Effect of Nitrogen Supply by Soil Depth on Sugarbeet Production and Quality

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ABSTRACT

Determining the effect of N supply by soil depth on sugarbeet production is important to continue fine-tuning management practices. To accomplish this objective, a greenhouse column study was conducted at USDA-ARS in Kimberly, ID. The study was conducted using 30 1 m x 0.3 m columns filled with 0.9 m of soil. The treatments consisted of adding N fertilizer at a rate of 132 kg N ha^{-1} differently to three 0.3 m soil depths. Although all treatments had a total N supply of 222 kg N ha^{-1} in the 0.9 m soil depth, the distribution of the N in the soil profile affected the yields and N uptake. Sugarbeet root mass, root sucrose mass, leaf mass, root N mass, and leaf N mass were higher for treatments where N fertilizer was added to depths 1 (0-0.3 m) and 2 (0.3-0.6 m) compared to when N fertilizer was added to depth 3 (0.6-0.9 m). The sugarbeets were not able to utilize N from depth 3 as efficiently as from depth 1 and depth 2. There were no treatment effects on sugarbeet quality factors. The findings of this study highlight the need to question the value of a depth 3 soil sample for determining N fertilizer requirements.

Additional Key Words: nitrogen, sugarbeet, N fertilizer placement, N fertilizer recommendations, *Beta vulgaris*

Abbreviations: TDR = time domain reflectometry, MAD = maximum allowable depletion

Nitrogen (N) supply is an important management factor for sugarbeet (*Beta vulgaris*) production because under- and over-supplying N relative to plant needs can both result in decreased profits (Stout, 1960). Under supplying N reduces root mass and sucrose yields while over supplying N may be related to decreased root sucrose content and increased root impurities which decreases sucrose extraction efficiency (Carter and Traveller, 1981; James et al. 1971). In addition, over supplying N can lead to increased N losses to the environment. The basis of current and past N management was to determine the amount of soil available N in the soil and then determine the amount of N fertilizer needed to meet the crops optimum N supply needs. Soil available N is determined as N in the forms of nitrate (NO_3-N) and ammonium (NH_4-N). The recommended depth of soil sampling has changed over time. Depths of 0-0.6 m have been recommended in the past (Moore et al., 2009; TASCO, 1997), while and 0-0.9 m is the current standard (TASCO, 2009; Walsh et al., 2019). The change from 0-0.6 m to 0-0.9 m was due to data indicating that significant amounts of N can be found in the 0.6-0.9 m depth and soil sample inorganic N data from sampling depth of 0-0.9 m being included in the determination of yield and total N supply relationships in research studies (Tarkalson et al., 2012; Tarkalson et al., 2016). To better understand the role of soil inorganic N in sugarbeet N management research is needed to specifically assess N uptake dynamics by soil depth. No research has specifically focused on sugarbeet N uptake dynamics by soil depth in the Pacific Northwest growing area. The objective of this study was to utilize a column study method to determine the effect of available N supply by soil depth on sugarbeet production.

Materials and Methods

The study was conducted in a climate-controlled greenhouse at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. The soil was a mix of a sandy soil and silt loam soil from local agricultural fields low in inorganic N. The texture of the soil mix was a Loamy Sand (Table 1). Prior to the start of the study, the soil was analyzed for at a commercial laboratory for selected constituents (Table 1) using the methodologies detailed in Gavlak et al. (2003 and 2005).

Table 1. *Soil analysis constituent concentrations.*

Constituent	Units	Reading	Basic Methodology Description[†]
Organic Matter	%	0.60	Gravimetric mass loss on ignition
pH		8.4	1:1 soil:water
Electrical Conductivity	mmhos cm^{-1}	1.7	1:1 soil:water
Lime	%	5.5	H_2SO_4 reaction/NaOH titration
NO_3-N	mg kg^{-1}	4.0	KCl extraction, Cd reduction
NH_4-N	mg kg^{-1}	2.6	KCl extraction
P	mg kg^{-1}	14.4	Bicarbonate extraction
K	mg kg^{-1}	83.3	Ammonium acetate extraction
S	mg kg^{-1}	36.3	NH_4F extraction
B	mg kg^{-1}	0.36	NH_4F extraction
Zn	mg kg^{-1}	0.30	DTPA extraction

Constituent	Units	Reading	Basic Methodology Description[†]
Fe	mg kg^{-1}	5.2	DTPA extraction
Mn	mg kg^{-1}	2.6	DTPA extraction
Cu	mg kg^{-1}	0.33	DTPA extraction
Cation Exchange Capacity	meq $100g^{-1}$	12.0	Calculation from Ca, Mg and Na
Ca	meq $100g^{-1}$	8.2	Ammonium acetate extraction
Mg	meq $100g^{-1}$	2.9	Ammonium acetate extraction
Na	meq $100g^{-1}$	0.60	Ammonium acetate extraction
Sand	%	79.0	Modified pipette
Silt	%	14.0	Modified pipette
Clay	%	7.0	Modified pipette

†Full methodologies are found in Gavlak et. al (2003). Sand, silt, and clay determination was from Gavlak et. al (2005).

The study was conducted using 30 plastic columns (30.5 cm inner diameter and 106.7 cm length) filled with 0.9 m of soil. The treatments consisted of adding N fertilizer at a rate of 132 kg N^{-1} to soil depths (depth 1 = 0-0.3 m, depth 2 = 0.3-0.6 m, and depth 3 = 0.6-0.9 m) in different configurations (Table 2). Each 0.0305m depth of soil contained 30 kg N ha^{-1} of residual inorganic N (NO_3-N + NH_4-N). In summary, the N treatments (kg total N ha^{-1} [total N = residual N + fertilizer N] in depths 1-2-3) were 162-30-30, 30-162-30, 30-30-162, 96-96-30, 30-96-96, 30-30-30. The rate of added fertilizer N (kg ha^{-1}) in depths 1-2-3 were 133-0-0, 0-133-0, 0-0-133, 66-66-0, 0-66-66, 0-0-0. Each treatment was replicated 6 times in a randomized block design. To set up the study, the soils were added in three separate 0.3 m depths increments at a bulk density of 1.49 g cm^{-3}. The N was added to the top of soil depths as urea ammonium nitrate (32% N) dissolved in 3.1 L of water (amount water needed to bring each soil layer up to approximately 70% of field capacity). The following method was followed to set up the columns: 1. Soil was added to Depth 3 (0.6-0.9 m) in all columns; 2. The soil in each column was leveled and set at the proper depth; 3. The 3.1 L of water with N or water with no N was added to the top of the soil and allowed to completely soak in; 4. Steps 1, 2 and 3 was performed for depths 2 (0.3-0.6m) and depth 1 (0.3-0.6m). To supply other needed nutrients, depth 1 (0-0.3 m) of all columns had 3.1 g of muriate of potash (257 kg K ha^{-1}), 5.4 g of triple super phosphate (336 kg P ha^{-1}), and 5.1 g of a micronutrient fertilizer (Micromax®, ICL Specialty Fertilizers) was added in the 3.1 L of water. This nutrient application rates from the micronutrient fertilizer were 84 kg S ha^{-1}, 42 kg Ca ha^{-1}, 21 kg Mg ha^{-1}, 119 kg Fe ha^{-1}, 7 kg Cu ha^{-1}, 7 kg Zn ha^{-1}, 17 kg Mn ha^{-1}, 0.7 kg B ha^{-1}, and 0.35 kg Mo ha^{-1}.

Table 2. *Treatment nitrogen amounts and application rates by depth.*

Depth ID	Depth Increment (m)	N Source	-----------------Treatment, kg N ha^{-1} in 1-2-3 depth ID's -----------------					
			162-30-30	30-162-30	30-30-162	96-96-30	30-96-96	30-30-30
1	0-0.3	Residual N	30	30	30	30	30	30
		Fertilizer N	132	0	0	66	0	0
		Total N	**162**	**30**	**30**	**96**	**30**	**30**
2	0.3-0.62	Residual N	30	30	30	30	30	30
		Fertilizer N	0	132	0	66	66	0
		Total N	**30**	**162**	**30**	**96**	**96**	**30**
3	0.62-0.9	Residual N	30	30	30	30	30	30
		Fertilizer N	0	0	132	0	66	0
		Total N	**30**	**30**	**162**	**30**	**96**	**30**
1+2+3	0-0.9	**Total N**	**222**	**222**	**222**	**222**	**222**	**90**

Irrigation for the treatments was determined using soil water measurements at a depth of 0.457 m. In three replications for each treatment, soil water content at a soil depth of 0.457 m was measured every 15 minutes using Acclima (Meridian, ID) TDR-310H time domain reflectometry (TDR) probes connected to a Campbell Scientific (Logan, UT) CR1000 data logger. The TDR probes were inserted 10 cm into the soil columns (perpendicular to the columns) through 3.4 cm holes cut through the plastic soil column. Each column was irrigated with two surface drip emitters, each with a flow rate of 1.89 L hr^{-1} for a total application rate of 3.78 L hr^{-1}. The average field capacity (FC) of the soil across all soils was 13.88% of soil volume. Because of variation in soil water content measurements across soil columns, data was normalized across all TDR probes with a base FC of 13.88%. This average for FC was obtained from data collected from May 15 and 16, a period of at least 48 hours after the soil at the 0.457 m depth was known to be saturated and allowed to drain to FC. Based on pressure plate analysis PWP was 55.02% of FC, this is equal to 7.64% of soil volume. A management allowable depletion (MAD) of available water of 55% was set as the depletion level above which the crop would be water stressed (Jensen et al., 1990). The 55% MAD was 10.45% of soil volume.

Sugarbeets were planted on April 23, 2021. Five sugarbeet seeds (variety = Crystal A702NT) were planted in each column and thinned to one plant per column after emergence (May 1, 2021). From planting to harvest, the greenhouse settings maintained a temperature range of between 10.0°C and 32.2°C. The greenhouse average daily low and high temperature during the study was 16.1°C and 30.0°C, respectively.

The sugarbeet leaves and roots were harvested from all columns on September 13, 2021. Total leaf (includes petioles) area at harvest was determined using a LI-3100 Area Meter (LI-COR Inc, Lincoln, NE). Leaves and roots were washed with water to remove all soil and other particulates. Leaves were oven dried at 60 deg C for 48 hours and a dry weight obtained. The leaves were then ground using an electric plant grinder to pass through a 2 mm sieve and analyzed for total N by combusting a 25 mg sample using a FlashEA1112 CNH analyzer (CE, Elantech, Lakewood, NJ). After the water from the washing was dried for the roots, each root was weighed. The roots were ground in a generic food processor. Half of the ground roots were frozen and sent to Amalgamated Sugar Company for sucrose and quality analysis. Percent sugar was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, NJ), a half-normal weight sample dilution, and aluminum sulfate clarification method [ICUMSA Method GS6-3 1994] (Bartens, 2005). Conductivity was measured using a Foxboro conductivity meter Model 871EC (Foxboro, Foxboro, MA) and brei nitrate was measured using a multimeter Model 250 (Denver Instruments, Denver, CO) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, NY). The other half of the ground root sample was weighed wet and oven dried at 90 deg C for 7 days and a dry weight and precent dry matter obtained. Dry leaves and roots were ground and analyzed for total N using a FlashEA1112 CHN analyzer.

Following harvest, the columns were cut lengthwise on opposing sides with a circular saw. The columns were then opened lengthwise and soil samples were obtained in the center of the top, middle and bottom 0.3 m segments at approximate depths of 0.15, 0.46, and 0.76 m, respectively. From each column, approximately 500 g of dry soil was collected from each depth and column for analysis of NO_3-N and NH_4-N. The soil samples were air dried then analyzed for nitrate-N (NO_3-N) and ammonium-N (NH_4-N) after extraction in 2M KCl (Mulvaney, 1996) using a flow injection analyzer (Lachat Instruments, Loveland, CO).

Several N use efficiency calculations were determined from N content in the plants and N inputs and supplies. Nitrogen recovery efficiency was calculated as:

$$\text{N Recovery Efficiency (\%)} = \left(\frac{\text{Total Plant N}}{\text{Total Soil Inorganic N (Soil + Fertilizer)}}\right) \times 100 \qquad (1)$$

where, Total Plant N is the grams of N in the sugarbeet leaf and root, and Total Soil Inorganic N is the grams of residual inorganic N (NO_3-N and NH_4-N) in the soil and N added from fertilizer.

Nitrogen removal efficiency was calculated as:

$$\text{N Recovery Efficiency (\%)} = \left(\frac{\text{Root N}}{\text{Total Soil Inorganic N (Soil + Fertlizer)}}\right) \times 100 \qquad (2)$$

where, Root N is the grams of N in the sugarbeet root, and Total Soil Inorganic N is the grams of residual inorganic N (NO_3-N and NH_4-N) in the soil and N added from fertilizer.

Fertilizer N uptake efficiency was calculated as:

$$\text{Fertilizer N Uptake Efficiency (\%)} = \left(\frac{-\text{Total Plant N}_{\mathit{Treatment}} - \text{Total Plant N}_{\mathit{0\text{-}0\text{-}0}}}{\text{Fertilizer N}}\right) \times 100 \qquad (3)$$

where, Total Plant $N_{Treatment}$ is the grams of N in the sugarbeet leaf and root of treatments with added N, Total Plant $N_{0\text{-}0\text{-}0}$ is the grams of N in the sugarbeet leaf and root of the 0-0-0 treatment, and Fertilizer N is the grams N added from fertilizer.

Results and Discussion

Adding fertilizer N to the columns resulted in higher sugarbeet water use. The total quantity of applied irrigation water differed between treatments based on differences in crop water extraction (Figures 1). The irrigation water management protocol was to keep soil water contents in all columns (0.457 m soil depth) similar over time and prevent water stress across all treatments. Over the course of the study, the soil water content for all treatments was maintained between FC and the 55% MAD level (Figure 2). As a result, treatment differences in production factors were due to N effects, not water stress effects. The treatments with the most water applied (greatest water uptake) were the 162-30-30, 30-162-30 and 96-96-30 treatments (treatments with fertilizer N added to depths 1 and 2). Averaged across these three treatments, total water applied was 47.3 L. The difference between these three treatments was only 0.5 L (1.1% of the total applied). The 30-30-162 and 30-96-96 treatments (treatments with fertilizer N added to depth 3) had similar water applications at an average of 41.5 L. The total average applied water for the 162-30-30, 30-162-30 and 96-96-30 treatments was 12.3% greater than the 30-30-162 and 30-96-96 treatments. The difference between these two treatments was only 0.5 L (1.2% of the total applied). The total average applied water for the 162-30-30, 30-162-30 and 96-96-30 treatments was 19.5% greater than the 30-30-30 treatment (total water applied = 38.1 L). The total average applied water for the 30-30-162 and 30-96-96 treatments was 8.1% greater than the 30-30-30 treatment.

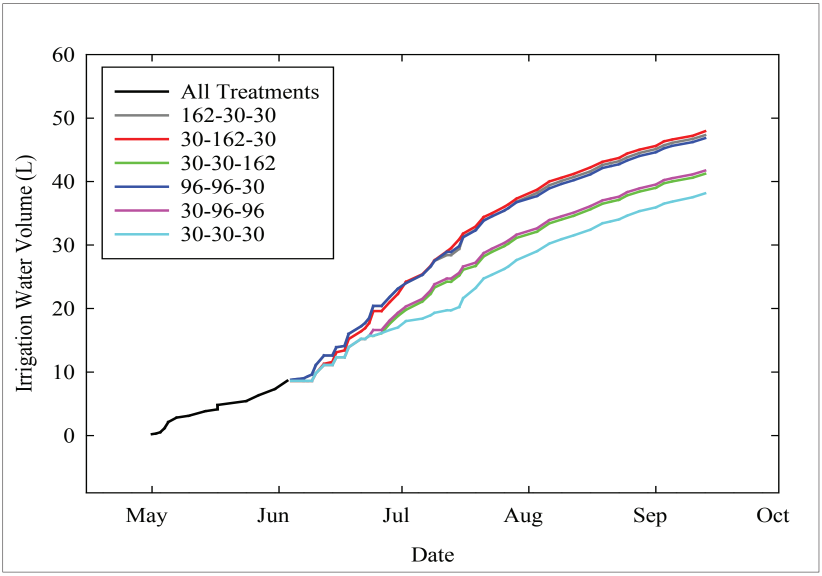

Figure 1. *Cumulative irrigation water input depth over the study period for N treatments.*

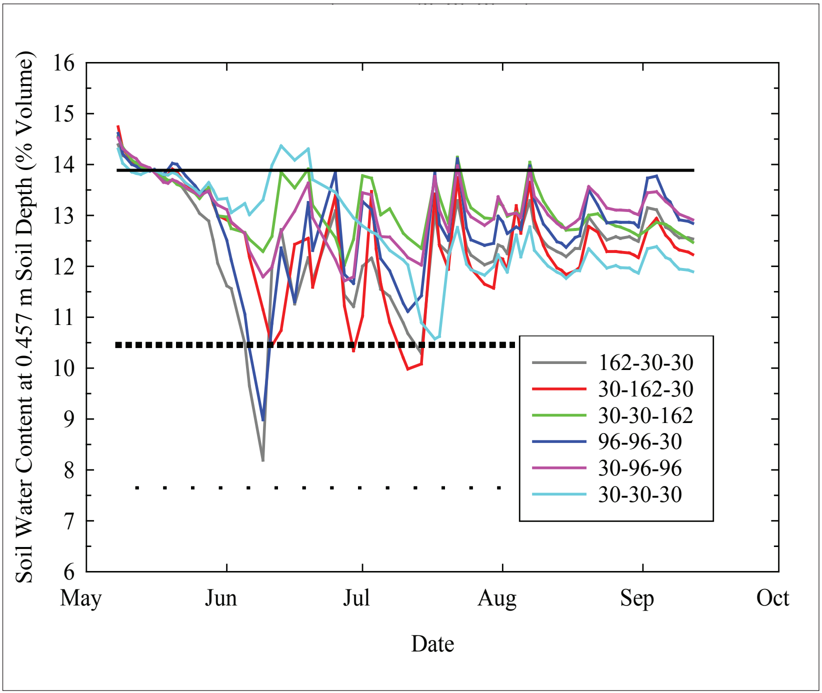

Figure 2. *Volumetric soil water content over time for the N treatments at soil depth of 0.46 m. Treatment values are the average of three replications. The solid line represents field capacity, the middle-dotted line represents 55% MAD of total available water, and the bottom dashed line represents permanent wilting point.*

Although all treatments (except the control) had a total N supply of 222 kg N ha^{-1} in the entire 0.9 soil depth, the distribution of the N in the soil profile affected the measured factors. There were significant treatment differences in root mass, leaf mass, total plant mass, root sucrose mass, root N mass, leaf N mass, total plant N mass, leaf area, N recovery efficiency, N removal efficiency, and fertilizer N uptake efficiency (Table 3). Soil depth 1 and 2 were more important in supplying N to sugarbeet than depth 3. Sugarbeet root mass, root sucrose mass, leaf mass, root N mass, and leaf N mass were significantly lower for treatments where the greatest proportion of total N supply was in the depth 3 (Figure 3, 4, and 5). This data indicates that sugarbeets were not able to utilize N from depth 3 as efficiently as from depth 1 and depth 2. Although no non -harvested fibrous root biomass was collected, roots were visually distributed through the entire 0.9 m soil depth. The sugarbeets were able to extract N equally from soil depths 1 and 2 to maximize yields and N uptake depth. Supplying 192 kg N ha^{-1} in depth 1 and depth 2 increased leaf mass, root mass, total plant mass, root sucrose mass, root N, and total plant N compared to the other treatments (Figures 3, 4, and 5). Sugarbeet yield and N uptake was maximized when N was located primarily in depth 1 (162-30-30), or in depth 2 (30-162-30 treatment), or split between depths 1 and 2 (96-96-30 treatment).

Table 3. *Probability values (P>F) from analysis of variance for measured sugarbeet production related factors. Bolded probability values are significant at the 0.05 level.*

Root Mass	*<0.001*
Leaf Mass	*<0.001*
Total Plant Mass	*<0.001*
Root Sucrose Mass	*<0.001*
Root Sucrose Conc.	*0.452*
Root Nitrate Conc.	*0.550*
Root Conductivity	*0.507*
Root N Conc.	*0.114*
Leaf N Conc.	*0.923*
Root N mass	*<0.001*
Leaf N mass	*<0.001*
Total Plant N mass	*<0.001*
Leaf Leaf Area	*<0.001*
N Recovery Efficiency	*<0.001*
N Removal Efficiency	*<0.001*
Fertilizer N Uptake Efficiency	*<0.001*
Soil NO_3-N, 0-0.3m	*0.569*
Soil NO_3-N, 0.3-0.6m	*0.958*
Soil NO_3-N, 0.6-0.9m	*0.095*

There were no significant treatment effects on sugarbeet root sucrose concentration, brei nitrates, or conductivity (Figure 4, Table 3). Even sugarbeets with 162 kg N ha^{-1} at depth 3 (30-30-162 treatment) had similar sugar % and sugar quality to all other treatments. Across all treatments the mean sucrose, brei nitrates, and conductivity were 19.3%, 163 mg kg^{-1}, and 0.76 mmhos, respectively (Figure 4). Published research is often contradictory on the effect of N supply on sugarbeet production and quality, with some research indicating that excess N can negatively affect sugarbeet quality and sucrose yields (James et al., 1971; Ruess and Rao, 1971; Marlande, 1990; Lauer, 1995), while other research indicating that excess N does not negatively affect sugarbeet quality and sucrose yields (Tarkalson et al., 2012; Lauer, 1995). Limited research has assessed the direct effects of N in deeper soil depths (> 0.6 m) on sugarbeet production and quality (Stevanato et al., 2010). Stevanato et al. (2010) found that high levels of available N in soil profiles greater than 0.6 m negatively affected sucrose content and quality. The reasons for the differing effects of deeper soil profile available N on sucrose content and quality is often a result of site-specific factors. For example, In the Po Valley in Italy, Stevanato et al. (2010) found that sugarbeet production was affected by available N to a depth of 3 m. Organic matter content at the 2 m and 3 m depths were high (10 to 25 g kg^{-1}), which resulted in high concentrations of NH_4-N at these depths, leading to decreased sugarbeet root sucrose and quality parameters. Soils in the sugarbeet growing areas of the Northwest U.S. have very low organic matter at these soil depths (Tarkalson and Bjorneberg, 2010). The sugarbeet industry in the Northwest U.S. production area often associates decreased root quality and sucrose concentrations with

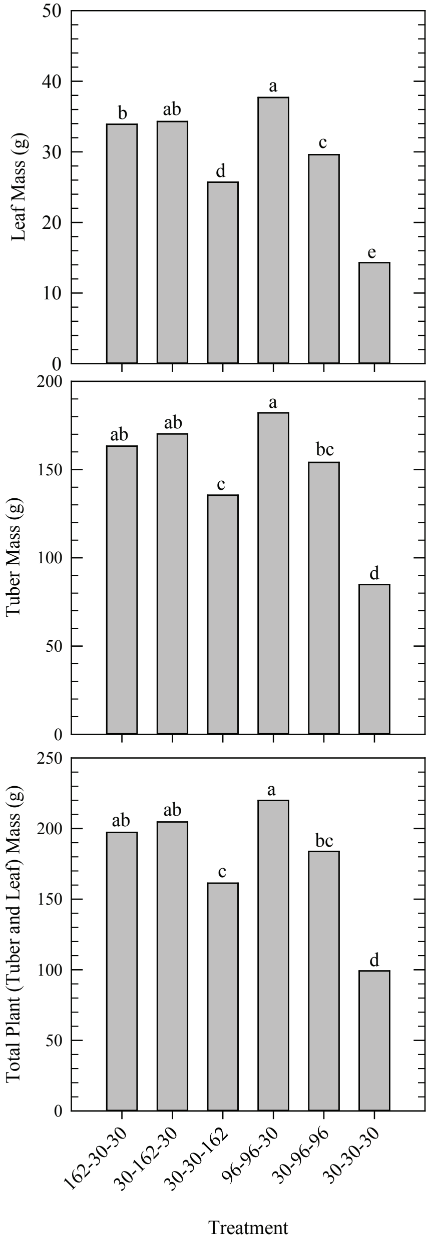

Figure 3. *Sugarbeet leaf mass, root mass, and total plant mass for all treatments. Columns with the same letter are not significantly different at the 0.05 probaility level based on LSD mean seperation method.*

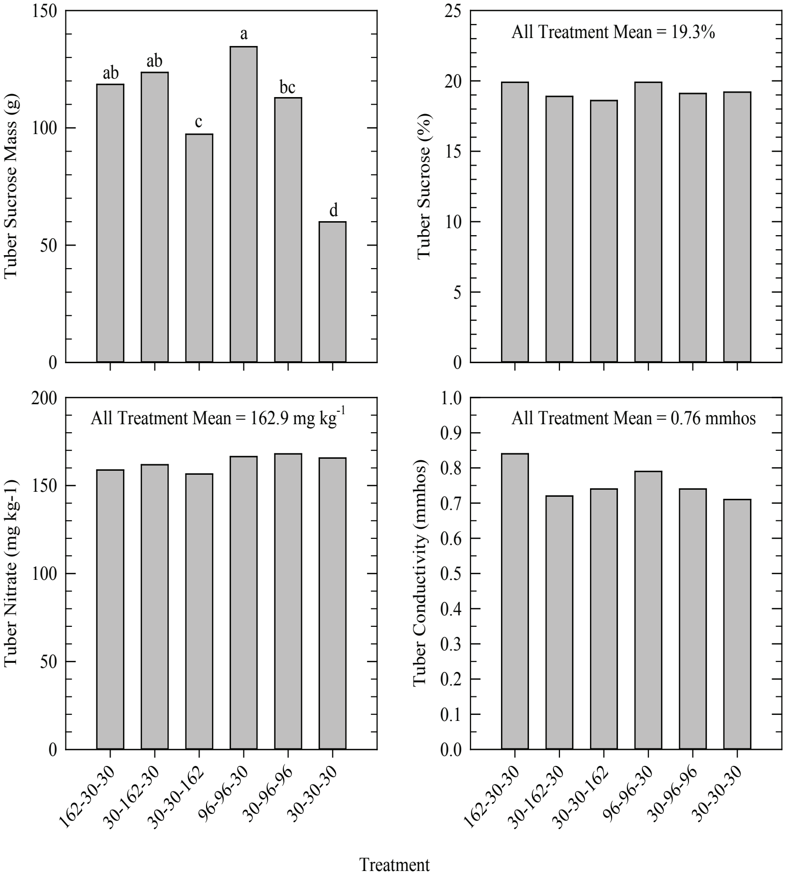

Figure 4. *Sugarbeet root sucrose mass, sucrose concentration, nitrate concentration, and conductivity for all treatments. Root sucrose mass columns with the same letter are not significantly different at the 0.05 probability level based on LSD mean seperation method. There were no significant treament differnces (by ANOVA) for root sucrose concentration, nitrate concentration, and conductivity (Table 1).*

elevated levels of available N in deeper soil depths (pers. comm.). However, there has been no research published that addresses the effects of deep N on sugarbeet production and quality in Northwest U.S. soils. In this study, we did not see any negative effects of higher N levels in depth 3 on sucrose content and quality (Figure 4). It is possible that the inefficiency of the sugarbeets to extract N from soil depth 3 resulted in the discrepancy. It is also possible that the shorter-than-normal growing season of these beets (141 days compared to an average 170+ for commercial field-grown sugarbeets) did not allow sufficient time for the negative effects of high N at depth to emerge.

The significant differences in plant tissue N masses between treatments were

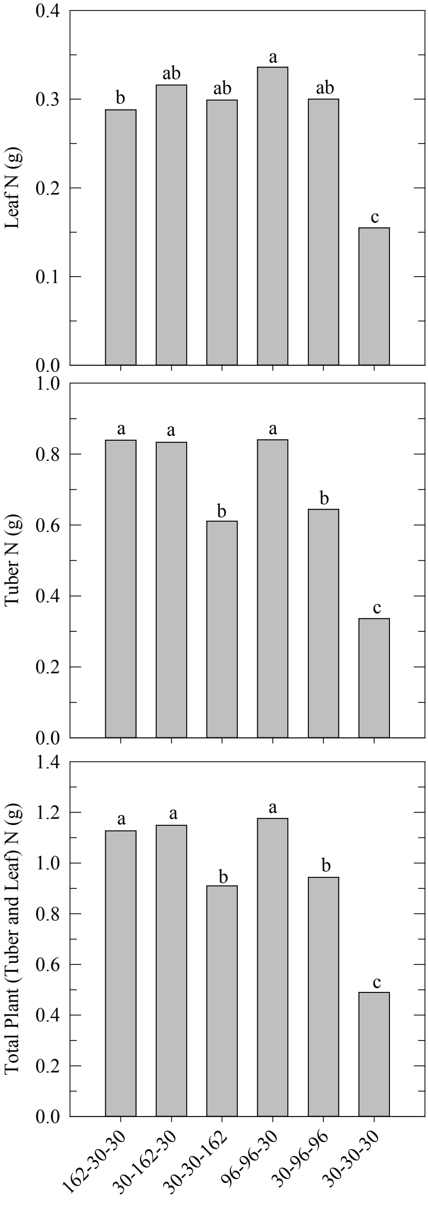

Figure 5. *Nitrogen in sugarbeet leaves, roots, and whole plant for all treatments. Columns with the same letter are not significantly different at the 0.05 probaility level based on LSD mean seperation method.*

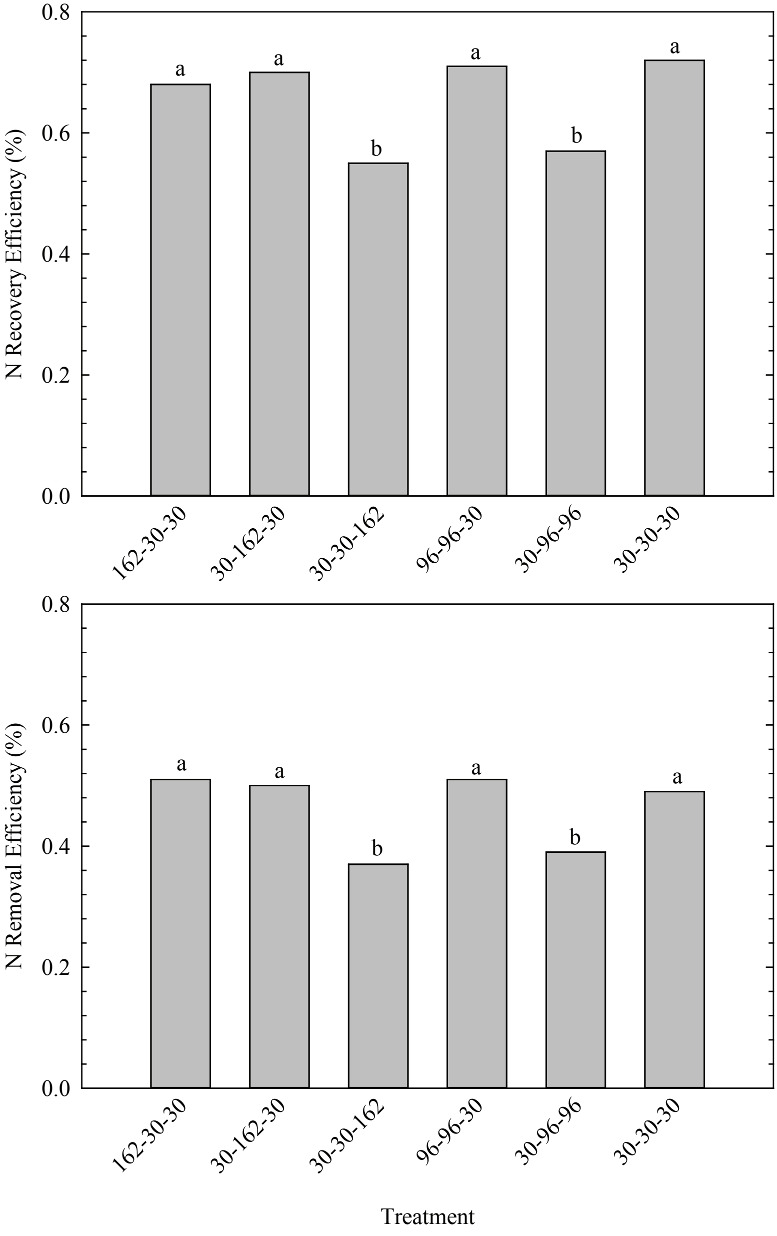

Figure 6. *Sugarbeet N recovery and removal efficiencies for all treatments. Columns with the same letter are not significantly different at the 0.05 probaility level based on LSD mean seperation method.*

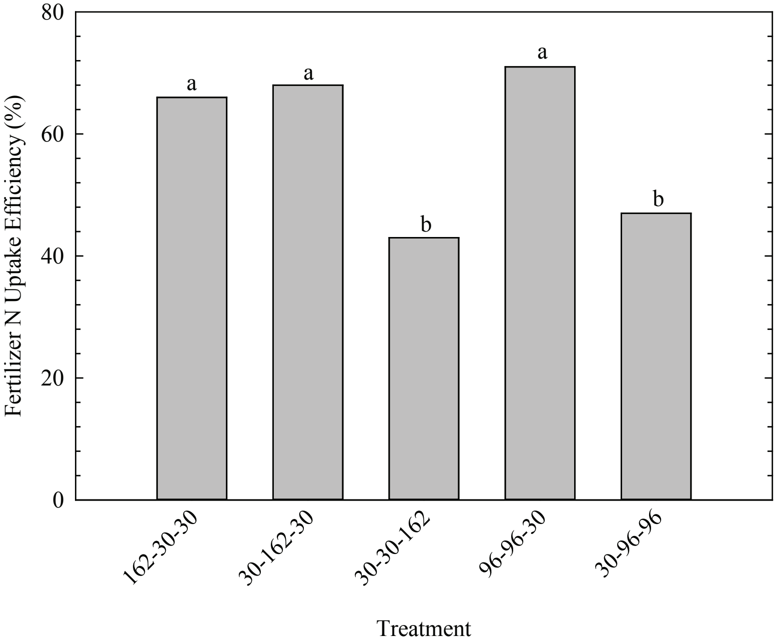

Figure 7. Sugarbeet agronomic N uptake efficiency. Columns with the same letter are not significantly different at the 0.05 probaility level based on LSD mean seperation method.

Table 4. *Soil nitrate concentrations (mg kg-1) in the 0-0.3, 0.3-0.6, and 0.6-0.9m depths at sugarbeet harvest.*

Treatment	0-0.3	0.3-0.6	0.6-0.9
224-0-0	0.78	0.93	1.25
0-224-0	0.79	0.78	0.9
0-0-224	0.99	0.74	0.48
112-112-0	0.72	0.64	0.71
0-112-112	0.6	0.70	0.82
0-0-0	0.54	0.65	0.96

due to the differences in plant mass, not plant N concentrations (Figure 6). The N use efficiency measurements (N recovery efficiency, N removal efficiency, and fertilizer N uptake efficiency) was greatest when 196 kg total N ha^{-1} was supplied in depths 1 and 2 compared to when some or all the 196 kg total N ha^{-1} supply was in depth 3 (Figures 6 and 7). The mean N recovery efficiency for the 162-30-30, 30-162-30, and 96-96-30 treatments was 70% compared to a mean of 56% for the 30-30-224 and 30-112-112 treatments (Figure 6). The mean N removal efficiency for the 162-30-30, 30-162-30, and 96-96-30 treatments was 51% compared to a mean of 38% for the 30-30-224 and 30-112-112 treatments (Figure 6). There were no differences in fertilizer N uptake efficiency for treatments supplying N in depth 1, depth 2, or a combination of the two (162-30-30, 30-162-30, and 96-96-30). The mean fertilizer N uptake efficiency for the 162-30-30, 30-162-30, and 96-96-30 treatments was 68% compared to a mean of 43% for the 30-30-224 and 30-112-112 treatments (Figure 7).

The findings of this study highlight the need to question the value of a depth 3 soil sample for informing fertilizer N recommendations. Sugarbeets did not extract N from depth 3 as efficiently as from depths 1 and 2. In addition, the level of N in depth 3 did not negatively affect root quality parameters. Given the increased effort required to collect 0.6 to 0.9 m soil samples, the cost/benefit of this practice needs to be further evaluated in the field. Current soil sampling recommendations in the Northwest U.S. sugarbeet growing area recommends sampling to 0.9 m (Amalgamated, 2021; Walsh et al., 2019). Although preliminary, this work suggests that fertilizer recommendations could possibly be improved by employing a weighting system that recognized the relative importance of each soil depth when evaluating soil test results.

Conclusions

The surface 0.6 m of soil was the most important depth in supplying N to maximize sugarbeet yield and N use efficiency. Nitrogen at deeper depths was not as available. When a portion or all the fertilizer N was supplied in depth 3 (0.6 to 0.9m) sugarbeet yields and N use efficiency was decreased. Soil sampling to a depth of 0.6m was sufficient to determine soil available N. The findings of this study highlight the need to question the value of a depth 3 soil sample. The N in depth 3 was not as available to the plant and did not negatively affect quality. The cost/benefit evaluation of taking a soil sample to include depth 3 needs to be further evaluated in the field. Future research can help elucidate the effect of soil depth N on sugarbeet production and quality in the field on various soil types.

References

Amalgamated Sugar Company. 2021. Sugarbeet Growers Guide Book. Amalgamated Sugar Company, LLC. Boise, ID.

Bartens, A., 2005. International Commission for Uniform Methods of Sugar Analysis Methods Book 2005. p. 431., Berlin, Germany.

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

Gavlak, R.G., D.A. Horneck, R.O. Miller, and J. Kotuby-Amacher. 2003. Plant, Soil, and Water Reference Methods for the Western Region. WCC-103 Publications, Fort Collins, CO.

Gavlak, R.G., D.A. Horneck, R.O. Miller, and J. Kotuby-Amacher. 2005. Plant, Soil, and Water Reference Methods for the Western Region. WCC-103 Publications, Fort Collins, CO.

James, D.W., A.W. Richards, W.H. Weaver, and A.L. Reeder. 1971. Residual soil nitrate measurements as a basis for managing nitrogen fertilizer practices for sugarbeets. J. Amer. Soc. Sugarbeet Technol. 16:313-322.

Jensen, M.E., R.D. Burman, and R.G. Allen, editors. 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practices no. 70. Am. Soc. Civil Eng., New York, NY.

Lauer, J.G. 1995. Plant density and nitrogen rate effects on sugarbeet yield and quality early in harvest. Agron. J. 87:586-591.

Marlander, B. 1990. Influence of nitrogen supply on yield and quality of sugarbeet. Z. Pflanzenernahr. Bodenk. 153:327-332.

Moore, A., J. Stark, B. Brown, and B. Hopkins. 2009. Southern Idaho Fertilizer Guide: Sugarbeets. CIS 1174. University of Idaho Extension. Moscow, ID.

Mulvaney, R.L. 1996. Nitrogen-inorganic forms. In: D.L. Sparks, editor, Methods of Soil Analysis: Part 3. SSSA Book Ser. 5. p. 1123–1184. Madison, WI.

Reuss, J.O. and P.S.C. Rao. 1971. Soil nitrate nitrogen levels as an index of nitrogen fertilizer needs of sugarbeets. J. Sugarbeet Res. 16:461-470.

Stevanato, P., C. Zavalloni, R. Marchetti, M. Bertaggia, M. Saccomani, J.M. McGrath, L.W. Panella, and E. Biancardi. 2010. Relationship between subsoil availability and sugarbeet processing quality. Agron. J. 102:17-22.

Stout, M. 1960. A new look at some nitrogen relationships affecting the quality of sugar beets. J. Am. Soc. Sugar Beet Technol. 9:389–398.

Tarkalson, D.D., and D.L Bjorneberg, 2010 Evaluation of nitrogen and phosphorus fertilizer placement with strip tillage for irrigated Pacific Northwest corn production. Online. Crop Management. doi:10.1094/CM-2010-0611-01-RS.

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

Tarkalson, D.D., D.L. Bjorneberg, S. Camp, G. Dean, D. Elison, and P. Foote. 2016. Improving nitrogen management in Pacific Northwest sugarbeet production. J. Sugarbeet Res. 53:14-36.

TASCO. 1997. Sugarbeet Growers Guide Book. Amalgamated Sugar Company, LLC. Boise, ID.

TASCO. 2009. Sugarbeet Growers Guide Book. Amalgamated Sugar Company, LLC. Boise, ID.

Walsh, O.S., D. Tarkalson, A. Moore, G. Dean, D. Elison, J. Stark, O. Neher, B. Brown. 2019. Southern Idaho Fertilizer Guide: Sugarbeets. Bul. 935. University of Idaho Extension. Moscow, ID.