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Sugar Beet Yield and Quality Prediction at Multiple Harvest Dates Using Active-Optical Sensors

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ABSTRACT

Yield prediction in sugar beet (*Beta vulgaris* L.) is important as a basis for in-season N application. Active optical sensors have been researched in sugar beet for yield estimation. A common field method for using active-optical sensors is to establish an N non-limiting area, and compare the yield predicted from sensor readings with readings from the rest of the field. Yield difference is the basis for calculation of N rate. Sugar beet gains root mass and sugar content with time. The objectives of these experiments were to utilize two active-optical sensors at two timings with canopy height measurements and relate readings to root yield and recoverable sugar yield at consecutive harvest dates. A 2-yr study in the Red River Valley of North Dakota and Minnesota was conducted on four sites to compare two active-optical sensors, GreenSeeker and Holland Crop Circle, red normalized differential vegetative index (NDVI), red edge NDVI, with and without canopy height for use in sugar beet yield prediction. The red NDVI and red edge NDVI, used at V 6–8 and V 12–14 were similar in their relationship to sugar beet yield over several harvest dates. The r^2 of sensor measurement and yield relationships at V 6–8 improved when canopy height was considered but not at V 12–14. Active-optical sensors when canopy height is considered could be used to predict sugar beet root yield and recoverable sugar yield over a range of harvest dates, which would be useful in developing algorithms for in-season N fertilization.

Sugar beet is an important source of sugar for human consumption, with 55% of U.S. sugar production coming from sugar beet, and 45% from sugarcane (*Saccharum officinarum* L.) (Bangsund et al., 2012; USDA, 2014). Yield prediction of crops early in the growing season, including sugar beet, is increasingly important for logistical and marketing efforts of farmers, sugar processors and commodity brokers, as well as for use in precision agriculture (Parke, 2014). Yield prediction is used as a precision agriculture tool because it can be used to identify N deficiency in crops if an N non-limiting area is present in the field to serve as an active-optical sensor reference (Tubana et al., 2008; Lukina et al., 2001; Raun et al., 2008).

SUGAR BEET AND NITROGEN

Sugar beet requires enough N to produce root mass yield, but too much N reduces sugar content and increases the concentration of ammonium in the root, which increases the cost of sugar processing (Franzen, 2004). Nitrogen rate early in the season is of particular concern. However, high residual N levels deep in the soil can result in late season uptake of N and decreased recoverable sugar yield (Franzen et al., 2004; Stevanato et al., 2010). On the other hand, high rainfall can result in N leaching from the rooting zone and high levels of denitrification can reduce available N in poorly drained soils, particularly those high in clay content typical of the central Red River Valley of North Dakota and Minnesota. In-season N application to N deficient sugar beet was found to increase root yield and recoverable sugar yield when season-long soil moisture was adequate (Lamb and Moraghan, 1993). Others have cautioned against the use of mid- to late-season N application because of the decrease in sugar beet quality that can result (Carter and Traveller, 1981). It is therefore very important that methods are developed that can identify premature N deficiency and adequate N in sugar beet and provide a guide to N rate required in-season, so that root yield increase and sugar concentration decrease is balanced to result in the greatest recoverable sugar yield.

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Abbreviations: CC, Crop Circle; GDD, growing degree day; GS, GreenSeeker; INSEY, in season estimate of yield; LAI, leaf area index; NDVI, normalized differential vegetative index..

YIELD AND NITROGEN RATE ALGORITHMS

As in all crops, actual yield of sugar beet is unknown until harvest. Therefore, N rate algorithms that rely on "yield goals" (Dahnke et al., 1988) have little practical use in determining the pre-plant or in-season N fertilizer rate. Recent studies have found that yield and response of crops to N fertilization are not related (Arnall et al., 2013). This means that within a variety, within a specific field with specific soil characteristics in a specific environment, response to N can be similar whether the yield is high or low at harvest (Arnall et al., 2013). Grain crops, such as wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sunflower (*Helianthus annuus* L.), and canola (*Brassica napus* L.) have a singular harvest weight unless harvest is conducted poorly or an environmental event reduces harvestability, such as high wind, hail, pod shatter, or harvest-period disease. Grain crops are annual plants that senesce, allowing the seed/grain to dry for harvest and storage. At the point of physiological maturity, harvestable mass of a grain crop does not increase. Sugar beet is a biennial plant. The year of planting, the sugar beet accumulates root mass, which at some date is harvested in the fall. Sugar beet harvest weight is a continuum of, most commonly, increased weight with time, accompanied by either sugar accumulation or sugar concentration loss depending on the environment (Draycott, 2006). Therefore, yield prediction of sugar beet is dependent on date, or rather growing degree days from planting, since growing degree days for a certain fall calendar date in North Dakota or Minnesota are different between years. Although studies have shown that sugar beet yield can be predicted by the early season use of active optical sensors, these studies considered a single harvest date defined by the experiment (Gehl and Boring, 2011; Hongo and Niwa, 2012).

SUGAR BEET HARVEST CONSIDERATIONS

The region of sugar beet production in North Dakota and Minnesota is the largest area of sugar beet production in the United States (Bangsund et al., 2012) with about 180,000 ha sugar beets harvested annually. Sugar beet pre-harvest begins anytime from 1 September through 15 September whose purpose is to bring the processing factories into sugar production efficiently before full harvest begins. Full harvest usually begins about 1 October, and can continue from 2 to 6 wk depending on weather conditions. During harvest time, sugar beet growing degree days continue to accumulate, as does a change, usually positive, in harvest weight (Draycott, 2006). In this important sugar beet growing region of North Dakota and Minnesota, the sugar beet growers are paid not on the harvest weight of sugar beet, but the recovered sugar weight after processing. Sugar beet hauling trucks are sampled as they enter the sugar beet accepting stations; the samples are analyzed and a formula is used to calculate the "recoverable sugar" that growers are paid for delivery. The recoverable sugar formula considers the weight delivered less the soil contaminants that are cleaned off before processing, the sucrose in the sugar beet, the loss to molasses, and K, Na, and especially ammonium N that is contained within the sugar beet that increases expenses related to processing. Nitrogen rate is especially important to sugar beet growers, since it influences the harvest weight, sugar content and ammonium N concentration of the sugar beet, which all are included in the grower payment formula. As N rate increases, harvest weight increases, ammonium N concentration increases, and sugar concentration decreases (Franzen, 2004). Any N rate formula for yield prediction should also include prediction for recoverable sugar yield.

ACTIVE-SENSOR IMAGERY AND SUGAR BEET

Early in the sugar beet growing season, leaf area index (LAI) has been shown to be a good predictor of sugar beet yield (Clevers, 1997). Leaf area index is the projection of the leaf surface onto the soil as a proportion of the entire soil surface (Ross, 1981). Combining an estimate of LAI using remote sensing from aerial imagery or satellite within a crop growth model has been used to predict sugar beet yield (Clevers, 1997; Guerif and Duke, 1998; Hongo and Niwa, 2012). Remote imagery does not measure LAI directly, but uses NDVI with red and near-infrared wavelengths as an estimator of LAI (Jordan, 1969). The basic formula for red-NDVI, which is based on red and near infrared light, follows:

NDVI = (Near infrared reading – Red reading)/(Near infrared reading + Red reading)

Although the basic NDVI formula is based on red and near infrared, green, red-edge and other wavelengths can be substituted into the basic NDVI formula instead of the red reading. Early season estimates of yield combined with known areas of adequate N have been to estimate in-season N deficiencies in sugar beet (Wiesler et al., 2002).

Active-optical sensors have successfully been used to predict sugar beet yield and quality (Gehl and Boring, 2011; Hongo and Niwa, 2012). Active-optical sensors emit their own coded light pulses, and read only their reflected light pulses, enabling readings during most day or night lighting conditions (Povh and de Paula Gusmao dos Anjos, 2014; Kipp et al., 2014). Advanced active-optical sensors not only have red NDVI capabilities, but red-edge NDVI as well. Red-edge NDVI is not a measurement of LAI, but measures "tint" instead. There is a high correlation of red-edge and chlorophyll content (Horler et al., 1983; Filella and Penuelas, 1994), without red-edge actually measuring the green wavelengths that humans see. Therefore, it essentially measures tint, that is related to chlorophyll content. One of the problems with using red NDVI is the saturation issue (Nguy-Robertson et al., 2012). As LAI values approach 1.0, meaning the leaves cover the inter-row spaces, differences in yield potential are masked because even stunted, yellow-leafed crop leaves can cover the inter-row space late in the growing season. Red-edge NDVI reflection is not dependent on LAI, so differences are still evident even though leaves cover the row regardless of their nutritional state (Mutanga and Skidmore, 2004). In sugar beet, leaves tend to cover the soil at about V12, especially in 56 cm or narrower row spacing. Canopy height has increased prediction of corn yield when combined with active-optical sensor readings (Sharma and Franzen, 2014). The use of leaf canopy height to aid in yield prediction in sugar beet has not been published in peer review literature although it has been researched (Franzen et al., 2003). The purpose of these experiments was to determine the relationship of red and red edge NDVI readings at two early season times with sugar beet yields resulting from N rate response experiments in sugar beet. Another objective was to determine the predictability of red NDVI, red edge NDVI, and canopy height over a series of possible sugar beet harvest dates on both sugar beet root yield and recoverable sugar yield, to form the basis for in-season N rate application using active-optical ground-based sensors.

METHODS

Four field experiments were conducted in North Dakota during 2012–2013. Details of the soils, cultivars, and other agronomic components of the study are provided in Table 1. Row width of sugarbeet planting at each of the sites was 56 cm, and all sites followed spring wheat grown the previous year. Each experiment was organized using a randomized complete block design with four replications and six N rate treatments as ammonium nitrate (34–0–0) granules applied broadcast by hand within a week before seeding. The N treatments were 0, 34, 67, 101, 135, and 168 kg h^{-1} applied as fertilizer, in addition to any residual N (Table 1) found before treatments were applied in a 60-cm soil sample composite. For all site-years, each experimental unit was 9.144 by 9.144 m. Soil samples from the 0- to 15-cm and 15- to 60-cm depths were collected at each site in each year before fertilizer application to determine residual soil nitrate, plant available P, K, and other relevant soil chemical properties (Table 1). After N treatments were applied, the experimental unit defining flags were removed, and a large flag was placed at each corner of the experiment so that the farmer or the fertilizer applicator would avoid the experiment when fertilizing the rest of the field. In addition, a 5 cm diam. steel washer was placed at a 10-cm depth in each corner of the experimental area under the flag to facilitate finding the site corners with a metal detector after the farmer cooperator finished planting.

The farmer cooperators seeded the sugar beet and applied herbicide and other inputs on the experimental areas when he conducted the activities on the rest of the field. After seeding, the corners of the experimental area were found using a GPS receiver and a metal detector. Two handheld ground-based active optical sensors were used to collect crop canopy optical reflectance data. The Holland Crop Circle ACS-470 Sensor (Holland Scientific Inc., Lincoln, NE) (CC) was utilized in both years. The 670 nm (red), 730 nm (red edge), and 760 nm (NIR) were used to calculate red NDVI (using the red and NIR bands) and red edge NDVI (using the red edge and NIR bands). In 2012, the first generation of GreenSeeker (Trimble, Sunnydale, CA) (GS), which provides 660 nm (red) and 770 nm (near infrared) was utilized and red NDVI was calculated. The second generation GS was procured before the 2013 season, which has two red edge channels, 710 and 735 nm, and it was used in the 2013 growing season. The red-edge NDVI used for comparisons in this manuscript was based on 710 nm readings. Optical reflectance was measured using the sensors positioned about 50 cm above the crop canopy, oriented with the sensor nadir with the sensor light emitted perpendicular to the row with the operator walking at 5 km h^{-1} next to a representative middle row within the defined area of each experimental unit/plot. The same row was not necessarily sensed at V6 and V12. Sensing date, growth stage at sensing, planting date, and

Table 1. Background information for sugar beet, sites, and soils.

Year	Site	Cultivar	NW corner GPS coordinate	Soil series and slope	Harvest stand	Spring residual nitrate	Olsen P	K	Organic matter	Growing season precipitation
					1000 plants ha^{-1}	kg ha^{-1}	—— mg kg^{-1} ——		g kg^{-1}	mm
2012	Crookston, MN	VanDerHave 36813RR	47°47′58.426″ N 96°35′55.436″ W	Bearden-silty clay loam†, 0 to 1% slopes	141	67	10	450	55	256
2012	Amenia, ND	Crystal 095	46°58′34.623″ N 97°15′04.762″ W	Fargo silty clay, 0 to 1% slopes	167	109	19	350	54	183
2013	Casselton, ND	Crystal 875	46°51′43.782″ N 97°18′47.800″ W	Fargo silty clay, 0 to 1% slopes	150	137	7	370	54	482
2013	Thompson, ND	Seedex Xavier	47°45′00.656″ N 97°05′23.046″ W	Bearden silty clay loam, 0 to 1% slopes	148	85	10	225	57	306

† Bearden-silty clay loam: fine-silty, mixed, superactive, frigid Aeric Calciaquoll. Fargo silty clay: fine, smectitic, frigid Typic Epiaquert.

harvesting dates are recorded in Table 2. Although individual site comparison at a single imaging date of yield and recoverable sugar yield and N rate can be analyzed using red NDVI or red edge NDVI without modification, multiple sensing and particular multiple site with multiple sensing requires normalization of readings based on a growing degree model. Based on the NDVI data, in season estimate of yield (INSEY) was calculated using the formula below:

$$INSEY = NDVI/GDD$$

where GDD refers to the accumulated positive growing degree days from planting date to sensing date (Raun et al., 2001). Growing degree days for each location were obtained from the nearest weather station supported by the website of the North Dakota Agricultural Weather Network (http://ndawn.ndsu.nodak.edu/). Normalized differential vegetative index refers to either red NDVI or red edge NDVI depending on the specific analysis.

Canopy height was measured using a tape measure from the soil surface to the apex of the leaf canopy on the same day as sensing. The leaves were not extended upward by hand, but only measured as they were configured in the field. If the reader considers the height at which a horizontal object would touch the highest point of the canopy, this is the point at which the height was measured. All heights analyzed were in centimeters. In 2012, sugar beet at Amenia were harvested at two dates and Crookston sugar beet at three dates; each harvest consisted of hand harvesting 3.05 m of row within each subplot. The third date at Amenia was not conducted due to the continuing drought (Table 1) causing the beet to lose moisture and interfere with root yield and sugar accumulation. The grower cooperator at Amenia realized that yield was actually starting to decrease with time, so the field was harvested very early relative to his usual harvest dates. Vegetative tops from all of the beets harvested from an experimental unit were removed in the field so that no green tissue remained on any sugar beet, then all of the sugar beets were placed within a large leather bag, tagged with a label specific to trial and plot number and sealed for delivery that day to East Grand Forks for quality analysis. The subsequent harvests were made at least two rows away from the previous harvest row. In 2013, Casselton and Thompson sugar beet were harvested at three dates. Dates of sensing and harvest for Casselton and Thompson are listed in Table 2.

Sugar beet sugar content and adjustments to yield, including subtraction of tare soil, was analyzed at the East Grand Forks American Crystal Sugar Tare Laboratory, East Grand Forks, MN, following delivery the date of harvest. SAS 9.3 (SAS Institute, Cary, NC) was used to perform analysis of variance to determine the effect of N application rate on sugar beet yield and quality, and to perform regression analysis on the relationships between sensor measurements, modification with canopy, and sugar beet root yield and recoverable sugar yield.

RESULTS

Sugar Beet Root Yield and Recoverable Sugar Yield Response to Nitrogen Rate

Root yield and recoverable sugar yield responses of sugar beet to N are shown in Table 3.The N rate at the first harvest date at Amenia (15 August, 3832 GDD) resulted in no significant yield or recoverable sugar yield differences, while at the second Amenia harvest date (29 August, 4289 GDD) root yield was maximized at the 101 kg N ha^{-1} rate (Table 3). At Crookston, root yield and recoverable sugar yield did not vary with N rate at the first harvest (15August, 3458 GDD). At the second harvest date at Crookston (29 August, 3862 GDD), root yield and sugar yield did not vary with N rate. At Casselton, root yield at the first harvest date (27 August, 3557 GDD) increased with N rate and recoverable sugar yield did not increase with N rate. At the second Casselton harvest date (16 September, 4210 GDD) yields did not vary with N rate. At the third Casselton harvest (30 September, 4609 GDD), root yield and recoverable sugar yield increased with N rate. At Thompson, sugar beet root yield and recoverable sugar yield increased with N rate at the first (27 August, 3385 GDD) and second harvest dates (17 September, 4029 GDD), while N rate did not affect yields at the third harvest date (1 October, 4396 GDD), probably due to a late infestation of sugar beet root aphid (*Pemphigus betae*) that likely caused random yield and sugar content affects within the experiment.

Regression Analysis of Sensor Readings and Canopy Height to Sugar Beet Root Harvest Yields

A summary of regression analysis of root yield and sensor INSEY with and without canopy height at Amenia and Crookston in 2012 for each site is provided in Table 4. At Amenia, the V6 sensing with the CC was significantly related to the 15 August root yield, and multiplying by canopy height

Table 2. Sugar beet experiments planting, harvest, and sensing dates, 2012–2013.

Site-year	Planting date	First sensing date	First sensing growth stage	Second sensing date	Second sensing growth stage	Harvest date (s)/GDD†
Crookston 2012	25 April	4 June	V6	21 June	V14	15 August (first)/3458‡ 29 August (second)/3862
Amenia 2012	12 April	24 May	V6	13 June	V14	15 August (first)/3832 28 August (second)/4289
Casselton 2013	13 May	20 June	V8	10 July	V12 to 14	27 August (first)/3557 09/16 second)/4210 09/30 (third)/4609
Thompson 2013	14 May	20 June	V8	10 July	V12	27 August (first)/3385 17 September (second)/4029 1 October (third)/4396

† GDD is growing degree days from planting date.

‡ Value following harvest date is GDD.

Table 3. Sugar beet root yield and recoverable sugar yield at Amenia and Crookston in 2012 and Casselton and Thompson in 2013.

	Amenia				Crookston			
	15 August harvest 3832 GDD†		28 August harvest 4289 GDD		15 August harvest 3458 GDD		29 August harvest 3862 GDD	
N rate	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield
kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
0	39.6a‡	7180a	43.7a	8830a	58.1a	8820a	67.2a	11,930a
34	42.2a	7470a	47.5ab	9410a	58.2a	9120a	69.9a	12,450a
67	41.8a	7580a	48.2ab	9560a	61.1a	9260a	69.3a	12,580a
101	47.0a	8010a	55.3b	9990a	61.1a	9040a	64.3a	11,710a
135	47.9a	8320a	48.1ab	9380a	60.8a	8870a	67.0a	11,920a
168	44.3a	7770a	45.6ab	8900a	62.0a	8700a	65.9a	11,740a

	Casselton 27 August harvest 3557 GDD		Casselton 16 September harvest 4210 GDD		Casselton 30 September harvest 4609 GDD		Thompson 27 August harvest 3385 GDD		Thompson 17 September harvest 4029 GDD		Thompson 1 October harvest 4396 GDD	
N rate	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield	Root yield	Recoverable sugar yield
kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
0	32.0a	5800a	43.1a	7330a	47.3ab	8130ab	42.3a	6,690a	56.9a	8,420a	69.6a	11,160a
34	32.6ab	5870a	43.5a	7500a	42.5a	7410a	54.6 b	8,250a	57.7ab	8,180a	64.3a	9,740a
67	32.7ab	6000a	45.5a	7740a	54.8ab	9511ab	50.2ab	8,000a	75.5 c	11,170 b	77.1a	12,170a
101	34.0ab	6140a	45.2a	7590a	50.6ab	8330ab	48.7ab	7,230a	64.0abc	9,370ab	73.9a	11,780a
135	33.8ab	5930a	49.4a	8100a	60.5b	9870 b	48.3ab	7,440a	66.1abc	8,940a	72.6a	11,490a
168	36.4b	6250a	51.2a	8250a	54.9ab	8660ab	46.9ab	6,960a	70.3bc	9,300ab	66.7a	10,310a

† GDD is growing degree days from planting to harvest date.

‡ Values followed by the same letter are not statistically different at $P < 0.05$.

Table 4. GreenSeeker (GS) and Crop Circle (CC) V 6–8 and V 12–14 r^2 values of regression analysis of red- normalized differential vegetative index (NDVI) based in season estimate of yield (INSEY) and red edge-NDVI based INSEY on sugar beet root yield at 2012 sites, Amenia and Crookston.

Site	Harvest	Stage	GSR†	GSRht	CCR	CCRht	CCRE	CCREht
Amenia	First	V6	ns‡	ns	0.60*	0.40	0.62	0.44
		V12	ns	ns	ns	ns	ns	ns
	Second	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns
Crookston	First	V6	ns	0.41	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns
	Second	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns
	Third	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns

* Significance at $P < 0.05$.

† GSR is GreenSeeker red-NDVI based INSEY; CCR is Crop Circle red-NDVI based INSEY; GSRht is GSR multiplied times canopy height; CCRht is CCR multiplied times canopy height; CCRE is Crop Circle red edge-NDVI based INSEY; and CCREht is CCRE multiplied times canopy height.

‡ ns denotes non-significance.

Table 5. GreenSeeker (GS) and Crop Circle (CC) V 6–8 and V 12–14 r^2 values of regression analysis of red- normalized differential vegetative index (NDVI) based in season estimate of yield (INSEY) and red edge-NDVI based INSEY on sugar beet recoverable sugar yield at 2012 sites, Amenia and Crookston.

Site	Harvest	Stage	GSR†	GSRht	CCR	CCRht	CCRE	CCREht
Amenia	First	V6	ns‡	ns	0.57*	0.41	0.56	0.43
		V12	ns	ns	ns	ns	ns	ns
	Second	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns
Crookston	First	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns
	Second	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns
	Third	V6	ns	ns	ns	ns	ns	ns
		V12	ns	ns	ns	ns	ns	ns

* Significance at $P < 0.05$.

† GSR is GreenSeeker red-NDVI based INSEY; CCR is Crop Circle red-NDVI based INSEY; GSRht is GSR multiplied times canopy height; CCRht is CCR multiplied times canopy height; CCRE is Crop Circle red edge-NDVI based INSEY, and CCREht is CCRE multiplied times canopy height.

‡ ns denotes non-significance.

Table 6. GreenSeeker (GS) and Crop Circle (CC) V 6–8 r^2 values of regression analysis of red-normalized differential vegetative index (NDVI) based INSEY and red edge-NDVI based in season estimate of yield (INSEY) and first and second harvest sugar beet root yield combining data from the 2012 Amenia and Crookston sites.

Harvest	Model	GS Red INSEY	GS red INSEY × canopy height	CC Red INSEY	CC Red INSEY × canopy height	CC Red edge INSEY	CC Red edge INSEY × canopy height
2012, First	Exponential	0.434*	0.615	0.546	0.718	0.622	0.727
	Linear	0.468	0.649	0.558	0.732	0.630	0.738
	Quadratic	ns†	0.689	0.625	0.760	0.681	0.774
2012, Second	Exponential	0.387	0.559	0.411	0.595	0.452	0.596
	Linear	0.397	0.579	0.415	0.609	0.454	0.609

* Significant at $P < 0.05$.

† The designation ns denotes non-significance.

did not strengthen the relationship. At Crookston, the only significant relationship of sensor readings with root yield was with the GS INSEY at V6 multiplied times canopy height with the 15 August root yield. The regression analysis of recoverable sugar yield and sensor INSEY with and without canopy height at Amenia and Crookston in 2012 for each site is provided in Table 5. At Amenia, the V6 CC sensing was significantly related to 15 August recoverable sugar yield, and multiplying times canopy height did not improve the relationship. There were not significant r^2 values at any harvest date with V6 or V12 sensing data at Crookston (Table 5). The INSEY data for V6 and V12 at Amenia and Crookston in 2012 were pooled and related to the first harvest sugar beet root yield (both sites harvested 15 August, with 3458 GDD and 3832 GDD, respectively). A summary of the first (V 6–8) and second (V 12–14) GS sensing regression analysis results of pooled 2012 data appear in Table 6. It is important to note that INSEY allows the inclusion of data sets that are not sensed at exactly

Table 7. GreenSeeker (GS) and Crop Circle (CC) V 12–14 r^2 values of relationships between in season estimate of yield (INSEY) with first and second harvest sugar beet root yield combining data from the 2012 Amenia and Crookston sites, and combining the 2013 Casselton and Thompson sites at first harvest. Regression analysis of sensor readings and combined 2013 and third harvest yields were not significant.

Year(s), Harvest	Model	GS Red INSEY	GS Red INSEY × canopy height	GS Red edge INSEY	GS Red edge INSEY × canopy height	CC Red INSEY	Red INSEY × canopy height	CC Red edge INSEY	CC Red edgeINSEY × canopy height
2012, First	Exponential	0.645*	0.302	na†	na	0.695	0.369	0.703	ns‡
	Linear	0.670	0.316	na	na	0.717	0.383	0.721	ns
	Quadratic	0.713	ns	na	na	ns	ns	ns	ns
2012, Second	Exponential	0.647	0.373	na	na	0.424	0.667	0.667	0.321
	Linear	0.649	0.366	na	na	0.417	0.661	0.661	0.312
2013, First	Exponential	ns	ns	ns	0.313	ns	ns	ns	ns
	Linear	ns	ns	ns	0.321	ns	ns	ns	ns

* Significance at $P < 0.05$.

† na means that the GS red edge capability was not available for comparison in the 2012 GS sensor.

‡ The designation ns represents a relationship that is not significant at $P < 0.05$.

Table 8. GreenSeeker (GS) and Crop Circle (CC) V 12-14 r^2 values of regression analysis of red normalized differential vegetative index (NDVI)-based in season estimate of yield (INSEY) and red edge NDVI-based INSEY with first and second harvest sugar beet root yield combining data from all four sites in 2012 and 2013.

Harvest	Model	GS Red INSEY	GS Red INSEY × canopy height	CC Red INSEY	CC Red INSEY × canopy height	CC Red edge INSEY	CC Red edge INSEY × canopy height
First	Exponential	0.760*	0.739	0.800	0.767	0.778	0.756
	Linear	0.770	0.737	0.803	0.766	0.781	0.755
Second	Exponential	0.867	0.917	0.736	0.881	0.726	0.878
	Linear	0.856	0.908	0.723	0.870	0.713	0.868

* Numerical values denote significance at $P < 0.05$.

the same growth stage. Without the division of the NDVI by growing degree days the relationships are growth stage sensitive. With the division of the NDVI by growing degree days, the relationships are not growth stage sensitive within at least two leaves plus or minus the mean growth stage (Raun et al., 2001). The exponential models and linear models of GS INSEY at V6–8 and V12–14 were similar in r^2 value in both years. The quadratic model r^2 value was also similar to the exponential and linear models in most first harvest relationships at V 6-8, except for the GS red INSEY. The only relationship at V 12–14 within which the quadratic model was significant was the GS red INSEY. The r^2 values of the regression models based on CC first (V6–8) and second (V12–14) sensing data are given in Table 6. All models except those marked with "ns" (not significant) are highly significant, with a very low p value (0.01–0.0001). At V6–8, including canopy height with sensor NDVI increased the strength of the relationship between sensor reading INSEY and root yield in every case.

Similar conclusions can be drawn from Table 7 in that (i) V 12–14 pooled 2012 site data without plant height information were more strongly related with first harvest root yield than including plant height, (ii) exponential and linear model r^2 values were similar and were more consistently significant compared to the quadratic models. The reason for the poor performance of the use of canopy height at the V 12–14 sensor reading date is most probably due to the extremely dry weather in 2012 (Table 1), which prevented normal canopy development and caused the canopy to open horizontally and not extend leaves vertically.

The INSEY data for each sensing period at the 2012 Amenia and Crookston sites were pooled and related to the second harvest (28 August, 4289 GDD at Amenia and 29 August, 3862 GDD at Crookston) sugar beet root yield using regression analysis. The relationships between sensor INSEY and second harvest root yield were highly significant. The r^2 values of pooled 2012 site exponential and simple linear regression models are listed in Table 6. Since in most comparisons the quadratic models were not significant in the second harvest, they were not included with the second harvest data. Including canopy height with red-NDVI INSEY and red edge-NDVI INSEY at V 6–8 improved the r^2 of the relationships, while including canopy height at V 12–14 only improved the r^2 of the CC red INSEY readings, but not the GS red INSEY or the CC red edge INSEY.

Pooled analysis of the 2013 Casselton, ND, and Thompson, ND, sites GS and CC red INSEY at V 6–8 and first sugar beet harvest (both sites 27 August, 3557 GDD at Casselton and 3385 GDD at Thompson) root yield were not significant and do not appear in any table. However, the the r^2 of the GS red edge INSEY multiplied times canopy height with the first harvest root yield was significant at V 12–14 (Table 7). Regression analysis of the pooled 2013 data from Casselton and Thompson between V 6–8 and V 12–14 sensing and the second and third harvests were not significant and are not listed in any table.

Using the pooled 2-yr and four-site data, three highly significant quadratic polynomial models with very high r^2 values (close to 1) were found between V 6–8 INSEY and first harvest root yield (Fig. 1–3). These figures indicate that at the early sugar beet growth stage of V 6–8, the sensor readings from GS red, CC red and CC red edge, with canopy height included, indicate that yield improvement could be made at lower sensor readings, while at higher sensor readings maximum yield is

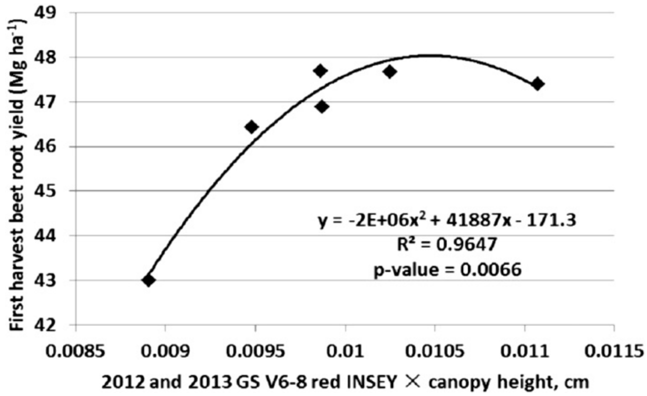

Fig. 1. Regression analysis relationship between the 2-yr, four site, combined GreenSeeker (GS) red in season estimate of yield (INSEY) at V 6–8 multiplied times canopy height in centimeters, and the first harvest sugar beet root yield.

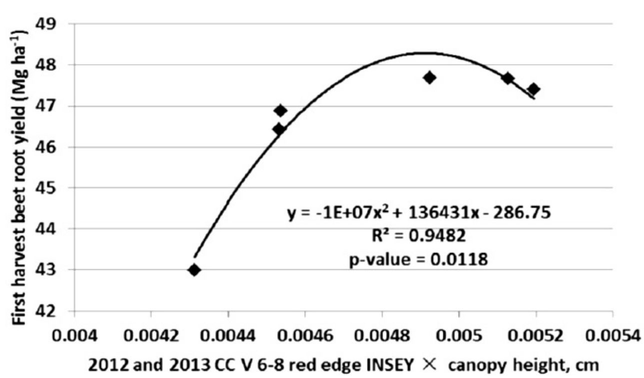

Fig. 2. Regression analysis relationship between the 2-yr, four site, combined Crop Circle (CC) red edge in season estimate of yield (INSEY) at V 6–8 multiplied times canopy height in centimeters, and the first harvest sugar beet root yield.

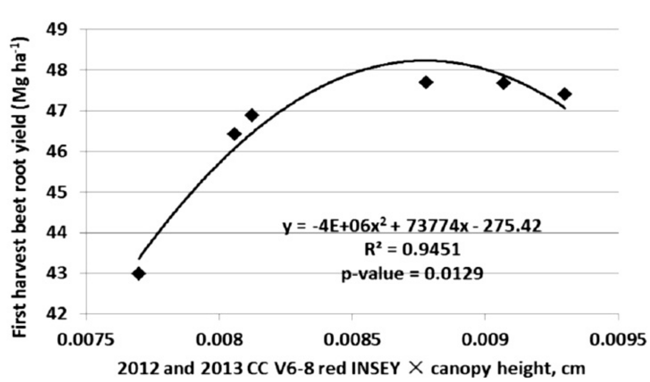

Fig. 3. Regression analysis relationship between the 2-yr, four site, combined Crop Circle (CC) red in season estimate of yield (INSEY) at V 6–8 multiplied times canopy height in centimeters, and first harvest sugar beet root yield.

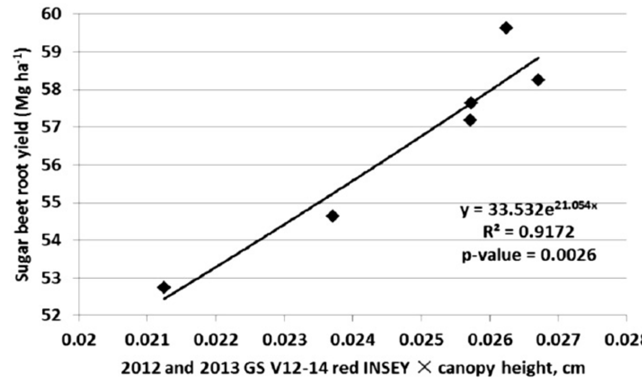

Fig. 4. Regression analysis relationship between 2 yr, four site, combined GreenSeeker (GS) red in season estimate of yield (INSEY) at V 12–14 multiplied times canopy height in centimers, and second harvest sugar beet root yield.

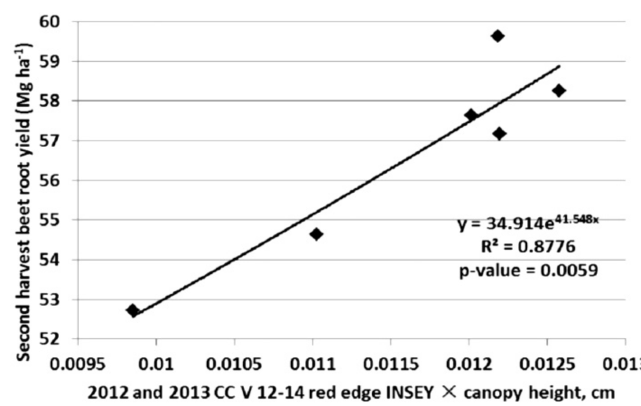

Fig. 5. Regression analysis relationship between 2 yr, four site, combined Crop Circle (CC) red edge in season estimate of yield (INSEY) at V 12–14 multiplied times canopy height in centimeters, and second harvest sugar beet root yield.

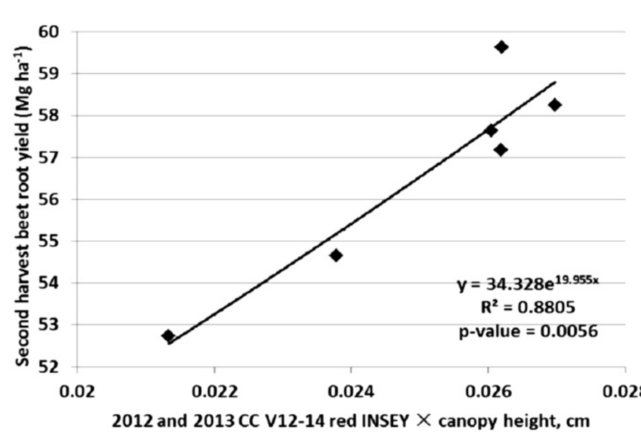

Fig. 6. Regression analysis relationship between 2 yr, four site, combined Crop Circle (CC) red in season estimate of yield (INSEY) at V 12–14 multiplied times canopy height in centimeters, and second harvest sugar beet root yield.

already predicted. Highly significant exponential and simple linear models with similar performance were found to be the best models for predicting sugar beet root yield using the V 12–14 INSEY, as demonstrated in Table 7. Including canopy height into the models did not improve model performance. GreenSeeker and CC performed similarly. At V 12–14, including height made little difference in yield prediction, so yield prediction was based most strongly on sensor reading only.

Highly significant exponential and linear models with high r^2 values were found in pooled data from 2012 and 2013, relating GS and CC V 12–14 readings with second harvest root yield (Table 8). The V 6–8 sensor readings did not significantly relate to second sugar beet yield with the 2-yr pooled data. With the V 12–14 s sensor readings, including plant height improved model performance of second harvest yield prediction of 2012 and 2013 combined data. Figures 4 to 6 illustrate the exponential models that include plant height. These highly significant relationships would help determine whether an in-season N application were needed when field sensor multiplied times canopy height readings were compared with those from an N non-limiting area within the same variety and soil within a field.

Relationship of Sensor Readings and Canopy Height to Recoverable Sugar Harvest Yields

The V 6–8 INSEY and V 12–14 INSEY were used to relate to the first harvest (15 August, both sites) recoverable sugar yield of Amenia and Crookston in 2012. Table 9 summarizes the r^2 values of the significant regression models. Except slightly improving the performance of the first sensing INSEY-involved regression models, the canopy height data decreased the performance of the best models. The failure of canopy height to increase the performance of the models was due to severe drought and the unusual tendency for the canopy to lie horizontal with the soil surface rather than the normal upright orientation, particularly at Amenia.

Two year, four-site data were pooled for regression analysis of recoverable sugar yield. A summary of the r^2 values of significant relationships between V 6–8 INSEY and the first harvest recoverable sugar yield is shown in Table 10. Sensor readings alone at V 6–8 were not significantly related to recoverable sugar yield. However, consideration of canopy height resulted in significant relationships with GS red INSEY, CC red INSEY, and CC red edge INSEY. For the V 12–14 INSEY, a quadratic polynomial model was found to be the best choice with the exception of the CC red INSEY, where either the linear or exponential model was highly significant. Including plant height improved model performance with the GS red INSEY and the CC red edge INSEY.

The r^2 values from regression analysis of the GS and CC red and red edge INSEY and the second harvest (28 August–16 September depending on the site) recoverable sugar yield (Table 10). The canopy height data at V 6–8 and V 12–14 tended to improve model performance. The exception was the CC red INSEY with canopy height and recoverable sugar yield relationship, which was nonsignificant. Figure 7 illustrates the linear relationship between CC V12–14 red INSEY and the second harvest recoverable sugar yield. This relationship indicates that comparison within variety within soil within a field of field sensor readings combined with canopy height readings in reference to sensor and canopy height readings from an N non-limiting area would result in recoverable sugar differences that could be related to N differences between the two locations.

DISCUSSION

The N rate treatments were necessary for these experiments for two reasons: first, N rates would contribute to understanding the relationship of N to sugar beet yield and quality, which is important in building a database to support active-optical sensor use to direct in-season N application in a similar manner as in corn (Franzen et al., 2014). Second, we expected N rate to increase sugar beet yield and recoverable sugar yield, which would be related to increased canopy reflectance. The response of sugar beet to N also helped to explain the relationship of active-optical sensor readings to yield.

Since sugar beet is harvested in North Dakota and Minnesota from mid-August through the end of October in some years, it is important to establish relationships between active-optical sensor readings and a series of yield dates. In addition, rainfall during a growing season can affect available N in the soil. The traditional in-season application timing for corn in the northern Plains of the United States is V 6–8 (Franzen, 2014); however, high rainfall after this time can result in leaching and denitrification losses, so the addition of the V 12–14 sensor use timing was considered appropriate for possible use in later season correction of serious environment-caused N deficiency. In 2012, the GS and CC V 6–8 sensor readings were related to first (15 August until 27 August) and second harvest (29 August until 17 September) sugar beet root yield. Including canopy height with INSEY increased the performance of the models. Including canopy height in yield prediction has improved the relationship between active-optical sensor readings in previous studies (Sui and Thomasson, 2006; Sharma and Franzen, 2014). In this study, manual measurement of canopy height was conducted; however, there are several automatic height instruments that might be investigated that would integrate into a variable-rate in-season N application algorithm (Sui and Thomasson, 2006). The V 12–14 sensor readings were related to first and second harvest sugar beet yield, but canopy height with only one exception reduced model performance, most likely due to the severe drought during 2012 that resulted in more horizontal leaf orientation instead of the normal upright leaf orientation. Amenia was most affected by the drought, but Crookston conditions closely followed, as there was little rain in each region until close to the last harvest date. Drought affects the growth of both sugar beet leaves and growth of roots, with varying effects on sugar yield depending on the stage of growth that drought effects the most (Choluj et al., 2004; Milford et al., 1985).The growing season of 2012 was characterized as a drought in most of the Midwest, with poor corn and soybean yields in most of the region. North Dakota was outside of the severe drought area, but dry conditions caused poor crop advancement after 1 August in our sugar beet research areas. The Amenia sugar beet root yield was only about 1500 kg ha^{-1} more at the second harvest compared to the yield at the first harvest (Table 3). This compares to the second harvest at Crookston, which was more than 3000 kg ha^{-1} greater than the first harvest date yield.

Regression analysis in 2013 of individual site V 6–8 and V 12–14 sensor readings with sugar beet root yields were not

Table 9. GreenSeeker (GS) and Crop Circle (CC) r^2 values of the regression relationships in sugar beet between V 6–8 and V 12–14 red normalized differential vegetative index (NDVI)-based in season estimate of yield (INSEY) and red edge NDVI-based INSEY and 2012 first and second harvest recoverable sugar yield at Amenia and Crookston combined.

Harvest, model	GS red INSEY	GS red INSEY × canopy height	CC red INSEY	CC red INSEY × canopy height	CC red edge INSEY	CC red edge INSEY × canopy height
First harvest				V 6–8		
Exponential	0.332*	0.419	0.425	0.490	0.489	0.495
Linear	0.350	0.422	0.432	0.482	0.492	0.483
Quadratic	ns†	0.485	0.483	0.574	0.535	0.599
				V 12–14		
Exponential	0.414	0.177	0.459	0.225	0.481	0.165
Linear	0.417	0.173	0.462	0.220	0.482	0.160
Second harvest				V 6–8		
Exponential	0.391	0.551	0.392	0.573	0.420	0.568
Linear	0.394	0.562	0.397	0.586	0.425	0.580
				V 12–14		
Exponential	0.682	0.404	0.685	0.442	0.657	0.330
Linear	0.679	0.392	0.684	0.431	0.651	0.317

* Significance at $P < 0.05$.

† The designation ns denotes non-significance.

Table 10. GreenSeeker (GS) and Crop Circle (CC) r^2 values, regression analysis of 2012 and 2013 sugar beet V 6–8 and V 12–14 sensing red normalized differential vegetative index (NDVI)-based in season estimate of yield (INSEY) and red edge NDVI-based INSEY and first and second harvest date recoverable sugar yield over four combined locations.

Harvest, model	GS red INSEY	GS red INSEY × canopy height	CC red INSEY	CC red INSEY × canopy height	CC red edge INSEY	CC red edge INSEY × canopy height
First harvest				V 6–8		
Exponential	ns†	0.422*	ns	0.414	ns	0.428
Linear	ns	0.438	ns	0.428	ns	0.440
First harvest				V 12–14		
Exponential	0.760	0.739	0.778	0.756	0.800	0.767
Linear	0.770	0.737	0.781	0.755	0.803	0.766
Quadratic	ns	0.907	ns	ns	0.943	0.961
Second harvest				V 6–8		
Exponential	ns	0.435	ns	ns	ns	0.421
Linear	ns	0.463	ns		ns	0.444
Second harvest				V 12–14		
Exponential	0.867	0.917	0.726	0.878	0.736	0.881
Linear	0.856	0.908	0.713	0.868	0.723	0.870

* Significance at $P < 0.05$.

† The designation ns denotes non-significance.

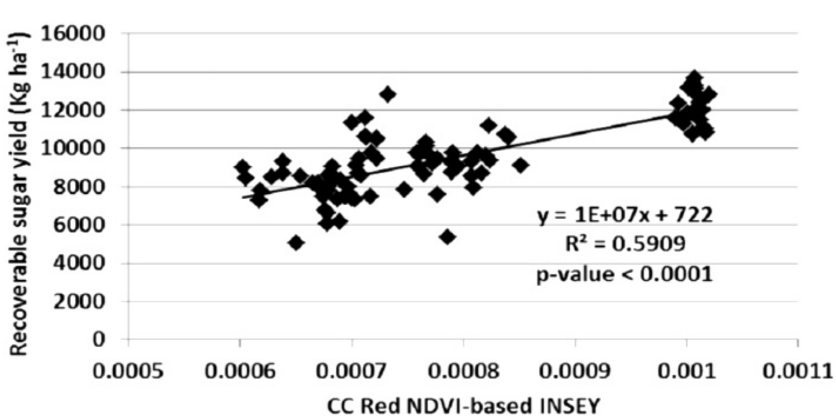

Fig. 7. Regression analysis relationship between 2 yr, four site, combined Crop Circle (CC) red in season estimate of yield (INSEY) at V 12–14 and second harvest recoverable sugar yield.

significant. However, the pooled 2012 and2013 data resulted in highly significant relationships of V 12–14 sensor readings with yield, with even greater relationships when canopy height was considered. There were significant root yield relationships with pooled 2012 and 2013 V 6–8 sensor data with canopy height included (Fig. 1–3). The regression models in Fig. 1–3 indicate that lower yields predicted at V 6–8 with lower sensor and canopy height readings may be improved through in-season N application; however, yield in these models maximizes at a higher sensor and canopy height reading. This is important because a limit to yield improvement would deter excessive N application that might contribute to lower sugar beet recoverable sugar yield at harvest. Regression analysis of recoverable sugar yield with sensor readings at the 2012 sites were significant at V6 and V12 at the first and second harvest dates. Performance of the regression models for recoverable sugar yield at V 6–8 and V 12–14 sensing was increased when canopy height was included. The recoverable sugar yield is important to Red River Valley sugar beet growers because growers are paid on a sugar cooperative formula that results in the recoverable sugar yield. Figures 4 to 6 indicate a continuum from lower yields to higher yields at V 12–14 with increasing sensor INSEY and canopy height. This means that an algorithm for in-season N application would indicate that yields increase with sensor INSEY at a later harvest date. However, this model only indicates the yield continuum, and not the recoverable sugar yield. Care should be taken not to overfertilize with lower sensor INSEY as lower sugar at harvest might result from over application of N. Any recommendations for in-season N application should include consideration of soil moisture and the possibility of higher yields with modest N applications. Rates of in-season N should be conservative, but if the difference in yield between lower field readings and the N non-limiting area are large, N application might be beneficial. Also, the relationships found in this study between pooled red INSEY and red edge INSEY and root yield and recoverable sugar yield (Tables 9 and 10, and Fig. 7) indicate that algorithms could be developed that consider the yield continuum of sugar beet root yield and sugar yield over time. An N non-limiting area within the field as a standard would provide a maximum yield prediction for the conditions in the field at time of sensing. Basing an N application on this in-field standard would serve to prevent over-application of N if root yield and recoverable sugar yield were limited by environmental conditions. Areas of the field ear-marked for earlier harvest would have lower yield expectations and lower N demand should differences in sensor readings indicate a need for in-season N. Fields or areas of a field that would be harvested a month later would benefit from a greater in-season N application should differences in sensor readings between field and the N non-limiting area be experienced. Sugar beet growers also tend to pre-determine which fields to harvest first based on the field history of wetness. Fields that tend to become wet with fall rains are generally harvested first, while fields with better harvest weather flexibility are left until last. The anticipated timing of sugar beet field harvest would also enter into any in-season N application algorithm.

CONCLUSIONS

Both the GS and CC active-optical sensors were useful in providing sensor data that was related to yields from a series of harvest dates. Sensor readings were most significantly related to yield within a site when root yield and recoverable sugar yield was related to N rate. Using the sensor at V 12–14 resulted in stronger relationships to root yield and recoverable sugar yield compared to readings at V 6–8. Consideration of canopy height was useful in increasing the performance of the sensor/yield models. Canopy height usefulness in increasing the relationships between sensor readings and yield is greatly reduced during drought when leaf canopy becomes horizontally positioned, instead of a maintaining a more upright orientation. Additional data are required within this region to confidently build an algorithm for directing in-season N rates, particularly at early sensing dates such as V 6–8. However, the results generated from these experiments support the pursuit of the use of active-optical sensors and canopy height measurements as tools to determine the need for in-season N and to help determine in-season N rates for greater recoverable sugar yield.

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