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Use of corn height measured with an acoustic sensor improves yield estimation with ground based active optical sensors

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ABSTRACT

Corn height measured manually has shown promising results in improving the relationship between active-optical (AO) sensor readings and crop yield. Manual measurement of corn height is not practical in US commercial corn production, so an alternative automatic method must be found in order to capture the benefit of including canopy height into in-season yield estimates and from there into in-season nitrogen (N) fertilizer applications. One existing alternative to measure canopy height is an acoustic height sensor. A commercial acoustic height sensor was utilized in these experiments at two corn growth stages (V6 and V12) along with AO sensors. Eight corn N rate sites in North Dakota, USA, were used to compare the acoustic height sensor as a practical alternative to manual height measurements as an additional parameter to increase the relationship between AO sensor readings and corn yield. Six N treatments, 0, 45, 90, 134, 179, and 224 kg ha^{-1}, were applied before planting in a randomized complete block experimental design with four replications. Height measurement using the acoustic sensor provided an improved yield relationship compared to manual height at all locations. The level of improvement of the relationship between AO readings multiplied by acoustic sensor readings and yield was greater at V6 growth stage compared to the V12 growth stage. At V12, corn height measured manually and with the acoustic sensor multiplied by AO readings provided similar improvement to the relationship with yield compared to relating AO readings alone with yield at most locations. The acoustic height sensor may be useful in increasing the usefulness of AO sensor corn yield prediction algorithms for use in on-the-go in-season N application to corn particularly if the sensor height is normalized within site before combining multiple locations.

1. Introduction

Use of precision agricultural techniques by farmers and ag-industry farm input providers has increased steadily over the past twenty-five years Precision agricultural methods for soil sampling have the ability to improve delineation of nutrient management patterns as a basis for site-specific nutrient application (Sadler et al., 2000). Crop yield is affected by pest infestation, rainfall, soil properties, climate variations, crop stress and landscape topography (Raun et al., 2005), which vary spatially and temporally and complicate site-specific nutrient management due to small-scale variability. On-the-go active-optical (AO) sensor technology has been used to detect small-scale variability of crop N status within a field, sometimes at as small a scale as 1 m^2, enabling more efficient N fertilizer application to corn, wheat, cotton and sorghum (Gitelson and Merzlyak, 1997; Raun et al., 2001 and 2002; Kitchen, 2006; Holland and Schepers, 2010; Franzen et al., 2014).

Algorithms developed for the use with AO sensors in relating crop yield with sensor readings contain considerable error despite their value in improving small-scale site-specific N management. The measurement of crop growth in another manner at the time of AO sensor reading may provide an improved yield prediction algorithm. Measuring corn height corn might help detect yield differences due to water stress, evapotranspiration rate, and other crop stresses (Sammis et al., 1988) at a scale similar to that of AO sensors. Under optimum N availability conditions, corn plants grow to their full potential and reach a maximum height; however, if there is a stress due to suboptimal water supply or fertilizer deficiency, plant height will be reduced along with yield (Venuprasad et al., 2008; Li et al., 2013). Crop height as a single

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factor could be used to measure the vegetative growth and potential yield of corn. Corn plant height is a highly sensitive growth parameter and is influenced by soil water content (Hussain et al., 1999), texture (Kladivko et al., 1986), fertilizer rate (Kapusta et al., 1996), and cultivation methods (Kladivko et al., 1986; Sharma and Franzen, 2014). Machado et al. (2002) found that corn height could explain 60% of yield variability.

Red NDVI (normalized differential vegetative index, [red − near infrared]/[red + near infrared]) reflectance is based on two-dimensional measurement of the plant canopy, and is most successfully utilized during early growth stages when leaves do not shade the inter-plant spaces completely. At later growth stages red NDVI readings fall into a narrow range from 0.85 to 0.95 and discrimination between weaker plants and healthier plants becomes impossible as leaves cover the soil surface regardless of plant health. This problem is called 'saturation' (Wilhelm et al., 2000; Haboudane et al., 2004; Sharma and Franzen, 2014). A weak relationship between red NDVI sensor readings and yield was found by Sharma and Franzen (2014) at the V12 stage of corn due to red NDVI saturation. Franzen et al. (2003), found improvement in estimation of sugar beet top leaf N concentration and dry matter content in Minnesota using the GreenSeeker® AO red NDVI readings at sugar beet harvest when optical sensor readings were multiplied by a manually obtained plant canopy height, which helped to overcome red NDVI saturation.

Manually measured corn height combined with AO sensors has improved the relationship between AO sensor readings and corn yield. Several studies have used corn height in addition to GreenSeeker® sensor readings to estimate yield (Sharma and Franzen, 2014; Freeman et al., 2007; Martin et al., 2012). In all of these studies, significant relationships were found between yield and AO sensor readings multiplied by corn height. Corn height alone has been used to estimate corn yield (Yin et al., 2011a,b; Machado et al., 2002; Katsvairo et al., 2003). Sharma and Franzen (2014) found that corn height can improve corn yield estimates and could be used along with AO sensor readings to improve the algorithms developed to direct in-season N rate application. Although including corn height may have the ability to improve AO sensor algorithms, manual measurement of plant height is highly labor intensive and impractical on a commercial scale.

Several nondestructive methods have been used to measure plant height, including image processing (Changgui and Wenyi, 2007), 3-D perspective view to measure tree height (Zhang and Huang, 2009), 3-D view with a 3 point correction (Han, 2011) and light detection and ranging (LIDAR) (Zhang and Grift, 2012). Using plant image for height measurement has been successfully tested by several researchers (Morden et al., 1997; Van Henten and Bontsema, 1995; Tarbell and Reid, 1991; Tarbell et al., 1991). Plant height could also be measured using high resolution ultrasound distance sensing of the crop canopy (Shrestha et al., 2002; Katsvairo et al., 2003) and stereo vision (Shrestha and Steward, 2001). Use of stereo vision is most applicable for small scale work in laboratories and greenhouses (Matsuura et al., 2001; Kanuma et al., 1998; Lines et al., 2001). In some studies, remote sensing techniques such as synthetic aperture radar (SAR) (Ulander et al., 1995; Dammert and Askne, 1998; Shimada et al., 2001) and airborne LIDAR (Nilsson, 1996; Magnussen et al., 1999; Persson et al., 2002; Kwak et al., 2007; Yamamoto et al., 2011) was used to measure the plant height. All of these techniques and instruments have been used effectively in the greenhouse or laboratory, but their practical application to use in the field is questionable.

In order to measure plant height at low cost in real-time and to incorporate plant height into AO sensor algorithms for use in in-season N management, the SenixView™ model TSPC-30S1-232 (Senix Corporation, Hinesburg, Vermont, USA) automated ultrasonic acoustic sensor was used at two different corn stages (V6 and V12). This study was conducted to compare the use of corn height measured with the acoustic sensor with corn height measured manually to determine if sensor height measurements combined with AO sensor readings are similarly related to corn yield as previous studies indicate using manually measured corn height combined with AO sensor.

2. Materials and methods

2.1. Research sites and soil analysis

Eight experimental sites were established on farm fields in 2013 in eastern and western North Dakota, USA. At each location, eight soil sample cores were taken before planting and N application using a 2.5-cm diameter hand probe. Soil cores were obtained to a depth of 0–15 cm for analysis of nitrate-nitrogen (N), phosphorous (P), potassium (K), zinc (Zn), organic matter, and pH. A 0–60 cm soil core depth was taken for residual soil nitrate-N analysis (Table 1). For preplant soil test analysis, soil samples were air-dried after they collected from the research site, ground to pass through a 2 mm screen, and thoroughly mixed. Nitrate-N was analyzed using cadmium reduction described by Gelderman and Beegle (1998). Plant available phosphorus was analyzed using

Table 1
Preplant soil analysis for the eight experimental sites.

Location	Depth cm	Nitrate-N (kg ha^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Zn (mg kg^{-1})	Organic matter (g kg^{-1})	pH
Arthur	0–15	5	9	110	1.16	22	6.6
	0–60	12					
Beach	0–15	17	22	300	0.85	30	6.2
	0–60	7					
Durbin	0–15	5	34	460	0.62	59	7.5
	0–60	45					
Jamestown	0–15	10	8	220	1.14	33	5.7
	0–60	12					
Mott	0–15	18	4	230	0.95	52	7.6
	0–60	10					
New Leipzig	0–15	24	16	560	1.46	52	5.6
	0–60	18					
Richardton	0–15	11	33	170	0.65	32	5.1
	0–60	8					
Rutland	0–15	20	8	415	0.72	61	7.0
	0–60	54					

the Olsen method (Olsen et al., 1954b), and plant available potassium by the 1-N ammonium acetate method (Thomas, 1982). The DTPA extraction (Lindsay and Norvell, 1978) together with atomic absorption spectroscopy detection was used for Zn analysis. Organic matter content was determined using the loss following ignition method (Schulte and Hopkins, 1996). Soil pH was analyzed using a 1:1 soil:deionized H_2O solution method (Watson and Brown, 1998). The eight experimental sites were planted by the cooperators using their choice of corn hybrid. The experimental site locations, soil series within location, planting date and sensor reading dates can be found in Tables 2 and 3. The experimental design at each experimental site was a randomized complete block, with six N treatments: control (no added N), 45, 90, 135, 189 and 224 kg N ha^{-1} applied as ammonium nitrate, with four replications. Each experimental unit (the area of each treatment within a replication) was 6.1 m long and 3.05 m wide. A 1.5 m wide lane was produced by cutting out standing corn at the soil surface at about V6 to separate replications and allow in-season field work without damaging corn within the experimental units. Some experimental sites had different row spacing (50–75 cm) because farmers had different planters; therefore, there were 4–6 rows present within each experimental unit depending on the experimental site.

No supplemental N was applied to the experimental site by the farmers. At experimental sites where fertilizer P, K or other nutrients were not applied by the grower because the fertilizer blend used on the field also contained N, supplemental P, K and Zn, if recommended by the soil test, was applied by the researchers in a broadcast application before planting. Phosphate was applied as mono ammonium phosphate (110 g kg^{-1} N, 520 g kg^{-1} P_2O_5 equivalent) and K as potassium chloride (60 g kg^{-1} K_2O equivalent) according to North Dakota State University recommendations (Franzen, 2010). If the soil analysis indicated that a site was deficient in Zn, zinc sulfate (360 g kg^{-1} percent Zn granules) at a rate of 11 kg ha^{-1} Zn was applied as a broadcast at the time of N treatment application. If any experimental site was found to be S deficient, gypsum was applied at 22 kg ha^{-1} S (112 kg ha^{-1} 200 g kg^{-1} S gypsum). At sites where S deficiency occurred after corn emergence, a similar rate of gypsum was applied as granules over the top of the corn in a broadcast application.

2.2. Description of the active-optical sensors and methods of use

The two AO sensors used in these experiments emit modular light pulses from diodes to generate particular wavebands which are absorbed by plant tissues. In the GreenSeeker™ (GS) (Trimble Navigation Limited, Sunnyvale, California, USA) bursts of light are emitted from diodes such that red (R) (660 nm) and near infrared (NIR) (710 nm) pulses alternately for 1 ms at 40,000 Hz, with each burst composed of about 40 pulses. The illuminated area in our study was positioned perpendicular to the direction of travel. According to Trimble, the GS field of view is constant for heights between 60 and 120 cm above the canopy. The operators of the GS consistently operated the sensors at 60–70 cm above the corn canopy. Outputs from the sensor are normalized differential vegetative indexes (NDVI), defined as [(NIR − visual wavelength)/(NIR + visual wavelength)].

The source of light for the Holland Scientific Crop Circle™ (CC) sensor (ACS-470, Holland Scientific, Lincoln, Nebraska, USA) is a modulated polychromatic light emitting diode (LED) array which can emit and measure light spectrums from 430 nm to 850 nm bands. For these experiments, we used two filters in the visible range (red 650 nm, red edge 730 nm) and one filter in the NIR (760 nm). The sensor was calibrated using software provided by Holland Scientific. Measurements can be collected at a rate of 2–20 readings per second. Values for CC measurements were the mean of measurements obtained within 6.1 m length of row is the average of about 4000 measurements when moving at 5 km h^{-1}. Outputs of the sensor are reflectance values that allow calculation of the vegetation indices red NDVI and red edge NDVI. The formulas for red NDVI and red edge NDVI follow:

$$\text{Red NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \text{ and Red Edge NDVI} = \frac{\text{NIR} - \text{Red Edge}}{\text{NIR} + \text{Red Edge}}$$

The NDVI readings from the GS and CC were obtained when the corn was about V6 and V12 (about 10 days to 2 weeks after V6) stages. Readings were taken 60–70 cm over the top of one interior corn row in each experimental unit and the row was noted so that the row being sensed was the row to be harvested after corn reached maturity. The NDVI was calculated within the CC instrument with built-in software, whereas the GS reflectance values were stored in a text file by the sensor software and NDVI values were calculated post-process using Microsoft Excel 2013.

For each experimental unit, the GS and CC readings consisted of 30–50 individual NDVI or reflectance measurements. Means for each treatment area were calculated by using in-house programs for GS and CC raw data developed for Excel (Fargo and Franzen, 2012). The relationship between sensor readings and yield was normalized using the value of 'in-season estimate of yield' (INSEY) (Raun et al., 2001). The INSEY was calculated by dividing the sensor reading by the growing degree days from the date of planting to sensing.

Table 2
GPS coordinates and soil series of experimental sites.

Locations	GPS coordinates	Soil type[a]
Arthur	47°06′50.963″N, 97°57′55.219″W	Coarse-silty, mixed, superactive, frigid Pachic Hapludolls
Beach	46°49′3.035″N, 103°59′40.451″W	Fine-silty, mixed, superactive, frigid Typic Haplustolls
Durbin	46°51′22.072″N, 97°09′28.366″W	Fine, smectitic, frigid Typic Epiaquerts
Jamestown	46°45′58.571″N, 98°47′55.930″W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
Mott	46°56′43.583″N, 102°19′10.919″W	Fine-loamy, mixed, superactive, frigid Typic Haplustolls
New Leipzig	46°26′44.051″N, 101°58′31.379″W	Fine, smectitic, frigid Vertic Natrustolls
Richardton	46°35′0.095″N, 102°21′41.364″W	Fine-loamy, mixed, superactive, frigid Typic Haplustolls
Rutland	45°57′50.176″N, 97°31′44.205″W	Fine, smectitic, frigid Pachic Vertic Argiudolls

[a] Soil type from Soil Survey Staff (2013).

2.3. Corn height measurement using the manual method or the SenixView® sensor

Manual corn height measurement was conducted on the same day and on the same rows as those subjected to GS and CC sensor and automatic height sensor measurements. The manual height was conducted by selecting three representative plants within the interior row to be sensed with the AO sensors in each experimental unit. A tape measure was used to determine the heights of three corn plants from the soil surface to about 5 cm above the corn whorl base (Fig. 1). The three measurements were averaged to provide the manual corn height within each experimental unit.

For automated height measurement, the SenixView acoustic height sensor model TSPC-30S1-232 (Senix Corporation, Hinesburg, Vermont, USA) was used. The SenixView sensor measures the distance of an object from to the sensor itself. The sensor is commercialized for research and development in industrial automation distance measurement. Typically, it is used for

Table 3
Tillage system, planting date, and date of the first and second sensing of the experimental sites.

Locations	Soil texture/Tillage	Planting date	1st sensing	V6 GDD[a]	2nd sensing	V12 GDD[a]	Corn variety
Arthur	Medium-textured conventional-till	5/15/13	6/20/13	516	7/10/13	979	Mycogen-2T222
Beach	No-till	5/15/13	7/01/13	498	7/17/13	804	Pioneer D-97
Durbin	High clay conventional-till	5/15/13	6/25/13	623	7/15/13	1095	Not Available
Jamestown	Medium textured no-till	5/11/13	6/18/13	424	7/09/13	870	Croplan 229VT2RTB
Mott	No-till	5/19/13	7/01/13	593	7/17/13	911	P8107
New Leipzig	No-till	5/07/13	7/01/13	662	7/17/13	980	P8954XR
Richardton	No-till	5/13/13	None	–	7/17/13	517	P8107
Rutland	No-till	5/08/13	6/18/13	754	7/09/13	1008	Mycogen 2G-161

[a] GDD is growing degree days from date of planting to the date of sensing at V6 or V12.

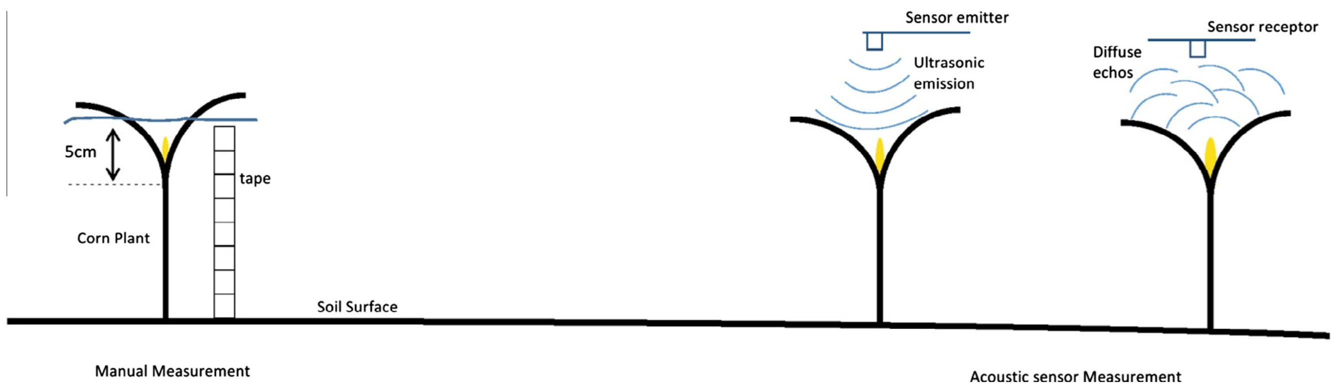

Fig. 1. Illustration of manual height and sensor measurement of corn canopy height. Corn canopy height is measured from soil surface to about 5 cm above the junction between the two fully upper leaves. Sensor height measurement is the result of near simultaneous emission of ultrasonic waves from a specific height above the soil surface, and reception of echos from multiple surfaces originating from the upper leaf canopy.

measuring liquid levels, motion controls, people detection, proximity sensing and dimensioning (SenixView™ data sheet http://www.senix.com/senixview.htm) therefore it has very high sensitivity towards any change in distance. The height sensor was calibrated with the software provided with the sensor.

The sensor was mounted on a two-wheel bicycle fabricated for this purpose with the front wheel smaller than the rear wheel to maintain a uniform height and balance between the rows (Fig. 2). Depending on the crop height, the height of the sensor from the ground was adjusted and measured from the soil surface by adjusting the telescoping pole on which the sensor was mounted before measurements. The values from the sensor were subtracted from the value of the height of sensor from the soil surface. After collecting the data, negative, zero, and any values less than 5 cm were deleted from the file recorded on the computer during post-processing. A Dell Mini (Dell Latitude 10ST2e, Dell, Inc., Round Rock, Texas, USA), placed on the bicycle in front of the operator, was connected to the sensor to collect the height data. The software, SenixView Version 3, was installed on the Dell Mini.

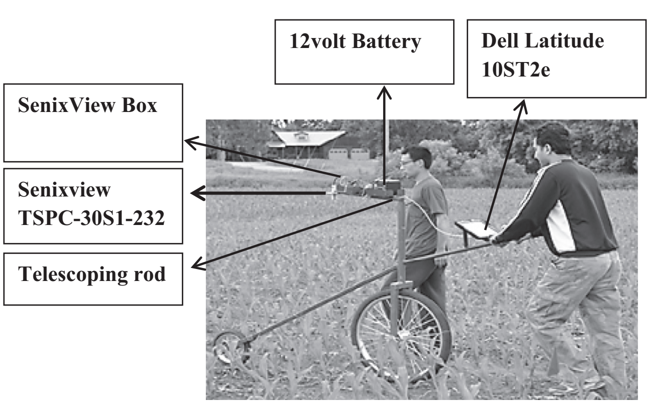

Fig. 2. Method of collecting data from SenixView® height sensor mounted on bicycle while connected with Dell Latitude 10ST2e.

Logging rate was set at one sample per second. The SenixView sensor records 20 echos per second, so each recorded measurement was the mean of 20 individual measurements. Typically, the number of recorded measurements taken in each experimental unit was 7–12, depending on the speed of the sensor operator. Speed varied with smoothness of the soil surface and moisture conditions within the site. Each echo measurement should be considered as an integration of heights from the crop canopy (Fig. 1). The canopy is not horizontal, so acoustic energy from the sensor strikes corn leaves at different angles. Whereas the manual height measurement once defined is similar for each plant regardless of leaf architecture. However, the acoustic sensor measurements are susceptible to different readings due to upright leaves, leaves that arch back to ground, and leaf movement with wind. The acoustic sensor measurements are therefore a trade-off between a firmly defined manual measurement, but is entirely impractical commercially, and a practical automatic measuring tool whose values inherently contain greater error.

The growth stages V6 and V12 were chosen because these represent two important times for possible in-season N application to corn. At V6, the corn plant has not yet determined maximum yield, so yield is not yet limited by shortage of N. An early in-season N application is usually made between V5 and V8. Using the INSEY normalization factor, an algorithm for in-season application to corn using the V6 data is valid for plus or minus two leaves; therefore, a V6 dataset helps to build an algorithm for V4 to V8 sensing, while an algorithm based on V12 data helps build an algorithm for V10 to V14 sensing, which then leads directly into tasseling and pollination. Therefore, V6 and V12 were chosen to operate AO sensors and height measurements in anticipation of future in-season algorithm development. The sensor height data from Durbin and Richardton at V6 was not collected due to wet soil conditions, where mud and crop residue built up on the tires and prevented practical use of the bicycle.

2.4. Harvest

The interior row (6.1 m in length less the outside ear at the beginning and end of each length) that was earlier sensed at V6 and V12 in each experimental unit was hand harvested after corn physiological maturity. An Almaco® (Almaco, Nevada, Iowa, USA) corn sheller was used that allowed complete shelling of wet and dry corn. Grain moisture at shelling was determined on a grain subsample using a Dickey-John® GAC-500 grain moisture and test weight instrument (Dickey-John, Auburn, Illinois, USA).

2.5. Statistical analysis

Regression analyses were conducted on sensor readings and yield in SAS for Windows 9.2 (SAS Institute, Cary, North Carolina, USA) using PROC REG with yield as dependent variable, and INSEY or INSEY multiplied by corn canopy manual height (INSEYMH) or INSEY multiplied by corn canopy sensor derived height (INSEYSH) (Sharma and Franzen, 2013) determined at V6 and V12 as the independent variable to evaluate the relationship between yield and corn canopy height. Linear regression equations were found to be the best descriptor of the regression relationships. The coefficient of determination (r^2) value was used to evaluate the linear regression relationships. Analysis of variance of yield and corn height was conducted in SAS using PROC GLM to compare differences between N treatments, with the LSD being used to separate treatment differences. A p-value of 5% probability (0.05) was used to statistically differentiate the treatments into those that were statistically different and those that were not. The means were further differentiated into values with a 1% probability (0.01) and 0.1 percent probability (0.001).

Table 4
Coefficients of determination (r^2) for the linear regressions between yield and manual height and acoustic sensor height and combined no-till sites with corn yield at V6 and V12. Corn heights at Richardton and Durbin at V6 were not obtained due to excessively wet conditions.

Location	Sensing stage	Manual height		Sensor height	
		r^2	Sig	r^2	Sig
Arthur (MTC)[a]	V6	0.28	–*	0.40	–***
	V12	0.44	–***	0.31	–**
Beach (NT)	V6	0.44	–***	0.49	–***
	V12	0.66	–***	0.25	–**
Durbin (CTC)	V12	0.60	–***	0.48	–***
Jamestown (NT)	V6	0.41	–***	0.31	–**
	V12	0.43	–***	0.18	–*
Mott (NT)	V6	0.12	NS	0.32	–**
	V12	0.00	NS	0.02	NS
New Leipzig (NT)	V6	0.26	–**	0.34	–***
	V12	0.35	–**	0.00	NS
Richardton (NT)	V12	0.01	NS	0.01	NS
Rutland (NT)	V6	0.03	NS	0.00	NS
	V12	0.16	–*	0.18	–*
No-till sites	V6	0.26	–*	0.14	–*
	V12	0.39	–**	0.38	–**

* Significance at 0.05 using the LSD statistic.
** Significance at 0.01 using the LSD statistic.
*** Significance at 0.001 using the LSD statistic.
[a] MTC is medium textured conventional tillage, CTC is clay textured conventional tillage, NT is no-till.

3. Results and discussion

The coefficients of determination of the linear regression between yield and INSEYSH (INSEY multiplied by sensor height) and yield and INSEYMH (INSEY multiplied by manual height) with the GS and CC sensor readings at V6 and V12 were significant at Arthur, Beach, Durbin and Jamestown (Table 4). At Mott, the coefficients of determination of yield and INSEYMH were not significant at V6 and V12, while that of yield and INSEYSH was significant only at V6. At New Leipzig, the coefficients of determination of yield and INSEYMH were significant related at V6 and V12, but that of yield and INSEYSH was only significant at V6. The coefficients of determination of yield with INSEYSH and INSEYMH were not significant at Richardton at V12 and wet field conditions prevented corn height sensing at V6. The coefficients of determination of the linear regression between yield and INSEYSH and INSEYMH were significant at Rutland only at V12. Normal corn development was compromised at Mott, New Leipzig and Richardton sites due to exceptionally high in-season rainfall and the corn plants struggled to overcome the effects of waterlogged soils throughout the summer.

The coefficients of determination of the linear regression between yield and INSEYSH with GS and CC sensor readings at V6 were significantly improved in 10 of 24 individual experimental site comparisons compared to that between yield and INSEY alone (Table 5). There were no differences in the coefficients of determination of the linear regression between yield and INSEYSH and those of yield and INSEY alone at 10 of 24 experimental site locations. Combining data from the no-till sites (Table 5), the coefficients of determination of the linear regression between yield and INSEYSH was improved over that of yield and INSEY alone in 2 of 4 comparisons, with no significant differences between the coefficients of determination of yield and INSEYSH and that of yield and INSEY alone in the remaining 2 comparisons. The coefficients of determination of linear regression between yield and INSEYSH with GS and C sensors were significant in 20 of 24 single site comparisons (Table 5).

The coefficients of determination of the linear regression between yield and INSEYSH with GS and CC sensor readings were significant in 31 of 32 individual experimental site comparisons at V12 (Table 5). The coefficients of determination of the linear regression between yield and INSEYSH with GS and CC sensor readings at V12 was improved in only 4 of 32 individual experimental site comparisons. There were no significant differences in the coefficients of determination of the linear regression between yield and INSEYSH with GS and CC sensor readings at V12 and that of yield and INSEY alone at 22 of 32 individual experimental site comparisons and 4 of 4 combined comparisons. The coefficient of determination of the linear regression of yield and INSEYSH with GS and CC sensor readings were reduced compared to that of yield and INSEY in 5 of 32 individual site comparisons. The V12 CC red edge INSEYSH was not significant at Richardton (Table 5).

The data behind the linear regressions of corn yield with INSEYSH and INSEYMH is provided in Table 6. Corn yield increased with N rate at Arthur, Beach, Durbin, Mott, New Leipzig and Richardton, but not at Jamestown and Rutland. Sensor measured corn height increased with N rate at Arthur (V6), Beach (V6, V12), Durbin (V12), New Leipzig (V6) and Richardton (V12).

Considering all sites, corn height measured with the sensor at V6 stage was more sensitive to N treatment compared to corn height measured manually (Table 6). In contrast, at V12 stage corn height measured manually resulted in greater treatment differences compared to corn height measured with the sensor. Corn height measured with the sensor at V6 increased with N rate at 3 of the 4 sites where corn yield increased with N rate. Corn height

Table 5
Coefficients of determination (r^2) of the linear regression of corn yield and INSEY (in-season estimate of yield), INSEYSH (in-season estimate of yield multiplied by sensor height), and INSEYMH (in-season estimate of yield multiplied by manual height) at V6 and V12 using the GS sensor or the CC sensor. Corn height at V6 was not obtained at the Richardton and Durbin sites due to excessively wet field conditions.

Site	Sensor[a]	GS Red		GS Red Edge		CC Red		CC Red Edge	
		V6	V12	V6	V12	V6	V12	V6	V12
Arthur	I	0.13*	0.29**	0.14*	0.34**	0.13*	0.45***	0.11	0.44***
	IS	0.29**	0.39**	0.35**	0.44***	0.32**	0.49***	0.28*	0.51***
	IM	0.07	0.45***	0.14*	0.50***	0.14*	0.55***	0.08	0.50***
Beach (NT)[b]	I	0.53***	0.69***	0.31**	0.71***	0.57***	0.67***	0.37**	0.67***
	IS	0.60***	0.70***	0.52***	0.73***	0.53**	0.68***	0.47***	0.67***
	IM	0.59***	0.75***	0.49***	0.76***	0.59***	0.73***	0.53***	0.73***
Durbin (CTC)	I	NA[c]	0.59***	NA	0.65***	NA	0.77***	NA	0.74***
	IS	NA	0.52***	NA	0.63***	NA	0.69***	NA	0.59***
	IM	NA	0.76***	NA	0.76***	NA	0.78***	NA	0.78***
Jamestown (NT)	I	0.55***	0.42***	0.53***	0.41***	0.48***	0.57***	0.48***	0.46***
	IS	0.48***	0.42***	0.44***	0.41***	0.45***	0.52***	0.46**	0.49***
	IM	0.53***	0.48***	0.49***	0.47***	0.48***	0.32**	0.49***	0.49***
Mott (NT)	I	0.18*	0.24*	0.12	0.35**	0.18*	0.30**	0.18*	0.23*
	IS	0.36**	0.30**	0.32**	0.33**	0.39**	0.40***	0.38**	0.39**
	IM	0.16**	0.05	0.14*	0.09	0.16*	0.10	0.17*	0.16*
New Leipzig (NT)	I	0.32**	0.30**	0.30**	0.32**	0.25**	0.30**	0.28**	0.26**
	IS	0.37**	0.32**	0.34**	0.35**	0.28**	0.35**	0.30**	0.30**
	IM	0.32**	0.34**	0.30**	0.34**	0.27**	0.33**	0.29**	0.31**
Richardton (NT)	I	NA	0.31**	NA	0.34**	NA	0.32**	NA	0.16*
	IS	NA	0.28**	NA	0.34**	NA	0.19*	NA	0.09
	IM	NA	0.33**	NA	0.37**	NA	0.47***	NA	0.40***
Rutland (NT)	I	0.24*	0.44***	0.22*	0.44***	0.11	0.33**	0.05	0.42***
	IS	0.09	0.30**	0.24*	0.33**	0.05	0.28**	0.03	0.31**
	IM	0.11	0.27***	0.11	0.26**	0.07	0.26**	0.04	0.26**
No-till sites	I	0.53***	0.60***	0.31**	0.58***	0.57***	0.53***	0.37**	0.52***
	IS	0.60***	0.45***	0.52***	0.50***	0.53***	0.58***	0.47***	0.56***
	IM	0.59***	0.43***	0.49***	0.43***	0.59***	0.49***	0.53***	0.46***

* Significance at $P < 0.05$ using the LSD statistic.
** Significance at $P < 0.01$ using the LSD statistic.
*** Significance at $P < 0.0001$ using the LSD statistic.
[a] I is INSEY (in-season estimate of yield = Sensor reading/growing degree days from planting date); IS is INSEY multiplied by normalized acoustic sensor height, IM is INSEY multiplied by normalized manual height.
[b] NT is no-till site, MCT is medium textured conventional tilled site, CCT, clay textured conventional till site.
[c] NA means not available. Corn height was not measured at Richardton and Durbin at V6 due to muddy conditions.

as measured by the sensor height at V12 increased with N rate at only 3 of 6 sites where yield increased with N rate. A probable explanation for the poor performance of the acoustic height sensor at V12 is the height limitation of our bicycle apparatus. At the extreme height of the sensor bicycle a height of about 175 cm could be achieved. At least one additional site was too tall for our apparatus to be used at V12 and that site therefore had no data and it is not included in this paper. At the 175 cm height it is also probable that upright leaves from the taller sites (Arthur, Jamestown and New Leipzig) interfered with readings as they obstructed canopy view, and confounded the data. Future experiments will need to have extended height of the sensor in excess of 50 cm above the canopy for greater consistency and improved results.

Although corn height as measured with an acoustic sensor or measured manually may improve yield prediction when multiplied by the AO sensor measurement within a site, across several sites the differing genetic height trait of the corn would prohibit universal use of actual height in an algorithm predicting corn yield. A better alternative would be to use the normalized height within a location to construct a normalized height-based algorithm with data from many experimental sites. The coefficients of determination of the linear regression of yield with INSEY, INSEYSH and INSEYMH of the GS and CC with sensor height and manual height normalized within each experimental site are provided in Table 7. At Arthur, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized within site were improved in 4 of 4 comparisons at V6 over that of INSEY alone. There were no differences in the coefficients of determination at Arthur of the linear regression of yield and INSEYSH with sensor height normalized within site compared to that of yield and INSEY alone. At Beach, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized within site were reduced in 1 of 4 comparisons at V6 over that of INSEY alone, and improved at 1 of 4 comparisons at V12. At Durbin, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors at V12 were not different than those of yield and INSEY alone.

At Jamestown, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized within site were reduced compared to yield and INSEY alone at 3 of 4 comparisons at V6. At V12, 1 of 4 comparisons were reduced and 2 of 4 comparisons were improved with INSEYSH with sensor height normalized within site compared to yield and INSEY alone. At Mott, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized within site were improved in 1 of 4 comparisons at V6, while 4 of 4 comparisons were reduced at V12.

At New Leipzig, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized within site were reduced at 1 of 4 sites at V12 compared to yield and INSEY alone, and there were no differences in the coefficients of determination of the remaining

Table 6
Treatment differences due to N rate between V6 and V12 growth stage corn height measurements made manually and with the acoustic sensor and corn yield.

Experimental Site	Treatment (kg ha^{-1})	Corn yield (kg ha^{-1})	V6 height		V12 height	
			Sensor (cm)	Manual (cm)	Sensor (cm)	Manual (cm)
Arthur	Control	6310^{d†}	18^{ab}	17a	131^{a}	92^{b}
	45	7460^{cd}	17^{ab}	18^{a}	130^{a}	94^{ab}
	90	8990^{ab}	22^{a}	19^{a}	131^{a}	107^{ab}
	135	7780^{bc}	18^{ab}	18^{a}	130^{a}	104^{ab}
	179	9270^{a}	21^{ab}	20^{a}	136^{a}	110^{a}
	224	8560^{abc}	15^{b}	20^{a}	132^{a}	108^{ab}
Beach	Control	4490^{d}	8^{b}	13^{b}	82^{b}	38^{bc}
	45	5370^{c}	9^{ab}	13^{b}	85^{ab}	36^{c}
	90	6060^{bc}	11^{ab}	16^{a}	86^{ab}	43^{b}
	135	6570^{ab}	10^{ab}	17^{a}	88^{a}	49^{a}
	179	6500^{ab}	14^{a}	16^{a}	88^{a}	49^{a}
	224	7050^{a}	11^{ab}	16^{a}	84^{ab}	49^{a}
Durbin	Control	6020^{c}	NA[a]	NA	11^{b}	51^{d}
	45	7530^{bc}	NA	NA	11^{b}	69^{bcd}
	90	7090^{bc}	NA	NA	14^{b}	66^{cd}
	135	8900^{a}	NA	NA	42^{a}	85^{abc}
	179	8430^{a}	NA	NA	38^{a}	100^{a}
	224	9720^{a}	NA	NA	42^{a}	93^{ab}
Jamestown	Control	9150^{a}	17^{b}	16^{a}	139^{a}	103^{a}
	45	9665^{a}	22^{a}	18^{a}	143^{a}	100^{a}
	90	8663^{a}	16^{b}	16^{a}	141^{a}	87^{a}
	135	9470^{a}	19^{ab}	16^{a}	139^{a}	100^{a}
	179	9839^{a}	19^{ab}	17^{a}	147^{a}	104^{a}
	224	10,070^{a}	23^{a}	18^{a}	146^{a}	105^{a}
Mott	Control	4476^{d}	25^{a}	22^{a}	107^{a}	59^{b}
	45	4853^{cd}	24^{a}	25^{a}	97^{a}	69^{a}
	90	5429^{bcd}	24^{a}	25^{a}	90^{a}	65^{ab}
	135	5854^{abc}	28^{a}	24^{a}	92^{a}	64^{ab}
	179	6057^{a}	25^{a}	24^{a}	93^{a}	68^{a}
	224	6515^{a}	30^{a}	27^{a}	97^{a}	61^{ab}
New Leipzig	Control	7537^{b}	21^{c}	25^{ab}	129^{a}	61^{b}
	45	7619^{b}	23^{bc}	22^{b}	129^{a}	69^{b}
	90	8391^{ab}	27^{ab}	24^{ab}	138^{a}	81^{ab}
	135	9589^{a}	26^{abc}	28^{ab}	138^{a}	85^{ab}
	179	8878^{ab}	29^{a}	30^{a}	145^{a}	101^{a}
	224	8807^{ab}	25^{abc}	30^{a}	126^{a}	77^{ab}
Richardton	Control	5960^{c}	NA	NA	45^{b}	40^{c}
	45	6270^{bc}	NA	NA	47^{ab}	44^{ab}
	90	6400^{bc}	NA	NA	48^{ab}	48^{a}
	135	7340^{a}	NA	NA	50^{a}	47^{a}
	179	7090^{ab}	NA	NA	49^{ab}	43^{bc}
	224	6900^{ab}	NA	NA	49^{ab}	43^{bc}
Rutland	Control	10,100^{a}	16^{a}	19^{a}	103^{a}	82^{a}
	45	10,410^{a}	18^{a}	19^{a}	110^{a}	86^{a}
	90	11,790^{a}	17^{a}	20^{a}	115^{a}	92^{a}
	135	9970^{a}	18^{a}	17^{a}	119^{a}	84^{a}
	179	10,850^{a}	17^{a}	20^{a}	115^{a}	95^{a}
	224	10,850^{a}	17^{a}	16^{a}	117^{a}	94^{a}

† Values followed by the same letter are not significantly different at $P < 0.05$, using the LSD statistic.
[a] NA means not available. Durbin and Richardton soils were too wet for height measurement at V6.

7 comparisons between yield and INSEYSH with the sensor height normalized and that of yield and INSEY alone.

There were no differences at Richardton between the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized compared to that of yield and INSEY alone. At Rutland, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized was improved in 3 of 4 comparisons at V6 compared to that of yield and INSEY alone. There were no differences at V12 at Rutland between the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized and that of yield and INSEY alone.

With the combined no-till sites, the coefficients of determination of the linear regression of yield and INSEYSH of the GS and CC sensors with sensor height normalized was reduced in 1 of 4 comparisons compared to that of yield and INSEY alone at V6. There were no differences in the coefficients of determination of the linear regression of yield and INSEYSH with sensor height normalized compared to that of yield and INSEY alone at V12.

4. Conclusions

Use of the SenixView acoustic sensor in these experiments automatically recorded corn height differences observed in the field (Fig. 3) and has the potential to improve yield prediction in corn. The sensor measured corn height provided improvement in the coefficient of determination of the linear regression of yield with INSEY in many comparisons. The use of manually measured corn height as an input to improve corn yield prediction when using AO sensors is impractical for commercial corn production,

Table 7
Coefficients of determination (r^2) between INSEY and acoustic sensor height normalized within each site, or manual height normalized within each experimental site and corn yield.

Site	Sensor[a]	GS Red		GS Red Edge		CC Red		CC Red Edge	
		V6	V12	V6	V12	V6	V12	V6	V12
Arthur	I	0.03	0.37***	0.06	0.51***	0.08	0.42***	0.04	0.45***
	IS	0.40***	0.56***	0.44***	0.62***	0.42***	0.55***	0.38***	0.57***
	IM	0.05	0.38***	0.11*	0.45***	0.13*	0.43***	0.11*	0.51***
Beach (NT)[b]	I	0.30**	0.67***	0.49***	0.32**	0.52***	0.67***	0.36**	0.32**
	IS	0.32**	0.51***	0.39***	0.40***	0.38**	0.51***	0.36**	0.40***
	IM	0.49***	0.69***	0.61***	0.61***	0.55***	0.69***	0.48***	0.61***
Durbin (CTC)	I	NA	0.59***	NA	0.68***	NA	0.73***	NA	0.71***
	IS	NA	0.59***	NA	0.59***	NA	0.59***	NA	0.59***
	IM	NA	0.61***	NA	0.61***	NA	0.63***	NA	0.63***
Jamestown (NT)	I	0.40***	0.36**	0.41***	0.48***	0.39**	0.04	0.41***	0.04
	IS	0.19*	0.30**	0.22**	0.39**	0.21**	0.35**	0.21**	0.29**
	IM	0.44***	0.39**	0.45***	0.51***	0.41***	0.44***	0.42***	0.35**
Mott (NT)	I	0.12*	0.19*	0.17*	0.20**	0.17*	0.19*	0.17*	0.20**
	IS	0.12*	0.02	0.15*	0.02	0.18*	0.02	0.21**	0.05
	IM	0.20**	0.08	0.24**	0.08	0.26**	0.08	0.26**	0.08
New Leipzig (NT)	I	0.30**	0.30**	0.31**	0.30**	0.33**	0.25**	0.28**	0.59***
	IS	0.31**	0.20**	0.33**	0.33**	0.25**	0.25**	0.26**	0.23**
	IM	0.20**	0.20**	0.30**	0.30**	0.25**	0.27**	0.29**	0.22**
Richardton (NT)	I	NA[c]	0.20**	NA	0.23**	NA	0.20**	NA	0.23**
	IS	NA	0.25**	NA	0.26**	NA	0.25**	NA	0.26**
	IM	NA	0.33**	NA	0.35**	NA	0.33**	NA	0.33**
Rutland (NT)	I	0.24**	0.44***	0.11	0.44***	0.11	0.33***	0.03	0.42***
	IS	0.21**	0.48***	0.24**	0.49***	0.19*	0.47***	0.16*	0.45***
	IM	0.09	0.44***	0.11	0.40***	0.15*	0.43***	0.14*	0.37***
No-till sites	I	0.28**	0.33**	0.26**	0.44***	0.37**	0.67***	0.35**	0.56***
	IS	0.30**	0.37**	0.31**	0.36**	0.35**	0.54***	0.35**	0.50***
	IM	0.22**	0.49***	0.22**	0.43***	0.30**	0.49***	0.31**	0.44***

* Significance at $P < 0.05$, using the LSD statistic.
** Significance at $P < 0.01$, using the LSD statistic.
*** Significance at $P < 0.0001$, using the LSD statistic.
[a] I is INSEY (in-season estimate of yield = Sensor reading/growing degree days from planting date); IS is INSEY multiplied by normalized acoustic sensor height, IM is INSEY multiplied by normalized manual height.
[b] NT is no-till site, MCT is medium textured conventional tilled site, CCT, clay textured conventional till site.
[c] NA means not available. Corn height was not measured at Richardton and Durbin at V6 due to muddy conditions.

Fig. 3. Visual difference in corn height in control treatment as compared to higher N treatments.

therefore use of a sensor to improve the relationship between yield and AO sensor reading is important. The normalization of sensor height within each site resulted in values that could be used to combine multiple sites into a yield prediction algorithm that includes the AO sensor reading, corn height measured with the height sensor, and yield data. Although the current database of corn height with corn yield is not sufficient to construct a usable algorithm for commercial use, it indicates that with a larger sensor height database such an algorithm might be possible that transcends differences in genetic corn hybrid height characteristics.

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