EVALUATION OF THE OSU NDVI POCKET SENSOR

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Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

2010

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2012

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CHAPTER I

INTRODUCTION

Abstract

There are methods to increase nitrogen use efficiency through optical sensor based nitrogen application; however, the sensors are expensive and cost prohibitive to farmers in the developing world. This study evaluated a reduced cost prototype Normalized Difference Vegetative Index (NDVI) sensor to determine if it could be used with the same level of accuracy as a commercial sensor. The stability of the prototype sensor (Pocket Sensor) to maintain an accurate calibration over time, the effect of operator on sensor readings, and sensor performance in maize and wheat were assessed. Sensor stability was evaluated using turf grass canopies over a 6 month period, and the effect of operator was tested using wheat canopies in existing field experiments. Sensor performance in wheat and maize was also tested in existing field experiments at the International Maize and Wheat Improvement Center (CIMMYT), Ciudad Obregon, Mexico. The prototype sensors were highly correlated to the commercial Greenseeker™ sensor in turf grass, wheat, and maize canopies (r^2>0.97, r^2>0.95, and r^2>0.91 , respectively). With adequate training there was no significant operator effect on sensor readings. The Pocket Sensors lacked some precision in comparison to the commercial sensor (NDVI of the commercial sensor ±0.02, ±0.05, ±0.06 in turf grass, maize, and

wheat); however, even with the reduced precision the cost of the sensor and robustness of N fertilizer algorithms compensate for this apparent weakness. The Pocket Sensor is a viable tool to determine NDVI in wheat and maize and make nitrogen recommendations based upon the data collected with this sensor.

Introduction

Nitrogen is commonly one of the most limiting nutrients in crop production (Girma et al., 2010; Szumigalski and Van Acker, 2006). Even though nitrogen is often limiting, nitrogen use efficiency (NUE) of applied fertilizer remains low. This is due to several factors including nitrogen run-off, leaching, volatilization, and plant losses (Raun and Johnson, 1999). Smil (1999) reported the world NUE to be close to 50% while Raun and Johnson (1999) reported a value of 33% for nitrogen use efficiency (NUE) using the formula:

NUE = [(total cereal N removed)-(N coming from the soil +
N deposited in the rainfall)] / (fertilizer N applied to cereals).

At the time, they showed that a 1% increase in the nitrogen use efficiency is worth more than $200,000,000. Regardless of the calculation difference between these two NUE ratios, it can be inferred that NUE is low and can be improved upon and that even small increases in NUE would result in huge economic savings.

In addition to realizing economic benefits, an increase in NUE would also have several positive environmental impacts. Even though nitrogen is essential for crop growth, excess nitrogen can be detrimental to the environment in a number of ways.

Nitrogen in surface water runoff can lead to algal blooms and eutrophication in affected bodies of water (Beman et al., 2005), in addition nitrogen can be lost through leaching, contaminating ground water (Riley et al., 2001), as well as N_20 gas emissions (Matson et al., 1998). N_20 is a potent greenhouse gas that has 300 times the warming potential of CO_2 (Raun and Johnson, 1999). These inefficient and harmful effects of nitrogen have been well documented in the United States and throughout the world. Malakoff (1998) estimated that more than $750,000,000 worth of excess N annually flows down the Mississippi River into the Gulf of Mexico. In the Yaqui Valley in Sonora, Mexico, satellite imagery has been used to document algal blooms in the Gulf of California that correspond to irrigation and fertilizer events. In addition, the algal blooms are proportionate in size to the amount of nitrogen that is estimated to be lost to surface water run-off (Beman et al., 2005). These examples demonstrate some of the economic and environmental consequences of poor NUE within developed and developing countries.

Combining low NUE rates with the fact that 70% of the world's nitrogen fertilizer is applied in developing countries (Heffer and Prud'homme, 2007) there is a large demand to develop methods that can be implemented in diverse regions of the world that will increase NUE, resulting in economic savings and lessen environmental impact. This paper will focus on the evaluation of the new OSU NDVI Pocket Sensor prototype, and how this instrument can help answer the question, "How do we maintain productivity, while reducing our environmental impact?"

CHAPTER II

REVIEW OF LITERATURE

Any attempt to solve the question of how to enhance our use of applied nitrogen fertilizers more efficiently should be built upon past knowledge. With such a large and important issue, many researchers have documented methods and tools to enhance NUE. Technologies ranging from vegetative indices to fertilization algorithms as well as agronomic practices have been used to increase NUE.

Development of Light Indices

Since Benedict and Swidler (1961) published results using light reflectance in the 625 nm range to estimate the relative amount of chlorophyll in a non-plant destructive method, there has been increasing interest in using light reflectance to measure plant characteristics. Thomas and Oerther (1972) used light (550 nm) as a method to quickly estimate the nitrogen content of sweet peppers. They hypothesized that nitrogen content could be estimated because it is expressed uniformly throughout the leaf.

The results of using one wavelength to measure crop parameters evolved into using combinations and mathematical manipulation of multiple wavelengths to describe vegetation. The result of combining multiple wavelengths by mathematical processes to describe plant vegetation or characteristics is known as a vegetation index (VI) (Wanjura and Hatfield, 1987). In 1973 one of the most used indices, and what would later become the Normalized Difference Vegetative Index (NDVI) was described. This index was sensitive to the amount of photosynthetic vegetation and was found to give good results of the amount of photosynthetic active biomass (Tucker, 1979). By 1984, Perry et al. summarized the results of nearly 50 different spectral radiance indices (VI's) that had been developed to express plant characteristics such as leaf area, percent ground cover, and biomass. The analysis of these indices showed that many displayed similar values and the results of different VI´s were concluded to be the same if the decisions based upon the indices were the same regardless of the index used.

Nitrogen Application and Spectral Radiance

Blackmer et al. (1994) suggested that light reflectance could be used to detect nitrogen deficiencies in growing corn leaves. Stone et al. (1996) not only documented nitrogen differences in wheat, but applied variable rate nitrogen based on spectral readings. They used a variation of NDVI and a linear relation with nitrogen content to determine nitrogen fertilizer application rates. This resulted in no difference in yield between variable rate application and the uniform N application; however, there were N savings between 32-57 kg ha^{-1}. Further work by Raun et al. (2001) showed that using NDVI values collected during the growing season could be used to predict crop yield potential. This was significant because if crop yield could be accurately predicted any application of nitrogen fertilizer could be tailored for the specific site, reflecting nitrogen status and need of the crop in order to achieve the estimated yield potential.

Continuing this work, Lukina et al. (2001) reported using in-season estimate of yield (INSEY), which was NDVI readings divided by the days from planting. In addition to estimating final yield, they also reported a method for nitrogen fertilizer recommendations based on spectral readings, called the Nitrogen Fertilization Optimization Algorithm (NFOA). Their method consisted of estimating yield, determining the amount of nitrogen that would be removed by the estimated grain yield, determining the amount of nitrogen the plant would take-up from the soil to produce the yield, and using NDVI from the crop to determine current (crop at time of sensing) N uptake level from the soil. This number, current N up-take of the crop, was then subtracted from the expected total N uptake level, resulting in a fertilizer recommendation to maximize yield potential.

Since the NFOA was reported, it has been updated with more information including the idea of a response index (RI) (Raun et al., 2002; Mullen et al., 2003). Mullen et al. (2003) described the RI as the crop response to additional nitrogen. The RI is also known to vary from year to year, so one year there may be a large response to applied N while the next year there could be little response to any applied nitrogen. Johnson and Raun (2003) hypothesized that farmers could use a non-nitrogen limiting strip and compare the non-limiting strip to the rest of the farmer's field as a diagnostic tool for making N fertilizer recommendations. If a difference can be noted visually, between the non-limiting nitrogen strip and the rest of the field which is a visual illustration of the RI, then there would be response to additional fertilizer. Raun et al. (2005a) published comprehensive work on the NFOA that included estimated yield potential, RI, and coefficient of variation (CV) as a parameter for crop uniformity. Using these methods, Raun et al. (2002) showed that NUE in winter wheat was improved by 15% compared to traditional fertilizer practices.

While the NFOA and associated methods provided one method to calculate nitrogen recommendations, it was not the only work in the field involving spectral radiance to develop N recommendations. Varvel et al. (1997) used chlorophyll meters and a sufficiency index to make fertilizer recommendations during the crop growing season. Zillmann et al. (2006) reported using red edge (720-740 nm) reflectance readings to estimate a chlorophyll index. This index was related to biomass, and by using proprietary relationships, N fertilizer recommendations were made.

Even though there are a variety of methods to use spectral radiance, there is an overwhelming body of evidence that suggests spectral radiance can be used for the efficient management of nitrogen. By using spectral data, researchers have documented maintaining crop yields while saving N fertilizer (Stone et al., 1996), demonstrating that early season N deficiencies could be corrected (Varvel et al., 1997), and that variable rate N management could be used efficiently when N was the limiting factor of crop growth (Zillmann et al., 2006).

Constraints to Improved Nitrogen Use Efficiency

The use of spectral radiance and the work to develop fertilization algorithms has led to the ability to increase NUE. Li et al. (2009) documented a 61% NUE in wheat in China using N fertilizer recommendations based on using optical sensing and a N fertilization algorithm. This is well above the worldwide NUE of 33% as documented by Raun and Johnson (1999), and this research was conducted in a developing country. In addition to using optical sensors, Raun and Johnson (1999) cited a variety of methods that could be used to improve NUE: including crop rotation, cultivar selection, type of nitrogen source, irrigation amount and timing, and timing and rate of nitrogen fertilizer application. With a variety of options and methods to improve NUE, it would be logical that the worldwide NUE would increase; however, this has failed to happen to any appreciable extent.

The use of optical sensors to manage N should increase around the world because of the benefits that they have shown. Using optical sensors to manage N fertilization has been shown to improve NUE (Li et al., 2009; Raun et al., 2002), decreased application of N without crop yield reduction (Stone et al., 1996; Ortiz and Raun, 2007), and improved farmer income (Ortiz and Raun, 2007). One of the main constraints hindering the adoption of this technology is the cost. Currently, a GreenSeeker sensor costs $4,500. This is definitely cost prohibitive to small farmers in the developing world as well as a large number of farmers in the United States. If a small, affordable NDVI sensor could be developed, it would have the potential to drastically improve N fertilizer management practices for farmers in the developed and developing world.

Objective

The objective of this study was to determine if a smaller, more cost-effective, prototype NDVI sensor (OSU NDVI Pocket Sensor) could be used to duplicate the results of larger, commercial NDVI sensors. This study examined the stability of the sensor calibration over time (where stability is the ability to reproduce similar sensor readings from one sensing time to the next over several days or months as compared to the GreenSeeker), the effect that the sensor operator had on sensor readings, and how the sensor operated in both maize (*Zea mays*) and wheat (*Triticum aestivum*). These data should have a significant impact upon both the development and commercialization of a compact, affordable NDVI sensor. In addition the data will be used to make recommendations for how and when to take sensor readings to obtain the same results as compared to the commercial sensor GreenSeeker.

CHAPTER III

METHODOLOGY

Several field experiments were conducted to compare NDVI readings between the OSU NDVI Pocket Sensor and the hand held GreenSeeker Sensor (Trimble Navigation, Sunnyvale, CA). The GreenSeeker Sensor measures normalized difference vegetative index (NDVI) by using a self-illuminated (active sensor) light source in the red and near infrared wavelengths, (660 ± 10 nm) and (780 ± 15 nm) respectively. The GreenSeeker calculates NDVI using the following formula: NDVI = $(\rho_{NIR} - \rho_{red}) / (\rho_{NIR} + \rho_{red})$ where ρ_{NIR} = the fraction of emitted NIR radiation returned from the sensed area (reflectance), and ρ_{red} = the fraction of emitted red radiation from the sensed area (reflectance). The GreenSeeker has an area of measurement of 1 cm X 60 cm when used in a normal operating range of 60 cm to 100 cm over the top of the crop canopy. This sensor collects > 10 readings per second and this information is stored in the IPAQ control unit.

The OSU NDVI Pocket Sensor is also an active sensor. In order to create a reduced cost sensor, the OSU NDVI Pocket Sensor has some reduced functions in comparison to the GreenSeeker. The sensor only collects 1 reading per second, and the area of measurement is circular in dimension, and at a height of 60 cm over the crop canopy it measures an area of 200 cm^2. The Pocket Sensor lacks on-board memory storage, and once a measurement is taken the screen shows the reading for 2 seconds, and then the data is erased from memory. The Pocket Sensor is also “field” calibrated to the GeenSeeker sensor. The calibration consists of measuring vegetation that represents a series of NDVI values with both the GreenSeeker and the Pocket Sensor. Pocket Sensor readings are then related to the GreenSeeker NDVI readings using a quadratic equation. The coefficients of the equation are then entered into the pocket sensor memory that automatically adjusts the Pocket Sensor readings to display the equivalent GreenSeeker NDVI value. While the GreenSeeker shows little effect to height and sensor orientation, the Pocket Sensor readings are significantly affected by height and angle of the sensor. To maintain similar readings all Pocket Sensor readings reported, unless otherwise noted, were taken at a height of 60 cm above the crop canopy by using a string with attached weight to maintain a uniform height above the canopy. In addition, a small bubble level was attached to the sensor. This bubble level provides sufficient guidance to maintain the sensor in a horizontal position with the ground.

Stability of Sensor Calibration

The first experiments conducted were to evaluate the stability of the sensor calibration. Several Pocket Sensors were calibrated at a height of 60 cm, and then subsequent readings were taken over the following 6 months in Ciudad Obregon, Sonora, Mexico, to evaluate sensor performance. To evaluate the calibration, Pocket Sensor and GreenSeeker readings were taken over selected turf grass canopies. Grass canopies provided very uniform surfaces that could be easily and accurately measured. In addition to being uniform, these areas were also readily available with time, where using field crops, wheat, corn, safflower, etc., would be dependent upon growth stage and fertilization practices. The areas measured were small plots that were approximately 1m

X 1m. GreenSeeker readings were used as the standard value, and GreenSeeker readings were taken from each plot before Pocket Sensor readings. This allowed confirmation that the area was uniform. Any location that showed a range greater than 0.015 NDVI with the maximum and minimum GreenSeeker NDVI value was discarded and other locations were found. Each time the calibrations were reviewed, ten locations, representing NDVI values from 0.150 to 0.850, were used. Three readings were taken with the GreenSeeker sensor and then three readings were taken with each of the Pocket Sensors. These data were analyzed using a simple linear regression procedure in SAS (2003), for each sensor for the entire trial period and for each measurement event. In addition to determining the coefficient of determination (r^2), the data were tested to see if the intercept and slope were different from 0 and equal to 1, respectively. This was tested using the assumption that if the Pocket Sensor and GreenSeeker were equivalent then the regression line should have a slope of 1 and intercept of 0.

Effect of Operator on Sensor Readings

The Pocket Sensor is much more susceptible to variations in height and angle. Due to this known variation, trials were conducted to find out what effect the sensor operator might have on the sensor readings. In Ciudad Obregon, various readings were collected in existing field trials to determine the amount of operator error in sensor readings. Four beds of wheat 10m long were measured for NDVI using two GreenSeeker sensors and three Pocket Sensors. The NDVI values from GreenSeeker sensors were used as the standard NDVI, and then plots were measured three times with each sensor. Two different operators used all the sensors in each row resulting in a 5 x 2 factorial arrangement. The measurements of the pocket sensor were then compared to one of the

GreenSeeker results. These data were analyzed using a SAS generalized linear model for a completely randomized design with a factorial arrangement of treatments. After initial data analysis was completed, selected single-degree-of-freedom contrasts were analyzed to determine differences in sensors and operators.

A similar experiment was also conducted using two different pocket sensors and two different operators. In this experiment, the results of the pocket sensors were compared to each other, with no GreenSeeker treatment representing a control NDVI. Data analysis was similar using a general linear model for analysis of variance for a 2 x 2 factorial with 8 locations. These experiments tested the effect of operators on sensor readings, and how accurately the pocket sensors could measure NDVI.

Sensor Readings in Maize

The Pocket Sensor was also evaluated in maize. In the Yaqui Valley, Sonora, Mexico, preliminary work focused on how to accurately measure NDVI in corn. Initial data collection showed that a single pocket sensor reading compared to a single GreenSeeker reading in maize did not provide accurate prediction of NDVI. It was determined that by taking an average of 3 readings with the pocket sensor and using that average as the predicted NDVI correlated well to the GreenSeeker (Data shown in Figures 1 and 2).

Following a late season freeze, maize on the CIMMYT experiment station was replanted. This allowed for data capture using the technique of taking one GreenSeeker reading and comparing it to an average of three pocket sensor readings over the same area as determined by preliminary work. NDVI readings were taken beginning at growth stage V4 (Ritchie et al., 1996) and continued until the maize was too tall to take added measurements. Growth stage was recorded for the measurements, and as the maize became too tall, the height of the plot was taken. Height was taken by measuring the height of the whorl, point from which Pocket Sensor readings were taken from three random plants in each plot. Data were analyzed similar to the calibration stability methods, using simple linear regression to determine the correlation of coefficient between the Pocket Sensor and GreenSeeker readings. Regression models were also determined for growth stage.

Sensor Readings in Wheat

Sensor readings were taken on existing experiments on the CIMMYT experiment station in Ciudad Obregon, Sonora, Mexico. Similar to the maize experiments, the experiment Y226, designed to test wheat response to differing levels of N, was selected for NDVI measurements with the Pocket Sensor and GreenSeeker. Y226 was planted in melgas, a flat planting surface, with 8 different durum and 8 different bread wheat varieties. There were five different rates of pre-plant N. One variety of bread wheat and one durum were selected for the majority of the readings. Sensor readings were taken four times during the growing season corresponding to growth stage Feekes 4-10 (Large, 1954). Three pocket sensor readings were taken and averaged, and then compared to Greenseeker readings. Simple linear regression was used to analyze the data, using the same procedure that was used in the calibration stability experiments.

CHAPTER IV

RESULTS

Stability of Sensor Calibration

Data were collected to evaluate the stability of the calibration of the Pocket Sensors. Stability is the ability of the sensor to read the same NDVI's over time. Over the six month period (December 6, 2010 - May 27, 2011), Pocket Sensor stability was maintained for all sensors, and there was no trend of the calibration changing over time. Table 1 displays the analysis of all of the data regarding stability. Of the five sensors tested, only Pocket Sensor#32 had a slope and intercept that was 1 and 0, respectively. The other Pocket Sensors differed from a slope of 1 and intercept of 0; however, the correlation was extremely high between the pocket sensors and GreenSeeker with coefficients of determination above $r^2 = 0.98$. With this high level of correlation, the Pocket Sensors accurately predicted NDVI, which is depicted in Figures 1-5. The Pocket Sensors did maintain a tight confidence interval with the average interval for the predicted sensor mean being ±0.018 and ±0.032 for the intercept and slope, respectively.

Not only was the overall stability excellent, but at each testing date the Pocket Sensors resulted in equivalent NDVI readings. It was common that the slope and intercept of the Pocket Sensor compared to the GreenSeeker would vary slightly each time; however, there were no trends to show that the stability of the calibration in the

Pocket Sensor changed or diminished over time. Tables 2-6 reports the individual sensor results for each evaluation period, and Figures 6-14 depict the average variability between testing dates.

Effect of Operator on Sensor Readings

Analysis of variance of the two experiments to evaluate the effect of the operator on sensor readings, are reported in Tables 7 and 8. Table 7 shows the results of 8 different wheat plots using two different pocket sensors and two operators. Five of the eight plots had no significant findings, while two of the plots had a significant interaction between sensor and operator, and one plot had a significant operator effect at the 0.05 significance level. Table 8 shows the results of the effect of different operators and sensors, including both GreenSeeker and Pocket Sensors. Two rows showed significant interaction between operator and sensor while the other two rows showed a significant effect for the sensor at alpha = 0.05 level. The sensor effect could be expected, as the GreenSeeker has more precision than the Pocket Sensor. Based on these findings a single degree of freedom contrast was evaluated to compare the two GreenSeeker sensors used in the experiment. The two GreenSeekers were statistically different in the two rows where a significant sensor by operator interaction occurred.

Sensor Readings in Maize

The Pocket Sensor readings in maize for growth stages 4-10 are summarized in Table 9. For growth stages V4-V10, the Pocket Sensors were highly correlated ($r^2 > 0.9$) and performed statistically similar to the GreenSeeker. Data were collected past the V10 growth stage; however, as the maize grows it becomes more difficult to obtain accurate measurements with the Pocket Sensors. Along with recording growth stages, the height of the plant whorl was also recorded. Once the plant whorl reached a height of 100 cm, Pocket Sensor readings diminished in value. This is most likely due to holding the Pocket Sensor above eye level (100 cm to canopy + 60 cm above the canopy =160cm) and an inability to hold the sensor level. Growth stage V11 and greater data were not included in the analysis because the best model occurred with V4-V10 data. Figures 17 and 18 display the relationship between Pocket Sensor and GreenSeeker readings in maize. Pocket Sensor readings in maize are listed by growth stage, including the line of best fit and correlation in Table 10 and Figures 19-29.

Sensor Readings in Wheat

Table 11 displays the Pocket Sensor data for wheat in Ciudad Obregon. For all data both sensors were statistically similar to the GreenSeeker with a slope of 1 and intercept of 0, respectively. Figures 31 and 32 show the line of best fit and correlation between the Pocket and GreenSeeker sensors from January 3-February 2, 2011, for selected wheat plots. Figure 30 shows all wheat plots in experiment Y226 compared to the GreenSeeker. One outlier was removed from this analysis of 160 plots. The correlation for all sensors for wheat data ($r^2 > 0.95$) was slightly higher than for the maize, which was most likely due to canopy structure differences between wheat and maize. Table 12 and Figures 33-39 include analysis of the wheat data based on time of collection.

CHAPTER V

DISSCUSSION

Stability of Sensor Calibration

The Pocket Sensors have good calibration stability. The Pocket Sensor readings collected over the six month period consistently reproduced similar NDVI values compared to the GreenSeeker. This is an excellent trait for a device that is being developed for developing countries. The stability displayed by the Pocket Sensor would allow for an initial calibration to be made, and then the Pocket Sensors could be used for extended periods of time without being concerned about the quality of readings. Over the six month period of testing, the sensors were used extensively, allowed to dissipate the battery, charged and used again and the stability of readings stayed constant.

Some variation in the stability data was found, however, it probably represents minor effects of the operator and ability to accurately measure a canopy with both the GreenSeeker and Pocket Sensors. While data were collected as precise as possible, it is very likely that the area of measurement of the sensors were not 100% accurate, if nothing else due to the type of sensing pattern, rectangular for the GreenSeeker and circular for the Pocket Sensor. Even with these limitations, the five Pocket Sensors tested performed on average of GreenSeeker NDVI ±0.02. This was determined by using the upper and lower 95% regression estimates and determining how the Pocket Sensor NDVI (95% confidence level) would deviate from a control value (Table 13).

Effect of Operator on Sensor Readings

Tests designed to determine the effect of the operator on sensor readings showed some significant differences between sensors and operators and well as sensor by operator interaction. However; upon inspection of the data, much of this variation was small. In the eight plots where pocket sensors were compared, only one sensor comparison differed by more than 0.03 NDVI. From the stability data, the accuracy of the Pocket Sensor is ±0.02 NDVI, along with the SED (Standard Error of the Difference of two equally replicated means) being approximately 0.012. With the known error in NDVI readings, it is not surprising to find data such as these, and further analysis of small difference in NDVI is discussed.

In the four rows where NDVI was read with 3 Pocket Sensors and 2 GreenSeeker sensors, there was a significant interaction between sensors and operators in two rows. The other two rows showed a significant effect for sensor. The effect of sensor should be expected as the GreenSeeker is slightly more precise, and the Pocket Sensor measures ±0.02 NDVI as measured by the GreenSeeker. While data were collected meticulously, the two rows with an interaction could be due to canopy changes from the first readings to the final readings. Care was taken not to step on or damage the canopy; however, operators walked beside the canopy in beds more than 60 times collecting the data, thus small changes could have taken place. Regardless of the reason for such differences in rows 2 and 3, Pocket Sensor differences were small and were within the range of values measured by the GreenSeekers.

Even with the differences that were observed, the data show that different operators can obtain similar results. This is extremely important for the Pocket Sensor because it is to be mass produced and there will be many operators. To obtain similar results, the operators should be trained and take sufficient amounts of data so that they are comfortable and confident using the Pocket Sensors. This training will help insure that the N fertilizer recommendations made by any operator are accurate.

Sensor Readings in Maize

The Pocket Sensors performed well in maize. By evaluating the confidence intervals and predicted NDVI's, maize readings should include an adjustment that is wider than readings over grass canopies. The average sensor reading in maize is NDVI±0.05 (Table 13). This adjustment is reasonable because of the difference in canopy architecture. In grass readings, the canopy was enclosed and uniform; however, in maize the plants grow up and there is space between the plants. This space and failure of the canopy to be completely closed probably results in the poor correlation at young vegetative stages V4 (Figures 19-21). Even though the V4 data were not highly correlated (r^2=0.32 compared to later growth stages r^2>0.8), the graph of these data were close to the expected values. Correlation was likely low due to the early growth stage and lack of early nitrogen stress. Beginning at V5 and later vegetative stages, the correlation and model improved most likely due to a more uniform canopy. Raun et al. (2005b) reported that the greatest variation occurred at V6 and as the canopy closed, the coefficient of variation (C.V.) among data readings decreased. Sensor readings were taken after growth stage V10; however, the models for these data were less accurate than data between V4-V10. Similar to the problem of a developed canopy, once the maize neared V12 there were problems taking readings due to the height of the plant. While this could be a concern as far as the utility of the Pocket Sensor, accurate data collection was maintained to V10. As Scharft et al. (2002) noted most top dress fertilizer applications occur before V8 because no special equipment is needed. After V8 it is likely that high clearance equipment will be needed to avoid damaging the maize and this equipment is not readily available in developing countries. The Pocket Sensor should be able to deliver the intended results of affordable and accurate N fertilizer recommendations in maize.

Sensor Readings in Wheat

The Pocket Sensor readings in wheat were highly correlated to the GreenSeeker. Based on confidence intervals, the accuracy of the Pocket Sensors was NDVI±0.06. Correlation between the Pocket Sensors and the GreenSeeker were higher in wheat than in maize. This is probably due to the short, well closed canopy that wheat develops compared to corn. Based on the results, the Pocket Sensor should be able to make N fertilizer recommendations in wheat.

Significance of Findings

While the GreenSeeker and Pocket Sensors were similar, they were often significantly different at the alpha = 0.05 level. While it would be excellent to see the GreenSeeker and Pocket Sensors read exactly the same, electronic components used in the two sensors suggests they will most likely not be the same. The GreenSeeker is built for precision and cost approximately $4,500. The Pocket Sensor has been designed to mimic the same results, but at less than one tenth the cost. Similar to the cost of any lab equipment, the more expensive instruments are often more precise. Many of the Pocket Sensors had 95% confidence levels within the GreenSeeker levels and several that were significantly different were different at small values of NDVI. With the ultimate goal of the Pocket Sensor to increase NUE in developing countries and return economic profit to farmers, what does a 0.02 or 0.05 NDVI difference signify? Nitrogen rates are based upon a reference strip, non-nitrogen limiting area, and the comparison to the farmer's field as summarized by Raun et al. (2005a). Table 14, made using the Sensor Based Nitrogen Rate Calculator (http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php) shows the difference in nitrogen recommendation rates for several NDVI values for both corn and wheat. Assuming the Pocket Sensor can accurately read ±0.02 NDVI, N recommendations would only vary within ±4-6 kg N ha^{-1} of the actual rate for corn and wheat, respectively. Even at ±0.05 NDVI, the recommended nitrogen would vary from the needed N rate by ±8-12 kg N ha^{-1} for corn and wheat, respectively. Lawrence and Yule (2007) reported that urea application was ±5 kg N ha^{-1} within the targeted application rate only 24% of the time using a disc spreader. Thus, a recommended rate from the Pocket Sensor, even with small errors, would usually be sufficiently close to the required rate that application error and other environmental variables could have more effect on crop growth than the amount of fertilizer applied.

Along with application rate, these experiments compared the Pocket Sensor to the GreenSeeker. While this made practical sense for evaluation of the Pocket Sensor, in field use the Pocket Sensor will be the only sensor used for both the reference and farmer practice. The Pocket Sensors were calibrated to one GreenSeeker, and in comparisons with other GreenSeeker sensors, effect of users on readings, often the same Pocket Sensor would be slightly, but consistently different from the GreenSeeker. This could be due to slight differences in calibration. The stability data in Figures 8-16 show a trend that a pocket sensor will consistently under or over value a range of NDVI's. For example a sensor which had below 0 intercept and more positive slope usually tended to keep this calibration. Thus, even though the sensor may not read the exact same NDVI as a GreenSeeker it will produce highly similar results. When only using one sensor for readings for NDVI, this may eliminate some of the variation, further enhancing the utility of the Pocket Sensor

Recommendations for Using the Pocket Sensor for N Application

Based on the results of this research, the Pocket Sensor should have excellent utility in making nitrogen recommendations. The Pocket Sensor lacks some precision compared to the GreenSeeker; however, adequate steps could be taken to overcome this limitation. The most probable would be to use the known accuracy and adjust Pocket Sensor readings accordingly. For N applications this may entail adding accuracy (+0.025 and +0.03 for maize and wheat, respectively) to the N rich strip portion of the field, while subtracting the same level of accuracy from the farmer practice. The readings from the N rich strip and farmer practice should be the average of 3 readings over each respective area, similar to the way data were collected for this study. This method will nearly always result in some fertilizer application, but any attempt to better manage fertilizer in the developing or developed world has to strike a balance between N to meet crop needs and enough N to reach maximum economic productivity while not resulting in increased environmental risk. Any method that under applies N and results in lost economic productivity will not find acceptance among farmers. In many high input, intensive agricultural areas in the developing world, often excess N is more of an issue than deficient N. For example, Ortiz-Monasterio and Raun (2007) found reduced N application and increased farmer profits in the Yaqui Valley by using sensor based nitrogen management. Using GreenSeeker sensors the average rate of N application was 69 kg N ha^{-1} less than the farmer practice.

Using the method of adding and subtracting one half of the known accuracy should result in reasonable fertilizer recommendations. Under the worst case scenario, if an actual N rich strip reading was NDVI -0.06 (full value of the known accuracy) and the farmer practice was NDVI+0.06 using the described method would result in a “miss” of the accurate recommendations by 0.06 NDVI or approximately 12 kg N ha^{-1}. While this would result in lower crop yield, this is an extreme example of the Pocket Sensor reading two plots at the most extreme values. While this is possible, this can be avoided by training because an actual 1.2 NDVI difference should be visible to the human eye. The opposite of this scenario calls for added and excess N, which would not result in reduced yields. In intensively managed areas, like the Yaqui Valley, the extra N may still be less than what the farmer would traditionally apply (Ortiz-Monasterio and Raun, 2005). The Pocket Sensor lacks some of the precision of the GreenSeeker; however, this precision was made up for in the reduced cost of the sensor. The mass production of this sensor and its adoption in the developing and developed world has the potential to increase farmer economic productivity and reduce the environmental problems associated with excess N fertilization.

CHAPTER VI

CONCLUSIONS

The Pocket Sensor performed remarkably well in comparison to the GreenSeeker. The results of this study show that the Pocket Sensor had good calibration stability over the six month period that it was tested. The results also indicated that different operators, with adequate training, can obtain similar results. In addition, the Pocket Sensor was highly correlated to GreenSeeker readings in wheat and maize. Data were collected during different growth stages of wheat and maize that allowed for correlation and optimal time of sensing, V4-V10 for maize, and Feekes 4-10 in wheat. The Pocket Sensor had reduced precision compared to the GreenSeeker; however, even with the reduced precision fertilizer recommendations made from the Pocket Sensor do not vary greatly from the optimal rate as determined with the GreenSeeker. Thus, the Pocket Sensor could be an effective tool for determining NDVI in maize and wheat as well as using the collected NDVI to make nitrogen fertilizer recommendations.

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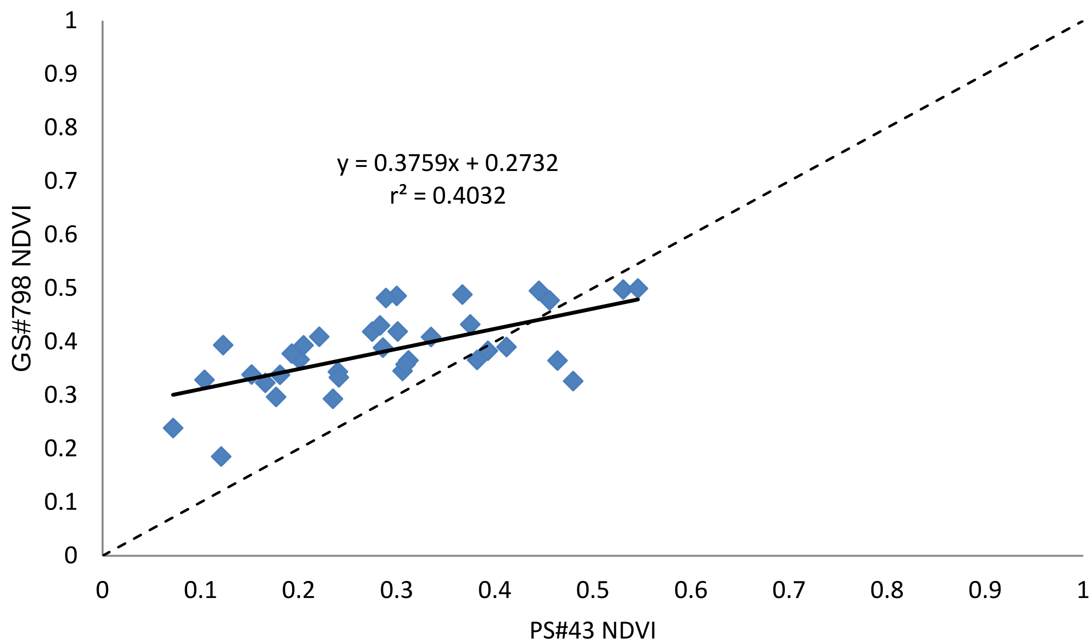

Figure 1. Relationship between one Pocket Sensor #43 NDVI reading and one GreenSeeker #798 NDVI reading, maize growth stage V5, Ciudad Obregon, Mexico, 2010.

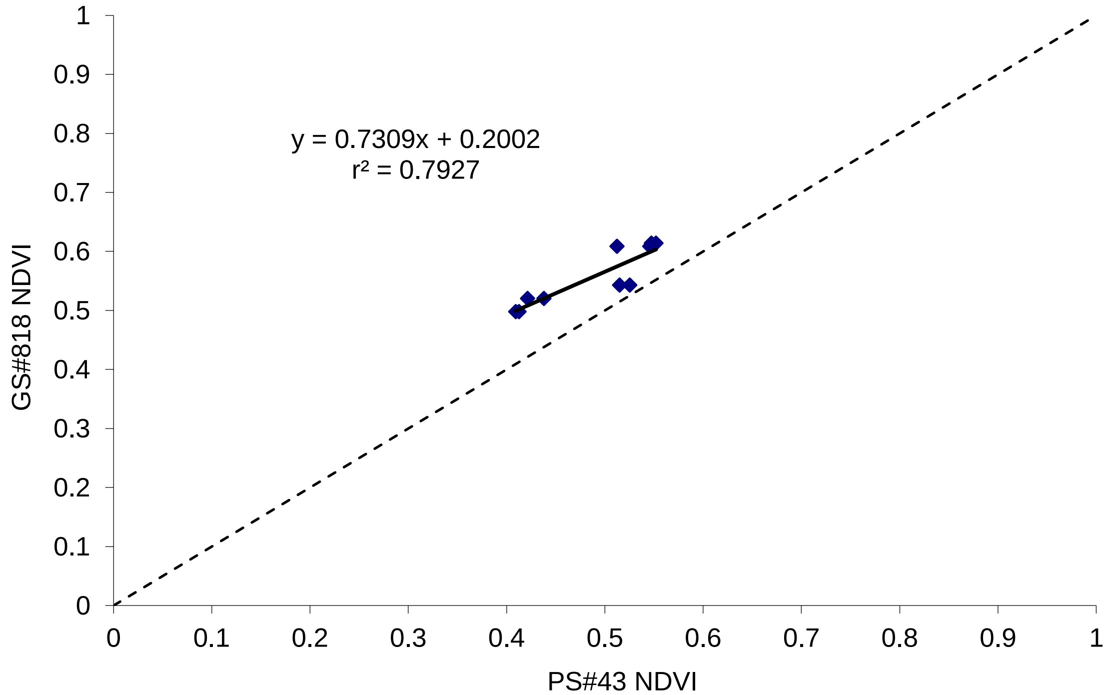

Figure 2. Relationship between 3 Pocket Sensor #43 NDVI readings averaged compared to one GreenSeeker reading, maize growth stage V5, Ciudad Obregon, Mexico, 2010.

Table 1. Stability data for five different Pocket Sensors from December 2010 to May 2011, testing for intercept=0 and slope=1.

Treatment	Sensor	Test Variable	Estimate	r^2	Pr> ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
All Stability Data*	32	Intercept = 0	-0.004	0.980	0.330	-0.013	0.005
All Stability Data*	32	Slope = 1	1.005		0.578	0.988	1.022
All Stability Data	19	Intercept = 0	-0.044	0.979	<.0001	-0.053	-0.034
All Stability Data	19	Slope = 1	1.081		<.0001	1.063	1.098
All Stability Data	27	Intercept = 0	-0.027	0.982	<.0001	-0.035	-0.019
All Stability Data	27	Slope = 1	1.069		<.0001	1.052	1.085
All Stability Data	37	Intercept = 0	-0.009	0.979	0.037	-0.018	-0.001
All Stability Data	37	Slope = 1	1.031		.0005	1.014	1.048
All Stability Data	20	Intercept = 0	-0.008	0.982	0.057	-0.016	0.000
All Stability Data	20	Slope = 1	1.025		.0019	1.009	1.040

*n=88 samples, all other sensors n=98

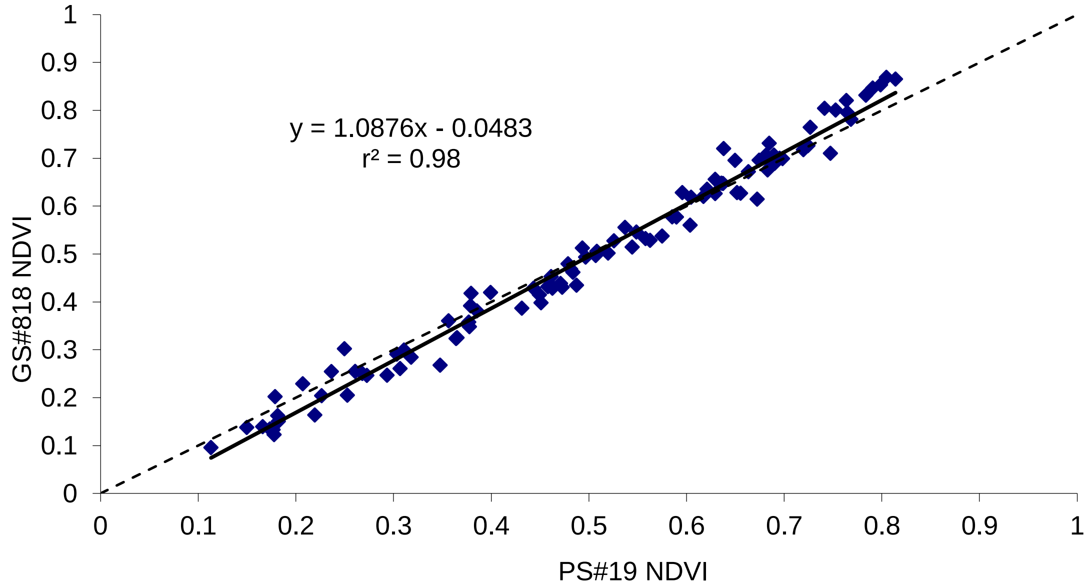

Figure 3. Relationship between NDVI sensor readings from Pocket Sensor#19 and GreenSeeker#818, December 2010 through May 2011.

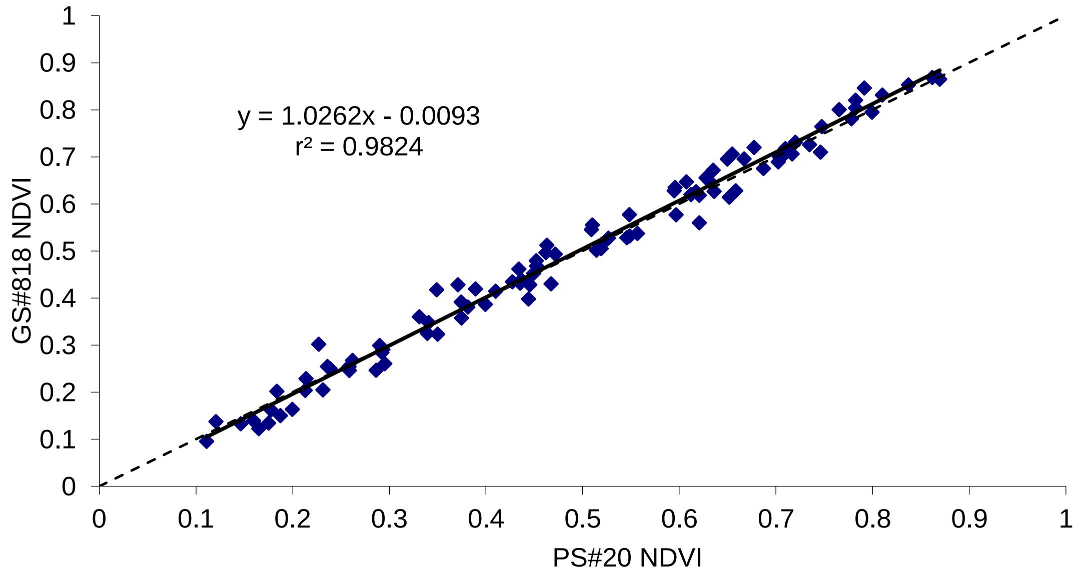

Figure 4. Relationship between NDVI sensor readings from Pocket Sensor#20 and GreenSeeker#818, December 2010 through May 2011.

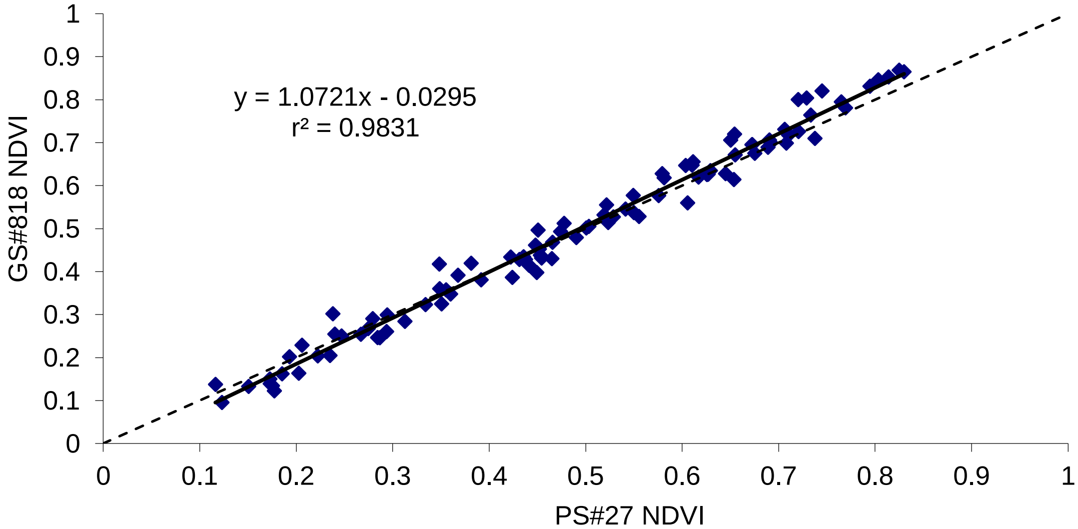

Figure 5. Relationship between NDVI sensor readings from Pocket Sensor#27 and GreenSeeker#818, December 2010 through May 2011.

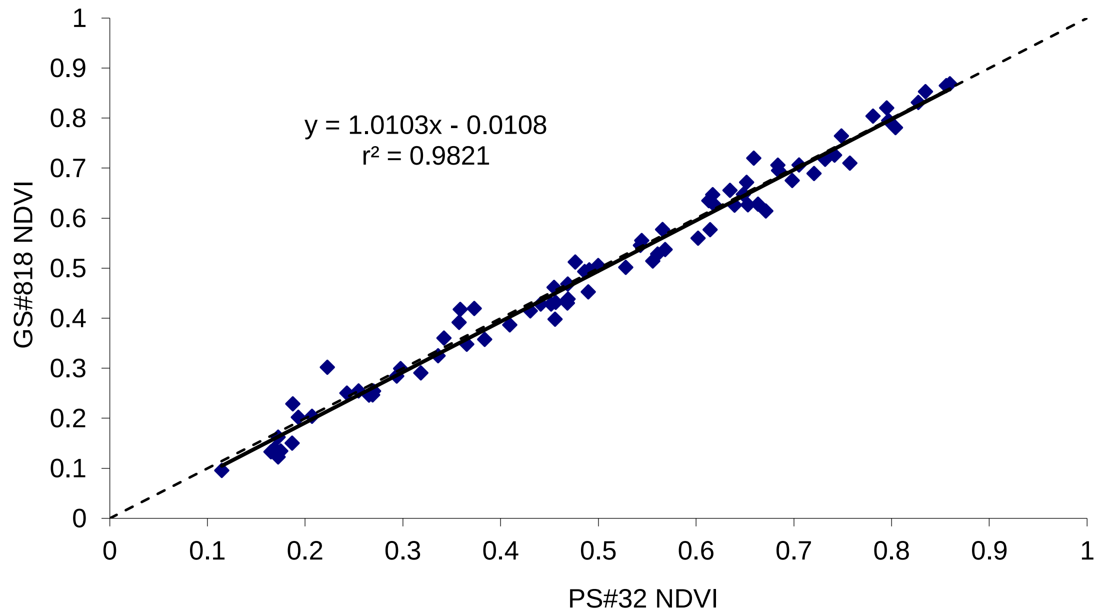

Figure 6. Relationship between NDVI sensor readings from Pocket Sensor#32 and GreenSeeker#818, December 2010 through May 2011.

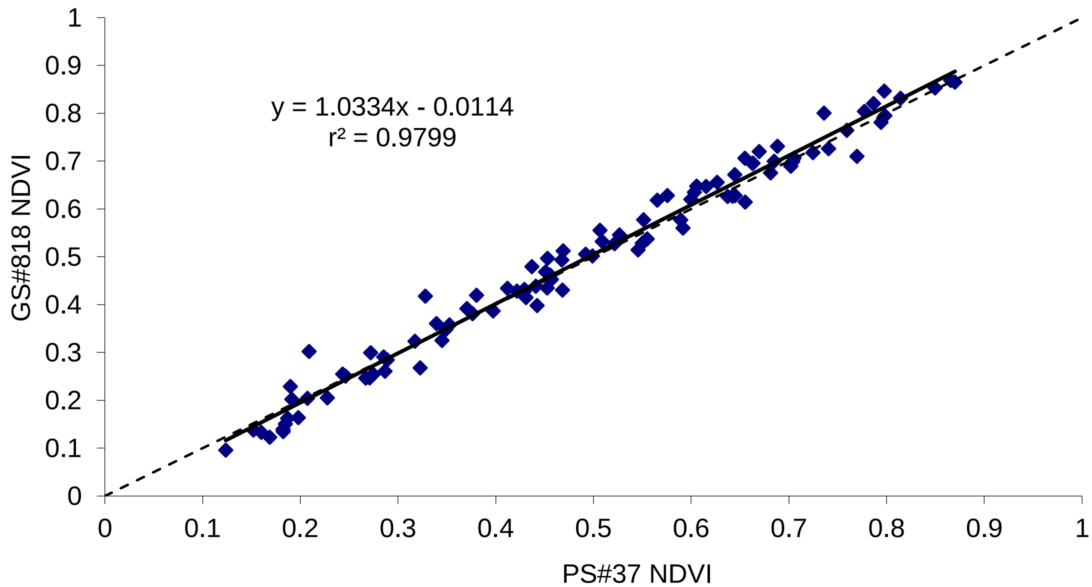

Figure 7. Relationship between NDVI sensor readings from Pocket Sensor#37 and GreenSeeker#818, December 2010 through May 2011.

Table 2. Calibration stability data for Pocket Sensor #19, testing that slope intercept=0 and slope=0 between December 2010 and May 27, 2011.

Data	n	Sensor	Test Variable	Estimate	r^2	Pr> ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
6-Dec-10	6	19	Intercept = 0	-0.014	0.987	0.140	-0.032	0.005
6-Dec-10		19	Slope = 1	1.047		0.030	1.005	1.090
14-Dec-10	10	19	Intercept = 0	0.001	0.972	0.965	-0.033	0.034
14-Dec-10		19	Slope = 1	0.999		0.964	0.933	1.064
3-Jan-11	10	19	Intercept = 0	-0.082	0.985	<.0001	-0.113	-0.050
3-Jan-11		19	Slope = 1	1.176		<.0001	1.119	1.233
19-Jan-11	12	19	Intercept = 0	-0.014	0.987	0.204	-0.037	0.008
19-Jan-11		19	Slope = 1	1.059		0.001	1.016	1.102
2-Feb-11	10	19	Intercept = 0	-0.060	0.985	0.000	-0.089	-0.030
2-Feb-11		19	Slope = 1	1.093		0.001	1.041	1.145
21-Feb-11	10	19	Intercept = 0	-0.068	0.983	<.0001	-0.098	-0.038
21-Feb-11		19	Slope = 1	1.069		0.015	1.014	1.124
15-Mar-11	10	19	Intercept = 0	-0.043	0.992	0.000	-0.063	-0.023
15-Mar-11		19	Slope = 1	1.082		<.0001	1.044	1.119
1-Apr-11	10	19	Intercept = 0	-0.094	0.995	<.0001	-0.110	-0.078
1-Apr-11		19	Slope = 1	1.161		<.0001	1.129	1.193
15-Apr-11	10	19	Intercept = 0	-0.067	0.993	<.0001	-0.087	-0.047
15-Apr-11		19	Slope = 1	1.106		<.0001	1.070	1.143
27-May-11	10	19	Intercept = 0	-0.074	0.980	0.000	-0.110	-0.039
27-May-11		19	Slope = 1	1.136		<.0001	1.073	1.199

n=sample size

Table 3. Calibration stability data for Pocket Sensor #20, testing that slope intercept=0 and slope=0 between December 2010 and May 27, 2011.

Data	n	Sensor	Test Variable	Estimate	r^2	Pr> ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
6-Dec-10	6	20	Intercept = 0	-0.001	0.982	0.911	-0.022	0.020
6-Dec-10		20	Slope = 1	1.002		0.933	0.954	1.050
14-Dec-10	10	20	Intercept = 0	0.021	0.977	0.166	-0.009	0.050
14-Dec-10		20	Slope = 1	0.977		0.429	0.918	1.036
3-Jan-11	10	20	Intercept = 0	-0.043	0.993	<0.001	-0.064	-0.022
3-Jan-11		20	Slope = 1	1.079		<0.001	1.043	1.115
19-Jan-11	12	20	Intercept = 0	0.019	0.991	0.035	0.001	0.037
19-Jan-11		20	Slope = 1	1.006		0.711	0.972	1.040
2-Feb-11	10	20	Intercept = 0	-0.005	0.982	0.744	-0.035	0.025
2-Feb-11		20	Slope = 1	1.019		0.480	0.965	1.073
21-Feb-11	10	20	Intercept = 0	-0.033	0.990	0.005	-0.055	-0.011
21-Feb-11		20	Slope = 1	1.006		0.776	0.965	1.046
15-Mar-11	10	20	Intercept = 0	-0.005	0.978	0.761	-0.036	0.027
15-Mar-11		20	Slope = 1	1.052		0.096	0.990	1.113
1-Apr-11	10	20	Intercept = 0	-0.050	0.993	<0.001	-0.068	-0.032
1-Apr-11		20	Slope = 1	1.089		<0.001	1.053	1.125
15-Apr-11	10	20	Intercept = 0	-0.007	0.992	0.464	-0.025	0.012
15-Apr-11		20	Slope = 1	1.028		0.104	0.994	1.063
27-May-11	10	20	Intercept = 0	-0.002	0.994	0.836	-0.019	0.015
27-May-11		20	Slope = 1	1.028		0.070	0.998	1.059

n=sample size

Table 4. Calibration stability data for Pocket Sensor #27, testing that slope intercept=0 and slope=0 between December 2010 and May 27, 2011.

Data	n	Sensor	Test Variable	Estimate	r^2	Pr> ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
6-Dec-10	6	27	Intercept = 0	-0.008	0.982	0.451	-0.029	0.013
6-Dec-10		27	Slope = 1	1.047		0.061	0.998	1.096
14-Dec-10	10	27	Intercept = 0	-0.011	0.977	0.470	-0.042	0.020
14-Dec-10		27	Slope = 1	1.042		0.171	0.981	1.104
3-Jan-11	10	27	Intercept = 0	-0.043	0.992	<0.001	-0.065	-0.021
3-Jan-11		27	Slope = 1	1.126		<.0001	1.086	1.166
19-Jan-11	12	27	Intercept = 0	-0.004	0.989	0.686	-0.024	0.016
19-Jan-11		27	Slope = 1	1.055		0.007	1.016	1.094
2-Feb-11	10	27	Intercept = 0	-0.024	0.973	0.209	-0.061	0.014
2-Feb-11		27	Slope = 1	1.065		0.061	0.997	1.133
21-Feb-11	10	27	Intercept = 0	-0.054	0.986	<0.001	-0.081	-0.028
21-Feb-11		27	Slope = 1	1.057		0.026	1.007	1.106
15-Mar-11	10	27	Intercept = 0	-0.050	0.996	<.0001	-0.064	-0.037
15-Mar-11		27	Slope = 1	1.092		<.0001	1.067	1.117
1-Apr-11	10	27	Intercept = 0	-0.067	0.987	<.0001	-0.091	-0.042
1-Apr-11		27	Slope = 1	1.150		<.0001	1.099	1.201
15-Apr-11	10	27	Intercept = 0	-0.044	0.991	0.000	-0.064	-0.023
15-Apr-11		27	Slope = 1	1.089		<.0001	1.050	1.129
27-May-11	10	27	Intercept = 0	-0.009	0.995	0.240	-0.025	0.007
27-May-11		27	Slope = 1	1.037		0.011	1.009	1.066

n=sample size

Table 5. Calibration stability data for Pocket Sensor #32, testing that slope intercept=0 and slope=0 between December 2010 and May 27, 2011.

Data	n	Sensor	Test Variable	Estimate	r^2	Pr> ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
6-Dec-10	6	32	Intercept = 0	0.015	0.972	0.222	-0.010	0.041
6-Dec-10		32	Slope = 1	0.998		0.949	0.939	1.057
14-Dec-10	10	32	Intercept = 0	0.017	0.970	0.322	-0.017	0.051
14-Dec-10		32	Slope = 1	0.964		0.277	0.898	1.030
3-Jan-11	10	32	Intercept = 0	-0.061	0.986	<0.001	-0.090	-0.032
3-Jan-11		32	Slope = 1	1.100		<0.001	1.050	1.151
19-Jan-11	12	32	Intercept = 0	0.012	0.992	0.163	-0.005	0.028
19-Jan-11		32	Slope = 1	0.997		0.867	0.966	1.029
2-Feb-11	10	32	Intercept = 0	-0.032	0.989	0.014	-0.057	-0.007
2-Feb-11		32	Slope = 1	1.037		0.090	0.994	1.081
21-Feb-11	10	32	Intercept = 0	0.012	0.989	0.163	-0.005	0.028
21-Feb-11		32	Slope = 1	0.997		0.740	0.966	1.029
15-Mar-11	10	32	Intercept = 0	-0.026	0.991	0.013	-0.047	-0.006
15-Mar-11		32	Slope = 1	1.038		0.047	1.001	1.076
15-Apr-11	10	32	Intercept = 0	-0.007	0.995	0.305	-0.022	0.007
15-Apr-11		32	Slope = 1	1.003		0.831	0.976	1.030
27-May-11	10	32	Intercept = 0	0.019	0.990	0.085	-0.003	0.041
27-May-11		32	Slope = 1	0.993		0.726	0.954	1.033

n=sample size

Table 6. Calibration stability data for Pocket Sensor #37, testing that slope intercept=0 and slope=0 between December 2010 and May 27, 2011.

Data	n	Sensor	Test Variable	Estimate	r^2	Pr> ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
6-Dec-10	6	37	Intercept = 0	0.005	0.972	0.681	-0.020	0.031
6-Dec-10		37	Slope = 1	1.015		0.617	0.955	1.075
14-Dec-10	10	37	Intercept = 0	0.014	0.965	0.451	-0.023	0.051
14-Dec-10		37	Slope = 1	0.981		0.600	0.909	1.054
3-Jan-11	10	37	Intercept = 0	-0.025	0.992	0.021	-0.046	-0.004
3-Jan-11		37	Slope = 1	1.061		0.002	1.024	1.098
19-Jan-11	12	37	Intercept = 0	0.022	0.978	0.108	-0.005	0.048
19-Jan-11		37	Slope = 1	1.000		0.998	0.949	1.051
2-Feb-11	10	37	Intercept = 0	-0.013	0.981	0.404	-0.043	0.018
2-Feb-11		37	Slope = 1	1.033		0.234	0.978	1.088
21-Feb-11	10	37	Intercept = 0	-0.020	0.988	0.089	-0.043	0.003
21-Feb-11		37	Slope = 1	0.981		0.362	0.939	1.023
15-Mar-11	10	37	Intercept = 0	-0.031	0.991	0.005	-0.052	-0.011
15-Mar-11		37	Slope = 1	1.071		0.001	1.031	1.110
1-Apr-11	10	37	Intercept = 0	-0.045	0.987	0.001	-0.069	-0.021
1-Apr-11		37	Slope = 1	1.129		<0.001	1.079	1.180
15-Apr-11	10	37	Intercept = 0	-0.005	0.995	0.506	-0.019	0.010
15-Apr-11		37	Slope = 1	1.018		0.184	0.991	1.045
27-May-11	10	37	Intercept = 0	-0.058	0.992	<0.001	-0.080	-0.035
27-May-11		37	Slope = 1	1.125		<0.001	1.085	1.165

n=sample size

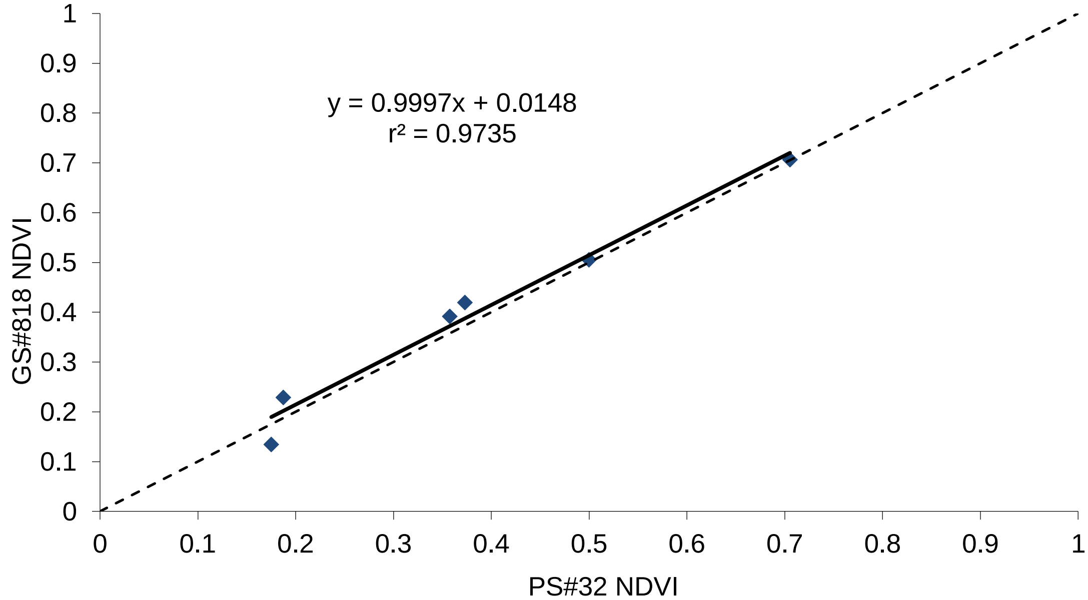

Figure 8. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, December 6, 2010.

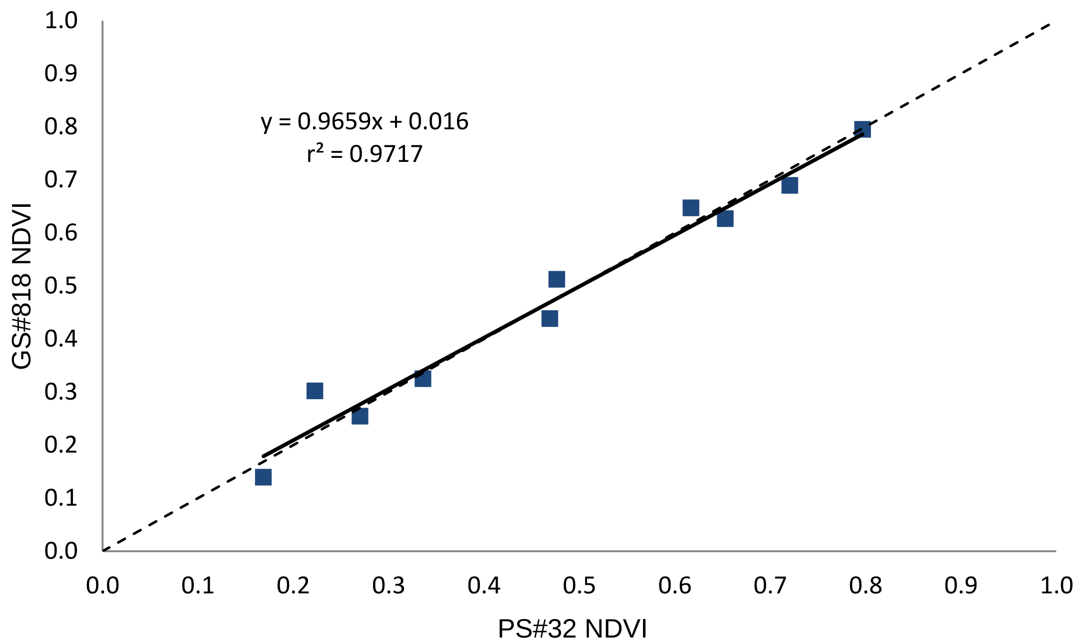

Figure 9. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, December 14, 2010.

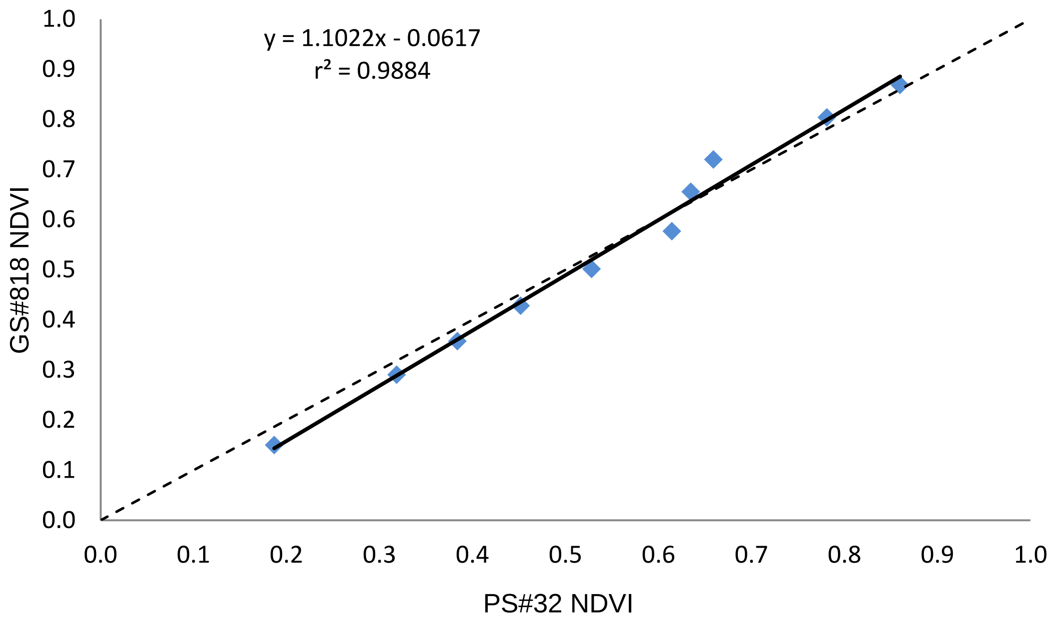

Figure 10. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, January 3, 2011.

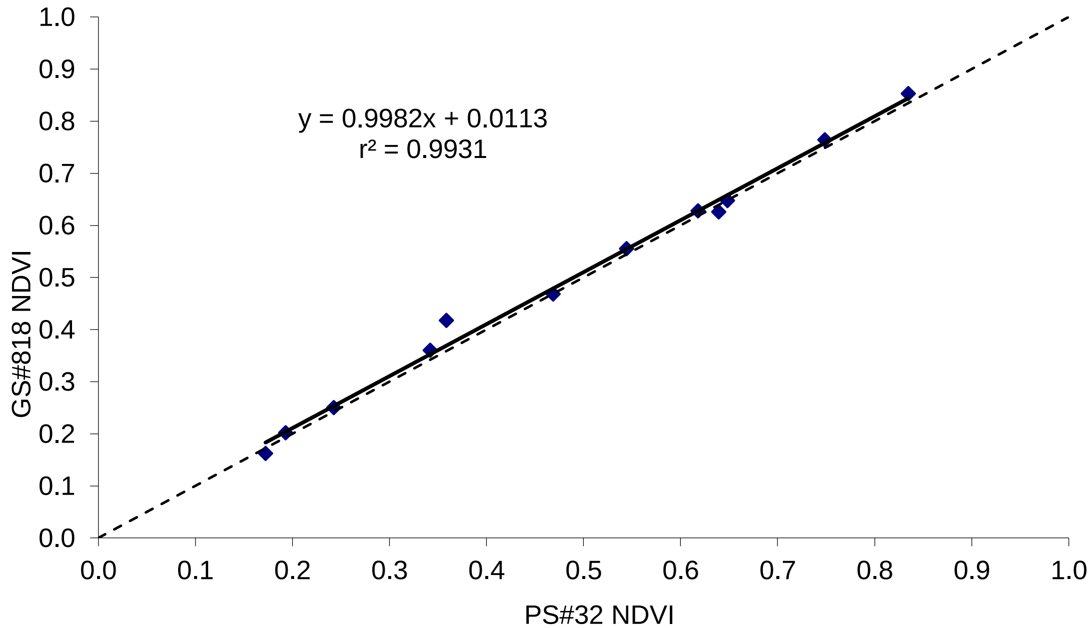

Figure 11. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, January 19, 2011.

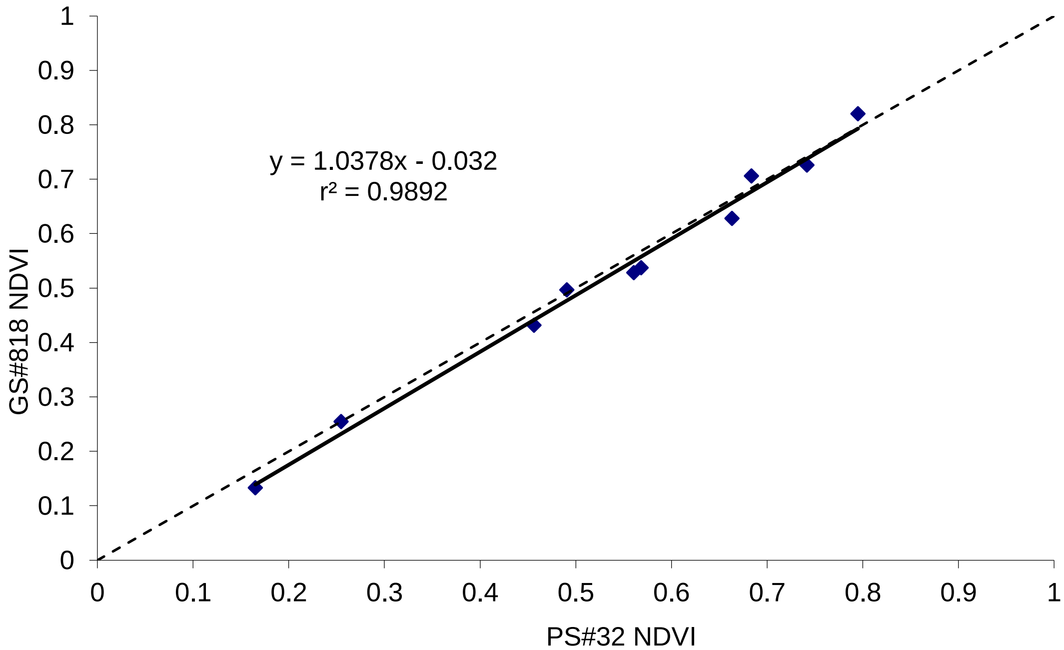

Figure 12. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, February 8, 2011.

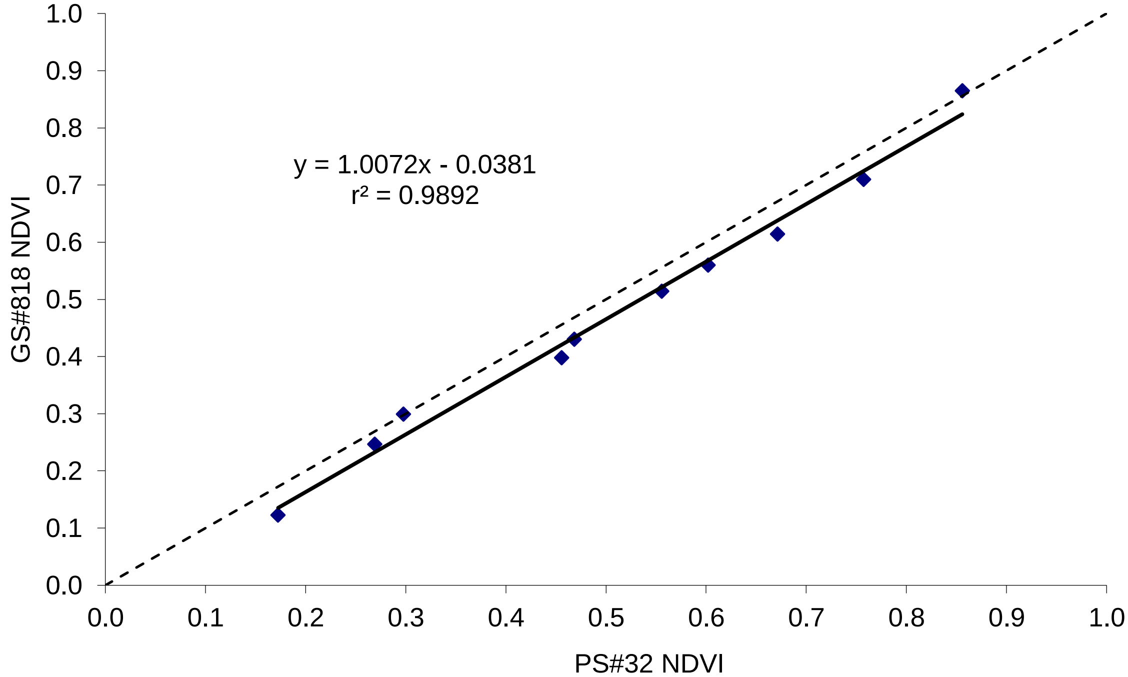

Figure 13. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, February 21, 2011.

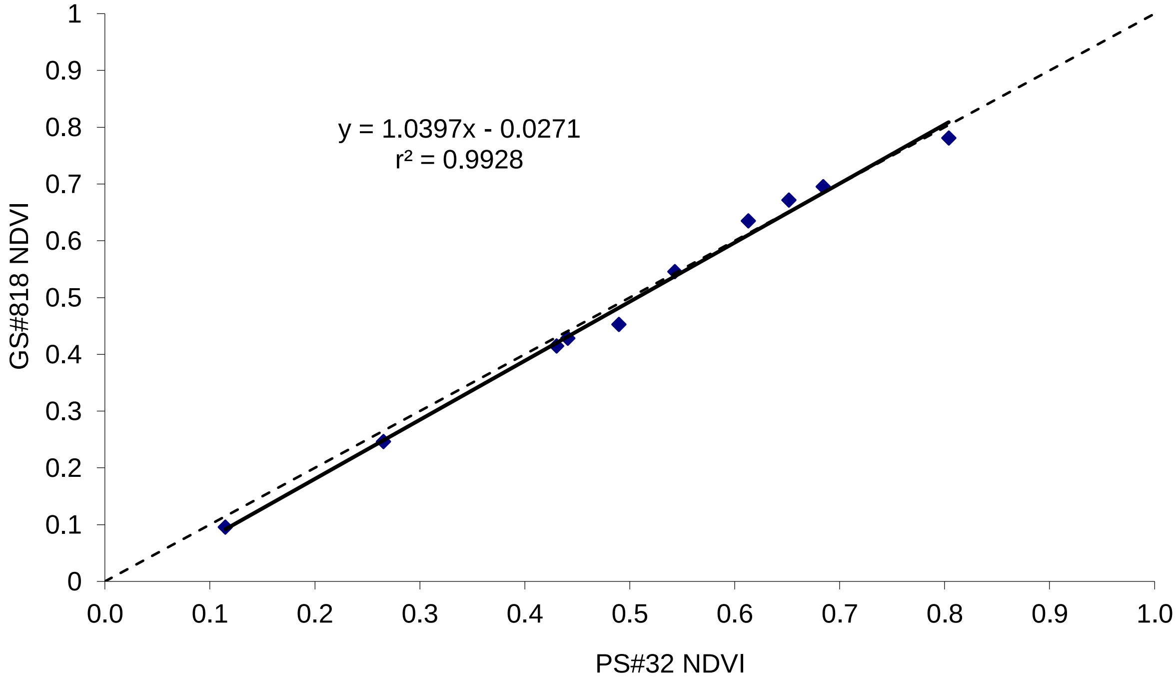

Figure 14. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, March 15, 2011.

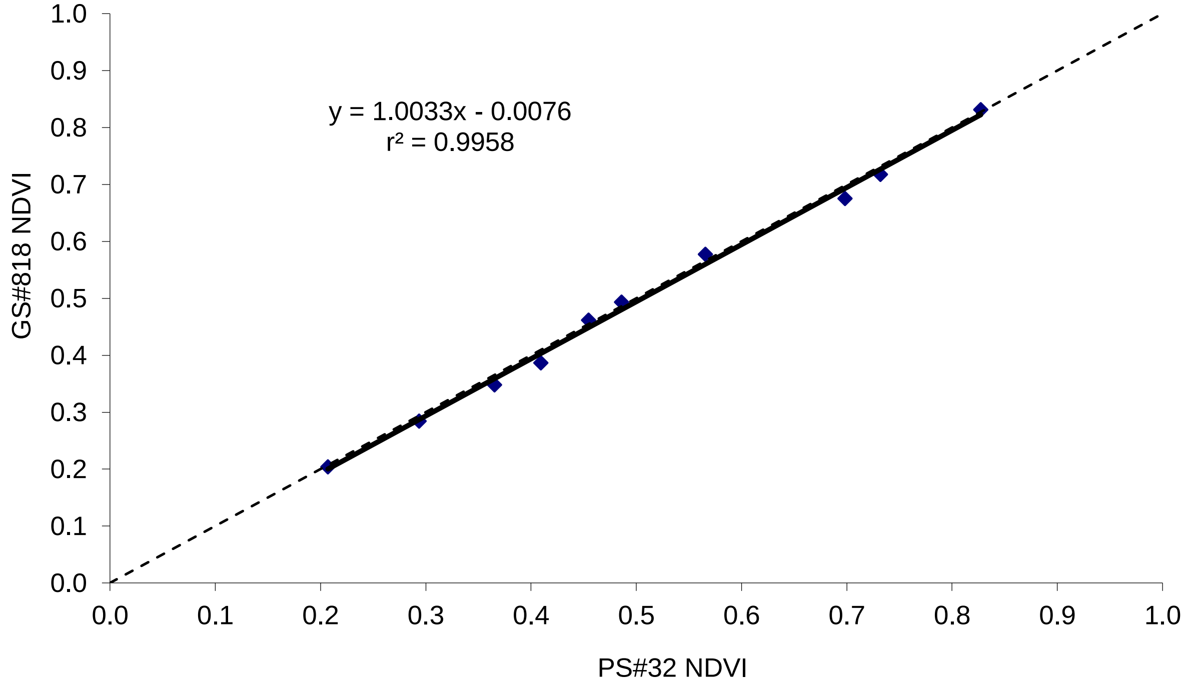

Figure 15. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, April 15, 2011.

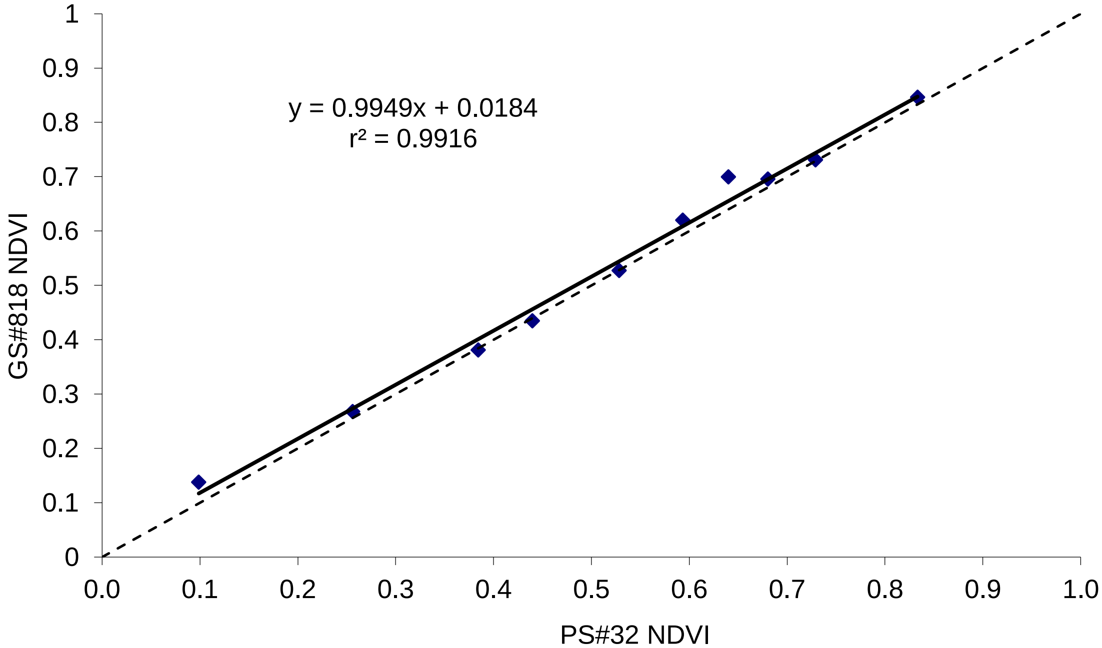

Figure 16. Sensor NDVI readings for Pocket Sensor #32 and GreenSeeker #818, Ciudad Obregon, Mexico, May 27, 2011.

Table 7. Analysis of variance evaluating sensors, and person operating sensors, Ciudad Obregon, Mexico, 2011.

Plot		2113 NDVI	2114 NDVI	2213 NDVI	2214 NDVI	2313 NDVI	2314 NDVI	2413 NDVI	2414 NDVI
Source of variation	df	**************************Mean Square Errors**************************							
operator	1	0.00031	0.00001	0.00012	0.00001	0.00004	0.00216*	0.00003	0.00005
sensor	1	0.00099	0.00128	0.00094	0.00000	0.00007	0.00200*	0.00034	0.00043
person*sensor	1	0.00261**	0.00000	0.00074	0.00029	0.00042	0.00002	0.00108	0.00145*
Residual error	8	0.00011	0.00039	0.00020	0.00026	0.00008	0.00029	0.00021	0.00022
SED		0.009	0.016	0.036	0.013	0.007	0.014	0.012	0.012
C.V.		1.7	3.2	2.4	2.8	1.3	3.1	2.7	2.5
r^2		0.811	0.293	0.535	0.125	0.443	0.645	0.462	0.520
		**************************Treatment Means***************************							
Person 1 PS#20		0.668	0.600	0.608	0.574	0.682	0.555	0.535	0.608
Person 2 PS#20		0.629	0.597	0.586	0.583	0.673	0.579	0.519	0.590
Person PS#32		0.621	0.620	0.575	0.585	0.675	0.527	0.526	0.574
Person 2 PS#32		0.640	0.618	0.584	0.574	0.690	0.556	0.549	0.600

* is significant at the alpha = 0.05 level

** is significant at the alpha = 0.01 level

PS—Pocket Sensor

SED- Standard error of the difference between two equally replicated means

C.V. coefficient of variation

Table 8. Analysis of variance evaluating sensors, and person operating sensors, Ciudad Obregon, Mexico, 2011.

Plot		Row 1 NDVI	Row 2 NDVI	Row 3 NDVI	Row 4 NDVI
Source of Variation	df	***************Mean Square Error***************			
Operator	1	0.00065	0.000154	0.017579	0.00001
Sensor	4	0.00771**	0.017572	0.012687	0.00261**
Person*Sensor	4	0.00031	0.00113*	0.00153**	0.00051
Residual Error	50	0.00041	0.000434	0.000255	0.00069
SED		0.012	0.012	0.009	0.015
C.V.		3.5	4.4	2.9	5.5
R^2		0.617	0.776	0.854	0.267
Treatment		***************Treatment Means***************			
PS#20 Person 1		0.596	0.522	0.601	0.503
PS#20 Person 2		0.604	0.518	0.558	0.483
PS#32 Person 1		0.617	0.497	0.597	0.486
PS#32 Person 2		0.616	0.495	0.575	0.500
PS#37 Person 1		0.553	0.425	0.567	0.454
PS#37 Person 2		0.576	0.461	0.498	0.464
GS#96 Person 1		0.557	0.434	0.525	0.471
GS# 96 Person 2		0.556	0.418	0.498	0.471
GS# 97 Person 1		0.568	0.471	0.539	0.480
GS# 97 Person 2		0.572	0.473	0.529	0.482
Contrast GS#96=GS#97		ns	**	**	ns

* is significant at the alpha = 0.05 level
** is significant at the alpha = 0.01 level
PS – pocket sensor
GS – Greenseeker sensor
ns not significant
SED- Standard error of the difference between two equally replicated means
C.V. coefficient of variation

Table 9. Simple linear regression between Pocket Sensors (PS) and GreenSeeker Sensors, V4-V10 growth stages in maize, Ciudad Obregon, Mexico, 2011.

Sensor	Crop	n	Test Variable	r^2	Estimate	Pr > ItI	Lower 95% Confidence Limit	Upper 95% Confidence Limit
PS#37	Maize	289	Intercept=0	0.912	0.010	0.236	-0.006	0.025
PS#37	Maize		Slope =1		0.995	0.787	0.960	1.031
PS#27	Maize	95	Intercept = 0	0.913	-0.015	0.315	-0.043	0.014
PS#27	Maize		Slope = 1		1.044	0.188	0.978	1.111

Pocket Sensor—independent variable

GreenSeeker—dependent variable

n=sample size

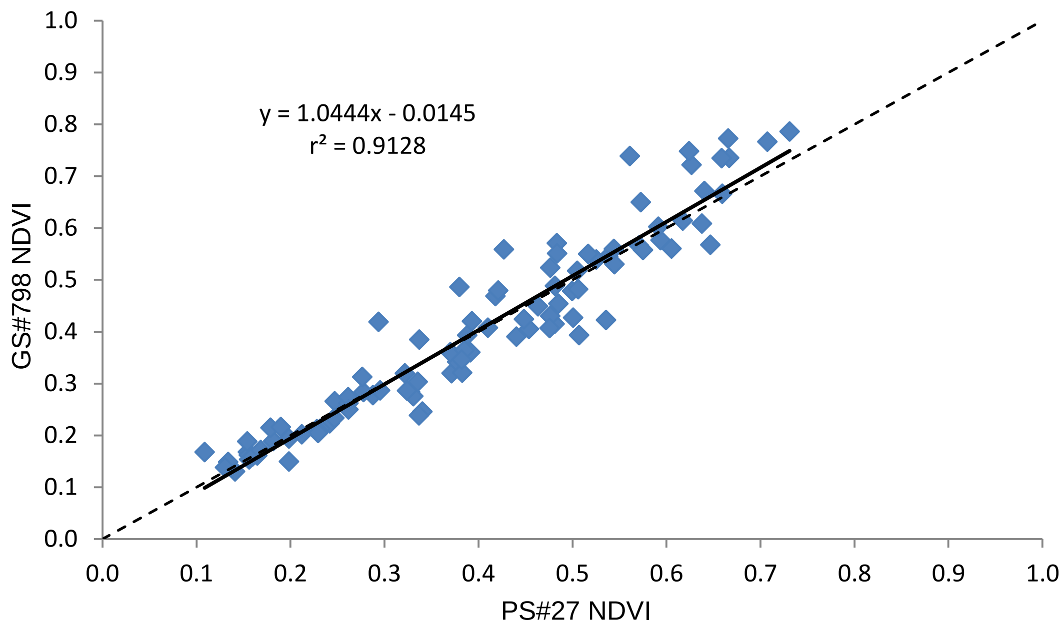

Figure 17. Relationship between Pocket Sensor #27 and GreenSeeker #798 NDVI readings in maize V4-V10 growth stages, Ciudad Obregon, Mexico, 2011.

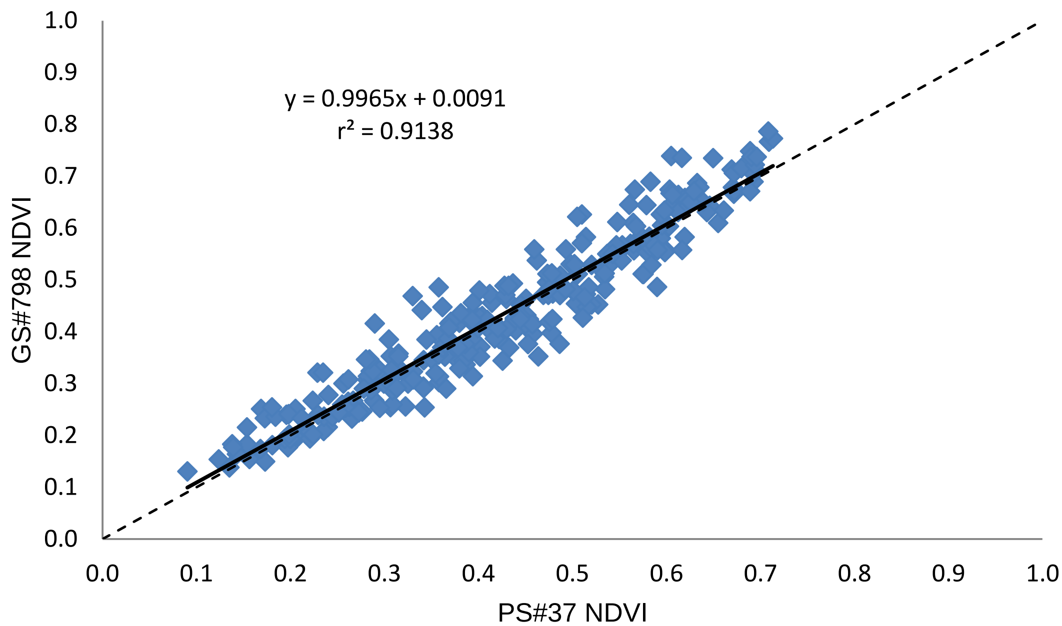

Figure 18. Relationship between Pocket Sensor #37 and GreenSeeker #798 NDVI readings in maize V4-V10 growth stages, Ciudad Obregon, Mexico, 2011.

Table 10. Linear regression for various combinations of GreenSeeker (GS) and Pocket Sensor (PS), from readings collected at different growth stages of maize, Ciudad Obregon, Mexico, 2011.

Maize Growth Stage	n	Sensor	r^2	Equation
V4	8	27	0.0183	GS=0.1017PS + 0.1393
V5	19	27	0.5773	GS=.5764PS + 0.0868
V6	6	27	0.9677	GS=0.7217PS + 0.0675
V7	19	27	0.9273	GS=0.9893PS - 0.0113
V8	4	27	0.9704	GS=1.0246PS - 0.0231
V9	11	27	0.6498	GS=0.8695 + 0.0442
V10	28	27	0.8113	GS=1.1279PS - 0.0257
V11	27	27	0.6045	GS=1.0191PS + 0.0424
V12	19	27	0.8085	GS=1.0327PS + 0.08
V13	14	27	0.4433	GS=1.2071PS - 0.0398
V14	7	27	0.0529	GS=-0.0569PS + 0.767
V4	3	37	0.3293	GS=0.2917PS + 0.1069
V5	8	37	0.9565	GS=0.8174PS + 0.0227
V6	51	37	0.8704	GS=0.7317PS + 0.0656
V7	82	37	0.8935	GS=0.8621PS + 0.0543
V8	46	37	0.8536	GS=0.9091PS + 0.0728
V9	42	37	0.8222	GS=0.9405PS + 0.0358
V10	57	37	0.8667	GS=0.9986PS + 0.0246
V11	65	37	0.7184	GS=0.956PS + 0.0674
V12	46	37	0.8213	GS=0.9531PS + 0.0863
V13	27	37	0.6479	GS=1.1063PS + 0.0018
V14	17	37	0.0561	GS=0.3128PS + 0.5292

n=sample size

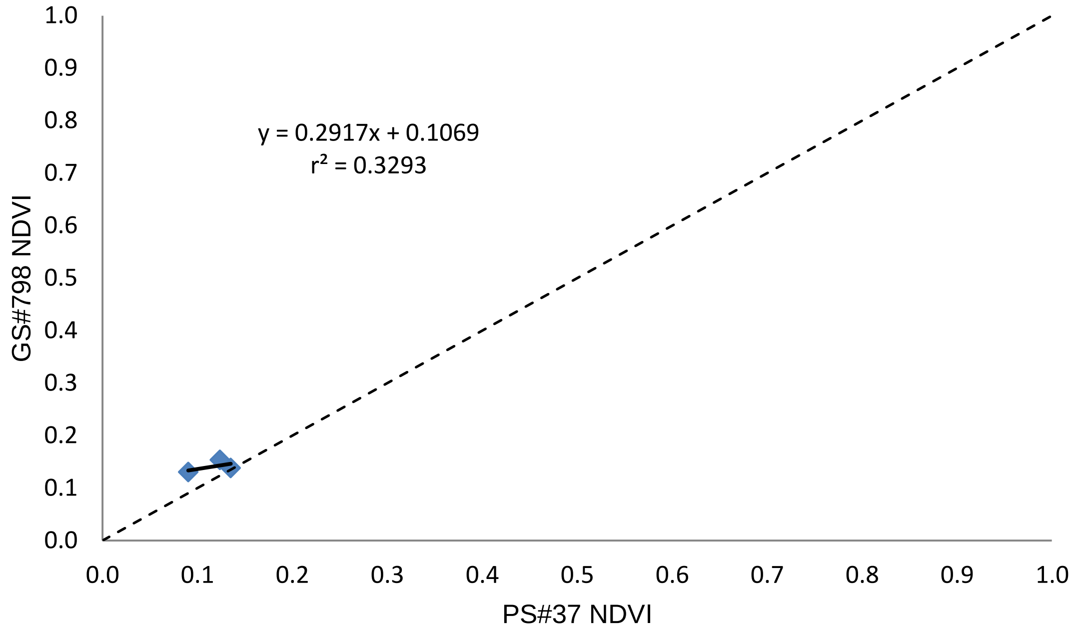

Figure 19. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V4, Ciudad Obregon, Mexico, 2011.

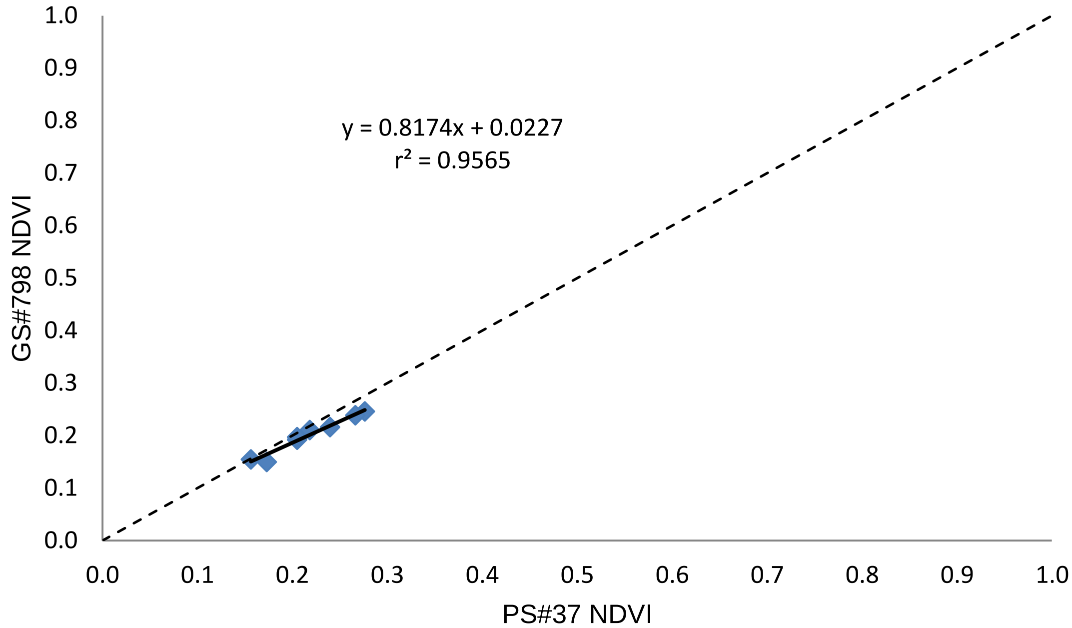

Figure 20. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V5, Ciudad Obregon, Mexico, 2011.

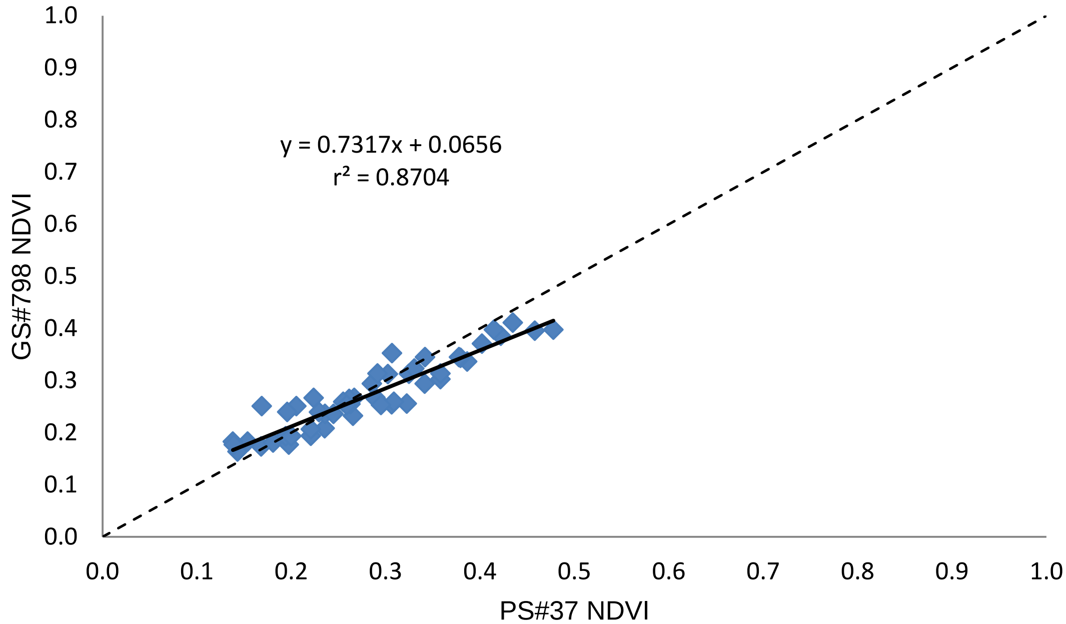

Figure 21. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V6, Ciudad Obregon, Mexico, 2011.

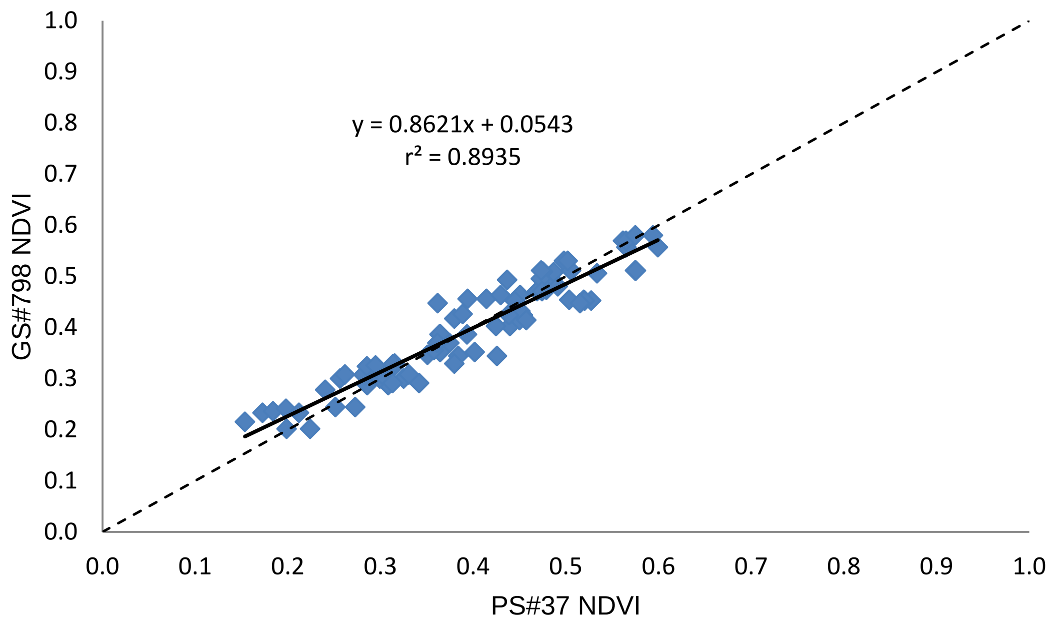

Figure 22. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V7, Ciudad Obregon, Mexico, 2011.

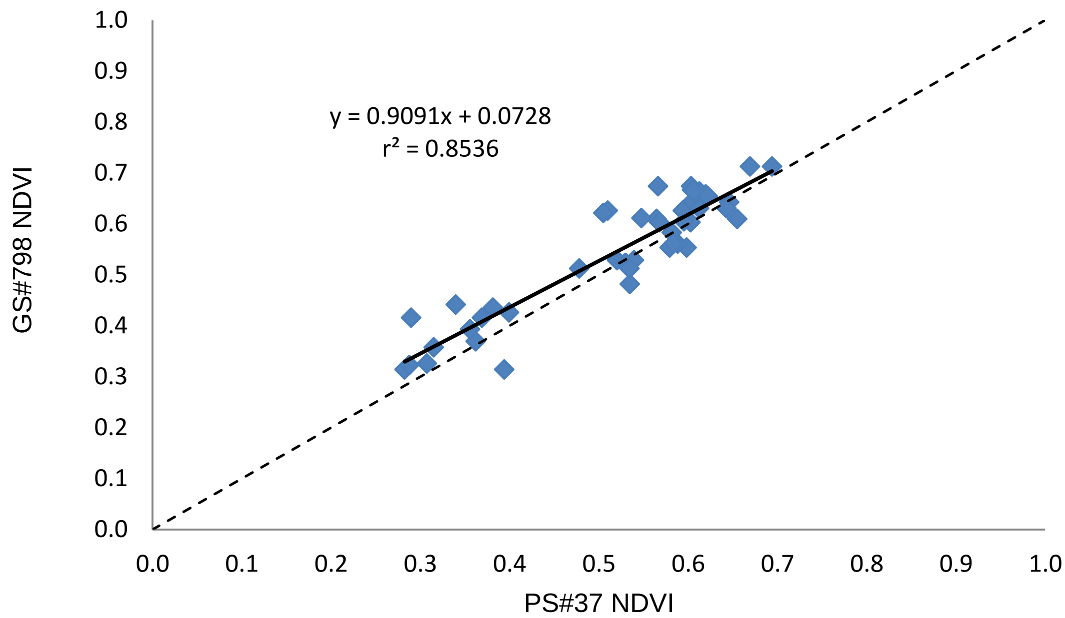

Figure 23. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V8, Ciudad Obregon, Mexico, 2011.

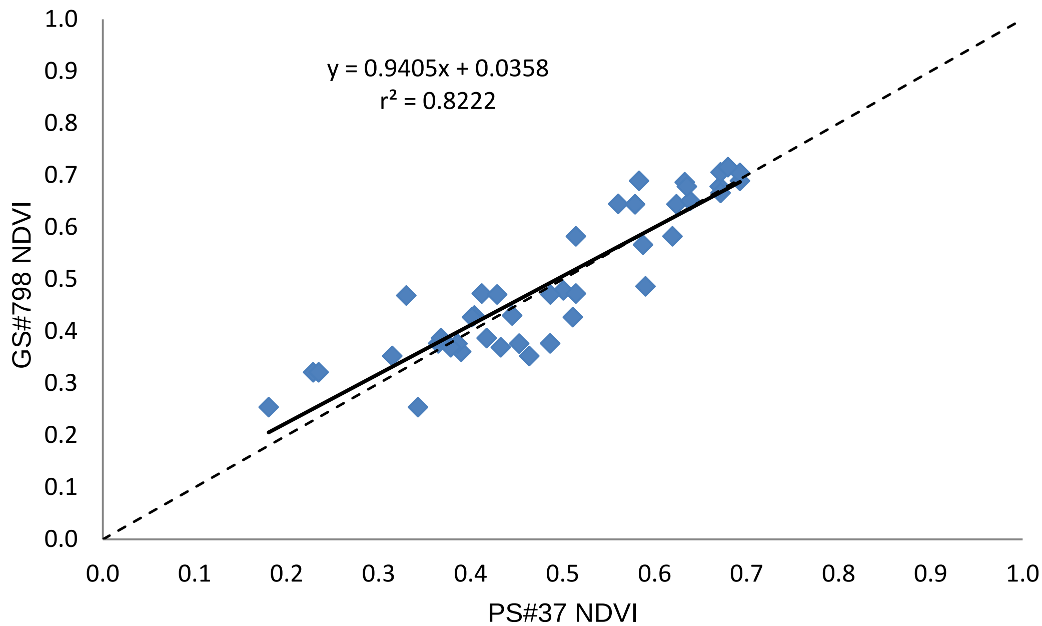

Figure 24. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V9, Ciudad Obregon, Mexico, 2011.

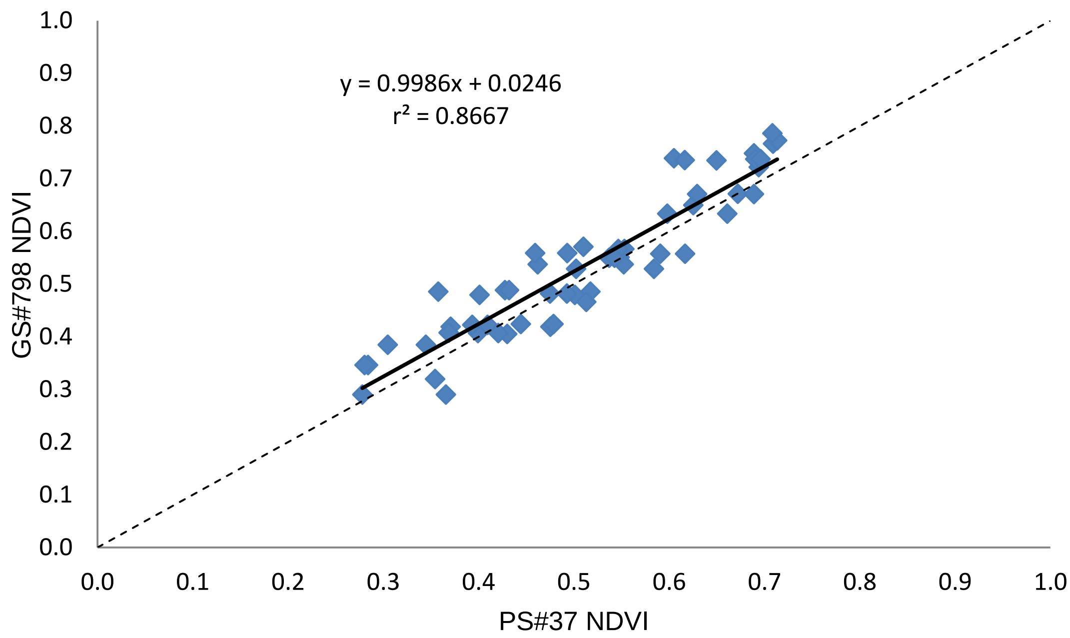

Figure 25. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V10, Ciudad Obregon, Mexico, 2011.

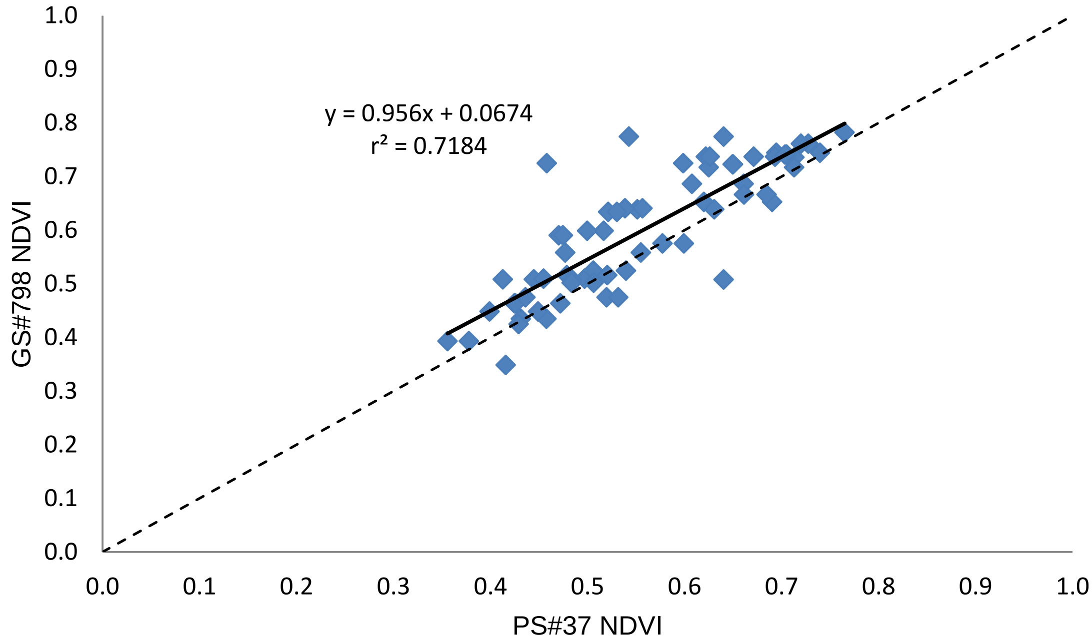

Figure 26. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V11, Ciudad Obregon, Mexico, 2011.

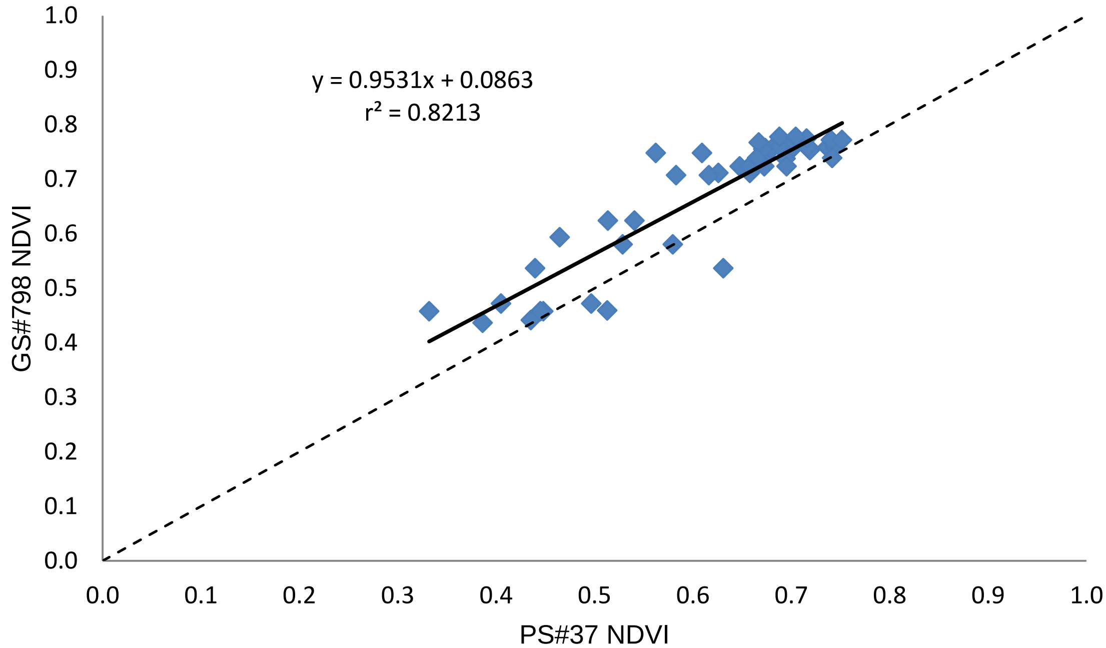

Figure 27. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V12, Ciudad Obregon, Mexico, 2011.

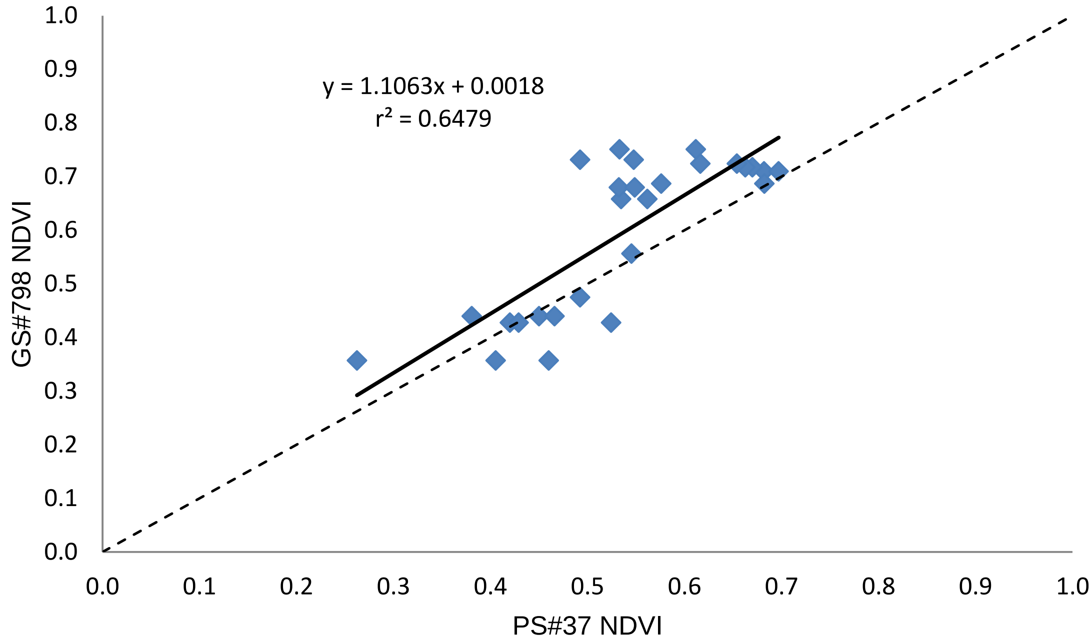

Figure 28. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V13, Ciudad Obregon, Mexico, 2011.

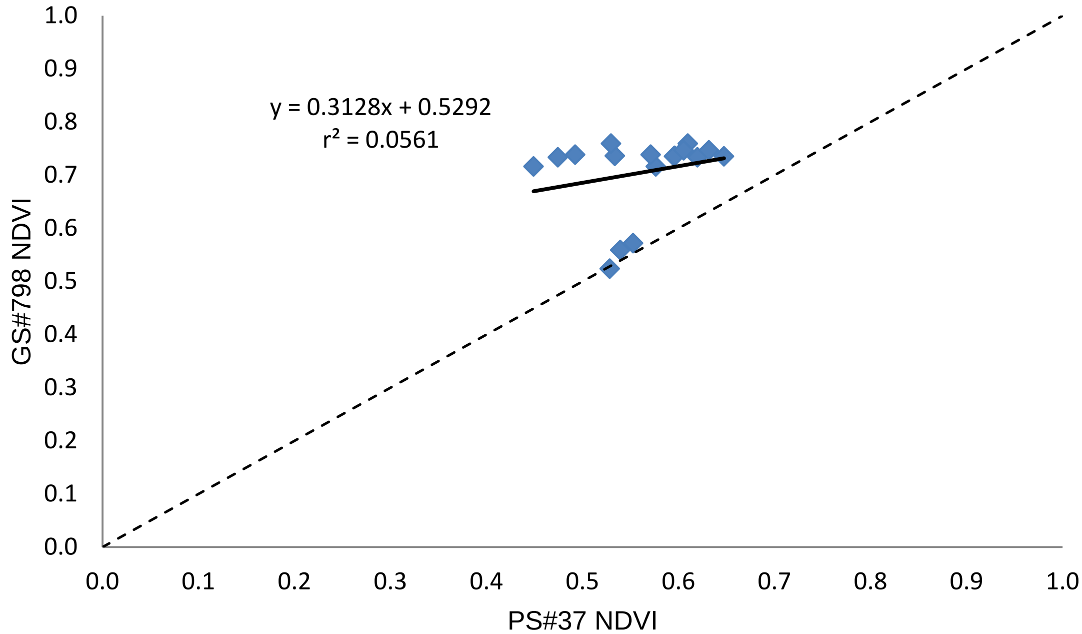

Figure 29. Relationship between Pocket Sensor #37 and GreenSeeker #798 for NDVI readings at maize growth stage V14, Ciudad Obregon, Mexico, 2011.

Table 11. Simple linear regression between the Pocket Sensors (PS) and GreenSeeker in wheat, Ciudad Obregon, Mexico, 2011.

Sensor	Crop	n	Test Variable	r^2	Estimate	Pr > ltl	Lower 95% Confidence Limit	Upper 95% Confidence Limit
20	All Wheat Data	80	Intercept	0.964	0.020	0.203	-0.011	0.051
20	All Wheat Data		Slope		0.994	0.774	0.950	1.037
32	All Wheat Data	60	Intercept	0.955	0.008	0.673	-0.031	0.048
32	All Wheat Data		Slope		0.998	0.958	0.942	1.055

Pocket Sensor—independent variable

GreenSeeker—dependent variable

n=sample size

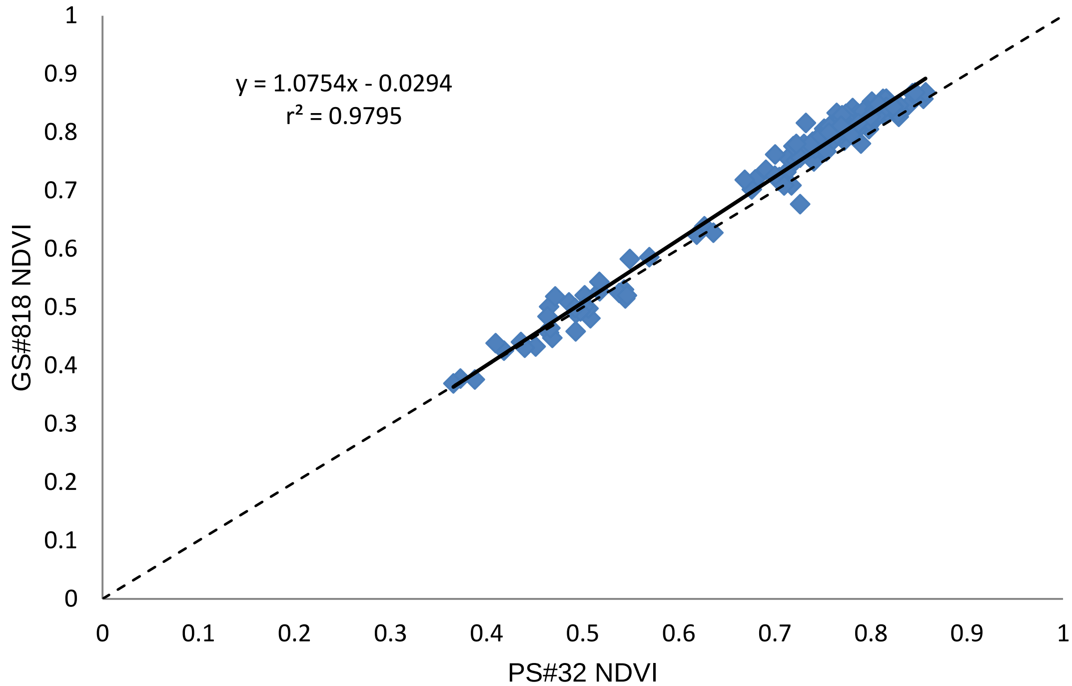

Figure 30. Relationship between Pocket Sensor #32 and GreenSeeker #818 NDVI readings in Y226 wheat trials Ciudad Obregon, Mexico, January 18, 2011.

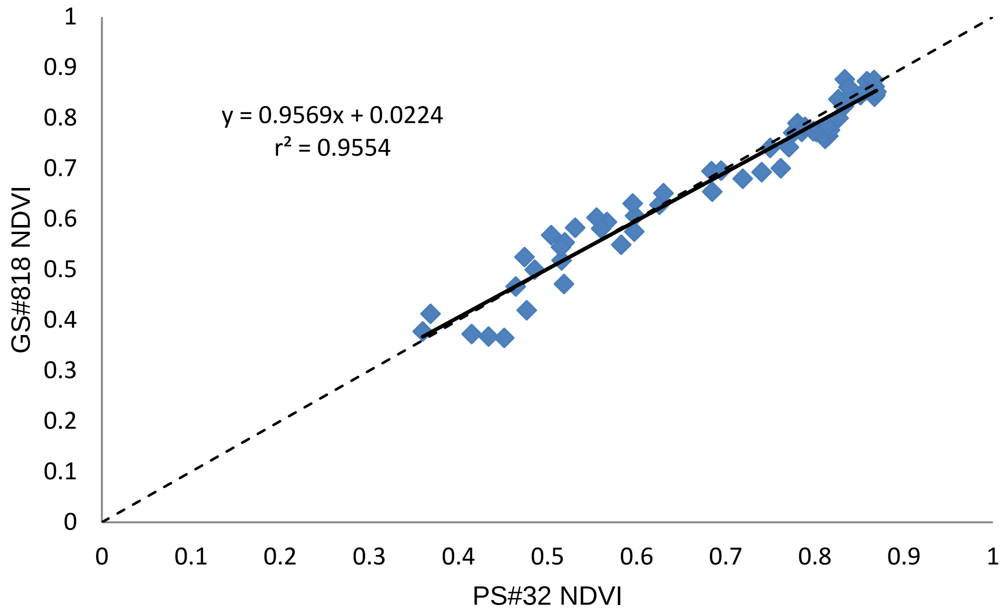

Figure 31. Relationship between Pocket Sensor #32 and GreenSeeker #818 NDVI readings for wheat growth stage Feekes 4-10, Ciudad Obregon, Mexico, 2011, January 3-February 2, 2011.

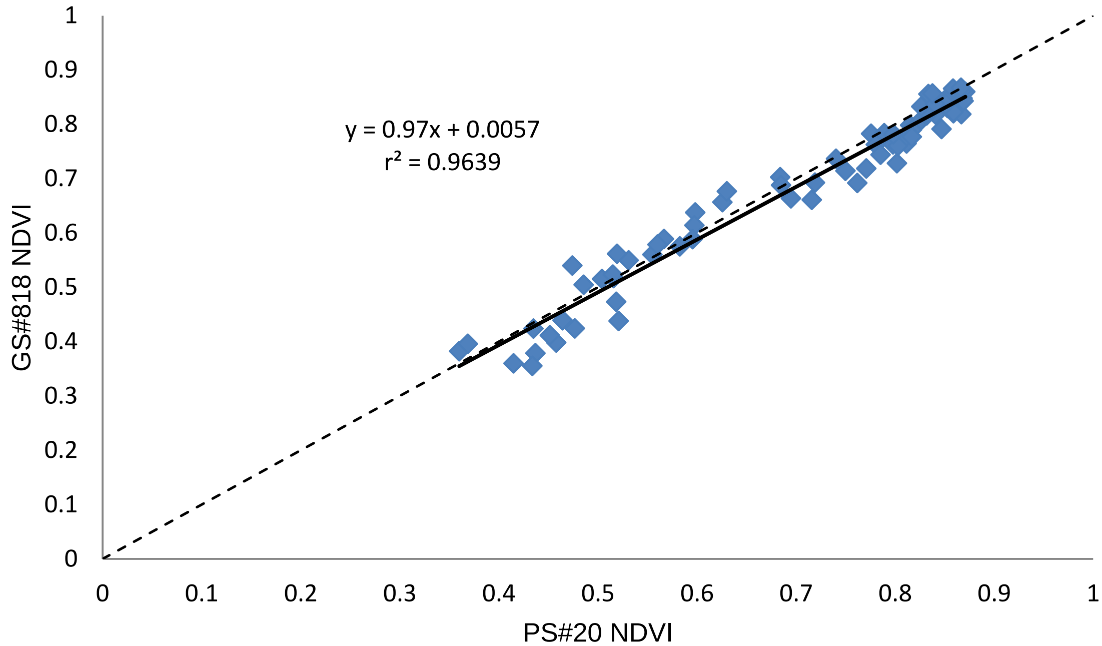

Figure 32. Relationship between Pocket Sensor #20 and GreenSeeker #818 NDVI readings for wheat growth stage Feekes 4-10, Ciudad Obregon, Mexico, January 3-February 2, 2011.

Table 12. Simple regression between the Pocket Sensors and GreenSeeker in wheat by date, Ciudad Obregon, Mexico, 2011.

Crop	n	Sensor	Test Variable	r^2	Estimate	Pr > ltl	Lower 95% Confidence Limit	Upper 95% Confidence Limit
Wheat January 3, 2011	20	20	Intercept	-0.038	0.972	0.137	-0.090	0.013
Wheat January 3, 2011		20	Slope	1.031		0.467	0.944	1.117
Wheat January 18, 2011	20	20	Intercept	0.028	0.971	0.353	-0.034	0.091
Wheat January 18, 2011		20	Slope	1.003		0.940	0.917	1.089
Wheat January 27, 2011	20	20	Intercept	0.084	0.988	<0.001	0.047	0.121
Wheat January 27, 2011		20	Slope	0.933		0.011	0.883	0.983
Wheat February 2, 2011	20	20	Intercept	0.103	0.993	<0.001	0.077	0.130
Wheat February 2, 2011		20	Slope	0.883		<0.001	0.848	0.917
Wheat January 3, 2011	20	32	Intercept	-0.092	0.939	0.034	-0.176	-0.008
Wheat January 3, 2011		32	Slope	1.128		0.075	0.986	1.270
Wheat January 18, 2011	20	32	Intercept	0.007	0.964	0.828	-0.064	0.079
Wheat January 18, 2011		32	Slope	1.027		0.575	0.929	1.125
Wheat February 2, 2011	20	32	Intercept	0.117	0.989	<0.001	0.084	0.150
Wheat February 2, 2011		32	Slope	0.860		<0.001	0.817	0.903

n=sample size

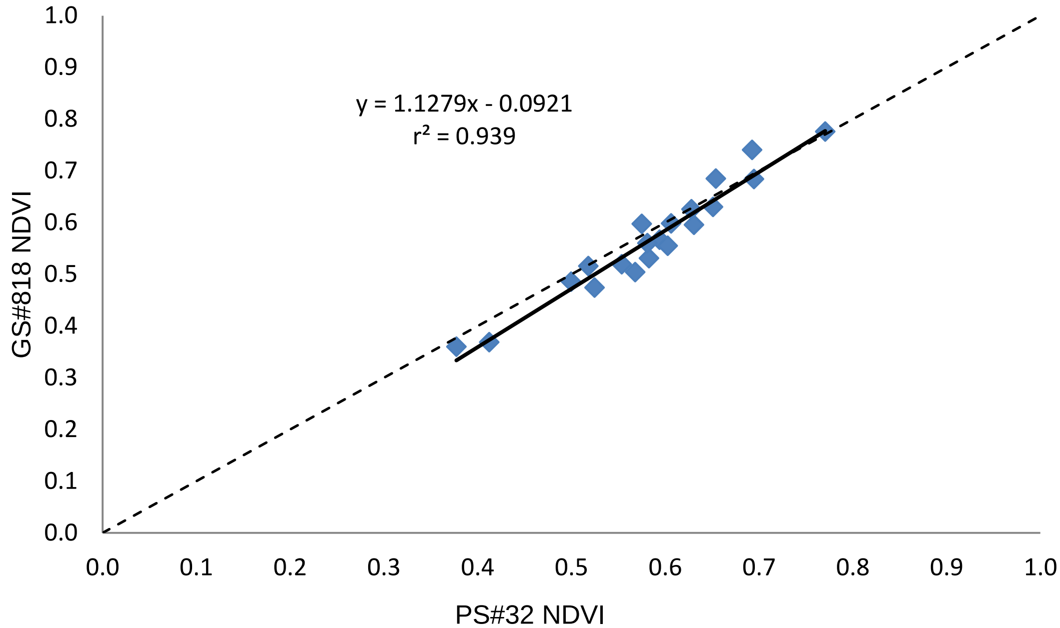

Figure 33. Relationship between Pocket Sensor #32 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, January 3, 2011.

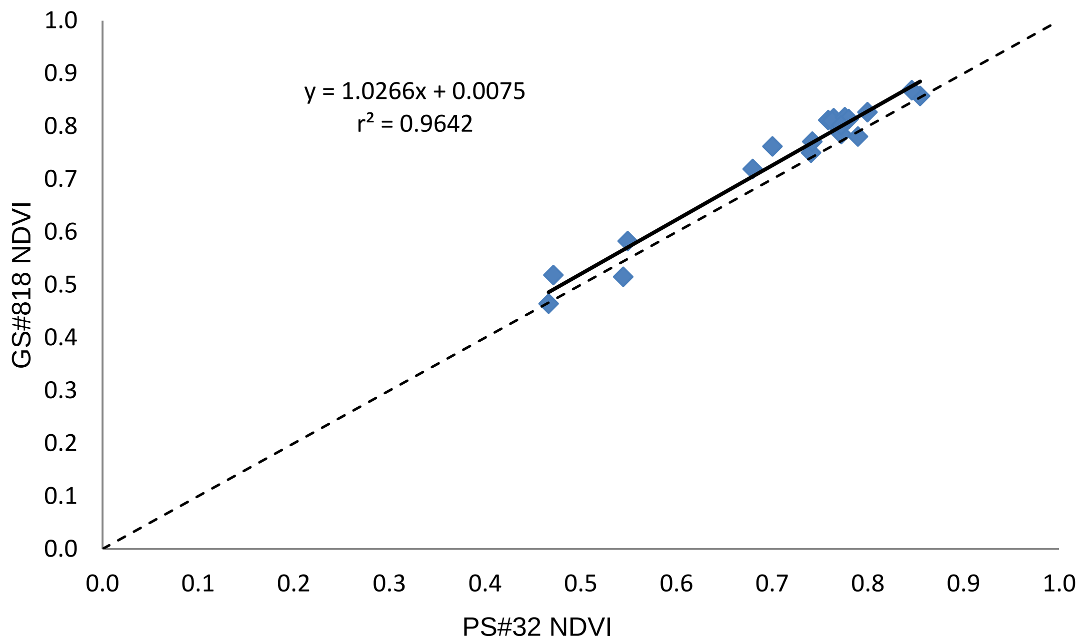

Figure 34. Relationship between Pocket Sensor #32 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, January 18, 2011.

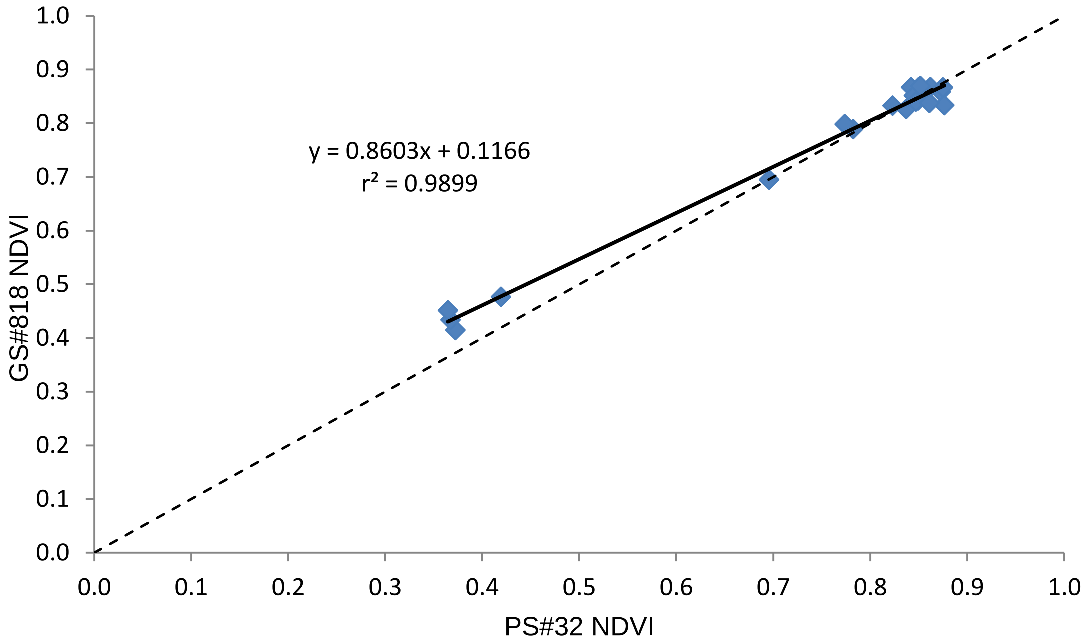

Figure 35. Relationship between Pocket Sensor #32 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, February 2, 2011.

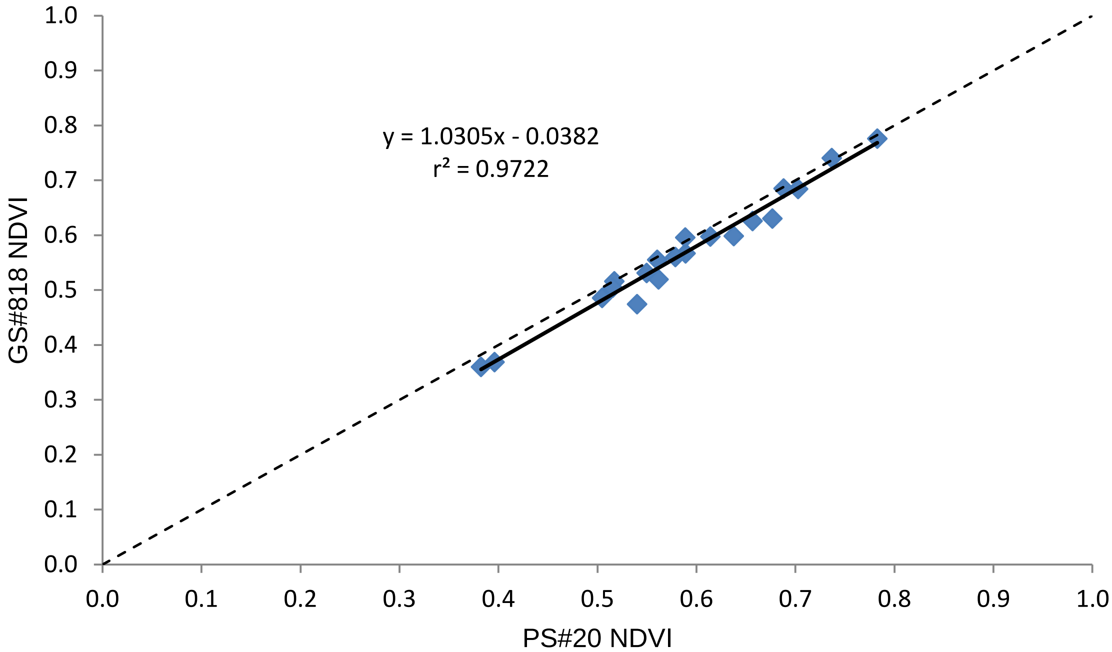

Figure 36. Relationship between Pocket Sensor #20 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, January 3, 2011.

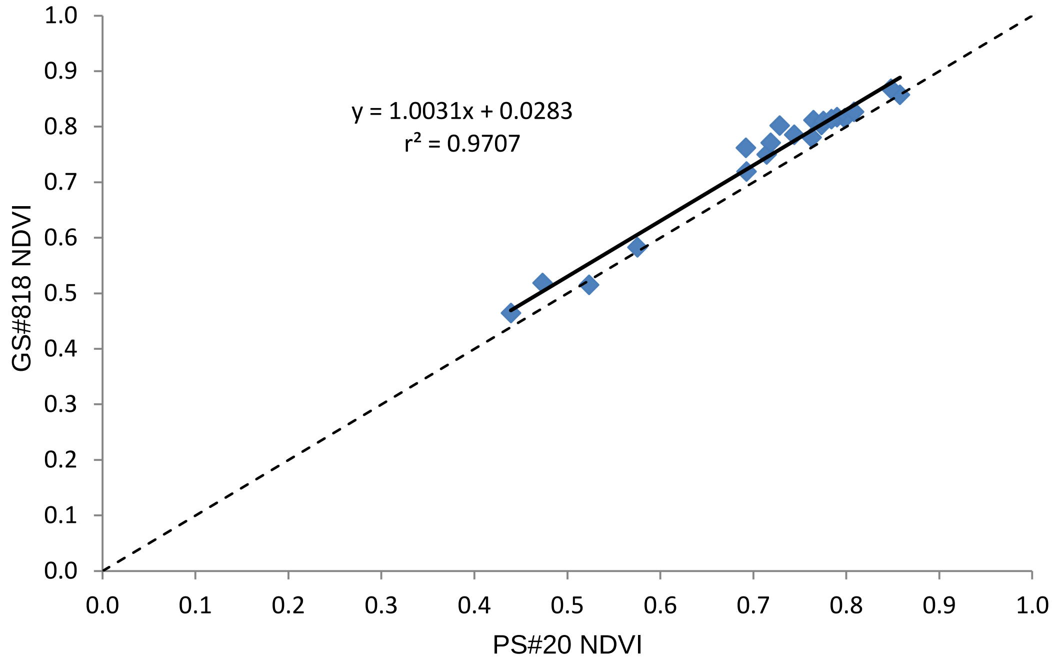

Figure 37. Relationship between Pocket Sensor #20 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, January 18, 2011.

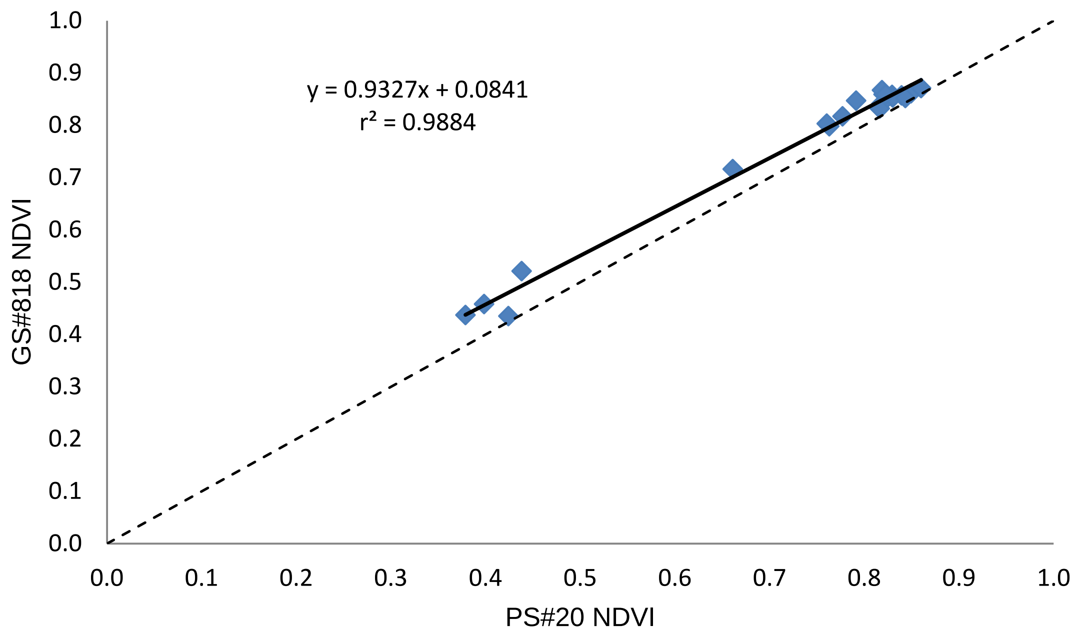

Figure 38. Relationship between Pocket Sensor #20 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, January 27, 2011.

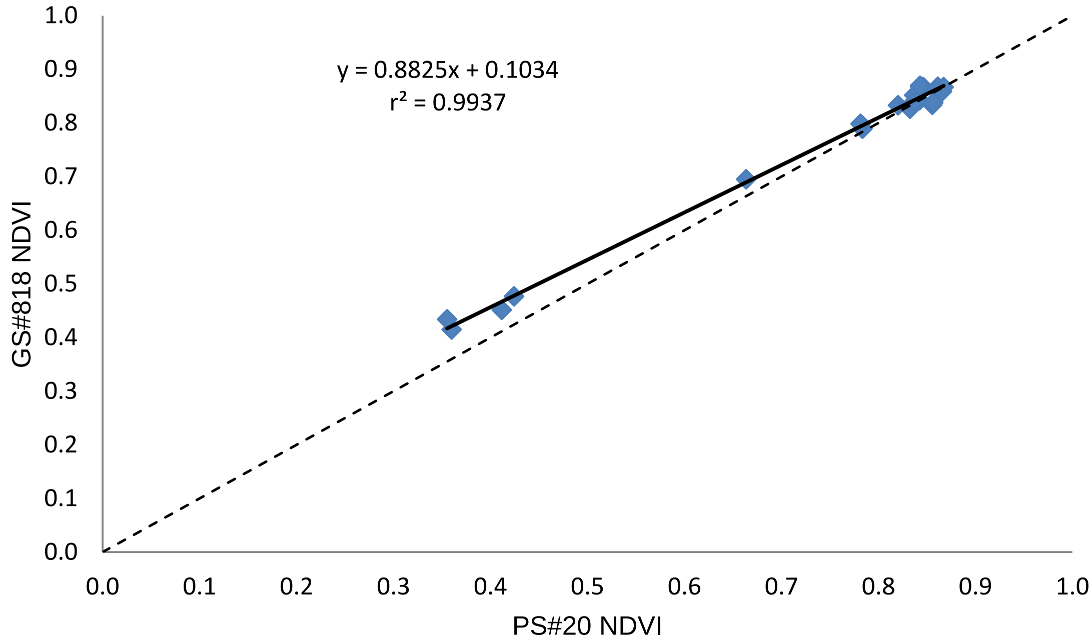

Figure 39. Relationship between Pocket Sensor #20 and GreenSeeker #818 NDVI readings in wheat Ciudad Obregon, Mexico, February 2, 2011.

Table 13. Pocket Sensor NDVI values based on 95% confidence levels for turf grass, wheat, and maize canopies.

			Pred. NDVI	Range NDVI	Pred. NDVI	Range NDVI	Pred. NDVI	Range NDVI	Pred. NDVI	Range NDVI	Pred. NDVI	Range NDVI	Mean NDVI by Sensor
Sensor	Crop	Type Estimate	0.4		0.5		0.6		0.7		0.8		
19	grass	average	0.388		0.497		0.605		0.713		0.821		
19	grass	95% extreme	0.372	0.016	0.479	0.018	0.585	0.020	0.691	0.022	0.797	0.023	0.020
20	grass	average	0.402		0.505		0.607		0.710		0.812		
20	grass	95% extreme	0.388	0.014	0.489	0.016	0.589	0.018	0.690	0.019	0.791	0.021	0.018
27	grass	average	0.401		0.508		0.614		0.721		0.828		
27	grass	95% extreme	0.386	0.015	0.491	0.017	0.596	0.018	0.701	0.020	0.807	0.022	0.018
32	grass	average	0.398		0.499		0.599		0.700		0.800		
32	grass	95% extreme	0.382	0.016	0.481	0.018	0.580	0.019	0.679	0.021	0.777	0.023	0.019
37	grass	average	0.403		0.507		0.610		0.713		0.816		
37	grass	95% extreme	0.388	0.016	0.489	0.018	0.590	0.019	0.692	0.021	0.793	0.023	0.019
27	maize	average	0.403		0.507		0.611		0.716		0.820		
27	maize	95% extreme	0.348	0.054	0.446	0.061	0.544	0.068	0.642	0.074	0.739	0.081	0.068
37	maize	average	0.408		0.508		0.607		0.707		0.806		
37	maize	95% extreme	0.378	0.030	0.474	0.034	0.570	0.037	0.666	0.041	0.762	0.044	0.037
20	wheat	average	0.418		0.517		0.616		0.716		0.815		
20	wheat	95% extreme	0.369	0.049	0.464	0.053	0.559	0.057	0.654	0.062	0.749	0.066	0.057
32	wheat	average	0.403		0.502		0.601		0.700		0.798		
32	wheat	95% extreme	0.346	0.057	0.440	0.062	0.534	0.067	0.628	0.071	0.723	0.076	0.067

Pred. NDVI—predicted NDVI based on Pocket Sensor Reading.
Range NDVI—NDVI difference from average predicted value.
Type Estimate: average—average value based on Pocket Sensor calibration.
95% extreme—most extreme value displayed by the Pocket Sensor with 95% confidence limit.

Table 14. Changes in nitrogen recommendations from varying NDVI values. Nitrogen recommendations were made from the Sensor Based Nitrogen Rate Calculator < http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php> accessed March 10, 2011.

Crop	Farmer Practice	N Rich Strip	N recommend	+0.025 NDVI	Δ N	-0.025 NDVI	Δ N	+0.05 NDVI	Δ N	-0.05 NDVI	Δ N
Wheat*	0.8	0.83	7.6	0	-7.6	14.8	7.2	0	-7.6	21.8	14.2
Wheat*	0.625	0.83	54.2	47.9	-6.3	60.3	6.1	41.6	-12.6	66.5	12.3
Wheat*	0.45	0.83	59	54.9	-4.1	63.3	4.3	85.5	26.5	67.9	8.9
Wheat*	0.6	0.65	12.4	5.7	-6.7	18.9	6.5	0	-12.4	25.4	13
Wheat*	0.5	0.65	38.4	31.9	-6.5	45	6.6	25.4	-13	51.8	13.4
Average Recommended Difference					-6.24		6.14		-3.82		12.36
Corn**	0.8	0.83	25.9	19.1	-6.8	32.3	6.4	12.1	-13.8	38.5	12.6
Corn**	0.625	0.83	66.8	61.3	-5.5	72.1	5.3	55.8	-11	77.5	10.7
Corn**	0.45	0.83	70.6	74.5	3.9	66.9	-3.7	78.6	8	63.4	-7.2
Corn**	0.6	0.65	24.2	18.2	-6	30	5.8	12.1	-12.1	35.8	11.6
Corn**	0.5	0.65	47.4	41.6	-5.8	53.3	5.9	35.8	-11.6	59.3	11.9
Average Recommended Difference					-4.04		3.94		-8.1		7.92

Δ N—Difference in nitrogen recommendation based on change in NDVI value.

*N recommendations determined for wheat at normal planting time sensed 1st week of March. N rich strip and farmer values are a range of what would normally be encountered in the field.

**N recommendations determined for corn with a normal planting date sensed during the 2nd week of June. N rich strip and farmer values are show both representative and extreme values found in the field.

APPPENDIX

Relationship of Pocket Sensor and GreenSeeker Readings for Combined Growth stages of Maize

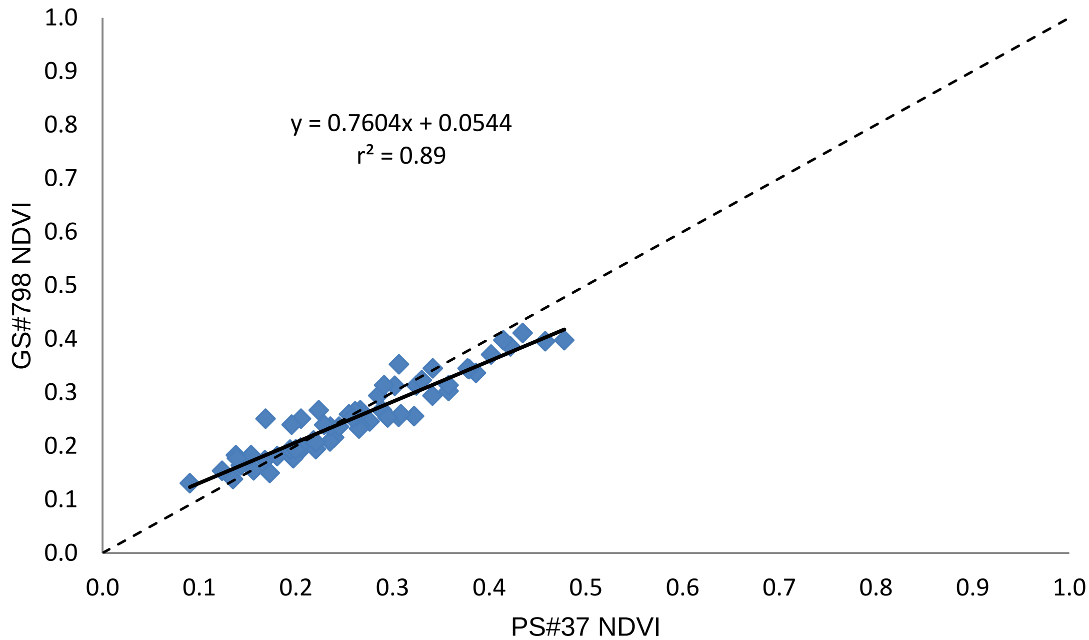

Figure A1.1. Relationship between Pocket Sensor #37 and GreenSeeker #798 NDVI readings in maize growth stage V4-V6, Ciudad Obregon, Mexico, 2011.

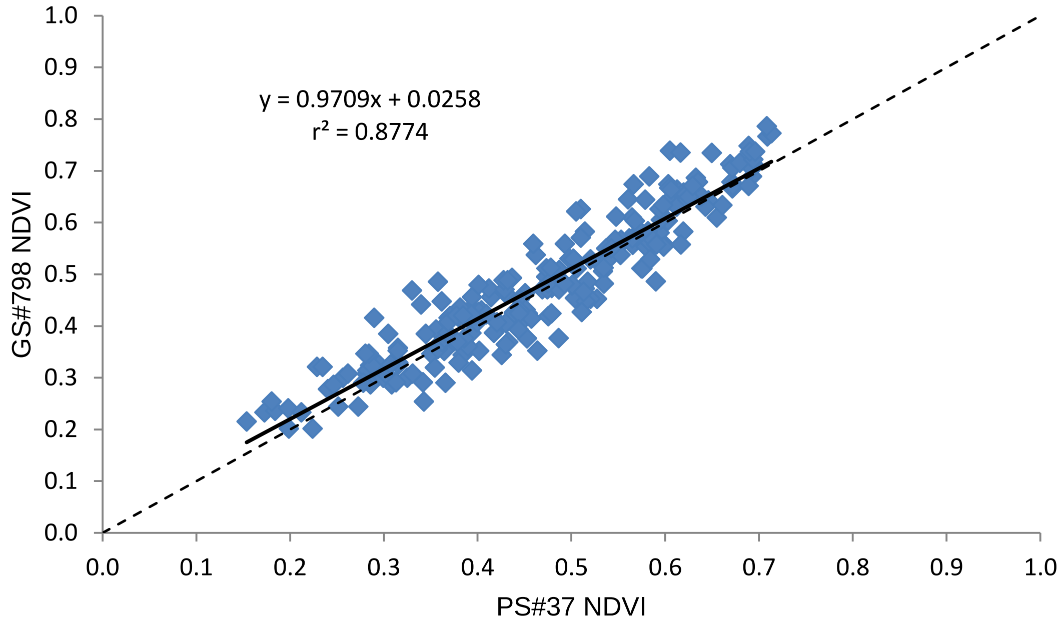

Figure A1.2. Relationship between Pocket Sensor #37 and GreenSeeker #798 NDVI readings in maize growth stage V7-V10, Ciudad Obregon, Mexico, 2011.

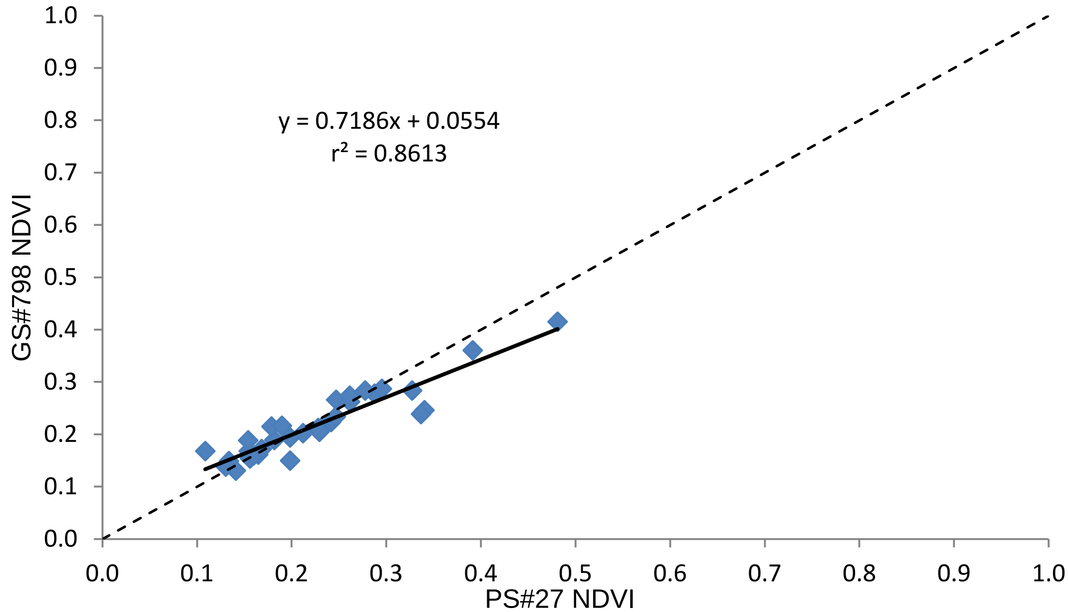

Figure A1.3. Relationship between Pocket Sensor #27 and GreenSeeker #798 NDVI readings in maize growth stage V4-V6, Ciudad Obregon, Mexico, 2011.

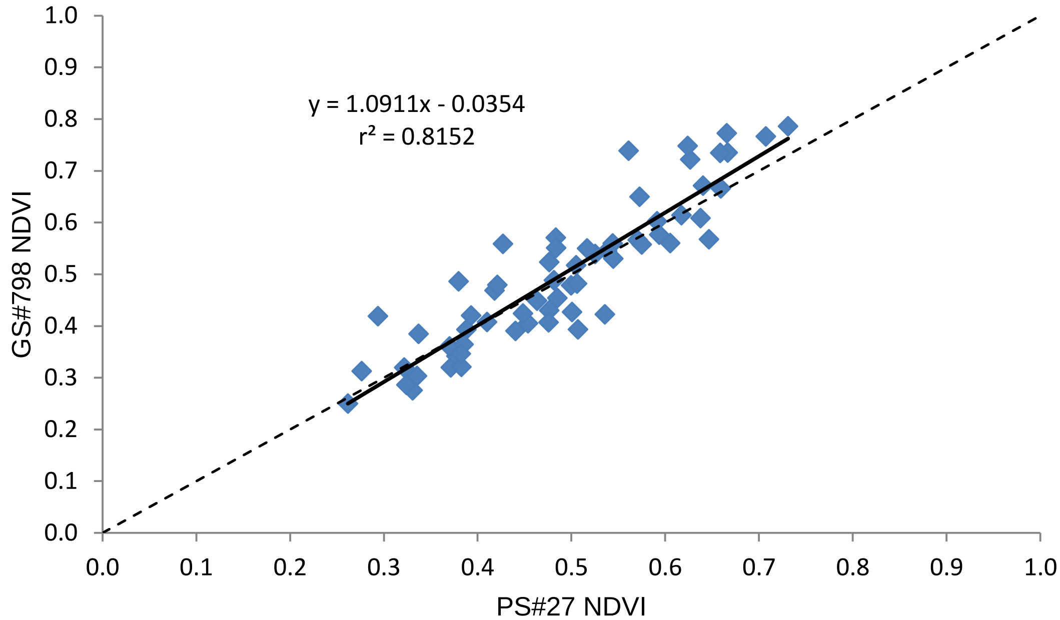

Figure A1.4. Relationship between Pocket Sensor #27 and GreenSeeker #798 NDVI readings in maize growth stage V7-V10, Ciudad Obregon, Mexico, 2011.

VITA

Jared Levi Crain

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF THE OSU NDVI POCKET SENSOR

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Completed the requirements for the Master of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in May, 2012.

Completed the requirements for the Bachelor of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in May 2010.

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Graduate research assistant for the Soil Fertility Program, Department of Plant and Soil Science, Oklahoma State University, Stillwater, Oklahoma 2011-2012. Assist with all aspects of soil fertility field trials including wheat, maize, sorghum, cotton, and soybeans crops. Maintenance and operation of small plot research equipment. Assist with data collection using NDVI, SPAD meters, ceptometers, and other remote sensing devices. Data processing and analysis using Microsoft Excel, Word, PowerPoint, and SAS software.

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Institution: Oklahoma State University Location: Stillwater, Oklahoma

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Scope and Method of Study:

This study evaluated the potential of a reduced cost prototype, Normalized Difference Vegetative Index (NDVI) sensor to make nitrogen recommendations in wheat and maize crops. Methods have been developed to use optical NDVI sensors to make nitrogen recommendations that improve nitrogen use efficiency, farmer economic productivity, and enhance environmental sustainability. However, these sensors are cost prohibitive to farmers in the developing world. The purpose of this study was to evaluate and develop methods to use the prototype sensor (Pocket Sensor) with the same accuracy as the commercial sensors. The study location was at the International Maize and Wheat Improvement Center (CIMMYT) in Ciudad Obregon, Mexico, during the 2010-2011 crop cycle. Data were collected from existing field trials in wheat and maize as well as turf grass canopies to evaluate the accuracy and precision of the Pocket Sensor. Along with evaluating the potential to use the Pocket Sensor to make nitrogen recommendations, the effect of different operators and the calibration stability, ability to obtain the same results over time, were evaluated.

Findings and Conclusions:

This study found that the Pocket Sensor was highly accurate and well correlated to the commercial sensor $r^2>0.97$, $r^2>0.95$, and $r^2>0.91$, respectively for grass, wheat, and maize canopies. The Pocket Sensor lacks some of the precision of the commercial sensor (NDVI of commercial sensor ±0.02, ±0.05, ±0.06 for turf grass, maize, and wheat, respectively). The Pocket Sensor readings are also stable over time, and users can expect to obtain similar NDVI readings as compared to the commercial sensor over a six month time frame. Additionally, different operators, who have had adequate training, can obtain similar results. Even with these slight variations in precision, the Pocket Sensor should be able to accurately predict nitrogen recommendations within ±4-6 kg nitrogen ha^{-1}, with a maximum error of ±8-12 kg nitrogen ha^{-1} in maize and wheat crops. The Pocket Sensor can be used as an effective tool to determine NDVI in wheat and maize as well as make nitrogen recommendations based on the NDVI readings collected with the Pocket Sensor.

ADVISER'S APPROVAL: Dr. William R. Raun