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Application note

A ground based platform for high throughput phenotyping

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ABSTRACT

The objective of this effort was to evaluate current commercially-available sensor technology (three sonic ranging and two NDVI sensors) for use in a ground-based platform for plant phenotyping and crop management decisions. The Global Positioning System (GPS) receiver from Trimble provided a high level of accuracy during our tests. Normalized Difference Vegetation Index (NDVI) data collected using the GreenSeeker sensors were more consistent and presented less variability when compared to the Decagon SRS sensor. The consistency could be due to the GreenSeeker system averaging readings of more rows. The tests also indicated that although sonic ranging sensor technology may be employed to obtain average plant height estimates, the technology is still a limiting factor for high-accuracy measurements at the plant level.

1. Introduction

Growers require innovative agricultural management tools to improve quality, productivity, and reduce production costs while remaining profitable. Precision agriculture is a management practice that involves better management of farm inputs such as fertilizers, herbicides, seed, and fuel by implementing best management practices at the right place and time (Mulla, 2013). Precision agriculture offers the opportunity to improve crop productivity and farm profitability through improved management of agricultural inputs (Mulla, 2013). Proximal remote sensing involves mounting sensors on a tractor, spreaders, sprayers or irrigation booms to assess crop growth and stress. Mobile platforms mounted with various remote sensors may facilitate management decisions in vegetable, fruit, and row crops and may be useful to accelerate crop breeding/cultivar development by phenotyping large segregating populations and identifying desirable traits related to earliness, disease, and insect resistance. These platforms may also assist breeders in finding varieties with specific traits that confer tolerance to key environmental stresses such as heat and drought. Several vehicle-based platforms have been proposed for crop phenotyping and to determine spatial and temporal plant characteristics (Sharma and Ritchie, 2015; Adrade-Sanchez Pedro et al., 2014; Sui and Thomasson, 2006; Montes et al., 2011). These vehicle platforms have been mounted with several combinations of sensors. The advantage of these sensors is that data can be collected extensively at low cost, without conducting a high number of destructive measurements. For example, Sui and Thomasson (2006) used sonic ranging sensors to determine plant height and optical sensors to determine spectral reflectance to correlate with leaf nitrogen concentration of cotton plants. Colaizzi et al. (2003) used a remote sensing system mounted aboard a linear moving irrigation system to monitor water status, nitrogen status, and canopy density by measuring four reflectance bands and soil temperature. Hunsaker et al. (2005) used remote sensing observations of NDVI obtained with a mobile platform to estimate crop coefficients and crop evapotranspiration. O'Shaughnessy et al. (2012) mounted infrared thermometers in a center pivot for irrigation scheduling. Imagery remote sensing technologies are mainly based on particular leaves and canopies' wavelength reflectance in the visible range of the spectrum RGB (red, green and blue), non-visible as (Infra-red) IR, and the emission of far-IR (thermal). Indices based on leaf/canopy reflectance can be used as an indicator of plant function because green vegetation absorbs a greater portion of the light reflected and depend directly on a leaf's pigment composition (e.g. chlorophylls and xanthophyll), which can be correlated with the plants' physiological status (Jones and Vaughan, 2010). The most employed index is the normalized difference vegetation index (NDVI) = (IR−R)/(IR + R); where IR (infrared) is the reflectance in the near-infrared band (800 nm) and (R) in the red band (680 nm). This index has commonly been used to detect plants and "greenness", due to the high IR reflectance of chlorophylls (Zarco-Tejada et al., 2012).

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Link et al. (2002) and Reusch et al. (2002) developed a tractor based passive sensor to determine crop N status based on NDVI. This sensor was formerly known as the Hydro-N sensor and later became known as the Yara-N sensor (Yara, Olso, Norway). Holland et al. (2004) developed an active crop sensor known as Crop Circle that was initially used to determine reflectance in the green and NIR bands to estimate crop N deficiencies. The rationale behind using green rather than red reflectance with Crop Circle was that the green NDVI is more sensitive to changes in chlorophyll concentration and potential crop yield than NDVI (Gitelson et al., 1996; Shanahan et al., 2008; Sripada et al., 2008). Some other low-cost NDVI sensors have been developed to study environmental and physiological constraints on photosynthesis (Gamon et al., 2015). Mobile platforms offer the opportunity to determine spatial and temporal characteristics of the plant when equipped with the right sensors. The objective of this paper was to evaluate current commercially-available sensor (three sonic ranging and two NDVI sensors) for use in a ground-based platform for plant phenotyping and crop management decisions.

2. Material and methods

2.1. Plant health sensing system

A mobile phenotyping platform was built on a Lee Agra 3218-GM open rider sprayer (Lee Spider, Lubbock, TX, US). A boom was attached to the front end of the platform frame to provide mechanical support for the sensors. Battery, solar panel, datalogger, and Global Positioning System (GPS) antennas were installed behind and above the platform's cabin. The boom was supported by three arms to reduce lateral movement. A hydraulic system allowed the vertical movement of the boom from approximately 1 to 3 m above ground and provided enough versatility to adjust to different crop types such as cotton, peppers, cantaloupes, etc.

The platform contained two independent data collection systems running simultaneously (Fig. 1). The first system consisted of a datalogger CR1000 (Campbell Scientific, Logan, UT, US) connected to a power supply with a charging regulator and rechargeable battery. The battery was recharged from an external 10-W photovoltaic solar panel (Cambell Scientific, Logan, UT, US). The datalogger and battery were enclosed in a box. The sensors were installed on the boom and connected to the datalogger. A GPS receiver (GPS16X-HVS, Garmin International Inc., Olathe, KS) was connected to the datalogger to geo-tag the location of the measurements. A spectral reflectance sensor (SRS) was used to monitor NDVI of the plant canopy (Decagon Devices, Inc, Pullman, WA, US). The SRS consists of two-band radiometers, where one radiometer measures incident radiation while the other measures reflected radiation with a field of view of 36° to measure canopy-reflected radiation. The data collected in each operation was downloaded from the datalogger to a computer. The data collected with the spectral reflectance sensor was plotted with the 3D Filed Pro 4.2 program. The first system also had two infrared radiometers (SI-111, Campbell Scientific, Inc., Logan, UT), two sonic ranging sensors (SR50A, Campbell Scientific, Inc., Logan, UT), and a temperature and relative humidity probe (HC2S3, Campbell Scientific, Inc., Logan, UT).

The second independent system consisted of a GPS receiver (AgGPS 162, Trimble Navigation Limited, Sunnyvale, CA) and two multi-spectral GreenSeeker RT 200 sensors (Trimble Navigation Limited, Sunnyvale, CA) which were connected to the Trimble Nomad 900 datalogger (Trimble Navigation Limited, Sunnyvale, CA). The system was configured to average the measurements from both sensors. The two NDVI systems were evaluated and compared by matching the time of the two GPS systems in a cotton field containing 35 entries. Each plot consisted of six rows spaced at 1.02 m with a row length of 12.2 m. The NDVI data collected was also plotted with the 3D Field Pro 4.2 program.

2.2. Evaluation of sonic ranging sensors

Three sonic ranging sensors were evaluated and compared to determine their accuracy in a static and dynamic setting (Table 1). In the static setting, cotton plant heights were measured by stopping the platform in the middle of a cotton plot. In the dynamic setting, the sensors were evaluated while the platform was in

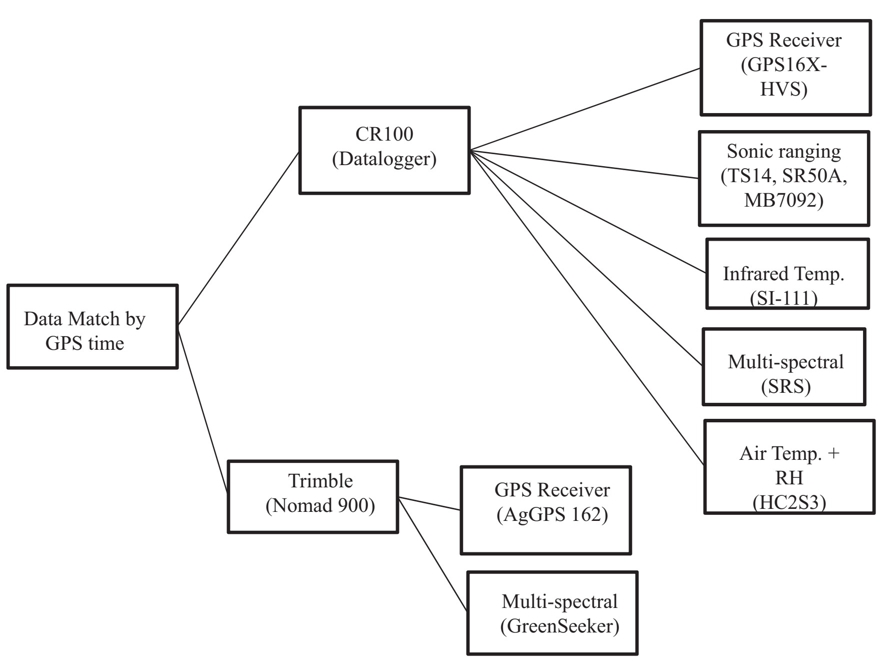

Fig. 1. Data were collected by two independent systems running simultaneously. Data were matched using Global Positioning System time for post-collection processing and analysis.

Table 1
Characteristics of the sonic range sensors evaluated with the mobile platform.

Characteristics	Sonic range sensor type		
	Campbell Scientific SR50 A	ToughSonc TS14	MaxBotix MB7092
Voltage (V)	12	10	5
Average Current Draw (mA)	2.25	4	3.4
Maximum Distance (m)	10	4.27	7
Resolution (mm)	0.25	0.086	10
Fastest Measurement Time (ms)	500	50	100
Characteristics	NDVI sensor type		
	GreenSeeker RT200	Decagon SRS	
NDVI wave bands	650 and 850 wavelengths	650 ± 2 and 850 ± 2 peak wavelengths	
Communication	Communicates only with Trimble datalogger	SDI-12	
Datalogger compatibility	Trimble. It comes with its own computer and integrated display	Decagon Em50, procheck, Campbell Scientific	

motion. The goal of testing three sensors while the platform was moving, was to identify whether any of these sensors were capable of providing consistent and accurate height readings. Sensors evaluated were the Campbell Scientific's SR50A (Cambell Scientific, Logan, UT), the ToughSonic's TS14 (Senix Corporation, Hinesburg, VT, USA), and the MaxBotix's MB7092 (MaxBotix Inc., Brainerd, MN, USA), which were mounted to the platform and connected to a CR1000 datalogger for simultaneous data collection. The mobile platform's ground speed was approximately 1 km/h during data collection.

The Campbell Scientific's SR50A has the lowest average current draw of the three sensors tested, at 2.25 mA operating at 12 V (Table 1). The SR50A has a recommended minimum distance of 50 cm making it the sensor with the largest minimum distance requirement. The drum of the sensor should be maintained at the minimum distance (of 50 cm) from the nearest target to attain the accuracy reported in the manual. The same sensor also has the largest maximum measurement distance of 10 m (Table 1). This sensor places second in the resolution of measurements, but comes last when comparing fastest measurement time. This sensor has some disadvantages over the other sensors in terms of specifications, but it has features that set it apart from the others (Table 2). The SR50A can measure the quality of its height measurements, which is described by the quality number and is an optional feature. The quality numbers are divided into four categories; (1) 0 (zero) means the sensor was unable to make a measurement, (2) between 152 and 210 represent proper measurements, (3) between 210 and 300 represent reduced echo signal strength, and (4) between 300 and 600 represent measurements with high uncertainty. These quality numbers are based on the signal strength of the echo and are calculated internally. The SR50A measures the distance to the first object hit by the signal. The SR50A's housing has a cone around the drum which causes signals to be emitted at a 30-degree angle, and for this reason, the size of objects in its field of view must clear 30 degrees. The manual recommends that any unwanted objects must be out of the area of view. The manual also states that the sensor may reject a reading if the target changes distance at a rate of 4 cm/s, which is a common situation when using a mobile platform to measure plants in the field.

ToughSonic's TS14 has the highest average current draw at 4 mA operating at 10 V. The TS14 has a minimum distance 10.2 cm and a maximum distance of 4.27 m (Table 1). This range of distances makes it the sensor with the shortest minimum and maximum measurement distances. It has a resolution of 0.086 mm and the fastest measurement time of 50 ms (Table 1). The downside of having such a fast measurement rate is that if the measurement rate is set too high, it may be quicker than the time it takes to receive an echo. Another possibility is that it may detect a delayed echo from a prior measurement cycle. The measurement rate will need to be taken into consideration depending on the particular application. This sensor comes with all filters off as default. Filters can be activated using the software SenixVIEW (Senix Corporation, Hinesburg, VT, USA). Several useful filters come with this software such as the ability to make measurements and then select the closest or furthest target in the sensor's field of view. By default, this sensor will measure the distance to the first object hit (i.e. closest) just like the SR50A. The TS14 is designed to have a narrow field of view (12 degrees).

The MaxBotix's MB7092 sensor has an average current draw of 3.4 mA while operating at 5 V (Table 1). This sensor places second in range with a minimum and maximum distance of 0.20 m and 7.0 m, respectively (Table 1). This sensor has the second-best resolution (1 cm) and measurement time (100 ms). By its specifications alone this sensor doesn't stand out, but some of its features may

Table 2
Advantages and disadvantages of the sonic range and NDVI sensors evaluated with the mobile platform.

Characteristics	Sonic range sensor type		
	Campbell Scientific SR50A	ToughSonc TS14	MaxBotix MB7092
Advantages:	- Filter for quality measurements - Versatility in measuring plant heights	- Best precision - Low cost	- Measure the maximum height and ignore small targets - Best accuracy in estimating maximum plant height - Low cost
Disadvantages:	- Last place in response time - Higher cost	- Highest current draw	- Lowest resolution
	NDVI sensor type		
	GreenSeeker RT200	Decagon SRS	
Advantages:	- Less variability	- Low cost - Can be connected to any datalogger	
Disadvantages:	- Comes with its own datalogger, software, and computer display - High cost	- It requires more ports of the datalogger to connect more sensors	

have a large impact. This sensor comes with electrical and acoustic noise resistance. According to the manual, the MB7092 prioritizes large targets over small targets when reporting a measurement. If similar sized objects are in the field of view, then the sensor will indicate the closest target. This sensor has a field of view width of less than 0.6 m at maximum range and less than 0.3 m at close to medium ranges when equipped with a full horn. According to tests shown in the manual, the sensor recognizes smaller objects better when they are located closer to the center of its field of view while larger objects can be detected further away from the center. The ability of this sensor to measure the distance to the largest body while ignoring the smaller ones may prove to be useful in some applications in agriculture. For example, when measuring the height of a plant one needs to place the sensor above the plant looking down. Leaves will have different surface areas which would, in theory, make it difficult for a sonic ranging sensor to measure the height of the plant. The ability of this sensor to ignore smaller targets can potentially lead to more accurate results in this application (Table 2).

2.3. Evaluation of spectral radiometer to measure NDVI

Two spectral radiometers were used to measure NDVI on different plots. The Spectral SRS sensor (Decagon Devices, Pullman, WA, USA) and the GreenSeeker cropping system (Westminster, CO, USA) were evaluated on 140 cotton plots. The GreenSeeker cropping system consisted of two NDVI sensors connected to the Trimble NOMAD 900 datalogger.

3. Results

3.1. Static sonic ranging measurements

Height measurements of cotton plants taken with the SR50 A sonic ranging sensors placed on the left and right sides of the tractor (i.e. two different rows simultaneously) were compared to plant height measured with a measuring tape directly under each sensor at the center of their respective field of view (Fig. 2). Measurements with the tape resulted in an average plant height of 89.9 and 90.5 cm and a standard deviation of 7.6 and 8.2 cm for the left and right rows, respectively. The left sensor measured an average height of 91.8 cm and a standard deviation of 6.8 cm while the right sensor measurements resulted in an average plant height of 92.8 cm with a standard deviation of 7.0 cm. Overall, under the conditions tested, both sensors tend to overestimate plant heights by approximately 2.0 cm on average (1.9 and 2.3 cm for left and right sensors, respectively).

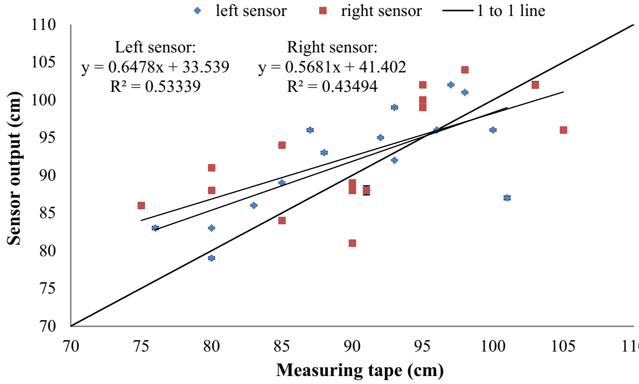

Fig. 2. Comparisons of Left and Right SR50A cotton height measurements with a tape.

3.2. Dynamic sonic ranging measurements

The height of individual pepper plants was measured manually and compared with readings obtained from three different sonic ranging sensors (Fig. 3). The SR50 sensor exhibited more variability in its height estimates when compared to the TS14 and MB7092 sensors. The SR50 may be the most problematic for this type of application since there were readings above the manual measurements and the readings of other sensors, as well as some negative values. For this sensor, the negative values may be attributed to quick changes in distance-to-target (>4 cm/s) possible under field conditions, causing the sensor to reject some readings. Pepper plants were planted in a single row at the center of an elevated bed (approximately 20 cm). All the sensors showed consistency in their ability to accurately measure the distance from the sensor to the raised bed, in between plants, as the platform moved (Fig. 3). The sensors also read plant height values that were lower than the manual readings. This is probably because the signal of the sonic ranging sensors did not hit the top of the plant and/or the uppermost reading was rejected by the sensor due to limited measurement time and field of view restrictions (Table 1). While sonic ranging sensors may be adequate for average measurements, restrictions on measurement time, distance to target, and field of view ultimately limit its throughput and applicability for plant-level research (Fig. 4).

3.3. NDVI measurements

The average NDVI readings measured with the spectral SRS sensor and the GreenSeeker cropping system for 140 cotton plots (35 entries, replicated 4 times) are presented in Fig. 5. The sensors took approximately 6–15 and 9–18 readings per plot, for the GreenSeeker and SRS sensors, respectively, depending on the platform's ground speed. The Decagon SRS sensor showed more variability in the readings that the GreenSeeker sensor (average standard deviation of measurements was 0.09 and 0.02 for the SRS and GreenSeeker, respectively). Overall, the average NDVI values were slightly higher for the Decagon SRS sensor when compared to the GreenSeeker sensor. In contrast, NDVI values for entries 3, 6, 17,

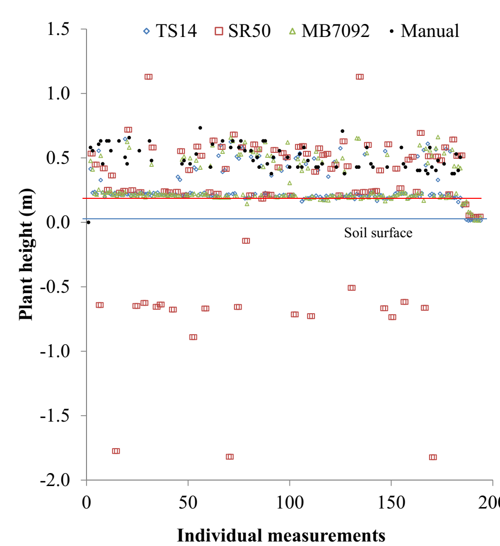

Fig. 3. Comparisons of three sonic ranging sensors with manual measurements in a pepperrow. Weslaco, TX, 2016. The black dots represent the height of each individual plant in the row. Red line represent the elevated bed in which pepper plants were planted.

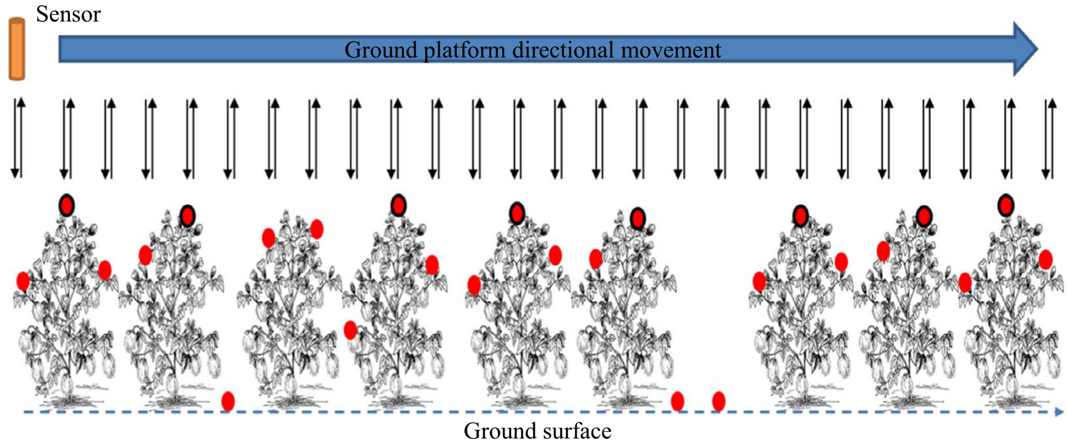

Fig. 4. Simulation of the movement of the platform and collection of ultrasound data. The red dots with black borders indicate the real, thus desired height of the plant.

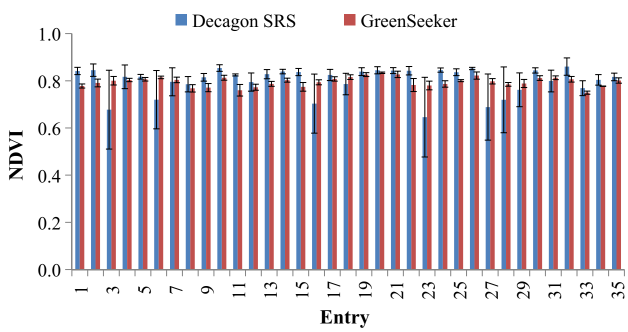

Fig. 5. Average Normalized Difference Vegetation Index (NDVI) measurements taken for cotton plants with a Decagon SRS and a GreenSeeker sensor. Plots contained approximately 90 plants. Bars represent ± standard error of measurements.

23, 27 and 28 were lower for the Decagon sensor when compared to the GreenSeeker sensor. The differences in NDVI values within the same entry are due to sensor reading differences, as the platform moved over each plot (Fig. 5).

3.4. Evaluation of NDVI values and GPS values

There were obvious differences in GPS accuracy between the Trimble and Garmin receivers tested. The output of an NDVI data collection run with the two systems in cotton at the Texas A&M AgriLife Research and Extension Center at Corpus Christi, TX is shown in Fig. 6. Images show raw data from the Trimble (Fig. 6, left) and Garmin receivers (Fig. 6, right). It is evident that the Garmin receiver did not produce straight lines, as was observed with the Trimble GPS receiver.

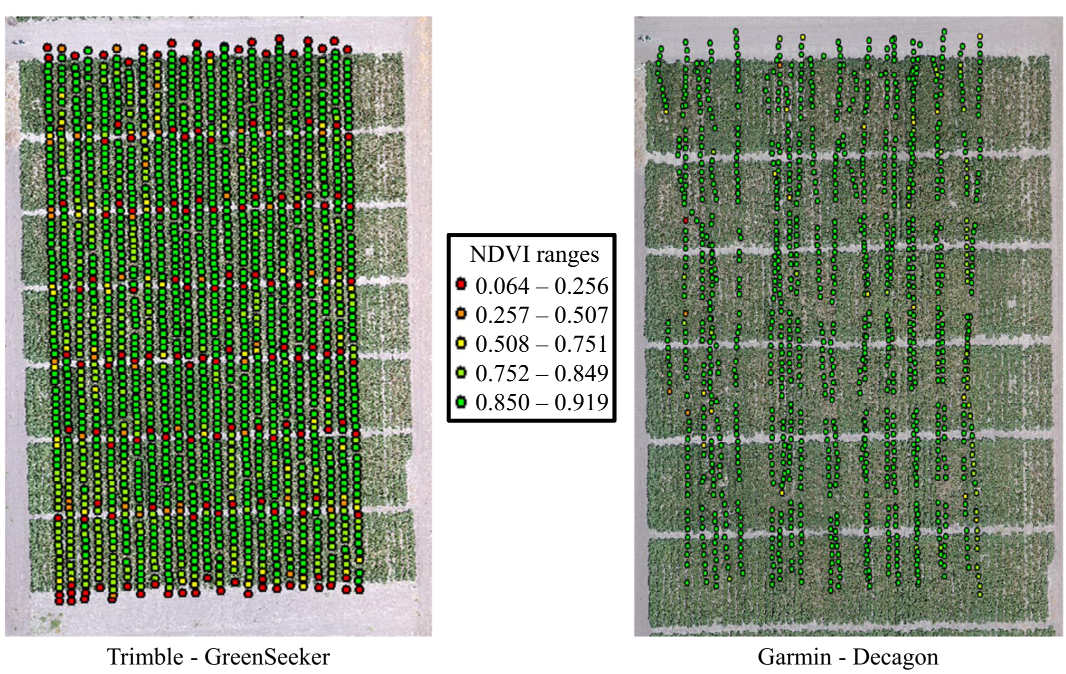

Fig. 6. Differences in GPS receiver accuracy. Normalized Difference Vegetation Index (NDVI) values are shown for reference. Data collected on 6/26/2015 at the Texas A&M AgriLife Research and Extension Center, Corpus Christi, TX. Red and green dots represent lowest and highest NDVI values, respectively.

4. Conclusions

A mobile platform coupled with sensors for crop phenotyping was developed. The Global Positioning System (GPS) receiver from Trimble provided better location accuracy during our tests when compared with the Garmin receiver. An accurate GPS receiver is important to develop prescription maps for precision agriculture applications. The three sensors evaluated for plant height measurements indicated that although sonic ranging sensor technology may be employed to obtain average plant height estimates, the technology is still a limiting factor for high-accuracy measurements at the plant level and that new alternatives need to be explored for ground-based mobile platforms. The sonic ranging sensors are highly accurate for static measurements and flat surfaces, but accuracy does decrease as sensor movement is introduced in the measurements. The Normalized Difference Vegetation Index (NDVI) data collected using the GreenSeeker sensors were more consistent and presented less variability when compared to the Decagon SRS sensor.

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References

Adrade-Sanchez Pedro, M., Gore, M., Heun, John T., Thorp, K.R., Carmo Silva, A.E., French, A.N., Salvucci, M., White, J., 2014. Development and evaluation of a field-based-thoughput phenotyping platform. Funct. Plant Biol. 41 (1), 68–79.

Colaizzi, Paul D., Barnes, E.M., Clarke, T.R., Choi, C.Y., Waller, P.M., 2003. Estimating soil moisture under low frequency surface irrigation using crop water stress index. J. Irrig. Drainage Eng. ASCE 129 (1), 27–35.

Gamon, J.A., Kovalchuck, O., Wong, C.Y.S., Harris, A., Garrity, S.R., 2015. Monitoring seasonal and diurnal changes in photosynthetic pigments with automated PRI and NDVI sensors. Biogeosciences 12 (13), 4149–4159.

Gitelson, A.A., Kaufmann, Y.J., Merzlyak, M.N., 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens. Environ. 58, 289–298.

Holland, K.H., Schepers, J.S., Shanahan, J.F., Horst, G.L., 2004. Plant canopy sensor with modulated polychromatic light. In: D.J. Mulla (Ed.), Proc. 7th intl. conf. precision agriculture. (CDROM). Minneapolis, MN: Univ. Minnesota.

Hunsaker, D.J., Barnes, E.M., Clarke, T.R., Fitzgerald, G.J., Pinter Jr, P.J., 2005. Cotton irrigation scheduling using remotely sensed and FAO-56 basal crop coefficients. Trans. ASAE 48 (4), 1395–1407.

Jones, H.G., Vaughan, R.A., 2010. Remote Sensing of Vegetation: Principles, Techniques, and Applications. Oxford University Press.

Link, A., Panitzki, M., Reusch, S., 2002. Hydro N-sensor: tractor mounted remote sensing for variable nitrogen fertilization. In: P.C. Robert (Ed.), Precision agriculture [CD-ROM]. Proc. 6th int. conf. on precision agric (pp. 1012e1018). Madison, WI, USA: ASA, CSSA, and SSSA.

Montes, J.M., Technow, F., Dhillon, B.S., Mauch, F., Melchinger, A.E., 2011. High-throughput non-destructive biomass determination during early plant development in maize under field conditions. Field Crops Res. 121 (2), 268–273.

Mulla, D.J., 2013. Twenty five years of remote sensing in precision agriculture: key advances and remaining knowledge gaps. Biosyst. Eng. 114 (4), 358–371. http://dx.doi.org/10.1016/j.biosystemseng.2012.08.009. ISSN 1537-5110.

O'Shaughnessy, S.A., Evett, S.R., Colaizzi, P.D., Howell, T.A., 2012. Grain sorghum response to irrigation scheduling with the time-temperature threshold method and deficit irrigation levels. Trans. ASABE 55 (2), 451–461.

Reusch, S., Link, A., Lammel, J., 2002. Tractor-mounted multispectral scanner for remote field investigation. In: P.C. Roberts (Ed.), Proc. of the 6th int. conf. on precision agriculture and other precision resources management (pp. 1385e1393). Madison, WI, USA: ASA, CSSA, and SSSA.

Shanahan, J.F., Kitchen, N.R., Raun, W.R., Schepers, J.S., 2008. Responsive in-season nitrogen management for cereals. Comp. Electron. Agric. 61 (1), 51–62.

Sharma, Bablu, Ritchie, G.L., 2015. High-throughput phenotyping of cotton in multiple irrigation environments. Crop Sci. 55 (2), 958–969.

Sripada, R.P., Schmidt, J.P., Dellinger, A.E., Beegle, D.B., 2008. Evaluating multiple indices from a canopy reflectance sensor to estimate corn N requirements. Agron. J. 100, 1553–1561.

Sui, R., Thomasson, J.A., 2006. Ground-based sensing system for cotton nitrogen status determination. Trans. ASABE 49 (6), 1983–1991.

Zarco-Tejada, P.J., González-Dugo, V., Berni, J.A.J., 2012. Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection using a micro-hyperspectral imager and a thermal camera. Remote Sens. Environ. 117, 322–337.