Optical sensors to predict sugarbeet yield, quality, and fertilizer nitrogen application rate1

Authors: Van Eerd, Laura L., MacFarlane, J. Mitchell, and Chahal, Inderjot

Source: Canadian Journal of Plant Science, 101(6) : 984-998

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjps-2021-0101

Canadian Science Publishing

ARTICLE

Optical sensors to predict sugarbeet yield, quality, and fertilizer nitrogen application rate[1]

Laura L. Van Eerd, J. Mitchell MacFarlane, and Inderjot Chahal

Abstract: Nitrogen (N) management is critical for sugarbeet (*Beta vulgaris* L.) because N inversely influences root yield and recoverable white sucrose per tonne (RWST). In Ontario, from 2015 to 2017, the use of optical sensors (e.g., a soil plant analysis development (SPAD) chlorophyll meter, GreenSeeker handheld crop sensor) was evaluated as a method to guide N application and harvest date (late-September, late-October) selection by predicting root yield RWST and partial profit margins. In a commercial field, 4 to 5 fertilizer N rates, and 8 to 12 cultivars were tested in a split block design experiment with three replications and two harvest dates. In all years, few cultivars (≤2) had a root yield response to applied N, which was attributed to high inherent soil fertility, and limited our evaluation of optical sensors to adjust in-season N applications. The optimal N rate to maximize RWST and profits was 0 to 45 kg $N{\cdot}ha^{-1}$ and confirmed their negative relationship to applied N. Optical sensor readings correlated negatively with RWST across the majority (>60%) of cultivars tested in mid-August and September. Across all cultivars, the regression model of optical sensors to predict RWST at early harvest was strongest ($R^2 = 0.48$ for SPAD; 0.24 for GreenSeeker) when readings were taken in early September. Although future research to refine this relationship is needed, we recommend the use of optical sensors, particularly the SPAD meter, in early September to guide harvest selection to maximize RWST.

Key words: GreenSeeker, SPAD meter, root yield, sugar, recoverable white sucrose, temperate climate, soil nitrogen fertility, variety, harvest date: RWST, normalized difference vegetation index NDVI.

Résumé : La gestion de l'azote est cruciale pour la culture de la betterave sucrière (*Beta vulgaris* L.), car cet élément influe sur le rendement des tubercules et la quantité de sucrose blanc récupérable par tonne (SBRT). De 2015 à 2017, les auteurs ont évalué des capteurs optiques (SPAD, GreenSeeker) en Ontario en vue d'établir si on pourrait s'en servir pour orienter les apports de N et déterminer la date de la récolte (fin septembre, fin octobre) en prévoyant le rendement en SBRT des tubercules et une partie de la marge bénéficiaire. À cette fin, ils ont testé le taux d'application d'un engrais N (4, 5) et le cultivar (8, 12) dans un champ commercial lors d'une expérience en tiroir reprise trois fois, à deux dates différentes pour la récolte. Peu de cultivars (≤2) ont vu leur rendement réagir à l'amendement azoté, quelle que soit l'année. On l'attribue à la grande fertilité inhérente du sol, qui a limité l'évaluation des capteurs optiques comme outil pour corriger les applications saisonnières de N. La quantité d'engrais N idéale pour optimiser le rendement en SBRT et les profits se situe entre 0 et 45 kg par hectare, ce qui confirme la relation négative de ces deux paramètres avec le taux d'application du N. Pour la plupart des cultivars testés (>60 %) à la mi-août et en septembre, le relevé des capteurs optiques est négativement corrélé au SBRT. Le modèle de régression des capteurs optiques censé prévoir le SBRT au début de la récolte atteint le maximum de sa fiabilité (R^2 = 0,48 pour le capteur SPAD; 0,24 pour le capteur GreenSeeker) quand on prend les relevés pris au début de septembre, pour la totalité des cultivars. Même s'il faudrait préciser cette relation en effectuant des recherches plus poussées, les auteurs préconisent l'usage d'un capteur optique, principalement le capteur SPAD, au début de septembre pour savoir quand récolter les betteraves afin d'obtenir la plus grande quantité de SBRT. [Traduit par la Rédaction]

Mots-clés : GreenSeeker, SPAD meter, rendement en tubercules, sucre, sucrose blanc récupérable, climat tempéré, azote du sol fertilité, variété, date de la récolte, indice de végétation par différence normalisée IVDN.

Received 27 April 2021. Accepted 15 July 2021.

L.L. Van Eerd, J.M. MacFarlane, and I. Chahal. School of Environmental Sciences, University of Guelph, Ridgetown Campus, Ridgetown, ON N0P 2C0, Canada.

Corresponding author: Laura L. Van Eerd (email: lvaneerd@uoguelph.ca).

[1]This article is part of a Special Issue entitled "Advancements in Canadian horticulture, in celebration of the 100th year of horticulture research at the University of Saskatchewan".

Introduction

Sugarbeet (*Beta vulgaris* L.), primarily grown for sucrose production, contains about 13%–22% sugar in the taproot (Heidari et al. 2008). Global sugarbeet production in 2019 was 278 million tonnes [Food and Agriculture Organization of the United Nations (FAO) 2019]. Of the world's sugarbeet production in 2019, 13.8% was produced by USA and Canada (FAO 2019). In southwestern Ontario, the harvested area of sugarbeet was approximately 3800 ha in 2016 (Statistics Canada 2016). Sugarbeet is an edible horticultural crop grown for sucrose production, but N management in sugarbeet is challenging (Carter and Traveller 1981). Nitrogen deficiency decreases root yield but increases sucrose concentration (Carter and Traveller 1981; DeBruyn et al. 2017; Afshar et al. 2019) and affects the economic returns from sugarbeet production (Märländer et al. 2003; DeBruyn et al. 2017, 2019). Growers are paid based on both sugarbeet root yield and recoverable white sucrose per tonne (RWST). With this payment structure and plant responsiveness, optimizing fertilizer N applications to maximize profits is complicated. Therefore, efficient fertilizer N management is crucial for optimizing sucrose production.

Nitrogen management that maximizes sugarbeet profitability is largely dependent on site, management practices (such as planting density, harvest date, cultivar grown), soil type, and weather conditions (Carter et al. 1975; Tarkalson et al. 2016; DeBruyn et al. 2017; Afshar et al. 2019;). Delaying sugarbeet harvest increases the root yield and RWST (Lauer 1995; Heidari et al. 2008; Al-Sayed et al. 2012; DeBruyn et al. 2017), hence the Michigan Sugar Company Inc. (MSC) offers a pre-rated early harvest incentive to the growers to provide compensation for expected low sucrose production. Additionally, several studies have reported contrasting results on the relationship between harvest date and N fertility on root yield and RWST (Eckhoff 1999; Lauer 1995; Jaggard et al. 2009). Given the inconsistent effect of harvest date and N fertility on sugarbeet production, there is a need to consider harvest date when considering fertilizer N management.

Sugarbeet cultivar type strongly influences sucrose content and root yield, mainly due to the differences in the interaction of the cultivar genotype with the agronomic management practices (such as harvest date) and environmental conditions (Curcic et al. 2018). Annually, MSC evaluates numerous cultivars (ca. 12) in commercial field-scale experiments across the growing region. While cultivars have been selected and brought to market based on productivity, having side-by-side comparisons is useful to evaluate root and sucrose yield. Tolerance to pest pressure [e.g., *Cercospora beticola* (Sacc.), *Rhizoctonia solani* (Kühn), and nematodes such as *Heterodera schachtii* (Schmidt)] is considered by growers when selecting which cultivar to grow, and both root and sucrose yield are dependent on pest pressure (Hauer et al. 2015; Pavlů et al. 2017). Thus, there may be a fitness penalty or advantage by growing pest-tolerant cultivars but the interactive effect of cultivar selection and response to N fertility is largely unknown. Overall, research comparing cultivar response to N fertility might contribute in improved grower recommendations, particularly by focusing on N rates that maximize sucrose and profitability.

With the aforementioned factors influencing N fertilizer management in sugarbeet, having tools to assist growers in their management decision would be useful. Optical sensors offer a promising strategy for rapid and frequent assessment of crop N status (Xiong et al. 2015). Optical sensors, such as the soil plant analysis development (SPAD) chlorophyll meter and the GreenSeeker handheld crop sensor, actively emit red and infrared wavelengths of light, to estimate crop N status by providing a score based on the chlorophyll content and greenness in the plant tissue (Sexton and Carroll 2002; Xiong et al. 2015). The SPAD utilizes transmittance of light through the leaf, whereas the GreenSeeker uses reflectance of light off the canopy (Xiong et al. 2015; Bu et al. 2016; Sharma and Bali 2017). Previously, the SPAD meter and GreenSeeker have been used primarily to monitor the N status of corn (e.g., Pfeffer et al. 2010; Bandhu and Parbati 2015; Sharma et al. 2015). In Michigan, the GreenSeeker showed promise in-season to predict sugarbeet root and RWST yield (Gehl and Boring 2011), but evaluation of cultivar and harvest date selection was beyond the scope of the study. Likewise, exploratory sugarbeet research by Turnbull and Van Eerd (2011) reported the usefulness of the SPAD meter as a potential tool to guide sugarbeet harvest. Sugarbeet cultivars vary somewhat in terms of leaf and canopy structure and greenness; thus, warranting the need to evaluate optical sensors using different cultivars.

Based on partial profit margins, a recommended rate of 136 kg N·ha^{-1} has been established for sugarbeet in southwestern Ontario (DeBruyn et al. 2017), which is similar to the root yield maximizing average rate of 109 kg N·ha^{-1} observed in Michigan (Gehl and Boring 2011). This present study aimed to assess if the profitable fertilizer N rate should be refined based on cultivar and harvest date. The goal of this research was to assess the utility of optical sensors (SPAD meter and GreenSeeker) in sugarbeet production. Within cultivars, we evaluated the ability of optical sensors (SPAD meter and GreenSeeker) to predict (*i*) in-season fertilizer N rate and (*ii*) sugarbeet root and RWST yield. We hypothesize that profit margins will be positively related to applied N (as we suspect root yield, not RWST, may be a stronger driver of payments) and vary by cultivar, but not by harvest date. As well, we hypothesize that both optical sensor readings collected in-season and at harvest will correlate to root and RWST yield, irrespective of cultivar. If effective, optical sensors would be a valuable decision-making tool for growers to (*i*) adjust in-season fertilizer N applications and (or) (*ii*) decide when to harvest to maximize root and RWST yield, and ideally profit margins.

Materials and Methods

Experimental design and site description

To evaluate the need for sugarbeet cultivar-specific fertilizer N recommendations and the performance of two optical sensors [SPAD-502 meter (Spectrum Technologies Inc., Plainfield, Illinois) and GreenSeeker (Trimble Navigation Ltd., Sunnyvale, CA], a fertilizer N response experiment was superimposed on an industry-led cultivar trial at a commercial field in Pain Court, Ontario, Canada from 2015 to 2017. With three replicates, the experiment was a split block design with cultivar as the main plot and fertilizer N rate as the split-treatment. Each split-plot was 17 to 21 m long and 3 m (four rows) wide with row spacing of 0.76 m. Cultivars were selected and randomized by Sugarbeet Advancement in association with the MSC and consisted of 8 to 12 cultivars planted with grower cooperator equipment as field-length strips (MSC 2015). The number of cultivars, and the specific cultivars tested, differed slightly from 2015 to 2017. In addition, the effect of harvest date (early and late) was included to evaluate sugarbeet response to applied fertilizer N and to assess the effectiveness of optical sensors in sugarbeet production.

Surface (15 cm) soil characteristics at the field sites were very similar as all three sites were within 500 m of each other and were managed by the same grower cooperator. Soil texture at the study sites was loam to silt loam. In 2016 and 2017, respectively, surface soil had 33 and 34 $g \cdot kg^{-1}$ soil organic matter (loss on ignition), 7.8 and 7.8 pH (1:1 soil-to-water), 21.5 and 22.3 $cmol_c\ kg^{-1}$ cation exchange capacity (ammonium acetate extraction), 28 and 28 $mg \cdot kg^{-1}$ P (Olsen sodium bicarbonate extractant), and 152 and 169 $mg \cdot kg^{-1}$ K (ammonium acetate extractant). Previous crop in the rotation was grain corn in all years. Sugarbeet was seeded on 15 Apr. 2015 and 2016 and on 14 Apr. 2017. As is typical and recommended by the industry, fertilizer was applied with the planter in a band 5 cm below and 5 cm beside the seed. In 2015 and 2016, potash (448 $kg \cdot ha^{-1}$) and monoammonium phoshate (11–52–0 at 12 $kg\ N \cdot ha^{-1}$) were applied. In 2017, 482 $kg \cdot ha^{-1}$ of a custom fertilizer blend of 9–12–8 with 15 S, 1.5 Mn, 1 Zn was used. On 24 Apr. 2015, prior to emergence, four rates of calcium ammonium nitrate (0, 45, 90 and 224 $kg\ N \cdot ha^{-1}$) were broadcasted. In 2016 and 2017, the N treatment approach was modified to in-season N application to mitigate early spring N losses, and to ensure there was sufficient N for sugarbeet development during the season (Carter et al. 1975). Five rates (0, 45, 90, 157, and 224 $kg\ N \cdot ha^{-1}$) of urea ammonium nitrate (28–0–0) were injected 8 cm below the soil surface and in between rows on 20 May 2016 and 2 June 2017. Fertilizer N treatments were applied before crop canopy row closure, which accounted for the variation in application dates between years. The grower used a fungicide program of five to six applications of various broad-spectrum fungicides. All other management practices were according to industry standards, except in 2016 when the sugarbeet field, and our experiment, was irrigated (not a typical sugarbeet production practice in the study region).

Optical sensor readings

From 2015 to 2017, optical sensor readings were taken at multiple dates (from June to end of October) during the sugarbeet growing season to determine the ability of optical sensors to predict (*i*) the need for in-season fertilizer N and (*ii*) sugarbeet root and RWST yield. Variation in sampling dates among study years was due to weather, limitations in labour, and accessibility to the commercial field. To facilitate optical sensor readings, the harvest area was established by flagging a 4 m length of the centre two rows, within the centre of each plot. GreenSeeker readings were measured by holding the meter 90 cm horizontally above the crop canopy over the two 4 m harvest areas (taking care to not walk next to, nor disrupt, the designated harvest area). The SPAD measurement was the average of 30 SPAD readings taken from the newest, fully expanded leaf of 30 random plants (i.e., one reading per leaf per plant) within the harvest area of each plot. The readings are unitless for both sensors; greater values indicate darker green leaves (SPAD) or crop canopy (GreenSeeker). To assess the effectiveness of optical sensors to adjust in-season fertilizer N applications, readings were taken in June prior to crop canopy row closure. To evaluate the usefulness of optical sensors to predict sugarbeet root yield and RWST, readings were taken periodically later in the growing season (mid-Aug. until the day of harvest).

Plant and soil measurements

Sugarbeet roots were harvested on 21 and 22 Sept. in 2015, 20 Sept. in 2016, and 27 and 28 Sept. in 2017 which represented the early harvest. Sugarbeet harvest dates of 16 and 17 Oct. in 2015, 24 Oct. in 2016, and 26 and 27 Oct. in 2017 represented the late harvest. All sugarbeet plants in the 4 m harvest area (represented by 4 m length of the centre two rows within the centre of each plot) were counted and hand dug from one row per harvest. Care was taken during the early harvest to not disturb the late harvest area. Leaves were removed at the crown and weighed separately from roots. A subsample of 12 randomly selected fresh roots was shipped to MSC (Bay City, MI) for sucrose and quality analysis. Sucrose concentration (sucrose %), clear juice purity (%) and recoverable white sucrose per tonne (RWST) were calculated using the equations described below.

$$\text{Sucrose content}(\%) = [(\text{RUD} - 0.10)0.8184] + 1.21$$

$$\text{Clear juice purity}\% = (\text{pol}/1.145\text{RSD} - 1.325)100$$

$$\text{RWST} = [(\text{sucrose}\% \times 18.4) - 22] \times \{[1 - (60/\text{clear juice purity}\% - 3.5)]/0.4\}$$

As outlined by Van Eerd et al. (2012) and Gehl and Boring (2011), RUD is the percentage of soluble solids made by a Rudolph refractometer, pol is the polarization of sucrose solution, and RSD is the refractive dry solids. Similar to industry standards, sugarbeet root yield and sucrose data were expressed as root fresh weight (DeBruyn et al. 2017). Root yield in $Mg{\cdot}ha^{-1}$ was calculated using the total root fresh weight from the harvest area. To determine the quantity of recoverable white sucrose per hectare (RWSH), root yield was multiplied by RWST.

To evaluate soil mineral N (SMN; nitrate-N and ammonium-N), composite soil samples (0–30 cm depth) of five cores (2.5 cm diameter) per plot with three fertilizer rates (1, 90, 224 kg $N{\cdot}ha^{-1}$) and three cultivars (B1399, CRR059, and SX-1235N but exchanging SX-1245N in 2017) were taken at both harvests in all years. Soil samples were frozen immediately and hand sieved (2 mm) prior to analysis, however, due to in-house instrument malfunction the samples were stored frozen until they were shipped to a commercial soil test lab (SGS Laboratories Inc. Guelph, ON) for analysis. Based on the soil texture at the study sites, soil bulk density of 1.4 $g{\cdot}cm^{-3}$ (NRCS USDA) was used to convert nitrate-N and ammonium-N concentration ($mg{\cdot}kg^{-1}$) to content (kg $N{\cdot}ha^{-1}$). Soil mineral N was calculated as the sum of nitrate-N and ammonium-N content in 0–30 cm depth. Deeper depths were not considered in this study as previous work in southwestern Ontario (18 site-years) showed no differences among fertilizer N rates at 30–60 cm depths (DeBruyn et al. 2017, 2019).

Partial profit margins

To determine the most profitable N rate for sugarbeet, a partial profit analysis was calculated based on revenue using the 5-yr average payment (\$48.5 Mg^{-1}) for sugarbeet by MSC. For each plot, the revenue generated based on root yield corrected for per plot RWST as a proportion relative to company average RWST in each year (131.5, 116, and 137.5 $kg{\cdot}Mg^{-1}$ for 2015, 2016 and 2017 respectively). If applicable, an early harvest bonus was applied as defined by the MSC payment schedule and calculated based on the date of crop harvest and the date of establishment of permanent piling yard in Ontario as described by DeBruyn et al. (2017, 2019). Piling yard establishment dates were on 17 Oct. 2015, 25 Oct. 2016, and 29 Oct. 2017. Based on our early harvest dates, payments for early harvest sugarbeet (\$ Mg^{-1}) were greater by 1.35, 1.49 and 1.45 times in 2015, 2016, and 2017, respectively. To calculate partial profit margins, expressed as \$ ha^{-1}, variable expenses applied per plot were the price of N fertilizer (\$1.31 kg^{-1}) as well as the trucking cost (\$5.44 Mg^{-1}).

Statistical analysis

All statistical analysis was conducted using SAS 9.4 with significance at a protected $P < 0.05$. Due to the differences in the specific cultivars tested, sample dates, and N rates among the study years, each year was analyzed individually. Using Proc Glimmix, the effect of treatments was evaluated on harvest yield data (root yield, RWST, RWSH, sucrose content, purity, and partial profit) and optical sensor readings. Fixed effects were cultivar, harvest date, and N rate, and their interactions while the random effect was replication. The assumptions of normality were met; hence, no data transformations were conducted. Least square means were presented using Tukey's comparative test at $P < 0.05$.

Relationships of fertilizer N treatments with sugarbeet yield parameters were evaluated using nonlinear regressions. Furthermore, linear, and nonlinear (quadratic and quadratic plateau model) regression analyses were conducted to assess the applicability of optical sensors to predict the rate of N fertilizer application for maximizing sugarbeet yield attributes. Due to a consistently better fit (i.e., greater r values) of nonlinear than linear functions for all measurements, we present nonlinear functions. Curves were presented to demonstrate positive or negative trends in the response of optical sensors to fertilizer N treatments. Correlation analyses were conducted to evaluate the relationship of optical sensors with applied N fertilizer and sugarbeet yield attributes. Correlations with $P < 0.05$ and $r \geq |0.6|$ were considered significant and relevant. Additionally, sugarbeet cultivars tested in this study were not consistent and varied among years; hence, relationships between N fertilizer treatments and sugarbeet crop attributes were evaluated separately for each cultivar. To further evaluate and compare the utility of each optical sensor as a predictive tool, sugarbeet yield attributes at each harvest and readings were pooled over years, cultivars and N rates and regression analysis performed. If the predictive equation was significant ($P < 0.05$) and relevant ($R^2 \geq 0.36$), then the optical sensor would be recommended to estimate root yield and (or) RWST at harvest.

Results and Discussion

For the tested parameters (RWST, root yield, and partial profit margins, SMN) in all three years, there were no three-way interactions detected among effects and few two-way interactions (only 4 out of 36 possible interactions of cultivar and N rate, cultivar and harvest date, and N rate and harvest date; Table 1). For instance, a significant interaction between cultivar and harvest date was observed for the partial profit margins in 2016 but

Table 1. Impact of fertilizer N rate, cultivar, and harvest date on mean recoverable white sucrose per tonne (RWST), sugarbeet root yield and partial profits from 2015 to 2017.

N fertilizer rate (N)	2015 RWST	2015 Root yield	2015 Partial profit	2016 RWST	2016 Root yield	2016 Partial profit	2017 RWST	2017 Root yield	2017 Partial profit
kg N·ha^{-1}	kg·Mg^{-1}	Mg·ha^{-1}	\$·ha^{-1}	kg·Mg^{-1}	Mg·ha^{-1}	\$·ha^{-1}	kg·Mg^{-1}	Mg·ha^{-1}	\$·ha^{-1}
0	152a	99.1c	5960ab	115a	123b	6590a	139a	103	5650a
45	149b	105b	6110a	109b	128ab	6380ab	138a	105	5608ab
90	146c	108b	6090a	106b	129ab	6140b	134b	105	5370b
157	n/a	n/a	n/a	100c	128ab	5650c	128c	105	5010c
224	133d	113a	5640b	94d	131a	5350c	123d	106	4750d
Cultivar (C)									
B12RR2N	151ab	103ab	6060abc	110a	125bcd	6240ab	133c	106bc	5410ab
B133N	137e	108ab	5640bc	103bc	135ab	6240ab	n/a	n/a	n/a
B1399	145cd	98.4b	5490c	103bc	117d	5410c	130cd	96.7de	4780c
B18RR4N	148abc	99.8b	5680bc	n/a*	n/a	n/a	n/a	n/a	n/a
CG333NT	143cd	114a	6280ab	101c	131abc	5860abc	125e	115a	5380ab
CG351NT	153a	106ab	6260ab	109a	129abc	6360a	138b	102cd	5400ab
CRR059	151ab	112a	6550a	103c	138a	6320a	130d	114a	5590a
CRR202	142de	110ab	5990abc	n/a	n/a	n/a	n/a	n/a	n/a
H9616	n/a	n/a	n/a	108ab	124cd	6100ab	143a	92.0e	5060bc
HM173	137e	106ab	5540c	n/a	n/a	n/a	n/a	n/a	n/a
SX1212	143cd	110ab	6080abc	n/a	n/a	n/a	n/a	n/a	n/a
SX1228	144cd	112a	6270ab	n/a	n/a	n/a	n/a	n/a	n/a
SX1235N	146bcd	98.4b	5560bc	102c	123cd	5650bc	n/a	n/a	n/a
SX1245	n/a	n/a	n/a	n/a	n/a	n/a	133c	103bc	5260ab
SX1251	n/a	n/a	n/a	n/a	n/a	n/a	129d	110ab	5330ab
Harvest date (H)									
Early	138b	105	6570a	101b	123b	6910a	133	105	6400a
Late	152a	108	5330b	109a	132a	5140b	133	104	4150b
Effects					*P*-values				
C	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
N	**<0.0001**	**<0.0001**	**0.0006**	**<0.0001**	**0.0199**	**<0.0001**	**<0.0001**	0.6070	**<0.0001**
C × N	0.5740	0.5660	0.5280	0.6980	0.4390	0.4280	**0.0477**	0.5500	0.7250
H	**<0.0001**	0.1110	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.8880	0.2550	**<0.0001**
C × H	0.5200	0.8010	0.6870	0.2440	0.1040	**0.0245**	0.9450	0.2100	0.4120
N × H	**0.0044**	0.4910	0.1110	0.7150	0.3220	0.2390	**0.0455**	0.5070	0.1000
C × N × H	0.4290	0.9850	0.9370	0.440	0.9997	0.9670	0.2820	0.9770	0.9770

Note: For each source of variation, different letters reflect a significant statistical difference according the Tukey's comparative test ($P < 0.05$) and indicated in bold font. n/a, Not applicable as N treatment was not included or the cultivar was not grown.

not in 2015 and 2017 (Table 1). Means comparative test (Tukey's) revealed that this interaction was due to the variable magnitude of difference in profits between harvest dates but for each cultivar, partial profits were greater with early than late harvest (data not shown) and attributed to the early harvest bonus as both yield and RWST were lower at early harvest. In agreement with our findings, others have reported inconsistent or no cultivar interactions with N fertilizer application rate and harvest date for the sugarbeet yield attributes (Halvorson and Hartman 1980; Lauer 1995).

The lack of interaction of N fertilizer with cultivar and harvest date for the tested sugarbeet crop attributes (Table 1) was perhaps due to the high inherent soil fertility (SMN content at harvest was >36 kg N·ha^{-1}) at the study sites. Previous in Ontario, SMN at sugarbeet harvest was less than 20 kg N·ha^{-1} in the surface 30 cm depth (DeBruyn et al. 2017, 2019). At harvest, SMN content was not different among N fertilizer application rates in all tested years (Supplementary Table S1[2]) and consistent with previous studies (DeBruyn et al. 2017; Marchetti and Castelli 2011). We recognize that the observed SMN concentrations are considerably greater than expected and attribute it to the inadvertent thawing of the samples and refreezing prior to analysis. Regardless, in each year, soil samples were similarly handled and stored; hence comparisons among treatments are valid.

Nonsignificant interactions of cultivar with N fertilizer and with harvest date suggests that harvest date selection and N fertilizer recommendations should not be cultivar specific; hence, suggesting that cultivar selection might not limit the potential usefulness of optical sensors in sugarbeet production. The lack of significant interactions (32 out of 36 interactions were $P > 0.05$) among treatments suggested that the tested effects (N fertilizer rate, harvest date, and cultivar) were largely independent of each other. Therefore, we focused on analyzing and presenting main effects of treatments on RWST, root yield, partial profit margins, and to a lesser extent SMN.

Cultivar-specific effects on sugarbeet crop attributes, profit margins, and soil mineral N content

With the exception of SMN ($P \geq 0.1368$), in all three years, root yield, RWST, and partial profit were significantly different among cultivars ($P < 0.0001$; Table 1 and Supplementary Table S1[2]), which was expected and consistent with previous research (Strausbaugh et al. 2010; Hauer et al. 2015; Pavlů et al. 2017). Our results suggested that across all years, CRR059 (avg. 6155 $\$\cdot ha^{-1}$) was the most profitable, whereas B1399 (avg. 5228 $\$\cdot ha^{-1}$) was the least profitable (Table 1; Fig. 1, Supplementary Figs. S1 and S2[2]). Likewise, a similar cultivar pattern was observed in root yield, where CRR059 had either the greatest or similar yield with the greatest yielding cultivar. High root yield does not always correspond to a high sucrose yield. For instance, in our study in 2016 and 2017, CRR059 had the greatest root yield but had lowest RWST. Cultivars H9616 and B12RR2N had the greatest, or among the greatest, RWST yielding cultivars in all three years.

It has been observed that cultivars which are resistant to different pests often produce low root yield in the absence of the pest (Strausbaugh et al. 2010; Hauer et al. 2015), while non-resistant cultivars do not have that inherent biological cost. For example, the *Cercospora*-tolerant B1399 cultivar (MSC 2016), tends to produce high root yield but low sucrose in conditions without fungal infestation. Hence, B1399 might not be as profitable under low disease pressure conditions and (or) with an effective plant protection spray program. The lack of interaction between harvest date and applied N suggests that growers do not need to take these management factors into consideration when selecting a cultivar to grow.

Effects of harvest date on sugarbeet crop attributes, profit margins, and soil mineral N content

The effect of harvest date on root yield and RWST was inconsistent among the tested years (Table 1). For instance, harvest date had no effect on root yield in 2015 and 2017, and on RWST in 2017 (Table 1). However, in 2016 mean root yield was 8.7 $Mg\cdot ha^{-1}$ greater at late harvest compared with early harvest. Our findings of greater root yield at late harvest was expected and consistent with earlier Ontario research (DeBruyn et al. 2017, 2019) and elsewhere (Lauer 1995; Heidari et al. 2008; Al-Sayed et al. 2012). Likewise, our findings of greater RWST in late harvest compared with early harvest in 2015 (14 $kg\cdot Mg^{-1}$) and 2016 (9 $kg\cdot Mg^{-1}$) was expected and consistent with previous research (Heidari et al. 2008, Al-Sayed et al. 2012; DeBruyn et al. 2017, 2019). The observed similar RWST between early and late harvest dates in 2017 was not expected but attributed to relatively drier conditions in Oct. 2017 (high mean air temperature and less total precipitation) than those of 2015 and 2016. Another contributing factor was that harvest dates were only one month apart; one would expect more differences if there was more time between harvest dates (i.e., if early harvest occurred in late-August rather than September).

In all three years, partial profit margins were greatest at the early harvest by \$1245 to \$2246 ha^{-1} (Table 1), and consistent with previous research (DeBruyn et al. 2017, 2019). This suggests that the early harvest bonus has a stronger influence on profits than root and sucrose yield. The payment structure of MSC provides financial compensation to growers for the reduction in yield and RWST expected at early harvest, but the ideal compensation program would be equivalent regardless of harvest date. It is noteworthy that in 2018, MSC modified payment based on the amount of recoverable white sucrose delivered to the factory as opposed to grower RWST relative to company average RWST; the latter was used in our partial profit analysis. Hence, we focused evaluation of optical sensors on root yield and RWST, then results can be applied regardless of the payment structure.

Surface (30 cm) SMN content was greater at late harvest compared with early harvest in 2015 (a difference of 63.8 $kg\ N\cdot ha^{-1}$) and 2017 (a difference of 16.1 $kg\ N\cdot ha^{-1}$), with a similar trend in 2016 (a difference of 8.9 $kg\ N\cdot ha^{-1}$) (Supplementary Table S1[2]). The extremely high SMN at late harvest in 2015 was attributed to improper soil handling and storage. Regardless, SMN at all other harvest is indicative of the inherent N fertility

[2]Supplementary data are available with the article at https://doi.org/10.1139/cjps-2021-0101.

of the study sites (>36 kg N·ha^{-1}). In contrast, DeBruyn et al. (2017) observed lower SMN at late vs. early harvest (a difference of 3.3 kg N·ha^{-1}) since N uptake in the sugarbeet crop continues over the fall, thereby lowering SMN. It is likely that any soil water recharge occurred without leaching events between harvests and decay of fibrous roots by late harvest may have contributed to the observed greater SMN at late harvest. Overall, our results of lower residual SMN and greater profit margins at early harvest suggests the potential for environmental and financial benefits, respectively, with early sugarbeet harvest.

Effects of nitrogen fertilizer application on sugarbeet crop attributes and profit margins

All crop attributes in each year, except root yield in 2017, were significantly different among N fertilizer application rates (Table 1). In addition to analysis of variance (Table 1), nonlinear regressions (due to better fit than linear regressions) were conducted to further understand the relationship of fertilizer N application rate on sugarbeet crop attributes (root yield, RWST, and partial profit margins) for each cultivar, at each harvest date, in each year (Fig. 1, Supplementary Figs. S1[2] and S2[2]). As expected, and consistent with previous research (Carter et al. 1975; Carter and Traveller 1981; Campbell 2002; DeBruyn et al. 2017; Gehl and Boring 2011; Van Eerd et al. 2012), increase in N fertilizer application rate increased root yield in two (2015 and 2016) out of three years (Table 1; Fig. 1, Supplementary Figs. S1 and S2[2]). However, in 2017, across all cultivars and harvest dates, root yield was not significantly different among N fertilizer treatments (Table 1; Fig. 1). Variability between years in sugarbeet root yield response to N fertilizer was consistent with Gehl and Boring (2011) and might be due to differences in soil N fertility among years.

In all three years, the lack of N fertilizer (i.e., 0 kg N·ha^{-1}) had the greatest RWST (Table 1) and a decrease in RWST was detected with an increase in N fertilizer application rate (Table 1 and Fig. 1, Supplementary Figs. S1[2] and S2[2]). The negative relationship between RWST and N fertilizer application rate was consistent with previous research (Carter et al. 1975; Tarkalson et al. 2016; DeBruyn et al. 2017; Afshar et al. 2019).

Like RWST, profit margins across all cultivars and harvest dates were negatively impacted and negatively correlated to N fertilizer application rate (Table 1 and Fig. 1, Supplementary Figs. S1 and S2[2]). For instance, in 2015, application of N fertilizer at 45 kg N·ha^{-1} had the greatest profit margin ($6111 ha^{-1}; Table 1) but was not statistically different from 0 kg N·ha^{-1}. In 2016 and 2017, the greatest mean partial profits of $6590 ha^{-1} and $5647 ha^{-1}, respectively, were obtained without applying in-season fertilizer N (i.e., 0 kg N·ha^{-1} treatment; Table 1). Combined, this research demonstrates the need to base N fertility recommendations on partial profits and not root yield alone. The negative relationships observed between profit margins and applied N fertilizer contrasted with the most profitable N rate of 136 kg·N ha^{-1} in Ontario (DeBruyn et al. 2017). The difference between these studies was attributed to the use of starter fertilizer and in-season application compared with preplant in the study by DeBruyn et al. (2017). However, in Michigan, the average N rate to maximize root yield was 109 kg N·ha^{-1} with starter fertilizer and in-season application (Gehl and Boring 2011). Our results demonstrated that profit margins were not positively related to applied N, hence, the study hypothesis of a positive association between profitability and applied N fertilizer rate was rejected. Undoubtedly, the high inherent soil fertility lead to the low fertilizer N rates needed to maximize profits, and points to the need to adjust industry recommended N rates based on individual field properties. Regardless, sugarbeet crop attributes (Table 1) responded to applied fertilizer N suggesting that exploration into the usefulness of optical sensor readings in these fields is valid.

Utility of optical sensor in sugarbeet production

To evaluate the study objective of assessing the applicability of optical sensors to predict in-season N fertilizer requirement correlation analysis was conducted. Optical sensors (SPAD and GreenSeeker) were considered to be relevant to the industry if 50% of tested cultivars had significant correlations ($P < 0.05$ and $r > |0.6|$) of optical sensor readings with the factor of interest [i.e., applied N and sugarbeet crop attributes (RWST, RWSH, root yield, purity, percent sucrose); Table 2]. The relationships of optical sensor readings with sugarbeet yield attributes were different among sampling times (Table 2 and 3). For instance, in 2017, a decrease in optical sensor readings (i.e., a decrease leaf or canopy greenness) from August compared with October (SPAD: 46.7 vs. 37.8; GreenSeeker: 0.87 vs. 0.62, respectively) was detected (Table 3). A change in readings over the growing season was not unexpected, as readings reflect changes in the crop N status (Xiong et al. 2015) as it grows and ultimately senescence, and was consistent with the observations of Gehl and Boring (2011) with the GreenSeeker. Thus, we focused on different time periods to evaluate usefulness of optical sensors for sugarbeet production.

Utility of optical sensor readings in June to adjust in-season N fertilizer application rate

Although the fertilizer N effect on optical sensor readings in June was significant, there was not a lot of differentiation among N rates (Table 3). Irrespective of the harvest date, there was a lack of relationship between optical sensor readings taken in June with (*i*) applied fertilizer N (Table 2; Fig. 2, Supplementary Figs. S3 and S4[2]) and (*ii*) sugarbeet yield attributes among cultivars (Table 2; Figs. 3, 4, Supplementary Figs. S3 and S4[2]). In agreement with other research (Turnbull and Van Eerd 2011; Gehl and Boring 2011), these results suggest that

Fig. 1. At early (left) and late (right) harvest, individual sugarbeet cultivar response to in-season, injected nitrogen fertilizer based on recoverable white sucrose per tonne (RWST; A, B), root yield (C, D) and partial profit margins (E, F) in 2017.

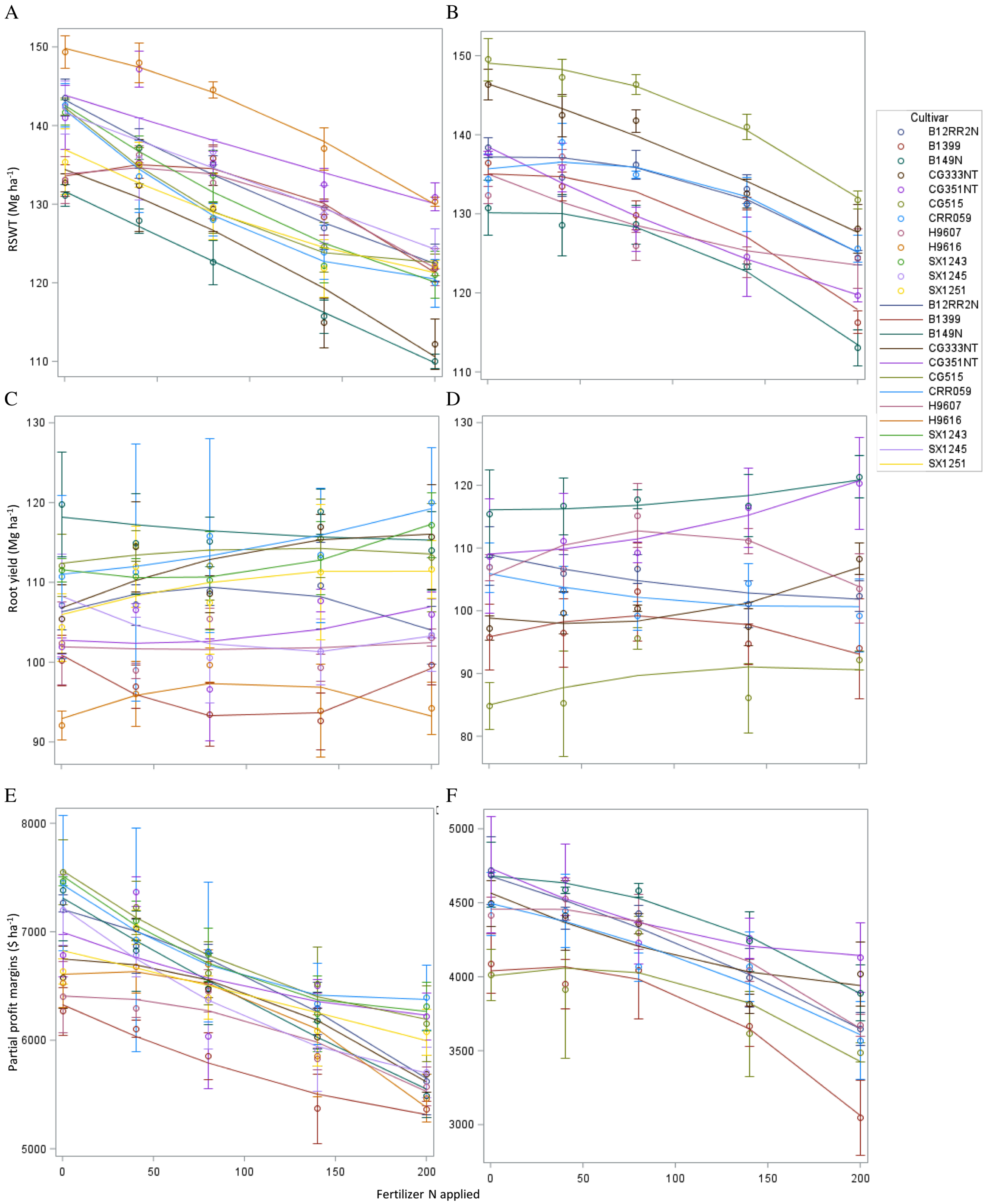


Table 2. Proportion of cultivars with significant correlations ($P < 0.05$ and $r > |0.6|$) of optical sensor [SPAD meter and GreenSeeker (GS)] readings with sugarbeet yield attributes at early and late harvest in 2015 to 2017.

Date of collecting optical sensor readings	Number of cultivars tested	N fertilizer rate (kg N·ha^{-1})		RWST (kg·Mg^{-1})		RWSH (Mg·ha^{-1})		Root yield (Mg·ha^{-1})		Sucrose content (%)		Purity (%)	
		Proportion of cultivars with significant correlations of optical sensor readings with yield variable											
		SPAD	GS	SPAD	GS	SPAD	GS	SPAD	GS	SPAD	GS	SPAD	GS
		Early harvest (Sept.)											
16 June 2016	8	0.13	0.25	0.13	0.13	0.13	0.13	0.13	0.5	0.25	0.13	0.13	0.13
13–14 June 2017	12	0.17	0.17	0.17	0	0.17	0.25	0.25	0.25	0.17	0.08	0.08	0
18–19 Aug. 2017	12	**0.75**	**0.75**	**0.67**	0.42	0.5	0.5	0	0.08	**0.67**	0.33	**0.75**	0.5
1–2 Sept. 2017	12	**0.83**	**0.92**	**0.83**	**0.67**	0.33	**0.58**	0	0.17	**0.83**	**0.67**	**0.75**	0.42
27–28 Sept. 2017*	12	**1**	**0.75**	**0.83**	**0.58**	0.33	0.5	0.08	0.17	**0.67**	**0.58**	**0.75**	0.5
21–22 Sept. 2015*	12	**0.83**	**1**	**0.75**	**0.92**	0	0.25	0.17	0.08	**0.67**	**0.92**	**0.58**	**0.58**
		Late harvest (Oct.)											
21–22 Sept. 2015	12	**0.83**	**1**	0.5	**0.75**	0	0.17	0.17	0.42	0.42	**0.67**	0.42	0.42
16 June 2016	8	0.13	0.25	0.25	0.38	0	0.38	0	0.25	0.25	0.38	0.25	0.13
13–14 June 2017	8	0	0.13	0	0.13	0.13	0	0.13	0.13	0	0.13	0	0.13
18–19 Aug. 2017	8	**0.63**	**0.88**	0.25	0.38	0.13	0.38	0	0.25	0.25	0.38	0.5	0.5
1–2 Sept. 2017	8	**0.75**	**0.88**	**0.75**	0.38	0.13	0.13	0	0.25	0.5	0.38	**0.63**	0.25
27–28 Sept. 2017	8	**1**	**0.75**	**0.88**	0.25	0.13	0.13	0	0.25	**0.75**	0.25	**0.63**	0.5
16–17 Oct. 2015 *	12	0.25	**0.83**	0.25	0.42	0	0	0	0	0.25	0.42	0.08	0
26–27 Oct. 2017*	8	0.5	0.5	0.13	**0.63**	0.13	0.13	0.13	0.25	0.13	**0.63**	0.25	0.5

Note: Bolded values indicate when over half of the cultivars tested had significant correlation of optical sensor readings with sugarbeet yield variable. *Day of sugarbeet harvest. RWSH, recoverable white sucrose per tonne.

Table 3. Impact of fertilizer N rate, cultivar, sampling date, and harvest date on mean optical sensor [SPAD and GreenSeeker (GS)] readings in 2015 to 2017.

Treatment	2015		2016		2017	
N Fertilizer Rate (kg N·ha^{-1})	SPAD	GS	SPAD	GS	SPAD	GS
0	34.0a	0.62a	44.6a	0.76a	41.1a	0.77a
45	36.3b	0.66b	47.5b	0.77ab	41.9a	0.78a
90	37.4b	0.67b	47.9b	0.77ab	43.7b	0.79b
157	n/a	n/a	48.2b	0.79b	45.5c	0.80c
224	40.1c	0.74c	48.4b	0.78b	46.3c	0.81c
Cultivar (C)						
B12RR2N	36.0cdef	0.71a	47.1a	0.74a	44.4b	0.80a
B133N	37.1bcd	0.65e	48.0a	0.79b	n/a	n/a
B1399	38.7bc	0.66cde	46.5ab	0.78b	44.2b	0.78bc
B18RR4N	33.5f	0.70ab	n/a*	n/a	n/a	n/a
CG333NT	36.0cdef	0.69abc	49.1a	0.77b	43.5b	0.79abc
CG351NT	35.9cdef	0.67bcde	48.8a	0.77ab	45.7a	0.78c
CRR059	34.9def	0.66de	46.9a	0.78b	44.0b	0.78c
CRR202	40.0b	0.69abcd	n/a	n/a	n/a	n/a
H9616	n/a	n/a	48.5a	0.80b	40.6c	0.80ab
HM173	44.5a	0.67bcde	n/a	n/a	n/a	n/a
SX1212	35.8def	0.67cde	n/a	n/a	n/a	n/a
SX1228	36.4cde	0.64e	n/a	n/a	n/a	n/a
SX1235N	34.1ef	0.67bcde	43.5b	0.78b	n/a	n/a
SX1245	n/a	n/a	n/a	n/a	43.7 b	0.79abc
SX1251	n/a	n/a	n/a	n/a	43.6 b	0.79abc
Sample Date (S)						
June	n/a	n/a	47.3	0.78	45.0b	0.78c
Aug.	n/a	n/a	n/a	n/a	46.7a	0.87a
Early Sept.	n/a	n/a	n/a	n/a	45.6b	0.87a
Early Harvest (late Sept.)	37.7a	0.73a	n/a	n/a	43.3c	0.79b
Late Harvest (late Oct.)	36.1b	0.62b	n/a	n/a	37.8d	0.62d
Effects			*P*-values			
S	**<0.0001**	**<0.0001**	n/a	n/a	**<0.0001**	**<0.0001**
C	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
S × C	**0.0001**	**0.0218**	n/a	n/a	**<0.0001**	**<0.0001**
N	**<0.0001**	**<0.0001**	**<0.0001**	**0.0048**	**<0.0001**	**<0.0001**
S × N	**<0.0001**	0.8400	n/a	n/a	**<0.0001**	**<0.0001**
C × N	**0.0054**	0.8307	0.7137	0.5397	0.9445	0.9586
S × C × N	0.4527	0.9950	n/a	n/a	0.9915	0.9972

Note: For each source of variation, different letters reflect a significant statistical difference according the Tukey's comparative test ($P < 0.05$) and are indicated in bold font. n/a, Not applicable as N treatment was not included, the cultivar was not grown or sample date was not conducted in that year.

in our experiment optical sensors would not have been a useful tool for making in-season fertilizer N adjustments to the sugarbeet crop. Similarly, in Ontario, Pfeffer et al. (2010) reported a lack of correlation between optical sensor readings taken at the time of in-season N application with corn yield, which limits utility to adjust fertilizer N applications during the corn season. Similarly, in our study there is not enough evidence to support the use of optical sensors to adjust in-season fertilizer N applications in sugarbeet.

Utility of optical sensor readings to predict crop attributes at harvest

While optical sensor readings might not be effective to adjust fertilizer N rate based on plant N status in June, we were also interested in evaluating whether or not sensors might be useful predictive tools to make harvest decisions. In contrast to our study hypothesis, few cultivars had significant correlations of optical sensor readings taken at all sampling times with either root yield or RWSH at both harvest dates (Table 2). This result

Fig. 2. Relationship of in-season, injected fertilizer nitrogen and optical sensor readings from SPAD meter (top) and GreenSeeker (bottom) taken in June (A, F), mid-August (B, G), early September (C, H), and on the day of sugarbeet harvest – late September (D, I) and late October (E, J) in 2017.

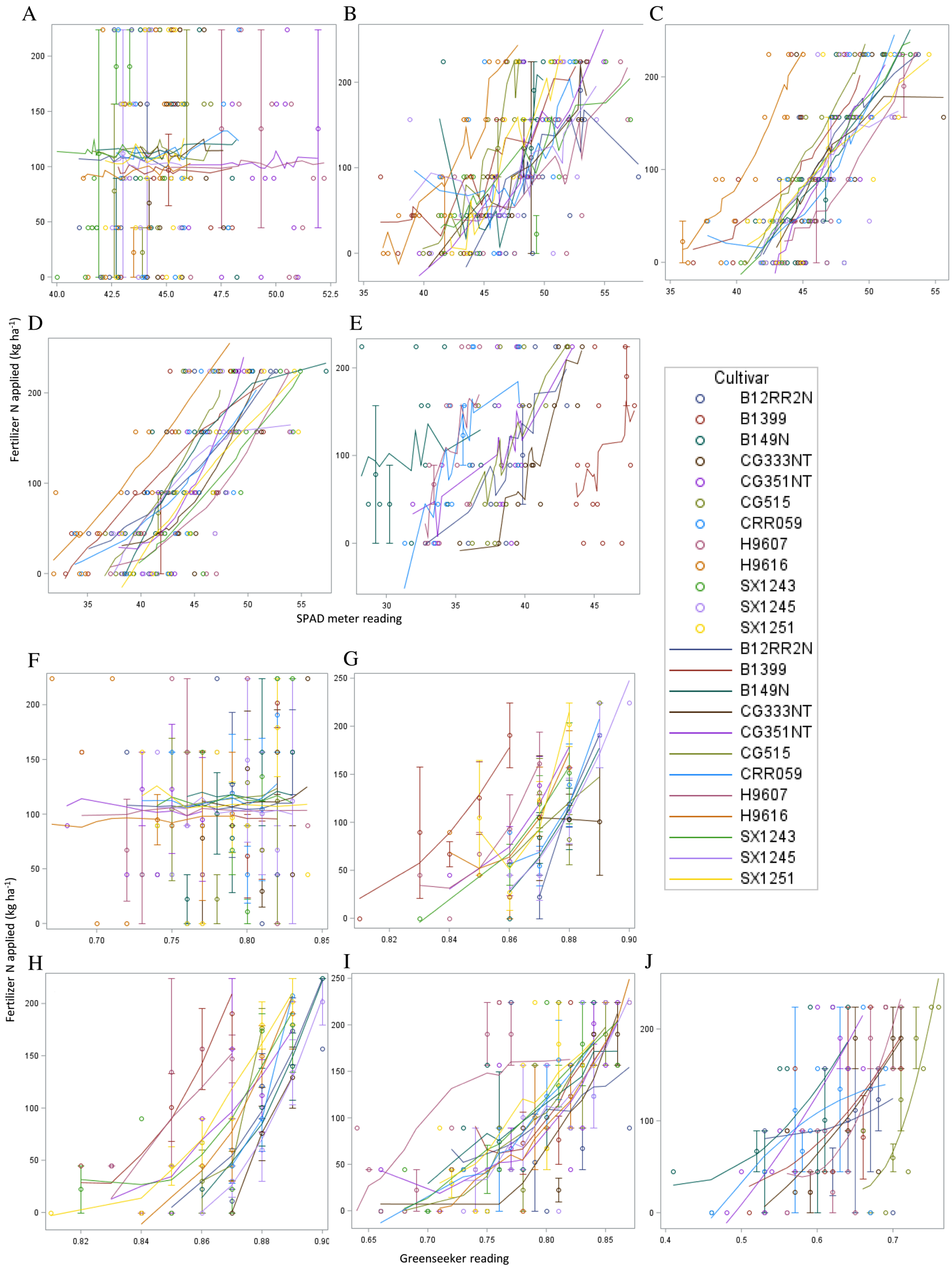
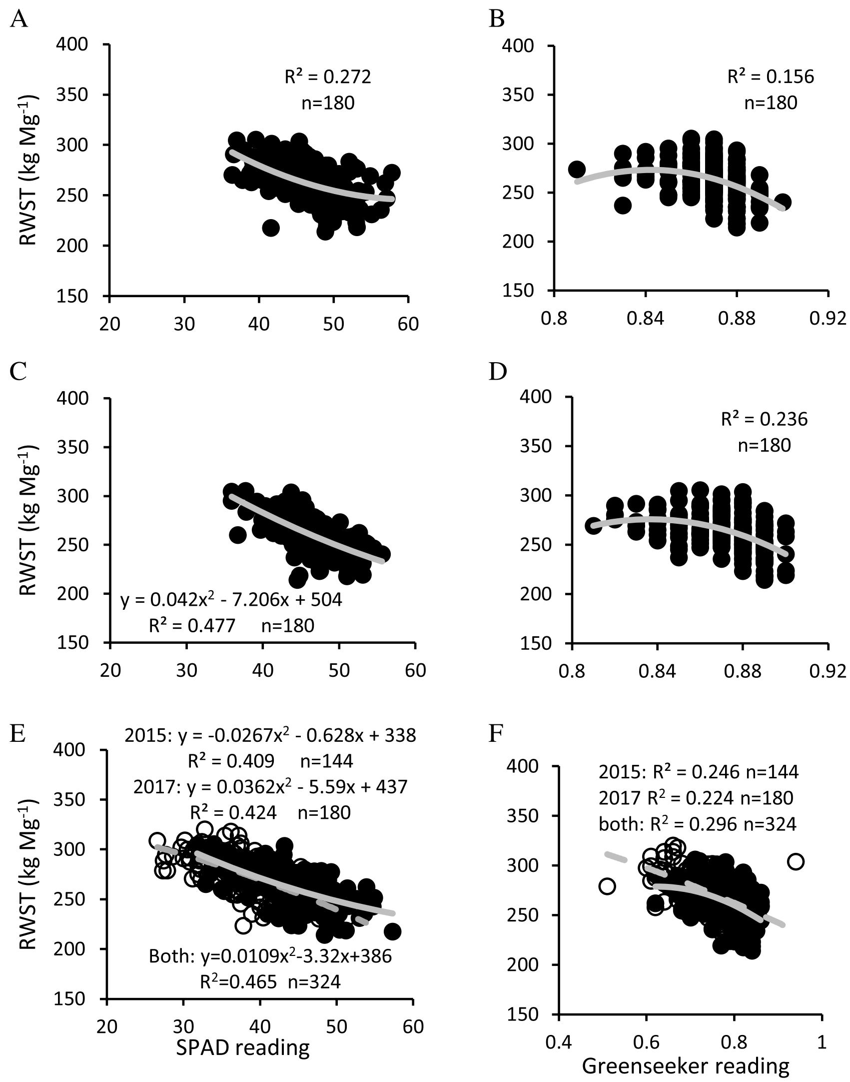


Fig. 3. At early harvest, relationship of recoverable white sucrose per tonne (RWST) and optical sensor readings from SPAD meter (left) and GreenSeeker (right) taken in mid-August (A, B), early-September (C, D), and on the day of sugarbeet early harvest - late September (E, F) in 2015 (E, F open circle) 2017 (closed circle). All prediction models were significant ($P < 0.0001$); only relevant ($R^2 \geq 0.36$) equations are shown. Note the change in scale on x axis in panel F.

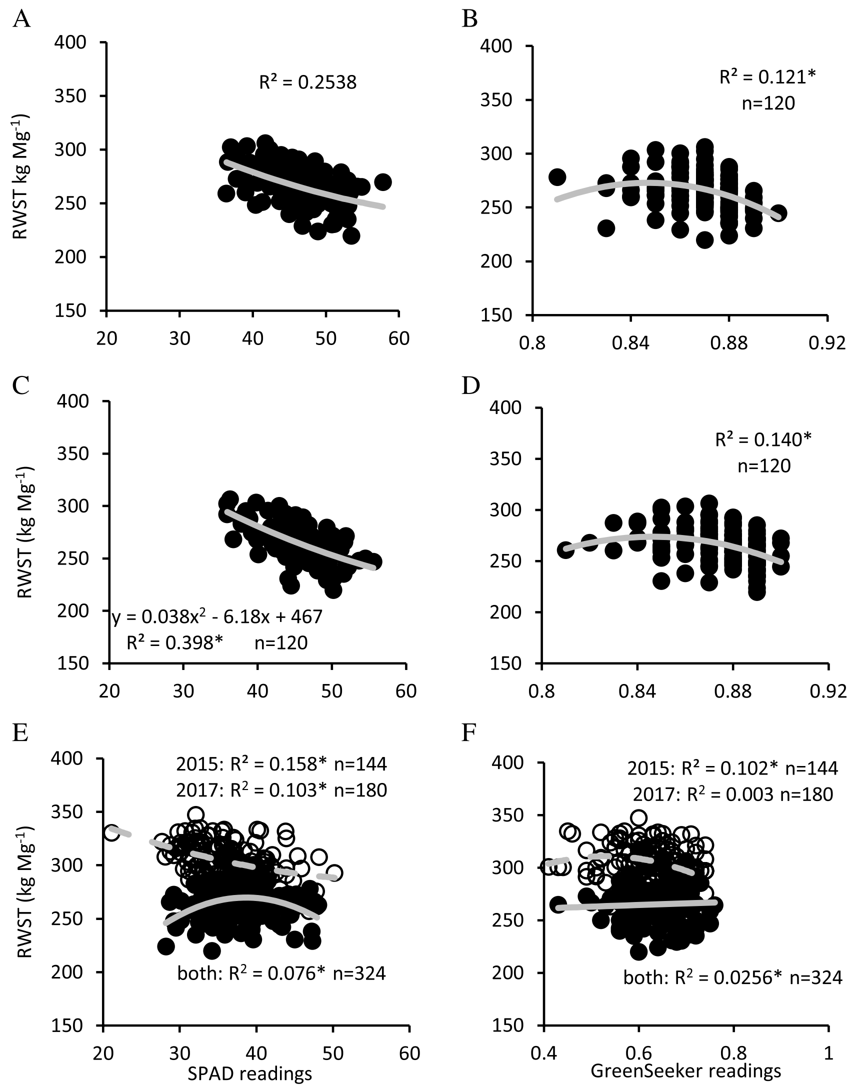


was attributed to the general lack of root yield response to applied N (Fig. 1, Supplementary Figs. S1 and S2[2]). In contrast, Gehl and Boring (2011) reported that GreenSeeker measurements showed promise to estimate root yield and RWSH later in the season (i.e., September). It is possible that significant correlations of root yield with optical sensor readings across cultivars might have been observed had the experiment been conducted in fields with more limiting N conditions and requires further research.

Unlike root yield, the majority of cultivars had a significant correlation of RWST with optical sensors readings (Table 2), except in June (Supplementary Figs. S4 and S4[2]). Later in the growing season (mid-August), a significant proportion of cultivars had correlations of optical sensor readings with applied fertilizer N as well as RWST, and percent sucrose and purity, particularly at the early harvest date (Table 2). The negative correlation of RWST with N applied (Fig 1, Supplementary Figs. S1 and S2[2]) and corresponding similar response of readings with RWST at early harvest (Table 2, Figs. 3 and 4, and Supplementary Figs. S5 and S6[2]) suggests that the RWST response to N fertility was detected with optical sensor readings. Hence, our hypothesis that there would be a relationship of RWST with optical sensor readings was accepted for sampling in mid-August to September (Figs. 3 and 4, and Supplementary Fig. S5[2]) but not in June (Supplementary Figs. S3 and S4[2]). The RWST relationship was not evaluated in a Michigan study evaluating GreenSeeker in sugarbeet production (Gehl and Boring 2011).

Interestingly, at the late harvest (October), the number of cultivars with significant correlations of optical sensor

Fig. 4. At late harvest, relationship of recoverable white sucrose per tonne (RWST) and optical sensor readings from SPAD meter (left) and GreenSeeker (right) taken in mid-August (A, B), early-September (C, D), and on the day of sugarbeet early harvest - late September (E, F) in 2015 (E, F open circle) and 2017 (closed circle). *Prediction models were significant ($P < 0.01$); only relevant ($R^2 \geq 0.36$) equations are shown. Note the change in scale on x axis in panel F.



readings with sugarbeet crop attributes decreased compared with at the early harvest (September) (Table 2). For instance, on the day of early harvest, RWST (Figs. 3, 4, Supplementary Fig. S6[2]) as well as sucrose content and purity (not shown) had significant negative correlation with optical sensor readings taken in mid-August to September (all dates in all years), but there were very few significant correlations at the late harvest (October) (Table 2). Readings taken the day of late harvest showed no correlation with N applied (Table 2; Fig. 2, Supplementary Fig. S6[2]). Likewise, models to predict RWST at late harvest using optical sensors were significant but not relevant (Fig. 4). These results were attributed to the decline in chlorophyll due to natural senescence of the crop rather than a response to fertilizer N. Similarly, Gehl and Boring (2011) reported that relationship between GreenSeeker readings and RWSH (RWST and sucrose concentration not reported) was weak during the early growing season (i.e., when in-season N application would occur), strongest during late summer, and decreased during late growing season (i.e., October). Therefore, we conclude that late October might represent the end of the window for the applicability of optical sensors across sugarbeet cultivars. Given that harvest typically concludes in the first week of November in Ontario and Michigan, there would be less need for the optical sensor readings in late October as few fields remain unharvested.

Given the correlations of optical sensor readings taken in mid-August to September with RWST in individual cultivars at early harvest, we explored the potential to provide an industry-relevant predictive equation for all cultivars. While statistically significant when readings were taken in mid-August through to early harvest ($P < 0.0001$), the only models deemed relevant (i.e., $R^2 > 0.36$) to predict RWST at early harvest were when SPAD meter data were collected in early September and on the day of early harvest (Fig. 3). The proportion of RWST variability explained by the model in SPAD readings taken in early September was 48% and >41% on the day of early harvest (Fig. 3). At these same time points, approximately half the variability (24%) was explained by the model in GreenSeeker readings (Fig. 3). Hence, future research to refine this relationship would be needed to more precisely estimate RWST. Regardless, the significant negative response (of all cultivars; Fig. 3) and significant negative correlations (of most cultivars; Table 2) between RWST and optical sensor readings suggests that lower readings of both optical sensors indicates greater RWST at early harvest. Thus, growers may use optical sensors from mid-August through September to guide their decision on which sugarbeet fields (or part thereof) to harvest in late September by comparing readings from fields and selecting based on relative RWST concentration (i.e., lower readings indicate greater RWST).

Results demonstrate a greater utility of the SPAD meter over the GreenSeeker in sugarbeet production. The predictive equations for the SPAD meter accounted for more of the variation in the data than the GreenSeeker (Figs. 3 and 4). Likewise, based on individual cultivars and across all sampling dates and harvest times, correlation analysis of optical sensor readings with applied fertilizer N and all sugarbeet yield attributes revealed the SPAD meter detected five more (out 26 instances) significant correlations than the GreenSeeker, but the trends among years was not consistent (Table 2). Consequently, the SPAD meter is recommended but selection of one optical sensor over the other might be more dependent on grower preference, labour requirements, applicability to other crops and (or) price.

Conclusions

Here we provide prediction equations of SPAD meter readings to estimate RWST at early harvest, but sensors were not predictive of the need for in-season fertilizer N nor root yield. The utility of either sensor is predicated on the assumption that there is a harvest decision to be made; that is, (*i*) early harvest is an option and (*ii*) there is more than one field or area to harvest. Our results suggest that the SPAD meter, and to a lesser extent the GreenSeeker, can be used in mid-August to September to differentiate between fields, where lower readings indicate greater RWST concentration in sugarbeet at the end of September. While many growers can visually estimate root yield, having a tool that differentiates RWST content would be valuable in deciding which field (or part therein) to harvest, assuming other factors influencing decision making are equal (i.e., plans for crop rotation and cover crops, amendment applications, disease pressure, soil texture and ease of harvest). While useful to differentiate, research efforts are needed on N-responsive soils to further develop predictive equations of optical sensor readings with RWST content.

Although there were differences among cultivars in root yield, RWST and partial profit margins, the general lack interactions of cultivar with harvest date as well as with N rate, suggests that growers do not need to adjust these management practices based on the cultivar grown. Due to the contrasting response of root yield and RSWT to applied N, it is critical that partial profit margins are used to determine optimal fertilizer rates. Applying fertilizer N at a rate that maximizes root yield would have resulted in over-application and up to \$450 ha^{-1} loss in profits. Optical sensors were not effective in predicting the need nor quantity of in-season fertilizer N; and hence are not recommended for this purpose. It is not known if this lack of relationship was due to crop characteristics, inherent high soil fertility and (or) the predictive capacity of the optical sensors tested. Future research assessing the applicability of optical sensors as a decision tool to modify the quantity of in-season fertilizer N applied to sugarbeet is necessary.

Acknowledgements

The authors are grateful to the Ontario Sugarbeet Growers Association, Michigan Sugar Company Inc. and the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), through the Ontario Agri-Food Innovation Alliance as well as MSC for in-kind quality analysis. We wish to acknowledge our grower cooperator for accommodating this research on farm and Mike Zink, Sean Vink and undergraduate students for their great work in the field and lab.

Conflict of Interest Statement

The authors declare no conflict of interest.

References

Afshar, R., Nilahyane, A., Chen, C., He, H., Stevens, B.W., and Iversen, W.M. 2019. Impact of conservation tillage and nitrogen on sugarbeet yield and quality. Soil Tillage Res. **191**: 216–223. doi:10.1016/j.still.2019.03.017.

Al-Sayed, H.M., Abd El-Razek, U.A., Sarhan, H.M., and Fateh, H.S. 2012. Effect of harvest dates on yield and quality of sugar beet varieties. Aust. J. Basic Appl. Sci. **6**(9): 525–529.

Bandhu, R.B., and Parbati, A. 2015. Use of optical sensor for in-season nitrogen management and grain yield prediction in maize. J. Maize Res. Develop. **1**(1): 64–70. doi:10.3126/jmrd.v1i1.14244.

Bu, H., Sharma, L.K., Denton, A., and Franzen, D.W. 2016. Sugar beet yield and quality prediction at multiple harvest dates using active-optical sensors. Agron. J. **108**: 273–284. doi:10.2134/agronj2015.0268.

Campbell, L.G. 2002. Sugar beet quality improvement. J. Crop Prod. **5**: 395–413. doi:10.1300/J144v05n01_16.

Carter, J.N., and Traveller, D.J. 1981. Effect of time and amount of nitrogen uptake on sugarbeet growth and yield. Agron. J. **73**: 665–671. doi:10.2134/agronj1981.00021962007300040023x.

Carter, J.N., Westermann, D.T., Jensen, M.E., and Bosma, S.M. 1975. Predicting nitrogen fertilizer needs for sugarbeets from residual nitrate and mineralizable nitrogen. J. Am. Soc. Sugar Beet Technol. **18**(3): 232–244. doi:10.5274/jsbr.18.3.232.

Curcic, Z., Ciric, M., Nagl, N., and Taski-Ajdukovic, K. 2018. Effect of sugar beet genotype, planting and harvesting dates and their interaction on sugar yield. Front. Plant Sci. **9**: 1041. doi:10.3389/fpls.2018.01041. PMID:30073010.

DeBruyn, A., O'Halloran, I.P., Lauzon, J., and Van Eerd, L. 2017. Effect of Sugarbeet Density and Harvest Date on Most Profitable Nitrogen Rate. Agron. J. **109**: 2343–2357. doi:10.2134/agronj2017.03.0141.

DeBruyn, A.H., O'Halloran, I.P., Lauzon, J.D., and Van Eerd, L.L. 2019. Nitrogen and phosphorus fertilizer timing, source, and placement in sugarbeet. Agron. J. **111**: 859–866. doi:10.2134/agronj2018.06.0404.

Eckhoff, J.L.A. 1999. Sugarbeet response to nitrogen at four harvest dates. J. Sugar Beet Res. **36**: 33–45. doi:10.5274/jsbr.36.4.33.

Food and Agriculture Organization of the United Nations. 2019. Production quantities of sugar beet by country; Average 1994–2019. [Online]. Available from http://www.fao.org/faostat/en/#data/ QC/visualize [27 Apr. 2021].

Gehl, R.J., and Boring, T.J. 2011. In-Season prediction of sugarbeet yield, quality, and nitrogen status using an active sensor. Agron. J. **103**: 1012–1018. doi:10.2134/agronj2011.0040.

Halvorson, A.D., and Hartman, G.P. 1980. Response of several sugar beet cultivars to N fertilization: Yield and corn tissue production. Agron. J. **72**: 665–669. doi:10.2134/agronj1980.000219 62007200040023x.

Hauer, M., Koch, H.J., and Märländer, B. 2015. Water use efficiency of sugar beet cultivars (*Beta vulgaris* L.) susceptible, tolerant or resistant to *Heterodera schachtii* (Schmidt) in environments with contrasting infestation levels. Field Crop. Res. **183**: 356–364. doi:10.1016/j.fcr.2015.07.003.

Heidari, G., Sohrabi, Y., and Esmailpoor, B. 2008. Influence of harvesting time on yield and yield components of sugar beet. J. Agri. Social Sci. **4**(2): 69–73.

Jaggard, K.W., Qi, A., and Armstrong, M.J. 2009. A meta-analysis of sugarbeet yield responses to nitrogen fertilizer measured in England since 1980. J. Agric. Sci., **147**: 287–301. doi:10.1017/S0021859609008478.

Lauer, J.G. 1995. Plant density and nitrogen rate effects on sugar beet yield and quality early in harvest. University of wyoming. Agron. J. **87**(3): 586–591. doi:10.2134/agronj1995.00021962008700030032x.

Marchetti, R., and Castelli, F. 2011. Mineral nitrogen dynamics in soil during sugar beet and winter wheat crop growth. European J. agron. Jun;**35**(1): 13–21. doi:10.1016/j.eja.2011.03.003.

Märländer, B., Hoffmann, C., Koch, H.-J., Ladewig, E., Merkes, R., Petersen, J., and Stockfisch, N. 2003. Environmental situation and yield performance of the sugar beet crop in germany: heading for sustainable development. J. Agron. Crop Sci. **189**: 201–226. doi:10.1046/j.1439-037X.2003.00035.x.

MSC. 2015. SBA Variety Trial. Page 19 in 2015 Variety trial results, Michigan Sugar Company. [Online]. Available from https://www.michigansugar.com/wp-content/uploads/2019/09/Variety-Trial-Results-2015.pdf. [26 Apr. 2021].

MSC. 2016. Rhizoctonia & Cercospora Varieties for 2017. Page 4 in 2016 Variety trial results, Michigan Sugar Company. [Online]. Available from https://www.michigansugar.com/wp-content/uploads/2016/12/Variety-Trial-Results-2016.pdf [26 Apr. 2021].

Pavlů, K., Chochola, J., Pulkrábek, J., and Urban, J. 2017. Influence of sowing and harvest dates on production of two different cultivars of sugar beet. Plant Soil Environ. **63**(2): 76–81. doi:10.17221/614/2016-PSE.

Pfeffer, A., Stewart, G., Janovicek, K., and Deen, W. 2010. Evaluation of canopy reflectance technology using a delta yield approach. Agron. J. **102**(5): 1453–1461. doi:10.2134/agronj2010.0092.

Sexton, P., and Carroll, J.. 2002. Comparison of SPAD chlorophyll meter readings vs. petiole nitrate concentration in sugarbeet. J. Plant Nutr. **25**(9): 1975–1986. doi:10.1081/PLN-120013288.

Sharma, L., and Bali, S. 2017. A review of methods to improve nitrogen use efficiency in agriculture. Sustainability 2018, **10**(1): 51. doi:10.3390/su10010051.

Sharma, L.K., Bu, H., Denton, A., and Franzen, D.W. 2015. Active-optical sensors using red NDVI compared to red edge NDVI for prediction of corn grain yield in North Dakota, USA. Sensors, **15**(11): 27832–27853. doi:10.3390/s151127832. PMID:26540057.

Statistics Canada. 2016. Sugar beet area by census division (CD), 2016 Canada. Statistics Canada, Agriculture Division, Census of Agriculture, 2016. [Online]. Available from https://www150.statcan.gc.ca/n1/pub/95-634-x/2017001/article/54904/catm-ctra-128-eng.htm [26 April 2021].

Strausbaugh, C., Eujayh, I., and Foote, P. 2010. Sugarbeet cultivar evaluation for bacteria root rot. J. Sugarbeet Res. **47**(1–2): 51–46. doi:10.5274/jsbr.47.1.51.

Tarkalson, D.D., Bjorneberg, D.L., Camp, S., Dean, G., Elison, D., and Foote, P. 2016. Improving nitrogen management in Pacific northwest sugarbeet production. J. Sugar Beet Res. **53**(1–2): 14–36. doi:10.5274/JSBR.49.3.79.

Turnbull, J.J.D., and Van Eerd, L.L. 2011. SPAD® chlorophyll meter as a decision-making tool to optimize recoverable white sugar in sugarbeet production. Plant Canada: Plant Adaptation to Environmental Change. Halifax, NS. 17–21 July 2011. Abstract # Wed/CSPP1130.

Van Eerd, L.L., Congreves, K.A., and Zandstra, J.W. 2012. Sugar beet (*Beta vulgaris* L.) storage quality in large outdoor piles is impacted by pile management but not by nitrogen fertilizer or cultivar. Can. J. Plant. Sci. **92**: 129–139. doi:10.4141/cjps2011-054.

Xiong, D., Chen, J., Yu1, T., Gao, W., Ling, X., Li, Y., et al. 2015. SPAD-based leaf nitrogen estimation is impacted by environmental factors and crop leaf characteristics. Sci. Rep. **5**: 13389. doi:10.1038/srep13389. PMID:26303807.