Development and Delivery of the Second Generation Optical Pocket Sensor for Maximizing Nitrogen Use Efficiency in Cereal Production Systems

Program to Improve the Adoption Rates and Efficiency of Best Management Practices to Protect Oklahoma Waters from Nonpoint Source Pollution

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FINAL REPORT

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EXECUTIVE SUMMARY

Nitrogen fertilizer is the most important and expensive controllable input in cereal crop production. In virtually all regions of the world where fertilizer nitrogen is used, it has resulted in increased yields. However, non-judicious use of this expensive input has also had serious and deleterious environmental impact on area waters through non-point source run-off. Methods and means of improving fertilizer nitrogen use efficiency are sought all over the world, and via this project, we have developed an applied, and affordable solution for N management in cereals.

As was proposed, this project has now delivered a potentially low-cost optical sensor that measures the normalized difference vegetative index (NDVI), and that can determine a growing crop's nitrogen needs. When used at the farm scale, this new sensor can replace the current GreenSeeker sensor. The word "potentially" is used, because the 67 prototypes that have been produced need commercial interest in order to produce them on a large scale. Nonetheless, the comprehensive development, re-design, and testing has delivered viable and working versions of an NDVI sensor that has now been fully tested in the USA and Mexico. Present algorithms for improved N recommendations in cereal production, can now be accessed using the new optical pocket sensor (http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php), since it produces exact "GreenSeeker NDVI" values. This was an important development criterion that was adhered to and that has been tested on all of the 67 prototypes developed. The pocket sensor had to work across the entire data range, and do so while delivering slopes of 1, and an intercept of 0. Once complete sensor testing and calibration had taken place, sensors were delivered to various locations in Oklahoma, and now many parts of the world. Using present day algorithms that are on-line, these fully tested N rate algorithms are now delivering N recommendations for those fortunate to have one of the new Oklahoma State University pocket sensors.

Future small-scale NDVI sensors will undoubtedly benefit from the design and testing encumbered in this project.

Background and Rationale

Improving Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) for cereal production in the world is estimated at 33% (Raun and Johnson, 1999). Since 1991, Oklahoma State University and the International Maize and Wheat Improvement Center (CIMMYT) have teamed to deliver improved fertilizer N rate recommendations for corn, wheat (winter and spring), rice, sorghum, canola, Bermuda grass, and cotton (http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php). This technology is tied to mid-season prediction of yield potential using NDVI (Normalized Difference Vegetative Index) measurements from optical sensors, and an estimate of N responsiveness utilizing nitrogen rich strips in farmer fields (Raun et al., 2005). N Rich Strips constitute applying a pre-plant fertilizer N rate at levels where no N deficiency will be encountered throughout the plant cycle. These N Rich Strips serve as a benchmark from which to gauge the need for added fertilizer N in the middle of the season by visually comparing this strip to the conventional farmer practice. A variant of the N Rich Strips is termed Ramp Calibration Strips, http://www.nue.okstate.edu/Index_RI.htm, which are applied preplant or soon thereafter, but unlike the N Rich Strips, a sequence of automated N rates are included to facilitate direct mid-season N rate interpretation, and making recommendations for achieving maximum yields. Using N rich strips and mid-season estimates of yield potential, our project realized increases in NUE of more than 15% above that of conventional methods (Raun et al., 2002).

The environmental impact of low nitrogen use efficiency occurring with adequate N fertilizer is also alarming. Malakoff (1998) estimated that excess N flowing down the Mississippi River in the United States, was valued at over $750,000,000. With drastically increased N prices today, that value exceeds 1 billion dollars per year.

Existing Efforts

We are currently extending sensor based N management in various states within the USA, Mexico, Argentina, Australia, Zimbabwe, Uzbekistan, India, and China. Algorithms are available on-line and are now being widely used by producers. In addition to the GreenSeeker^{TM} sensors, we have constructed and engineered variable N rate applicators capable of treating each individual maize plant on-the-go. While certainly not feasible for the developing world, it is important to know what can be delivered and where the outer boundaries exist in terms of increasing production and nitrogen use efficiency. We have been successful in introducing nitrogen fertilizer management systems using N Rich strips and optical sensors to Oklahoma farmers. The primary limitation in the adoption of the technology is the cost of existing sensors.

Methods

Our project has capitalized on the recent development and success of the GreenSeeker^{TM} optical sensor system for managing N fertilizer created by Oklahoma State University and commercialized by NTech Industries, Inc., Ukiah, California. Most recently, NTech Industries was purchased by Trimble Co. (San Francisco, CA, producer of GPS equipment).

This project was originally initiated to redesign the existing $4,000.00 GreenSeeker handheld optical sensor as an affordable rugged easy to use sensor. With this new sensor we expected to determine nitrogen needs of the growing crop in the same way as the GreenSeeker sensor. Development of the proposed sensor was critical because farmers have seen a rapid increase in the cost of N fertilizer as well as increased pressure to better manage the use of N fertilizer.

At this time, it is impossible to determine appropriate fertilizer N rates in cereal production systems with other technologies. Our research has shown that the only way to determine crop response to additional N fertilizer is to establish preplant N Rich Strips in each field on top of the farmer practice. As weather changes from one year to the next, so too does the amount of N mineralized from soil organic matter and that deposited in the rainfall. As a result, the crop's nitrogen requirement and the optimum N application rate changes drastically from year to year. The GreenSeeker^{TM} system combines optical sensor measurements to calculate yield potential, response to additional fertilizer, and to determine the N fertilizer application rate. Oklahoma State University has developed optical sensors and the agronomic science required to make N rate determinations and has implemented and tested these over many years. However the cost of the GreenSeeker sensor has limited the adoption by individual farmers, and in the third world. This project thus proposed to package a new, affordable optical sensor with proven agronomic science and extension methodology in a smaller unit for Oklahoma farmers and producers in other parts of the world.

In a legume rotation system, particularly soybeans, previous year legume growth, cereal yield levels, environment (wet, dry, etc.), disease, residue management, and weed control, all affect the demand for fertilizer N. These and other factors interact to produce different N fertilizer requirements from year to year or planting to planting when more than one crop is grown in a single year. The N Rich Strip can integrate N demand into a visually interpretable and biologically accurate methodology for optimizing N inputs. Judicious use of fertilizer N is simply not possible without accounting for temporal variability. While soil testing does provide highly accurate information for virtually all nutrients, this methodology is not readily available in the third world nor does it account for the rapidly changing availability of highly mobile nitrogen. This is why there is an increased demand for a more easily adoptable technology like the N Rich Strip and an associated sensing technology.

Our approach applies N based on projected yield potential of the crop and N demand to reach that potential. Both are influenced by temporal variability, but both are independent of one another. The N Rich Strips serve to identify the relative demand for fertilizer N, but, in themselves, do not quantify the demand. Using the optical pocket sensor, we will be able to determine NDVI from the N Rich Strip or Ramp and the farmer practice and calculate the crops' response to additional N, the response index (RI). Furthermore, using the same NDVI values and region specific yield prediction equations, our proven methodology predicts yield potential by estimating the amount of biomass produced per day. This comes from extensive research showing that growth rate or biomass produced per day (estimated using NDVI from the previously described GreenSeeker^{TM} optical sensor) early in the season is in fact correlated with final grain yield (Raun et al., 2005). Using our approach, the amount of mid-season N to be applied to achieve optimum yields can be determined and that achieves the highest possible nitrogen use efficiency.

In the OSU system for managing N fertilizer, mid season fertilizer N rates are determined using the following equation.

$$YPN = RI\ YP0$$

This equation states that the potential yield with sufficient, but not excessive fertilizer (YPN) is directly proportional to the product of the potential yield without additional fertilizer (YP0) and the nitrogen response index (RI). YP0 is calculated by the following equation:

$$YP0 = Ae^{-b\frac{NDVI}{GD}}$$

Extensive research by OSU and the International Maize and Wheat Improvement Center (CIMMYT) has shown that an exponential function best relates optical sensor measurements of NDVI to potential yield. However, the prediction can be improved by dividing NDVI by days of active growth (GD) or cumulative growing degree days (GDD) depending on the crop. The parameters A and B are crop specific and can (but frequently do not) change by region.

Nitrogen fertilizer application rate is computed by:

$$R = \frac{YPN - YP0}{C}\eta$$

Where the application rate, R, is the difference between the yield potential with and without additional N fertilizer divided by percentage of N required to produce one unit of grain, C, multiplied by a nitrogen uptake efficiency factor, η. C is crop specific and can be cultivar specific. η is determined experimentally.

This approach is now used for 28 functional algorithms around the world, for a range of crops, and all algorithms use these basic equations. The only major difference is that region and crop specific parameters for each yield prediction equation are required.

Results

Sensor Development

Successful completion of this proposal depended on the development of a reliable and durable optical pocket sensor. The central design of this sensor employed active sensing technology that allows for highly precise NDVI readings (NIR-red/NIR + red) from plant canopies. Initial work by Stone et al. (1996) using passive sensors showed that NDVI could be reliably used to predict total forage N uptake from plant materials. This work was expanded to include active sensors that can accurately determine NDVI, day or night (Stone et al., 2005).

The Greenseeker™ sensors based on the work of Stone et al. (1995) were originally developed to be integrated into a mobile agricultural fertilizer applicator. These sensors are used in a battery powered hand held configuration through the addition of a handle, a handle mounted pocket computer and battery system. The heritage of the original sensor design provided opportunity for large cost reductions for a design focused on low-cost hand-held use. The current Greenseeker™ design supports many features that were unnecessary in our hand-held design. Those include a myriad of high speed communication interfaces that allow integration into mobile agricultural equipment, an optical view control system that controls sensor view as height above the plant canopy varies, a system for driving solenoid actuated spray nozzles, very high sampling rate to accommodate fast sprayer speeds, dual detector technology to allow "on the fly" automated calibration, and a handle mounted PDA computer to capture data. All of these features were eliminated with no compromise in performance in the pocket sensor (PS) developed here. In addition, the elimination of the high speed communications interfaces and fast sampling speeds allowed for a much lower performance microprocessor. This, combined with the elimination of the controlled view and automated calibration, allowed for a very low power design (Figure 1). The integration of a low-cost display in the PS allowed for the elimination of the pocket computer and communications interface on the OPS.

Figure 1. Optical pocket sensors with NDVI display readings on the top, and active sensor reading on the bottom.

The original version of the pocket sensor used one NIR LED and one RED LED for the light sources. Experimentation showed that reflected light was insufficient for accurate measurement. After a substantial amount of testing the basic design of the current version was finalized. The production version of the pocket sensor used eight (8) RED LEDs and four (4) NIR LEDs as the light sources. In addition, the current production version includes several design modifications that help reduce sensor noise and improves accuracy and repeatability.

Field Testing

The underlying premise behind the construction of a new sensor that would be more affordable for third world farmers was the ability to reproduce, exactly, the NDVI values produced by the GreenSeeker sensor. Thus, once several prototypes had been vetted that could reliably provide red, NIR, and NDVI index values at fixed heights, it became immediately important to establish the relationship between pocket sensor values and that of the GreenSeeker sensor.

As is illustrated in Figures 2 and 3, rigorous testing for each and every sensor produced was embedded in our procedures for spring wheat, winter wheat, and corn. Before sensors were accepted for potential delivery to producers, they were tested versus the GreenSeeker sensor. For all sensors, the target was to have slopes equal to one and intercepts of 0. This is apparent in the 6 sensors for which pocket sensor (PS) and GreenSeeker (GS) data are reported.

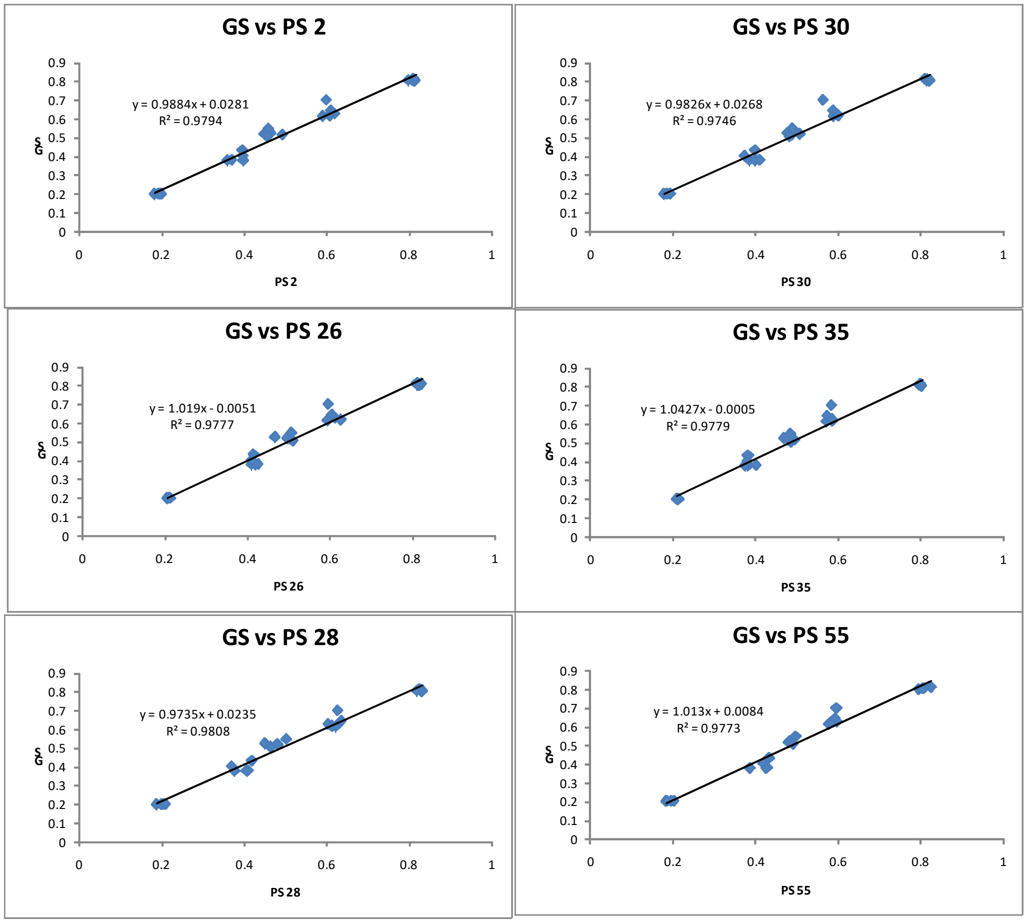


Figure 2. Field testing for pocket sensor 2, 30, 26, 35, 28, and 55 versus the GreenSeeker sensor. NDVI values collected with the pocket sensor were then tested versus the values for the GreenSeeker from 30 random locations in a spring wheat field, in Ciudad Obregon, MX.

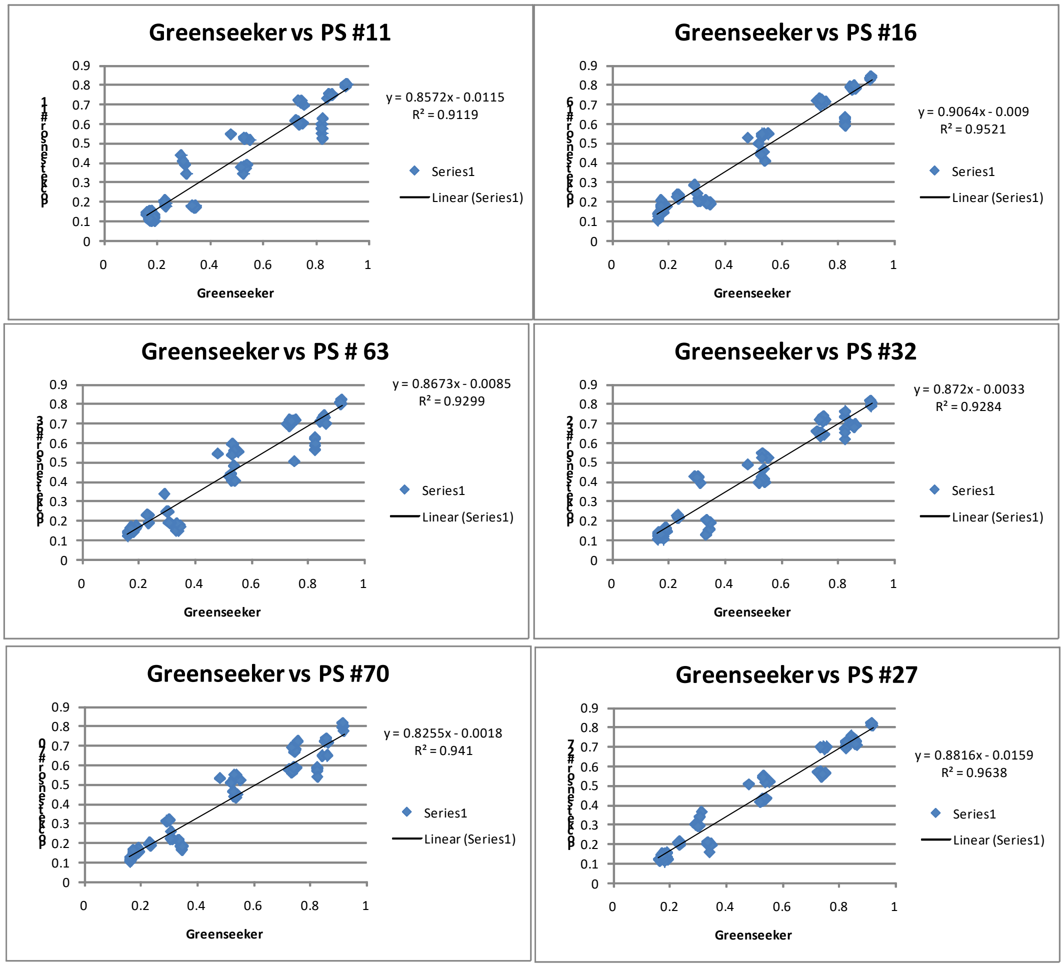


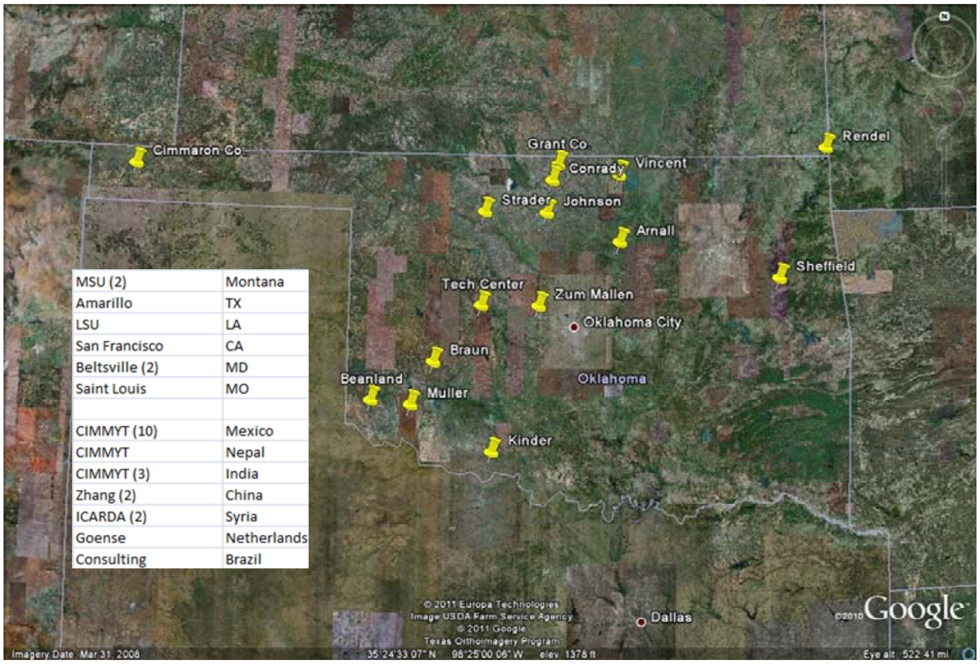
Figure 3. Field testing for pocket sensor 11, 16, 63, 32, 70, and 27 versus the GreenSeeker sensor. NDVI values collected with the pocket sensor were then tested versus the values for the GreenSeeker from 50 random locations in a winter wheat field, Stillwater, OK.

In addition to evaluating different crops, alternative conditions under which these pocket sensors are operated have been evaluated. Higher temperature, low humidity conditions in Ciudad Obregon Mexico and lower temperature, higher humidity conditions in Stillwater OK (Figures 4 and Figure 5).

Figure 4. Evaluation and testing of the OSU pocket sensor versus the GreenSeeker sensor in Ciudad Obregon, MX.

Figure 5, OSU pocket sensor in use by producer Brooke Strader, near Homestead, OK.

As delineated in our original proposal, these sensors had a specific target for Oklahoma producers. Where these sensors are currently located and being used is illustrated in Figure 6. As is noted, the majority are located in the wheat belt regions of western Oklahoma. Also included in this figure are the locations around the world for other sensors that have been delivered. A complete list of the sensors produced, where they are located, and email addresses for the users involved is reported in Table 1. Also, included is a complete list of the Oklahoma producers receiving pocket sensors that Dr. Arnall will coordinate well into the future, and beyond the scope of this grant.



MSU (2)	Montana
Amarillo	TX
LSU	LA
San Francisco	CA
Beltsville (2)	MD
Saint Louis	MO
CIMMYT (10)	Mexico
CIMMYT	Nepal
CIMMYT (3)	India
Zhang (2)	China
ICARDA (2)	Syria
Goense	Netherlands
Consulting	Brazil

Figure 6. Location of optical pocket sensors in Oklahoma, other U.S. states (Montana, Texas, Louisiana, California, Maryland, and Missouri), and in other regions of the world (Mexico, Nepal, India, China, Syria, Netherlands, and Brazil).

Table 1. Pocket sensor number, final destination and email address for the entities receiving pocket sensors.

Number	Pocket sensor #	Final Desination:	email
1	Original	Soil Fertility Shop	
2	050710-01	Ted Mayfield, Trimble	ted_mayfield@trimble.com
3	050710-02	Peter Quan, USDA NASS R&D, 3251 Old Lee Hwy, Fairfax, VA	peter_quan@nass.usda.gov
4	050710-03		
5	050710-04	Dr. Kyle Freeman - Ellisville, MO; Monsanto	kyle.freeman@monsanto.com
6	050710-06	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
7	050710-07	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
8	050710-08	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
9	050710-09	Louisiana State University - Yumiko Kanke and Dr. Tubana	ykanke1@tigers.lsu.edu ; Btubana@agcenter.lsu.edu
10	050710-10	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
11	050710-11	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
12	050710-12	India - CIMMYT - Dr. Raj Gupta	rajgupta@cgiar.org
13	050710-13	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
14	050710-14	Kent - getting fixed	dieball@suddenlinkmail.com
15	050710-15	India - CIMMYT - Dr. Bijay Singh	bijaysingh20@hotmail.com
16	050710-16	waiting to be sent back	
17	050710-17	India - CIMMYT - Dr. Raj Gupta	rajgupta@cgiar.org
18	050710-18	India - CIMMYT - Dr. Bijay Singh	bijaysingh20@hotmail.com
19	050710-19	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
20	050710-20	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
21	050710-21	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
22	050710-22	Dr. Hailin Zhang - OSU	hailin.zhang@okstate.edu
23	050710-24	John Deere: Western Equipment - Jerry May and Jason Lawl	jmay@westernequipmentllc.com
24	050710-25	waiting to be sent back	
25	050710-26	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
26	050710-27	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
27	050710-28	John Lamers -- CIMMYT/ICARDA	j.lamers@zef.uzpak.uz
28	050710-29	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
29	050710-30	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
30	050710-31	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
31	050710-32	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
32	050710-33	Kent - getting fixed	
33	050710-34	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
34	050710-35	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
35	050710-36	Dr. Hailin Zhang - OSU	hailin.zhang@okstate.edu
36	050710-37	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
37	050710-38	Augustin Bianchini - Argentina	
38	050710-39	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
39	050710-40	Kent - getting fixed	dieball@suddenlinkmail.com
40	050710-41	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
41	050710-43	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
42	050710-44	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
43	050710-45	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
44	050710-46	Dr. Hailin Zhang - OSU	hailin.zhang@okstate.edu
45	050710-47	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
46	050710-48	Kent - getting fixed	dieball@suddenlinkmail.com
47	050710-49	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
48	050710-51	Netherlands - Daan Goense	
49	050710-52	Brazil with consulting firm (September 7, 2010)	
50	050710-53	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
51	050710-54	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
52	050710-55	John Lamers -- CIMMYT/ICARDA	j.lamers@zef.uzpak.uz
53	050710-56	Olga Walsh - Montana State University	olga.walsh@montana.edu
54	050710-57	Kent - getting fixed	dieball@suddenlinkmail.com
55	050710-58	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
56	050710-60	Kent - getting fixed	dieball@suddenlinkmail.com
57	050710-61	Louisiana State University - Yumiko Kanke and Dr. Tubana	ykanke1@tigers.lsu.edu ; Btubana@agcenter.lsu.edu
58	050710-62	Kent - getting fixed	dieball@suddenlinkmail.com
59	050710-63	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
60	050710-64	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
61	050710-65	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
62	050710-66	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org
63	050710-67	USDA NASS R&D - Peter Quan, 3251 Old Lee Hwy, Fairfax, VA	peter_quan@nass.usda.gov
64	050710-68	Dr. Brian Arnall - OSU PASS Extension	b.arnall@okstate.edu
65	050710-69	Olga Walsh - Montana State University	olga.walsh@montana.edu
66	050710-70	Mexico - CIMMYT - Jared Crain/Dr. Ivan Ortiz-Monasterio	jared.crain@okstate.edu ; i.ortiz-monasterio@cgiar.org

Table 2. Pocket sensors delivered, cooperator, location in Oklahoma, and sensor serial #, that will continue to be coordinated by Dr. Brian Arnall, soil fertility extension, Oklahoma State University.

Sensor	Cooperator	Town	Sensor Serial #
1	Brent Rendel	Miami	8
2	Jimmey Kinder	Walters	58
3	Cherrie Brown	Biose City	34
4	Heath Beanland	Hollis	39
5	Larry Johnson	Enid	53
6	Brook Strader	Homestead	54
7	Keith Brownbecl	Weatherford	65
8	Bryan Vincent	Ponca City	6
9	Brent Conrade	Pond Creek	13
10	Matt Muller	Altus	31
11	Rick Zum Maller	El Reno	28
12	Brian Sheffield	Webbers	44
13	Grant County	Medford	10
14			49
15	Brian Arnall	Stillwater	

Future of the Pocket Sensor

Identification of component and production resources as well as education in strategies for managing production of the pocket sensors could assist in controlling the ultimate cost of these devices. Oklahoma State University now has demonstrated expertise in developing plant reflectance sensors, including the original Greenseeker™ and now the pocket sensor. As was proposed, the first 67 pocket sensors were manufactured locally. This effort included producing and executing designs, testing the initial devices and manufacturing. These prototypes formed the basis for the first and ensuing OPS designs. An agreement to manufacture these devices for current and future demands could be made locally or with Trimble Co.

Based on OSU experience with Greenseeker™ sensors, several practical issues associated with field use of the pocket sensor have now been incorporated. This has included an incredibly functional USB charging system. Calibration of sensors (sensor to sensor and sensor to GreenSeeker) has been critical in maintaining performance and verifying functionality. Via this funded work, we have verified by-sensor calibration with the GreenSeeker.

As a part of this process we have simultaneously educated farmers in the use of N Rich Strips, especially those who have received sensors. Based on field sensor work that we initiated in 1992 in the United States, Mexico, and Argentina, it will take more time before this technology is uniformly adopted.

The principal investigators have a history of extension of improved N management to Oklahoma farmers and county extension educators. Via this proposal and the generation of what could be an affordable, commercially available sensor, widespread adoption of the OSU N management strategy is now a possibility. In Oklahoma, the pilot program to distribute these sensors to a select group of farmers has been successful. We must now work even more closely with these farmers to assist them with their current practices, and how their pocket sensor combined with the N Rich Strip can benefit them and others.

The new optical pocket sensor has increased utility in being easily portable, and much more affordable than the current GreenSeeker sensor. However, it is important to note that these sensors will not replace what is currently used - on-board variable rate applicators (Figure 7). Trimble Co. currently sells variable N rate applicators capable of sensing and treating at the boom-width resolution. However, OSU currently has in place the technology to sense and fertilize individual corn plants, on-the-go. We believe that is the future for nutrient management.

Figure 7. On-the-go variable N fertilizer sprayer developed at Oklahoma State University capable of applying prescribed fertilizer N rates to each individual corn plant.

Similar to the wide scale adoption of grain moisture meters by farmers in the 1970's and 1980's, we envision broad acceptance of the optical pocket sensor for deciphering mid-season fertilizer N rates for various crops, especially in our current environment where N fertilizer prices are rapidly approaching $1.00 per pound. Our proven algorithms for prescribing fertilizer N rates based on NDVI measurements have made the development of the pocket sensor all that more attractive.

Project Summary and Output

From July 2008 to June 2010, 67 optical pocket sensors were manufactured and field tested. This followed almost 2 years of comprehensive testing, design, and re-design of various sensor components and boards. From June 2010 to present, we have distributed 60 of the pocket sensors and have trained each recipient in the use of the optical pocket sensors in the field. This has been followed by the development of a web site where user manuals are now available in both Spanish and English and where suggestions for design of future sensors have been made. Also, issues of re-calibration of the sensors currently being used all over the world, are addressed on this site.

http://nue.okstate.edu/Pocket_Sensor/Pocket_Sensor.htm

Similar to what we have done documenting the benefits of using the GreenSeeker sensor, along with OSU recommendations, data has been collected using the pocket sensor and that will continue well into the future. Increased NUE for any of the producers using the OSU pocket sensor and our on-line recommendations is expected, consistent with that already reported by Raun et al. (2002).

http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php

As others have noted increased NUE at the same overall fertilizer N rate leads to decreased runoff (Lopez-Bellido et al., 2006), thus the environmental benefits of using our system, and the decreased risk to surface water supplies from N fertilizers is an added benefit. Our sincere thanks are extended to the Oklahoma Conservation Commission, Water Quality Division for their vision in supporting this work.

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APPENDICES

I. OSU Pocket Sensor Tips (PPT file attached)

II. OSU Pocket Sensor Guidelines

III. Pocket Sensor Suggestions (re-design)

Pocket Sensor Guidelines

1) The sensor comes pre-calibrated to a Greenseeker sensor. (The manual below would indirectly suggest that the sensor might not be calibrated.)
2) The sensor can be calibrated to an "NDVI" sensor (not just a Greenseeker).
3) The existing Greenseeker calibration must be turned to FALSE (G, F) before re-calibrating.

One thing that needs to be enforced is charging the battery of the pocket sensor every night. Also, before calibration, the sensors need to be fully charged. This will ensure the sensor is operating at its best.

Charging

- Attach the provided USB cable attachment to the front side of the pocket sensor, then plug in the USB cable directly into a USB port on a computer. Charge for 3-4 hours.
- Battery life is approximately 6-10 hours, depending on operation.
- A "batt" symbol will appear in the upper left-hand corner of the LCD screen if a low-battery condition occurs.

Operation

- Before use, check to ensure that the 4 LEDs on the top and bottom of the sensors are working. Only the LEDs on the top and bottom, not the two LEDs on the sides, will flash during operation. If all 4 LEDs on the top and bottom are not working, the sensor needs to be repaired.
- Be careful not to obstruct the light source when using the Pocket Sensor. Grip the sensor on the sides as this will keep hands and fingers from impeding the light source.
- Care must be taken to keep the pocket sensor level while sensing, at a height of 24" to 30" (60-75 cm) above the crop canopy. The target is circular with a dimension shown in Figure 1.
- To operate, place the pocket sensor at the appropriate height above the canopy, then push and hold the red button.

- While holding the red button, walk slowly down the treatment (or strip) that you want to sense. You will notice the NDVI value being displayed on the screen changing once per second during operation.
- When you are done sensing, release the red button and note the last number displayed on the screen. This is the average of all readings that were taken while the button was depressed.
- Write down or remember this number quickly, because it will only be displayed for a few seconds before it disappears. Ensuing readings once the red button is pressed again start anew.
- The pocket sensor does not have the capability of storing data, so you must record the NDVI values that you need after each operation.

Figure 1. Target dimension for different sensing distances

Storage

- Store in the cardboard box provided. **Be very cautious** about placing the pocket sensor face down on any surface, as this could scratch the LED lenses.

Error Messages

- An error message may be displayed on the screen if something is wrong. The following messages may appear, with the correct description:
  - E01 – calculated NDVI value is less than 0, which is invalid
  - E02 – calculated NDVI value is greater than 1, which is invalid
- Often error messages can be corrected by adjusting the height of the sensor and maintaining a right angle with the soil.

Hours of Operation

- The pocket sensor should provide the same readings day or night, as this is an active sensor. You will not want to use the sensor if it is raining or in extreme heat or cold.

This should already have been accomplished, but if not, re-calibration procedures follow.

Calibration Procedure for Pocket Sensor:

1. **Before the Pocket Sensor can be calibrated, any existing calibration must be set to 0. To do this:**

A. Plug the pocket sensor into a USB port on a computer, and follow the Installation instructions to download the driver onto the pocket sensor. The correct driver to download is the Silicon Labs CP210x USB to UART Bridge. This can be downloaded from http://www.silabs.com/products/mcu/pages/usbtouartbridgevcpdrivers.aspx and select the correct computer operating system.

B. A terminal program must be downloaded onto the computer to communicate with the pocket sensor. Go to https://sites.google.com/site/terminalbpp/ and download the terminal program available on that website.

C. With the pocket sensor plugged into the computer, open the terminal program. At the top of the page, make sure the settings are as follows:

- **a.** Baud rate: 19,200
- **b.** Data bits: 8
- **c.** Parity: none
- **d.** Stop bits: 1
- **e.** Handshaking: none

D. Select the correct COM port by looking at the Device Manager on your computer to determine where the Silicon Labs CP210x USB to UART Bridge is located.

E. Hit the "Connect" button at the top-left corner of the screen.

F. In the bottom portion of the screen, press "**p**" to print calibration numbers and the menu options.

- a. --**Caution!!!** **DO NOT** press "f" while on the menu page, as this will restore the memory to the default settings, and will render the sensor unusable until reset by an OSU Engineer!!!!

G. Press "g" to set the coefficients for the calibration equation.

H. Once "g" is entered, the terminal will display "**Enter CalNum.u8Flag.(T/F)……**" press "f". If "f" is not entered, the sensor will read 0.000 for all readings and values.

I. The formula is in the form of: $y = Ax^2 + Bx + C$. The values A, B, and C need to display 0 for calibration

-- "**Enter CalNum.fpA….**" Enter 0 for A, then press Enter
-- "**Enter CalNum.fpB….**" Enter 0 for B, then press Enter
-- "**Enter CalNum.fpC….**" Enter 0 for C, then press Enter

J. In the terminal program select "Disconnect" the sensor has now been set to its original calibration, and can be calibrate with the GreenSeeker.

2. Calibration must be done with a Greenseeker. Take at least 70-100 readings with both the Pocket Sensor and the Greenseeker over different types of surfaces (bare soil, different shades of vegetation, etc.).

Note: Make sure that the areas sensed by both the Greenseeker and Pocket sensor are exactly the same. Pick an area about 24” (60 cm) square, that is flat and homogenous.

Note: Begin calibration readings with the GreenSeeker. If the chosen area to calibrate the Pocket Sensor has more than 0.01 variability with the GreenSeeker, choose a different area to calibrate the Pocket Sensor. This will allow for the best readings and generation of calibration coefficients.

3. Enter the NDVI values of both Greenseeker and Pocket sensor into Microsoft Excel. Place the Pocket sensor values in the left column (for the independent, x-axis) and the Greenseeker values in the right column (for the dependent, y-axis).

4. Plot these values as a scatter plot. Make sure that Pocket sensor values are on the x-axis and Greenseeker values are on the y-axis.

5. On the scatter plot, right-click on the mouse over the points, and select “Add Trendline”.

6. On the Trendline menu, select “Polynomial” on the Regression Type, and “2” on the Order. Also check the boxes for “Display Equation on chart” and “Display R-squared value on chart”.

7. The Excel chart will now display the calibration equation that needs to be entered into the pocket sensor for calibration.

Entering the Calibration Equation into the Pocket Sensor:

1. Connect the Pocket Sensor to the computer and open the terminal program as outlined in previous section.
2. Press “p” to print calibration numbers and menu options.
--**Caution!!!** **DO NOT** press “f” while on the menu page, as this will restore the memory to the default settings, and will render the sensor unusable until reset by an OSU Engineer!!!!

3. Press “g” to set the coefficients for the calibration equation.

4. Once “g” is entered into the terminal, enter the values for the calibration equation.

5. Press “t” for True when it states “**Enter CalNum.u8Flag.(T/F)……**”

6. The formula is in the form of: $y = Ax^2 + Bx + C$. The values A, B, and C will then be entered into the terminal program:
-- “**Enter CalNum.fpA….”** Enter value for A, then press Enter
-- “**Enter CalNum.fpB….”** Enter value for B, then press Enter
-- “**Enter CalNum.fpC….”** Enter value for C, then press Enter

Be careful to note the sign (+ or -) for the Ax^2 value.

7. The Pocket Sensor is now calibrated and ready for use. Press "Disconnect" in the upper-left corner of screen to disconnect the device.

Note: While the Pocket sensor is plugged into the terminal program, it is possible to capture individual sensor readings. To do this, plug the sensor into the computer and connect to the terminal program, and press "p" to display the sensor values.

Experiences with the PocketSensor:

During calibration of the Pocket sensor at the CIMMYT Research Station in El Batan, Mexico, some considerations were: Wheat is planted on raised beds, and at the time of sensing the wheat was headed out (Reproductive Stage). The height of the wheat and the distance between beds allowed the GreenSeeker to read soil background while the Pocket sensor was only able to read the rows of wheat, the soil was too far away. It is imperative that both the GreenSeeker footprint and Pocket sensor be over the same targeted area to get an accurate calibration. **Note:** This may not be an issue when the wheat is vegetative and the soil is still within range of the Pocket sensor.

Pocket Sensor Suggestions for the Re-Design

Pocket Sensor Suggestions

1. Change the location of the button.
    a. Suggestions range from putting the trigger button on the side of the sensor so it can be activated with the thumb instead of index finger to a more pistol like hand grip. Various reasons that have been suggested for these changes are: If the sensor had a more pistol like grip it would be easier to keep level. For long field measurements it would be more ergonomic to press the button with the thumb than hold the button with the index finger.
    b. Locations to move the button include:
        i. To the right side of the sensor, this would allow a right handed person to easily activate the sensor.
        ii. Put a lateral extension on the back of the sensor so it looks like a table tennis racket. The button could then be placed on the underside of the handle.
        iii. Pistol grip with the button configured as the trigger.
        iv. Inverted pistol grip- The handle would be higher than the sensor allowing the sensor to be closer to the crop canopy without having to bend to adjust the sensor. The button would also be similar to a trigger.

   c. From the meetings in El Batan and Ciudad Obregon (technicians and scientist) to the farmer producer meetings in Navajoa and Hauntabambo (farmers and technicians) this has been suggested in every meeting. Each suggestion has also been made independently, not the same person at multiple meetings or previous comment about button location.
   d. From multiple field measurements -over 500- in 3-4 hours the button does become difficult to press and maintained pressed. In addition some sensors seem to have more difficult buttons which require more pressure to operate. In a single field, this may not be a problem, but for a crop scout/ technician that may measure fields all day long this may be more of an issue.

2. Change the button to an on/off toggle switch.
   a. Along with button location it has been suggested for field type NDVI readings that the button would be difficult to press for long periods. A switch that could be manually turned on and off may be easier to use.
   b. A toggle switch could resolve ergonomic issues and could probably replace the current location of the button without adjusting the location or adding a handle.
3. Change the time that the average NDVI is displayed.
   a. When working with the technicians at Ciudad Obregon (GreenSeeker and sensor training) there were several comments about the rapid display of the average. There was a consensus among 6-8 technicians that a longer time to display the average would be helpful, especially since the average is then erased, and the only way to recover it would be to take another field reading. This could result in a significant time to retake measurements.
   b. Change the software to display the average for 4-5 seconds.
   c. This was a popular idea when it was suggested for people that tested the sensor.
   d. (From a research perspective and taking multiple readings—small plot measurements—I like 2 seconds. I don't want to wait 5 seconds before beginning the next reading; however, in a field situation where 2-3 lengthy readings are taken, the extra display time may be a benefit to end users.)
4. Guard on the bottom of the sensor.
   a. Currently, there are just the four (sometimes four or two) clear buttons on the back of the sensor that keep the sensor LEDs and lens from contacting the surface at resting. While the buttons work on flat surfaces—tables—when the surfaces are not flat, it would be likely that the LEDs can contact the surface leading to damage. This could be especially true in field conditions when the sensor is carried in vehicles put on unlevel surfaces, etc.
   b. Cover the back of the sensor with a raised area that goes around the entire sensor instead of just the four corners. While this will not provide protection from everything, it may help ensure an unlevel surface does not damage the sensor.
   c. This came from one of the scientist at El Batan. While taking readings with several sensors for calibration, it was obvious that this could help better protect the LEDs. It would assist when the sensor is not placed on a level surface—ground, pickup bed, dashboard of vehicle that would be more representative of field use conditions.
   d. In addition to protecting the LEDs, this will also provide a tangible guard for people operating the sensor to know if their fingers or hand placement on the

sensor will affect readings. As noted in Stillwater and Obregon, if the sensor is held with fingers gripping the bottom, the sensor readings can change. For a sensor that is mass produced, a tangible guard that could be emphasized in training to use the sensor would be an easy approach to ensure correct operation and NDVI measurements.

5. Battery Symbol
    a. Currently, there is no way to tell what level the battery is at. This could allow a user to use the sensor with low batteries and obtain incorrect reading. Currently, besides charging before use, when the battery runs down, all numbers are displayed more faintly.
    b. Provide either a battery symbol or a program that would display the battery is too low to function correctly.
    c. Several of the technicians and workers have commented on the battery and questioned how to tell if the battery is charged sufficiently.
6. Alternate way to calibrate the sensor without the GreenSeeker.
    a. While calibration with the GreenSeeker is good, it requires the use of a GreenSeeker and having access to one. If the Pocket Sensor is going to be used in remote parts of the world, this may prove to be difficult.
    b. Use different color of papers to calibrate the sensor. If this were to work, each sensor may come with 7-8 different papers representing the NDVI values and be able to generate the calibration curve and equivalent NDVI readings.
    c. Suggestion from CIMMYT scientist in El Batan.