SUGARBEET YIELD AND QUALITY RESPONSE TO NITROGEN FERTILIZER RATE AND IN-SEASON PREDICTION OF YIELD AND QUALITY USING ACTIVE-OPTICAL SENSOR

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Sugarbeet Yield and Quality Response to Nitrogen Fertilizer Rates and In-Season Prediction of Yield and Quality Using Active-Optical Sensor

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Nitrogen (N) management is one of the important factors in sugarbeet production. Under-application of N-fertilizer results in lower root yield while over-application of N-fertilizer can result in decreased sugar concentration and recoverable sugar. In recent years active-optical sensors have been investigated for in-season prediction of sugarbeet yield and quality and to make N management decisions. This study was conducted at four sites in the Red River Valley to determine the sugarbeet yield and quality response to N fertilizer rates and to determine the relationship of NDVI with sugarbeet yield and quality. The yield response to N fertilizer rates was significantly quadratic, however, sugar concentration did not show response to N fertilizer rates. In-season NDVI readings were strongly related with root yield and sugar yield. Active sensing during the growing seasons shows promise as a means to predict sugarbeet root yield and sugar yield.

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INTRODUCTION

Nitrogen (N) management is a critical factor in sugarbeet production. Under-application of N fertilizer can result in reduced root yield while over-application can result in decreased sugar concentration and recoverable sucrose, increased production cost and contamination of ground and surface water (Tarkalson, 2011; Franzen, 2003; Lamb et al., 2001). Thus, fine tuning N management for sugarbeet is important for maximizing economic return for growers (Gehl and Boring, 2011). The variability in N- use- efficiency (NUE) by crops due to N loss pathways and soil moisture conditions, along with increasing public concern regarding environmental pollution by nitrate and nitrite oxide emissions as well as high fertilizer-N costs, make N fertilizer management a challenging task in sugarbeet production (Tsialtas and Maslaris, 2013). The current N recommendation of 146 kg ha^{-1} as a total of fertilizer and 0-120 cm depth available soil nitrate (NO_3 –N) for the Red River Valley has been published and utilized since 2001. (Lamb et al., 2001, Franzen, 2003). Since these N recommendations were adopted, sugarbeet yield in the Red River Valley has increased from an average of 43 Mg ha^{-1} to 66 Mg ha^{-1} in 2014 (USDA, ERS,2015). The sugarbeet yield increase may be due to the cultivation of genetically improved sugarbeet varieties, the use of glyphosate tolerant varieties and the resulting improvement in weed control that until lately was achieved by its use, improvement in overall production practices, and favorable growing seasons; however, the role of N cannot be ignored and requires further exploration.

Monitoring plant N status during the growing season is a possible option for improved sugarbeet N management. Timely and accurate detection of in-season crop N status may contribute to developing improved N management practices, thereby improving sugarbeet yield and quality (Anderson et al., 1988). Different plant and soil based indices such as the use of

SPAD chlorophyll readings, soil testing, petiole-N analysis, and remote sensing technologies including ground based active-optical sensors are being investigated as tools that might be used to predict in-season crop N status and to aid in making crop nutrient management decisions. There are different remote sensing systems including: satellite sensing, aerial sensing, and ground-based sensing. Satellite and aerial imaging sensors are passive, which means that the radiation received by the sensor comes from solar reflectance. The most promising ground based sensors use an active source of light, meaning that the instrument emits light sources and measures the light source reflection to the instrument, using some system to filter out all other ambient light (Gehl and Boring). Actively growing green plants strongly absorb radiation in the visible region of the spectrum while strongly reflecting radiation in the near infrared region (Sultana et al., 2014). The strong contrast of absorption and scattering of radiation of red and near-infrared bands can be combined into different quantitative indices of vegetation condition (Panda et al., 2010). These mathematical combinations of surface reflectance at two or more wavelengths designed to highlight a particular property of vegetation are known as vegetative indices (Bu, 2014). Different vegetation indices can be computed using reflectance data. Among different vegetation indices, Normalized Difference Vegetation Index (NDVI) is the proven measure of total aboveground green biomass (Bu. 2014). The red NDVI (Normalized Difference Vegetation Index) is a function of the difference in the reflectance characteristics of plant tissue in the red and NIR bandwidths and red edge NDVI is the function of reflectance characteristics of plant tissue in red edge and NIR bandwidths. The latest practice of using active sensor for in-season prediction of sugarbeet yield and quality can be a valuable tool in sugarbeet N management, harvest scheduling and prioritization (Gehl and Boring, 2011, Bu et al., 2015), which in turn can improve the economic returns to the growers.

The objectives of this study were i) to determine the effect of fertilizer-N rates on sugarbeet yield and quality in the Red River Valley, and ii) to determine the relationships between NDVI calculated using reflectance data from a hand-held active-optical sensor and sugarbeet yield and quality.

LITERATURE REVIEW

Sugarbeet production in the USA

The USA is one of the largest sugar producing countries in the world, and sugarbeet accounted for 55 percent of the total USA sugar production (Ali, 2004). Sugarbeet is grown in 12 states spreading across the Great Lakes, upper Midwest, the Great Plains and far west regions of the country. Major sugarbeet growing states include Minnesota, Idaho, North Dakota, Michigan, Montana, Nebraska, Ohio, Wyoming, Colorado, California, Oregon and Washington. Sugarbeet yields are highest in the far west region and are lowest in the upper Midwest region. In 2014 average beet yield in California was 100 Mg ha^{-1} while in Minnesota average yield was only 50 Mg ha^{-1} (USDA, ERS, 2015). In the United States, total sugarbeet production has increased from 23373 thousand Mg in 2011 to 28454 thousand Mg in 2015. During the same period area planted with sugarbeet decreased from 555 thousand hectares to 478 thousand hectares (USDA, ERS, 2015). This decrease in sugarbeet planting area might be due to the displacement of sugarbeet by cold tolerant corn. With decreasing planting area, producing sufficient beet to meet the growing sugar demand is a challenging task and demands a holistic improvement in sugarbeet production management from genetic improvements to nutrient management.

Sugarbeet nitrogen management

Root yield, extractable sucrose per ton and purity percentage are greatly affected by the N application rate (Lamb et al., 2013). Optimum fertilizer N management promotes vigorous early season plant growth, reducing the number of days to canopy closure, which allows the sugar beet to utilize the solar energy more efficiently to make sucrose (Lamb et al., 2001). Under-application of N fertilizer can result in reduced root yield while over-application can result in decreased sugar content and recoverable sucrose percentage, increased production cost and contamination of ground and surface water (Tarkalson, 2011; Franzen, 2003; Lamb et al., 2001). As the producers are paid based on recoverable sugar per ton basis, economic return depends on both yield and quality. Increasing fertilizer N may increase the yield but at the cost of increasing soluble non-sucrose constituents such as potassium (K), sodium (Na), and soluble N, which prevent sucrose from crystallizing and reduce processed sugar yield (Pollach et al., 1996). Thus, to optimize sugarbeet N fertilization, consideration should be taken to make only enough N for adequate top growth during the growing season and supply of N from the soil should be depleted a few weeks prior to harvest (Reitmeier, 2001).

Sugarbeets acquire N primarily from three sources: (i) residual soil nitrate (NO_3^-)-N, (ii) soil N mineralization from organic matter, and (iii) fertilizer –N (Lamb et al, 2010). Thus, in establishing fertilizer –N recommendations for sugarbeet, N supply from the other two sources needs to be considered. The original N recommendation of 134 kg ha^{-1} of soil plus fertilizer N was set as the standard in the Red River Valley to achieve a yield goal of 45 Mg ha^{-1} (Cattanach et al., 1992). The yield goal-based N recommendation has now been discontinued because over fields, yield and N rate are unrelated (Franzen, 2003; Lamb et al., 2001). Sugarbeet plant can effectively extract N from depths greater than 100 cm at late in the season (Anderson et al., 1972) and accounting for soil N in 0-120 cm can help improve the accuracy of sugarbeet N recommendation. Currently 146 kg ha^{-1} of fertilizer plus 0-120 cm soil available NO_3^--N is recommended for the Red River Valley (Lamb et al., 2001). If only 0-60 cm depth soil NO_3^- -N is considered then N recommendation is 112 kg ha^{-1} (Franzen, 2003). Malnou et al. (2006) reported that, in mineral soil, soil nitrate (NO_3^-) N assessment did not help improve the fertilizer recommendation for sugarbeet and that, in the absence of organic manure, 100 kg ha^{-1} fertilizer N produced the highest yield.

Effect of nitrogen on sugarbeet yield

Sugarbeet yield can vary from year to year due to weather and management practices but yields have tended to grow over time. A study of research data from 1980 to 2014 showed a steady increase in sugarbeet yield (Fig. 1.-a). In the USA, sugarbeet yields have increased from 42 Mg ha^{-1} in 1993 to 69 Mg ha^{-1} in 2015 (USDA, ERS, 2015).This steady increase in yield might be primarily due to the improvement in genetics and overall management (Tarkalson, 2011); however, improved N management has likely been another important contributing factor. Since 1980 sugarbeet yield response to N fertilizer addition has also increased (Fig. 1.-b). Tarkalson (2011) also concluded that N use efficiency (NUE) of sugarbeet has improved over time. The increased NUE has multiple advantages including: decreased N losses, less soil and ground water contamination and higher economic returns to the producers.

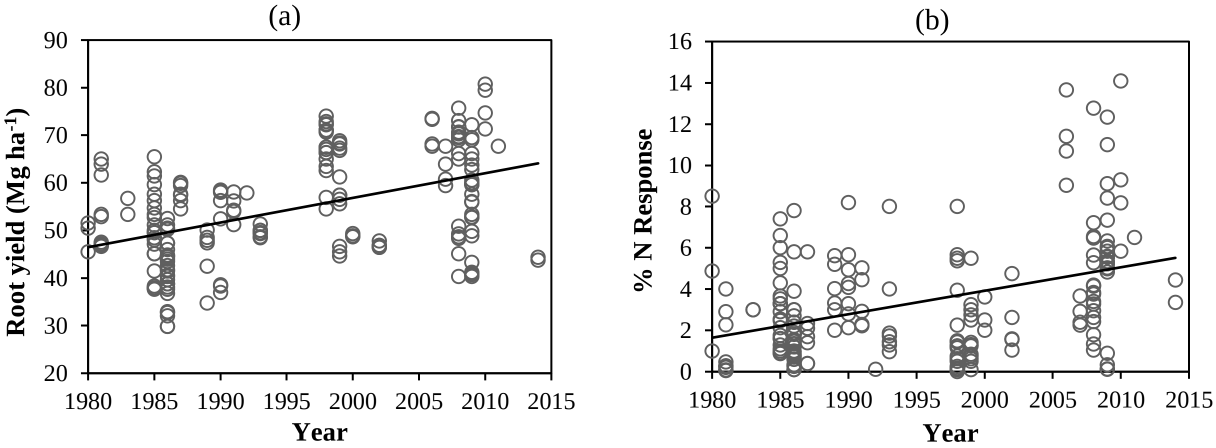

Figure 1. Sugarbeet root yield trends from 1980 to 2014 (a) and sugarbeet yield response to incremental N rate calculated using formula, Percent N Response = $\{(Y_N - Y_0)/N\}\times100$, where Y_N = yield in response to N addition, Y_0 = yield without N, and N = amount of fertilizer N added (b).

Nitrogen is one of the vital nutrients for sugarbeet growth and sugarbeet mostly acquires N in the nitrate (NO_3^-) form (Draycott, 2006). Biomass produced in the leaves is transported to and accumulated in the root. Root yield is therefore indirectly affected by fertilizer N rates. Supplemental fertilizer-N when soil-N is deficient produces rapid development of leaf canopy which intercepts more light leading to more photosynthate production; however fertilizer does not directly affect the conversion of intercepted radiation to dry matter (Draycott, 2006). Light interception and dry matter production increases up to LAI of 3 to 4 (Sims, 2013). Optimum N is needed to promote early rapid canopy growth, but the entire season's N likely does not need to be present at this time (Carter and Traveller 1981).

Various researches have been conducted to establish the effects of N rates, N sources, N application timing and N application methods on sugarbeet yields (Franzen et al., 2013; Sims 2012; Carter and Traveller 1981; Lamb et al., 2012; Anderson and Peterson, 1988; Lamb and Morgan, 1993). Most of the past research concluded that sugarbeet root yield first increases and then stabilizes with incremental N rates (Draycott, 2006), showing a quadratic response function to N. Anderson and Peterson (1988) reported a quadratic response of sugarbeet root yield to incremental N rates and yield was maximized at 200 to 275 kg ha^{-1} N but the top growth showed a positive linear relationship with fertilizer N rates. Tsialtas and Maslaris (2013) also reported that sugarbeet yield showed a quadratic response to N rates and yield was predicted to become maximum with 252.5 kg N ha^{-1}. Sims (2008, 2009, and 2010) also reported a significant root yield response to N rates. The yield response was significantly quadratic in most of the sites and year and the yield maximizing N rates varied across sites and year. In 2010, 168 kg N ha^{-1} produced the highest yield, while in 2009 the yield maximizing N rates ranged between 134 to 168 kg ha^{-1}. The yield maximizing N rate for sugarbeet is declining over time, this may be due to the cultivation of genetically improved sugarbeet varieties and improvement in overall production practice (Tarkalson, 2011)

Effect of nitrogen on sugarbeet root quality

Sugarbeet roots are comprised of water, dry matter, total soluble solids, total insoluble solids, sugar, non-sugar soluble solids, soluble nitrogenous organic compounds, soluble non-nitrogenous organic compound and soluble mineral matter (Draycott and Christenson, 2003). Relative concentrations and balance of these constituents in the root determine the sugarbeet quality. Sugarbeet quality is expressed in terms of various indicators like sugar content, purity, sugar loss to molasses (SLM), recoverable sugar (RS). Sugarbeet quality is affected by various factors including growing condition, weather situation at harvest, fertilizer, variety, and harvest time (Draycott, 2006). Effect of N fertilizer on sugarbeet quality have been one of the prime concerns in sugarbeet production management and number of researches were conducted in the past to study the effects of N on sugarbeet quality (Anderson and Peterson, 1988; Halverson and Hartman, 1975; Halverson and Hartman, 1980; Moraghan, 1987; Lamb et all, 2011; Franzen et al., 2013). Most of the past research studies have concluded that both sugar concentration and recoverable sugar tends to decreases with increasing N rates. Most of the reduction in sugar concentration with incremental N rates can be accounted for increased water retention by taproot leading to decreased dry matter percentage of the root (Darycott, 2006). The negative effect N fertilizer on recoverable sugar is also due to increased concentration of soluble nitrogenous compounds in roots which hinder the extractability of sugar from sugarbeet roots (Draycott and Christenson, 2003). Sugarbeet-SLM – function of sodium (Na), Potassium (K) and α-amino-N (α-AM-N) concentration in the root –is also affected by N fertilizer rates. Increasing N rates leads to higher α-amino-N (α-AM-N) concentration in sugarbeet roots (Draycott, 2006) which in turn increases the sugar loss to molasses (SLM). Unlike sugar content, α-amino-N (α-AM-N) is affected by N fertilizer even at lower rates (Draycott, 2006).

The amount of N present in the sugarbeet root steadily increases from emergence to harvest (Draycott, 2006) and sugarbeet plants accumulate from 202 to 247 kg ha^{-1} N under non limiting growing condition. Accumulation of N beyond this level has adverse effect on sugarbeet root quality (Armstrong and Milford, 1985). To achieve high quality sugarbeet, the supply of N from soil should be exhausted a few weeks prior to harvest. The necessary period of deficiency is usually 4 to 8 weeks before harvest (Hills et al., 1982), but may be less with thicker stands and smaller roots (Loomis and Ulrich, 1962). Excessive N supply after mid-season increases impurities and moisture content of the root (Carter, 1986), thus lowering extractable sugar and sugar content (Carter and Traveller, 1981). Halverson and Hartman (1975) reported that, in comparison to control, sugar concentration decreased significantly when N rates exceeded 112 kg ha^{-1}. Also, soil N levels of more than 252 kg ha^{-1} in June resulted in sharp decrease in sugar concentration. Halverson and Hartman (1980) reaffirmed their previous findings and reported a negative linear response of sugar concentration to incremental fertilizer N rates. Anderson and Peterson (1988) reported a similar effect of N rates on sugarbeet quality. They further concluded that larger top weights are not needed for efficient sucrose production; once the top growth is adequate to intercept the incident light, further production of top growth caused by higher N is inefficient in terms of obtaining optimum sugar yield. Tsialtas and Maslaris (2013) also reported a declining trend of sugar concentration with increasing N rates, though the reduction in sugar concentration was not significant. Lamb et al. (2011) found a declining trend of both sugar concentration and extractable sucrose with incremental N rates and split application and different N sources (ESN and Urea) also did not have significant effect on sugar content and extractable sugar. Later, Franzen et al. (2013) concluded that splitting N fertilizer in two dose –half pre-plant and half side dress, did not help improve the sugar concentration in comparison to all pre-plant application, but applying all fertilizer-N as side dress resulted in significant reduction in recoverable sugar. Lamb and Morgan (1993) reported that foliar application of N during the growing season did not help improve sugarbeet yield and recoverable sugar was reduced with foliar application.

Ground based sensor and vegetation indices

In recent years, remote sensing has been widely applied to various agricultural research and practices, including in-season N management and in-season prediction of crop yield and quality (Weiser et al., 2002; Hoffman and Blomber, 2004; Taal et al., 2006; Franzen et all, 2010; Panda et al., 2010; Gehl and Boring, 2011; Hongbo and Niwa, 2012; Huang et al., 2013; Sultana et al., 2014; Kouadio et al., 2014; Bu et al., 2015; Thompson et al., 2015). There are different remote sensing systems including: space sensing, aerial sensing, and ground-based sensing. Most of the ground based sensor measure the absolute reflectance using polychromatic light source and three photodetector measurement channels at 670, 730 and 780 nm (Gehl and Boring). Active sensors utilize their own energy source to emit electromagnetic radiation of specific wavelength and the radiation reflected off the crop is measured by the photodiode located at the front of the sensor head (Sultana et al., 2014). Thus the active sensors can be used both in the day and night and are not affected by clouds.

Actively growing green plants strongly absorb radiation in the visible region of the spectrum while strongly reflecting radiation in the near infrared region (Sultana et al., 2014). The strong contrast of absorption and scattering of radiation of red and near-infrared bands can be combined into different quantitative indices of vegetation condition (Panda et al., 2010). These mathematical combinations of surface reflectance at two or more wavelengths designed to highlight a particular property of vegetation are known as vegetative indices (Bu, 2014).

Different vegetation indices that can be computed using reflectance data include: Normalized difference vegetation index (Red NDVI), Normalized difference vegetation index – Red Edge (Red edge NDVI), Simple Ration (SR), Enhanced Vegetation Index (EVI), Green Atmospherically Resistant Vegetation Index (GARI), Wide Dynamic Range Vegetation Index (WDRVI), Chlorophyll Index (CI) etc. These indices can be used in prediction of leaf area index (LAI), photosynthesizing ability, primary production, total dry matter (TDM), and crop yield (Sultana et al. 2014). Among different vegetation indices, red NDVI and red edge NDVI are proven measure of total aboveground green biomass (Bu. 2014). Red NDVI is a function of the difference in the reflectance characteristics of plant tissue in the red and near-infrared bandwidths and red edge NDVI is the function of reflectance characteristics of plant tissue in red edge and near-infrared bandwidths. NDVI are calculated using the formula,

Red NDVI = (NIR – Red)/(NIR + Red)

Red edge NDVI = (NIR – Red Edge)/(NIR + Red edge)

Where, NIR = near-infrared reflectance, Red = red reflectance,

Red edge = red edge reflectance.

In-season yield and quality prediction using crop sensor

Remote sensing has been widely investigated recently as a tool to monitor crop condition and help make in-season estimates of crop yield and quality (Hoffman and Blomber, 2004; Franzen et al., 2010; Panda et al., 2010; Gehl and Boring, 2011; Hongbo and Niwa, 2012; Huang et al., 2013; Sultana et al., 2014; Kouadio et al., 2014; Bu et al., 2015). The use of NDVI in in-season prediction of sugarbeet yield and quality has a potential to be a valuable tool in sugarbeet N management, field harvest scheduling and prioritization (Gehl and Boring, 2011), which in turn can improve the economic returns to the growers and sugarbeet processors. Hongbo and

Niwa (2012) studied on the relationship of NDVI, sugarbeet crop height, SPAD and root yield. They found a strong relationship between (SPAD × plant height) measured in July and root yield. The (SPAD × plant height) was in turn related with NDVI with r^2 value of 0.6. This way, they concluded that, NDVI can be used as early as three months before harvest to make root yield estimation. Weiser et al. (2002) also reported a significant relationship between sensor reading collected after 14 weeks of planting and root yield, with r^2 value ranging between 0.63 to 0.65 and the strength of relationship was weaker for earlier season sensor data. Gehl and Boring (2011) also reported a significant relationship between NDVI measured at different growing degree day (GDD) and recoverable sugar per area basis(RWSA), which is function of yield and sugar content (r^2 ranging from 0.71 to 0.89). They found that the strength of relationship tended to be weakest for early season sampling, then increased during midseason sampling and again declined at late season. This may be due to sugarbeet leaf area index (LAI) reach maximum at around 16-18 weeks after planting (Weiser et al., 2002). Root yield is determined by growth status of the beet tops in July. Sugarbeet with larger amount of leaf and stem in July produce higher root yield (Hongbo and Niwa, 2012). Hoffman and Blomberg (2004) also found a significant relationship between sugarbeet yield and NDVI ($r^2 = 0.47$) using satellite imagery. Bu et al. (2015) reported on the use of NDVI combining with growing degree day (GDD) and crop height for in-season yield prediction of sugarbeet harvested at different growing degree day (GDD). They found strong relationship between in-season estimate of yield (INSEY), calculated by dividing NDVI by GDD and then multiplying by canopy height, and root yield at different harvest dates. The strength of relationship as indicated by r^2 value was stronger at V 6-V 8 than V 12-V 14 stages. They also found that the sensor readings were most significantly related to yield in sites where root yield and recoverable sugar yield were related to N rates.

MATERIALS AND METHODS

Site description and experimental design

Field experiments were established at four on-farm sites in the Red River Valley of North Dakota and Minnesota near Crookston, MN, Ada, MN, Hickson, ND and Sabin, MN, during 2015 growing season. Site descriptions including soil type, selected pre-plant soil chemical and physical properties, previous crop, and planting and harvest dates are presented in Table 1.

Table 1. Site description including soil type, selected pre-plant soil chemical properties, previous crop, and planting and harvest dates.

Characteristic	Crookston, MN	Ada, MN	Hickson, ND	Sabin, MN
Texture	Silty Clay Loam	Loam	Silty Clay	Sandy Loam
Soil Series†	Wheatville	Glyndon	Fargo	Wyndmere
Initial Soil N (0-60 cm) kg ha^{-1}	17.9	52.6	59.3	52.6
Olsen P (ppm)	6.0	22	13	10
Extractable K_2O (ppm)	215	100	445	113
pH (1:1)	7.9	8.2	7.5	8.2
EC (ds m^{-1})	0.41	0.30	0.61	0.62
Previous Crop	Wheat	Wheat	Sugarbeet	Soybean
Planting date	April 30	April 27	May 3	April 23
Harvest date	September 24	September 21	September 15	September 21

†The taxonomic class of the soil series in the experimental sites are,

Wheatville: Coarse-silty over clayey, mixed over smectitic, superactive, frigid Aeric Calciaquolls

Glyndon: Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls

Fargo: Fine, smectitic, frigid Typic Epiaquerts

Wyndmere: Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls

At each experimental site, sugarbeet yield and quality responses were determined for five urea-N application rates, 0, 112, 146, 179 and 213 kg N ha^{-1}. Treatments were arranged in a randomized complete block design with four replications. Each experimental unit was 3.35 m wide and 9.14 m in length (at Crookston experimental site experimental unit length was 10.67 m) consisting of six rows with row spacing 0.56 m. For the 112 and 146 kg N ha^{-1} rates, the entire rate of urea N-fertilizer was applied pre plant in the form of urea on the same day of planting immediately before tillage. While for 179 and 213 Kg N ha^{-1} rates, a pre-plant urea of 146 kg N ha^{-1} was applied pre-plant as other pre-plant treatments, -and the remaining urea was top-dressed during the last week of May. The split of application was conducted because previous research has indicated sugarbeet germination injury when pre-plant N rates 112 Kgha^{-1} (Draycott, 2006). The sugarbeet cultivar 'Crystal 093' was planted with a John Deere Planter in the first week of May (Table 1). Roundup® herbicide was applied twice for weed control and Quadris® was applied at the 4-6 leaf stage and again three weeks later to help control Rhizoctonia root rot. Three fungicide, Inspire®, Topsin® and Headline® were applied for Cercospora leaf spot control. At Crookston, cultivar 'Crystal 981' was planted with a Monosem planter; Roundup® herbicide was applied three times and Stinger® once for weed control; Quadris® was applied on June 10 to supplement Rhizoctonia root rot control. Cercospora leafspot was controlled with two fungicide application: Supertin® + Topsin® and Headline®.

For yield determination, the center two rows of each experimental unit were mechanically harvested on during third week of September, discarding the sugarbeet root at each end of the harvest row due to alley effects. The tops of these roots were spray painted using fluorescent-red paint after the topping operation but before root harvest within the hour (Table 1). A sub sample of 15-20 roots were placed in a leather harvest bag and along with identifying tag sent to the American Crystal Sugar Quality Tare Lab, East Grand Forks, MN for quality analysis the same date as harvest. Sugar concentration, alpha-amino nitrogen (α-AM-N), sodium

(Na) and potassium (K) concentration were analyzed. Sugar loss to molasses (SLM) was calculated using modified Carruther's equation (Carruthers, 1961).

$\text{SLM} = 1.5 \times ((3.5\times \text{Na}) + (2.5 \times \text{K}) + (9.5 \times \text{AM-N}))/11000$

Recoverable sugar per area basis is calculated using the formula,

$\text{Recoverable Sugar (RS)} = (\text{Sugar\%} - \text{SLM\%}) \times 20 \times \text{Yield}$

Soil sampling and analyses

Initial soil samples were collected from each site before fertilizer application for analysis of basic soil physical and chemical properties. Standard methods were used to determine bulk density (Blake and Hartge, 1986), apparent cation exchange capacity by addition (Chapman, 1965), Olsen-P (Frank et al., 1998) and available K using dried soil (Warncke and Brown, 1998) were determined. The selected soil physical and chemical properties of experimental sites are presented in Table 1. In-season soil inorganic N concentrations to a 0-30 cm depth were determined on soil samples collected at a two week interval from planting to harvest. For soil ammonia (NH_4^+) and nitrate (NO_3^-) concentration determination, soil samples were kept frozen until analysis. A 6.5 gm field moist soil was extracted with 2 M KCl using Whatman no. 42 filter paper and analyzed for NH_4^+ and NO_3^- using a Timberline Ammonia Analyzer ® (Timberline Instruments, Boulder, CO, USA). Gravimetric soil moisture content was determined by oven drying a field moist subsample at 105 °C and gravimetric water content was used in calculating soil NH_4^+ and NO_3^- concentration on an oven dry soil basis.

Ground based active optical sensor and reflectance data collection

Canopy optical reflectance data were recorded twice during the growing season using a Holland Crop Circle ACS-470 Sensor™ (Holland Scientific Inc., Lincoln, Nebraska, USA) and again at harvest using a RapidSCAN CS-45 Handheld Crop Sensor (Holland Scientific Inc., Lincoln, Nebraska, USA). The sensors measure height independent absolute reflectance using polychromatic modulated light source and three photodetector measurement channels: 670 (red), 730 (red edge) and 780 nm (NIR). The center two rows of each experimental unit were individually scanned from 0.6 m above the crop canopy at each sampling event by walking along the middle two rows. The calculated red NDVI and red edge NDVI values were averaged per experimental unit.

Statistical analyses

Analyses of variances was performed using PROC GLM in SAS 9.4 (SAS Institute, 2010) to evaluate differences in active-optical sensor reading, soil inorganic N analysis and, yield and quality due to N treatments, soil inorganic N among fertilizer treatments and to evaluate the main effect of N on sugarbeet yield and sugar content. Correlation and regression analyses were performed in SAS enterprise 6.1(SAS Institute, 2010) to evaluate relationship of NDVI with sugarbeet root yield and sugar yield.

RESULTS AND DISCUSSION

Growing conditions

Growing season monthly precipitation totals and average temperature are presented for each experimental site in Table 2. The daily precipitation is presented at each experimental site is presented in Figure 2. Mean air temperatures were similar across the sites with monthly average temperature ranging from 7 ^{0}C in April to 22 ^{0}C in July. The Hickson site received the highest rainfall of 446 mm during the growing season, while the Sabin site received the lowest rainfall totals of 301 mm. Gravimetric soil moisture content in the 0-30 cm soil depth ranged from 0.15 to 0.24 g g^{-1} during the growing season. Soils were wettest in the months of May and June. The soil was relatively dry at planting at all experimental sites, While Crookston, Ada and Sabin soils again became dry late in the growing season. The Ada and Sabin sites received more than 100 mm less cumulative rainfall during the growing season compared to normal rainfall, while the Hickson site received 39.7 mm more cumulative rainfall than normal.

Table 2. Monthly total precipitation and average monthly temperature during growing season at each experimental sites taken from the nearest NDAWN weather station.

	Crookston, MN		Ada, MN		Hickson, ND		Sabin, MN	
Month	Precip. (mm)	Temp (^{0}C)	Precip. (mm)	Temp (^{0}C)	Precip. (mm)	Temp (^{0}C)	Precip. (mm)	Temp (^{0}C)
Apr	16.0	7.0	19.6	7.0	15.9	8.0	12.4	8.0
	(-14.5) †	(1)	(-16.2)	(1)	(-18.6)	(1)	(-27.9)	(1)
May	108	12	119	12	200	13	143	13
	(33.9)	(-1)	(36.4)	(-2)	(128.3)	(-1)	(62.3)	(-2)
Jun	67.8	18	99.6	18	63.8	20	57.7	19
	(-28.7)	(0)	(-14.2)	(0)	(-35.3)	(1)	(-47.2)	(0)
Jul	53.8	21	65.2	21	71.0	22	46.5	22
	(-22.4)	(0)	(-28.1)	(0)	(0.2)	(1)	(-35.0)	(0)
Aug	45.5	20	26.2	19	54.3	20	27.4	20
	(-38)	(0)	(-43.2)	(-1)	(-10.7)	(0)	(-40.4)	(-2)
Sep	4.57	17	12.4	17	41.0	18	13.7	18
	(-57.4)	(3)	(-54.6)	(3)	(-24.2)	(3)	(-61)	(3)
Total	296		342		446 (39.7)		301	
	(-117)		(-120)				(-149)	

†The values in the parenthesis indicate the deviation from normal.

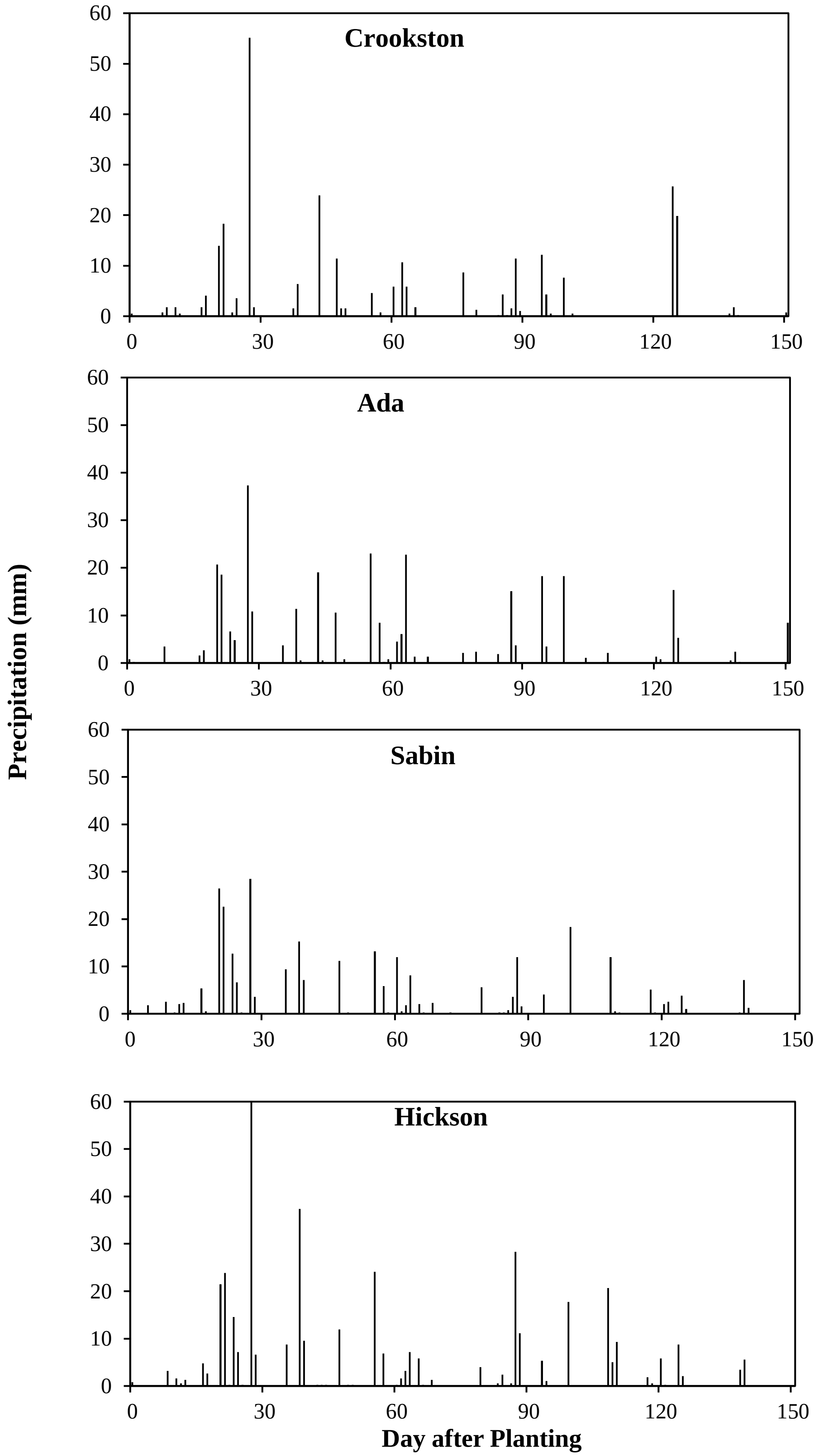

Figure 2. Daily precipitation at each experimental site.

Inorganic soil N during the growing season

Similar patterns for available soil inorganic N (NH_4^+ and NO_3^-) to a 0-30 cm soil depth were observed during growing season at the four experimental sites (Fig.1). Available soil N was high in May, then decreased in early June, and again became high toward late June. After July, soil inorganic N did not fluctuate much and levels remained similar until harvest. During the first month after planting (the late May sampling dates in Fig. 1), available soil-N was significantly higher in the experimental units compared to experimental units with control treatments at Crookston, Ada and Hickson. Inorganic soil N did not differ significantly among treatments receiving fertilizer N. Soil-N measured at mid-July and later did not differ significantly between any fertilizer N treatments.

At the first sampling at the end of May, the range of inorganic soil N was 30-78 kg ha^{-1} at Ada, 25-84 kg ha^{-1} at Crookston, 20-67 kg ha^{-1} at Hickson and 13-15 kg ha^{-1} at Sabin. In all experimental sites, except Sabin, inorganic soil N in N fertilizer applied experimental units was significantly higher than that in experimental units with control treatment. At the second sampling date of mid-June, inorganic N was found to be lower than that in late May; and ranged from 4-12 kg hac^{-1} at Crookston, 4-22 kg ha^{-1} at Ada, 4-22 kg ha^{-1} at Hickon and 2-10 kg ha^{-1} at Sabin. Inorganic soil N again increased at the sampling towards the end of June; and ranged from 17-99 kg ha^{-1} at Crookston, 23-81 kg ha^{-1} at Ada, 22-80 kg ha^{-1} at Hickson and 7-38 kg ha^{-1} at Sabin. Inorganic soil N in the experimental units with treatments ≥179 kg N ha^{-1} was significantly higher compared to other treatments. The high inorganic soil N towards the end of June might be due to N mineralization owing to increased temperature and higher precipitation. Inorganic soil N at harvest did not differ significantly with N treatment; and ranged from 9-11 kg ha^{-1} at Crookston, 16-20 kg ha^{-1} at Ada and 5-7 kg ha^{-1} at Sabin.

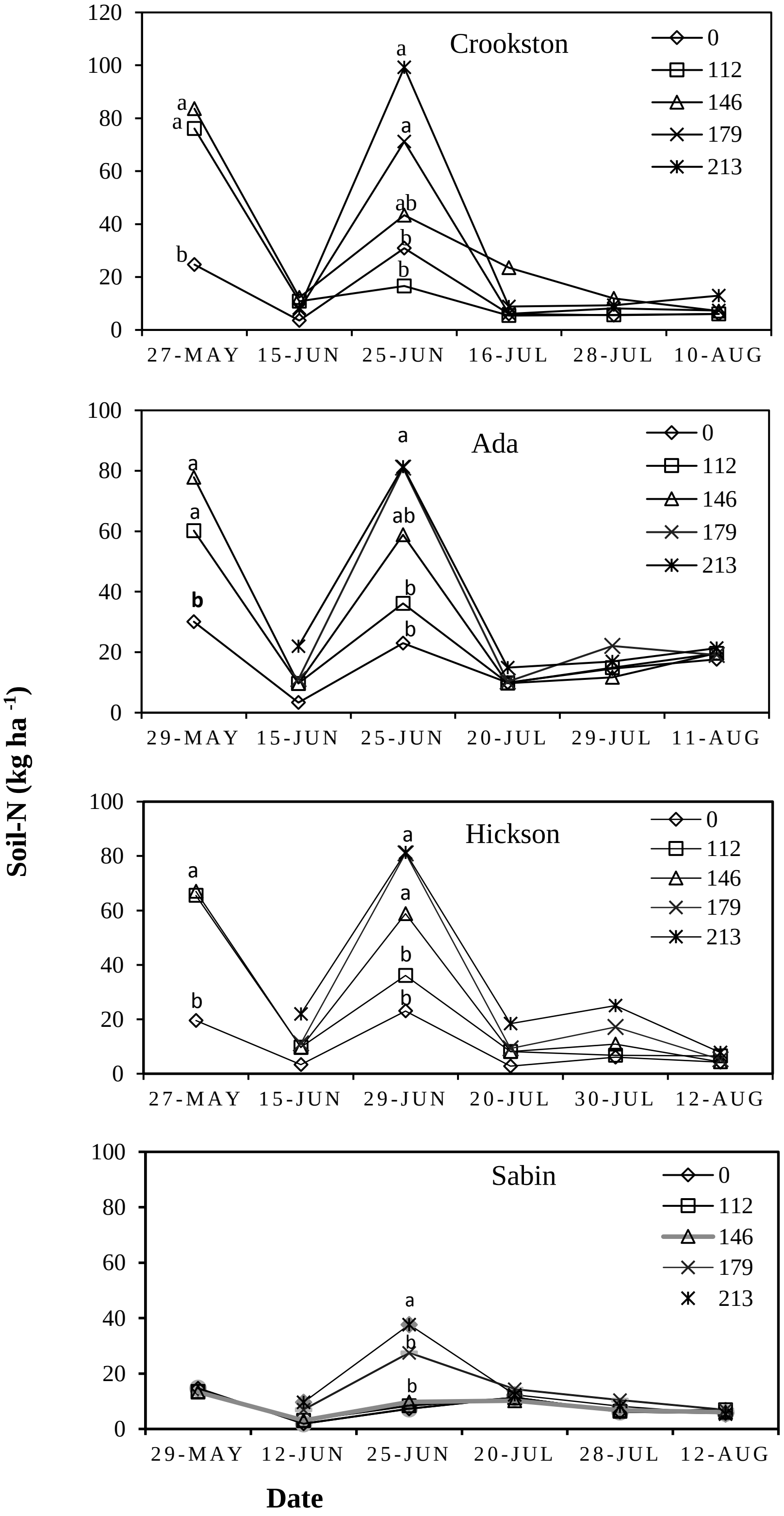

Figure 3. Soil inorganic N (NH_4^+ and NO_3^-) during the growing season.

Root yield

Sugarbeet root yield response to the N fertilizer treatments are presented in Table 3. Plot yield ranged from 43 Mg ha^{-1} to 97 Mg ha^{-1} across the four sites. Sugarbeet yield response to N fertilizer rates was not consistent across sites. Averaged across treatments, Ada site had produced highest yield of 86 Mg ha^{-1} while the Hickson site had produced lowest yield of 54 Mg ha^{-1}. At Crookston, yield ranged from 42 Mg ha^{-1} to 73 Mg ha^{-1}. The N fertilizer rate of 179 kg ha^{-1} produced highest average yield of 67 Mg ha^{-1} and further increasing N fertilizer to 213 Mg ha^{-1} decreased yield to 59 Mg ha^{-1}. N fertilizer rate of 179 kg ha^{-1} resulted in 6.7 Mg ha^{-1} higher yield than the current recommended N fertilizer rate of 146 kg ha^{-1}, but the difference was not statistically significant at 95% confidence level. At Ada, yield ranged from 69 Mg ha^{-1} to 98 Mg ha^{-1}. N fertilizer rate of 146 kg ha^{-1} produced highest yield of 89 Mg ha^{-1}. Further increasing N rate to 179 kg ha^{-1} and 213 kg ha^{-1} reduced yield to 87 Mg ha^{-1} and 88 Mg ha^{-1}, though the yield reduction was not statistically significant at 95% level of confidence. At Hickson, yield ranged from 47 Mg ha^{-1} to 61 Mg ha^{-1}. Fertilizer-N rate of 146 kg ha^{-1} produced highest average yield of 56 Mg ha^{-1}. Further increasing N rate to 179 kg ha^{-1} and 213 kg ha^{-1} reduced yield to 53 Mg ha^{-1} and 55 Mg ha^{-1}. At Sabin, yield ranged from 67 Mg ha^{-1} to 82 Mg ha^{-1}. N fertilizer rate of 213 kg ha^{-1} resulted in highest average yield of 80 Mg ha^{-1} though the yield were not significantly affected by fertilizer N rates.

At three of four experimental sites, the yield response to N fertilizer rates was significant, with a quadratic N response having a coefficient of determination (r^2) value ranging from 0.52 to 0.54 (Figure 2). Most of the increase in root yield at lower N rates might be due to rapid canopy development at early growing stage which might lead to higher photosynthate accumulation. Previous research indicates that an N rate of 103 ± 10 kgha^{-1} is sufficient to produce 85% of the sugarbeet canopy (Malnaou et al., 2006). The reduction in root yield at a higher N rate might be due to the production of top dry matter to the detriment of root dry matter (Draycott, 2006). Sugarbeet yield response to N fertilizer rate largely depends on its effect on canopy development (Malnou et al., 2006). Fertilizer-N response is not likely unless sugarbeet plants not treated with fertilizer are N deficient before the establishment of a complete leaf canopy (Moraghan, 1987), as complete canopy gives the maximum rate of photosynthate accumulation (Winter, 1998). Previous research findings on sugarbeet yield response to N fertilizer are contradicting. Anderson and Peterson (1988), Carter et al. (1974), Halverson and Hartman (1980) reported a significant increase in sugarbeet yield with increasing N rates. Sims (2010) found that root yield was significantly affected by N rates and was near maximum at N fertilizer rate of 135 to 168 kg ha^{-1}. In contrast to those findings, Rykbost and Dovel (2015) and Sims (2011) reported that incremental applied N rates had little effect on root yields; however, the method by which fertilizer was applied impacted the root yield. Bu et al. (2016) also found no significant yield response to incremental N fertilizer rates from 0- 168 kg ha^{-1} at two out of five sites in the Red River Valley. They found that in all the five sites yield response to fertilizer-N rates was non-significant at least for one harvest date when harvested at multiple dates between 3385 and 4609 GDD (Bu et al., 2016). The best explanation to resolve the apparent inconsistency of sugarbeet yield to N rate is that sugarbeet yield is maximized by the total of soil available N and fertilizer N. if soil available N is sufficient for maximum sugarbeet yield, additional N supply from fertilizer N will not drive sugarbeet yield any higher.

Table 3. Sugarbeet root yield means for N fertilizer rate treatments at four experimental sites.

Treatments Kg ha^{-1}	Root yield (Mg/ha) Crookston	 Ada	 Hickson	 Sabin
0	48.32 ± 5.23c†	76.82 ± 5.96 b	53.73 ± 1.79	69.90 ± 3.15
112	59.91± 5.04 ab	86.40 ± 5.46 a	52.90 ± 4.78	75.00 ± 6.47
146	60.41 ± 5.99 ab	89.42 ± 5.56 a	55.84 ± 3.59	78.26 ±2.83
179	67.16 ± 4.83 a	87.05 ± 1.71 a	53.36 ± 6.95	78.30 ± 2.91
213	58.90 ± 4.76 b	87.96 ± 2.13 a	55.30 ± 4.38	80.01 ± 1.14
LSD (α = 0.05)	7.84	6.49	NS†††	NS

†Different lower case letters within the same column indicate significant difference at P<0.05.

††NS, non-significant at P < 0.05.

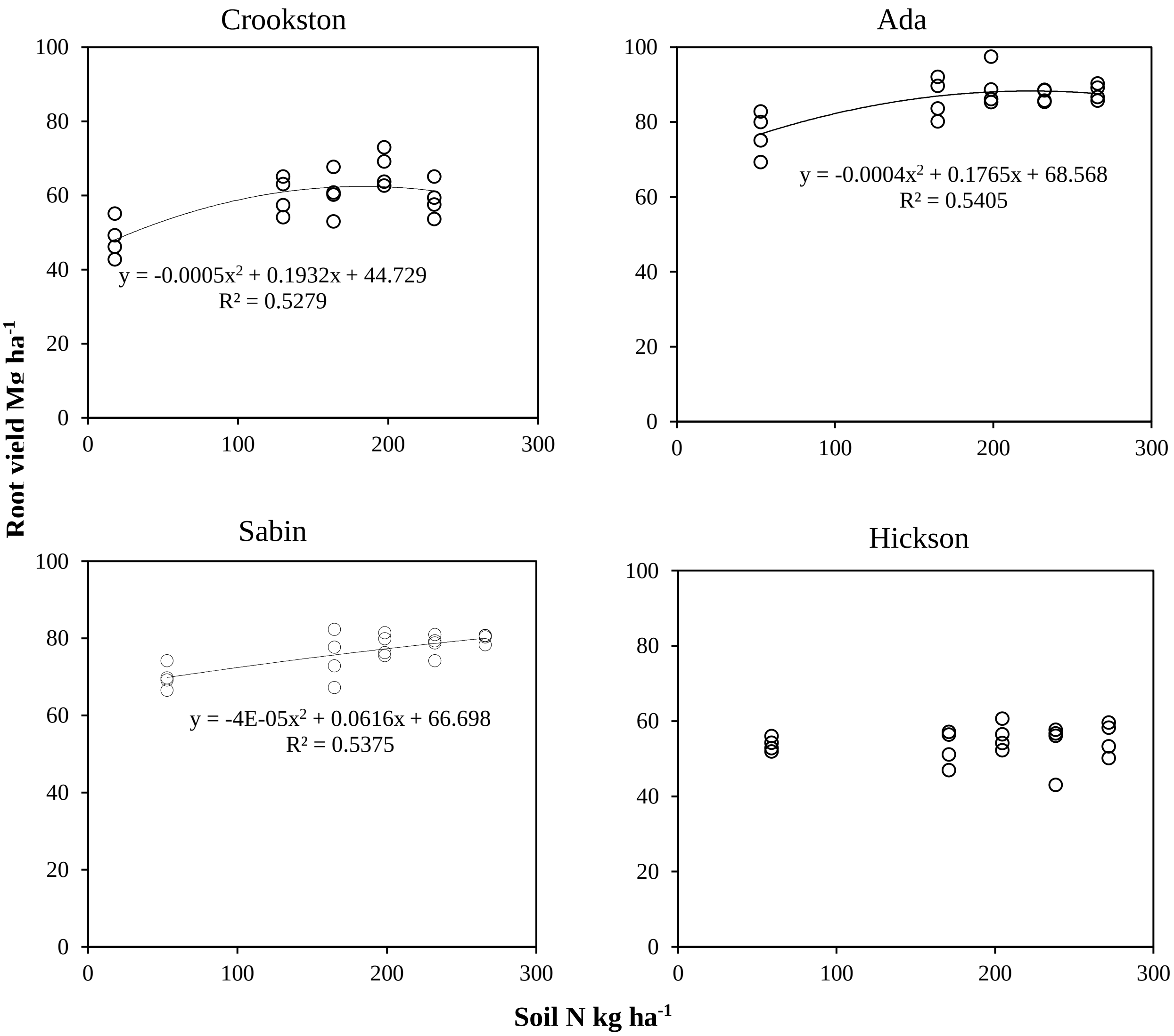

Figure 4. Sugarbeet root yield response to N fertilizer rates at four experimental sites.

Sugar concentration

None of the experimental sites showed a sugar concentration response to fertilizer-N application rates (Table 4). Across all sites, sugar concentration ranged from 148 g kg^{-1} to 186 g kg^{-1}. At Crookston, sugar concentration ranged from 164 g kg^{-1} to 183 g kg^{-1}. At Crookston, control treatment resulted in highest sugar concentration of 174.3 g kg^{-1} and N fertilizer rate of 179 kg ha^{-1} resulted in lowest sugar concentration of 169.0 g kg^{-1}. At Ada, sugar concentration ranged from 158 g kg^{-1} to 168 g kg^{-1}. N fertilizer rate of 146 Mg ha^{-1} resulted in highest average sugar content of 165 g kg^{-1} and further increasing N fertilizer to 179 kg ha^{-1} and 213 kg ha^{-1} reduced sugar content to 160.8 g kg^{-1} and 161.5 g kg^{-1} respectively. At Hickson, sugar content ranged from 148 g kg^{-1} to 180.9 g kg^{-1}. Control treatment resulted in highest average sugar content of 170 g kg^{-1} and N fertilizer rate of 179 kg ha^{-1} resulted in lowest sugar content of 159.8 g kg^{-1}. At Sabin, sugar content ranged from 168 g kg^{-1} to 186 g kg^{-1}. N fertilizer treatment of 213 kg ha^{-1} resulted in highest average sugar content of 176.5 g kg^{-1} and N fertilizer rate of 179 kg ha^{-1} resulted in lowest sugar content of 174.8 g kg^{-1}. At all sites, recoverable sugar per area basis (Mg ha^{-1}) did not show significant response to fertilizer N rates (Table 5).

Most of the previous studies on sugar content response to N fertilizer rates reported a decrease in sugar concentration with increasing N rates (Anderson and Peterson, 1988; Carter et al., 1975; Halverson and Hartman, 1980; Halverson and Hartman 1975). Most of the reduction in sugar concentration with increasing N rates can be accounted for increased water retention by the taproots (Draycott, 2006). Depending on root water content, soil type and growing conditions, response of sugar content to N rates may not be significant. Carter et al. (1974), Sims (2009) and, Tsialtas and Maslaris (2013) reported that despite a declining trend increasing N rate did not have a significant negative effect on sugar concentration.

Table 4. Sugar concentration (g kg $^{-1}$) means for N fertilizer rate treatments at four experimental sites.

N rate kg ha^{-1}	Sugar concentration (g kg $^{-1}$)			
	Crookston	Ada	Hickson	Sabin
0	174.3 ± 5.2†	163.3 ± 3.4	170.0 ± 6.4	174.8 ± 4.5
112	174.0 ± 2.9	164.3 ± 4.5	168.2 ± 8.7	175.5 ± 4.0
146	172.3 ± 7.3	165.0 ± 2.1	168.9 ± 1.9	176.0 ± 9.3
179	169.0 ± 2.7	160.8 ± 3.5	159.8 ± 8.7	174.8 ± 4.8
213	169.5 ± 4.4	161.5 ± 2.8	162.1 ± 11	176.5 ± 3.3
LSD ($\alpha = 0.05$)	NS††	NS	NS	NS

†± Standard deviation.

††NS represents non-significant at $P < 0.05$.

Table 5. Recoverable sugar (Mg ha^{-1}) means for N fertilizer rate treatments at four experimental sites.

N rate kg ha^{-1}	Recoverable Sugar (Mg ha^{-1})			
	Crookston	Ada	Hickson	Sabin
0	7.74 c†	11.78	8.38	11.52
112	9.48 ab	13.18	8.09	12.37
146	9.35 ab	13.58	8.53	12.91
179	10.2 a	12.74	7.51	12.84
213	8.90 b	12.97	8.03	13.21
LSD ($\alpha = 0.05$)	1.10	NS††	NS	NS

†Means followed by the same letter within a column are not different at $P < 0.05$.

††NS represents non-significant at $P < 0.05$.

Sugar loss to molasses (SLM)

At three of four experimental sites SLM significantly increased with increasing N fertilizer rate (Table 6). Across all the sites, SLM was the lowest for control treatment and was the highest for N rate of 213 kg ha^{-1} at Crookston, and for 179 kg ha^{-1} at Ada and Hickson. Sims (2010) also reported an increasing trend of sugar loss to molasses with increasing N fertilizer rates. The increased SLM with higher N rates might be primarily due to increasing α-amino-nitrogen (α-AM-N) concentration caused by increased N uptake by sugarbeet (Draycott, 2006).

Table 6. Sugar loss to molasses (SLM) means for N fertilizer rate treatments at four experimental sites.

N rate	Sugar Loss to Molasses (SLM%)			
kg ha^{-1}	Crookston	Ada	Hickson	Sabin
0	1.39 c†	1.00 c	1.38 c	0.98
112	1.55 bc	1.16 bc	1.47 c	1.06
146	1.70 ab	1.31 ab	1.60 bc	1.07
179	1.65 ab	1.43 a	1.86 a	1.08
213	1.81 a	1.40 a	1.74 ab	1.13
LSD (α = 0.05)	0.20	0.21	0.23	NS††

† Means followed by same letter within a column are not different at $P < 0.05$.
†† NS, non-significant at $P < 0.05$.

In-season normalized difference vegetation index (NDVI)

The red NDVI and red edge NDVI recorded at different dates are presented in Table 7. The red NDVI and red edge NDVI measurements were taken on July 2, July 10 and at harvest; Gehl and Boring (2011) reported that mid-season NDVI can best relate to yield compared to early and late season NDVI measurements. Because not all sites planted on same date and sugarbeet growth varied by planting date and site-specific growing conditions, the data collected were organized by GDDs. The NDVI data were divided into two ranges: 800-1000 GDD corresponding to July 2 sampling; 1000-1200 GDD corresponding to July 10 sampling. At both

800-1000 GDD and 1000-1200 GDD,   NDVI recorded in N fertilizer applied plots were significantly higher than in the control plots but among N fertilizer applied plots NDVI values were not significantly different. At Hickson, red NDVI measurements for treatments between 0 and 179 kg ha^{-1} were statistically similar and only significantly different was between control and 213 kg ha^{-1}. At Crookston and Ada, red NDVI recorded at 1000-1200 GDD on N treated plots were different from the control but not each other. Similarly, at Crookston red edge NDVI measurements recorded at 800-1000 GDD and 100-1200 GDD were statistically similar for all N rates >112kg ha^{-1}.

For all sites, red NDVI recorded at harvest was not significantly different for different N rate treatments. This is probably because red NDVI measurements 'saturate' when leaves cover the soil surface as they do later in the growing season for sugarbeets (Sharma et al., 2015). At Crookston, Ada and Hickson, red edge NDVI at harvest did not differ with N rate; however, at Sabin harvest red edge NDVI for treatments >146 kg ha^{-1} N were greater than that for 112 kg ha^{-1} and control treatments.

Gehl and Boring (2011) reported that in season red NDVI measurements taken between 650 and 1400 GDD were statistically similar for all the N rate treatments except control and red NDVI measurements collected between 1900 and 2300 GDD were similar for N rates of more than 90 kg ha^{-1}. This might be due to fertilizer-N rate of 103 ± 10 kg ha^{-1} being sufficient to produce 85% of the sugarbeet canopy (Malnaou et al., 2006). Saturation might be another cause for insignificant difference in red NDVI for N rates. When the leaf canopy entirely covers the inter row space, yield potential are masked as even the stunted, nutrient deficient crop can produce canopy enough to cover the inter row space late in season (Bu et al., 2016).

Table 7. Red NDVI readings of sugarbeet foliage by N fertilizer rate and growing degree day range and at harvest.

N rate	Crookston	Ada	Hickson	Sabin
kg ha^{-1}	Red NDVI			
	800-1000 GDD			
0	0.6357 b	0.6141 b	0.7150 b	0.6115 c
112	0.75385 a	0.7238 a	0.7455 ab	0.6816 b
146	0.7361 a	0.7498 a	0.7400 ab	0.7033 ab
179	0.7558 a	0.7458 a	0.7405 ab	0.7405 a
213	0.7589 a	0.7638 a	0.7763 a	0.7492 a
Prob. >F	0.0064	0.0004	0.0444	0.0010
	1000-1200 GDD			
0	0.6849 b	0.6822 b	0.7490 d	0.6835 c
112	0.8094 a	0.7883 a	0.7609 cd	0.7402 b
146	0.8064 a	0.8067 a	0.7895 bc	0.7408 b
179	0.8057 a	0.8143 a	0.7780 ab	0.7773 ab
213	0.7781 a	0.8221 a	0.7870 a	0.7890 a
Prob. >F	0.0046	0.0002	0.0137	0.0004
	Harvest			
0	0.8337	0.7183	0.7586	0.7933
112	0.8266	0.7264	0.7830	0.7987
146	0.8268	0.7293	0.7841	0.7967
179	0.8269	0.7229	0.7950	0.8026
213	0.8223	0.7285	0.8026	0.8063
Prob. >F	NS†	NS	NS	NS

†Means followed by the same letter within a column are not different at $P < 0.05$.

††NS, non-significant at $P < 0.05$.

Table 8. Red edge NDVI readings of sugarbeet foliage by N fertilizer rate and growing degree day range and at harvest.

N rate	Crookston	Ada	Hickson	Sabin
kg ha^{-1}	Red edge NDVI			
	800-1000 GDD			
0	0.2642 b†	0.2262 c	0.2735 c	0.2619
112	0.3210 a	0.2730 b	0.2994 ab	0.2743
146	0.3160 a	0.2863 ab	0.2973 ab	0.2672
179	0.3259 a	0.2882 ab	0.2916 bc	0.2730
213	0.3293 a	0.2991a	0.3187 a	0.2816
Prob. >F	0.0034	0.0003	0.0283	NS††
	1000-1200 GDD			
0	0.2228 b	0.2566 c	0.3088 c	0.2454 c
112	0.2680 ab	0.3086 b	0.3277 b	0.2732 ab
146	0.2724 ab	0.3190 ab	0.3315 b	0.2712 b
179	0.2908 a	0.3269 ab	0.3414 a	0.2886 ab
213	0.3160 a	0.3354 a	0.3464 a	0.2943 a
Prob. >F	0.0001	< 0.0001	< 0.0001	0.0004
	Harvest			
0	0.2831	0.2083	0.2357 c	0.2619
112	0.2784	0.2091	0.2581 b	0.2743
146	0.2841	0.2192	0.2651 ab	0.2672
179	0.2842	0.2170	0.2735 ab	0.2730
213	0.2849	0.2125	0.2806 a	0.2816
Prob. >F	NS	NS	0.0089	NS

†Means followed by the same letter within a column are not different at P < 0.05.

††NS, non-significant at P < 0.05.

In-season yield and quality prediction

The regression analysis of red NDVI and red edge NDVI with sugarbeet root yield and recoverable sugar yield are presented in Table 8. At three of four sites, the coefficients of determination (r^2) of the regression of red NDVI with sugarbeet root yield and that with recoverable sugar yield were significant. The coefficients of determination of the regression of the red edge NDVI with sugarbeet root yield and recoverable sugar were also significant at three sites. In contrast to previous finding (Gehl and Boring, 2011 and Bu et al., 2016), quadratic regression function is found to best fit the relationship of red NDVI and red edge NDVI with sugarbeet root yield and recoverable sugar yield.

At Crookston, the coefficients of determination (r^2) of the regression of red NDVI and red edge NDVI recorded at 800-1000 GDD and 1000-1200 GDD with root yield and recoverable sugar yield were significant with r^2 value ranging from 0.37 to 0.53 and 0.35 to 0.51 respectively. The strength of relationship of red NDVI and red edge NDVI with tonnage yield as well as recoverable sugar yield, as indicated by r^2 value, was strongest for red edge NDVI at 1000-1200 GDD. At Ada, the coefficients of determination (r^2) of the regression of red NDVI and red edge NDVI recorded during growing season with root yield and recoverable sugar yield were significant, and r^2 values ranged from 0.50 to 0.58 and 0.37 to 0.52 respectively. At Ada, red NDVI recorded at 1000-1200 GDD was most strongly related with both root yield and recoverable sugar with r^2 value of 0.62 and 0.52 respectively. At Sabin, red NDVI recorded at 800-1000 GDD and 1000-1200 GDD were significantly related with root yield and recoverable sugar. Also, red edge NDVI at both GDD range were significantly related to sugar yield, however, red edge NDVI recorded at 1000-1200 GDD was not significantly related with root yield. At Hickson, the coefficients of determination (r^2) of the regression of the NDVI with tonnage yield and sugar yield were not significant.

Across all sites, NDVI recorded at harvest were not related to root yield and recoverable sugar. Similar to previous finding (Bu et al., 2016), among all the sites, sensor reading were most significantly related to root yield and recoverable sugar in Ada, where relationship between N rate and yield were also strongest (Figure 1). When the regression analysis was done combining data from Crookston, Sabin and Ada sites, quadratic response functions are found to best fit the relationship of NDVI with tonnage yield and recoverable sugar. The regression model was found to be significant for all the sensing dates including the day of harvest with P values less than 0.01 (Table 9). The strength of relationship, as indicated by r^2 value, was found to be strongest with NDVI recorded at 800-1000 GDD, strength decreased at 1000-1200 GDD and again improved for NDVI at harvest. Gehl and Boring (2011) also reported that RWSA, which is the function of yield and sugar content, was strongly related to mid-season NDVI recorded in-between 1200 and 2300 GDD. In most of the sites and sensing dates, red edge NDVI showed a stronger relationship with root yield than red NDVI. This may be due to capability of red edge NDVI to provide measurement of chlorophyll content in contrast to red NDVI, which is essentially dependent on LAI (Bu et al., 2016).

Table 9. Regression coefficients (r^2) values of regression analysis of red NDVI and red edge NDVI measured at different GDD range and at harvest on sugarbeet root yield and recoverable sugar yield.

		Sugarbeet root yield		Recoverable sugar yield	
Sites		Red NDVI	Red edge NDVI	Red NDVI	Red edge NDVI
Crookston	800-1000 GDD	0.37	0.38	0.35	0.36
	1000-1200 GDD	0.49	0.53	0.47	0.51
	Harvest	NS†	NS	NS	NS
Ada	800-1000 GDD	0.50	0.51	0.37	0.37
	1000-1200 GDD	0.63	0.58	0.52	0.48
	Harvest	NS	NS	NS	NS
Hickson	800-1000 GDD	NS	NS	NS	NS
	1000-1200 GDD	NS	NS	NS	NS
	Harvest	NS	NS	NS	NS
Sabin	800-1000 GDD	0.60	0.43	0.55	0.47
	1000-1200 GDD	0.40	ns	0.58	0.46
	Harvest	NS	0.35	NS	NS

† NS, non-significant at $P < 0.05$.

Table 10. Regression coefficients (r^2) values of regression analysis of red NDVI and red edge NDVI with root yield and recoverable sugar yield combining data from Crookston, Ada and Sabin sites.

	Root yield		Recoverable sugar yield	
Date	Red NDVI	Red edge NDVI	Red NDVI	Red edge NDVI
800-1000 GDD	0.41*	0.36*	0.22*	0.40*
1000-1200 GDD	0.14*	0.20*	0.14*	0.22*
Harvest	0.20*	0.32*	0.33*	0.17*

* Significant at $P < 0.05$

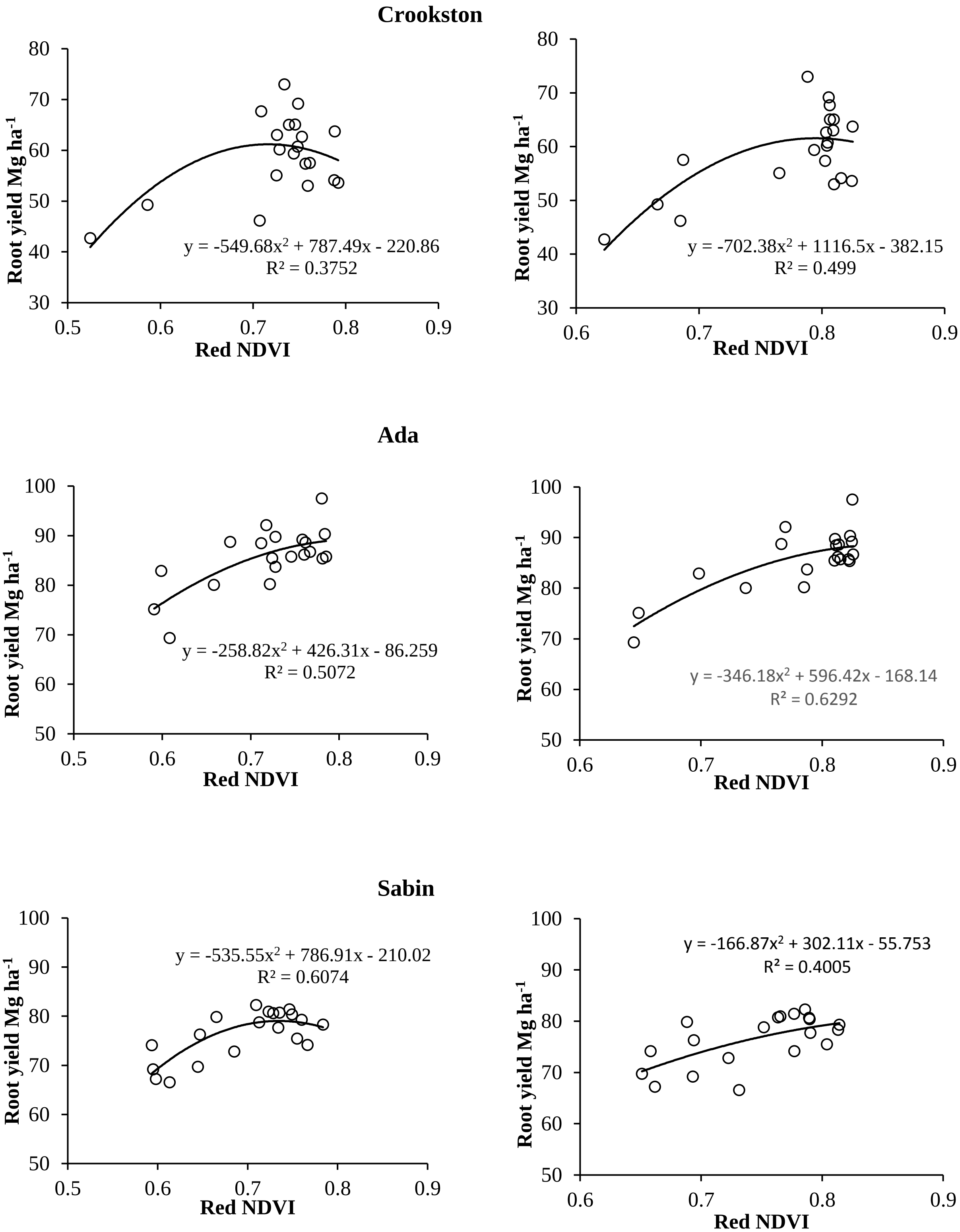

Figure 5. Regression analysis relationship between sugarbeet root yield and red NDVI measured at 800-1000 GDD (left) and 1000-1200 GDD (right) at Crookston, Ada and Sabin.

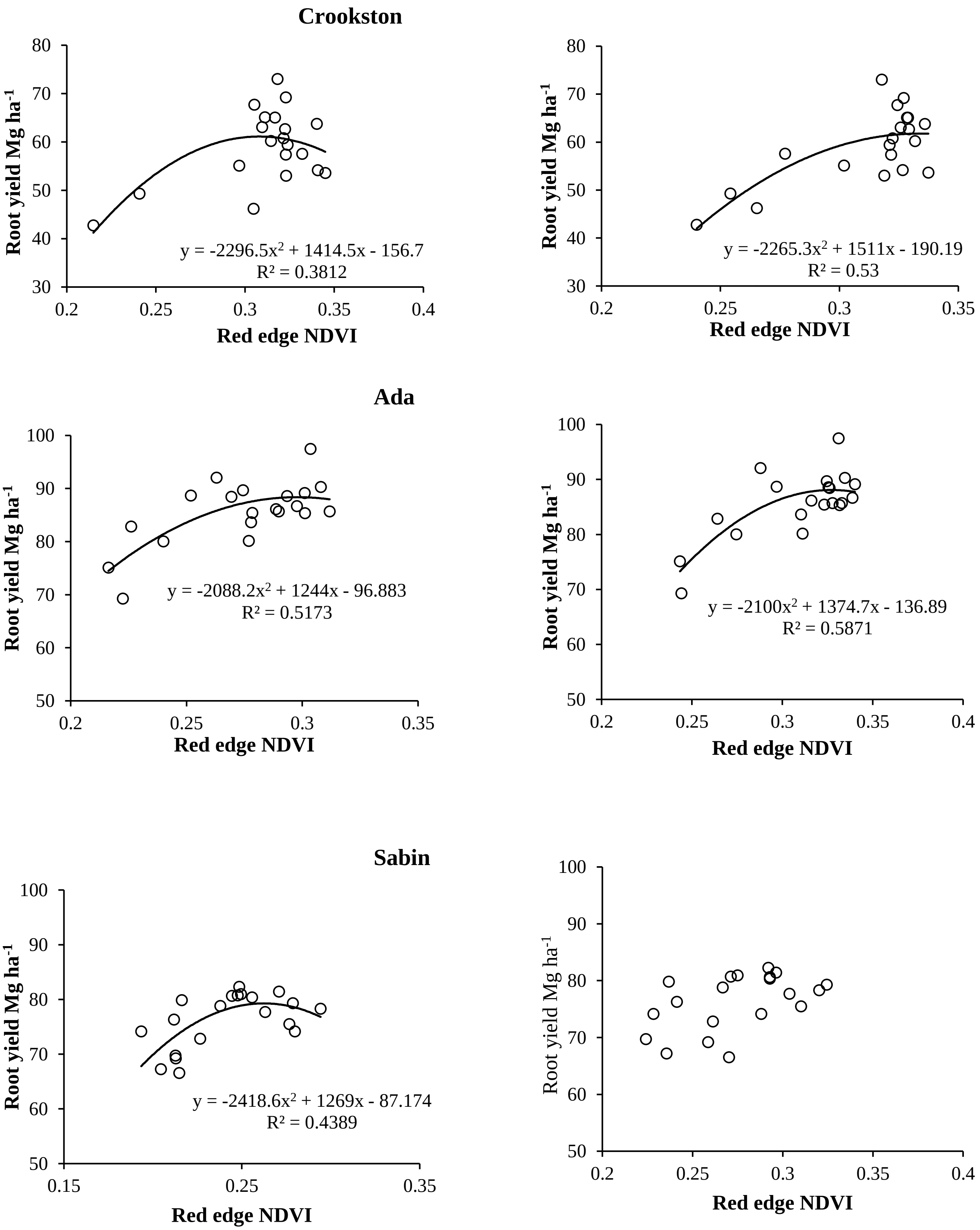

Figure 6. Regression analysis relationship between sugarbeet root yield and red edge NDVI measured at 800-1000 GDD (left) and 1000-1200 GDD (right) at Crookston, Ada and Sabin.

Correlation analysis between yield, sugar content, RWSA, SLM, soil-N, red NDVI and red edge NDVI

Pearson correlation coefficient of relationships among sugarbeet yield, sugar concentration, RWSA, soil-N, red NDVI and red edge NDVI recorded at different dates for different sites are presented in Table 10-14. At Crookston and Ada, sugarbeet yield is positively correlated with red NDVI and red edge NDVI recorded at 800-100 GDD. Also, at Ada, yield and soil N measured on June 25 were significantly correlated (r = 0.74). At Sabin, yield showed a significant positive correlation with soil-N measured during the growing season and the highest ‘r’ value was observed for soil-N measured on June 25. At Sabin, yield was significantly correlated with in-season red NDVI and red edge NDVI. At Hickson, sugar concentration was negatively correlated with soil-N measured on July 28 (r = -0.60) and also with red NDVI recorded at harvest (r = -0.51). At Hickson, sugar concentration showed a significant negative correlation with soil-N measured in July 28 (r = -0.60) and also with red NDVI recorded at harvest (r = 0.51). Analysis of data combined from all the sites, showed significant negative correlation between yield and NDVI recorded at harvest (r = -0.49). Combining data from all the sites, sugar concentration and soil-N measured at different dates during the growing season were negatively correlated.

This indicates that canopy biomass at early July is an important determinant of yield however canopy biomass at harvest could have negative effects to both yield and sugar concentration. Also, yield was correlated with soil N measured on June 25, indicating that this period is a critical period in sugarbeet N management for better yield.

At all experimental sites, SLM was positively correlated with in-season NDVI and soil N. Also, when the analysis was done combining data from all experimental sites, SLM showed significant positive correlation with soil-N and NDVI, with ‘r’ value 0.66 to 0.77 and 0.34 to 0.77. The strength of correlation of SLM was found strongest with soil-N measured on June 25 and red NDVI measured at 800-1000 GDD. This indicates that though sufficient soil-N is required during early July to develop and maintain sufficient canopy biomass to produce higher yield, it may result in increased sugar loss to molasses (SLM%); and higher soil-N in the late season can have more pronounce effect. This may be primarily due to increasing α-amino-nitrogen (α-AM-N) concentration caused by increased N uptake by sugarbeet (Draycott, 2006). Our findings indicate that mid-season red NDVI and red edge NDVI can be successfully used for yield and quality prediction.

Table 11. Pearson correlation coefficient (r) values of correlation analysis between yield, sugar content, RWSA, soil N, red NDVI and red edge NDVI measured at different dates at Crookston site.

	Yield	Sugar concentration	RWSA	SLM %	Soil N June 25	Soil N July 28
Sugar concentration	-0.4996*					
RWSA	0.96772*	-0.284				
SLM %	0.40577	-0.22217	0.29481			
Soil N June 25	0.23287	-0.42127	0.10234	0.47473*		
Soil N July 28	-0.04228	-0.10522	-0.12968	0.48988*	0.39003	
Red edge NDVI (800-1000 GDD)	0.57268*	-0.06806	0.54287*	0.86394*	0.32636	0.3946
Red edge NDVI (1000-1200 GDD)	0.08014	-0.05686	0.03185	0.36947	0.02294	0.45495*
Red NDVI (800-1000 GDD)	0.56847*	-0.02967	0.54875*	0.86125*	0.28291	0.38485
Red NDVI (1000-1200 GDD)	0.05532	-0.03661	0.01032	0.35622	0.01055	0.45544*

*Significant at P <0.05.

Table 12. Pearson correlation coefficient (r) values of correlation analysis between yield, sugar content, RWSA, soil N, red NDVI and red edge NDVI measured at different dates at Ada site.

	Yield	Sugar Concentration	RWSA	SLM %	Soil N June 25	Soil N July 28
Sugar concentration	-0.00378					
RWSA	0.91835*	0.35996				
SLM %	0.40564	-0.33502	0.11969			
Soil N June 25	0.74332*	0.1265	0.67082*	0.55996*		
Soil N July 28	0.07412	0.26953	0.15522	0.00859	0.20053	
Red edge NDVI (800-1000 GDD)	0.69118*	0.02109	0.57598*	0.65254*	0.75713*	0.22675
Red edge NDVI (1000-1200 GDD)	0.74566*	0.04156	0.63389*	0.65638*	0.81834*	0.13943
Red NDVI (800-1000 GDD)	0.71025*	0.01879	0.59985*	0.61962*	0.73659*	0.16593
Red NDVI (1000-1200 GDD)	0.79983*	0.07114	0.70245*	0.61706*	0.83098*	0.12788

*Significant at P <0.05.

Table 13. Pearson correlation coefficient (r) values of correlation analysis between yield, sugar content, RWSA, soil N, red NDVI and red edge NDVI measured at different dates at Hickson site.

	Yield	Sugar Concentration	RWSA	SLM %	Soil N June 25	Soil N July 28
Sugar concentration	0.07508					
RWSA	0.76217*	0.69414*				
SLM %	0.25925	-0.6865*	-0.32236			
Soil N June 25	-0.13688	-0.41426	-0.41071	0.56426*		
Soil N July 28	0.03953	-0.6025*	-0.39561	0.67421*	0.54598*	
Red edge NDVI (800-1000 GDD)	0.09061	-0.4243	-0.22462	0.4211	0.61334*	0.68272*
Red edge NDVI (1000-1200 GDD)	-0.05897	-0.57394	-0.44251	0.64243*	0.6955*	0.7457*
Red NDVI (800-1000 GDD)	0.02105	-0.5465*	-0.33952	0.40542	0.51511*	0.70799*
Red NDVI (1000-1200 GDD)	-0.13911	-0.6588*	-0.53389	0.55556*	0.46572*	0.68217*

*Significant at P <0.05.

Table 14. Pearson correlation coefficient (r) values of correlation analysis between yield, sugar content, RWSA, soil N, red NDVI and red edge NDVI measured at different dates at Sabin site.

	Yield	Sugar concentration	RWSA	SLM %	Soil N June 25	Soil N July 28
Sugar concentration	-0.05698					
RWSA	0.8884*	0.40255				
SLM %	0.46792*	-0.25179	0.25482			
Soil N June 25	0.59335*	0.05207	0.54817*	0.47558*		
Soil N July 28	0.47826*	0.09335	0.48076*	0.16873	0.43729	
Red edge NDVI (800-1000 GDD)	0.56877*	0.29372	0.64246*	0.33443	0.55109*	0.47061*
Red edge NDVI (1000-1200 GDD)	0.49845*	0.48977*	0.67468*	0.15754	0.54309*	0.43784
Red NDVI (800-1000 GDD)	0.72426*	0.17352	0.7275*	0.46189*	0.60737*	0.49801*
Red NDVI (1000-1200 GDD)	0.62919*	0.42184	0.76341*	0.22944	0.60172*	0.53029*

*Significant at P <0.05.

Table 15. Pearson correlation coefficient (r) values of correlation analysis between yield, sugar content, RWSA, soil N, red NDVI and red edge NDVI measured at different dates combining data from all four experimental sites.

	Yield	Sugar Content	RWSA	SLM %	Soil N June 25	Soil N July 28
Sugar concentration	-0.09582					
RWSA	0.96444*	0.16181				
SLM %	-0.4977*	-0.3655*	-0.6366*			
Soil N June 25	-0.094	-0.4729*	-0.2446*	0.6084*		
Soil N July 28	0.22027*	-0.5355*	0.06819	0.21849	0.48843*	
Red edge NDVI (800-1000 GDD)	-0.2730*	-0.19509	-0.3663*	0.77587*	0.64116*	0.28509*
Red edge NDVI (1000-1200 GDD)	0.04343	-0.22418	-0.02919	0.21877	0.28913*	0.38416*
Red NDVI (800-1000 GDD)	0.03872	-0.16227	-0.04663	0.54607*	0.53668*	0.34082*
Red NDVI (1000-1200 GDD)	0.19266	-0.13974	0.14498	0.04147	0.13906	0.33806*

*Significant at P <0.05

CONCLUSIONS

Sugarbeet yield response to N-fertilizer rate varied across the experimental sites and in three of the four sites yield was affected by N rate. At the responsive sites, there was a quadratic yield response to N rate, with coefficients of determination of the yield and N rate relationships ranfing from 0.52-0.54. Sugar concentration did not decrease significantly with N fertilizer rates. Sugar loss to molasses (SLM) decreased with increasing N rates. The red NDVI and red edge NDVI readings recorded by the Holland Crop Circle active-optical sensor at 800-1000 GDD and 1000-1200 GDD were related to both root yield (r^2 ranging from 0.37 to 0.63) and recoverable sugar yield (r^2 ranging from 0.35 to 0.58). The red NDVI and red edge NDVI readings recorded at harvest using Holland RapidScan active-optical sensor were not significantly related to root yield and recoverable sugar except at Sabin site. These results indicate that active-optical sensors can be used to predict root yield and to determine whether in-season N application might be beneficial. Additional body of data would be required to develop algorithms for use in directing in-season N application to sugarbeet.

REFERENCES

Ali, M.B., 2004. Characteristics and production costs of U.S. sugarbeet farms. In 2004 Economic Research Service/USDA report.

Anderson, F.N. and G.A. Peterson. 1988. Effect of incrementing nitrogen application on sucrose yield of sugarbeet. Agron. J. 80:709-712.

Baver, L.D. 1964. Nitrogen effects on sugar crops. J. of A.S.S.B.T. 13:21-26.

Blake, G.R., and K.H. Hartge. 1986. Methods of soil analysis, part 1. ASA and SSSA, Madison, WI

Bu, H. 2014. Yield and quality prediction using satellite passive imagery and ground based active optical sensors in sugarbeet, spring wheat, corn and sunflower. M.S. thesis, North Dakota State Univ., Fargo.

Bu, H., L.K. Sharma, A. Denton, and D.w. Franzen. 2016. Sugarbeet root yield and quality prediction at multiple harvest dates using active-optical sensors. Agron. J. 108:273-284.

Carter, J.N. 1986. Potassium and sodium uptake by sugarbeets as affected by nitrogen fertilization rate, location, and year. J. of A.S.S.B.T. 23:121-141.

Carter, J.N. and D.J. Traveller. 1981. Effect of time and amount of nitrogen uptake on sugarbeet growth and yield. Agron. J. 73:665-671.

Carter, J.N., C.H. Pair, and D.T. Westerman. 1975. Effect of irrigation method and late season nitrate nitrogen concentration on sucrose production by sugarbeets. J. of the A.S.S.B.T. 18:332-342.

Carter, J.N., M.E. Jensen, and S.M. Bosma. 1974. Effect of row spacing and nitrogen rate on root and sucrose yield of sugarbeets in southern Idaho. J. of the A.S.S.B.T. 18:274-379.

Cattanach, A.C., W.C. Dhanke, and C. Fanning. 1992. Fertilizing Sugarbeet. North Dakota State University Extension Bulletin SF-714. North Dakota State Univ. Fargo, ND.

Chapman, H.D. 1965. Methods of soil analysis, part 2. ASA and SSSA, Madison, WI

Christenson, D.R., and M.B. Butt. 2000. Response of sugarbeet to applied nitrogen following field bean (Phaseolus vulgaris L.) and corn (Zea Mays L.). J. of Sugarbeet Research. 37:1-16.

Clevers, J.G.P.W. 1996. A simplified approach for prediction of sugarbeet based on optical remote sensing data. Remote Sens. Environ. 61:221-228.

Draycott, A.P. 2006. Sugarbeet. Blackwell Publishing Professionals. Ames, Iowa.

Draycott, A.P. and D.R. Christenson. 2003. Nutrients for sugarbeet production. CABI Publishing. Cambridge, MA.

Eckhoff, J.L. 1999. Sugarbeet response to nitrogen at four harvest dates. J. of Sugarbeet Research. 36:33-45.

Eckhoff, J.L. and C.R. Flynn. 2008. Sugarbeet response to nitrogen under sprinkler and furrow irrigation. J. of Sugarbeet Research. 45:19-29.

Frank, K., D. Beegle and J. Denning. 1997. Phosphorus. In Recommended Chemical Soil Test Procedures for the North Central Region. (Ed.) J.R. Brown. North Central Regional Research Publication No. 22 1 (revised) pp. 2 1-29.

Franzen, D. 2003. Fertilizing sugarbeet. NDSU Extension Services, North Dakota State University Extension Bulletin SF-714 (Revised). North Dakota State Univ. Fargo, ND.

Gehl, R.J. and T.J. Boring. 2011. In-season prediction of sugarbeet yield, quality and nitrogen status using an active sensor. Agron. J. 103:1012-1018.

Halverson, A.D., G.P. Hartman, D.F. Cole, V.A. Haby, and D.E. Baldridge. 1978. Effect of N fertilization on sugarbeet crown tissue production and processing quality. Agron. J. 70:876-880.

Halvorson, A.D. and G.P. Hartman. 1975. Long term nitrogen rates and sources influence sugarbeet yield and quality. Agron. J. 67:389-393.

Halvorson, A.D. and G.P. Hartman. 1980. Response of several sugarbeet cultivars to N fertilization: Yield and crown tissue production. Agron. J. 72:665-669.

Hills, F.J. and A. Ulrich. 1976. Soil nitrate and the response of sugarbeets to fertilizer nitrogen. J. of the A.S.S.B.T. 19:118-124.

Hills, F.J., G.V. Ferry, A. Ulrich, and R.S. Loomis. 1962. Marginal nitrogen deficiency of sugarbeets and the problem of diagnosis. J. of the A.S.S.B.T. 12:477-484.

Hoffmann, C.M. and M. Blomberg. 2004. Estimation of leaf area index of Beta Vulgaris L. based on optical remote sensing data. J. of Agron. And Crop Sci. 190:197-204.

Hongbo, C. and N. Katsuhisa. 2012. Yield prediction of sugarbeet through combined use of satellite data and meteorological data. J. of Agri. Sci. 4:251-261.

Huang, J., X. wang, X. Li, H. Tian, and Z. Pan. 2013. Remotely sensed rice yield prediction using multi-temporal NDVI data derived from NOAA's-AVHRR. PLoS ONE 8(8): e70816. doi:10.1371

Kelley, J.D. and A. Ulrich. 1965. Distribution of nitrate nitrogen in the blades and petioles of sugarbeet hrown at deficient and sufficient levels of nitrogen. J. of the A.S.S.B.T. 14:106-116.

Kouadio, L., N.K. Newlands, A. Davidson, and A.C. Chipanshi. 2014. Assessing the performance of MODIS NDVI and EVI for seasonal crop yield forecasting at the ecodistrict scale. Remote Sens. 6:10193-10214. doi:10.3390/rs61010193.

Lamb, J.A., A.L. Sims, L.J. Smith, and G.W. Rehm. 2001. Fertilizing sugarbeet in Minnesota and North Dakota. University of Minnesota Agriculture Extension. Available at http://www.extension.umn.edu/agriculture/sugarbeets

Lamb, J.A., and J.T. Moraghan. 1993. Comparison of foliar and preplant applied nitrogen fertilizer for sugar beet. Agron. J. 85:290-295.

Lamb, J.A., M.W. Bredehoeft, and C. Dunsmore. 2010 Turkey litter effects on sugarbeet production. In 2010 Sugarbeet Research and Extension Reports. Available at http://www.sbreb.org

Lamb, J.A., M.W. Bredehoeft, and C. Dunsmore. 2011 Nitrogen management strategies for increasing sugarbeet root quality. In 2011Sugarbeet Research and Extension Reports. Available at http://www.sbreb.org

Lamb, J.A., M.W. Bredehoeft, C. Dunsmore, and N. Van. 2013. Nitrogen management strategies for increasing sugarbeet root quality. In 2013Sugarbeet Research and Extension Reports.

Malnou, C.S., K.W. Jaggard, and D.L. Sparkes. 2006. A canopy approach to nitrogen fertilizer recommendation for the sugarbeet crop. Eur. J. Agron. 25:254-263.

Marchetti, R. and F. Castelli. 2011. Mineral nitrogen dynamics in soil during sugarbeet and winter wheat crop growth. Eur. J. Agron. 35:13-21.

Moraghan, J. 1987. Nitrogen fertilizer trials. Sugarbeet Research and Extension Reports. 18:89-97.

Nguy-Robertson, A., A. Gitelson, Y. Peng, A. Vina, T. Arkebauer and D. Randquist. 2012. Green leaf area index estimation in maize and soybean: Combining vegetation indices to achieve maximal sensitivity. Agron. J. 104:1336-1347.

Pnada, S.S., D.P. Ames and S. Pamigrahi. 2010. Application of vegetation indices for agricultural crop yield prediction using neural network techniques. Remote Sensing. 2:673-696.

Pollach, G., W. Hein and, G. Rosner. 1996. Definition of the ‘internal quality’ of sugarbeet. Zuckerindustrie 121:332-344.

Reitmeir, L.J. 2001. Nitrogen management in a potato, sugarbeet and small grain crop rotation. M.S. thesis, North Dakota State Univ., Fargo.

Sims, A.L. 2008.Challenging current nitrogen recommendation: Sugarbeet response to nitrogen in different RRV locations and soils – Report 1. In 2008 Sugarbeet Research and Extension Reports.

Sims, A.L. 2009. Challenging current nitrogen recommendation: Sugarbeet response to nitrogen in different RRV locations and soils – Report 2. In 2009 Sugarbeet Research and Extension Reports.

Sims, A.L. 2010. Challenging current nitrogen recommendation: Sugarbeet response to nitrogen in different RRV locations and soils – Report 3. In 2010 Sugarbeet Research and Extension Reports.

Sims, A.L. 2012. Nitrogen management in sugarbeet grown in the finer textured soil of the RRV. In 2012 Sugarbeet Research and Extension Reports.

Sims, A.L. 2013. Nitrogen management in sugarbeet grown in the finer textured soil of the RRV. . In 2013Sugarbeet Research and Extension Reports.

Stevenato, P., M. Saccoumani, M. Bertaggia, A. Bottacin, M. Cagnin, M. Biaggi, and E. Biancardi. 2004. Nutrient uptake traits related to sugarbeet yield. J. of Suagrbeet Research. 41:89-99.

Stevens, W.B., R.D.Violett, S.A. Skalsky, and A.O. Mesbah. 2008. Response of eight sugarbeet varities to increasing nitrogen application: I. root, sucrose and top yield. J. of Sugarbeet Research. 45:65-83.

Stevens, W.B., R.G. Evans, J.D.Jabro, and W.M. Iversen. 2011. Sugarbeet productivity as influenced by fertilizer band depth and nitrogen rate in strip tillage. J. of Sugarbeet Research. 48:137-155.

Sultana, S.R., A. Ali, A. Ahmad, M. Mubeen, M. Zia-Ul-Haq, S. Ahmad, and H.Z.E. Jaafar. 2014. Normalized difference vegetation index as a tool for wheat yield estimation: A case study from Faisalabad, Pakistan. The Scientific World Journal. 2004: id 725326. doi:10.1155/2014/725326

Tarkalson, D. 2011. Nitrogen requirements for sugarbeets: a summary of past and present research findings. Proceedings of Idaho nutrient management conference: 2012. 6:15-19.

Tarkalson, D.D., D.L. Bjorneberg, and A. Moore. 2012. Effect of tillage system and nitrogen supply on sugarbeet production. J. of Sugarbeet Research. 49:79-102.

Thompson, L.J., R.B. Ferguson, N. Kitchen, D.W. Franzen, M. Mamo, H. Yang, and J.S. Schepers. 2015. Model and sensor based recommendation approaches for in-season nitrogen management in corn. Agron. J. 107:2020-2030.

Tsialtas, J.T. and N. Maslaris. 2013. Nitrogen effects on yield, quality and K/Na selectivity of suagrbeets grown on clays under semi-arid, irrigated conditions. Int. J. Plant Prod. 7:355-372.

USDA, ERS. 2015. U.S. sugar production. Available at http://www.ers.usda.gov/topics/crops/sugar-sweeteners/background.aspx#production

Warncke, D., and J.R. Brown. 1998. Potassium and other basic cations. p. 31–33. In J.L. Brown (ed.) Recommended chemical soil test procedures for the North Central region. North Central Regional Publ. No. 221 (Rev.). Missouri Exp. Stn. Publ. SB 1001. Univ. of Missouri. Columbia.

Weiser, F., M. Bauer, M. Kamh, T. Engels and S. Reusch. 2002. The crop as an indicator for sidedress nitrogen demand in sugarbeet production: Limitation and perspectives. J. Plant Nutr. Soil Sci. 165:93-99.

Winter, S.R. 1998. Suagrbeet response to residual and applied nitrogen in Texas. J. of Sugarbeet Research. 35:43-62.

Wu, J., D. Wang, C.J. Rosen and M.E. Bauer. 2007. Comparison of petiole nitrate concentration SPAD chlorophyll reading, and QickBird satellite imagery in detecting nitrogen status of potato canopies. Field Crop Research. 101:96-103.