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Development of a sensing device for detecting defoliation in soybean

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Abstract. Estimating defoliation by insects in an agricultural field, specifically soybean, is performed by manually removing multiple leaf samples, visually inspecting the leaves for feeding, and assigning a value representing a "best guess" at the level of leaf material missing. These estimates can require considerable time and are subjective. The goal of this study was to design a low-cost system containing light sensors and a microcontroller that could remotely record and report long-term and real-time defoliation from the field. In experiments to evaluate the effectiveness of light sensors in measuring defoliation at different light intensities, sensors were subjected to two sets of simulated defoliation covers made out of card board (0, 25, 50, 75, or 100%) and paper (0, 15, 30, 50, 60, or 100%) while exposed to 7 different light intensities. The results indicated that, as light intensity increased, accuracy of the sensing system improved. This paper also exhibits the potential of the developed sensor for real-time defoliation estimation in the field.

Keywords. *light sensor, defoliation sensor, defoliation estimation*

Introduction

Insects are soybean's yield-limiting pests, *Glycine max* (L.) *Merr*, and defoliating species such as green cloverworm, *Hypena scabra* (F.), soybean looper, *Chrysodeixis includens* (Walker), velvetbean caterpillar, *Anticarsia gemmatalis* Hübner, various species of beetles, grasshoppers, and others can cause significant loss of foliage. Defoliation caused by insect pests is one of the universal indicators of soybean injury. This type of injury to a soybean plant could reduce its ability to make up its lack of nutrients and water (Owen et al. 2013). The impact on soybean yield depends as to when the defoliation started. Several researchers (Turnipseed 1972; Gregorutti, V.C. 2012; Owen et al. 2013) reported a significant reduction of yield when defoliation injury started at the early reproductive phase with a severe level of defoliation. Additionally, defoliation has also affected the quality of soybean seed in which the seed weight decreased (Turnipseed 1972) and the protein concentration was reduced (Turnipseed 1972; Burton et al. 1195).

Generally, soybean growers and consultants practice integrated pest management (IPM) and economic threshold (ET) for defoliation when making treatment decisions. Insect pest management in soybeans across numerous states suggest procedures in estimating defoliation condition. Even though each state may have different procedures and sampling techniques, scouting and randomly selecting leaf samples to visually compare to a set of defoliation diagrams (Steffey 1997; Hammond et al. 2014; Allen et al. 2015; Knodel et al. 2015; Stewart et al. 2015) is a common practice. Weekly visits to each field are advised (Greene 2016). In South Carolina, it is recommended that trifoliate leaves (at least 10) randomly chosen from representative areas of the field are visually evaluated to the extent of defoliation. The recommended ET for defoliation is when leaf-area loss reaches 30% before bloom and 15% thereafter (Greene 2016). This practice of visual estimation is prone to subjective evaluation, as estimates can vary from one individual to the next (Ritchie and Bernarz 2005; Owen et al. 2013), and are typically overestimated (Rice 2002; Koch 2013; Islam 2014, Tooker, 2015). Moreover, a practice like this would require significant effort and commitment.

To obtain an accurate defoliation estimate, it may require the use of a leaf area meter machines such as LI-3100 and/or digital imaging systems. However, the use of these devices may be destructive to soybean plant, for it requires leaf removal. Furthermore, it still does not solve the problems of tediousness and labor intensity.

The limitations of these existing practices demand the development of a nondestructive automated sensing device that records long-term and real-time levels of defoliation. An automated system could improve the efficiency of data collection and precision (Jiang et al. 2008). A closely related technique was presented by Tewolde et al. (2005), who used a light-sensing segment and microcontroller that were laid under a corn canopy to nondestructively measure defoliation. However, the accuracy of the technique depends on several factors that includes row spacing, plant height, and time of measurement.

The objectives of this study were to: 1) design and develop a sensing device using a low-cost light sensors and microcontroller to estimate defoliation level; 2) test and evaluate the accuracy of the defoliation estimates of the system by using a simulated defoliation cover. Results from testing the system would be used to develop a remote sensing device to be placed in the soybean field that will automatically inform the crop manager of defoliation levels via a wireless communication module.

Materials and methods

Theoretical Background

The calculation for the amount of defoliation can be represented using the area between curves from the geometric integral formulas. The area between functions, $f(x)$ and $g(x)$ over $[a,b]$ can be calculated by

$$A = \int_b^a \left[f(x) - g(x) \right] dx \tag{1}$$

where *A* is the Area between the functions *f(x)* and *g(x)*. Equation 1 can be expanded as shown in Equation 2.

$$A = \int_b^a f(x)dx - \int_b^a g(x)dx = A_{f(x)} - A_{g(x)} \tag{2}$$

The second equation provides a direct solution by calculating the area of each function over the interval *[a,b]* and taking the difference. Based on this equation, the area A will be zero if and only if *f(x) = g(x)*, or as *g(x)→f(x).*

In relation to calculating the defoliation, *f(x)* therefore is the measured light intensity over the top of the canopy while *g(x)* is the measured light intensity underneath the canopy. The calculated area therefore will have values between *f(x)* and *0* as the value of *g(x)* increases. If the measured value of *f(x)* is the same as *g(x)*, then the calculated area is zero which also means that the defoliation is at its maximum. Since the calculation of area is inversely proportional to the amount of defoliation, Equation 2 can be modified as shown in Equation 3.

$$Defoliation = 1 - A = 1 - \left[\int_b^a f(x)dx - \int_b^a g(x)dx \right] \tag{3}$$

Defoliation can be computed as long as the calculated area (*A*) will not be more than 1. Constraining *A* to 1 is the same as normalizing the values of *A* as shown in equation 4, and equation 5 is the result of distributing *f(x)*,

$$Defoliation = 1 - \left[\frac{\int_b^a f(x)dx - \int_b^a g(x)dx}{\int_b^a f(x)dx} \right] \tag{4}$$

$$Defoliation = 1 - \left[\frac{\int_b^a f(x)dx}{\int_b^a f(x)dx} - \frac{\int_b^a g(x)dx}{\int_b^a f(x)dx} \right] \tag{5}$$

The equation for Defoliation can therefore be simplified to

$$Defoliation = \frac{\int_b^a g(x)dx}{\int_b^a f(x)dx} \tag{6}$$

Multiplying Equation 6 by one hundred will give the percentage of defoliation.

Sensor calibration

The designed sensors were calibrated relative to a commercialized lux meter (DM-LX1330B, Dr. Meter, China) prior to data collection. Lux readings were recorded from the lux meter and sensors for three minutes at the same height from the ground. Readings were recorded at four different levels of light intensity generated by a 7-level dimmable LED desk lamp with no interference from outside light. Linear regression was used to generate the calibration equation. The average lux value of the recorded readings from the commercialized lux meter was regressed on the average lux value of the sensor (Figure 5).

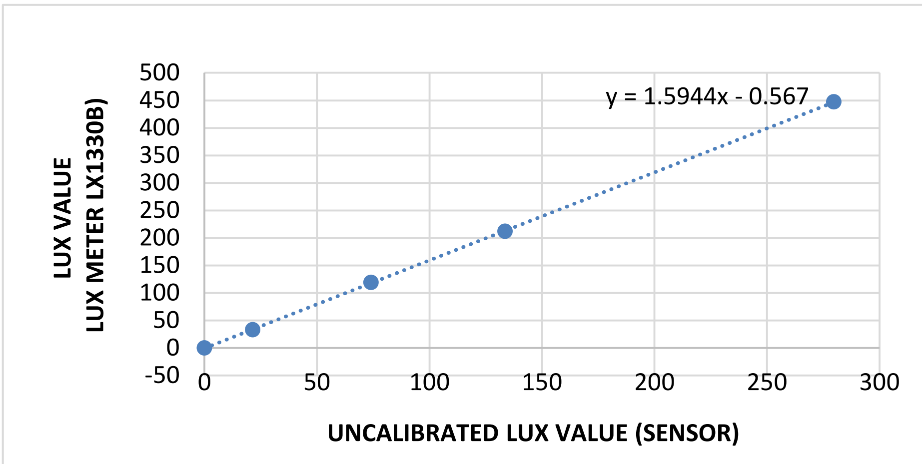

Figure 5. Calibration equation using linear regression

The equation below was then used on the experiment in calculating the true light intensity.

$$Lux = 1.5944Sensor - 0.567 \tag{5}$$

System Prototype

The system prototype was assembled by combining a microcontroller (SAMD21, ATMEL, USA), light-sensor module, 8 Megabit flash memory, and 4GB micro-SD card for a data storage (Figure 1). The microcontroller was programmed to request digital information from the light-sensors via an I2C communication protocol.

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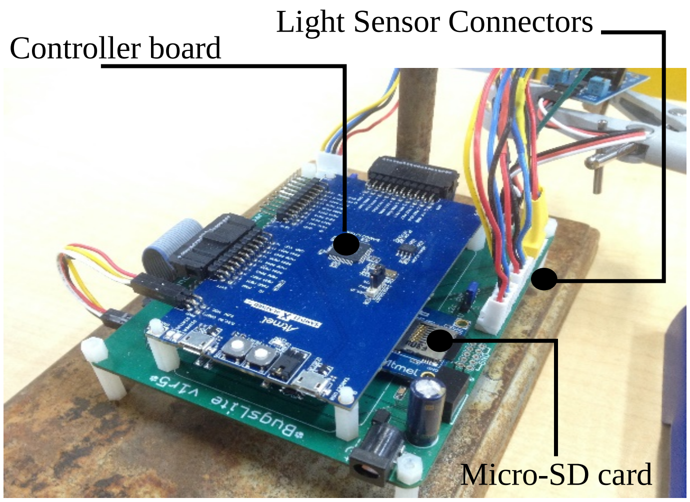
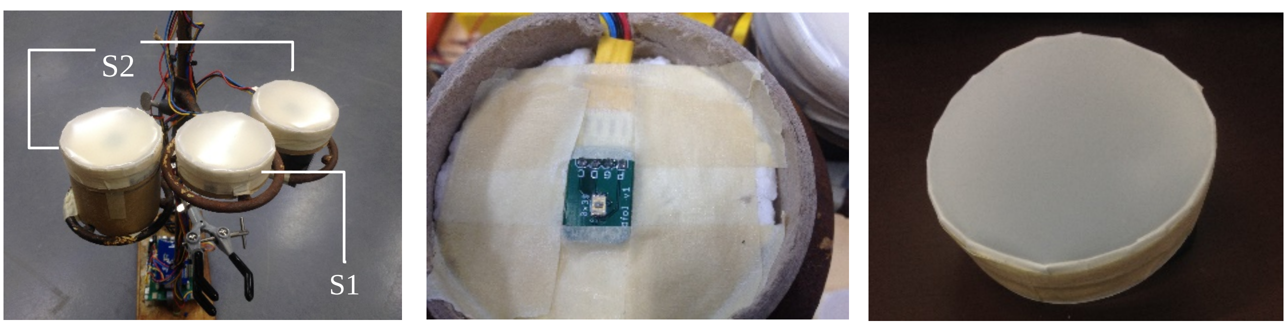


Figure 1. Prototype for main controller board

In the current work, three sets of light sensor modules were created. The light sensor module was designed by affixing a wired light sensor (TSL2560, AMS-TAOS, USA) to a foam padded cardboard tube (figure 2b) with diffuser film (Optigrafix, Grafix Plastics, USA) stretched over the top with a gap of 10 mm (from film to sensor) (figure 2c). The diffuser was used to spread the incoming light which enabled the light sensor to measure the light absorbed from any area of the diffuser film.

The setup of a defoliation sensor was composed of two light sensor modules designated as S1 and S2. The S1 sensor measures the direct incoming light which was normally located on top of the plant canopy while S2 sensor measures the incoming light under the plant canopy. There were only three light sensors for the current setup, thus, two sensor modules, S2A and S2B, were used to measure the incoming light underneath the canopy for comparison purposes.



(a) (b) (c)

Figure 2. Setup of (a) defoliation sensor module is composed of (b) light sensor and (c) diffuser film.

Environment Condition and Experimental Design

The experiments were conducted at the Sensor and Automation Laboratory of the Edisto Research and Education Center (EREC) of Clemson University. The tests were performed in a controlled environment where the height of the sensors (S1 and S2) was set at the same level from the ground and a 7-level dimmable LED desk lamp (TT-DL11, Taotronics, USA) was used as the only light source. The lighting conditions were represented as lux_1, lux_2, lux_3, lux_4, lux_5, lux_6, and lux_7, where lux_1 was the dimmest condition and lux_7 was the brightest condition. The LED desk lamp was placed directly above the light sensors at a distance of about 419 mm from the top of the sensor. The setup allowed for testing of the effects of different light intensities on the precision and accuracy of estimating the simulated defoliation level.

In the initial testing, treatments were evaluated as a 7 x 5 factorial with 2 replications, with factors including light intensity levels (7 light intensities from LED desk lamp) and a cardstock covers simulating defoliation (5 defoliation levels: 0, 25, 50, 75, 100%) (Figure 3). The simulated level of defoliation was created by cutting a piece of circular cardstocks (7 cm diameter) and removing regular areas equivalent to each defoliation level. Because the number of sensors available during the test was limited, each replication was performed by testing a random treatment.

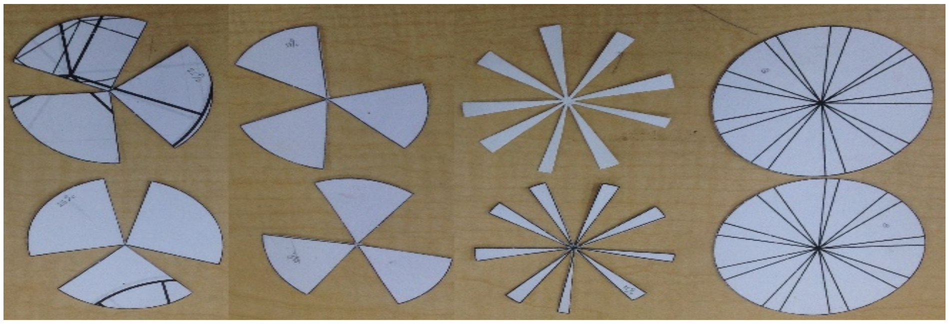


Figure 3. Simulated defoliation levels of 25, 50, 75, and 0 (left to right) to cardstock covers for testing defoliation sensor.

An additional experiment was conducted evaluating treatments as a 5 x 8 factorial with 2 replications, with factors including light intensity (5 highest intensities from LED desk lamp) and filter paper (7 cm diameter) covers simulating defoliation (0, 15, 30, 60 and 100%) (Figure 4). Simulated levels of defoliation were made with standard paper by randomly punching holes in the filter paper until enough area was removed to equate to each defoliation level. The same physical setup was used in the first experiment, except that replication was performed by grouping treatments by defoliation level and testing a random treatment from the group.

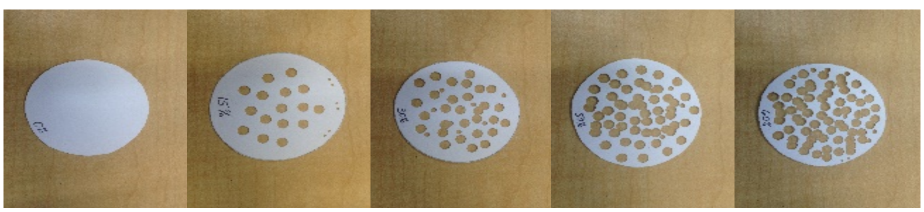


Figure 4. Simulated defoliation Level 0, 15, 30, 50 and 60 (left to right) to filter paper for testing defoliation sensor.

The microcontroller was programmed to request digital information from S1 and S2 light sensors every second. The data from each sensor was used to calculate the equivalent light intensity or lux value.

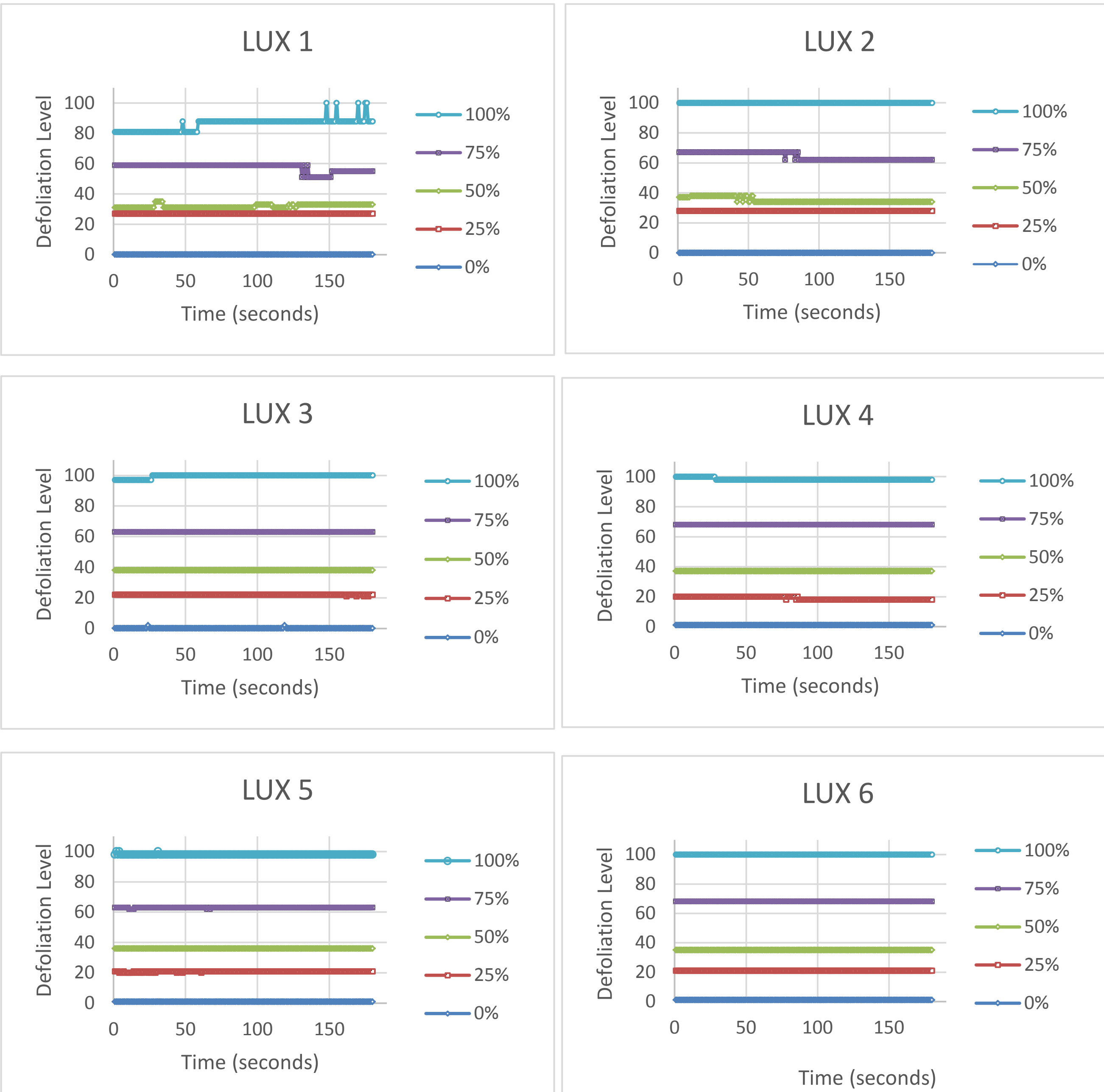
The computed lux value and percent ratio were stored on a text file in a micro-SD card. The data was collected in a 3 minute period for each treatment. Linear regression analyses was used to demonstrate the reliability and accuracy of the system. The slope of the regression line was used to indicate the average accuracy of the estimated defoliation level and R^2 represents the reliability.

Results

Results from the first set of defoliation covers

Responses from the sensors (Figure 6 and 7) indicated changes in estimate of defoliation when covered with cardstock disks of known/simulated defoliation. Likewise, a slight change in the estimate of defoliation was observed for each simulated defoliation cover between the light intensities lux_2 to lux_7. Comparing the precision of the defoliation estimate between light intensity for the three minute period, it was observed in Figures 6 and 7 that as light intensity increases the precision or consistency of the defoliation estimate was improved especially at higher level of defoliation. For example, at 100% defoliation, the defoliation estimates at all instances in the three minute period were getting closer to each other as the light intensity increased.

The accuracy of the defoliation estimates from the sensors was verified with linear regression analysis (Figure 8). In the same figure (Figure 8), the linear regression of the defoliation level estimation results from defoliation sensor one (Figure 8a) and defoliation sensor two (Figure 8b) are shown. Each data point in the figure indicates the average defoliation in a three minute period of different light intensities, and the actual defoliation level with reference to the abscissa and the ordinate, respectively. The average accuracy of the first defoliation sensor was 96.09% and that of second defoliation sensor was 97.7%, both with the same high reliability of R^2 = 0.969.



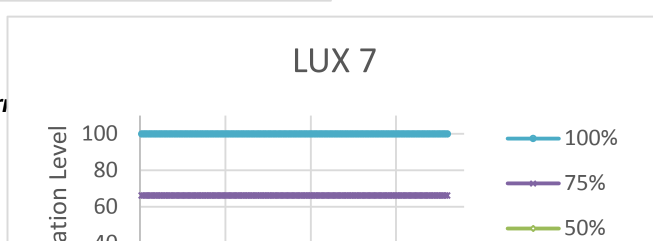
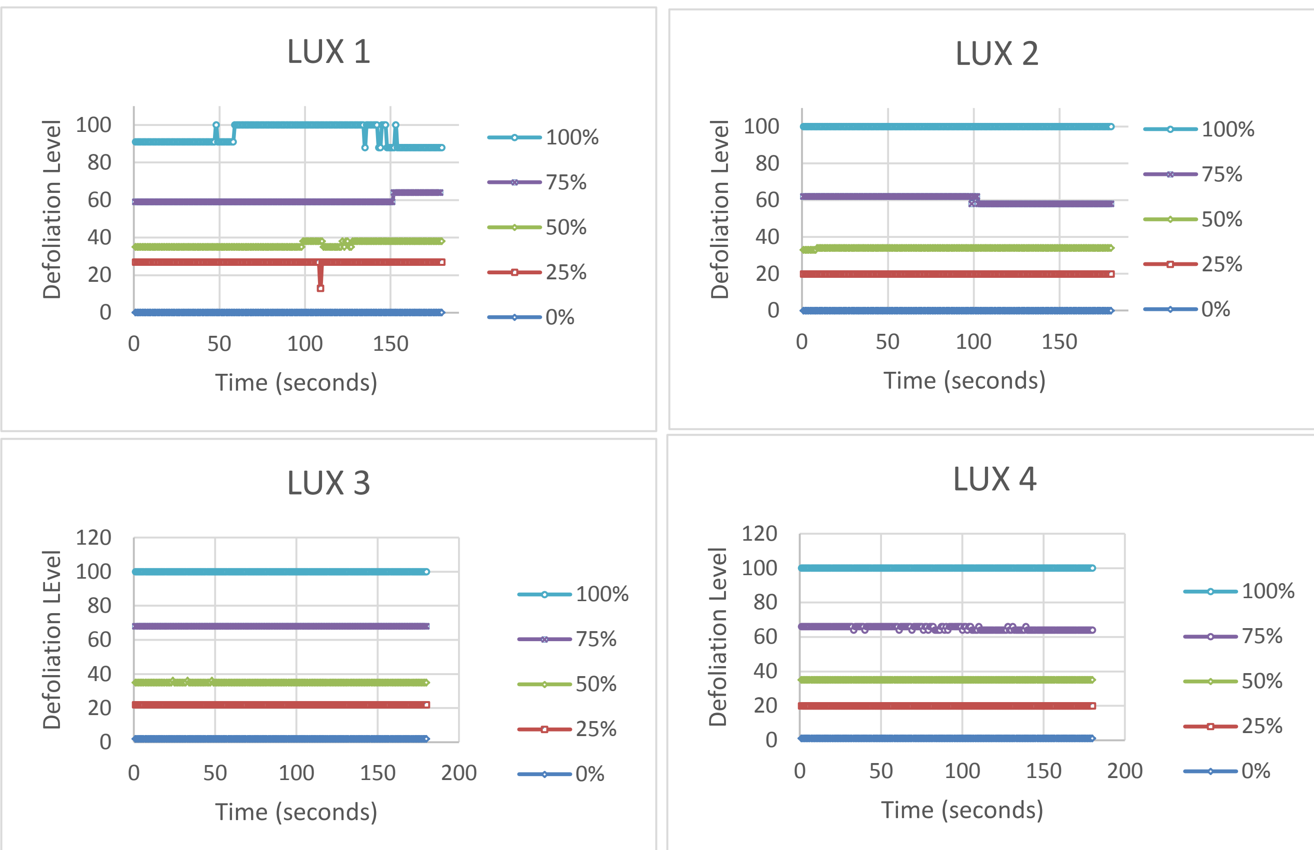


Figure 6. Estimates of defoliation from the first defoliation sensor to cardstock covers with varying levels of simulated defoliation at light intensities lux_1 to lux_7.



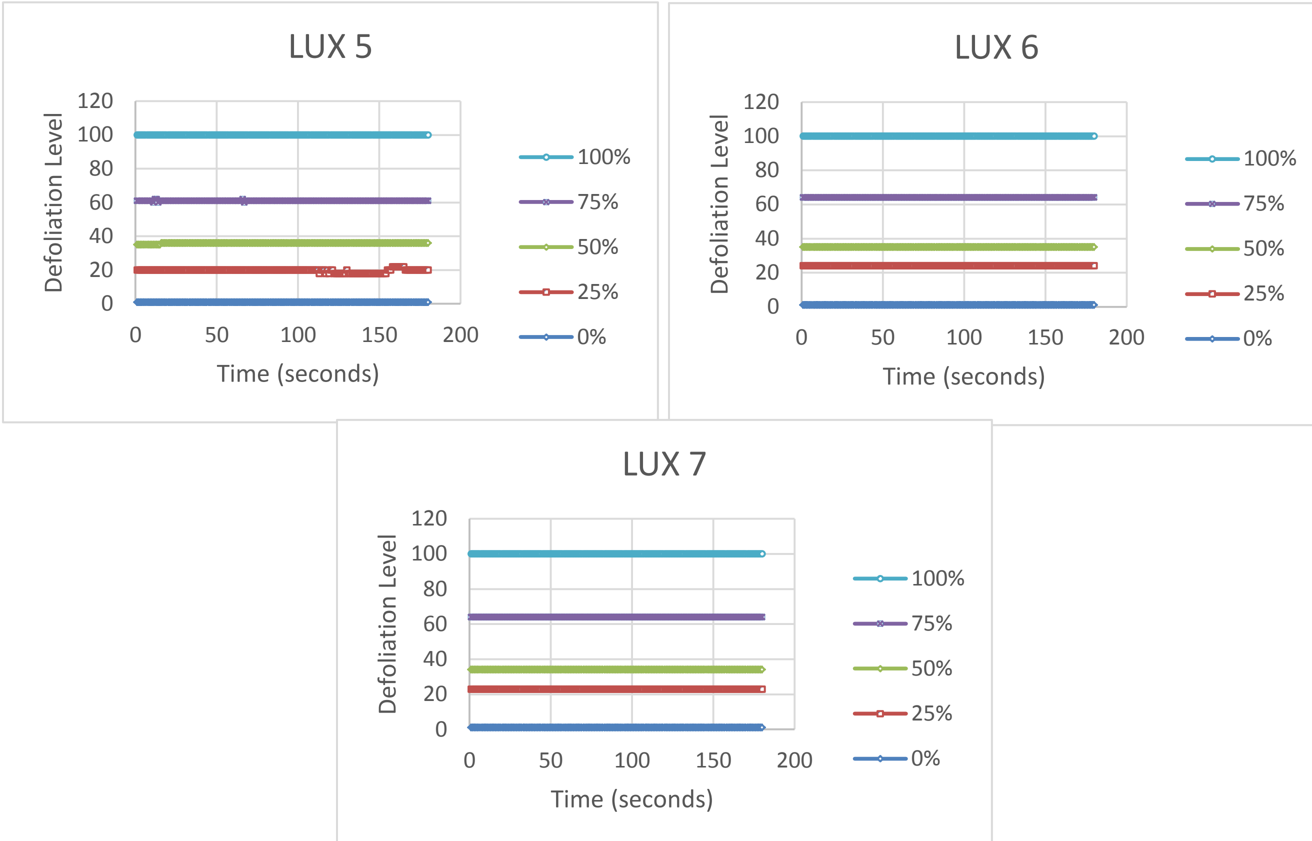


Figure 7. Estimates of defoliation from the second defoliation sensor to cardstock covers with varying levels of simulated defoliation at light intensities lux_1 to lux_7.

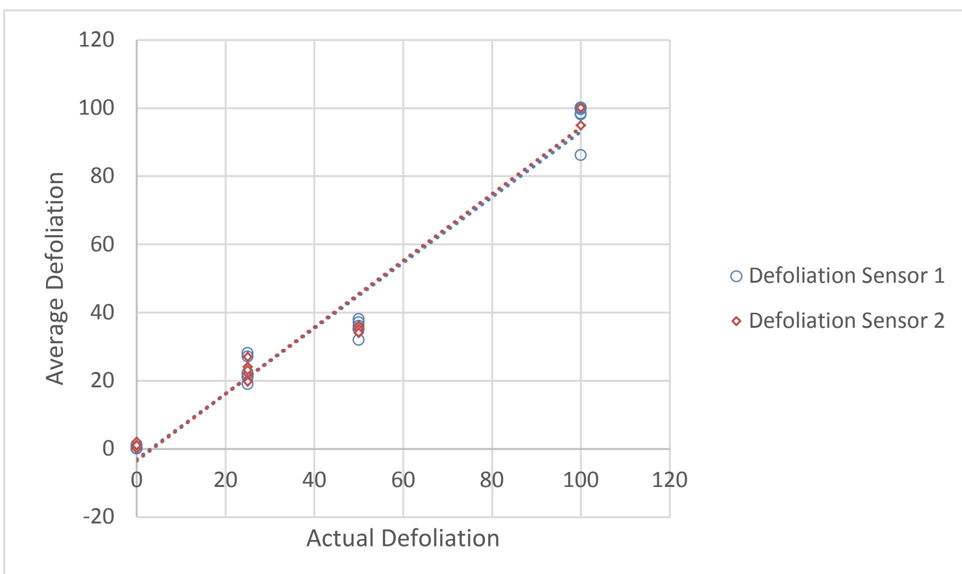


Figure 8. Linear regression line of defoliation accuracy resulting from first defoliation sensor with slope and R^2 equal to 0.9609 and 0.969 respectively and second defoliation sensor with slope and R2 equal to 0.9779 and 0.9696 respectively.

Results from the second set of defoliation covers

Similar to the previous experiment with cardstock covers, responses from the sensors (Fig. 9 and 10) indicated changes in estimates of defoliation when covered with filter paper disks of known/simulated defoliation. However, changes in the estimates of defoliation were smaller for each cover when the light intensity was varied. The accuracy in detecting actual defoliation levels as light intensity varied decreased compared with the previous experiment by about 10%. The average accuracy (Figure 11) of the first defoliation sensor was 87.18% and that of the second defoliation sensor was 89.83% but both had very high reliability.

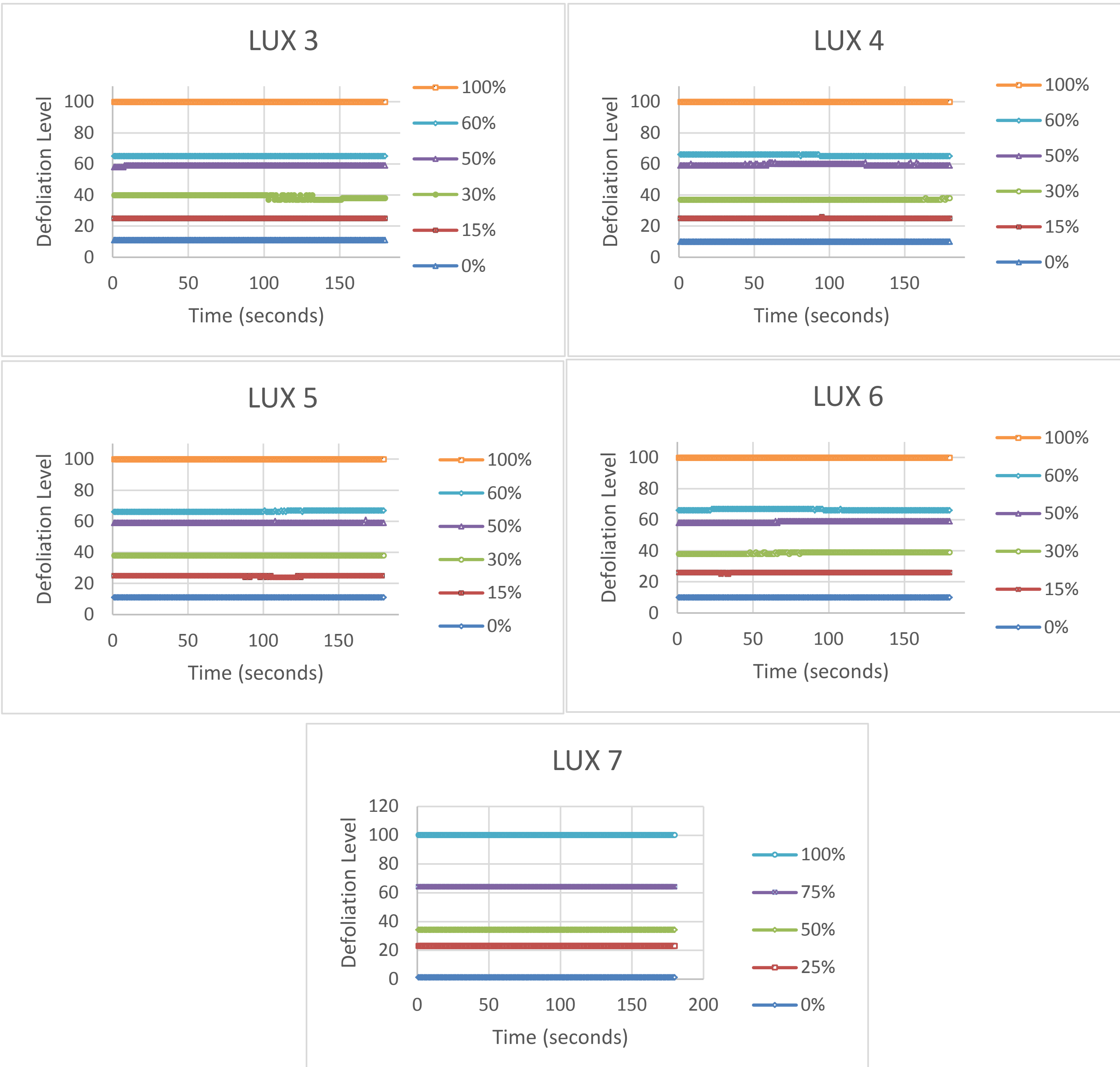
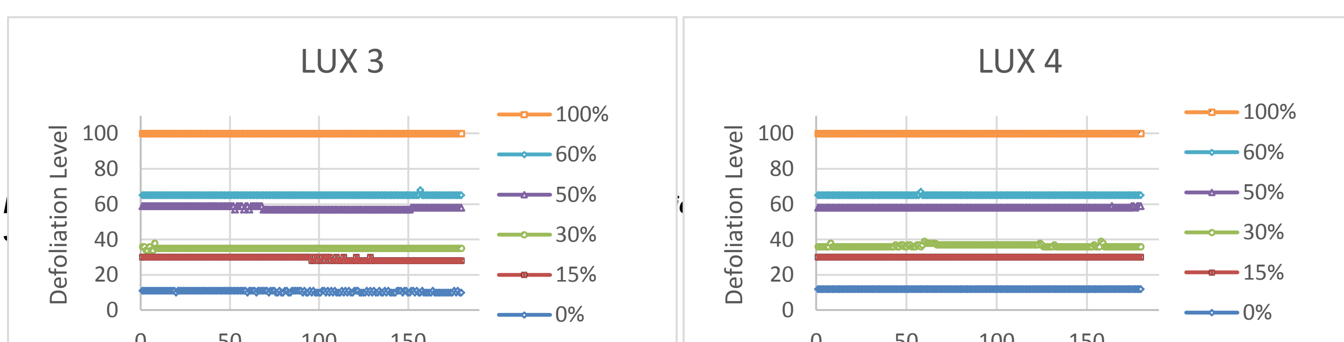


Figure 9. Estimates of defoliation from the first defoliation sensor to filter paper covers with varying levels of simulated defoliation at light intensities lux_3 to lux_7.



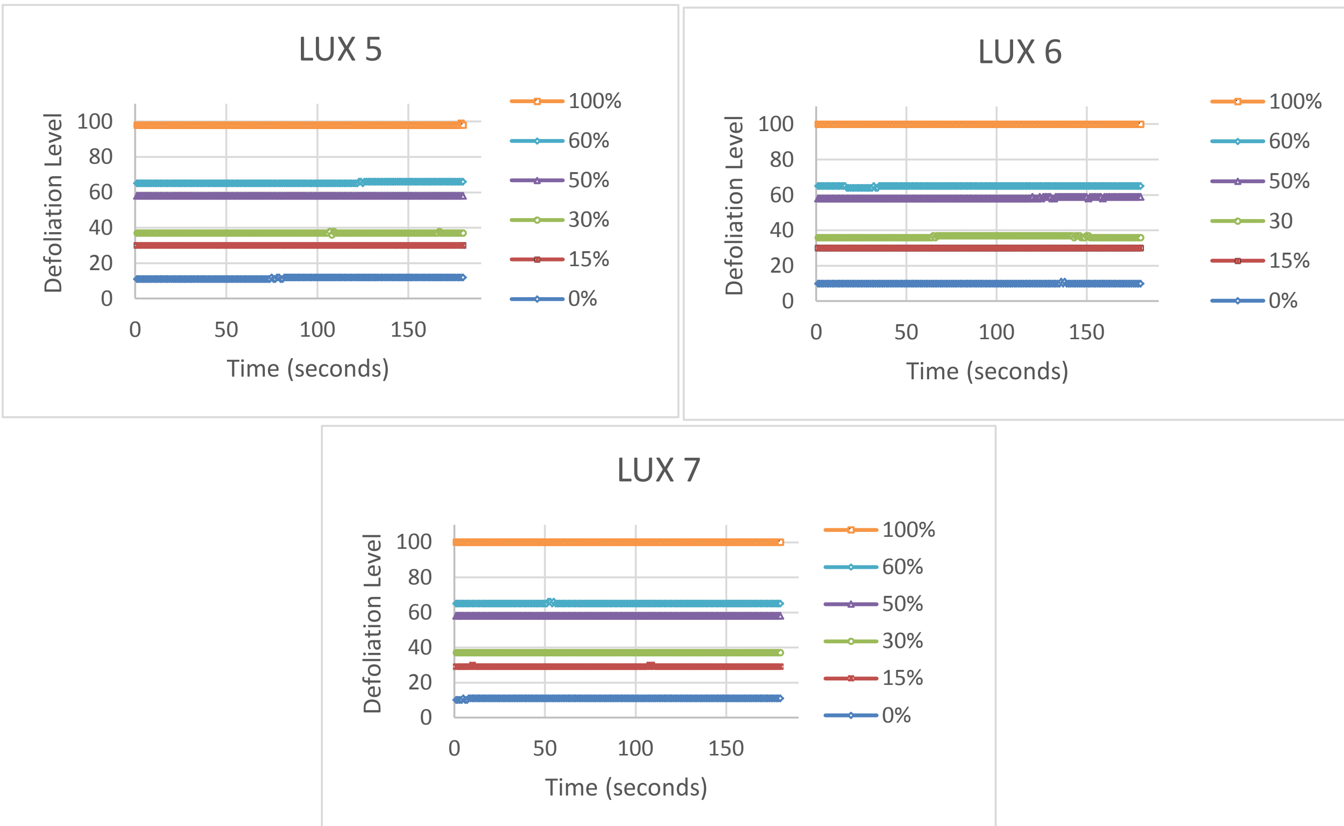


Figure 10. Estimates of defoliation from the second defoliation sensor to filter paper covers with varying levels of simulated defoliation at light intensities lux_3 to lux_7.

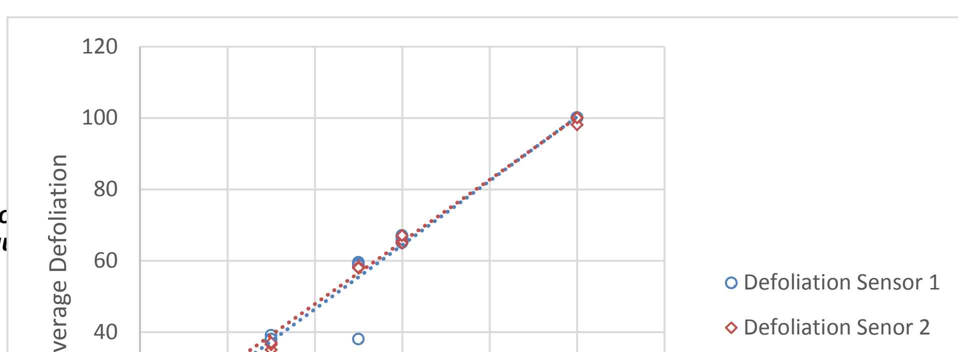


Figure 11. Linear regression line of defoliation accuracy resulting from first defoliation sensor with a slope and R^2 equal to 0.8982 and 0.9803 respectively and second defoliation sensor with a slope of and R^2 equal to 0.8718 and 0.994 respectively.

Discussion

The ability to use sensors in agriculture has enabled more efficient production strategies; particularly when timely inputs are required after data are collected, analyzed, interpreted, and used to make management decisions. The current standard practice for monitoring defoliation caused by insects in a crop, such as soybean, is to manually remove leaves and visually estimate leaf loss. Because of the inefficient and subjective nature of this sampling, a light sensor system was designed and tested for potential to estimate defoliation via instrumentation. The results indicated that the light sensors were capable of estimating various levels of simulated defoliation under varying lighting conditions. However, the sensors required bright lighting to increase precision or consistency and ensure acceptable accuracy in estimating the level of simulated defoliation. The decrease in the accuracy between the first experiment and the second experiment may be due to the materials used for the cover. The paper filter was not thick enough to intercept the light. Thus, a test on actual leaf cover is needed.

Conclusion

This study developed a light sensor-based defoliation sensor. The results showed a change of the defoliation level estimate when there was a change in defoliation cover. Moreover, a small and/or insignificant change on the estimated value of defoliation, per defoliation cover, was observed when the lighting condition was changed. The recorded results of this study demonstrated the feasibility that defoliation level can be estimated by means of light sensors. However, the developed defoliation sensor needs bright lighting conditions to ensure precision and accuracy in estimating the defoliation level.

Further experiments are still needed to be performed, specifically on the actual leaf cover and with sunlight as the light source in order to make changes and calibrations to improve robustness of the measurements. Future development would provide a proximal system that utilizes these defoliation sensors with a wireless module to send defoliation data to the cloud.

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