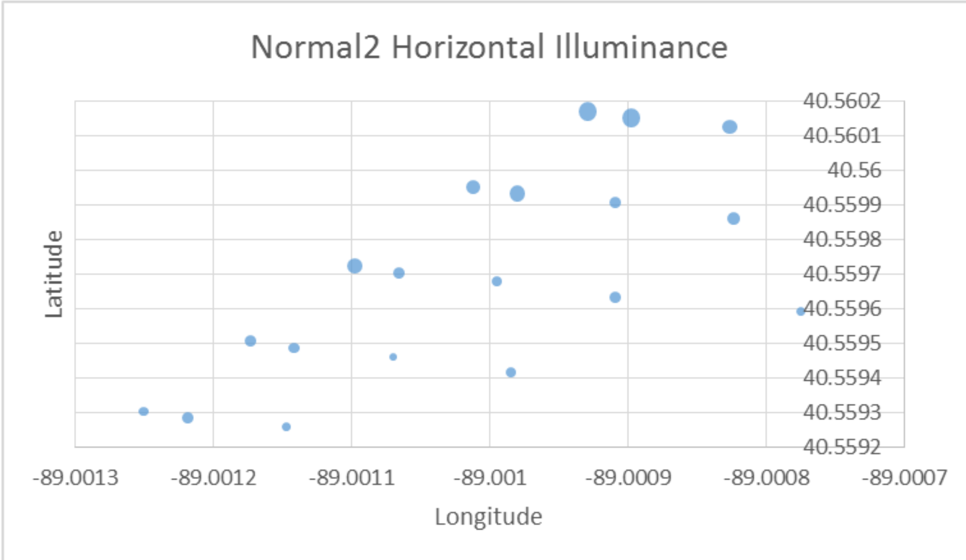



**Figure 29. Horizontal illuminance at Normal2.**

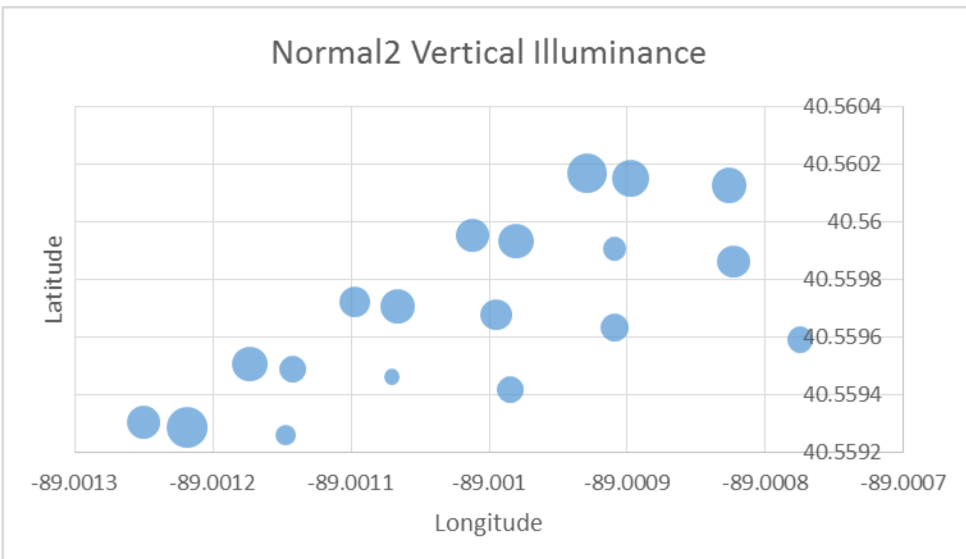



**Figure 30. Vertical illuminance at Normal2.**

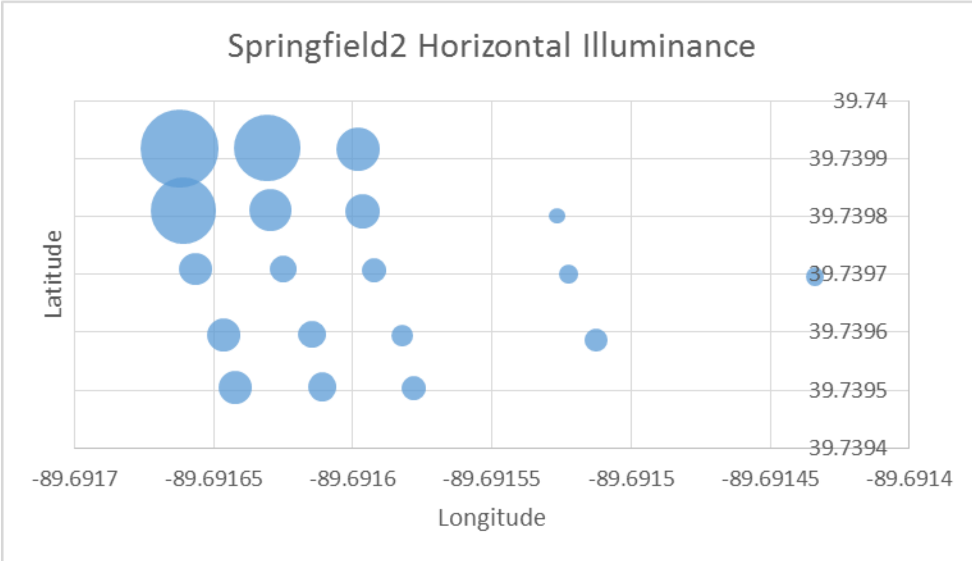



**Figure 31. Horizontal illuminance at Springfield2.**

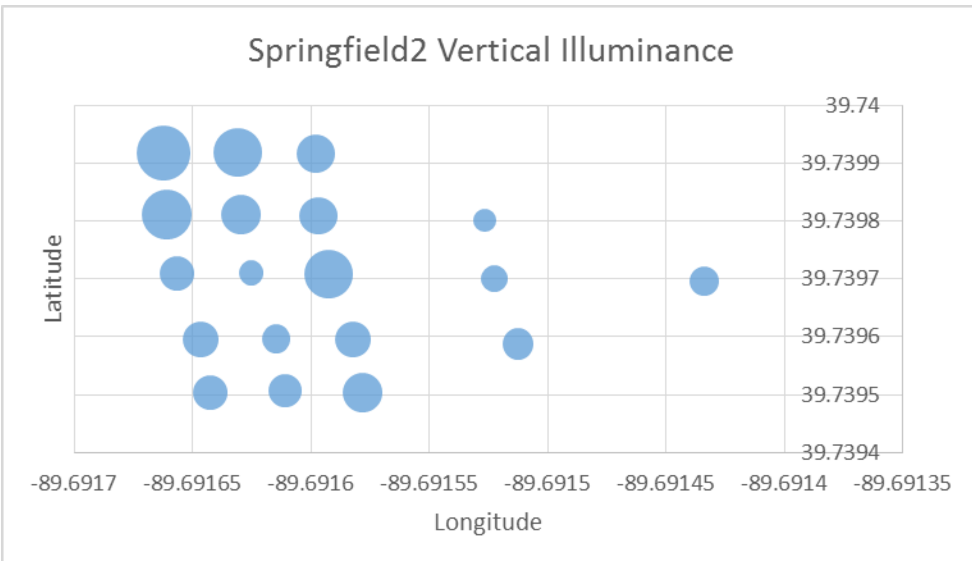



**Figure 32. Vertical illuminance at Springfield2.**

### 4.2.2 Light Trespass from Vehicle Headlamps

Light trespass from headlamps was characterized for three of the seven fields. When vehicles passed by the Peoria field, the vertical illuminance peaked at 1 lx. For the Pleasant Plains field, the vertical illuminance generated by headlamps varied from 1 lx when passing by on IL-125, to 1.5 lx when approaching the field from the north on IL-123 and turning east onto IL-125. At the Springfield1 site, the light trespass ranged between 0.3 and 0.5 lx.

### 4.2.3 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 0.00 to 0.15 lx in the fields sampled, with an average of 0.1 lx. The ambient vertical illuminance averaged 0.2 lx. The ambient measurement included skyglow and the light from the moon, which was full during the measurements.

### 4.2.4 Roadway Lighting Levels

The lighting values for the roadway lighting were also collected. The summary values for the nearest lane to the field are shown in Table 6. Appendix A contains the summary values for all of the lanes of the adjacent roadways.

**Table 6. Lighting Level Summary Values for Adjacent Roadways**

| | Horizontal Illuminance | | | Vertical Illuminance | | |
|---|---|---|---|---|---|---|
| **Near Lane** | **Max** | **Min** | **Avg** | **Max** | **Min** | **Avg** |
| Pleasant Plains | 19.35 | 0.00 | 6.18 | 0.47 | 0.00 | 0.07 |
| Springfield1 | 9.91 | 0.10 | 3.93 | 1.02 | 0.00 | 0.36 |
| Assumption | 30.17 | 0.00 | 3.54 | 7.24 | 0.00 | 1.89 |
| Normal1 | 47.68 | 0.43 | 16.74 | 2.51 | 0.66 | 1.46 |
| Peoria | 52.58 | 2.77 | 19.01 | 3.29 | 0.63 | 1.62 |
| Normal2 | 24.09 | 0.10 | 7.23 | 1.72 | 0.14 | 0.96 |
| Springfield2 | 84.17 | 0.63 | 14.64 | 3.89 | 0.00 | 1.23 |

It is noteworthy here that all of these roadway lighting installations would be considered typical. It should also be noted, however, that the lighting installations at Assumption and the SpringField1 sites were below Illuminating Engineering Society (IES) standards.

## 4.3 RELATIONSHIP TO LIGHTING

There were three primary interests for the analysis: (1) soybean growth and yield effects, (2) development delays, and 3) variety effects. Height, NDVI, pod and seed weight, and estimated seed yield were used to estimate total soybean growth effects. Reproductive stage measurements contributed to the estimate of the amount of time the lighting delays plant development. The relationship between lighting and these characteristics between fields were used to determine whether the lighting impact is also dependent on the soybean variety used.

These results are presented first as a consideration of plant growth, then of the plants at harvest and finally as a consideration of the impact of the varietals.

### 4.3.1 Periodic Growth and Development Measurements

The three metrics considered in the growth measurements were R-stage, NDVI, and plant height. Each of these is considered first in a general overview followed by a complete statistical analysis.

#### *4.3.1.1 General Overview*

The periodic measurements showed some interesting trends. The following charts show example data from the Normal1 field, where growth differences were most prevalent, and illustrate the differences seen in the field. The R-stage data, and thus maturity of the plants at the high and low illuminance sample locations, are shown in Figure 33. R-stage is a quantized measurement; therefore, there is some quantization error. As shown, the development stages of the plants in the low illuminance levels were consistently higher than the development stages of the plants in the high illuminance areas. A quadratic fit shows that the intercepts are dramatically different, although the low illuminance fit does not pass through an R-Stage of 1 due to errors in the measurement. In addition, the high illuminance plant development did not accelerate like the low illuminance plant development.

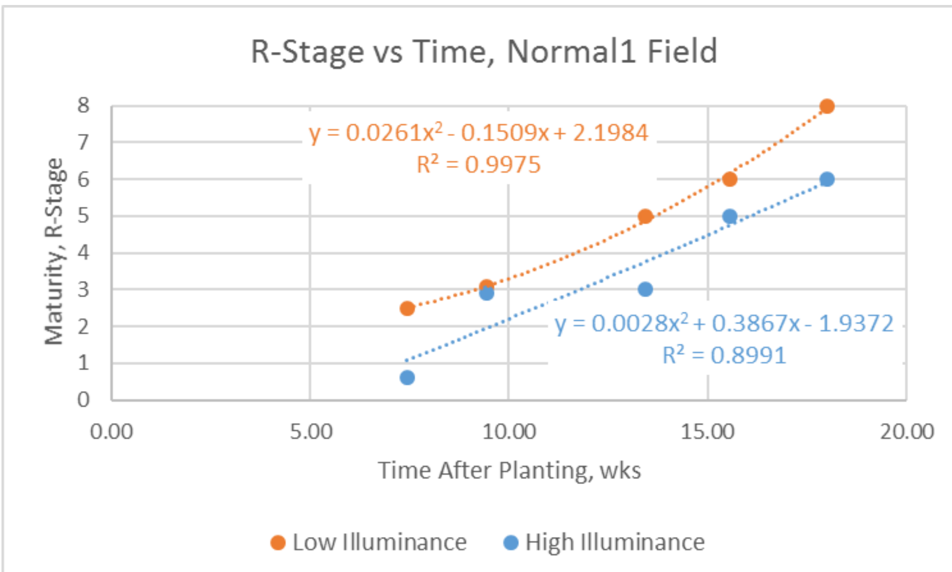



**Figure 33. Average R-stage vs. time for high and low illuminance sample location.**

Figure 34 shows the average height for high and low illuminance sample locations. As the shape preserving interpolant model indicates, the plants in the low illuminance sample location reached maximum height just after the second sampling (10–11 weeks) at the R3 stage. In contrast, plants in the high illuminance sample location didn't reach maximum height until 15.6 weeks at the R5 stage, and they exceeded the height of the low illuminance plants by 15 in. for this field. This may be a result of delayed development, but is more likely etiolation of the stem caused by relatively low light levels during nighttime.

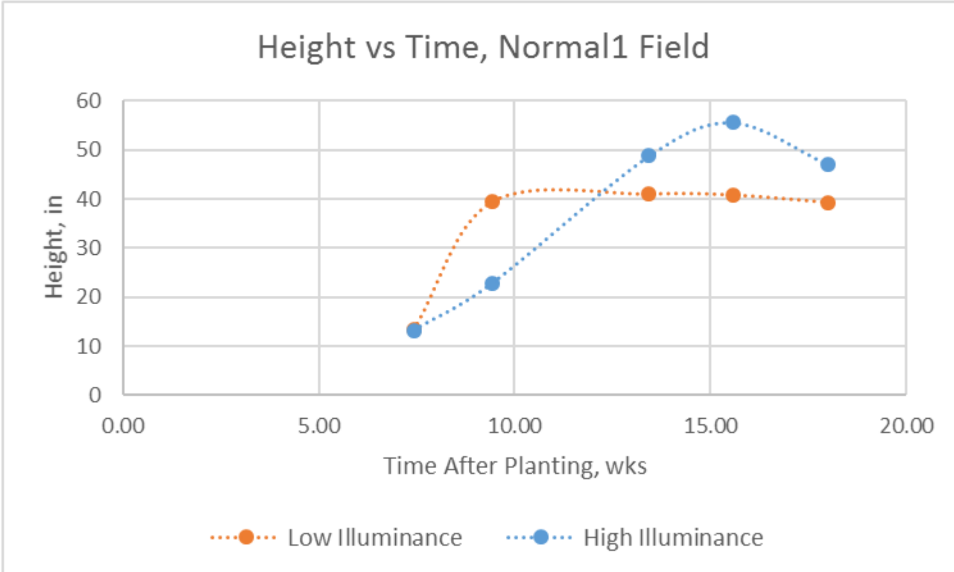



**Figure 34. Average height vs. time for high and low illuminance sample location.**

Figure 35 shows the average NDVI for the same sample locations. As an estimate of plant biomass, NDVI shows more subtle differences between high and low illuminance sample locations. NDVI usually peaks at the R4 to R5 stages and then steadily declines as leaves fall from the plant. Although plants growing under the low illuminance regime exhibited this trend, the NDVI of plants growing under high illuminance begin decreasing soon after flowering, which may indicate poorer overall health of the crop.

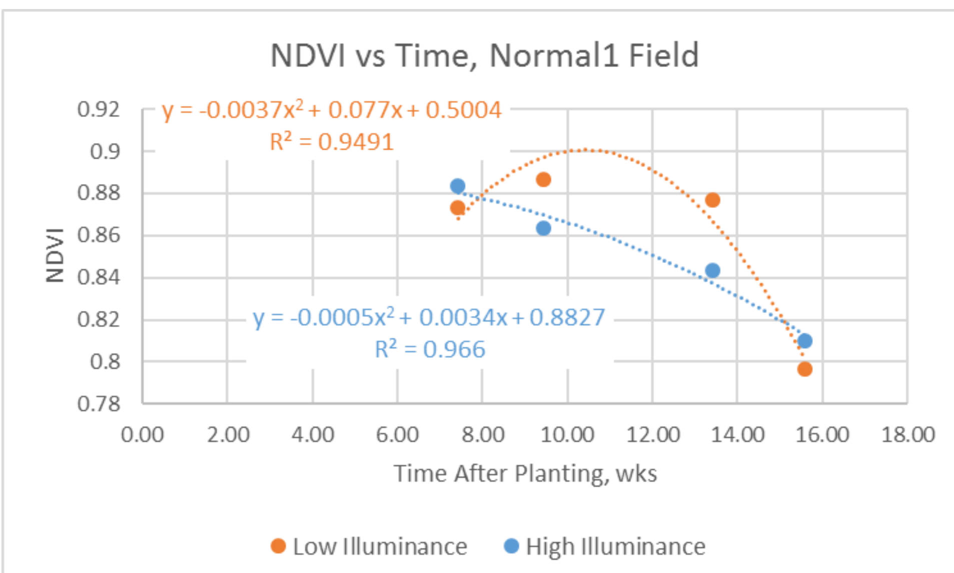



**Figure 35. Average NDVI vs. time for high and low illuminance sample locations.**

At Pleasant Plains (the intersection of IL-125 and IL-123), on September 22, 2016, the plants were still at R7 near the roadway, but they were approaching R8 in the remainder of the field

(Figure 36). Just 4 days later during the hand harvest, the majority of the field had turned to R8, with only the first few rows delayed in maturity at or near R8 with yellowing leaves (Figure 37). The delay in maturity caused by lighting may be measured in days at this site, due in part to the residential side shielding at the site.

**Figure 36. Pleasant Plains, September 22, 2016.**

**Figure 37. Pleasant Plains, September 26, 2016.**

In contrast, the Normal1 site, County Road 1700N (Normal), had soybean plants with significantly delayed maturity (Figure 38) in semicircle shapes around the base of the luminaires.

**Figure 38. Normal1, September 22, 2016.**

A field with similar lighting, IL-50 and Orange Prairie Road (Peoria), had similar immaturity plants near the luminaires on September 22, 2016 (Figure 39), but the immaturity region had shrunk considerably by September 26 (Figure 40).

**Figure 39. Peoria, September 22, 2016.**

**Figure 40. Peoria, September 26, 2016.**

Figure 41 shows green (R6 or R7) plants on the edge of the field nearest the roadway lighting, but primarily R8 plants in the field.

**Figure 41. Springfield2, September 27, 2016, showing R8 maturity in the majority of the field.**

### *4.3.1.2 Statistical Analysis*

Plant development was delayed by 2 to 2.5 weeks by lighting and the delay was related to the horizontal illuminance.

A mixed model statistical approach was used to analyze the data with respect to sampling. No interaction was found between the lighting and the sampling timing in the periodic data. The other factors are analyzed below.

4.3.1.2.1 Plant Maturity Progression Analysis by R-Stage

Trespass lighting delayed plant development in all fields where the horizontal illuminance was above 2 lx. The data also show that the delay was at least 2.3 weeks, as shown by the differences in the second to last sample and harvest maturity levels. Plants may be able to mature if the farmer leaves them in the field for an additional 2 to 3 weeks and if they do not experience freezing temperatures during this harvest delay.

In Figure 42, the mean R-stage value across all the fields is shown relative to the binned horizontal illuminance and sample week. A linear model was fitted to the data using linear regression for each sampling in order to compare the binned averages from one sample period to another. The bins used in the analysis of the growth development data (Table 7) were different from the bins used in the yield analysis in order to improve the power of the estimates. The variances in the mean curve shapes are not likely due to plant physiology but are more likely due to errors in the observation. Given that R-stage measurement is discrete and not quantitative (resulting in some quantization error), the variance could be due to sampling times that happened to fall in the middle of an R-stage relative to the growth progression in the field. Therefore, differences in the curve shapes, such as those found in Figure 42, should be considered carefully. Nonetheless, there is a downward trend in the data related to horizontal illuminance starting with the first sample at 7.4 weeks then again at 13.4 weeks. The plants started to accelerate in development after 7.4 weeks, especially for horizontal illuminances up to 3.25 lx. Also, the development of the plants at 3.25 lx was almost linear in progression while those in low illuminance exhibited a growth acceleration between 9.4 and 13.4 weeks.

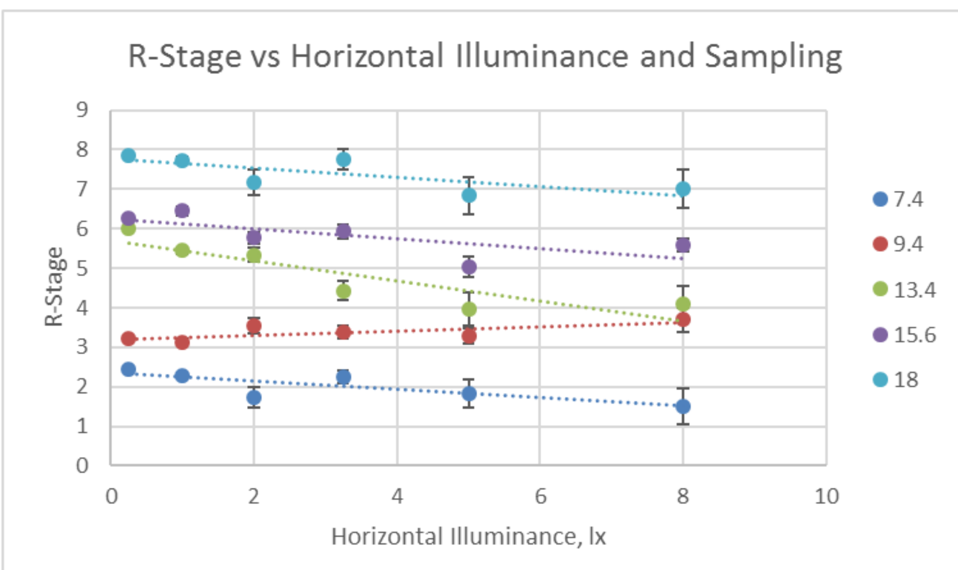



**Figure 42. Development stage vs. sample week and horizontal illuminance.**

**Table 7. Bins Used for Illuminance for Analysis of Periodic Measurements**

| Bin Level | Min | Max |
|---|---|---|
| **0.25** | 0 | 0.25 |
| **1** | 0.25 | 1 |
| **2** | 1 | 2 |
| **3.25** | 2 | 3.25 |
| **5** | 3.25 | 5 |
| **8** | 5 | 8 |

From the R-stage data versus sampling week and horizontal illuminance, the plants matured from stage 6 to 6.5 to stage 8 in 3.4 weeks at 0.25 and 1 lx horizontal illuminance, which is about 0.44 maturity stages per week. Given that the average R-stage is approximately 7 at 5.0 lx and 8.0 lx, then the plants above 3.25 lx were approximately 2.3 weeks delayed. Only the Normal1 site had horizontal illuminance above 8 lx horizontal, and that was for only one sample location.

The correlation of maturity with vertical illuminance (Figure 43) shows almost no delay in maturity up to 3.25 lx vertical and a 2.3 week delay up to 5.0 lx vertical, but approximately a 7-week delay between 5.0 and 8.0 lx vertical, suggesting a stronger influence of vertical illuminance over horizontal illuminance.

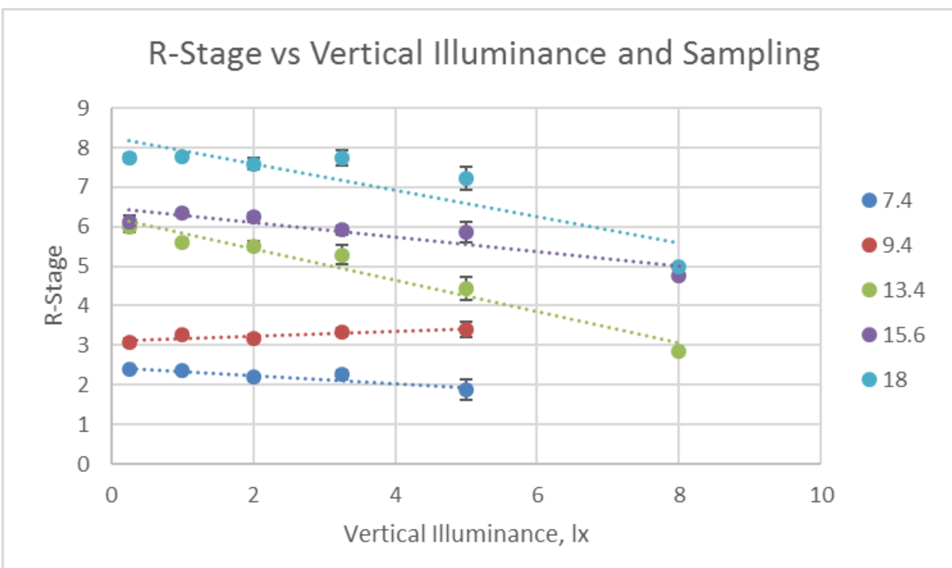



**Figure 43 Development stage vs. sample week and vertical illuminance.**

Similarly for R-stage versus total illuminance, as shown in Figure 44, the R-stage versus sample week and total illuminance shows a downward trend above 2 lx in magnitude. As with horizontal and vertical illuminance, the development accelerated over time from the 13.4- to-18-week samples at the 8 lx combined lighting levels.

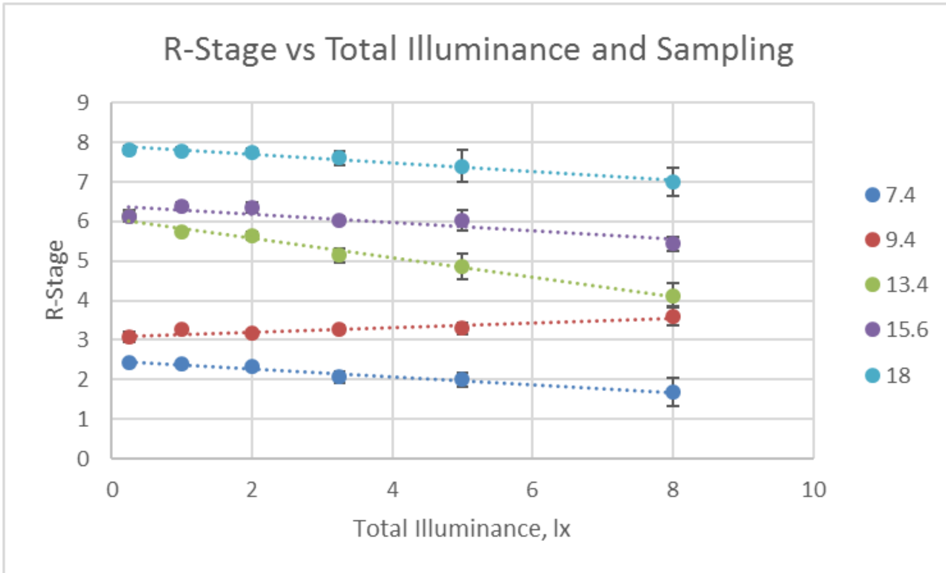



**Figure 44. Development stage vs. sample week and total illuminance.**

The correlation of R-stage with the ratio of vertical illuminance to horizontal illuminance is shown in Figure 45. This R-stage analysis seems to indicate the development delay and thus maturity is more correlated to a low vertical to horizontal illuminance ratio.

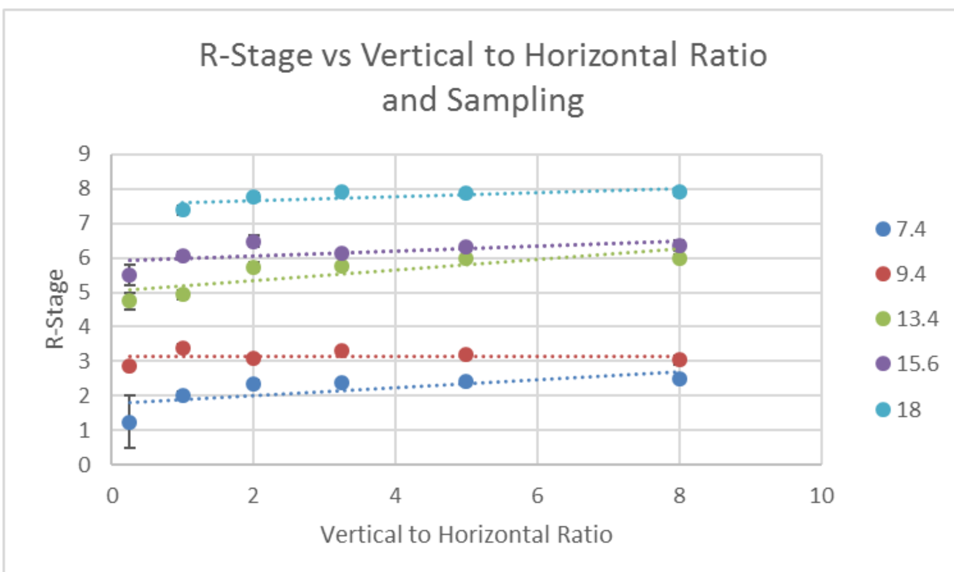



**Figure 45. Development stage vs. sample week and vertical to horizontal ratio.**

4.3.1.2.2 Height Measurement Analysis

Figure 46 through Figure 49 show the relationships between average normalized plant height and lighting level. There was little effect of lighting on normalized height below 2.0 lx that can be separated from the variance regardless of whether the lighting was horizontal, vertical or the total illuminance. There was a general trend upward for height versus each of the illuminance measurements. The effect of lighting ratio seems to show a slight decrease in height with increasing lighting ratio, but lighting ratio had no effect on the growth of the plants.

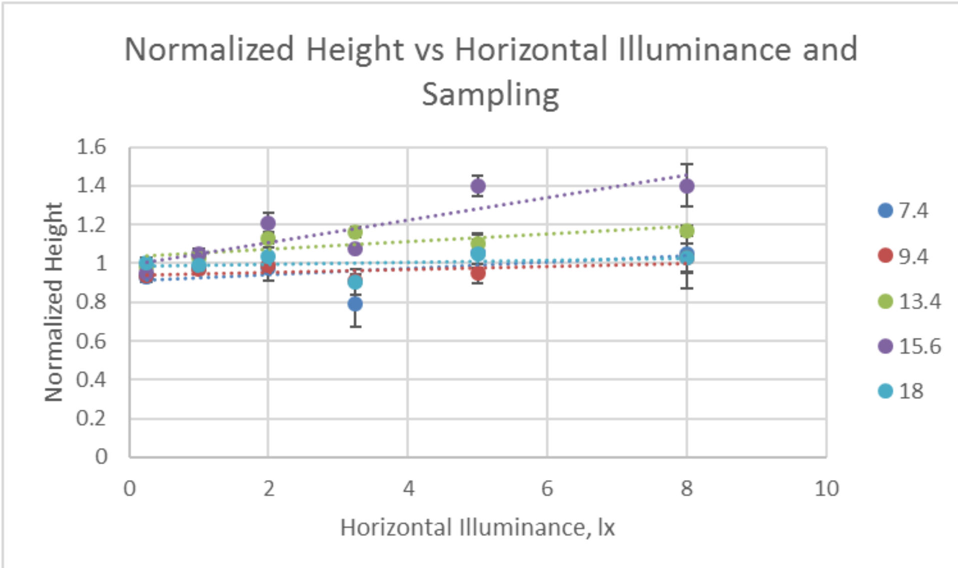



**Figure 46. Plant height vs. sample and horizontal illuminance.**

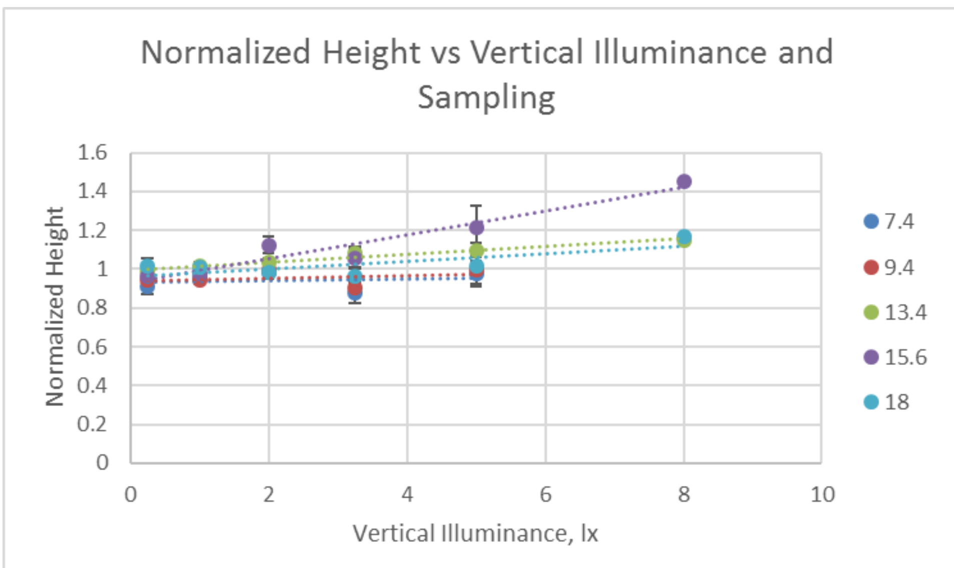



**Figure 47. Plant height vs. sample and vertical illuminance.**

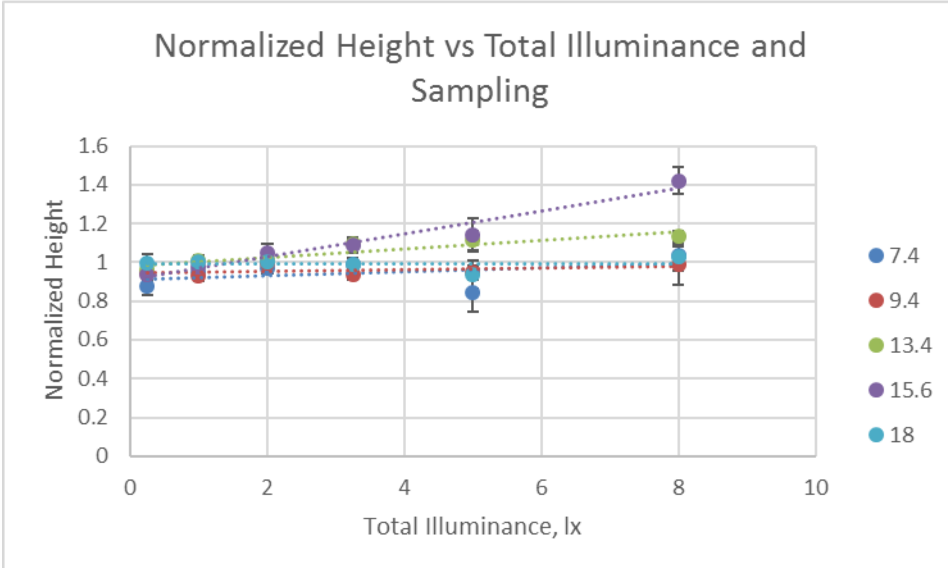



**Figure 48. Plant height vs. sample and total illuminance.**

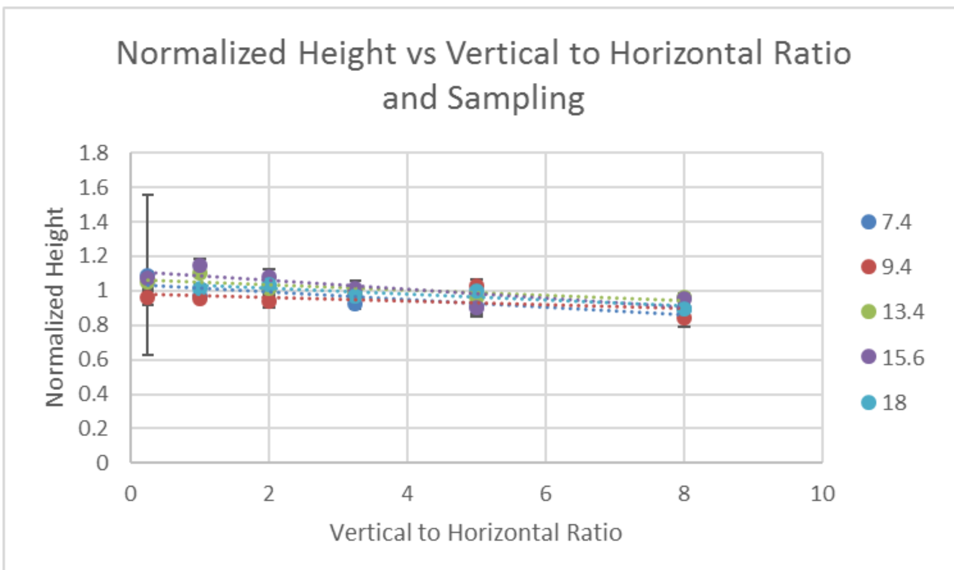



**Figure 49. Plant height vs. sample and vertical to horizontal ratio.**

4.3.1.2.3 NDVI Measurement Analysis

No correlation was found relating NDVI to illumination at any of the sites. Figure 50 through Figure 53 illustrate the relationship of NDVI to horizontal illuminance for each site. Log-linear curve fits seemed to fit best to the data. However, there was no practical difference in the NDVI relative to the lighting.

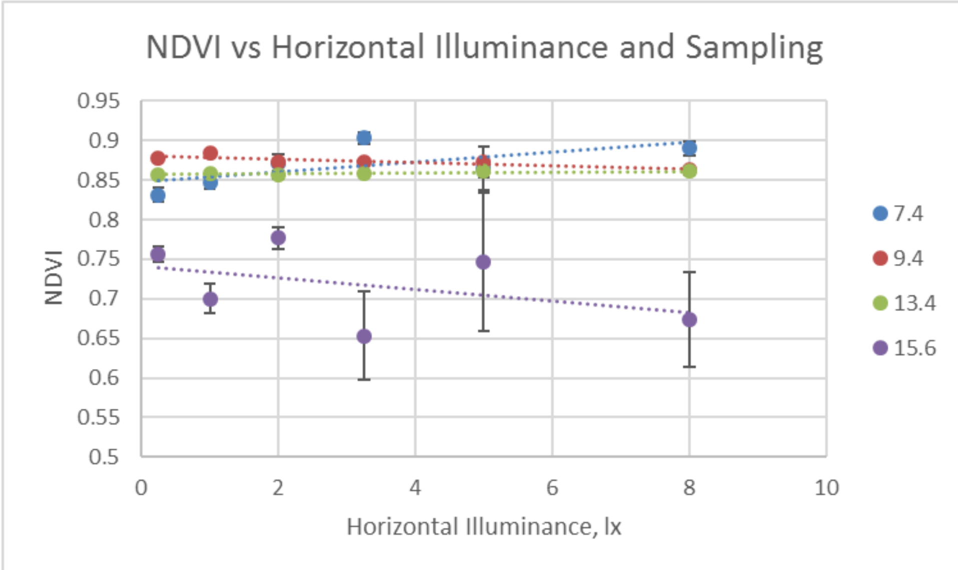



**Figure 50. NDVI vs. Sample and Horizontal Illuminance**

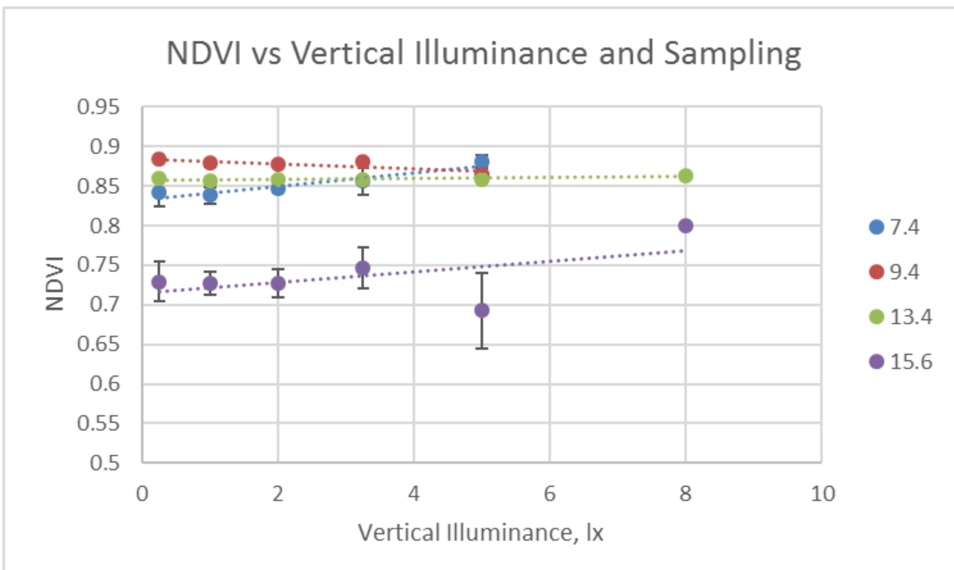



**Figure 51. NDVI vs. sample and vertical illuminance.**

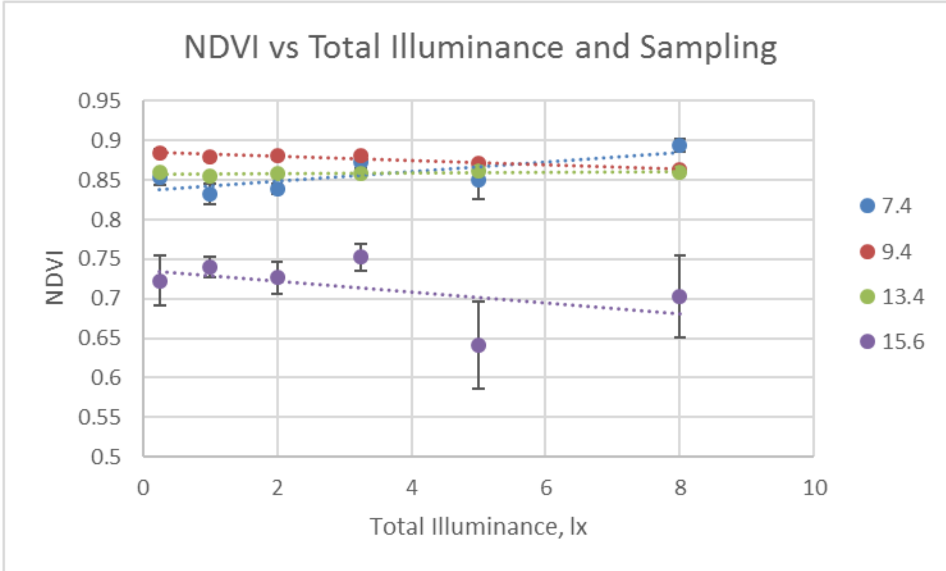



**Figure 52. NDVI vs. sample and total illuminance.**

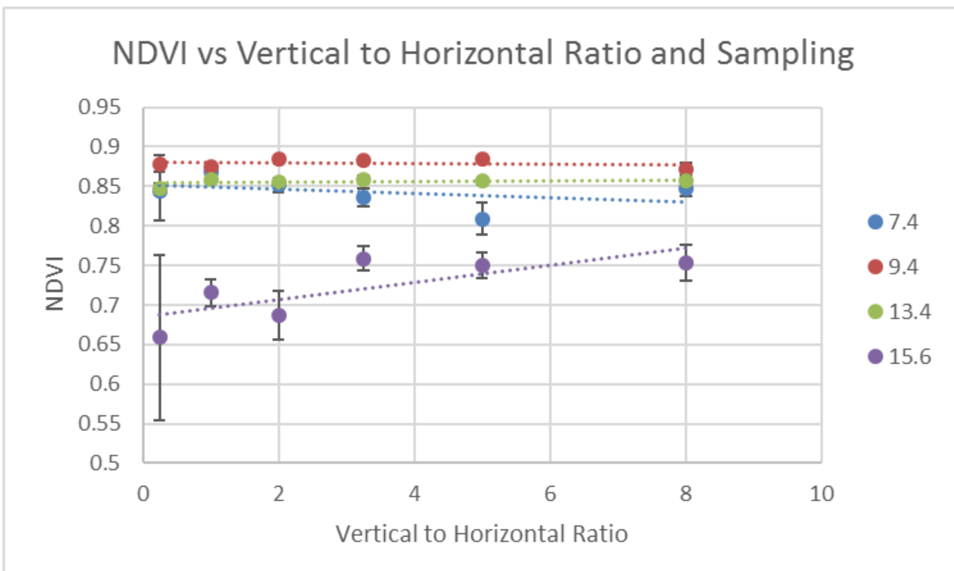



**Figure 53. NDVI vs. sample and vertical to horizontal ratio.**

### *4.3.1.3 Growth Analysis Conclusions*

Height and stage of the plant maturity were both affected by trespass illuminance values. The limit for the effect seemed to be approximately 3.3 lx for vertical, horizontal, and total illuminance. There was no statistically significant interaction between the NDVI samplings and the lighting. Finally, the plant development accelerated and recovered in maturity as long as the horizontal illuminance did not exceed 8.0 lx.

### 4.3.2 Analysis of Plant Characteristics Versus Lighting at Harvest

While the growth delays are interesting, 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 the farmer can obtain for the crop due to the buyer's drying costs. Therefore, both moisture content and yield affect the money a farmer can make from the field.

The metrics of plant height, pod and seed weight, percentage moisture, and yield were all considered at harvest in a general overview; however, the most critical factors — percent moisture and yield — were considered in a more detailed statistical analysis.

#### *4.3.2.1 General Overview*

Several relationships showed a change between plant characteristics and horizontal illuminance. Figure 54 shows that, in general, the average height of a plant increased as horizontal illuminance increased. These are raw results, so there was a substantial scatter in the data. This is likely due to the number of confounding factors not controlled by this experiment, such as variety, soil properties, and crop management.

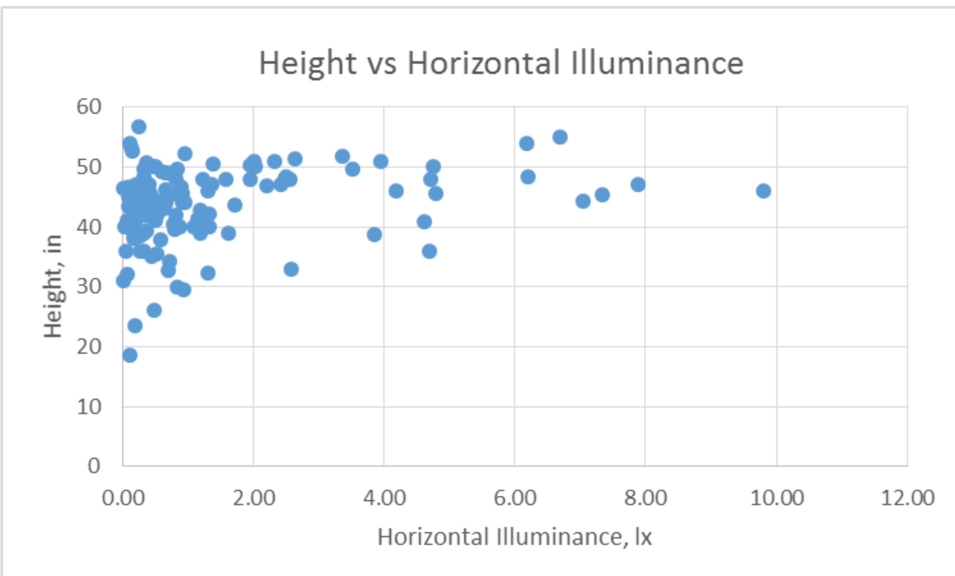



**Figure 54. Height vs. horizontal Illuminance.**

Pod and seed weight, after drying, from each sample location is shown in Figure 53 versus horizontal illuminance. In general, pod and seed weight decreased as horizontal illuminance increased (Figure 55). The yield estimate follows a similar trend with perhaps a little less scatter in the estimate (Figure 56).

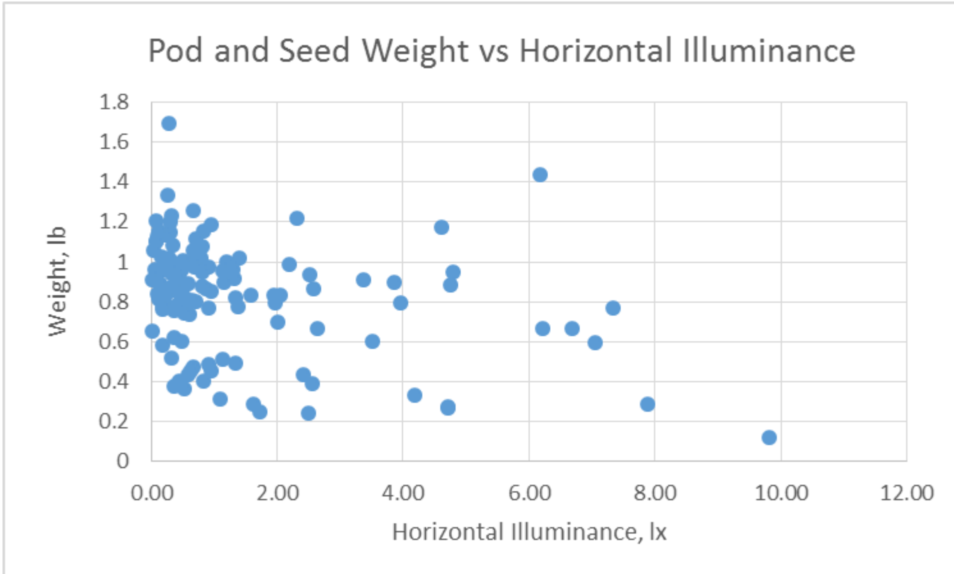



**Figure 55. Pod and seed weight vs. horizontal illuminance.**

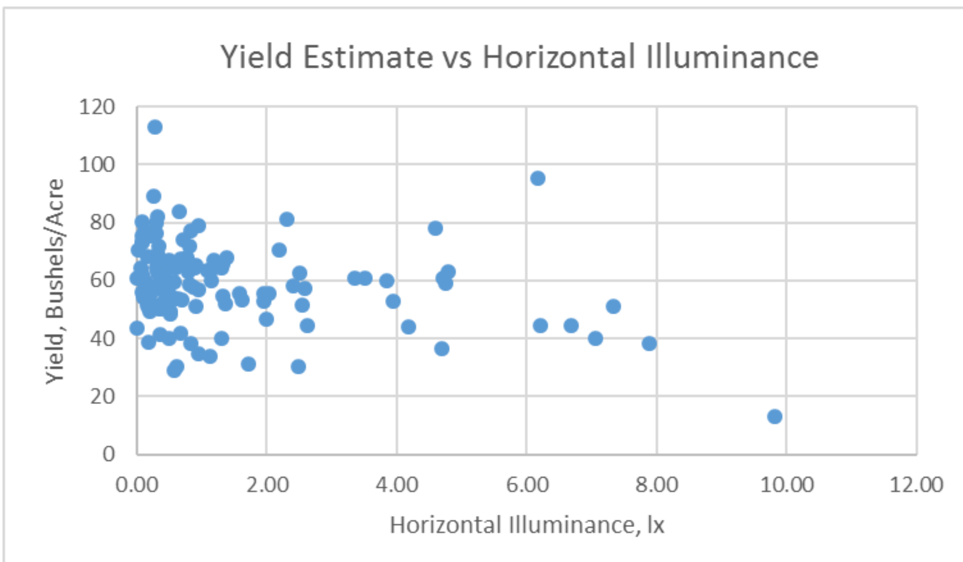



**Figure 56. Yield estimate vs. horizontal illuminance.**

Plant moisture tended to increase with increasing horizontal illuminance (Figure 57) but approached an asymptote, as expected, because plants cannot be 100% water.

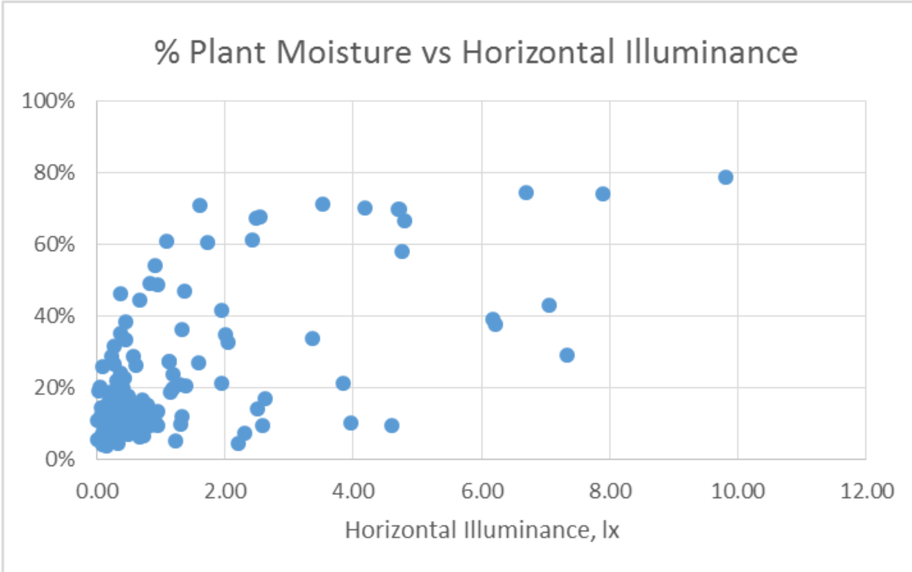



**Figure 57. Percent plant moisture vs. horizontal illuminance.**

The maturity of the plants measured on the R-Stage scale is show in Figure 58 versus the horizontal illuminance in lx. As the figure shows, the plants were distributed between an R-Stage of 7 and 8 for light levels below 1.0 lx, but the number of stage 8 plants was reduced to zero by a horizontal illuminance of approximately 7.0 lx. The average maturity of the plants harvested for this project were not below R5 despite the disruption of the length of night for the plants that were illuminated.

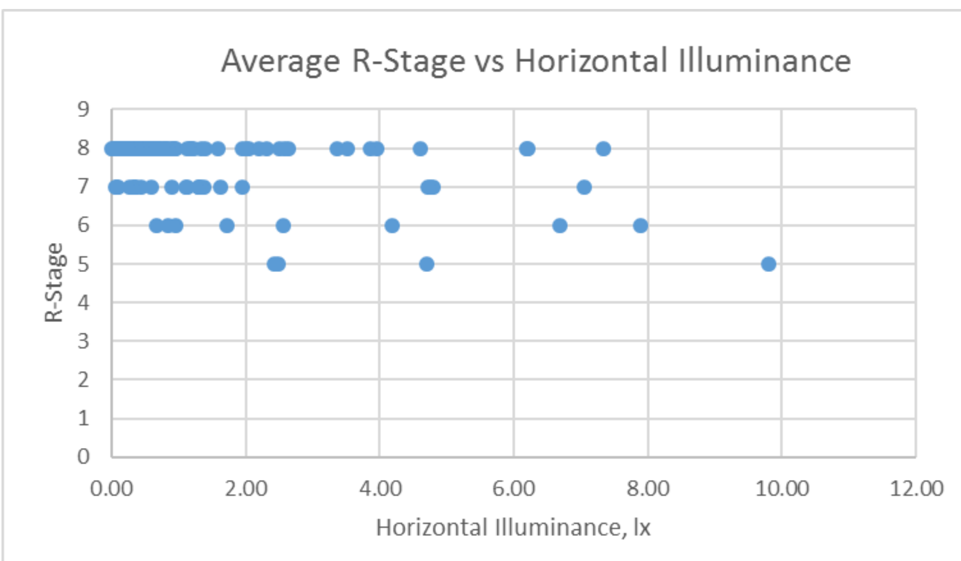



**Figure 58. Plant R-Stage vs. horizontal illuminance.**

The plant characteristic data for all of the fields were also analyzed versus vertical illuminance. The relationships were similar to those for horizontal illuminance, but the scatter was more pronounced (Figure 59 and Figure 60).

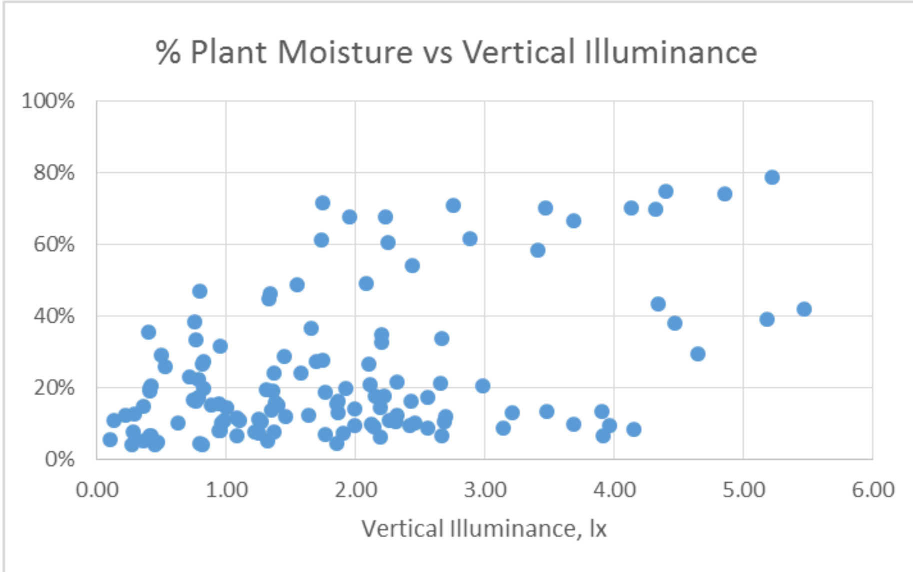



**Figure 59. Plant moisture vs. vertical illuminance.**

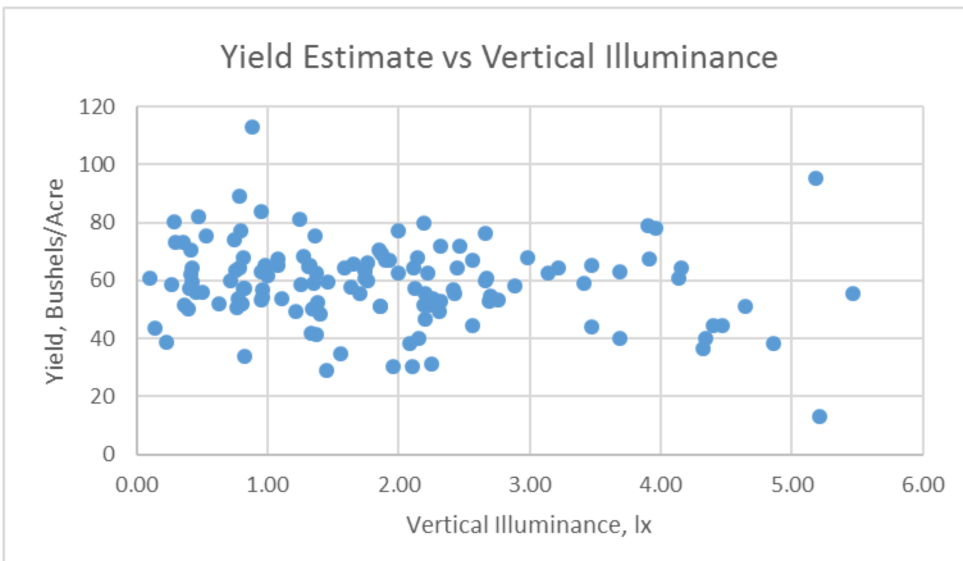



**Figure 60. Yield estimate vs. vertical illuminance.**

The R-Stage versus vertical illuminance is shown in Figure 61. Vertical illuminance had an effect similar to the horizontal illuminance on plant maturity.

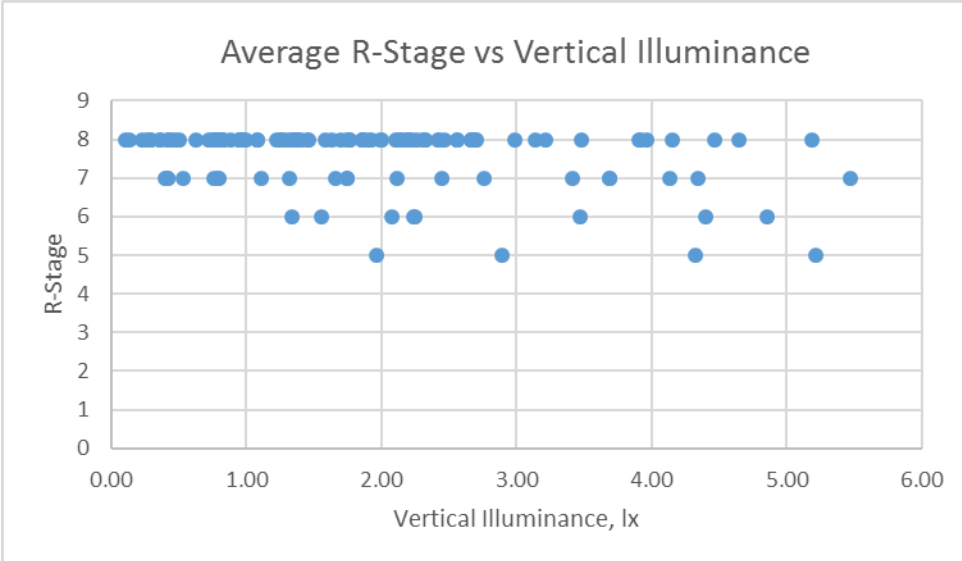



**Figure 61. Average R-Stage vs. Vertical Illuminance.**

Given that the plants seemed to be affected by both horizontal illuminance and vertical illuminance, 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. In particular, the yield estimate and R-Stage versus total illuminance was analyzed.

As shown in Figure 62, the yield estimate had more variance versus total illuminance than versus the horizontal illuminance as shown in Figure 56, further illustrating the dependence on horizontal and vertical illuminance. Similarly, Figure 63 shows the R-Stage variance versus the total illuminance, with a different distribution than the horizontal or vertical illuminance dependence shown in Figure 58 and Figure 61, respectively.

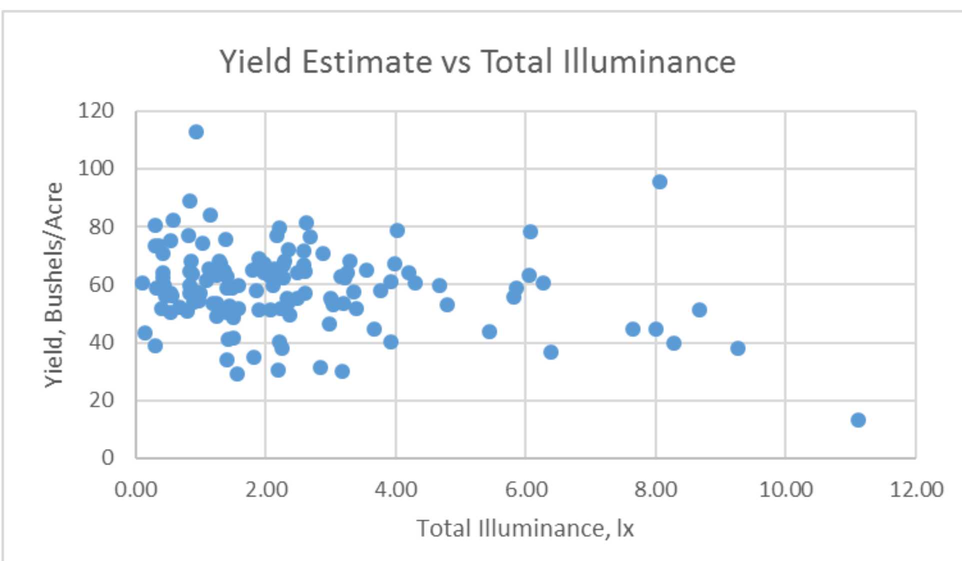



**Figure 62. Yield estimate vs. total illuminance.**

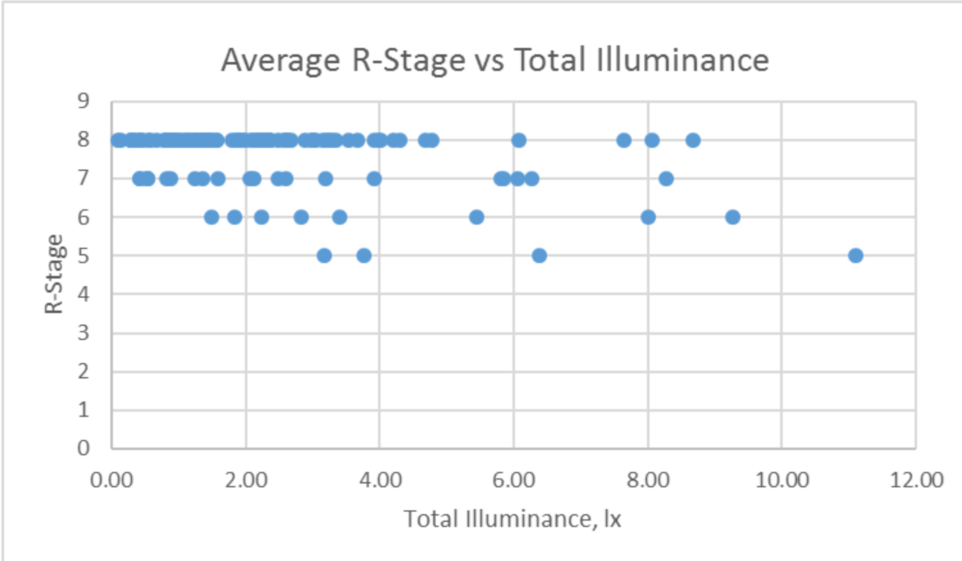



**Figure 63. R-Stage vs. total illuminance.**

To account for confounding variables not controlled for, such as soil quality, moisture, weeding method, and others field-specific variables, the plant characteristics were normalized by field and analyzed by field. Height, pod and seed weight, and yield were normalized by dividing by those data at the location farthest from the light source in each field. The normalized results versus horizontal illuminance are shown Figure 64 through Figure 67.

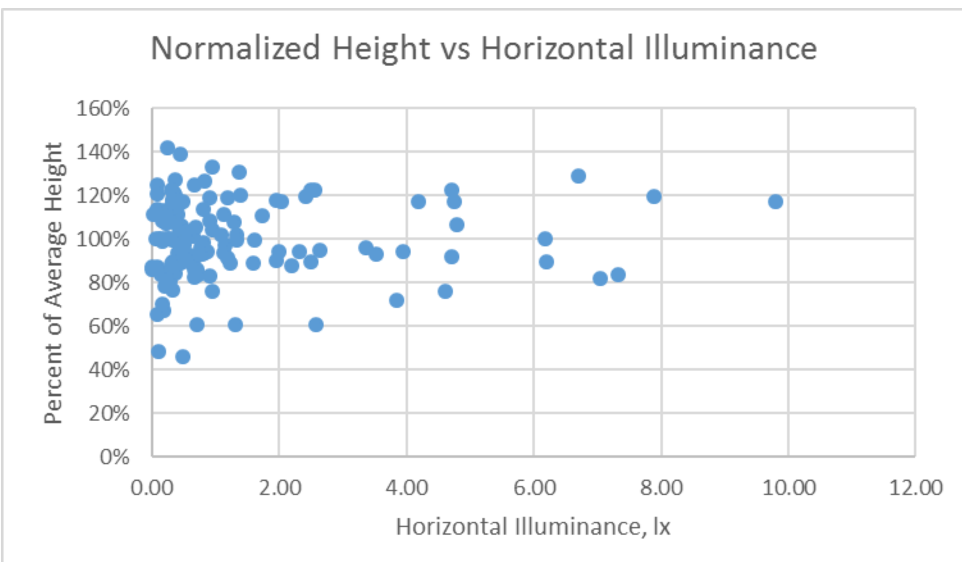



**Figure 64. Normalized height for all sites vs. horizontal illuminance.**

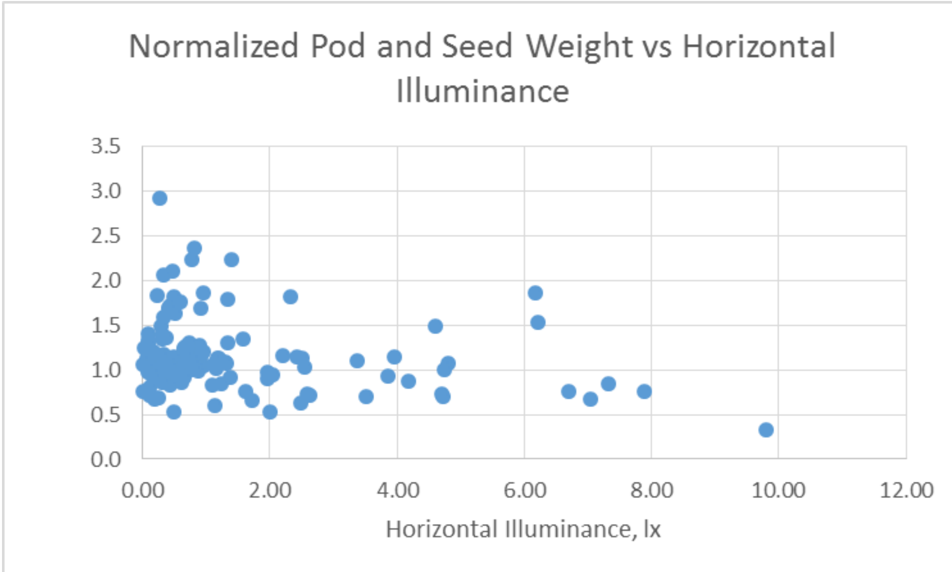



**Figure 65. Normalized pod and seed weight vs. horizontal illuminance.**

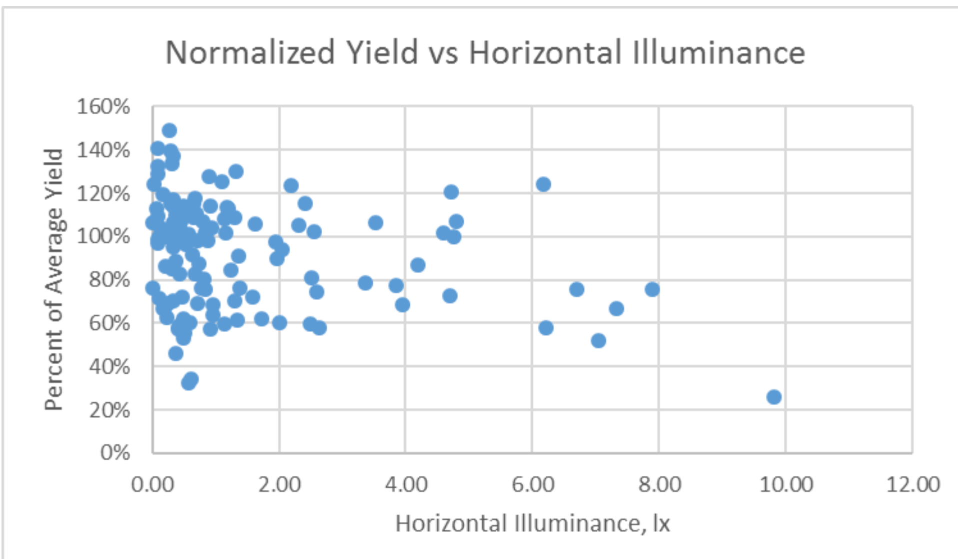



**Figure 66. Normalized yield vs. horizontal illuminance.**

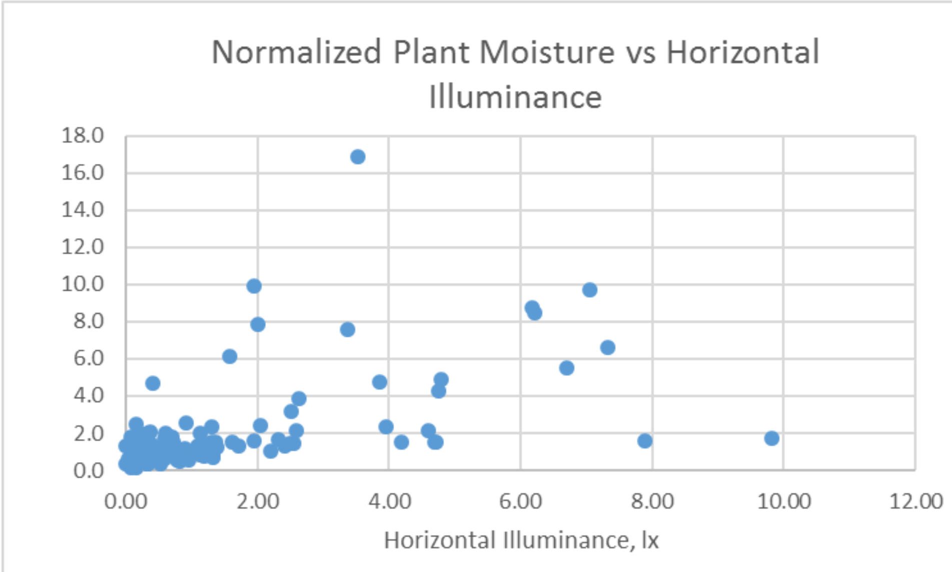



**Figure 67. Plant moisture, normalized by site, vs. horizontal illuminance.**

While the normalization did not seem to reduce the scatter in the data, it is believed that the normalized data should be used for the statistical analysis in order to account for potential differences in the field characteristics.

### *4.3.2.2 Statistical Analysis*

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

#### 4.3.2.2.1 Normalized Plant Moisture Content at Harvest

Excess plant or seed moisture is the primary reason soybeans cannot be harvested if there is a delay in maturity. ANOVAs were run on the normalized plant moisture data with respect to total illuminance, horizontal illuminance, and vertical illuminance. The generalized linear model (GLM) fitting results to total illuminance are shown in Table 8. As shown, the variation in normalized plant moisture significantly correlates with total illuminance, field, and the interaction of those two main effects. Because there were six varieties of the soybean planted on different dates in seven fields, variety and planting date variances are lumped in with the other uncontrolled variances. Although variety and planting date may have affected delays in maturity, this cannot be determined from these data.

**Table 8. GLM Fit Result s for Normalized Plant Moisture vs. Total Illuminance**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Total illuminance** | 10 | 130.34 | 13.03 | 5.22 | <.0001 |
| **Field** | 6 | 85.51 | 14.25 | 5.71 | <.0001 |
| **Total illuminance * Field** | 22 | 98.99 | 4.50 | 1.80 | 0.028 |

The mean normalized plant moisture was plotted against the binned total illuminance in Figure 68. The error bars represent the standard error. A cubic function was fitted to the normalized, un-binned data using least squares regression and is shown as a trend line to help illustrate the binned results. The cubic intercept was forced to (0, 1) since zero illuminance should result in the norm and the un-binned data utilized to weight the residuals by the number of samples in each bin. The equation is also shown in Figure 68. Care should be used in utilizing the trend line model, as the coefficient of determinance ($R^2$) was very small. Cubic models were similarly calculated for the analysis of vertical and horizontal illuminance.

The 8, 10, and 12 lx bins had only one sample, so the standard error could not be calculated. Because the data were normalized by the measurements from a plant far from the light source, any average more than 1 would indicate an impact of lighting on the plants

The normalized plant moisture mean at 1 lx total illuminance is 0.997, indicating no effect of lighting. At 2 lx the mean is 1.11, indicating an effect of lighting on the moisture of the plants, although it is not clear whether such an increase in plant moisture content would prevent the farmer from being able to harvest. At 3.0 lx, the normalized plant moisture is 1.51, and at 4 lx, there is a much larger (2.68-fold) increase in plant moisture, which would definitely prevent timely harvest of the soybean plants. The cubic model shows that the plant moisture would drop at illuminance levels above 8 lx, but the values for 1–4 lx are similar to the binned means. The more conservative limit would be the larger illuminance value of 3 lx.

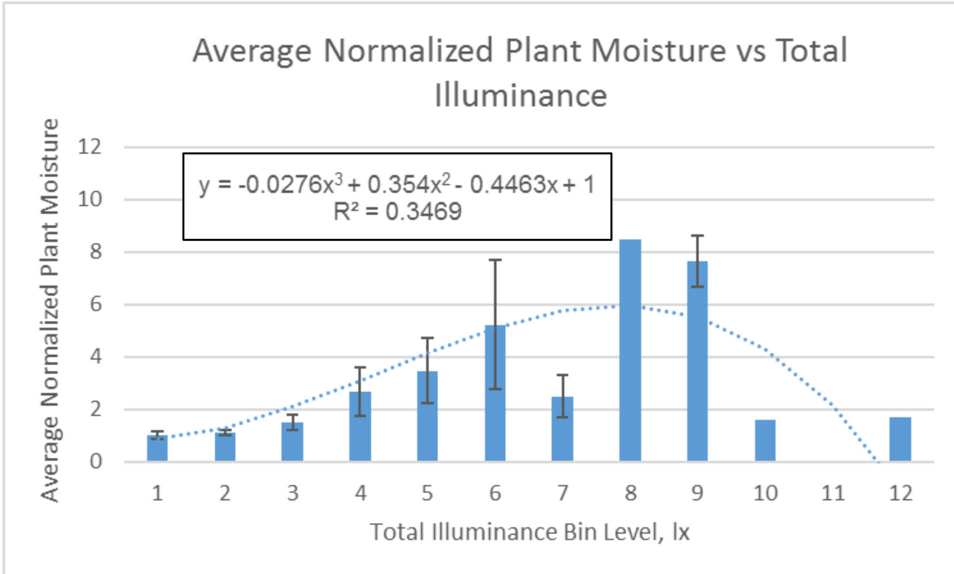



**Figure 68. Average normalized plant moisture vs. binned average total illuminance. The error bars represent the standard error**

A pairwise comparison was calculated, with the results shown in Table B-1 (Appendix B), which presents significant pairwise comparisons of the normalized plant moisture with respect to the binned horizontal illuminance. There is significance between the 1, 2, 3, and 4 lx levels, but lx levels 1, 2, and 3 are not significantly different from one another.

The resulting fit of horizontal illuminance to normalized plant moisture is shown in Table 9, which shows that all of the factors are significant with respect to the normalized plant moisture.

**Table 9. GLM Fit of Normalized Plant Moisture to Horizontal Illuminance and Field**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Horizontal Illuminance** | 7 | 255.66 | 36.52 | 36.48 | <.0001 |
| **Field** | 6 | 98.24 | 16.37 | 16.35 | <.0001 |
| **Horizontal Magnitude*Field** | 13 | 159.52 | 12.27 | 12.26 | <.0001 |

The average normalized plant moisture versus total illuminance is shown in Figure 69 again with a cubic model based on the normalized un-binned data shown as a trend line. At 1 lx horizontal, the average normalized plant moisture is 1.06. At 2 lx, the average is 2.08 times the plant moisture farther out in the field, which will cause issues during harvest. The cubic model shows that the 4 lx samples likely include anomalies, but that the normalized plant moisture exceeds 2.0 x norm before 2.0 lx.

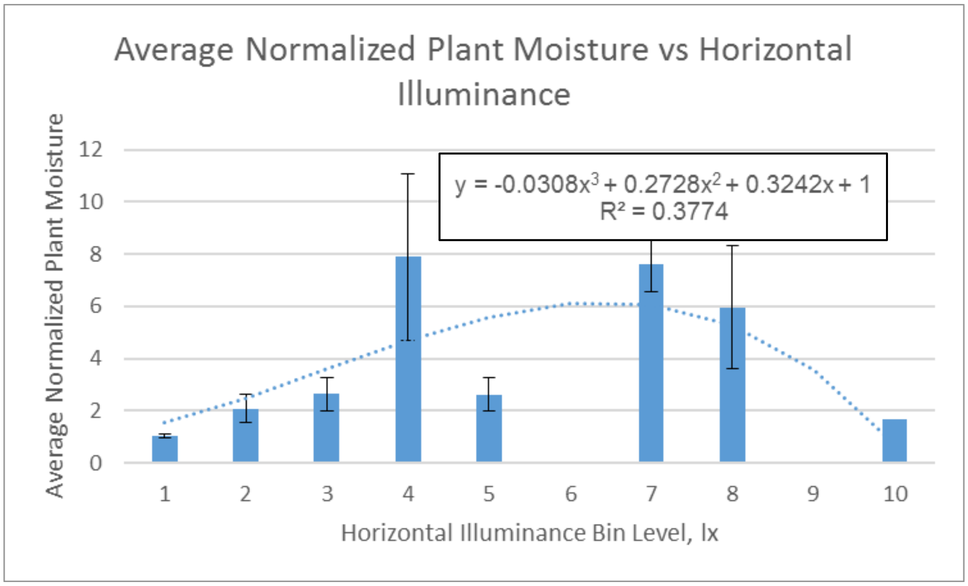



**Figure 69. Average normalized plant moisture vs. horizontal illuminance.**

The significant pairwise comparisons of horizontal illuminance binning versus normalized plant moisture are provided in Appendix B, Table B-2. The 2, 3, and 4 lx plant moisture means are all significantly different from the 1 lx bin. The 2 and 3 lx plant moisture means are not significantly different from each other. This means that between 1 and 2 lx horizontal illuminance, the plant moisture content of the plants may be such that they cannot be harvested.

Finally, the GLM fit of the normalized plant moisture to vertical illuminance also results in significance of the vertical illuminance and field. This interaction is shown in Table 10. The mean plant moisture content versus plant moisture variance by field is expected. In the binned model, the mean normalized plant moisture (Figure 70) is 1.08 at 1 lx but jumps to 1.65 by 2 lx. However, the pairwise comparisons show that the difference between 1 and 2 lx vertical illuminance is not significant (Appendix B, Table B-2), but the difference is significant between 1 and 3 lx. At a vertical illuminance of 3 lx, the average normalized plant moisture is 1.85 times the norm. The cubic model fit to the normalized un-binned data shows a rapidly increasing plant moisture with increasing vertical illuminance and shows that the binned analysis tends to underestimate the normalized plant moisture for these data. However, with an $R^2$ of 0.229, the data is only weakly correlated with the cubic model.

**Table 10. GLM fit of Normalized Plant Moisture to Vertical Illuminance and Field**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Vertical Illuminance** | 5 | 81.86 | 16.37 | 5.92 | <.0001 |
| **Field** | 6 | 97.98 | 16.33 | 5.91 | <.0001 |
| **Field*Vertical Illuminance** | 21 | 124.39 | 5.92 | 2.14 | 0.0066 |

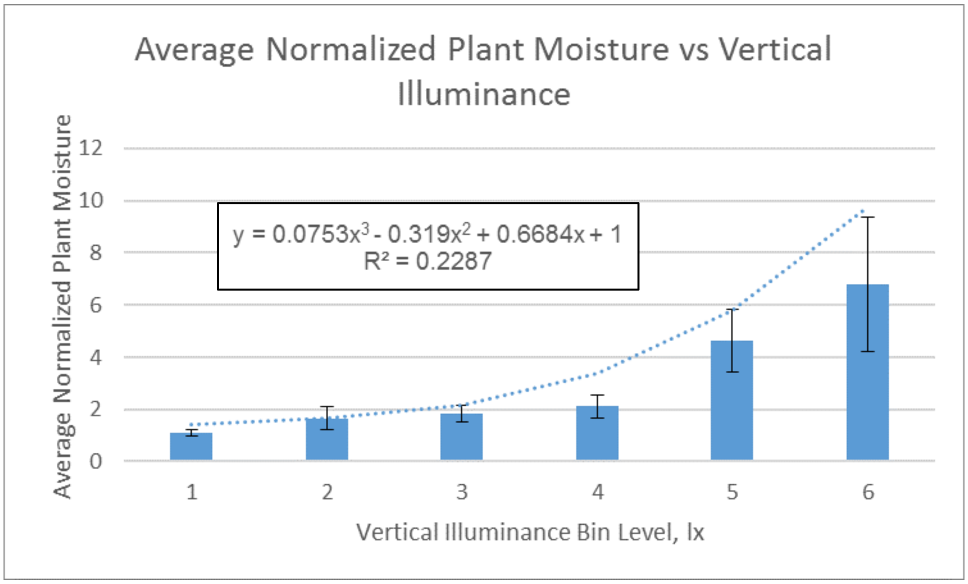



**Figure 70. Average normalized plant moisture vs. vertical illuminance.**

4.3.2.2.2 Maturity (R-Stage) at Harvest

Dry matter accumulation ceases once the soybean plant reaches R7 (physiological maturity) and the crop will eventually dry down and can be harvested. Although most leaves have fallen by the beginning of R7, the seeds still contain about 60 percent moisture, well beyond the marketable seed moisture of 13% (Pederson, 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 plants at R-Stage were analyzed with respect to the illumination levels. ANOVAs were run on the R-Stage data with respect to total illuminance, horizontal illuminance, and vertical illuminance. The model fitting results to total illuminance are shown in Table 11. As shown, the variation in R-Stage significantly correlates statistically with total illuminance, field, and the interaction of those two main effects, which is probably a reflection of variety, planting date, and environmental differences.

**Table 11. GLM Fit Results for R-Stage vs. Total illuminance**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Total illuminance** | 10 | 9.88 | 0.99 | 4.65 | <.0001 |
| **Field** | 6 | 13.98 | 2.33 | 10.97 | <.0001 |
| **Total illuminance * Field** | 22 | 8.39 | 0.38 | 1.80 | 0.0285 |

The mean R-Stage was plotted against the binned total illuminance in Figure 71 along with a binomial model regressed to the normalized un-binned data. For the R-Stage data, the linear coefficient was not used in order to allow the slope to approach zero at zero lx. In addition, an intercept was not forced since R-Stage is quantized. This resulted in the better fit to the data than a cubic model. Similarly, R-Stage versus horizontal and vertical illuminance data were also fitted with binomials without the linear term. Again, care must be used in the interpretation of the binomial model because of the low $R^2$.

The 8, 10, and 12 lx bins had only one sample, so the standard error could not be calculated. As stated previously, an R-Stage of 7 or larger is not likely to prevent the soybean from being harvested, but soybeans still in the R7 stage when the rest of the crop is mature could delay harvest by several days. As Figure 71 shows, the average R-Stage does not drop below 7 until a total illuminance of 6 lx. The R-Stage increases above 7 for 8 and 9 lx; however, there is only one sample at 8 lx and an error of +/-0.5 in the R-Stage measurement at 9 lx. The binomial model crosses R7 at 6.9 lx total illuminance. Therefore, from a harvesting standpoint, the limit for total illuminance should be 6.9 lx.

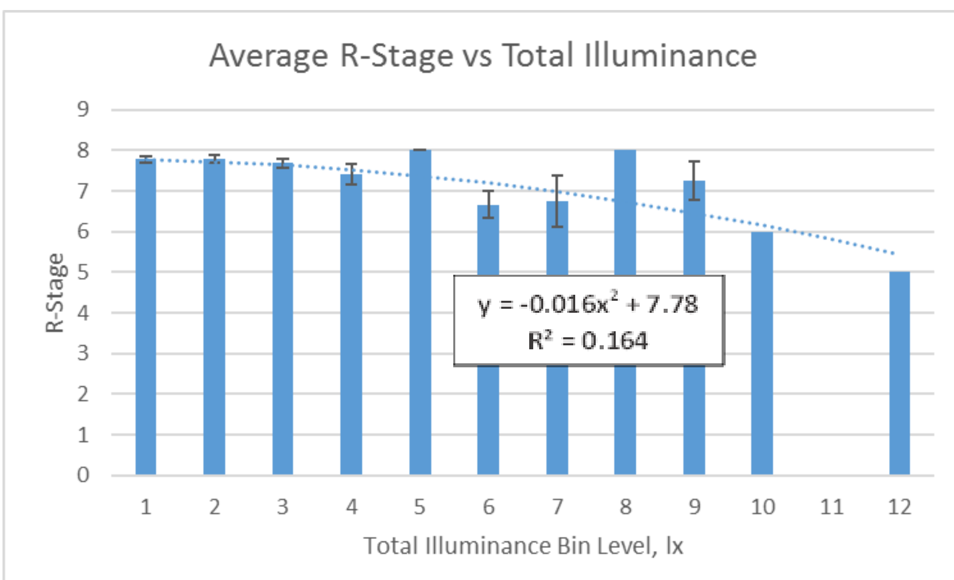



**Figure 71. Average R-Stage vs. binned average total illuminance.**

A pairwise comparison was calculated, with the results shown in Table B-6 (Appendix B), which presents significant pairwise comparisons of the R-Stage with respect to the binned total illuminance. There is no statistical difference between the 1, 2, and 3 lx averages. However, the 4, 5, and 6 lx levels are all statistically significantly different from each other and different for each of the 1, 2, and 3 lx values

The resulting fit of horizontal illuminance to R-Stage is shown in Table 12, which shows that all of the factors are significant with respect to the R-Stage.

**Table 12. GLM Fit of R-Stage to Horizontal Illuminance and Field**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Horizontal Illuminance** | 7 | 6.79 | 0.97 | 5.44 | <.0001 |
| **Field** | 6 | 21.83 | 3.64 | 20.41 | <.0001 |
| **Horizontal Magnitude*Field** | 13 | 8.82 | 0.68 | 3.81 | <.0001 |

The average R-Stage versus total illuminance is shown in Figure 72 with a binomial fit to the raw data. At 5 lx horizontal, the average R-Stage is 6.5, which will cause issues during harvest. There were no samples within the 6 lx or 9 lx bins, and only one sample in the 10 lx bin, so no errors were calculable. There were 4 samples in the 4 lx bin, but they all were R-Stage 8, so the standard error was 0.  The binomial model crosses R7 at 5.7 lx horizontal illuminance.

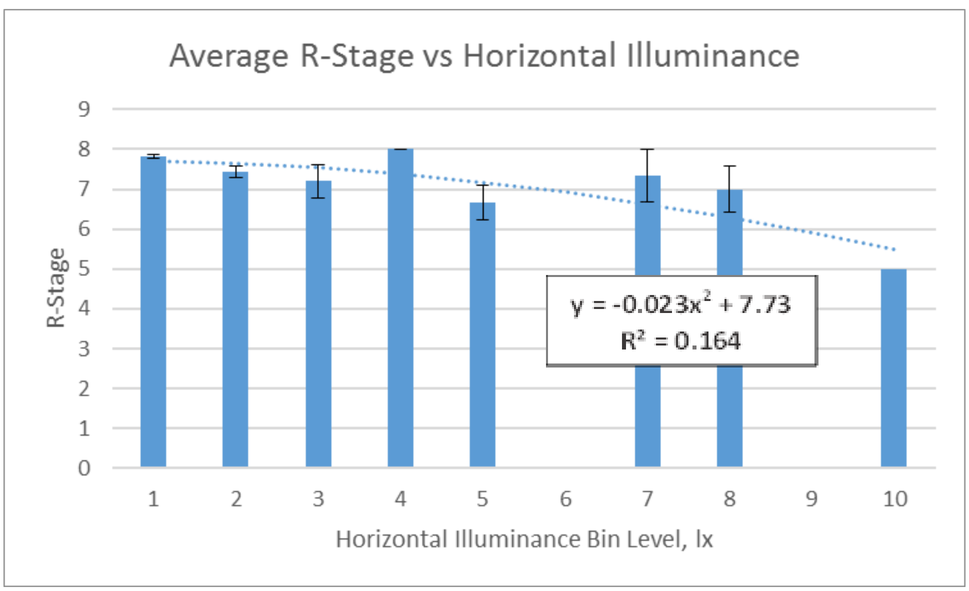



**Figure 72. Average R-Stage vs. horizontal illuminance.**

The significant pairwise comparisons of horizontal illuminance binning versus R-Stage are shown in Appendix B, Table B-7. The 5 lx bin value of R-Stage is significantly different from the 1, 2, 3, 4 and 7 lx bins. This means that between 4 and 5 lx horizontal, the R-Stage (maturity) of the plants will be such that they cannot be harvested due to leaf retention and stem moisture.

Finally, the GLM fit of the R-Stage to vertical illuminance also results in significance of the vertical illuminance and field, but not the interaction, as shown in Table 13. In the binned model, the R-Stage versus vertical illuminance (Figure 73) is 6.67 at 5 lx but the binomial model fit to the raw data crosses the R7 stage at 4.5 lx. The pairwise comparisons show that the difference between 5 lx and all other vertical illuminance below that level is significant, but the difference between 5 and 6 lx vertical illuminance is not significant (Appendix B, Table B-8).

**Table 13. GLM fit of R-stage to Vertical Illuminance and Field**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Vertical Illuminance** | 5 | 5.79 | 1.16 | 4.82 | 0.0006 |
| **Field** | 6 | 18.12 | 3.02 | 12.57 | <.0001 |
| **Field*Vertical Illuminance** | 21 | 7.47 | 0.36 | 1.48 | 0.1024 |

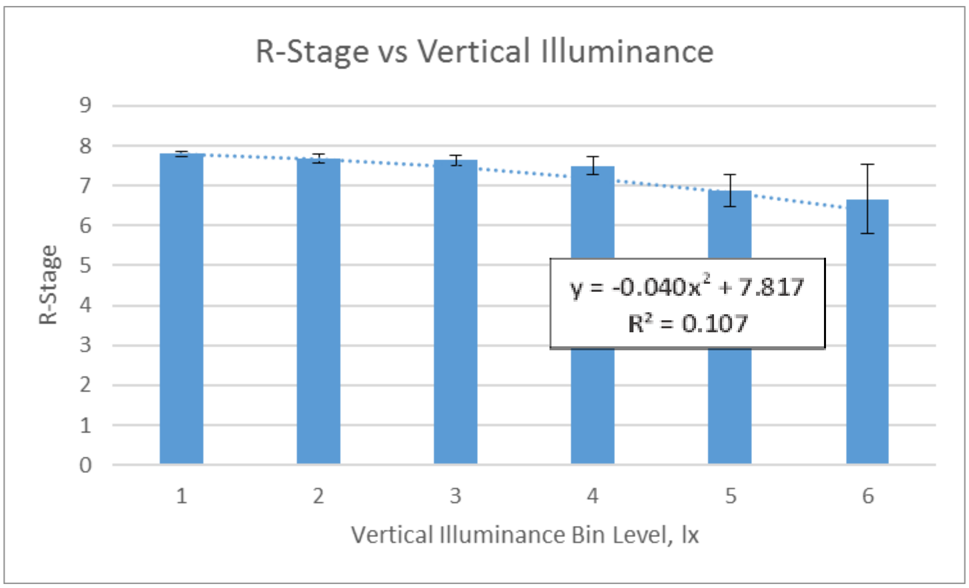



**Figure 73. Average R-Stage vs. vertical illuminance.**

<u>4.3.2.2.3 Normalized Yield at Harvest</u>

Yield was estimated by using the pod and seed weight after drying, and correcting for the seed weight sampled in each field. The results of a GLM fit with both total illuminance and field are shown Table 14. Total illuminance and field are significant with respect to yield but not the interaction of the two.

**Table 14. GLM Model Fit Results for Normalized Yield vs. Total illuminance**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Total illuminance** | 10 | 0.71 | 0.07 | 1.76 | 0.0786 |
| **Field** | 6 | 1.78 | 0.30 | 7.32 | <.0001 |
| **Total illuminance*Field** | 22 | 0.44 | 0.02 | 0.50 | 0.9684 |

Figure 74 shows the relationship between the mean normalized estimated yield versus the total illuminance as well as a cubic fit to the un-binned normalized data. Like the normalized plant moisture, the y intercept of the model was set to 1 at 0 lx. The model was again fit using a least squares regression.

The normalized yield dropped below 100% above 1 lx but remained above 88% (0.88) through 7 lx total illuminance. The mean normalized yield at 1 lx was significantly different (statistically) from 2, 3 and 4 lx, but 2, 3, and 4 lx values were not statistically significantly different from each other (Appendix B, Table B-4). There was a jump back up to 100% normalized yield at 7 lx, and the pairwise analysis shows the difference between 7 and 8 lx was significant, but there were no significant differences between the mean yields from 4 to 7 lx. The model fit shows the normalized yield fell quickly to near 90% by 2 lx total illuminance, but didn't fall below 90% yield until 6.3 lx and below 80% at 8.2 lx. Conservatively, then, a limit of 6.3 lx total illuminance should be used to limit the yield effect on the soybean.

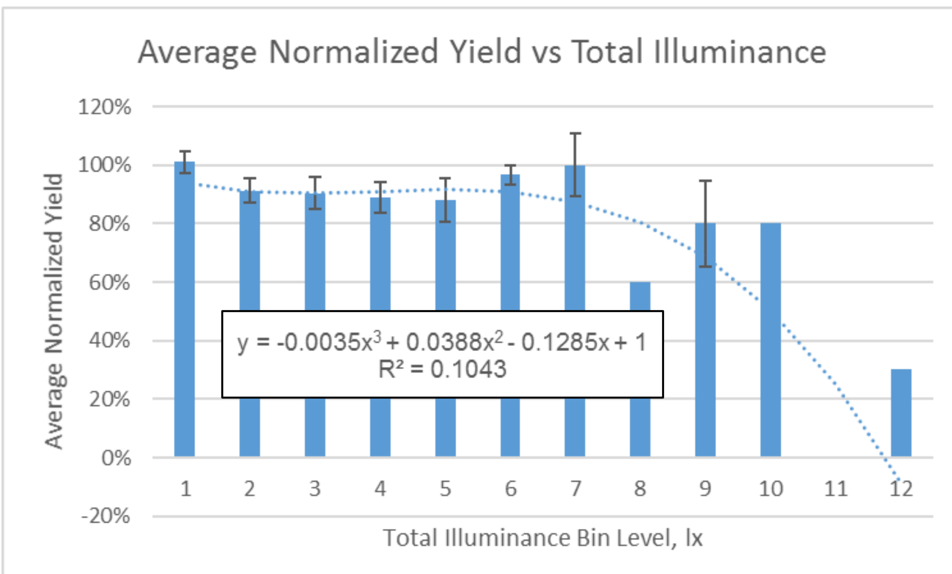



**Figure 74. Average normalized yield vs. binned total illuminance.**

The GLM fit of the normalized yield to horizontal illumination resulted in significant correlations with field and horizontal illuminance but not the interaction (Table 15).

**Table 15. GLM Model Fit Results for Normalized Yield vs. Horizontal Illuminance**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Horizontal Illuminance** | 7 | 0.72 | 0.10 | 2.82 | 0.0100 |
| **Field** | 6 | 0.92 | 0.15 | 4.21 | 0.0008 |
| **Horizontal Illuminance *Field** | 13 | 0.38 | 0.03 | 0.79 | 0.6651 |

The means of the normalized estimated yield versus horizontal illumination show a general downward trend with a horizontal illumination above 5 lx (Figure 75). A cubic model fit to the raw data shows the trend was similar to the total illuminance fit, in that there was a plateau of 87% until 6 lx, also shown in Figure 75. At 5 lx, the average normalized yield was 98%. By 7 lx, the normalized yield falls to 87%. However, the pairwise comparisons between horizontal illuminances 1 through 7 are not statistically significant (Appendix B, Table B-5), suggesting that the yield may not be affected by horizontal illuminance until it exceeds 7 lx. However, the model drops to 87% at 2.0 lx and to 80% at 7.1 lx horizontal. The discrepancy between these two values could be due to the difference in the modeling approaches, or noise in the un-binned data. A horizontal illuminance of 6.0 lx should be used to maintain a yield of at least 87%.

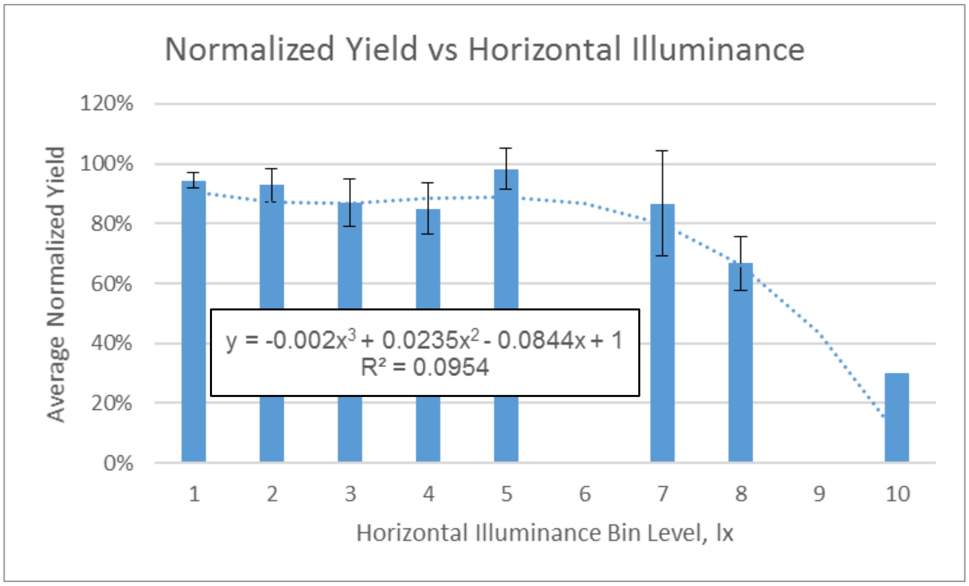



**Figure 75. Average normalized yield vs. binned horizontal illuminance.**

Analysis of the normalized yield versus field and vertical illuminance resulted in field being significant, interaction of the vertical illuminance and field being significant (Table 16), but vertical illuminance not being significant. Normalized yield versus vertical illuminance is shown in Figure 76, with a cubic model fit to the raw data. As the figure shows, the normalized yield drops from 1 at 1 lx to 0.94 at 2 lx and 0.84 at 3 lx. The model drop has a low curvature and a very low $R^2$ value, indicating very weak correlation. The model drops below 90% at 2.3 lx but does not drop below 80% until 5.5 lx. However, the statistics show that this is not statistically significant and therefore could be a result of random error in these data.

**Table 16. GLM Model Fit Results for Normalized Yield vs. Vertical Illuminance**

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| **Vertical Illuminance** | 5 | 0.26 | 0.05 | 1.48 | 0.2039 |
| **Field** | 6 | 1.42 | 0.24 | 6.67 | <.0001 |
| **Vertical Illuminance *Field** | 21 | 1.12 | 0.05 | 1.50 | 0.0952 |

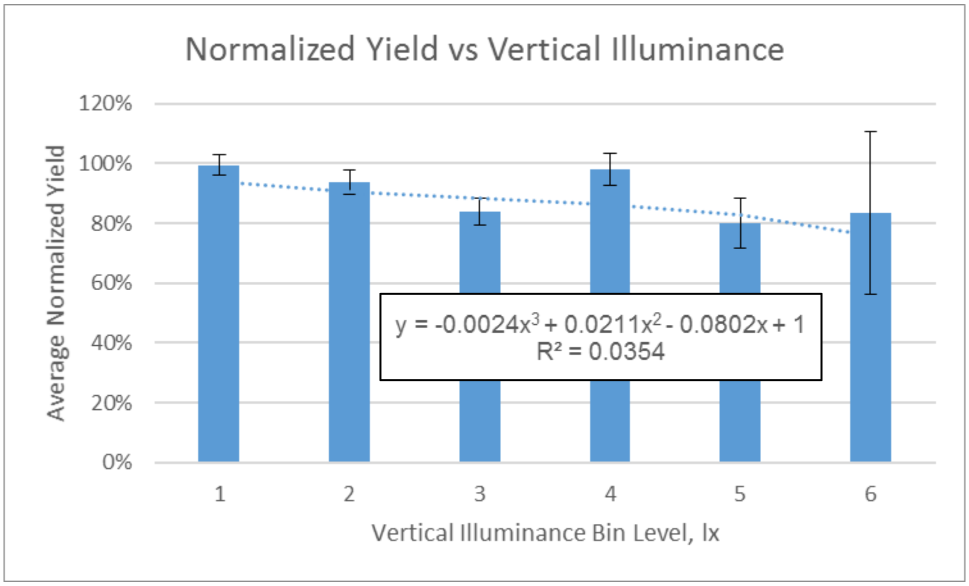



**Figure 76. Average normalized yield vs. vertical illuminance.**

### *4.3.2.4 Harvest Conclusions*

The analysis of the mean normalized plant moisture shows the plants closer to the lighting had a higher moisture content than the plants farther away, that very low lighting levels of 3.0 lx total illuminance could double the plant's moisture, and that the correlations with the lighting level were statistically significant. However, plant moisture by itself does not determine harvestability without considering the maturity and leaf drop.

Based on R-Stage, the limits for trespass illuminance are 5.7 lx horizontal and 4.5 lx vertical to enable mechanical harvesting and threshing. The total illuminance should not exceed 6.9 lx. However, the vector sum of 5.7 lx horizontal and 4.5 lx vertical is 7.3 lx, which is very close to the limit for total illuminance. Therefore, total illuminance does not need to be considered.

The average maturity of the plants harvested for this project were not below R5. 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.

Yield is limited by horizontal illuminance, which should be kept to no more than 6.0 lx to maintain a yield above 87%. To maintain a yield above 90%, the horizontal illuminance should be limited to 1.0 lx. The yield appears to also be limited by total illuminance, but this is likely just the effect of the horizontal illuminance, especially since vertical illuminance does not have a statistically significant effect on yield.

It is important to note that these results, based on the measurements taken in the field, show that the vehicle headlamp impact is minimal: the instantaneous light output from the headlamps is less than 1.0 lx vertical. There is no expectation of headlamp impact.

### 4.3.3 Impact of Field

From the ANOVA analyses of the plant characteristics at harvest, the interaction of field and illumination (horizontal, vertical, and total illuminance) was statistically significant for normalized plant moisture. With respect to normalized yield, only the interaction of field with total illuminance and field with vertical illuminance was found to be statistically significant. Therefore, the effect of lighting on the soybean plant may be related to one of the many uncontrolled factors in "Field," including variety and planting date. However, the analysis does not necessarily support that conclusion.

Figure 77 through Figure 79 show the interactions of the binned illuminances and field. Data points without error bars are single samples at that particular binning of illuminance. Starting with the interaction of total illuminance and field versus average normalized plant moisture (Figure 77), there is a general upward trend for Springfield1, Springfield2, and Peoria. However, the error bars are very large, or non-existent, because of too few samples at the higher illuminance values. Therefore, there is not a clear interaction between field and total illuminance.

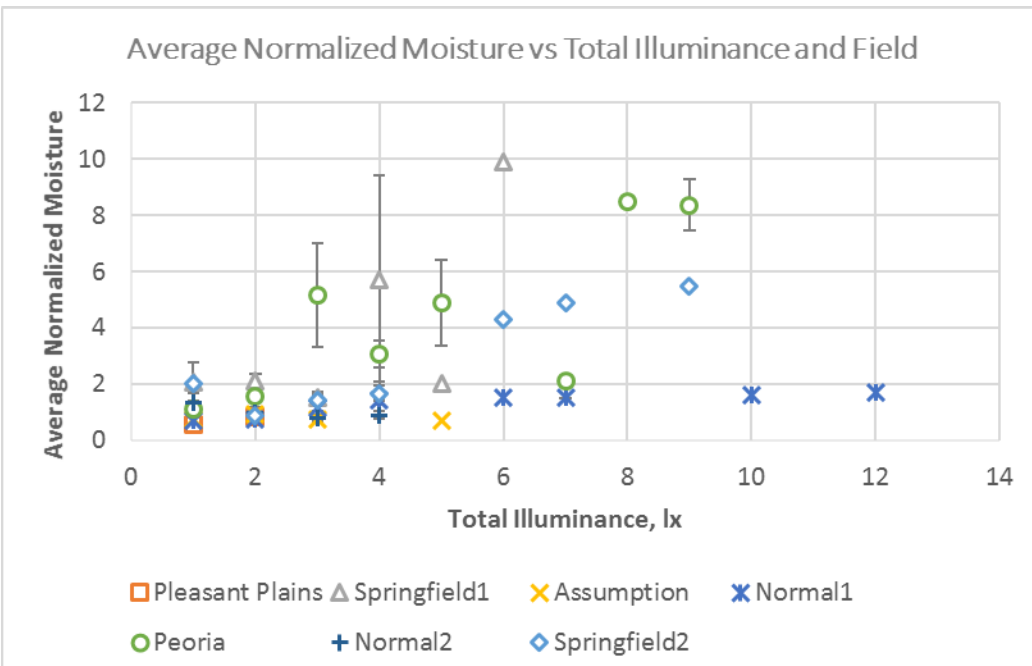



**Figure 77. Mean normalized plant moisture vs. total illuminance and field.**

Likewise, the plots of the mean normalized plant moisture versus the interaction of field with horizontal illuminance (Figure 78) and vertical illuminance (Figure 79) do not show a clear interaction resulting from error and scatter.

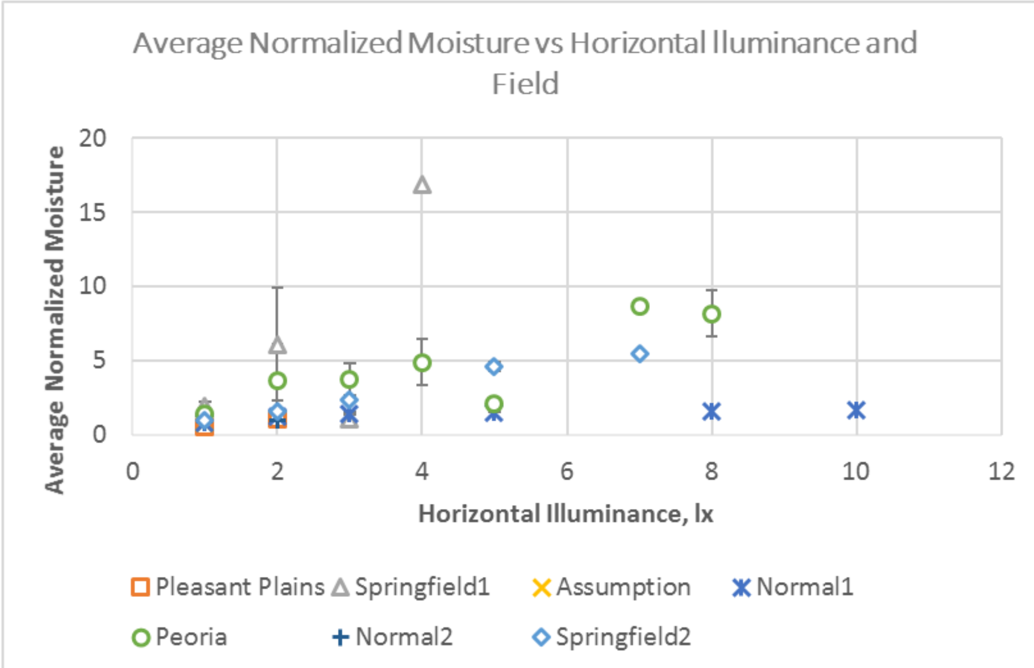



**Figure 78. Mean normalized plant moisture vs. horizontal illuminance and field.**

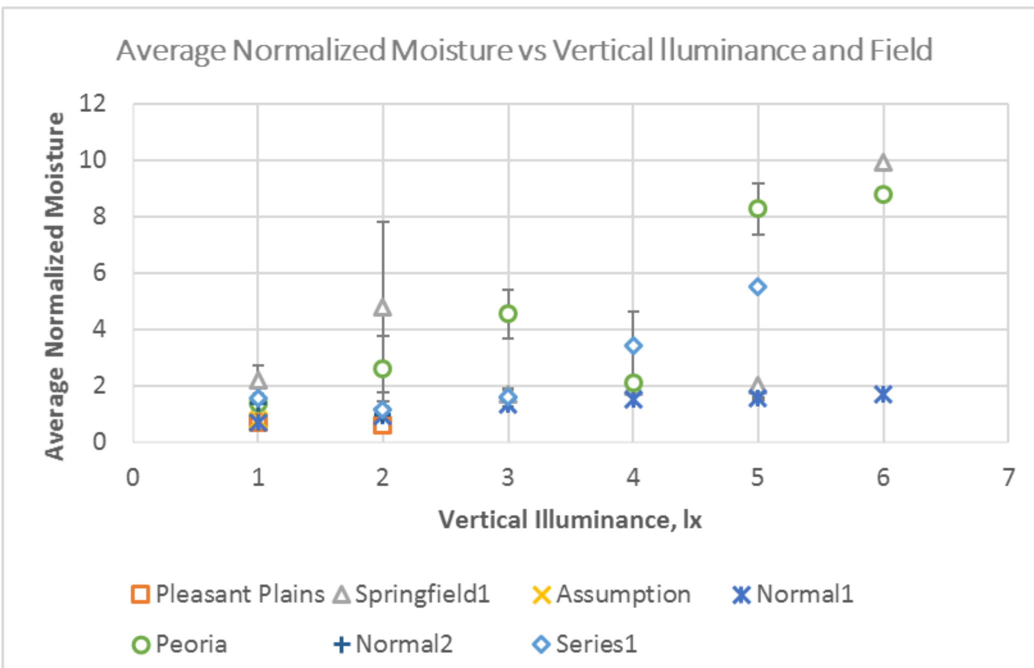



**Figure 79. Mean normalized plant moisture vs. vertical illuminance and field.**

For R-Stage, significance was found for the interactions of total illuminance and horizontal illuminance with field, but not for vertical illuminance. Since total illuminance is the vector sum of horizontal and vertical illuminance, only the interaction of horizontal illuminance was analyzed (Figure 80). As can be seen, there is a downward trend in most of the fields with respect to increasing horizontal illuminance, but each field is unique.

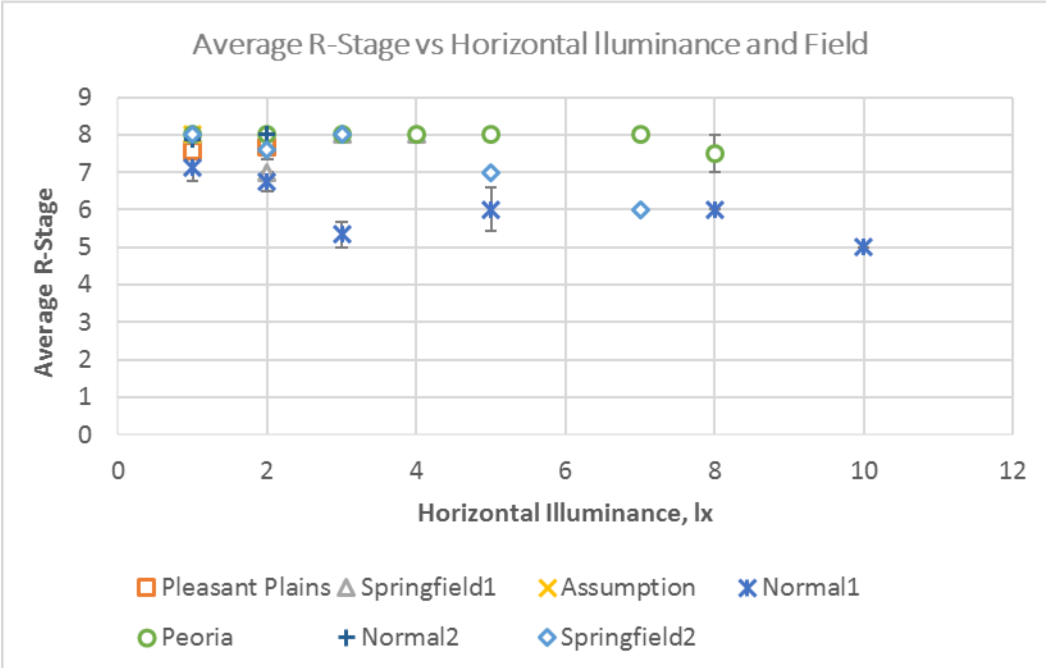



**Figure 80. R-Stage vs. the interaction of field and horizontal illuminance.**

For normalized yield versus the interactions of field with vertical illuminance (Figure 81), which was found significant by ANOVA, there again is too much error and scatter to define a clear interaction. Therefore, the significance of this interaction is likely an anomaly in the sample data.

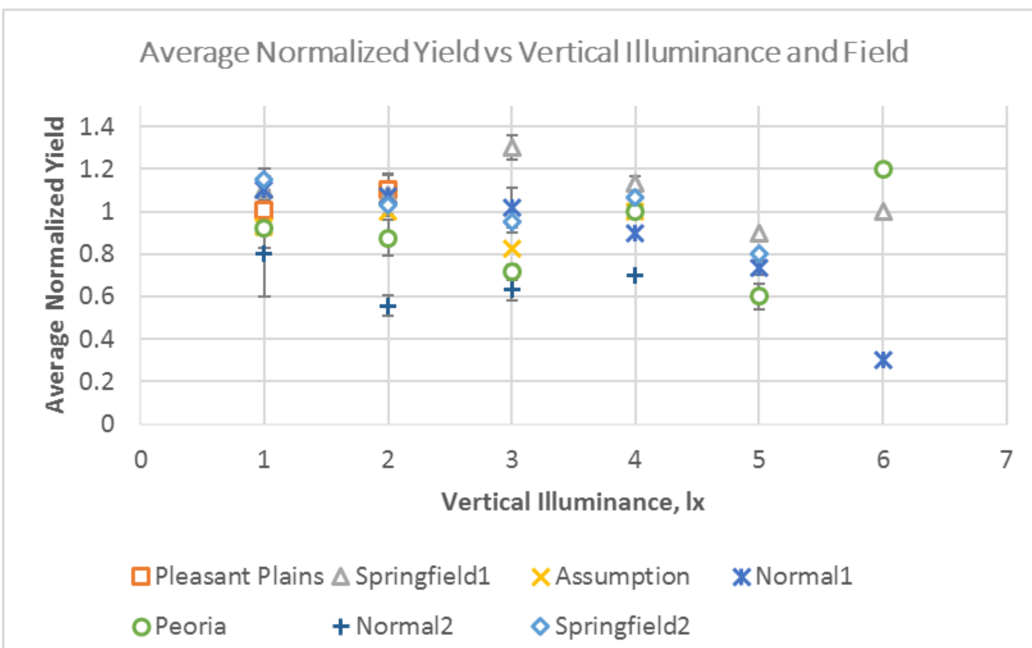



**Figure 81. Mean normalized yield vs. vertical illuminance and field.**

#### *4.3.3.1 Field Conclusion*

The variance (and thus error) is large in the analysis of field-specific lighting effects because there were many uncontrolled factors. This is in spite of normalization of each field's data. There is no clear evidence that there is a difference in lighting response between different fields.

# 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.

## 5.1 YIELD

Soybean maturation delays affect the farmer because green plants, which are full of moisture, will jam a combine, requiring the farmer to stop and remove the jam by hand. Plant moisture is not necessarily representative of seed maturity. Seed must be physiologically mature before they can be marketed. However, once plants reach the R7 stage (physiologically mature; high plant moisture; few green leaves; no green pods or seed), mechanical harvesting can eventually be completed but could be delayed by 2 or more weeks. Plants not reaching the R8 stage by the time the rest of the field is harvested will not likely be harvested at that time. The decision to come back to the field and harvest will depend on the farmer's time and logistics. The ideal seed moisture is 13%, but as much as 16% moisture can cause harvesting issues. Excess seed moisture content also lowers the value per bushel due to drying costs either assumed by the farmer or assessed by the buyer upon delivery. Therefore, R-Stage and moisture content can affect the money a farmer can make from the field.

Soybean yield was estimated from the dried pod and seed weight. Together, the moisture and the bean yield allowed determination of the impact that lighting has on the total bean harvest.

From a plant moisture standpoint, it appears that the limits for trespass illuminance are 2.0 lx horizontal and 3.0 lx vertical. However, because a soybean plant uses all of the light that reaches it, whether vertical or horizontal illuminance, the total illuminance sets a limit of the combination of the two. The total illuminance, which is calculated as the square root of the sum of the square, should not exceed 3.0 lx. It is noteworthy that no headlamps reached these limits and, as such, vehicle headlamps do not impact plant growth. These values do not guarantee that the seeds will be at an ideal moisture content, but they will at least enable the farmer to mechanically harvest and thresh the beans.

However, the result of the analysis of R-Stage versus illuminance suggests that estimate of lighting requirements based on plant moisture may be overly conservative. Since plants reaching R7 can eventually be harvested, significantly more illuminance may be permissible. For horizontal illuminance of up to 5.7 lx and vertical illuminance of up to 4.5 lx, plants were able to obtain the R7 stage. The total illuminance limit of the plant was found to be very similar to the vector combination of these values, and therefore it does not need to be considered. In addition, the average maturity of the plants harvested for this project were not below R5. This shows that the plants all did flower eventually, suggesting that the photoperiodicity of the soybean is related to both the night length and the total illuminance during the night.

Bean yield per plant was also affected by horizontal illuminance but was not related to vertical illuminance, and therefore the significance of the relation of yield to total illuminance was due to the horizontal component. The bean yield decreased slightly with increasing light levels. To keep the yield above 87%, the horizontal illuminance of trespass light should be kept below 6.0 lx. Since this is larger than the harvesting limit, the harvesting limit of 5.7 lx horizontal illuminance should keep the yield in the range of 87-88%.

It is important to note that the yield reduction and harvestability are not ubiquitous across the field; it is only in the areas where the lighting is present at high enough levels. Using the illuminance limit values, the average area affected was calculated for each site. Polygons were used to approximate the affected areas (triangles or rectangles or both) in GIS software. The areas were scaled by the length of road parallel to the side of the affected roadway to get an estimate of the area within each field that would be delayed in development to less than R-Stage 7. Figure 82 shows an example (Normal1 site) of the approximation of the areas affected and the scaling length, based on horizontal illuminance. In this plot, the blue and green data points are at or above R-Stage 7. The area approximation is shown as a white triangle, and the scaling length is shown in pink. Area approximation was performed by hand and was estimated using horizontal, vertical, and magnitude. For this field, horizontal illuminance affected the largest area.

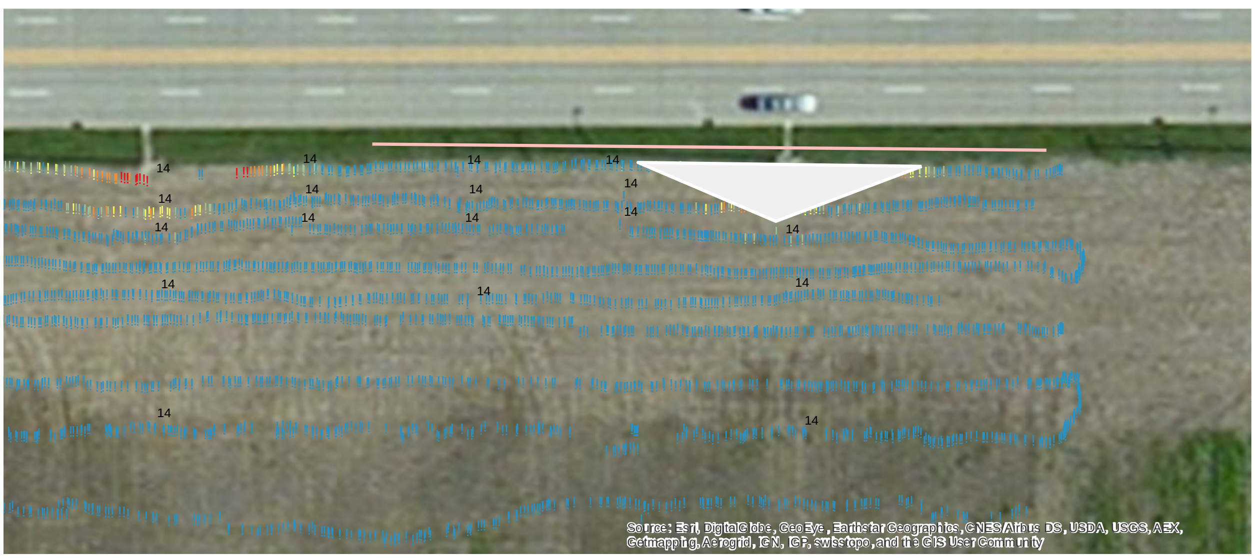



**Figure 82. Illustration of approximation of affected area based on horizontal illuminance. Horizontal illuminance 5 lx or less is green and blue. The area approximation is shown as a white triangle, and the scaling length is shown in pink.**

Table 17 shows the areas estimated for each field per unit length of roadway where the lighting is above the limits calculated from the analysis. These areas would have too much moisture to harvest compared with the rest of the field. The remainder of the field would not be delayed enough to prevent harvest.

**Table 17. Areas Affected by Lighting for Each Site Included in the Study, and Averages**

| Site | Base, ft | Base 2, ft | Width, ft | Length of Affected Area Parallel to Roadway | Affected Area, $ft^2$ | Affected Area per ft Roadway, $ft^2/ft$ | Shape Approximation |
|---|---|---|---|---|---|---|---|
| Pleasant Plains | 0 | | 0 | 160 | 0 | 0.00 | No effect |
| Springfield1 | 26 | 14.00 | 3 | 220 | 1092 | 4.96 | multiple rectangles |
| Assumption | 0 | | 0 | 158 | 0 | 0.00 | No effect |
| Normal1 | 78 | | 21 | 180 | 819 | 4.55 | triangle |
| Peoria | 65 | 75.00 | 23 | 204 | 1610 | 7.89 | trapezoid |
| Normal2 | 55 | 17.00 | 1 | 777 | 935 | 1.20 | rectangle |
| Springfield2 | 68 | | 17 | 300 | 578 | 1.93 | triangle |
| Average | | | | | | 2.93 | |

## 5.2 MATURATION DELAY

There is little if any correlation between maturity (R-stage) of the plants and the illuminance levels at sites where the horizontal illuminance was less than 2.0 lx. From the periodic measurements, that delay is approximately 2–3 weeks at horizontal illuminance of 5 lx and up. However, plants exposed to no more than 8.0 lx horizontal illumination can mature if left in the field, as observed at the Peoria site. Above 8.0 lx horizontal illumination, it is not clear whether plants will mature or not, based on the R-stage data, and harvestability will depend on frost/freeze date.

The periodic data also showed a general increase in the normalized height with increased illumination with no apparent difference between horizontal or vertical illuminance. The impact of trespass lighting on NDVI, and thus plant health, seems to be limited or non-existent based on the periodic data.

## 5.3 IMPACT ON VARIETIES

From the ANOVA analyses of plant characteristics at harvest, the interaction of field and illumination (horizontal, vertical, and magnitude) was statistically significant for normalized plant moisture. With respect to normalized yield, only the interaction of field with total illuminance and field with vertical illuminance were found to be statistically significant. Therefore, the effect of lighting on the soybean plant may be related to one of the many uncontrolled factors in “Field,” including variety. However, the analysis does not support that conclusion due to large variances and errors that overlap for most of the lighting values in spite of normalization of each field’s data. There is no clear evidence of a difference in lighting response between different varieties.

Further study may be warranted with a more controlled experiment. A study to address the varietal question is envisioned to include more samples in fewer fields with very similar lighting characteristics. This would increase the power and reduce the error in the data. Another approach would be to request that a farmer plant two different varietals in the same field, though this might be challenging to accomplish.

## 5.4 SOLUTIONS FOR REDUCING IMPACT

There are three impacts of HPS (high-pressure sodium) roadway lighting trespass on soybean growth: yield, maturity delays, and height. Height does not seem to benefit the yield or maturation of the plants, so there is no need to address the height impact. Therefore, the impact reduction will focus on retaining yield and mitigating impacts on maturity.

Moving forward, a specification that limits light trespass into a soybean field needs to be considered, and a draft specification is included in this report. However, additional approaches can be considered.

An educational outreach campaign could be used to inform farmers that soybean plants near lights reach maturity two 2 to 3 weeks after initial field harvest if left in the field, and if freezing temperatures do not kill the plants prematurely. However, this approach does not mitigate the costs farmers would incur in reharvesting.

Another potential solution to reducing the impact of roadway trespass lighting would be to install or maintain lighting intelligently. Roadway lighting standards, such as IES RP-8, continue to be improved and should be used to determine whether the roadway lighting is needed at all for the particular areas where soybean farms are in close proximity to the road. This applies for both existing and future lighting projects. New guidance allows for adaptive lighting to be used based on traffic volume and other factors (IES ANSI RP-8, 2014). While HPS lights are not typically dimmable, they can be turned off at midnight, for example, allowing the soybean plants to have at least 5 or 6 hours of much lower lighting levels. There are wireless control systems that can control HPS lights. Deductively, the soybean photoperiodicity is related to both the night length and the illuminance of the plant during that night. However, the relationship between photoperiodicity, illuminance levels, and illuminance time was not determined by this study. Therefore, this might not be the best approach unless the trespass lighting levels are near the upper limits. In those cases, shortening the time the HPS lights are on should reduce the delay in maturation.

Another avenue that seemed to work well at the Pleasant Plains site is to use house side shields on the existing HPS lighting. As seen in the data, the house side shields kept the average horizontal and vertical illuminance well below 1.0 lx while maintaining 19 lx average horizontal roadway lighting. However, that was only true on the house side of the luminaires. The field across from the luminaire was not characterized. That said, house side shields would be ineffective at limiting light trespass across a two-lane rural road due to their design.

Finally, LED roadway lighting has become a cost-effective replacement for HPS luminaires that have reached the end of their lifespan. The capital cost can also often be justified by the offset of nearly half of the utility costs when municipalities are paying for energy use. In addition, LED luminaires have better distribution than HPS lighting and can often be ordered with nearly zero light trespass. LED lights can also be dimmed, enabling significantly more options for adapting light to maintain safety by providing more light when needed, but reducing light when traffic volume is low to diminish the impact on the soybean.

Another potential benefit of LED luminaires is the spectrum of the lighting. As described in the literature search, the impact of lighting on soybean growth is not the same across all wavelengths. Due to the limited selection of soybean fields, the researchers for this project were unable to study the spectral dependency of the lighting effect, so that should be included in future work.

## 5.5 DRAFT SPECIFICATIONS

Trespass light from the roadway luminaire into soybean fields should be limited to the values listed in Table 18. These values are based on the limits found from the analysis of the R-Stage data and from the yield data. These values will ensure that the plants are eventually harvestable and that the yield will be at least 87–88% of the norm for the field.

**Table 18. Illuminance Specifications to Minimize Soybean Impact**

| Illuminance | Maximum, lx |
|---|---|
| **Horizontal** | 5.7 |
| **Vertical** | 4.5 |

# CHAPTER 6: CONCLUSIONS

The study found three main effects of lighting on soybean plants: maturation delays, yield reduction, and height increase. Based on the data collected, it was determined that the soybean can be delayed anywhere from 2 to 7 weeks when exposed to light trespass from typical high-pressure sodium (HPS) lighting used on Illinois roadways.

From a harvesting standpoint, the limits for trespass illuminance are 5.7 lx horizontal and 4.5 lx vertical to enable mechanical harvesting and threshing. Yield is also limited by horizontal illuminance, which should be kept to no more than 5.7 lx to maintain yield greater than 87%.

The vehicle headlamp impact was not significant because no headlamp measurement of light trespass reached the 4.5 lx vertical limit. Also, since ambient lighting, including skyglow, was less than 0.2 lx, it was not significant compared to the other lighting levels.

Height and stage of plant maturity were both affected by trespass illuminance during the growing period. The limit for the effect seemed to be a minimum of 3.3 lx for vertical, horizontal, and/or total illuminances to prevent delay in the maturation of the plants during the growing season. However, plants will eventually mature as long as the horizontal illuminance does not exceed 8.0 lx. No statistically significant interaction was found between the lighting and the sampling timing during the periodic growth measurements.

From the ANOVA analyses of the plant characteristics at harvest, the interaction of field and illumination (horizontal, vertical, and magnitude) was statistically significant for normalized plant moisture. However, the analysis of the means of the plant characteristics versus field and illuminance had errors that overlapped for most of the lighting values in spite of normalization of each field’s data. There is no clear evidence that there is a difference in lighting response between different varietals.

Further study to address the variety question and spectral question is still needed. As roadway lighting transitions to LED, the effects found in this study will need to be adjusted to account for the different spectral content. In addition, a more specific study of varieties designed to increase statistical power and reduce variance may be needed to conclude that there is no interaction between lighting and variety.

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# APPENDIX A: FULL ROADWAY LIGHTING MEASUREMENTS

**Table A-1. Roadway Lighting Measurements for Pleasant Plains**

| Pleasant Plains | Near Lane | Center Lane | Far Lane |
|---|---|---|---|
| Horizontal Illuminance, avg. | 6.18 | 6.77 | 5.52 |
| Minimum | 0.01 | 0.10 | 0.20 |
| Maximum | 19.35 | 18.03 | 14.88 |
| Uniformity | 617.71 | 67.73 | 27.58 |
| Vert., in the direction of travel, avg. | 0.07 | 0.41 | 0.51 |
| Minimum | 0.00 | 0.00 | 0.04 |
| Maximum | 0.47 | 0.99 | 1.25 |

**Table A-2. Roadway Lighting Measurements for SpringField1**

| Springfield1 | Near Lane | Far Lane |
|---|---|---|
| Horizontal Illuminance, avg. | 3.93 | 2.81 |
| Minimum | 0.10 | 0.27 |
| Maximum | 9.91 | 6.26 |
| Uniformity | 3927% | 1042% |
| Vert., in the direction of travel, avg. | 0.36 | 0.72 |
| Minimum | 0.00 | 0.00 |
| Maximum | 1.02 | 2.24 |

**Table A-3. Roadway Lighting Measurements for Assumption**

| Assumption | Near Lane |
|---|---|
| Horizontal Illuminance, avg. | 3.54 |
| Minimum | 0.01 |
| Maximum | 30.17 |
| Uniformity | 353.89 |
| Vert., in the direction of travel, avg. | 1.89 |
| Minimum | 0.00 |
| Maximum | 7.24 |

**Table A-4. Roadway Lighting Measurements for Normal1**

| Normal1 | Near Lane | Center Lane | Center Lane | Far Lane |
|---|---|---|---|---|
| Horizontal Illuminance, avg. | 16.74 | 18.13 | 10.16 | 5.97 |
| Minimum | 0.43 | 1.09 | 0.43 | 0.76 |
| Maximum | 47.68 | 45.67 | 23.23 | 11.72 |
| Uniformity | 38.94 | 16.64 | 23.62 | 7.85 |
| Vert., in the direction of travel, avg. | 1.46 | 1.65 | 1.17 | 1.02 |
| Minimum | 0.66 | 0.83 | 0.53 | 0.17 |
| Maximum | 2.51 | 2.70 | 2.21 | 2.31 |

**Table A-5. Roadway Lighting Measurements for Peoria**

| Peoria | Near Lane | Center Lane | Center Lane | Far Lane |
|---|---|---|---|---|
| Horizontal Illuminance, avg. | 19.01 | 15.37 | 11.22 | 18.54 |
| Minimum | 2.77 | 4.94 | 4.02 | 2.44 |
| Maximum | 52.58 | 35.11 | 26.85 | 44.49 |
| Uniformity | 6.86 | 3.11 | 2.79 | 7.60 |
| Vert., in the direction of travel, avg. | 1.62 | 1.74 | 1.51 | 1.40 |
| Minimum | 0.63 | 0.89 | 0.50 | 0.43 |
| Maximum | 3.29 | 3.03 | 2.80 | 3.03 |

**Table A-6. Roadway Lighting Measurements for Normal2**

| Normal2 | Shoulder and Right Turn Lane | Center and Left Turn Lane |
|---|---|---|
| Horizontal Illuminance, avg. | 7.23 | 7.91 |
| Minimum | 0.10 | 0.07 |
| Maximum | 24.09 | 24.29 |
| Uniformity | 72.29 | 113.04 |
| Vert., in the direction of travel, avg. | 0.96 | 1.06 |
| Minimum | 0.14 | 0.14 |
| Maximum | 1.72 | 1.78 |

**Table A-7. Roadway Lighting Measurements for SpringField2**

| Springfield2 | Near Lane | Far Lane |
|---|---|---|
| Horizontal Illuminance, avg. | 14.64 | 11.51 |
| Minimum | 0.63 | 0.20 |
| Maximum | 84.17 | 49.45 |
| Uniformity | 23.24 | 57.53 |
| Vert., in the direction of travel, avg. | 1.23 | 0.97 |
| Minimum | 0.00 | 0.04 |
| Maximum | 3.89 | 2.34 |

# APPENDIX B: PAIRWISE COMPARISON TABLES

## Table B-1. Pairwise Comparisons of Normalized Moisture vs. Total illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Total illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| **01–02** | –0.1183 | –0.7695 | 0.5329 | |
| **01–03** | –0.51 | –1.183 | 0.1629 | |
| **01–04** | –1.6796 | –2.4673 | –0.8919 | *** |
| **01–05** | –2.4831 | –3.7453 | –1.2209 | *** |
| **01–06** | –4.2365 | –5.8213 | –2.6516 | *** |
| **01–07** | –1.5031 | –2.8951 | –0.1112 | *** |
| **01–08** | –7.5031 | –10.169 | –4.8377 | *** |
| **01–09** | –6.6531 | –8.0451 | –5.2612 | *** |
| **01–10** | –0.6031 | –3.2685 | 2.0623 | |
| **01–12** | –0.7031 | –3.3685 | 1.9623 | |
| **02–03** | –0.3917 | –1.0598 | 0.2763 | |
| **02–04** | –1.5613 | –2.3449 | –0.7777 | *** |
| **02–05** | –2.3648 | –3.6244 | –1.1052 | *** |
| **02–06** | –4.1182 | –5.7009 | –2.5354 | *** |
| **02–07** | –1.3848 | –2.7745 | 0.0048 | |
| **02–08** | –7.3848 | –10.049 | –4.7207 | *** |
| **02–09** | –6.5348 | –7.9245 | –5.1452 | *** |
| **02–10** | –0.4848 | –3.149 | 2.1793 | |
| **02–12** | –0.5848 | –3.249 | 2.0793 | |
| **03–04** | –1.1696 | –1.9713 | –0.3678 | *** |
| **03–05** | –1.9731 | –3.2441 | –0.7021 | *** |
| **03–06** | –3.7264 | –5.3183 | –2.1346 | *** |
| **03–07** | –0.9931 | –2.393 | 0.4068 | |
| **03–08** | –6.9931 | –9.6627 | –4.3235 | *** |
| **03–09** | –6.1431 | –7.543 | –4.7432 | *** |
| **03–10** | –0.0931 | –2.7627 | 2.5765 | |
| **03–12** | –0.1931 | –2.8627 | 2.4765 | |
| **04–05** | –0.8035 | –2.1388 | 0.5318 | |
| **04–06** | –2.5569 | –4.2005 | –0.9132 | *** |
| **04–07** | 0.1765 | –1.2821 | 1.6351 | |
| **04–08** | –5.8235 | –8.5243 | –3.1227 | *** |
| **04–09** | –4.9735 | –6.4321 | –3.5149 | *** |
| **04–10** | 1.0765 | –1.6243 | 3.7773 | |
| **04–12** | 0.9765 | –1.7243 | 3.6773 | |
| **05–06** | –1.7533 | –3.6702 | 0.1635 | |
| **05–07** | 0.98 | –0.7807 | 2.7407 | |
| **05–08** | –5.02 | –7.8952 | –2.1448 | *** |
| **05–09** | –4.17 | –5.9307 | –2.4093 | *** |
| **05–10** | 1.88 | –0.9952 | 4.7552 | |
| **05–12** | 1.78 | –1.0952 | 4.6552 | |
| **06–07** | 2.7333 | 0.7287 | 4.738 | *** |
| **06–08** | –3.2667 | –6.2974 | –0.2359 | *** |
| **06–09** | –2.4167 | –4.4213 | –0.412 | *** |
| **06–10** | 3.6333 | 0.6026 | 6.6641 | *** |
| **06–12** | 3.5333 | 0.5026 | 6.5641 | *** |
| **07–08** | –6 | –8.9345 | –3.0655 | *** |
| **07–09** | –5.15 | –7.006 | –3.294 | *** |
| **07–10** | 0.9 | –2.0345 | 3.8345 | |
| **07–12** | 0.8 | –2.1345 | 3.7345 | |
| **08–09** | 0.85 | –2.0845 | 3.7845 | |
| **08–10** | 6.9 | 3.1881 | 10.6119 | *** |
| **08–12** | 6.8 | 3.0881 | 10.5119 | *** |
| **09–10** | 6.05 | 3.1155 | 8.9845 | *** |
| **09–12** | 5.95 | 3.0155 | 8.8845 | *** |
| **10–12** | –0.1 | –3.8119 | 3.6119 | |

The triple asterisks indicate significant differences in the mean values.

## Table B-2. Pairwise Comparisons of Normalized Moisture vs. Horizontal Illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Horizontal Illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| **01–02** | −1.028 | −1.459 | −0.5971 | *** |
| **01–03** | −1.5847 | −2.14 | −1.0295 | *** |
| **01–04** | −6.8447 | −7.6944 | −5.995 | *** |
| **01–05** | −1.578 | −2.2796 | −0.8765 | *** |
| **01–07** | −6.5447 | −7.5204 | −5.569 | *** |
| **01–08** | −4.9114 | −5.887 | −3.9357 | *** |
| **01–10** | −0.6447 | −2.3153 | 1.0259 | |
| **02–03** | −0.5567 | −1.2117 | 0.0984 | |
| **02–04** | −5.8167 | −6.7347 | −4.8986 | *** |
| **02–05** | −0.55 | −1.3329 | 0.2329 | |
| **02–07** | −5.5167 | −6.5524 | −4.4809 | *** |
| **02–08** | −3.8833 | −4.9191 | −2.8476 | *** |
| **02–10** | 0.3833 | −1.323 | 2.0897 | |
| **03–04** | −5.26 | −6.2426 | −4.2774 | *** |
| **03–05** | 0.0067 | −0.851 | 0.8643 | |
| **03–07** | −4.96 | −6.0533 | −3.8667 | *** |
| **03–08** | −3.3267 | −4.42 | −2.2334 | *** |
| **03–10** | 0.94 | −0.8019 | 2.6819 | |
| **04–05** | 5.2667 | 4.1946 | 6.3387 | *** |
| **04–07** | 0.3 | −0.9685 | 1.5685 | |
| **04–08** | 1.9333 | 0.6648 | 3.2018 | *** |
| **04–10** | 6.2 | 4.3431 | 8.0569 | *** |
| **05–07** | −4.9667 | −6.1411 | −3.7923 | *** |
| **05–08** | −3.3333 | −4.5077 | −2.1589 | *** |
| **05–10** | 0.9333 | −0.8606 | 2.7273 | |
| **07–08** | 1.6333 | 0.2772 | 2.9894 | *** |
| **07–10** | 5.9 | 3.9822 | 7.8178 | *** |
| **08–10** | 4.2667 | 2.3489 | 6.1845 | *** |

The triple asterisks indicate significant differences in the mean values.

## Table B-3. Pairwise Comparisons of Normalized Moisture vs. Vertical Illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Vertical Illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| **01–02** | –0.5643 | –1.1981 | 0.0694 | |
| **01–03** | –0.7648 | –1.418 | –0.1116 | *** |
| **01–04** | –1.0303 | –2.0091 | –0.0514 | *** |
| **01–05** | –3.5228 | –4.5946 | –2.451 | *** |
| **01–06** | –5.7103 | –7.3648 | –4.0557 | *** |
| **02–03** | –0.2005 | –0.8617 | 0.4607 | |
| **02–04** | –0.4659 | –1.4502 | 0.5183 | |
| **02–05** | –2.9584 | –4.0352 | –1.8817 | *** |
| **02–06** | –5.1459 | –6.8037 | –3.4882 | *** |
| **03–04** | –0.2655 | –1.2623 | 0.7314 | |
| **03–05** | –2.758 | –3.8462 | –1.6697 | *** |
| **03–06** | –4.9455 | –6.6107 | –3.2802 | *** |
| **04–05** | –2.4925 | –3.8024 | –1.1826 | *** |
| **04–06** | –4.68 | –6.4978 | –2.8622 | *** |
| **05–06** | –2.1875 | –4.057 | –0.318 | *** |

The triple asterisks indicate significant differences in the mean values.

## Table B-4. Pairwise Comparisons of Normalized Yield vs. Total illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Total illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| 01-02 | 0.09725 | 0.01426 | 0.18024 | *** |
| 01-03 | 0.10593 | 0.02017 | 0.19169 | *** |
| 01-04 | 0.12114 | 0.02075 | 0.22153 | *** |
| 01-05 | 0.12937 | -0.03148 | 0.29023 | |
| 01-06 | 0.04271 | -0.15927 | 0.24468 | |
| 01-07 | 0.00937 | -0.16802 | 0.18677 | |
| 01-08 | 0.40938 | 0.06969 | 0.74906 | *** |
| 01-09 | 0.20937 | 0.03198 | 0.38677 | *** |
| 01-10 | 0.20937 | -0.13031 | 0.54906 | |
| 01-12 | 0.70938 | 0.36969 | 1.04906 | *** |
| 02-03 | 0.00867 | -0.07647 | 0.09381 | |
| 02-04 | 0.02389 | -0.07598 | 0.12375 | |
| 02-05 | 0.03212 | -0.12841 | 0.19265 | |
| 02-06 | -0.05455 | -0.25626 | 0.14717 | |
| 02-07 | -0.08788 | -0.26498 | 0.08922 | |
| 02-08 | 0.31212 | -0.02741 | 0.65165 | |
| 02-09 | 0.11212 | -0.06498 | 0.28922 | |
| 02-10 | 0.11212 | -0.22741 | 0.45165 | |
| 02-12 | 0.61212 | 0.27259 | 0.95165 | *** |
| 03-04 | 0.01521 | -0.08696 | 0.11739 | |
| 03-05 | 0.02345 | -0.13853 | 0.18542 | |
| 03-06 | -0.06322 | -0.26609 | 0.13965 | |
| 03-07 | -0.09655 | -0.27496 | 0.08186 | |
| 03-08 | 0.30345 | -0.03677 | 0.64367 | |
| 03-09 | 0.10345 | -0.07496 | 0.28186 | |
| 03-10 | 0.10345 | -0.23677 | 0.44367 | |
| 03-12 | 0.60345 | 0.26323 | 0.94367 | *** |
| 04-05 | 0.00824 | -0.16194 | 0.17841 | |
| 04-06 | -0.07843 | -0.2879 | 0.13104 | |
| 04-07 | -0.11176 | -0.29765 | 0.07412 | |
| 04-08 | 0.28824 | -0.05596 | 0.63243 | |
| 04-09 | 0.08824 | -0.09765 | 0.27412 | |
| 04-10 | 0.08824 | -0.25596 | 0.43243 | |
| 04-12 | 0.58824 | 0.24404 | 0.93243 | *** |
| 05-06 | -0.08667 | -0.33095 | 0.15762 | |
| 05-07 | -0.12 | -0.34439 | 0.10439 | |
| 05-08 | 0.28 | -0.08643 | 0.64643 | |
| 05-09 | 0.08 | -0.14439 | 0.30439 | |
| 05-10 | 0.08 | -0.28643 | 0.44643 | |
| 05-12 | 0.58 | 0.21357 | 0.94643 | *** |
| 06-07 | -0.03333 | -0.28881 | 0.22215 | |
| 06-08 | 0.36667 | -0.01958 | 0.75291 | |
| 06-09 | 0.16667 | -0.08881 | 0.42215 | |
| 06-10 | 0.16667 | -0.21958 | 0.55291 | |
| 06-12 | 0.66667 | 0.28042 | 1.05291 | *** |
| 07-08 | 0.4 | 0.02602 | 0.77398 | *** |
| 07-09 | 0.2 | -0.03653 | 0.43653 | |
| 07-10 | 0.2 | -0.17398 | 0.57398 | |
| 07-12 | 0.7 | 0.32602 | 1.07398 | *** |
| 08-09 | -0.2 | -0.57398 | 0.17398 | |
| 08-10 | -0.2 | -0.67305 | 0.27305 | |
| 08-12 | 0.3 | -0.17305 | 0.77305 | |
| 09-10 | 0 | -0.37398 | 0.37398 | |
| 09-12 | 0.5 | 0.12602 | 0.87398 | *** |
| 10-12 | 0.5 | 0.02695 | 0.97305 | *** |

The triple asterisks indicate significant differences in the mean values.

## Table B-5. Pairwise Comparisons of Normalized Yield vs. Horizontal Illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| Horizontal Illuminance Comparison | Difference Between Means | 90% Confidence Limits | | |
| 01-02 | 0.01693 | -0.06519 | 0.09905 | |
| 01-03 | 0.07471 | -0.03111 | 0.18052 | |
| 01-04 | 0.09471 | -0.06723 | 0.25664 | |
| 01-05 | -0.03863 | -0.17233 | 0.09507 | |
| 01-07 | 0.07804 | -0.1079 | 0.26397 | |
| 01-08 | 0.27804 | 0.0921 | 0.46397 | *** |
| 01-10 | 0.64471 | 0.32634 | 0.96307 | *** |
| 02-03 | 0.05778 | -0.06706 | 0.18261 | |
| 02-04 | 0.07778 | -0.09718 | 0.25274 | |
| 02-05 | -0.05556 | -0.20476 | 0.09365 | |
| 02-07 | 0.06111 | -0.13627 | 0.25849 | |
| 02-08 | 0.26111 | 0.06373 | 0.45849 | *** |
| 02-10 | 0.62778 | 0.30259 | 0.95296 | *** |
| 03-04 | 0.02 | -0.16725 | 0.20725 | |
| 03-05 | -0.11333 | -0.27678 | 0.05011 | |
| 03-07 | 0.00333 | -0.20502 | 0.21169 | |
| 03-08 | 0.20333 | -0.00502 | 0.41169 | |
| 03-10 | 0.57 | 0.23804 | 0.90196 | *** |
| 04-05 | -0.13333 | -0.33764 | 0.07097 | |
| 04-07 | -0.01667 | -0.25841 | 0.22507 | |
| 04-08 | 0.18333 | -0.05841 | 0.42507 | |
| 04-10 | 0.55 | 0.19613 | 0.90387 | *** |
| 05-01 | 0.03863 | -0.09507 | 0.17233 | |
| 05-07 | 0.11667 | -0.10714 | 0.34047 | |
| 05-08 | 0.31667 | 0.09286 | 0.54047 | *** |
| 05-10 | 0.68333 | 0.34146 | 1.0252 | *** |
| 07-08 | 0.2 | -0.05843 | 0.45843 | |
| 07-10 | 0.56667 | 0.20119 | 0.93214 | *** |

The triple asterisks indicate significant differences in the mean values.

## Table B-6. Pairwise Comparisons of R-Stage vs. Total illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Total illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| 01-02 | -0.0066 | -0.1966 | 0.1834 | |
| 01-03 | 0.0916 | -0.1048 | 0.2879 | |
| 01-04 | 0.3695 | 0.1396 | 0.5993 | *** |
| 01-05 | -0.2188 | -0.587 | 0.1495 | |
| 01-06 | 1.1146 | 0.6522 | 1.577 | *** |
| 01-07 | 1.0313 | 0.6251 | 1.4374 | *** |
| 01-08 | -0.2188 | -0.9965 | 0.559 | |
| 01-09 | 0.5313 | 0.1251 | 0.9374 | *** |
| 01-10 | 1.7813 | 1.0035 | 2.559 | *** |
| 01-12 | 2.7813 | 2.0035 | 3.559 | *** |
| 02-03 | 0.0982 | -0.0967 | 0.2932 | |
| 02-04 | 0.3761 | 0.1475 | 0.6048 | *** |
| 02-05 | -0.2121 | -0.5797 | 0.1554 | |
| 02-06 | 1.1212 | 0.6594 | 1.583 | *** |
| 02-07 | 1.0379 | 0.6324 | 1.4434 | *** |
| 02-08 | -0.2121 | -0.9895 | 0.5653 | |
| 02-09 | 0.5379 | 0.1324 | 0.9434 | *** |
| 02-10 | 1.7879 | 1.0105 | 2.5653 | *** |
| 02-12 | 2.7879 | 2.0105 | 3.5653 | *** |
| 03-04 | 0.2779 | 0.0439 | 0.5118 | *** |
| 03-05 | -0.3103 | -0.6812 | 0.0605 | |
| 03-06 | 1.023 | 0.5585 | 1.4875 | *** |
| 03-07 | 0.9397 | 0.5312 | 1.3481 | *** |
| 03-08 | -0.3103 | -1.0893 | 0.4686 | |
| 03-09 | 0.4397 | 0.0312 | 0.8481 | *** |
| 03-10 | 1.6897 | 0.9107 | 2.4686 | *** |
| 03-12 | 2.6897 | 1.9107 | 3.4686 | *** |
| 04-05 | -0.5882 | -0.9779 | -0.1986 | *** |
| 04-06 | 0.7451 | 0.2655 | 1.2247 | *** |
| 04-07 | 0.6618 | 0.2362 | 1.0874 | *** |
| 04-08 | -0.5882 | -1.3763 | 0.1998 | |
| 04-09 | 0.1618 | -0.2638 | 0.5874 | |
| 04-10 | 1.4118 | 0.6237 | 2.1998 | *** |
| 04-12 | 2.4118 | 1.6237 | 3.1998 | *** |
| 05-06 | 1.3333 | 0.774 | 1.8926 | *** |
| 05-07 | 1.25 | 0.7362 | 1.7638 | *** |
| 05-08 | 0 | -0.839 | 0.839 | |
| 05-09 | 0.75 | 0.2362 | 1.2638 | *** |
| 05-10 | 2 | 1.161 | 2.839 | *** |
| 05-12 | 3 | 2.161 | 3.839 | *** |
| 06-07 | -0.0833 | -0.6683 | 0.5016 | |
| 06-08 | -1.3333 | -2.2177 | -0.449 | *** |
| 06-09 | -0.5833 | -1.1683 | 0.0016 | |
| 06-10 | 0.6667 | -0.2177 | 1.551 | |
| 06-12 | 1.6667 | 0.7823 | 2.551 | *** |
| 07-08 | -1.25 | -2.1063 | -0.3937 | *** |
| 07-09 | -0.5 | -1.0415 | 0.0415 | |
| 07-10 | 0.75 | -0.1063 | 1.6063 | |
| 07-12 | 1.75 | 0.8937 | 2.6063 | *** |
| 08-09 | 0.75 | -0.1063 | 1.6063 | |
| 08-10 | 2 | 0.9169 | 3.0831 | *** |
| 08-12 | 3 | 1.9169 | 4.0831 | *** |
| 09-10 | 1.25 | 0.3937 | 2.1063 | *** |
| 09-12 | 2.25 | 1.3937 | 3.1063 | *** |
| 10-12 | 1 | -0.0831 | 2.0831 | |

The triple asterisks indicate significant differences in the mean values.

## Table B-7. Pairwise Comparisons of R-Stage vs. Horizontal Illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Horizontal Illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| 01-02 | 0.36732 | 0.1855 | 0.54914 | *** |
| 01-03 | 0.61176 | 0.37749 | 0.84604 | *** |
| 01-04 | -0.18824 | -0.54677 | 0.1703 | |
| 01-05 | 1.1451 | 0.84909 | 1.44111 | *** |
| 01-07 | 0.47843 | 0.06676 | 0.8901 | *** |
| 01-08 | 0.81176 | 0.4001 | 1.22343 | *** |
| 01-10 | 2.81176 | 2.10689 | 3.51664 | *** |
| 02-03 | 0.24444 | -0.03194 | 0.52083 | |
| 02-04 | -0.55556 | -0.94292 | -0.16819 | *** |
| 02-05 | 0.77778 | 0.44743 | 1.10812 | *** |
| 02-07 | 0.11111 | -0.3259 | 0.54812 | |
| 02-08 | 0.44444 | 0.00744 | 0.88145 | *** |
| 02-10 | 2.44444 | 1.72447 | 3.16442 | *** |
| 03-04 | -0.8 | -1.21458 | -0.38542 | *** |
| 03-05 | 0.53333 | 0.17146 | 0.89521 | *** |
| 03-07 | -0.13333 | -0.59464 | 0.32797 | |
| 03-08 | 0.2 | -0.2613 | 0.6613 | |
| 03-10 | 2.2 | 1.46503 | 2.93497 | *** |
| 04-05 | 1.33333 | 0.88099 | 1.78568 | *** |
| 04-07 | 0.66667 | 0.13145 | 1.20189 | *** |
| 04-08 | 1 | 0.46478 | 1.53522 | *** |
| 04-10 | 3 | 2.21652 | 3.78348 | *** |
| 05-07 | -0.66667 | -1.16219 | -0.17115 | *** |
| 05-08 | -0.33333 | -0.82885 | 0.16219 | |
| 05-10 | 1.66667 | 0.90975 | 2.42358 | *** |
| 07-08 | 0.33333 | -0.23884 | 0.90551 | |
| 07-10 | 2.33333 | 1.52415 | 3.14251 | *** |
| 08-10 | 2 | 1.19082 | 2.80918 | *** |

The triple asterisks indicate significant differences in the mean values.

## Table B-8. Pairwise Comparisons of R-Stage vs. Vertical Illuminance

| Comparisons significant at the 0.1 level are indicated by *** | | | | |
|---|---|---|---|---|
| **Vertical Illuminance Comparison** | **Difference Between Means** | **90% Confidence Limits** | | |
| 01-02 | 0.36732 | 0.1855 | 0.54914 | *** |
| 01-03 | 0.61176 | 0.37749 | 0.84604 | *** |
| 01-04 | -0.18824 | -0.54677 | 0.1703 | |
| 01-05 | 1.1451 | 0.84909 | 1.44111 | *** |
| 01-07 | 0.47843 | 0.06676 | 0.8901 | *** |
| 01-08 | 0.81176 | 0.4001 | 1.22343 | *** |
| 01-10 | 2.81176 | 2.10689 | 3.51664 | *** |
| 02-03 | 0.24444 | -0.03194 | 0.52083 | |
| 02-04 | -0.55556 | -0.94292 | -0.16819 | *** |
| 02-05 | 0.77778 | 0.44743 | 1.10812 | *** |
| 02-07 | 0.11111 | -0.3259 | 0.54812 | |
| 02-08 | 0.44444 | 0.00744 | 0.88145 | *** |
| 02-10 | 2.44444 | 1.72447 | 3.16442 | *** |
| 03-04 | -0.8 | -1.21458 | -0.38542 | *** |
| 03-05 | 0.53333 | 0.17146 | 0.89521 | *** |

The triple asterisks indicate significant differences in the mean values.