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ORIGINAL ARTICLE

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UAV-based NDVI estimation of sugarbeet yield and quality under varied nitrogen and water rates

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Abstract

The accuracy of the traditional soil and plant-based techniques for assessing sugarbeet demand for nitrogen (N) and yield prediction is generally low. Refining N and irrigation water management is a key to maximizing return for sugarbeet (*Beta vulgaris* L.) growers from agronomic, economic, and environmental perspective. The use of Normalized Difference Vegetative Index (NDVI) in combination with the unmanned aerial vehicle (UAV)-based data collection for in-season estimation of sugarbeet root yield and sugar concentration has potential for precision N management. Sugarbeet field trials were conducted in Idaho in 2019 and 2020 to assess (1) effects of water and N fertilizer rates on yield and estimated recoverable sugar (ERS) and (2) feasibility of predicting root yield and ERS using UAV NDVI. At the lowest N rate, application of water at 100% level resulted in greater yield, compared to 50%, in both years. At higher N rates, 50% level produced higher yields. At each N level, application of water at 100% level resulted in lower ERS, compared to 50%. The UAV NDVI was strongly correlated with root yield and ERS. The relationship between UAV NDVI and root yield and ERS was stronger in July (60 days after planting) compared to June (40 days after planting). Estimating the yield and ERS potential in late June/early July and topdressing the crop before the end of July may help to improve N use efficiency while optimizing sugarbeet production.

1 | INTRODUCTION

The profitability of sugarbeet (*Beta vulgaris* L.) production is based on maximizing three parameters—root yield, sucrose concentration, and sucrose recovery efficiency—or the estimated recoverable sugar (ERS) (Walsh et al., 2019). Efficient nitrogen (N) and irrigation water management are vital for sustainable and profitable sugarbeet production.

Nitrogen deficits can reduce root yield and sucrose concentration. Application of N in excess of sugarbeet crop demand typically leads to vigorous aboveground biomass growth, while negatively impacting sugarbeet root development and sugar accumulation (Franzen, 2003; Shock et al., 2000; Walsh et al., 2019). Further, overapplication of N can reduce sucrose concentration and increase nitrate impurities that tend to lower the sucrose recovery due to impeded sucrose crystallization

Abbreviations: ERS, estimated recoverable sugar; ET, evapotranspiration; ET_c, crop evapotranspiration; NDVI, Normalized Difference Vegetative Index; NIR, near infrared; NUE, N use efficiency; UAV, unmanned aerial vehicle.

and reduced processed sugar yield (Bauer et al., 2001; The Amalgamated Sugar, 2022; Walsh et al., 2019).

In a comprehensive review describing N fertilization effect on sugarbeet vegetative growth and root yield and quality, Varga et al. (2022) report that (1) the growth of sugarbeet roots throughout the vegetative stages has a linear trend, and the most significant root growth occurs from mid-July to September and (2) sugarbeet crop need for N is at peak during the time of most intensive leaf growth (June). Although some studies showed that N deficiency in sugarbeets could be effectively corrected by top-dressing N through June (Gilbert et al., 1981), most reports claim that all required N should be applied and plant-available by six leaves growth stage (The Amalgamated Sugar, 2022; Walsh et al., 2019). Thus, it is vital to determine the appropriate N fertilizer rates for N responsive fields as early in the season as possible.

Sugarbeets are considered one of the higher water consuming crops—typically, substantial amount of water is required to produce sugarbeets, especially due to longer growing season, compared to other crops (Kiymaz & Ertek, 2015; Mahmoodi et al., 2008). Tarkalson et al. (2018) observed that in arid climates, the sugarbeet root and ERS yields were maximized, when water input (irrigation + precipitation) of 598 and 605 mm were applied, respectively. Application of the appropriate irrigation amount and timing can optimize sugarbeet production while minimizing disease pressure, water costs, and N leaching. Excessive irrigation can increase sugarbeet root weight, but lower sugar concentration (The Amalgamated Sugar, 2022; Walsh et al., 2019). However, deficit irrigation and water scheduling can deliver large (up to 20%) water savings without causing substantial reduction in yield or quality (Esmaeili & Yasari, 2011; Topak et al., 2011). Previous reports showed that sugarbeets may tolerate mid-season and late season water stress, making the sugarbeets suitable for production with limited irrigation (Mahmoodi et al., 2008). In fact, as shown by Wittenmayer and Schilling (1998), sugarbeet plants respond to mild water stress by increasing the taproot proportion relative to whole-plant biomass, indicating that root yield is not always negatively impacted by mild/short-span water limitations.

Studies have shown that N and water uptake by plants is fundamentally interactive (Randall and Goss, 2008; Raun and Schepers, 2008). Crop response to applied N is strongly affected by plant-available water and vice versa. Soil moisture levels influence both N release from applied fertilizers and N mineralization reactions (Zhang et al., 2017). The benefits of applied N fertilizers to crops are minimized in a water-limited environment, while excessive irrigation may result in N leaching, negatively impacting crop yield (Fu et al., 2014). In most irrigated crop production areas, as soils developed under semi-arid conditions, the soil organic matter (OM) content and N mineralization rates are typically low (Bilboa et al., 2004), necessitating addition of N to optimize sugarbeet production. On the other hand, insufficient or excessive N fertilization in turn reduces water use efficiency, impacting both yield and quality (Fu et al., 2014; Zhang et al., 2017).

Core Idea

- The UAV-based NDVI was strongly correlated with sugarbeet root yield and the estimated recoverable sugar (ERS).
- The relationship between UAV NDVI and root yield and ERS was stronger in July (60 days after planting), compared to June (40 days after planting).
- Determining the sugarbeet crop yield and ERS potential in late June/early July and topdressing before the end of July may help to improve N use efficiency while optimizing production.

Determining optimum water and N fertilizer levels should be done by utilizing locally grown varieties and considering management practices prevalent in the production area. Balanced N nutrition is of extreme importance to sugarbeet producers' revenue and factory processing. Refining N management is a key to maximizing economic return for sugarbeet growers from agronomic, economic, and environmental perspective. However, the usefulness and accuracy of the traditional soil and/or plant-based testing techniques for assessing sugarbeet crop demand for N and yield prediction is generally low. This is further complicated by the water × N interaction, coupled with a considerable temporal variability (year effect) on sugarbeet crop response to applied N, making pre-plant soil testing (Jaggard et al., 2009), and in-season petiole analysis (Shock et al., 2000) not reliable for nutrient status monitoring and/or yield and quality estimation. High residual soil N (Shock et al., 2000) and low available soil moisture (Marschner, 1995) tend to affect the petiole nitrate values. Poor correlation of petiole nitrate concentrations with sugarbeet yield and quality limits the development of successful methodology for monitoring sugarbeet growth and N levels and for yield and quality prediction in-season. In-season tracking of plant N levels throughout the growing season has been examined as a potential measure of sugarbeet demand for N.

Precision nutrient and water management has been highlighted for optimizing fertilizer and irrigation water inputs because it accounts for both spatial (in space) and temporal (in time) variability of crop N demand and supply (Diacono et al., 2013; Miao et al., 2007; Poudel et al., 2021). Active-light sensors have shown promise for in-season estimation of root yield and ERS in sugarbeet fields (Gehl & Boring, 2011).

The use of crop reflectance and Normalized Difference Vegetative Index (NDVI) for the in-season assessment of sugarbeet root yield and sugar concentration has the potential to be a valuable tool for precision N management and as the harvest scheduling and prioritization tool. For instance, the sugarbeet production is limited in suitable storage days and processing plant capacity. In this limited operation window, the profitability is directly related to the ERS (Gehl & Boring, 2011). The in-season NDVI-based prediction of sugarbeet yield and quality would be of tremendous value to the growers and the sugarbeet production and processing industry.

Advances in remote sensing have led to the development of unmanned aerial vehicle (UAV)-based data collection and processing methodology that enables to monitor crop growth and development and estimation of crop yield and quality mid-season. This methodology is based on detecting and measuring the optical attributes of plants and their associated vigor and health properties. Crop-specific spectral features of canopy measured with UAVs furnished with multispectral and/or hyperspectral cameras have been used to evaluate various biochemical and physiological characteristics of crops (Wang et al., 2022). To list a few examples, reflectance of spectral band and calculated vegetation indices have been used to estimate plant biomass N content (Fu et al., 2022; Osco et al., 2019), leaf chlorophyll content (Singhal et al., 2019), leaf area index (Gong et al., 2021), biomass production (Zhang et al., 2021), and crop yield (Li et al., 2020).

As an indicator of photosynthetically active biomass, NDVI has been successfully utilized for yield prediction of various crops such as wheat (*Triticum aestivum* L.), corn (*Zea mayz* L.) (Solie et al., 2012), rice (*Oryza sativa* L.) (Harrell et al., 2011), sugarcane (*Saccharum officinarum* L.) (Lofton et al., 2012), potatoes (*Solanum tuberosum* L.) (Sharma et al., 2017), and sugarbeets (*Beta vulgaris* L.) (Gehl & Boring, 2011), and so on.

Remote sensing for tuber crops such as sugarbeets is typically more challenging and not as straightforward as for other crops like grasses. This is because remote sensing using hand-held and/or aerial-based tools we aim to characterize the sugar storing roots of sugarbeet plants located below ground. Several researchers, however, have demonstrated success in developing a UAV-based methodologies for sugar content prediction (Wang et al., 2022) and weed monitoring (Khoshboresh-Masouleh & Akhoondzadeh, 2021). The sensor-based yield prediction models capitalize on the information NDVI provides about the nutrient status of the leaves. The aboveground biomass is responsible for capturing the sunlight and CO_2 to support the growth and development of the sink plant parts—the taproots (Bala & Islam, 2009; Gómez et al., 2020).

2 | OBJECTIVES

The objectives of this study were (1) to analyze the effects of water and N fertilizer rates on yield and quality of sugarbeets, and (2) assess the feasibility of predicting sugarbeet root yield and ERS using UAV-based spectral reflectance measurements.

We hypothesized that (1) the effect of irrigation on sugarbeet root yield and ERS should be more pronounced than the effect of applied N and (2) UAV NDVI should accurately estimate sugarbeet root yield and ERS in-season.

3 | MATERIALS AND METHODS

3.1 | Experimental locations

Field trials were conducted at the University of Idaho, Southwestern Research and Extension Center, Parma, Idaho, in 2019 and 2020. The experimental site is characterized by the semi-arid climate with long, cold, moderately snowy winters, and dry hot summers. To establish the baseline residual soil nutrient levels, soil samples were obtained from the upper 60 cm depth from 15 randomly selected locations within the field approximately 2 weeks before planting. The samples were combined and mixed to produce a composite soil sample representative for the entire field. The samples were analyzed using the Complete Soil Test for agricultural soils analysis at the Western Laboratories (Parma, ID). Detailed methods for soil laboratory analysis are described in Yang et al. (2018). Latitude/longitude, planting dates, soil type, and preplant soil characteristics for both site-years are reported in Table 1.

3.2 | Treatment establishment

Four row plots of sugarbeets (var. BTS 2570) were planted at a depth of 1.2 cm using a custom built six row Monosem vacuum planter (Monosem Inc., Edwardsville, KS). Plant density was approximately 170 sugarbeet plants per 30 m, with seed spacing of 20.3 cm. With the row spacing of 55.9 cm, the plots were 12.2 m long, trimmed to 10.7 m before harvest. The previous crop in 2019 was corn, and in 2020 the crop was potato. The experimental plots were arranged in a split-plot design with six replications in a 2 × 3 factorial setup, resulting in a total of 36 plots for each site-year. Water level was the main plot (50% and 100% of crop evapotranspiration, ET_c).

Nitrogen level was the sub-plot and included low, medium, and high N rates, corresponding to 112, 224, and 336 kg N ha^{-1} (residual soil N plus supplemental fertilizer N from urea, 46-0-0, applied pre-plant, lightly incorporated with tillage). To minimize the effect of N and water application on neighboring plots, additional four row border plots were planted between the experimental plots. Irrigation was applied utilizing the sub-surface drip irrigation system with the drip tape installed at 10 cm-depth. The 100% ET_c treatment represented well-watered conditions, while the 50% ET_c enabled

TABLE 1 Latitude/longitude, planting date, soil type, and preplant soil characteristics[a] (top 60 cm) for 2 site-years in Idaho

Site-year	Latitude/longitude	Planting date	Soil type[b]	pH	OM (%)	Soil residual N (kg ha^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	$SO_4{}^{2-}$S (mg kg^{-1})
Parma, Idaho									
2019	43°80′36.21′′ N, 116°94′55.29′′ W	April 18	Greenleaf-Owyhee silt loams, 0–1% slopes	8.1	1.9	112	30	350	17
2020	43°80′47.08′′ N, 116°94′30.53′′ W	April 9		8.4	2.0	110	37	225	12

[a]Detailed methods for soil laboratory analysis described in Yang et al. (2018).
[b]Owyhee, coarse-silty, mixed, superactive, mesic Xeric Haplocalcids.

us to assess the influence of deficit irrigation on sugarbeets during the growing season. Irrigation was applied to match 100 and 50% rates of estimated model ET_c. The Kimberly-Penman evapotransportation (ET) model (Wright, 1982) was used for ET_c calculation. The model assesses ET_c by modeling alfalfa-reference ET from data measured at a local AgriMet weather station (U.S. Bureau of Reclamation, Parma, ID, located within 1 km of the experimental site) and multiplying the reference ET by a crop-specific coefficient (K_c) that varies throughout the season based on the sugarbeet growth stage (Wright, 1982). The K_c values ranged from 0.22 at plant emergence, 1.0 at full canopy cover, and 0.7 at maturity (U.S. Bureau of Reclamation, 2022). Rates of ET_c were based on nonwater limited conditions. Thus, water was applied to plots depending on ET_c demand through the season and the amount of irrigation applied was adjusted to account for precipitation. Each treatment was irrigated independently, with electrically operated valves controlling the flow of water to each plot. An Irritrol-MC-PLUS-B-Controller (Irritrol Systems, Riverside, CA, USA) was used to control the opening and closing of the valves. The drip lines had emitters spaced 80 cm apart with emitter flow rate of 2 L h^{-1}. Flow meters and emitters were tested at the beginning of each growing season to ensure proper calibration. Irrigation was terminated about 1 week before harvest.

3.3 | In-field sampling and measurements

In-field sampling was done at 40 and 60 days after planting (early June and mid-July, respectively), coinciding with four and eight leaves growth stages. Sugarbeet plant height, dry biomass weight and total N concentration, and NDVI were measured in each plot. The NDVI computed as a ratio of absorbed and reflected red and near infrared (NIR) light is a spectral index widely used to assess crop conditions throughout the growing season. The NDVI values may range from 0 to 1, with higher values associated with health, vigorous plant biomass. Plant height was determined by measuring the height of 15 randomly selected plants per plot, from the tip of the top leaf to the soil surface. Hand-harvested aboveground biomass (leaves and the top 2 cm of taproot) from the 15 randomly selected plants per plot were oven-dried at 120°C for 48 h and weighted to determine dry biomass weight. Dried biomass samples were analyzed for total N concentration at Brookside Laboratories, Inc (New Bremen, OH) using the official Association of Official Analytical Chemists combustion method 990.03 (crude protein) with extended uncertainty of ±5%.

FIGURE 1 Multispectral RedEdge M (MicaSense, Seattle, WA) camera mounted on a UAV Matrice 100 (DJI, Los Angeles, CA) utilized to collect the aerial imagery, Parma, ID, 2020

Matrice 100 UAV (DGI, Los Angeles, CA) equipped with RedEdge M camera (MicaSense Inc., Seattle, WA) was used to obtain aerial-based spectral measurements (Figure 1).

The UAV was flown at an altitude of 100 m above the ground level within 2 h of solar noon. The RedEdge M camera captures images of high resolution within six spectral bands: red (640–244,680 nm), green (530–570 nm), blue (530–570 nm), red-edge (730–740 nm), and NIR (770–810 nm) (Mamaghani & Salvaggio, 2019). Data collected with the UAV were processed with Micasense Atlas software (MicaSense, Inc, Seattle, 247 WA) and Pix4Dmapper software (Version 4.3.33) (Pix4D SA, Lausanne, Switzerland), as detailed by Walsh et al. (2018).

The NDVI was calculated as: NDVI = (ρNIR − ρRed)/(ρNIR + ρRed), where ρ_{NIR} and ρ_{Red} is the fraction of emitted NIR and red radiation, respectively, returned from the sensed crop canopy (reflectance).

In late September, sugarbeets were scalped to a 3.8-cm sized disc and harvested. Three 10-kg samples were taken from each plot for root yield (ton ha^{-1}) and quality [sugar concentration (%), ERS (kg ha^{-1}), conductivity (mmhos cm^{-1}), brei nitrate content (mg kg^{-1})] determination at the Amalgamated Sugar beet quality laboratory, Boise, ID.

3.4 | Statistical analysis

Data were analyzed using SAS 9.4 (SAS Institute, Cary, NC). Analysis of variance (ANOVA) was performed using PROC MIXED to determine differences in NDVI among N and water application treatments, and to determine the main effects of N rate and irrigation on sugarbeet growth parameters (plant height, biomass weight, and N concentration), root yield and quality (sugar concentration, conductivity, brei nitrate content, and ERS). Proc CORR was used to determine the Pearson correlation coefficients between N and water levels, and UAV NDVI and sugarbeet root yield, and ERS. Figures and regressions were generated using Microsoft Excel (v. 2205; Microsoft Corp.).

4 | RESULTS AND DISCUSSION

4.1 | Growing conditions

Monthly and seasonal air temperature, precipitation, and ET from planting to harvest are detailed in Table 2. The overall 2019 and 2020 season mean temperatures were comparable (18.3˚C and 18.2˚C, respectively) and close to the 11-year mean temperature value of 18.4˚C (Table 2). Mean temperatures in June, July, and August were slightly higher in 2019 compared to 2020. Total precipitation in 2020 (205 mm) was much greater than in 2019 (144 mm); in both years, precipitation was higher than the 11-year value of 94 mm. The 11-year value reflects very low precipitation amounts in several years, such as 2011, 2012, and 2018, in which less than 76 mm of precipitation was received annually from planting to harvest (extreme drought years). The combination of temperature and precipitation is reflected in the total grass-based reference ET values of 1,142 mm in 2019, 1,152 mm in 2020, comparable to 1,166 mm 2010–2020 average (Table 2). In general, the temperature and precipitation trends in 2019 showed that the weather was less favorable for crop production compared to 2020. Although the mean temperatures were comparable, precipitation was much less frequent, and sporadic (minimal precipitation in June, no precipitation in July) in 2019.

4.2 | Plant height, June

Plant height was overall slightly higher in 2020 (ranging from 23.5 to 28.9 cm) compared to 2019 (21.6 to 25.3 cm) (Table 3). In both years, N and water treatments resulted in statistically significant ($p < 0.05$) differences in plant height. The shortest plants in both years were associated with treatment 2 (112 kg N ha^{-1} + 100% ET). In 2019, the treatments 5 and 6 with highest N rate (336 kg N ha^{-1} + 50% ET, and +100% ET) as well as treatment 3 (112 kg N ha^{-1} + 50% ET) resulted in taller plants. In 2020, the tallest plants were noted with treatment 6, highest N rate and highest water application (336 kg N ha^{-1} +100% ET), as well as treatment 3 (112 kg N ha^{-1} + 50% ET).

4.3 | Plant height, July

Plant height was higher in 2020 (27.0 to 42.7 cm) compared to 2019 (23.8 to 29.9 cm) (Table 3). In both years, significantly shorter ($p < 0.05$) plants were noted for treatments with lower N and water rates, compared to higher N and water rates. In 2019, application of 100% ET with the highest N rate of 336 kg N ha^{-1} resulted in significantly taller ($p < 0.05$) plants, compared to 50% ET, while in 2020, the 100% ET treatment's plant height was numerically greater, but not statistically significant.

4.4 | Biomass weight, June

In both years, the lowest biomass weight was noted for treatments 1 and 2 with the lowest N rate (112 kg N ha^{-1} + 50% ET, and +100% ET) (Table 3). As a general trend, the biomass production increased at higher N and water rates in both years. In 2019, numerically highest biomass weight was observed with treatment 6, highest N and water rates (336 kg N ha^{-1} + 100% ET), the differences were not statistically significant for treatments beyond the lowest N rate of 112 kg N ha^{-1}, independent of the water rate. In 2020, application of 100% ET water rate did not increase biomass weight at both 224 and 336 kg N ha^{-1}, compared to 50% ET. This indicates that N may have been more important for biomass production, compared to irrigation, which makes sense with cooler, wetter year. This agrees with findings by Wang et al. (2021) reporting that, under the same irrigation level, N application increased biomass dry matter accumulation in sugarbeet leaves.

TABLE 2 Monthly and seasonal air temperature, precipitation, and evapotranspiration planting to harvest for 2 site-years in Idaho (U.S. Bureau of Reclamation, 2021)

Year	April	May	June	July	August	September	Season
Mean temperature (˚C)							
2019	11.6	15.3	19.3	23.2	23.3	17.0	18.3
2020	11.2	15.7	18.6	22.9	23.1	17.5	18.2
2010–2020	10.7	15.5	19.6	24.2	23.0	17.6	18.4
Total precipitation (mm)							
2019	36.6	73.9	4.3	0.0	8.6	20.8	144
2020	13.2	74.7	64.0	30.0	2.3	20.8	205
2010–2020	21.0	30.9	18.0	7.4	3.1	13.7	94
Total grass-based reference evapotranspiration, ET_0 (mm)							
2019	128	170	236	248	216	144	1142
2020	143	184	206	255	220	143	1151
2010—2020	135	185	230	258	213	145	1166

4.5 | Biomass weight, July

Biomass production was much more accelerated from June to July in 2020 compared to 2019 (Table 3). In July 2019 and 2020, biomass weights ranged from 364 to 704 g, and from 893 to 1,724 g, respectively. In general, three separate groups of treatments stand out in both years: treatments 1 and 2, treatments 3 and 4, and treatments 5 and 6. The separation is clearly associated with N level, rather than with water application; the higher the N rate, the greater the biomass weights, but higher water application within the same N rate did not always result in greater biomass production.

Both plant height and biomass weight went from comparable in June to much greater in 2020 for July compared to 2019. This may be partially explained by the substantially higher precipitation in 2020, compared to 2019 in June and July (Table 2). June and July 2019 were much drier and warmer, compared to June–July in 2020.

Previous research has shown that sugarbeet plants absorbed only about 25% of the incoming solar radiation in May, and up to 83% in June, indicating tremendous biomass production expansion occurring in early summer (Hoffmann & Kluge-Severin, 2010). The most rapid sugarbeet leaf formation occurs from the beginning of June (canopy closure) and mid-July, with the largest daily increase in sugarbeet leaf expansion from mid-June to mid-July (Varga et al., 2022).

4.6 | Biomass N concentration, June

Biomass N concentration values were comparable for both years ranging from 3.7% to 4.6% in 2019, and from 3.8% to 4.8% in 2020 (Table 3). Overall, the biomass N concentration values were within the typically reported range—N concentration in the leaves of sugarbeet plants is from 2.2% to 3.5% (Varga et al., 2022). Bergmann (1992) stated that the optimum N concentration of fully developed mature sugarbeet leaves (50–60 days after germination) should be 4.0%–6.0%. On the other hand, Draycott and Christenson (2003) reported that N concentrations in sugarbeet leaf blades typically range between 2.2% and 3.5%.

In both years, the same trend was noted: the lowest biomass N concentration at lowest N and water rates (treatments 1 and 2), and the highest biomass N concentration at highest N and water rates (treatments 5 and 6). At medium N rate of 224, 50% ET (treatment 3) resulted in significantly greater ($p < 0.05$) biomass N concentration, compared to treatment with 100% ET (treatment 4). In both years, 50 and 100% ET resulted in statistically the same biomass N concentrations at the same N rates; in fact, 100% ET resulted in numerically lower N concentration values, compared to 50% ET within each N rate. This trend makes sense since the plant available N uptake drives N accumulation in the plant. Grzebisz et al. (2010) reported that leaves and petioles of healthy sugarbeet plants hold a large amount of N in the nitrate form. Bilir and Saltali (2021) showed that N fertilizer rates can greatly influence N concentration in the sugarbeet leaves. Additionally, higher irrigation water application rates may encourage vegetative growth, while resulting in lower N concentrations in leaves.

4.7 | Biomass N concentration, July

Sugarbeets nutrient uptake is at maximum in July, when water needs are typically the highest. Malnou et al. (2008) showed

TABLE 3 Sugarbeet plant height (cm), biomass weight (g), biomass N concentration (%), and unmanned aerial vehicle Normalized Difference Vegetative Index (UAV NDVI) for 2 site-years in Idaho

Treatment	June				July			
	Plant height (cm)	Biomass weight (g)	Biomass N (%)	UAV NDVI	Plant height (cm)	Biomass weight (g)	Biomass N (%)	UAV NDVI
2019 growing season								
112 kg N ha^{-1} + 50% ET	22.2b	111b	3.9b	0.34c	23.8c	364c	2.6	0.59d
112 kg N ha^{-1} + 100% ET	21.6b	111b	3.7b	0.48c	24.1c	435c	2.6	0.60d
224 kg N ha^{-1} + 50% ET	24.8a	189a	4.4a	0.52ab	25.7c	518bc	2.8	0.73c
224 kg N ha^{-1} + 100% ET	23.6ab	172a	4.1b	0.53ab	27.9b	526bc	2.7	0.77b
336 kg N ha^{-1} + 50% ET	25.3a	184a	4.6a	0.50b	27.8b	704a	3.0	0.78b
336 kg N ha^{-1} + 100% ET	25.1a	208a	4.5a	0.55a	29.9a	654ab	2.8	0.82a
2020 growing season								
112 kg N ha^{-1} + 50% ET	26.0ab	104b	4.1b	0.53	27.0c	893c	1.4	0.64
112 kg N ha^{-1} + 100% ET	23.5b	100b	3.8b	0.52	27.2c	1,101c	1.3	0.66
224 kg N ha^{-1} + 50% ET	28.9a	135ab	4.6a	0.55	35.4b	1,473ab	1.4	0.71
224 kg N ha^{-1} + 100% ET	25.8ab	132ab	4.2b	0.57	34.4b	1,202bc	1.4	0.74
336 kg N ha^{-1} + 50% ET	26.4ab	154a	4.8a	0.56	42.0a	1,705a	1.6	0.69
336 kg N ha^{-1} + 100% ET	28.5a	132ab	4.6a	0.56	42.7a	1,724a	1.5	0.69

Note: The values followed by the same letters within each column indicate nonsignificant difference at $p < 0.05$ based on the analysis of variance (ANOVA) procedure utilizing the Duncan's multiple range test.

that the sugarbeet plants take up 102–147 kg N ha^{-1} in mid-July, the time at which the leaf area index is the highest, while N uptake slows down considerably by the end of July (Varga et al., 2022).

In our trial, by July, the biomass N concentrations declined as the plants grew, developed, and expanded more new, larger leaves, thus, leading to N dilution. Wang et al. (2021) noted that both N and water application increased N accumulation in the sugarbeet biomass. The differences in biomass N concentration values were not statistically significant among treatments in both years. Also, in both years, numerically higher biomass N concentration was noted for treatment 5, with the highest N rate and lower water level (336 kg N ha^{-1} + 50% ET) (Table 3).

The analysis of variance (Table 4) has shown that N was a primary source of variation in sugarbeet vegetative characteristics. Nitrogen and water effects were significant ($p < 0.05$) for six and one out of eight evaluated parameters, respectively. While year × ET interaction was significant ($p < 0.05$) for just one parameter (biomass N concentration measured in July), year × N interaction was significant ($p < 0.05$) for five out of eight parameters (Table 4). This suggests that temporal variability in sugarbeet vegetative characteristics response to N was more pronounced compared to response to applied water.

4.8 | Conductivity and brei nitrate content

Conductivity is a measurement used to assess the quality of sugar beet roots. Typically, a strong correlation between conductivity and fresh pulp juice purity is expected (Salama et al., 2019). In our trial, in 2020, conductivity (ranging from 0.64 to 0.72 mmhos cm^{-1}) was overall slightly higher than in 2019 (Table 5). While the treatments had no statistically significant effect on conductivity in 2019 (0.60 to 0.65 mmhos cm^{-1}),

TABLE 4 Analysis of variance (ANOVA) for 2 site-years (combined)

Effect	June Plant height	June Biomass weight	June Biomass N	June UAV NDVI	July Plant height	July Biomass weight	July Biomass N	July UAV NDVI
Year	0.1091	0.0134	0.5668	<0.0001	<0.0001	0.0294	0.0598	0.3315
ET	0.6173	0.1776	<0.0001	0.6585	0.1849	0.7460	0.8765	0.1944
N	0.3802	<0.0001	<0.0001	<0.0001	<0.0001	0.0282	0.6067	0.0002
Year × ET	0.1079	0.4004	0.4506	0.7552	0.2148	0.9411	0.0019	0.7042
Year × N	0.0226	0.0036	0.9375	<0.0001	<0.0001	0.4984	0.2801	0.0179
ET × N	0.0104	0.0780	0.1985	0.5587	<0.0001	0.0007	0.7172	0.8744
Year × ET × N	0.0026	0.0508	0.6867	<0.0001	<0.0001	<0.0001	0.3254	0.7951

Note: The table shows the sources of variation and probability values for the *F* tests of each main effect and interactions for plant height, biomass weight, biomass N, and UAV NDVI.
Abbreviation: UAV NDVI, unmanned aerial vehicle Normalized Difference Vegetative Index.

TABLE 5 Sugarbeet conductivity (mmhos cm^{-1}), brei nitrate content (mg kg^{-1}), root yield (ton ha^{-1}), sugar concentration (%), and estimated recoverable sugar (ERS) (kg ha^{-1}) for 2 site-years in Idaho

Treatment	Conductivity (mmhos cm^{-1})	Brei nitrate (mg kg^{-1})	Root yield (ton ha^{-1})	Sugar concentration (%)	ERS (kg ha^{-1})
2019 growing season					
112 kg N ha^{-1} + 50% ET	0.64	95.8	58.9d	17.1b	7105d
112 kg N ha^{-1} + 100% ET	0.63	79.8	66.0b	16.5c	10,101b
224 kg N ha^{-1} + 50% ET	0.65	78.7	67.6c	17.5a	8710c
224 kg N ha^{-1} + 100% ET	0.61	82.0	76.0a	16.8b	12,327a
336 kg N ha^{-1} + 50% ET	0.61	95.2	62.9c	17.2ab	8556c
336 kg N ha^{-1} + 100% ET	0.60	80.8	84.6a	17.0b	12,333a
2020 growing season					
112 kg N ha^{-1} + 50% ET	0.69ab	180.7	84.4	18.4ab	13,380
112 kg N ha^{-1} + 100% ET	0.65b	140.6	86.8	18.1b	13,634
224 kg N ha^{-1} + 50% ET	0.72a	160.7	98.6	18.7ab	15,818
224 kg N ha^{-1} + 100% ET	0.64b	179.3	93.4	18.4ab	14,900
336 kg N ha^{-1} + 50% ET	0.72a	171.9	92.7	18.8a	14,987
336 kg N ha^{-1} + 100% ET	0.70ab	184.3	89.8	18.6ab	14,366

Note: The values followed by the same letters within each column indicate nonsignificant difference at $p < 0.05$ based on the analysis of variance (ANOVA) procedure utilizing the Duncan's multiple range test.

conductivity was higher for treatments that received 50% ET water (treatments 1, 3, and 5) in both years.

Wang et al. (2021) observed that both N fertilization and irrigation have increased N accumulation in sugarbeet roots. Brei nitrate content represents a measurement of nitrate impurities that impedes sugar extraction. Brei nitrate concentrations (concentrations of nitrate impurities in the sugarbeet roots remaining at harvest), should not exceed 200 mg kg^{-1} to optimize sugar concentration in the roots. Idaho-based studies indicated that sugar concentration tends to decrease by 0.5% for every 100 mg kg^{-1} of brei nitrate (Walsh et al., 2019). As with conductivity, in our trial, brei nitrate content values were higher in 2020 (140.6–184.3 mg kg^{-1}) compared to 2019 (78.7–95.8 mg kg^{-1}) (Table 5). No statistically significant differences in brei nitrate content were associated with N and water treatments, however, numerically higher brei nitrate values typically corresponded to lower ERS values (Table 5). In our trial, in both years, the brei nitrate values were below the maximum recommended 200 mg kg^{-1} (Table 5), which could partially explain the nonsignificant differences in brei nitrate values.

4.9 | Root yield

To achieve high-yielding sugarbeet roots, sugarbeet crop has high nutrient and water demands. In our trial, sugarbeet root yield was notably higher in 2020 compared to 2019 (Table 5). Root yield ranged from 58.9 to 84.6 t ha^{-1} in 2019, and from 84.4 to 98.6 t ha^{-1} in 2020. This is consistent with 2020 being a cooler, wetter year (Table 2), taller plants, higher biomass weight, and higher biomass N concentration for 2020, compared to 2019 (Table 3). The highest root yield values obtained in our trial were slightly below, but comparable to the average statewide sugarbeet root yield levels in Idaho for 2019 and 2020 of 87.4 t ha^{-1} and 90.8 t ha^{-1}, respectively (USDA NAAS, 2020, 2021).

In our study, sugarbeet root yield response to N and water rates was similar in both years, although the differences associated with treatments in 2020 were not statistically significant. In both years, treatment 1, lowest N, and water rate resulted in lowest root yield. At the lowest N rate of 112 kg N ha^{-1}, application of 100% ET resulted in higher root yield, compared to 50% ET, in both years. At higher N rates, treatments 4 and 6 (224 kg N ha^{-1}, and 336 kg N ha^{-1} + 50% ET) were associated with the greatest root yield values in both years (Table 5). A report by Wittenmayer and Schilling (1998) showed that sugarbeet plants responded to mild water stress by increasing the root proportion relative to whole-plant biomass volume, suggesting that root yield is not always negatively affected by water limitations. Results by Starke and Hoffmann (2014) indicated that the differences in the proportion of sugarbeet root dry matter at varied N rates were not very pronounced.

Varga et al. (2022) reported that N rate of 240 kg N ha^{-1} resulted in an increase in sugarbeet biomass production and root yield, respectively, (82.8 t ha^{-1} and 42.9 t ha^{-1}) compared to the control treatment (42.7 t ha^{-1} and 38.2 t ha^{-1}). On the other hand, higher N rates significantly increased N assimilation of the vegetative plant parts, but decreased biomass partitioning to the roots, resulting in lower harvest index (Tsialtas & Maslaris, 2013). In our trial, the applied rates appeared to not affect partitioning to the roots, most likely due to high but not excessive N rates applied.

In semi-arid and arid environment, the effect of N rates on root yield and sugar concentration was not significant, and the irrigation treatments had a significant effect (Topak et al., 2016). Similarly, a study by Tsialtas and Maslaris (2013) revealed that sugarbeet root yield and ERS response to N was year-dependent: a positive effect of N fertilization was noted only in 1 out of 4 years.

Jahedi et al. (2012) observed no increase in sugarbeet root yield between 180 and 240 kg N ha^{-1} of N fertilizer. Similarly, Tsialtas and Maslaris (2013) found no differences in sugarbeet root yield and ERS between 120 and 240 kg N ha^{-1} rate. Esmaeili and Yasari (2011) reported that root yield increased with higher N rates, although the differences in root yield at 100 and 150 kg N ha^{-1} were not significant. Under various irrigation treatments, sugarbeet root yield increased with N rates increase up to 160 kg N ha^{-1}, however, increasing N rate to 240 kg N ha^{-1} did not further enhance root yield (Barzegari et al., 2017).

In an N-response trial in Idaho, sugarbeet root yields ranged from 48.3 t ha^{-1} and 64.6 t ha^{-1} as N rates increased from 100 to 300 kg N ha^{-1}. There was a significant difference from the 100 (caused economic loss) to 165 kg N ha^{-1} but increasing N rates to 235 and 300 kg N ha^{-1} did not result in significantly higher sugarbeet root yield (Wahlert et al., 2011).

4.10 | Sugar concentration and ERS

Typically, the sugar (98% of total is sucrose, with minimal fractions of fructose and glucose) concentration in sugarbeet roots is between 13% and 20% (Ernst et al., 2021; Varga et al., 2022). In our trial, the sugar concentration values ranged from 16.6% to 17.5% in 2019, and from 18.1% to 18.8% in 2020 (Table 5), which is in line with the previously reported values.

Although the differences in sugar concentrations among treatments were more distinct in 2019, the effects of N and water rates resulted in statistically significant ($p < 0.05$) differences in both years. Treatment 2 (lowest N rate, highest water rate; 112 kg N ha^{-1} + 100% ET) resulted in the lowest sugar concentration values in both years. At each N level, application of water at 100% ET was associated with lower sugar concentration values compared to 50% ET (Table 5). These findings suggest that N may be the primary driver for sugar accumulation within the sugarbeet roots, and higher water applications may result in dilution of sugar contained in the roots. In a study by Tsialtas and Maslaris (2013), however, N rates did not significantly affect sugar concentration of the sugarbeet roots.

Sugar yield (ERS) is typically linearly related to biomass production and N uptake (Varga et al., 2022). However, Last et al. (1983) has shown that N rates above 200 kg N ha^{-1} did not increase sugar yield; in fact, sugar yield was maximized with 125 kg N ha^{-1} rate. Furthermore, Varga et al. (2022) reported that increasing N rate to 240 kg N ha^{-1} resulted in decreased sugar concentration to 15.7%, compared to 17.1% in the control treatment, although the ERS was virtually the same, averaging 5.7 t sucrose ha^{-1}. Although N fertilization tends to increase the root yield, the linear model has a negative trendline for the sucrose content. Literature review suggested that N application tends to increase sugarbeet root biomass, while negatively impacting root quality (higher N at harvest, and lower ERS) (Varga et al., 2022).

In our trial, the ERS ranged from 7105 to 12,333 kg ha^{-1} in 2019, and from 13,380 to 14,987 kg ha^{-1} in 2020 (Table 5). As expected, in both years, the lowest ERS values were associated with treatment 1 (lowest N and water rate; 112 kg N ha^{-1} + 50% ET). While there were substantial differences in the ERS values in both years, the differences in ERS associated with treatments were statistically significant ($p < 0.05$) only in 2019. The ERS values represents a combination of sugarbeet root yield, sugar concentration, and the sugar extraction

TABLE 6 Analysis of variance (ANOVA) for 2 site-years (combined)

Effect	Conductivity	Brei nitrate	Root yield	Sugar concentration	ERS
Year	0.1237	<0.0001	<0.0001	<0.0001	<0.0001
ET	0.0911	0.5886	<0.0001	0.1133	<0.0001
N	0.5456	0.3967	0.0094	0.0057	0.0092
Year × ET	0.0079	0.7827	<0.0001	<0.0001	0.0004
Year × N	0.9131	0.3869	0.5523	0.2092	0.5230
ET × N	0.3676	0.0374	0.2006	0.0470	0.1860
Year × ET × N	0.0116	0.2026	0.4504	0.0525	0.3883

Note: The table shows the sources of variation and probability values for the *F* tests of each main effect and interactions for conductivity, brei nitrate, root yield, sugar concentration, and ERS.
Abbreviation: ERS, estimated recoverable sugar.

efficiency. In 2020, while the differences in sugar concentration were statistically significant ($p < 0.05$), the root yield values were not, likely causing the nonsignificant differences in the overall values of ERS in that year.

The N-response trial in Idaho has shown that sugar content generally increased as the N rates decreased, with the 100 kg N ha^{-1} resulting in the highest sugar content of 19.12%, compared to 18.8% at the 300 kg N ha^{-1} rate, and the differences in sugar concentration were not statistically significant. The same trend was noted for the ERS values; higher N rates resulted in lower ERS, but the differences were not significant, except between 100 and 165 kg N ha^{-1} rate (Wahlert et al., 2011). Wang et al. (2021) found that, under the same irrigation regime, higher N rates resulted in higher ERS values. Although sugarbeets, classified as semi-halophyte plants, considered tolerant to water limited conditions (Francois & Maas, 1999), the insufficient irrigation tends to significantly decrease crop productivity and, thus, profitability (Tsialtas & Maslaris, 2013). Indeed, while water deficit increased sugar concentration in the roots, the root yield was negatively impacted (Almani et al., 1997).

As reported by Varga et al. (2022), the application of N fertilizer can increase the sugarbeet root yield; they note, however, that a linear model had a negative trendline for the sugar concentration. This was not the case in our trial. The analysis of variance (Table 6) has shown that N has significantly ($p < 0.05$) affected sugarbeet root yield, sugar concentration, and the ERS. Water application was a significant source of variation for root yield and ERS. While Wang et al. (2021) reported that, under the same N level, sugar concentration in sugarbeet roots was higher with higher amounts of water applied, at all N rates, higher sugar concentration was associated with 50% ET treatments, compared to 100% ET in our trial (Table 5). Results by Topak et al. (2016) agree with our findings (Table 6) that the effect of N rates × irrigation treatment interaction on root yield and ERS was not significant. Evaluating eight sugarbeet varieties, Stevens et al. (2008) concluded that (due to a significant interaction of sugar concentration to total dry matter ratio) the varieties may significantly differ in N response based on differences in photosynthate partitioning between the aboveground biomass and roots. This may explain varied results achieved in previous trials reporting differences in sugarbeet response to N.

While year × ET interaction was significant ($p < 0.05$) for sugarbeet root yield, sugar concentration, or ERS, the year × N interaction was not significant (Table 6). This suggests that temporal variability in sugarbeet root yield and quality characteristics response to applied irrigation was more pronounced compared to response to N.

4.11 | UAV NDVI versus root yield

NDVI is an indicator of photosynthetically active biomass. Bauer et al. (2001) concluded that remote sensing may serve as a precise diagnostic tool for evaluation and monitoring the sugarbeet N status and N fertilizer demands of the sugarbeet crop in-season. An analysis of NDVI data by Gat et al. (2000) pinpointed June–July as a time in the growing season with the highest sugarbeet leaf density. Remote sensing can accurately reflect differences in sugarbeet biomass production and yield at varying N application (Tugrul, 2021). High correlation between spectral indexes, such as NDVI, is related to chlorophyll content, N, and water availability and sugarbeet yield (Joalland et al., 2018). Several authors state that NDVI is the spectral index most useful for accurately estimating physiological differences in sugarbeet crop associated with in-season stress and/or varied agricultural inputs (Dash et al., 2017; Thorp and Tian, 2004).

In our trial, the UAV NDVI values ranged from 0.34 to 0.55 and from 0.52 to 0.57 in June of 2019 and 2020, respectively (Table 3). In July, the UAV NDVI values were notably higher than in June, reflecting the plant growth and development, leaf expansion, and closure of the canopy. The UAV NDVI values were between 0.59 and 0.82 and between 0.64 and 0.74 in July 2019 and 2020, respectively.

Figures 2 and 3 illustrate the relationships between the UAV-based NDVI obtained in June and July and sugarbeet

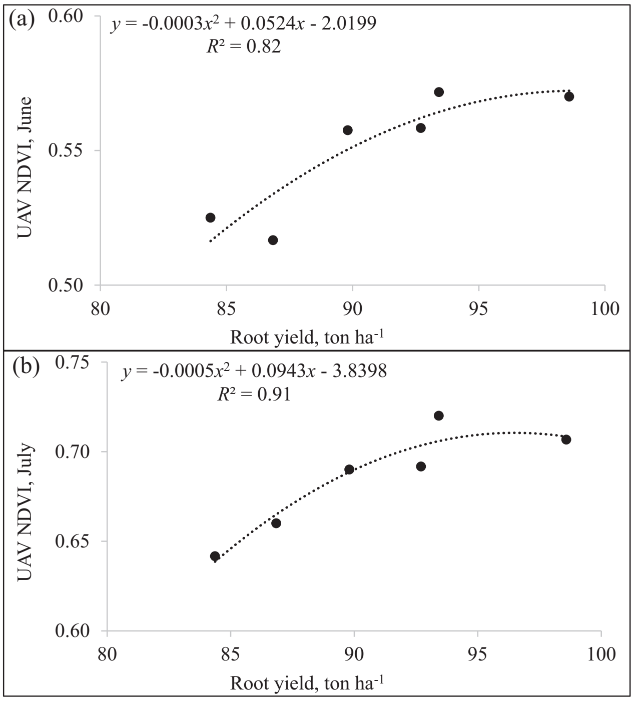

FIGURE 2 Relationship between Normalized Difference Vegetative Index (NDVI) obtained in June (a) and July (b) in 2019 with the Multispectral RedEdge M (MicaSense, Seattle, WA) camera mounted on an unmanned aerial vehicle Matrice 100 (DJI, Los Angeles, CA) (UAV NDVI) and sugarbeet root yield

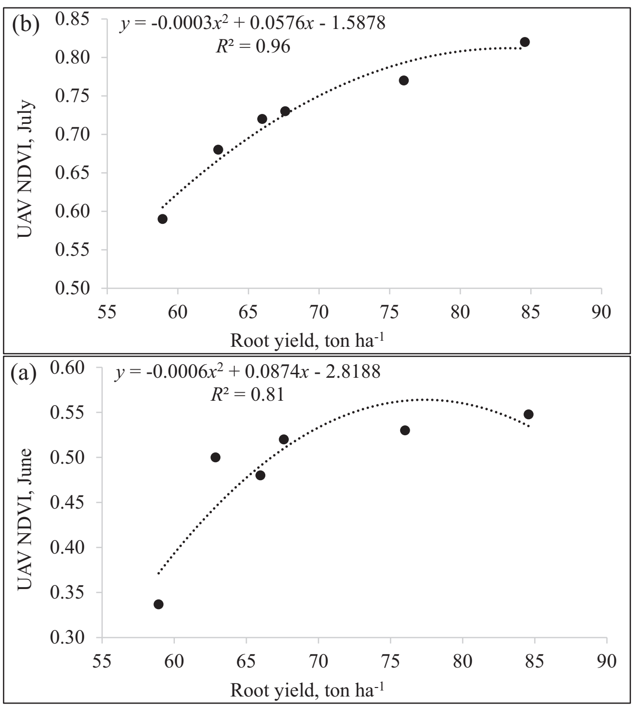

FIGURE 3 Relationship between Normalized Difference Vegetative Index (NDVI) obtained in June (a) and July (b) in 2020 with the Multispectral RedEdge M (MicaSense, Seattle, WA) camera mounted on an unmanned aerial vehicle Matrice 100 (DJI, Los Angeles, CA) (UAV NDVI) and sugarbeet root yield

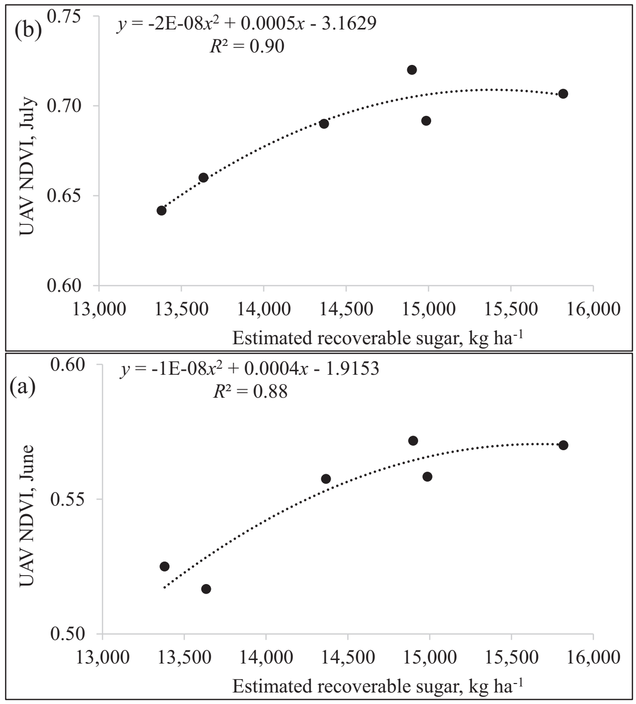

FIGURE 4 Relationship between Normalized Difference Vegetative Index (NDVI) obtained in June (a) and July (b) in 2020 with the Multispectral RedEdge M (MicaSense, Seattle, WA) camera mounted on an unmanned aerial vehicle Matrice 100 (DJI, Los Angeles, CA) (UAV NDVI) and sugarbeet estimated recoverable sugar (ERS)

root yield for 2019 and 2020, respectively. Polynomial relationship was observed for both years and NDVI measuring times (June and July). In both years, the relationship was stronger for July UAV NDVI compared to June. In 2019 and 2020, the R^2 value was 0.91 and 0.96 for July versus 0.82 and 0.81 in June, respectively (Figures 2 and 3). As the strength of the NDVI–yield relationship increased from June to July, it seems appropriate to suggest that NDVI-based yield estimation should be more accurate in July, when the plants are fully developed, and the canopy is closed.

4.12 | UAV NDVI versus ERS

As with UAV NDVI versus root yield, the relationship between the UAV NDVI and ERS (Figures 4 and 5) was strong and polynomial. The R^2 values of 0.88 and 0.78 were achieved in June of 2019 and 2020, and 0.90 and 0.88 in July of 2019 and 2020, respectively. Thus, in our trial, the same trend was noted for ERS as for the root yield: in both years, the relationship was stronger for July UAV NDVI compared to June. The consistent trends in relationships between UAV NDVI and ERS observed in our trial suggest that spectral measurements may be utilized for accurate in-season estimation of ERS as the key quality parameter reflecting productivity.

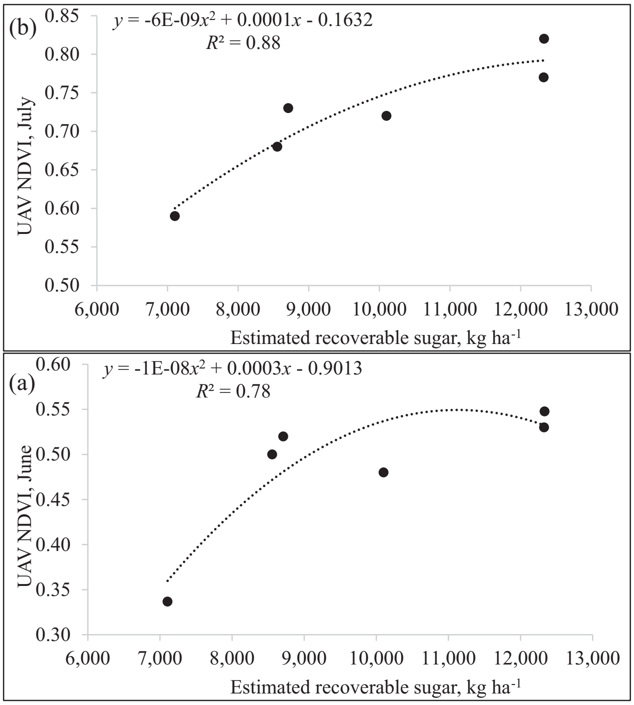

FIGURE 5 Relationship between Normalized Difference Vegetative Index (NDVI) obtained in June (a) and July (b) in 2020 with the Multispectral RedEdge M (MicaSense, Seattle, WA) camera mounted on an unmanned aerial vehicle Matrice 100 (DJI, Los Angeles, CA) (UAV NDVI) and sugarbeet estimated recoverable sugar (ERS)

It is normally recommended to apply all N to sugarbeet crop preplant to ensure N is available for plant uptake by four to six leaf growth stage in early June. However, some reports suggest that N application can be delayed until later in the season without negatively impacting sugarbeet root yield and quality. In a study by Bauer et al. (2001), sugarbeet root yield and quality were not significantly affected by the timing of N application, resulting in comparable sugar yields (ERS). They reported that topdressing sugarbeets with N at 8, 12, 16, and even 20 weeks after planting resulted in the same ERS values as the preplant N fertilization. To illustrate, when sugarbeets were 100% fertilized preplant, and when N was split-applied (preplant + topdress at 20 weeks after planting), the ERS were virtually the same. Jones et al. (2011) noted that sugarbeets grown under irrigation can be fertigated by adding N in irrigation water. This enables to time the N application to match the crop N needs. As pointed out by Jones et al. (2011), the N demand of the sugarbeet seedlings is low, and as early leaves mature the demand for N increases due to N required for taproot growth and development.

Indeed, Carter & Traveller (1981) caution that applying N after full canopy closure may result in increased aboveground biomass growth at the expense of sugar accumulation in the roots. They suggested that the application of N to sugarbeets should not be delayed until the end of July. They stated that N fertilization later in-season, when the sugar accumulation is peaking, may result in decreased sugar accumulation. At the same time, they found that in-season N application have enhanced N uptake and resulted in greater N use efficiency (NUE), compared to the same N rate applied all preplant. They also note that in-season N fertilization tends to minimize N losses from the sugarbeet fields, an important agronomic, economic, and environmental consideration.

Idaho is one of 11 U.S. sugarbeet growing states and ranks second, nationally, in production of sugarbeets. The sugarbeet industry contributes 1.7% of the Idaho gross state product. Idaho growers plant sugarbeets on more than 68,795 ha annually, harvesting over 20% of total sugarbeets (tonnage) produced in the United States (Walsh et al., 2019). Although sugarbeets are a vital commodity for the state of Idaho, no comprehensive agronomic/soil fertility trials in sugarbeets have been systematically conducted in this production area. Earlier agronomic trials in sugarbeets in Idaho have shown that plant available (soil residual plus fertilizer) N levels that would ensure adequate aboveground biomass establishment and growth to maximize sugar production are required (Carter & Traveller, 1981). They found that calculating N requirements based on preplant soil tests have not always been successful. The field trials conducted throughout southern Idaho have shown that significant differences in sugarbeet root yield and ERS were commonly obtained, even with comparable total available N levels (Carter et al., 1976). Indeed, some of the differences in sugarbeet yield and quality may have been associated with climatic factors/temporal variability (Loomis et al., 1971). However, the differences were often seen in the same growing season, but between adjacent fields (Carter & Traveller, 1981), indicating the importance of considering the effect of spatial variability (Follet et al., 1970).

In line with the discussion above, future research should focus on assessing the efficacy of in-season and split-applied N fertilization for optimized sugarbeet yield and quality. This work should incorporate locally grown varieties and take advantage of the state-of-the-art precision agriculture tools, such as UAV-based sensing to better understand N uptake in sugarbeets and to facilitate sensor-based N management. As previous studies and this current trial results have shown, there is a strong potential for developing sensor-based N rate prescriptions based on the preplant soil sampling coupled with in-season remote sensing.

5 | CONCLUSIONS

In this study, we analyzed the effects of water and N fertilizer rates on yield and quality of sugarbeets. Additionally, we accessed the feasibility of predicting sugarbeet root yield and ERS using UAV-based spectral reflectance measurements. In our trial, at the lowest N rate, application of 100% ET resulted in greater root yield, compared to 50% ET, in both years. At higher N rates, 50% ET treatments have produced higher root yields. At each N level, application of water at 100% ET was associated with lower sugar concentration values compared to 50% ET, supporting previous findings that N may be the key driver for sugar accumulation within the sugarbeet roots. Although the differences were statistically significant in the first year only, the same trend was noted in both years. Nitrogen affected sugarbeet root yield, sugar concentration, and the ERS. Water application was a significant source of variation for root yield and ERS. The results have supported our hypotheses that (1) the effect of irrigation on sugarbeet root yield and ERS should be more pronounced than the effect of applied N and (2) UAV NDVI should accurately estimate sugarbeet root yield and ERS in-season. The UAV NDVI was well correlated with both sugarbeet root yield and ERS, with July NDVI resulting in a stronger relationship compared to NDVI measured in June. Based on the results of this trial, and as revealed by the literature review, strong possibility exists for developing sensor-based N recommendations for sugarbeets. We conclude that determining the sugarbeet crop yield and ERS potential in late-June/early July, and topdressing the crop before the end of July may help to improve NUE while optimizing sugarbeet production.

AUTHOR CONTRIBUTIONS

Olga S. Walsh: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing–original draft; and writing–review and editing. **Eva Nambi**: Data curation; writing–original draft; and writing–review and editing. **Sanaz Shafian**: Conceptualization; data curation; funding acquisition; investigation; methodology; resources; and software. **Dileepa M. Jayawardena**: Data curation; investigation; methodology; project administration; resources; and supervision. **Emmanuella Owusu Ansah**: Writing–original draft and writing–review and editing. **Ritika Lamichhane**: Writing–original draft and writing–review and editing. **Jordan R. McClintick-Chess**: Data curation; investigation; methodology; resources; and supervision.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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