Sensors have become valuable tools in agriculture when decisions regarding inputs require precision and speed. For example, factors in estimating defoliation in row crops, such as intensive labor and, in particular, subjectivity, are greatly reduced with the use of sensors that can remove these limitations and biases. Estimates of defoliation are almost always overestimated due to human error and biased, unconscious efforts to locate injury. To address these issues, the accuracy and preciseness of a light-based sensor to detect defoliation was tested by measuring simulated levels of defoliation (0-100%) on paper “leaves” at seven light intensities. Results indicated that higher lux values were detected through thinner paper (filter paper) than through thicker paper (cardstock), demonstrating that leaf thickness could potentially affect accuracy of the light-sensor system. Despite some light penetrating the thinner paper with simulated defoliation levels, the two light sensors tested yielded accurate and precise predictions of defoliation (R² > 0.95). This light-sensor approach could potentially be used in the field to report real-time measurements of defoliation in row crops, such as soybeans, or in other plant-based systems where losses of leaf area require monitoring in order to prevent economic injury.

**Keywords:** defoliation, soybean, peanut, light detection sensors, controller
Introduction

Defoliation caused by insect feeding is a major limiting factor to row crop production (Holden 2002; Ohnesorg and Hunt 2015). The impact of defoliation on crop quality and yield is an area of pest management that should be continually studied to reduce the risk of nutrition deficiency and to feed the growing population. To feed the expected world population of 8.5 billion in 2030 from the current 7.3 billion (United Nations 2017), it was decided at the 2008 World Food Security conference that food production needs to increase by 50% (Ainsworth et al. 2011) to meet the impending demands.

Soybean (Glycine max L. Merr.) is the most produced and second most exported crop in the United States (Ash 2018). The seed composition (18% oil and 38% protein) makes processed soybeans an attractive source for protein in the animal feed industry and for vegetable oil (SC Soybean Board 2018). Over the past decade, demand for soybean oil as a source for biodiesel, an industry dominated by corn, has risen (Ash et al. 2006).

Injury caused by insect pests can be a major limiting factor to producing soybeans. In 2017, an annual estimation of control costs for and losses to insects was compiled from 36% of soybean acreage (nearly 100% of the Southeast and less than 50% of Mid-West) in the United States. It was found that the stink bug (Hemiptera: Pentatomidae) complex, which made up 38% of the control costs and losses, was the most expensive insect pest of soybeans, followed by corn earworm, Helicoverpa zea (Boddie), and soybean looper, Chrysodeixes includens (Walker), a prolific defoliating pest of the crop (Musser et al. 2018). Various other species of caterpillars, grasshoppers, and beetles cause foliage damage (Greene 2017). Economic injury, in the form of defoliation, can be caused by one or more species concurrently, with point estimates of defoliation reported as averages (Ohnesorg and Hunt 2015) and the offending species identified and controlled, if necessary. In South Carolina, action thresholds for defoliating insect pests in soybeans are 30 or 15% leaf loss before or after bloom, respectively (Greene 2017). Loss of foliage during vegetative growth is less important than defoliation during reproductive growth in soybeans, so when the injury occurs is important (Ohnesorg and Hunt 2015). For example, 40% defoliation during the vegetative growth and 20% defoliation after bloom each cause 3-7% yield reduction (Rice 2002). It has also been found that defoliation decreases seed number, seed size (measured as dry weight), and seed protein content (Turnipseed 1987; Burton et al. 1995). Furthermore, defoliation in indeterminate varieties during the flowering stage decreases plant height and lodging, while defoliation at later stages hastens maturity (Banks and Bernardi 1987). Although soybeans can withstand leaf area loss without affecting yield significantly, at least 90% of available light should be intercepted by the canopy, so growing conditions are important for this. Environmental conditions favorable for soybean development help the crop compensate for foliage loss by allowing adequate growth, branching, and light capture throughout the season (Ohnesorg 2015).

Peanuts is also a major row crop grown globally for its seed protein content (25-30%) and in the southern United States as a summer forage crop (Leuck et al. 1967). Like soybeans, insect feeding on different parts of the crop, such as the stem and roots, can lead to yield loss and impacts on plant height and other plant characteristics (Abbott et al. 2019). Foliage feeding pests include thrips, corn earworm, soybean looper, spider mites, and other pests (Mulder and Berberet 2012; Anco 2017). However, the defoliation threshold is not well understood across the southeastern United States, especially in new cultivars. Recently, Abbott et al. (2019) conducted a study in Mississippi to determine canopy defoliation thresholds at 40 and 80 days after emergence (DAE), two critical growth stages when pegging and pod fill start, for 0, 20, 40, 60, 80, and 100% defoliation. It was found that defoliation only
significantly affected pod yield at 80 DAE when yield was reduced by 18.6 kg/ha for every 1% increase in canopy defoliation. This corresponds to a report by Oklahoma State University Cooperative Extension Service stating that yield reductions were observed in peanuts with defoliation occurring between 60 and 90 DAE (Mulder and Berberet 2012). This can be explained by the fact that 80 DAE is when peanuts are at the height of the reproductive stage in contrast to 40 DAE, the late vegetative or early reproductive stage. Plants can compensate and recover from injury at early reproductive stages compared with plants further along in reproductive growth (Abbott et al. 2019).

Standard procedure for estimating percentage of leaf area loss in soybeans is to randomly pick 20 leaflets from the top, middle, and bottom thirds of randomly selected plants in the field, for a total of 60 leaflets. These are then compared to a visual guide (Koch 2016) for estimating the percentage of defoliation. After the values are recorded, the average is taken, representing the overall defoliation for the field (Steffey 1997; Koch 2016). This method is time-consuming and subjective. Estimates of defoliation are typically overestimated, due to measurements taken exclusively in the upper canopy instead of throughout the entire canopy (top, middle, and bottom) and through unintentional biases to select injured leaves (Ohnesorg and Hunt 2015).

Measuring defoliation with equipment, such as leaf area meters or other digital imaging systems is possible and can provide accurate estimates, but destructive samples are often still required, and significant efforts are still required in transporting equipment and physically maneuvering around the field. Tewolde et al. (2005) measured the leaf area of cotton nondestructively using an instrument consisting of a light-sensing segment and a microcontroller that were placed under the canopy. To improve the accuracy of the instrument, factors such as placement of the meter, row-spacing, and timing of measurement needed to be considered.

These limitations call for a non-destructive automated sensing device that remotely records and reports long-term and real-time defoliation from the field. The objectives of this study were to 1) optimize a sensing device using a low-cost light sensor and microcontroller to estimate defoliation levels and 2) test and evaluate the accuracy of the defoliation estimates measured by the device by using simulated defoliation covers. Results from testing this system would be used to develop a remote sensing device placed in fields of soybean or other crops of interest that automatically informs the crop manager of defoliation levels via a wireless communication module.

Materials and Methods

Development of the light detecting defoliation sensor

Experiments were conducted in a controlled environment at Clemson University’s Sensor and Automation Laboratory at the Edisto Research and Education Center (EREC) near Blackville, South Carolina, during 2018-2019. The assembly of a microcontroller (SAMD21, ATML, USA), light sensor module, 8 Megabit flash memory, and 4GB micro-SD card enabled the microcontroller to request digital information from the light sensors via an I2C communication protocol (Fig. 1). Three sets of light sensor modules were used to measure direct incoming light. The light was spread with diffuser film (Optigrafix, Grafix Plastics, USA) that was stretched over the top of foam padded cardboard and measured with a wired light sensor (TSL2560, AMS-TAOS, USA) placed 10 mm below the diffuser film. Light absorbed from any area of the diffuser film was received by the light sensor. The light sensor module that measured direct incoming light from above the plant canopy was designated as S1, while the other two light sensor modules, S2A and S2B (Fig. 2), measured light coming from beneath the plant canopy and were used for comparison purposes.
Fig. 1. Main controller board for defoliation sensor prototype.

Fig. 2. Defoliation sensor module with diffuser film spread over the light sensor for S2A, S1, and S2B.

**Sensor calibration**

Prior to data collection, a commercialized lux meter (DM-LX1330B, Dr. Meter, China) was used to calibrate each of the three defoliation sensors. A 7-level dimmable LED desk lamp (TT-DL11, Taotronics, USA) was placed 419 mm directly above the defoliation sensor being calibrated, and the other two sensors were covered with cardstock paper and a heavy weight to ensure the accuracy of the lux values from the sensor. The average light intensities are as follows: \( \text{lux}_0 = 0 \) (desk lamp turned off), \( \text{lux}_1 = 45 \) (dimmest condition), \( \text{lux}_2 = 106 \), \( \text{lux}_3 = 160 \),
lux$_4$ = 221, lux$_5$ = 282, lux$_6$ = 334, and lux$_7$ = 572 (brightest condition).

The lux meter was placed at the base of the desk lamp. Over a course of 30 seconds, the lux values from the sensors and the lux readings from the lux meter were recorded for each of the eight light intensities from the desk lamp with no interference from outside light. The lux values recorded from the lux meter were then regressed on the average lux values from the sensors.

To determine the accuracy of these calibration equations, three treatments per each of the eight light intensity levels were performed for a total of 24 treatments. The treatments were numbered in order of the dimmest to brightest light intensity. Using the RAND formula in one column and the RANK formula in the next column in Excel, the order of the treatments was randomized for each sensor. The treatments were conducted the same way as the sensor calibration.

**Testing of the light detection defoliation sensor**

A 7-level dimmable LED desk lamp was used as the only light source in a controlled environment by placing it 419 mm from the top of either S2A or S2B. This allowed for precise and accurate estimates of simulated defoliation levels at the different light intensities.

Two experiments were conducted to test the preciseness and accuracy of the defoliation sensors. In one experiment, regular areas were cut from circular cardstocks (7 cm diameter) so that the area removed equaled the desired defoliation level. The factorial design (7 x 5) included two replications of seven light intensities from the desk lamp (lux$_1$ – lux$_7$) and five defoliation levels (0, 25, 50, 75, and 100%) (Fig. 3). In the other experiment, circular filter papers (7 cm diameter) were hole punched until the area removed equaled the desired defoliation level. This factorial design (5 x 6) also included two replications of the five highest light intensities from the desk lamp (lux$_3$ – lux$_7$) and six defoliation levels (0, 15, 30, 50, 60, and 100%) (Fig. 4). In both experiments, if defoliation covers were being tested on S2A, then the desk lamp would be 419 mm directly above the sensor with S2B covered; if the treatments were on S2B, then the desk lamp would be 419 mm directly above the sensor with S2A covered. S1 was uncovered at all times.

**Fig. 3.** Simulated defoliation (0, 25, 50, and 75%, left to right) covers of cardstock paper for testing defoliation light sensors.

**Fig. 4.** Simulated defoliation (0, 15, 30, 50, and 60%, left to right) covers of filter paper for testing defoliation light sensors.
Digital information from the S1 and S2 sensors was taken every second as requested by the microcontroller and calculated for the equivalent light intensity or lux value. This value and percent ratio were stored on a text file in a micro SD card. Each experimental run took 3 minutes. The lux values recorded from the sensors were used to calculate defoliation percentages (Eq. (6)). The S2A and S2B lux values represented the g(x) value, and the S1 lux values represented the f(x) value. The reliability and accuracy of the system was examined through linear regression analyses; the slope indicated the average accuracy of the estimated defoliation level, and $R^2$ represented the reliability.

**Testing of sensors in the greenhouse**

A third experiment using live plants (peanuts) was conducted in the greenhouse mid-afternoon with the shades uncovered. S2A and S2B were lowered to the base of the plant, while S1 was moved to the top of the metal pole so that it was above the tallest leaves. S2A and S2B were about 254 cm above the bench and S1 was about 47 cm above the bench. Defoliation levels (0, 50, and 100%) were simulated on the plants by manually removing leaves before testing (Fig.5).
**Calculation of defoliation**

Defoliation was estimated by using the formula for the area under the curve from the geometric integral formulas. The calculated area (A) between the functions f(x) and g(x) limited by [a,b] is found by

\[ A = \int_a^b [f(x) - g(x)] \, dx \]  \hspace{1cm} (1)

By expanding the formula, the area A will be zero if and only if f(x) = g(x), or as g(x) → f(x).

\[ A = \int_a^b f(x) \, dx - \int_a^b g(x) \, dx = A_f(x) - A_g(x) \]  \hspace{1cm} (2)

In relation to calculating the defoliation, f(x) is the measured light intensity over the top of the canopy while g(x) is the measured light intensity underneath the canopy. Thus, the values of A will be between f(x) and 0 as the value of g(x) increases. If A equals zero, this means that f(x) is the same as g(x) indicating that defoliation is at its maximum. Since the area A is inversely proportional to the amount of defoliation, the equation can be modified as seen below.

\[ \text{Defoliation} = 1 - A = 1 - \left[ \int_b^a f(x) \, dx - \int_b^a g(x) \, dx \right] \]  \hspace{1cm} (3)

The value for A cannot be more than 1 when calculating for defoliation. Constraining A to 1 is the same as normalizing the values of A as shown below.

\[ \text{Defoliation} = \frac{\int_b^a f(x) \, dx - \int_b^a g(x) \, dx}{\int_b^a f(x) \, dx} \]  \hspace{1cm} (4)

\[ \text{Defoliation} = \int_b^a g(x) \, dx \int_b^a f(x) \, dx - \int_b^a g(x) \, dx \int_b^a f(x) \, dx \]  \hspace{1cm} (5)

Simplifying this equation and multiplying it by 100% gives the estimate of defoliation

\[ \text{Defoliation} = \frac{\int_b^a g(x) \, dx}{\int_b^a f(x) \, dx} \times 100\% \]  \hspace{1cm} (6)

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Fig. 6. Linear regression with calibration equation for defoliation light sensors a) S2A, b) S1, and c) S2B.
Results and Discussion

Linear regression and box plots

The results from the calibration of the three sensors resulted in a linear regression for each sensor that was used as the calibration equation (Fig. 6). The three calibration equations below were used in the experiments to calculate the true light intensity for each respective sensor.

\[
\text{lux} = 0.0335 \times S2A \text{ sensor} - 4.8845 \\
\text{lux} = 0.0361 \times S1 \text{ sensor} + 1.9878 \\
\text{lux} = 0.0381 \times S2B \text{ sensor} + 3.3137
\]

Box plots for each sensor were created to find the error between the actual lux values from the lux meter and the predicted lux values calculated from the calibration equation (Fig. 7).

Measurement of defoliation using cardstock cover

The calculated defoliation percentages for both S2A and S2B were relatively close to the actual defoliation level (±10) over 30 seconds. However, S2B had higher calculated defoliation percentages most noticeably at 25 and 100% defoliation levels for all seven light intensities (Fig. 9). At 100% defoliation, the calculated defoliation percentages were more than 10 above the actual defoliation level. Despite the large error, overall, both sensors were accurate according to the linear regression. The $R^2$ of S2A was 0.9806, while the $R^2$ of S2B was 0.9743 (Fig. 10), both of which showed high reliability. This could be due to most of the light from the desk lamp not permeating through the thicker paper. For example, at 0% defoliation, the calculated defoliation was between 2-3% for all seven light intensities.

Fig. 7. Error between lux values from defoliation light sensors and lux meter values a) S2A, b) S1, and c) S2B.
Fig. 8. Estimates of defoliation from S2A cardstock covers for a) lux1, b) lux2, c) lux3, d) lux4, e) lux5, f) lux6, and g) lux7.
Fig. 9. Estimates of defoliation from S2B cardstock covers for a) $lux_1$, b) $lux_2$, c) $lux_3$, d) $lux_4$, e) $lux_5$, f) $lux_6$, and g) $lux_7$. 

AJAR: https://escipub.com/american-journal-of-agricultural-research/
Fig. 10. Linear regression for accuracy of defoliation light sensors.

Measurement of defoliation using filter paper
Both S2A and S2B had lux values much higher than the actual defoliation level (±10) over 30 seconds for all seven light intensities. Like the cardstock experiment, S2B had higher calculated defoliation percentages than S2A, but this occurred at all seven light intensities. At 0% defoliation for both sensors (Figs. 11 and 12), all calculated defoliation percentages were between 15-17%. This can be explained by the amount of light that could pass through the filter paper compared with the cardstock paper. Interestingly, at 100% defoliation for S2A, the calculated defoliations were more accurate than in the cardstock experiment. Like the cardstock experiment, despite the large error, overall, both of the sensors were accurate according to the linear regression. The R² of S2A was 0.9568, while the R² of S2B equaled 0.9509, both of which showed high reliability (Fig. 13).

Measurement of defoliation in greenhouse
As expected, for both S2A and S2B, 0% defoliation had the lowest lux values and 50% and 100% defoliation had the second and third highest lux values, respectively (Fig. 14a,b). Although, the lux values from S2B (Fig. 14b) at 100% defoliation were only slightly higher than the lux values at 50% defoliation. There was a decrease in the 50 and 100% defoliation in S2A during the last two minutes of the experiment (Fig. 14a), while both 0 and 100% defoliation increased in S2B (Fig. 14b) throughout the five-minute duration. Interestingly, there was a decrease in the 50% defoliation in S2B during the first two minutes. It is highly likely that sunlight, reflected off of metal and glass sections of the greenhouse, contacted portions of the sensors and peanuts, causing the measured decrease. Ideally, the sensor prototype would have been tested outside of a structure where the only shadows would have been from the foliage of the plants. Despite the large error during some portions of the five-minute duration, overall both of the sensors were accurate according to the linear regression. The R² of S2A was 0.9594 while the R² of S2B was 0.9615 (Fig. 15), indicating high reliability and making this experiment in the greenhouse more reliable than the filter paper experiment.

Future refinements for both the cardstock and filter paper experiments to test the accuracy of the sensors would be to place the filter paper covers 419 mm below the desk lamp, with the lux meter below the cover to record a more accurate lux value. Additionally, the head of the desk lamp could be turned at different angles relative to the surface of the sensors, and the sensors could be tested at different heights to simulate defoliation levels in the top, middle, and bottom plant canopy.
Fig. 11. Estimates of defoliation from S2B cardstock covers for a) \textit{lux}_3, b) \textit{lux}_4, c) \textit{lux}_5, d) \textit{lux}_6, and e) \textit{lux}_7.
Fig. 12. Estimates of defoliation from S2B cardstock covers for a) lux3, b) lux4, c) lux5, d) lux6, and e) lux7.
Fig. 13. Linear regression for accuracy of light sensors to predict simulated defoliation of paper disks.

Fig. 14. Estimates of defoliation in the greenhouse study using peanuts for a) S2A and b) S2B.
Conclusion
Regarding decision making and limitations in practices, sensors have become a necessity in agriculture. The sensor prototypes in this experiment were developed to address automated estimating of defoliation in cropping systems. Intensive labor, damage to soybeans, and subjectivity are factors in defoliation estimations that would be eliminated with this sensor-based approach. Despite some variability, both sensors were highly reliable and accurate in measuring light penetration through simulated or actual defoliated leaves in the laboratory or greenhouse. Further testing with crops under field conditions is necessary.

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