In-season Accumulation and Partitioning of Macronutrients and Micronutrients in Irrigated Sugar Beet Production

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ABSTRACT

The yield of sugar beet (*Beta vulgaris* L.) has almost doubled from 1993 to 2018 in the U.S. There is interest in understanding how increased root yield potential in sugar beet production systems has influenced the in-season nutrient uptake patterns in the plants. In 2014, a study was conducted to evaluate amounts and rates of dry matter, macro- (N, P, K, Ca, Mg, S, and Na) and micro-nutrients (Fe, Mn, Zn, Cu, and B) accumulated by a single herbicide-resistant sugar beet variety (BTS 21RR25) on an irrigated Portneuf silt loam soil of southern Idaho. Nitrogen, P, and K fertilizers were applied at agronomic rates based on soil test values. Whole plants were destructively sampled at 16-d intervals from 9 June (germination) to 30 September 2014 (at harvest), separated into tops and roots, and analyzed for dry matter amount and nutrient concentrations to estimate amounts and rates of nutrient accumulation. Mean root yield was 67.5 tonne ha^{-1}. Mean total accumulation at harvest was approximately 50.2 Mg ha^{-1}, 268, 69, 529, 200, 122, 109, 28, 13, 1.85, 0.64, 0.16, and 0.68 kg ha^{-1} for dry matter, N, P, K, Na, Ca, Mg, S, Fe, Mn, Zn, Cu, and B, respectively. Dry matter, P, Cu, Mg, Mn,

and Fe mean accumulations at harvest were between two-fold and seven-fold greater than previously reported. In contrast, N, K, S, Na, Ca, Zn, and B mean accumulations were within range of previously reported values. Findings from this study may be used to support nutrient management decision-making efforts for irrigated sugar beet production systems.

Additional Key Words: Sugar beet; plant tissue testing; macronutrient uptake; micronutrient uptake; dry matter; irrigated production systems.

Abbreviations: NH_4–N = ammoniacal–nitrogen, DTPA = diethylenetriaminepentaacetic acid, ICP–AES = inductively coupled plasma–atomic emission spectrophotometer, NO_3–N = nitrate–nitrogen, SO_4–S = sulfate–sulfur.

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) is the leading raw material for extracted sugar in the U.S., with 57% of U.S. sugar production (~9 million tons) contributed by sugar beet in 2017-18 (USDA-ERS, 2018). Sugar beet is an important annual cash crop grown in a wide variety of temperate climatic conditions and has ranged from 41.6 Mg ha^{-1} in 1993 to an average of 71.1 Mg ha^{-1} in 2017-18 in the U.S. (USDA-ERS, 2018). To maintain the increased production, it is essential to adopt improved management practices across a broad spectrum of disciplines (e.g. nutrients, irrigation, etc.) and improved crop varieties (Scott and Jaggard, 2000; El-Geddawy et al., 2008; Hoffmann and Loel, 2015; Curcic et al., 2018; Hoffmann and Kenter, 2018).

Nutrient application timing can be a challenge for producing profitable beet yields, sugar content, and sucrose recovery efficiency while minimizing the nutrient losses (via surface runoff, leaching, and gases) to the environment (Moore et al., 2009). For example, Smith et al. (1973) found that nitrogen (N) uptake by roots and total nutrient uptake by roots and tops were greater in spring applications than in fall applications, while the total percentage of N in the roots remained unaffected. Carter and Traveller (1981) indicated that, based on soil tests, N fertilizer should be applied before planting or during the early plant growth stages for maximum economy in sugar beet and sucrose production under irrigated field conditions on a Portneuf silt loam soil near Twin Falls, Idaho. Moreover, splitting N applications between pre-plant and in-season applications can be effective in limiting N losses to the environment and increasing N use efficiency for increased beet yield, sugar content and economic returns, especially on sandy soils (Moore et al., 2009). Hence, annual soil testing is needed to observe changes in soil fertility and optimize plant N and other nutrient availability during growing season to improve N and nutrient use efficiency and lower input

costs for sugar beet cropping system (Bravo et al., 1989; Draycott and Christensen, 2003; Hergert, 2010).

Soil testing reflects the amount of nutrients potentially available to the plant roots from the soil, but does not indicate how much of a particular mineral nutrient the plant actually needs or is able to absorb (Draycott and Christensen, 2003; Christenson and Draycott, 2006). This additional information is best achieved by plant tissue analysis, which is an important method for determining fertilizer schedules to optimize crop nutrient availability during the growing season (Bravo et al., 1989; Draycott and Christensen, 2003). Plant tissue analysis includes measuring the rate and amount of dry matter accumulation and partitioning of nutrients in the various tissues, measuring differences in uptake at varying growth stages, or measuring both partitioning of nutrients and overall uptake at different growth stages. Plant tissue analysis is being widely used for wheat (Rose et al., 2007), canola (Rose et al., 2007), corn (Karlen et al., 1988), maize (Ciampitti et al., 2013; Ciampitti and Vyn, 2013), and potato (Horneck and Rosen, 2008).

Nutrient uptake research efforts in sugar beets were predominantly conducted prior to 2005, when average root yields were significant lower than current yields as discussed above. These studies include evaluation of in-season whole plant uptake of macro- and micro-nutrients (Draycott and Christensen, 2003; Christenson and Draycott, 2006), partitioned macro- and micro-nutrient uptake at harvest under various rates of soil conditioner (Sepaskhah et al., 1980), partitioned macronutrient uptake at harvest and/or during the season (Mackenzie et al., 1957; Eslami et al., 1988; Bravo et al., 1989; Matsi et al., 2005), and partitioned micronutrient uptake at harvest (Choluj et al., 2004; Matsi et al., 2005). One recent study compared micronutrient concentrations in conventional and glyphosate-resistant sugar beet plant tissue, but did not provide information on in-season plant nutrient uptake (Holtschulte et al., 2011). Hence, current interest in understanding how increased root yield from 1993 to 2018 in the U.S has influenced the in-season nutrient uptake patterns in the plants in sugar beet production systems is limited.

In order to plan an effective nutrient management program for sugar beets, a comprehensive and current understanding of in-season dry matter accumulation, nutrient uptake, and nutrient partitioning is necessary to determine the period of maximum nutrient uptake, nutrient distribution among tops and roots, and total removal of nutrients. Information on these parameters would be useful for improving plant growth and identifying potential sugar impurities for sugar beets produced in an irrigated production system. Thus, the study objective was to evaluate amounts, rates, and partitioning dynamics of dry matter, macronutrients, and micronutrients accumulated by a current sugar beet variety (BTS 21RR25) produced on an irrigated Portneuf silt loam soil of southern Idaho over one growing season.

MATERIALS AND METHODS

Study Site Description

The study was conducted on a sprinkler irrigated Portneuf silt loam (Coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) soil at the USDA-ARS research station in Kimberly, Idaho. The 30-yr historic (1995–2015) mean annual precipitation and temperature were 20.4 cm and 7.7 °C, respectively, as recorded at the weather station located at USDA-ARS, Kimberly, Idaho (AgriMet, 2016).

Fertilizer-only treatment plots from a larger manure amendment study were selected for the purpose of this study. Each experimental plot (12.2 m wide and 18.3 m long) was replicated four times in a randomized complete block design. Based on pre-plant soil test analysis (see the next section) and University of Idaho fertilizer recommendations for sugar beet production (Moore et al., 2009), 109 kg N ha^{-1} (75 kg N ha^{-1} as urea [46-0-0] and 34 kg N ha^{-1} as monoammonium phosphate [MAP, 11-52-0], 151 kg P_2O_5 ha^{-1} as MAP, and 84 kg K_2O ha^{-1} as muriate of potash [0-0-60]) were applied to meet the expected nutrient requirements of the crop. Fertilizer was broadcasted to the field using a hand-held garden fertilizer spreader (Scotts Handy Green II Hand-Held Broadcast Spreader, Scotts Miracle-Gro Company, Marysville, OH, USA) on 17 April 2014 and incorporated into the soil with a roller harrow on the same day. On 5 May 2014, a glyphosate-resistant sugar beet variety BTS 21RR25 (Betaseed, Inc., Kimberly, ID, USA) was planted at a seeding rate of 134,425 seeds ha^{-1} at 1.9 cm seeding depth in a 56-cm wide row and 14.0 cm spacing between plants within the row. Glyphosate herbicide (Loveland Products, Loveland, CO, USA) was applied at a rate of 2.33 L ha^{-1} on 2 June 2014 for the purpose of weed control. A total of 44.6 cm of irrigation water were applied using a solid set system with Nelson R2000WF Rotator sprinklers equipped with 3.2-mm nozzles, operated at 414-kPa pressure, and spaced on a 12.2-m × 12.2-m grid from 6 May to 10 September 2014.

Pre-plant Soil Sampling and Analyses

Pre-plant soil samples were collected on 18 March 2014. A 5.72-cm diameter soil auger (JMC Soil Samplers, Clements Associates Inc., Newton, IA, USA) was used to collect soil samples from 0- to 30-cm (surface) and 30- to 60-cm (subsurface) depths with 10 and 5 subsamples composited from the surface and subsurface soil depths, respectively. Prior to chemical analysis, soils were air-dried at 40 °C for 24 h, ground using an Agvise Soil Crusher (Agvise Laboratories, Northwood, ND, USA), and passed through a 2-mm sieve. Table 1 shows a description of the pre-plant soil properties.

Soil texture was determined using the hydrometer method (Gee and Or, 2002). Soil pH was measured with a digital pH meter (Orion, Thermo Scientific, Waltham, MA, USA) and soil electrical conductivity (EC) was measured in a 1:1 soil to deionized water suspension with a conductivity

Table 1. Mean (n = 4) pre-plant soil properties, collected on 18 March, 2014. The soil series was a Portneuf silt loam, located in Kimberly, Idaho.

Soil parameter	0-30 cm depth	30-60 cm depth
Soil pH	7.9	7.9
Soil EC (mmhos cm^{-1})	0.8	0.8
Organic matter (%)	1.4	0.9
Nitrate-N (mg kg^{-1})	8.1	3.2
Ammonium-N (mg kg^{-1})	3.5	1.9
Olsen P (mg kg^{-1})	11.9	4.1
Olsen K (mg kg^{-1})	113	86
Available B (mg kg^{-1})	0.5	0.3
DTPA Cu (mg kg^{-1})	1.0	0.8
DTPA Fe (mg kg^{-1})	9.8	6.8
DTPA Mn (mg kg^{-1})	5.1	2.8
DTPA Zn (mg kg^{-1})	2.5	0.6
Sulfate-S (mg kg^{-1})	9.5	17.0
Calcium carbonate (%)	6.6	13.5

bridge (YSI Model 31, YSI Inc., Yellow Springs, OH, USA). Soil organic matter content was determined by the Sims/Haby colorimetric method (Sims and Haby, 1971) using a spectrometer (Spectronic 301, Milton Roy Co., Warminster, PA, USA). Soil inorganic N (NH_4^+–N and NO_3^-–N) was extracted using 2 M KCl (Mulvaney, 1996) and the supernatant was analyzed on a flow injection analyzer (Lachat Instruments, Loveland, CO, USA) for both NH_4^+–N and NO_3^-–N concentrations. The sodium bicarbonate-based Olsen method was used to extract plant-available P and K (Olsen et al., 1954; Olsen and Sommers, 1982). The supernatant was analyzed on a spectrometer and a flame photometer (Allied IL943, GMI, Ramsey, MN, USA) for Olsen P and Olsen K, respectively. Available soil B was extracted using the procedure of McGeehan et al. (1989) and Gavlak et al. (2005) and the supernatant was analyzed using an inductively coupled plasma atomic emission spectrophotometer (ICP-AES) (Optima 3200, PerkinElmer, Waltham, MA, USA). Available Cu, Fe, Mn, and Zn were extracted using the 0.005 M diethylenetriamine-pentaacetic acid (DTPA; pH 7.3) extraction method (Lindsay and Norvell, 1978; Gavlak et al., 2005) and the supernatant was analyzed using an ICP-AES. Sulfate sulfur (SO_4–S) was extracted and analyzed using the procedure of Kalra and Maynard (1991) and Gavlak et al. (1997). Calcium carbonate content in the soil was determined by shaking 1.0 g of air-dried soil, ground to pass a 100-mesh sieve (<150 µm), with 25 mL of the 0.4 M acetic acid on an orbital shaker for 16 h and the percent

calcium carbonate was calculated using the procedure of Gavlak et al. (1997).

Plant Tissue Sampling and Analyses

Nutrient uptake was measured eight times on various days after planting (DAP; 9 June or 35 DAP, 24 June or 50 DAP, 11 July or 67 DAP, 28 July or 84 DAP, 12 August or 99 DAP, 27 August or 114 DAP, 16 September or 134 DAP, and 30 September or 148 DAP) during the 2014 growing season by sampling total biomass of plant tops (aboveground tissue) and roots. Whole plant samples were destructively collected at a targeted 16 d interval from 9 June (germination) to 30 September (at harvest) by hand-digging 1.5 m row length in the center of each plot, with a minimum distance of 5 m from plot edges. Whole plant samples were separated into two parts, tops and roots, by removing tops manually with a beet knife at the base of the petiole as described by Jorritsma and Oldfield (1969) and Milford and Houghton (1999).

Root samples were made up of both roots and crown tissue (hereafter referred to as roots). Soil was wiped off of beet tops and roots by hand. Roots were weighed at the time of tissue sampling in the field using a field scale (Ohaus Corporation, Parsippany, NJ, USA) to record total fresh root weight and then were transported to the University of Idaho's Twin Falls Research and Extension Center, Twin Falls, ID where they were washed with distilled water and excess moisture was removed with paper towels. In early season sampling (9-24 June 2014), the entire root sample from each plant was processed; during late season sampling (11 July to 30 September 2014) the roots were cut in half lengthwise, with one half kept for analysis and the other half discarded. Remaining root halves were cut into approximately 2.54 cm width cubes using standard kitchen knives. A representative subsample of the beet cubes was collected and oven dried at 60 °C for 72 h for the determination of dry matter content. The remainder of the beet cubes were placed in a blender (Vitamix Corporation, Cleveland, OH, USA) for wet grinding. Between 10 and 60 ml of distilled water was added during blending to create a uniformly textured beet root puree. The beetroot puree was spread on parchment paper at a thickness of 0.25 to 0.50 cm, and oven dried at 60 °C for 72 h. The dried sample, which resembled very dry fruit leather, was pulverized using a mortar and pestle, ground with a coffee grinder (Hamilton Beach Custom Grind, Hamilton Beach Brands, Inc., Glen Allen, VA, USA), and stored at room temperature until analyzed.

Beet tops were weighed in the field using a field scale to record shoot fresh weight. The entire top sample was processed during the early season sampling period (9-24 June 2014). Approximately one-third of the tops were sub-sampled by laying leaves on a table and collecting every third leaf. A sub-sample of tops was collected and transported to the University of Idaho's Twin Falls Research and Extension Center during the late season sampling period (11 July to 30 September 2014). Tops sub-samples were weighed, dried for 72 h at 60 °C, and weighed again to

obtain dry matter weight. The dried top samples were ground using a Wiley mill grinder (Arthur H. Thomas Co., Sedesboro, NJ, USA) fitted with a 2-mm sieve, and stored at room temperature until analyzed.

Dried and ground roots and tops plant tissue sample analyses were conducted by AGVISE Laboratories in Northwood, ND, USA. Samples (roots and tops) were analyzed for total N using a combustion analyzer (Elementar Americas Inc., Mt. Laurel, NJ, USA). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) were determined by weighing 0.5 g dried, 0.84-mm (20 mesh screened) tissue samples and adding 5.0 mL concentrated nitric acid (HNO_3) into 50-mL digestion tubes (Jones, 2001). The sample tubes were digested into a port of a digestion block at 125 °C. After 1-h the digests were cooled, 3.0 mL of 30% hydrogen peroxide (H_2O_2) was added to the tubes and further digested at 125 °C until the digests were clear. The digests were then cooled and diluted to a volume of 10 mL with 20% hydrochloric acid (HCl), vortexed, and filtered (Jones, 2001). Filtrates were analyzed for P, K, Ca, Mg, Na. S, Fe, Mn, Zn, Cu, and B using an ICP-AES.

Data Analysis

To evaluate the intra-seasonal variation, planting, and harvest, derivatives were set at zero to fit the curves for each plant fraction showing dry matter and nutrient accumulation amounts and rates as a function of sampling date during the growing season. Nutrient concentrations and dry matter data (Tables 2 and 3) were used in equation [1] to calculate the accumulation of each nutrient by sugar beet tops and roots while daily accumulation rate for each nutrient in different plant parts was calculated using the equation [2].

Amount of each nutrient accumulation = average nutrient concentration × dry biomass amount, [1]

$$\text{Daily accumulation rate} = (NA_{(t)} - NA_{(0)})/d, \quad [2]$$

Where, NA = nutrient accumulation, t = final date, 0 = starting date, and d = total number of days between two sampling dates.

RESULTS AND DISCUSSION

Amount and Rate of Dry Matter Accumulation

The partitioning pattern of our dry matter accumulation over the entire growing season was similar to other accumulation studies (Mackenzie et al., 1957; Cooke and Scott, 1993; Draycott and Christensen, 2003). Whole plant dry matter accumulation at beet harvest was 50.2 Mg ha^{-1}, with a root:top ratio of 6.2:1 (Fig. 1A; Table 2). Dry matter accumulation and root:top ratio were 2.3 and 2.2 times greater than what was previously reported by Scott and Jaggard (1993), where average dry matter accumulation and root:top ratio at harvest

Table 2. Mean (n = 4) dry matter accumulation and macronutrient concentration in sugar beet tops and roots over the course of a full growing season. The crop was grown under irrigated conditions on a Portneuf silt loam from May 5th to October 3rd, 2014 in Kimberly, Idaho.

Sampling date	Days after planting (DAP)	Tops		Roots		Tops		Roots	
		Mean	*SD**	Mean	*SD*	Mean	*SD*	Mean	*SD*
		Dry matter, Mg ha^{-1}				N, g kg^{-1}			
06/09/14	35	0.10	*0.01*	0.01	*0.00*	47.5	*4.0*	25.1	*1.7*
06/24/14	50	1.51	*0.35*	0.51	*0.06*	41.5	*2.7*	18.0	*2.1*
07/11/14	67	2.97	*0.82*	2.14	*0.4*	33.4	*2.6*	7.9	*0.6*
07/28/14	84	4.15	*0.58*	16.9	*2.1*	22.6	*2.5*	5.4	*0.4*
08/12/14	99	5.52	*0.69*	26.2	*3.2*	21.8	*1.3*	3.8	*0.7*
08/27/14	114	6.05	*0.31*	36.3	*2.8*	26.9	*1.3*	3.1	*0.7*
09/16/14	134	6.17	*0.46*	40.8	*3.5*	22.8	*3.4*	3.0	*0.7*
09/30/14	148	6.97	*0.58*	43.2	*2.8*	19.0	*1.3*	3.0	*0.5*
		P, g kg^{-1}				K, g kg^{-1}			
06/09/14	35	4.6	*0.3*	4.1	*0.2*	40.2	*2.1*	36.0	*0.9*
06/24/14	50	4.2	*0.1*	3.5	*0.1*	34.1	*1.7*	23.2	*1.5*
07/11/14	67	3.3	*0.2*	2.3	*0.1*	38.1	*2.7*	13.0	*0.4*
07/28/14	84	2.2	*0.1*	1.7	*0.04*	40.2	*4.6*	10.1	*1.0*
08/12/14	99	2.1	*0.1*	1.5	*0.02*	37.4	*2.4*	8.5	*0.9*
08/27/14	114	2.2	*0.1*	1.4	*0.03*	34.9	*1.7*	7.6	*0.9*
09/16/14	134	2.3	*0.1*	1.2	*0.03*	40.9	*1.0*	6.5	*0.2*
09/30/14	148	2.1	*0.1*	1.3	*0.05*	39.9	*1.8*	5.9	*0.3*
		Na, g kg^{-1}				Ca, g kg^{-1}			
06/09/14	35	41.0	*1.3*	7.0	*0.5*	12.9	*0.3*	4.0	*0.4*
06/24/14	50	40.7	*3.7*	5.8	*1.1*	11.7	*0.4*	1.6	*0.1*
07/11/14	67	33.0	*2.1*	2.9	*0.7*	11.5	*2.2*	1.2	*0.1*
07/28/14	84	33.1	*1.3*	1.3	*0.1*	10.9	*0.5*	1.1	*0.04*
08/12/14	99	27.9	*1.6*	0.9	*0.1*	11.6	*1.4*	1.2	*0.03*
08/27/14	114	25.5	*0.8*	0.8	*0.1*	10.1	*0.5*	1.0	*0.05*
09/16/14	134	24.7	*3.3*	0.5	*0.05*	8.7	*1.1*	1.1	*0.10*
09/30/14	148	25.5	*1.9*	0.5	*0.05*	11.7	*0.4*	1.0	*0.03*
		Mg, g kg^{-1}				S, g kg^{-1}			
06/09/14	35	11.0	*0.5*	3.2	*0.1*	3.9	*0.1*	1.3	*0.1*
06/24/14	50	10.7	*0.7*	1.9	*0.1*	3.7	*0.1*	1.0	*0.1*
07/11/14	67	7.5	*0.7*	1.6	*0.03*	3.2	*0.2*	0.6	*0.03*
07/28/14	84	6.5	*0.2*	1.7	*0.1*	3.0	*0.2*	0.4	*0.00*
08/12/14	99	5.9	*0.5*	1.7	*0.1*	2.7	*0.3*	0.4	*0.03*
08/27/14	114	5.1	*0.4*	1.8	*0.1*	2.7	*0.2*	0.3	*0.02*
09/16/14	134	4.4	*0.5*	1.8	*0.1*	2.5	*0.4*	0.3	*0.00*
09/30/14	148	5.8	*0.4*	1.6	*0.1*	2.2	*0.1*	0.3	*0.00*

*SD = Standard Deviation

Figure 1. Partitioned plant tissue dry matter (DM) and nitrogen (N) accumulation over time for glyphosate resistant sugar beet variety (BTS-21RR25) which was grown under irrigated conditions on a Portneuf silt loam in Kimberly, Idaho in 2014. Data points represent mean (n = 4) value by sampling event. Individual graphs represent: A) cumulative DM accumulations, B) daily DM accumulation rate, C) cumulative N accumulations, and D) daily N accumulation rate.

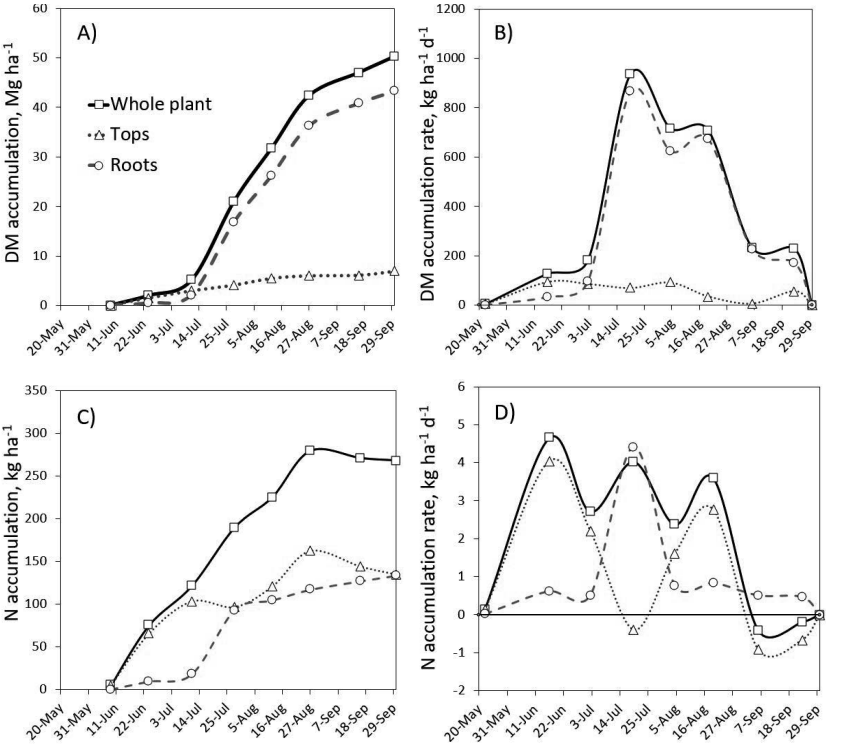


Figure 2. Partitioned plant tissue phosphorous (P) and potassium (K) accumulation over time for glyphosate resistant sugar beet variety (BTS-21RR25) which was grown under irrigated conditions on a Portneuf silt loam in Kimberly, Idaho in 2014. Data points represent mean (n = 4) value by sampling event. Individual graphs represent: A) cumulative P accumulations, B) daily P accumulation rate, C) cumulative K accumulations, and D) daily K accumulation rate.

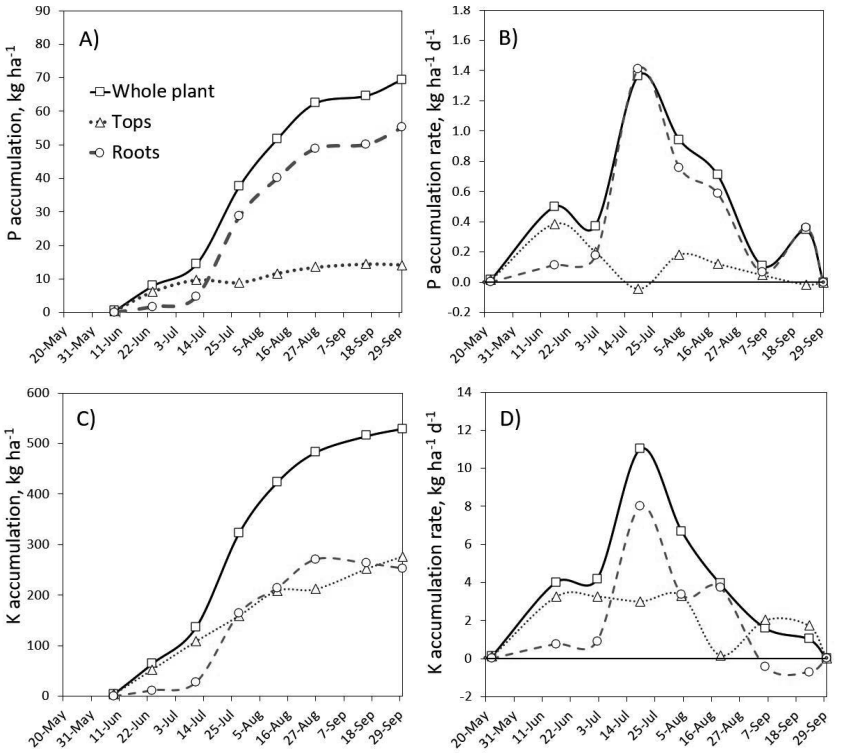


Figure 3. Partitioned plant tissue sodium (Na) and calcium (Ca) accumulation over time for glyphosate resistant sugar beet variety (BTS-21RR25) which was grown under irrigated conditions on a Portneuf silt loam in Kimberly, Idaho in 2014. Data points represent mean (n = 4) value by sampling event. Individual graphs represent: A) cumulative Na accumulations, B) daily Na accumulation rate, C) cumulative Ca accumulations, and D) daily Ca accumulation rate.

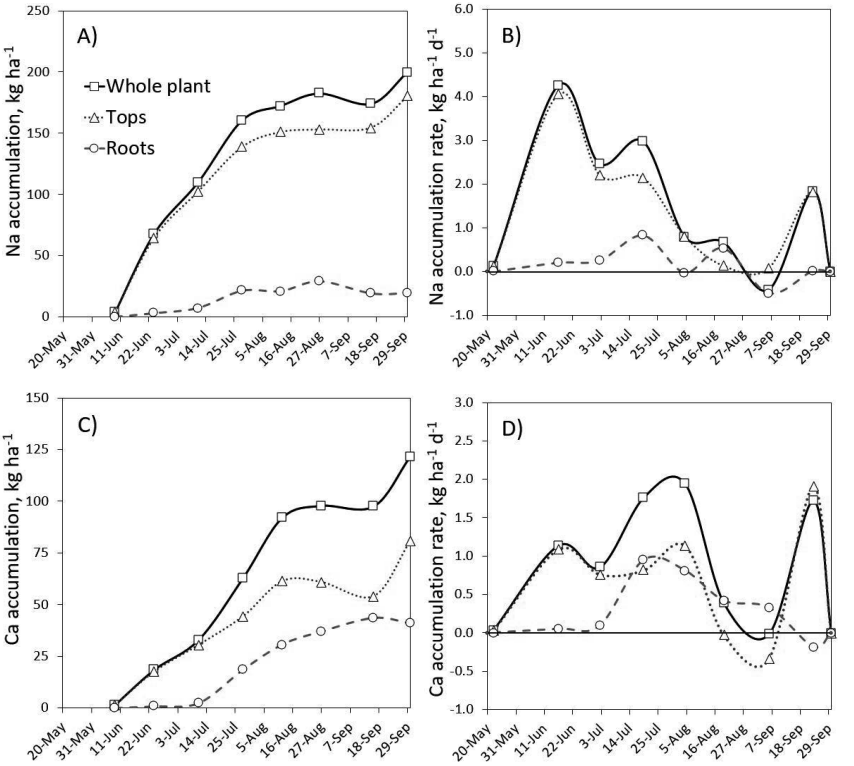
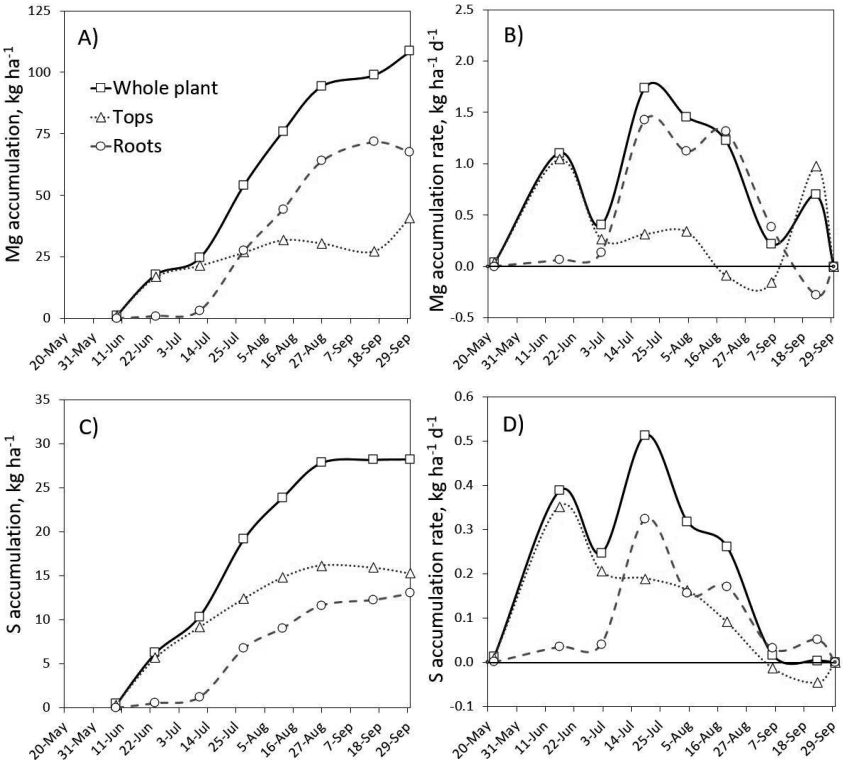


Figure 4. Partitioned plant tissue magnesium (Mg) and sulfur (S) accumulation over time for glyphosate resistant sugar beet variety (BTS-21RR25) which was grown under irrigated conditions on a Portneuf silt loam in Kimberly, Idaho in 2014. Data points represent mean (n = 4) value by sampling event. Individual graphs represent: A) cumulative Mg accumulations, B) daily Mg accumulation rate, C) cumulative S accumulations, and D) daily S accumulation rate.



were 21.5 Mg ha^{-1} and 2.8:1, respectively. Findings from Scott and Jaggard (1993) were based on 13 site-years of irrigated conventional sugar beets grown in Suffolk, UK from 1978 to 1990. The increases in dry matter yield in the current study may be partially attributed to recent advances in sugar beet breeding (Loel et al., 2014; Hoffmann and Kenter, 2018) and changes in agronomic practices (Scott and Jaggard, 2000; El-Geddawy et al., 2008; Curcic et al., 2018). Location differences, including soil type (Goodman 1968; Webster et al., 1977) and temperature regime (Milford et al., 1980; Milford et al., 1985; Tsialtas and Maslaris, 2014) may also contribute to yield differences between the two studies.

Daily dry matter accumulation rates showed one peak period (on 19 July 2014, 75 DAP) of accumulation of 936 kg ha^{-1} day^{-1} (Fig. 1B), with 93% of accumulation occurring in the root during the peak period. This finding illustrates the importance of maximizing nutrient availability prior to and during the peak period to achieve optimal root yields.

Amounts and Rates of Macronutrients Accumulation

Macronutrient accumulations from the present study were compared with previous findings published in widely referenced sugar beet management textbooks that are currently used by sugar beet agronomists who are designing nutrient management plans for sugar beet production fields (e.g. Draycott and Christenson, 2003; Christensen and Draycott, 2006). They comprehensively reviewed nutrient uptake, accumulation, and partitioning by tops, roots, and whole plant in Europe between 1970 and 2000 in a wide range of locations, soils, and inputs. In comparison to these summaries, the differences in amounts and rates of macronutrients accumulated by a current sugar beet variety (BTS 21RR25) produced on an irrigated Portneuf silt loam soil of southern Idaho over one growing season are discussed in the next few paragraphs.

Mean N accumulation was approximately 268 kg ha^{-1} at harvest with accumulations of 135 and 133 kg ha^{-1} in the tops and roots, respectively (Fig. 1C; Table 2). The amount of total N accumulation at harvest was within the reported uptake range of 137-355 kg ha^{-1} (tops: 59-215 kg ha^{-1} and roots: 78-140 kg ha^{-1}) as summarized by Draycott and Christenson (2003). The decreases in top and root tissue N concentration over the season were similar to previously reported findings (Bravo et al., 1989; Draycott and Christenson, 2003; Cariolle and Duval, 2006; Grzebisz et al., 2012).

Nitrogen accumulation rates (Fig. 1D) showed three distinct accumulation phases and one loss phase. The highest total N uptake rate was 4.6 kg ha^{-1} d^{-1} (24 June 2014; 50 DAP), and uptake was dominated by top growth, with 85% of accumulated N located in the tops. The second highest total N uptake rate was 4.0 kg ha^{-1} d^{-1} (28 July 2014; 84 DAP) and about 49% of N taken up by the plant was stored in the root. However, N uptake was again dominated by the tops during 28 July to 27 August 2014 (84-114 DAP), with 58% of N accumulated in the tops

during this period, which showed the third highest total N uptake rate at 3.6 kg ha^{-1} d^{-1}. This is an interesting finding, as the majority of dry matter accumulation was occurring in the roots during this period (Fig 1B). However, loss of N occurred from 27 August (114 DAP) to 30 September (148 DAP), with an N decrease of 27.5 kg ha^{-1} in the tops and an increase of 16.4 kg ha^{-1} in the roots (Fig. 1C). This N loss likely occurred due to the transport of N from areas with low metabolic activity, such as tops (old leaves), to areas with high growth rates, like the roots, with a net loss of 11.1 kg ha^{-1}. The phenomena of N translocation during the late season was in line with previously reported N uptake studies (Bürchy and Biscoe, 1983; López-Bellido et al., 1994).

Mean P accumulation at harvest was approximately 69.4 kg P ha^{-1} with accumulations of 14.2 and 55.2 kg P ha^{-1} in the tops and roots fraction, respectively (Fig. 2A; Table 2). Draycott and Christensen (2003) reported similar P accumulation in the tops fraction (15.7 kg ha^{-1}) but significantly less P accumulation in the root fraction (20.2 kg P ha^{-1}) in comparison to the present study. Tops and root tissue P concentrations were similar between the two studies; therefore, higher root P accumulation in this study is attributed to greater dry matter accumulation in the roots rather than increasing P concentrations (Table 2). Peak accumulation rates (Fig. 2B) in the roots and tops fractions were approximately 1.4 (28 July 2014; 84 DAP) and 0.4 kg P ha^{-1} d^{-1} (24 June 2014; 50 DAP), respectively. These peak P rates in tops and roots were most likely needed for ATP production to transfer energy during photosynthesis and to support cell walls (phospholipids) for plant growth (Draycott and Christensen, 2003).

Mean K accumulation at harvest was approximately 529 kg K ha^{-1} with accumulations in tops and root fractions of approximately 276 and 253 kg K ha^{-1}, respectively (Fig. 2C; Table 2). While root:tops K accumulation ratio ranged from 1:1.5 to 1:2.0 in previous studies (Draycott and Christensen, 2003), the K root:tops ratio in the current study was approximately 1:1. Peak accumulation rates in the roots and tops fractions were approximately 8.0 and 3.3 kg K ha^{-1} d^{-1}, respectively (Fig. 2D). The K accumulation rate curve was dominated by a single peak from 11 July to 27 August 2014 (67-114 DAP). However, K was likely transported from the roots to the tops fraction during the late season (16-30 September 2014; Fig. 2D). This translocation may lead to better sugar quality in the roots at the expense of the tops becoming the dominant photosynthate sink (Carter, 1986; Bravo et al., 1989; Draycott and Christensen, 2003). Though studies provide evidence of K promoting the translocation of photosynthate in plants (Conti and Geiger, 1982), the information on mechanism(s) responsible for late season K translocation from roots to tops is limited and needs further investigation (Eslami et al., 1988).

Sodium (Na) uptake is commonly observed in sugar beet plants, serving at times as a partial substitute for K (Carter et al., 1986;

Christensen and Draycott, 2006). Mean Na accumulation at harvest was approximately 200 kg Na ha^{-1} with accumulations in tops and root fractions of approximately 180 and 20 kg Na ha^{-1}, respectively (Fig. 3A; Table 2). The Na accumulation pattern was similar to those reported previously (Christensen and Draycott, 2006), even though total dry matter accumulation was more than doubled. Daily Na accumulation rate in the tops fraction peaked at 4.0 kg Na ha^{-1} d^{-1} (24 June 2014; 50 DAP), with a second peak of 1.8 kg Na ha^{-1} d^{-1} occurring in the tops fraction at harvest (Fig. 3B).

Calcium (Ca) is needed for cell division, elongation, providing stability to cell walls by the formation of calcium pectate, and enzymatic activation (Draycott and Christensen, 2003; Kauss, 1987). Mean Ca accumulation at harvest was 122 kg Ca ha^{-1} (Fig. 3C; Table 2). Approximately 66 and 34% of the Ca was located in the tops and root fractions, respectively. The Ca accumulation distribution within the plant at harvest was similar to that of Bravo et al. (1989) at 120 kg Ca ha^{-1}. The majority of the Ca accumulation occurred between 9 June and 27 August 2014. Daily accumulation rates for Ca showed peaks for tops and root fraction of 1.9 (at harvest) and 0.9 kg Ca ha^{-1} d^{-1} (28 July 2014; 84 DAP), respectively (Fig. 3D).

Magnesium (Mg) is needed by the plant for reactions associated with respiration, photosynthesis, protein synthesis, enzyme activation and energy (ATP) transfer (Draycott and Christensen, 2003; Christensen and Draycott, 2006). Mean Mg accumulation at harvest was 109 kg ha^{-1}, with approximately 38 and 62% of the Mg in the tops and roots, respectively (Fig. 4A; Table 2). At harvest, the Mg accumulation in the current study was four times, of what Christensen and Draycott (2006) had reported. They also showed a distribution of 70% of Mg in the tops, while only 38% of Mg in the plant was found in the tops for the current study. In the current study, daily Mg accumulation rate in tops peaked at 1.0 kg ha^{-1} day^{-1} (24 June 2014; 50 DAP) due to lower mean root/top ratio (Fig. 4B). During 11 July to 27 August 2014, two peaks in the roots dominated daily Mg accumulation rates. The first peak was occurring on 19 July 2014 or 84 DAP (1.4 kg ha^{-1} d^{-1}) followed by a second peak of 1.3 kg ha^{-1} d^{-1} on 19 August 2014 or 114 DAP. During 16-30 September 2014, Mg likely translocated from roots to tops as was indicated by negative accumulation rate in the roots and simultaneous increase in tops (Fig. 4B).

Mean S accumulation at harvest was 28 kg S ha^{-1}, with 13.0 kg S ha^{-1} in the tops and 15 kg S ha^{-1} (Fig. 4C; Table 2). Sulfur accumulation at harvest was within the range of 13 to 100 kg S ha^{-1} as summarized by Draycott and Christensen (2003). Peak S accumulation rates occurred 50 DAP at a rate of 0.39 kg S ha^{-1} d^{-1}, with a second peak of 0.51 kg S ha^{-1} d^{-1} occurring at 84 DAP (Fig. 4D). Negative S accumulation rates in the tops portion (-0.05 kg S ha^{-1} d^{-1}) contrasted by positive S accumulation rates in the roots portion (0.05 kg S ha^{-1} d^{-1}) at harvest (30 September

2014) indicate possible S translocation from tops to roots (Fig. 4D).

In contrast to Draycott and Christenson (2003) and Christensen and Draycott (2006) summaries, the sugar beets in our study took up similar amounts of N, K, and S with approximately twice the amount of dry matter yield. This suggests that N, K, and S fertilizer application rates may not need to be adjusted, despite the dramatic increase in dry matter accumulations. Differences in nutrient accumulations in the roots and tops portion of the sugar beet was hypothesized to be related to dry matter production and nutrient concentrations of roots and tops. Greater nutrient accumulations in the roots may allow for greater nutrient removal, while greater nutrient accumulations in tops may create more recycling of nutrients back into the soil through leaf senescence (Eslami et al., 1988).

Amounts and Rates of Micronutrients Accumulation

Mean Fe accumulation at harvest was 13.5 kg ha^{-1}, with 1.0 kg Fe ha^{-1} in the roots and 12.5 kg Fe ha^{-1} in the tops (Fig. 5A; Table 3). This finding did not follow Fe accumulation patterns described by Draycott and Christensen (2003), where expected accumulations were estimated to be only 1.9 kg Fe ha^{-1} at harvest. In addition to dry matter content differences, Fe concentrations in the tops (2,042 mg Fe/kg) were 10-fold greater at harvest than the estimated concentration of 200 mg kg^{-1} reviewed by Draycott and Christensen (2003), although the cause for this increase is not known. The observed decrease in mean whole plant Fe accumulations on 16 September 2014 from 9.8 to 5.1 kg Fe ha^{-1} appears to be a function of high variation in the Fe concentrations in the tops among the four replications (Table 3), and not likely to be an indication of an actual loss of Fe from the plant. Daily Fe accumulation rate in the tops peaked at 0.30 kg ha^{-1} d^{-1} followed by a second peak at 0.69 kg ha^{-1} d^{-1} (Fig. 5B).

Mean Mn accumulation at harvest was 1.85 kg ha^{-1}, with 1.12 and 0.73 kg ha^{-1} in the roots and tops, respectively (Fig. 5C; Table 3). Manganese accumulations at harvest were 3.6 times greater than average Mn uptake of 0.52 kg ha^{-1} reported by Draycott and Christensen (2003). The increase in Mn accumulations in the current study can be partially attributed to increased Mn accumulations in tops, as the Mn concentration in the tops (120 mg kg^{-1}) was more than double the Mn concentrations in tops reported by Draycott and Christensen (2003). While there has been speculation that glyphosate-resistant sugar beet varieties are susceptible to Mn and other micronutrient deficiencies (Holtschulte et al., 2011), Mn deficiencies were not detected in the glyphosate-resistant sugar beet variety evaluated in the present study. Daily Mn accumulation rates at 50 DAP (8.5 g ha^{-1} d^{-1}), 99 DAP (14.9 g ha^{-1} d^{-1}), and 148 DAP (25.8 g ha^{-1} day^{-1}) were dominated by the tops (Fig. 5D). Daily Mn accumulations in the roots showed peak accumulation of 24.6 g ha^{-1} day^{-1} at 99 DAP (12 August 2014). Negative accumulation rate in the tops (-9 g ha^{-1} day^{-1}) on 16 September 2014 reflects likely translocation of Mn from tops to roots (Fig 5D).

Table 3. Mean (n = 4) micronutrient concentration in sugar beet roots and tops over the course of a full growing season. The crop was grown under irrigated conditions on a Portneuf silt loam from May 5th to October 3rd, 2014 in Kimberly, Idaho.

Sampling date	Days after planting (DAP)	Tops		Roots		Tops		Roots	
		Mean	*SD**	Mean	*SD*	Mean	*SD*	Mean	*SD*
		Fe, mg kg^{-1}				Mn, mg kg^{-1}			
06/09/14	35	469	*109*	1,200	*153*	69	*3*	52	*5*
06/24/14	50	431	*58*	162	*8*	99	*2*	27	*2*
07/11/14	67	770	*188*	82	*5*	121	*29*	25	*3*
07/28/14	84	352	*22*	68	*10*	83	*6*	26	*1*
08/12/14	99	1,254	*276*	91	*12*	110	*12*	31	*2*
08/27/14	114	1,326	*164*	69	*6*	105	*10*	29	*2*
09/16/14	134	510	*124*	55	*7*	67	*8*	29	*2*
09/30/14	148	2,042	*161*	21	*6*	120	*8*	26	*2*
		Zn, mg kg^{-1}				Cu, mg kg^{-1}			
06/09/14	35	40	*1.3*	35	*1.3*	8.5	*0.3*	8.5	*1.0*
06/24/14	50	37	*1.2*	23	*0.9*	8.8	*0.5*	6.5	*0.3*
07/11/14	67	31	*2.6*	14	*0.3*	8.0	*0.4*	3.8	*0.3*
07/28/14	84	21	*1.1*	11	*0.5*	6.3	*0.3*	3.5	*0.3*
08/12/14	99	24	*2.1*	12	*0.00*	5.5	*0.3*	3.0	*0.0*
08/27/14	114	24	*1.7*	12	*0.5*	6.8	*0.5*	3.0	*0.0*
09/16/14	134	19	*1.7*	11	*0.6*	6.0	*0.0*	3.0	*0.0*
09/30/14	148	25	*0.7*	11	*0.6*	6.3	*0.3*	2.8	*0.3*
		B, mg kg^{-1}							
06/09/14	35	29	*0.4*	18	*0.4*				
06/24/14	50	33	*0.6*	17	*1.2*				
07/11/14	67	39	*2.0*	13	*0.4*				
07/28/14	84	37	*1.1*	13	*0.6*				
08/12/14	99	35	*1.6*	12	*0.3*				
08/27/14	114	37	*0.9*	11	*0.5*				
09/16/14	134	39	*2.4*	12	*0.9*				
09/30/14	148	35	*1.4*	11	*0.3*				

*SD = Standard Deviation

Figure 5. Partitioned plant tissue iron (Fe) and manganese (Mn) accumulation over time for glyphosate resistant sugar beet variety (BTS-21RR25) which was grown under irrigated conditions on a Portneuf silt loam in Kimberly, Idaho in 2014. Data points represent mean (n = 4) value by sampling event. Individual graphs represent: A) cumulative Fe accumulations, B) daily Fe accumulation rate, C) cumulative Mn accumulations, and D) daily Mn accumulation rate.

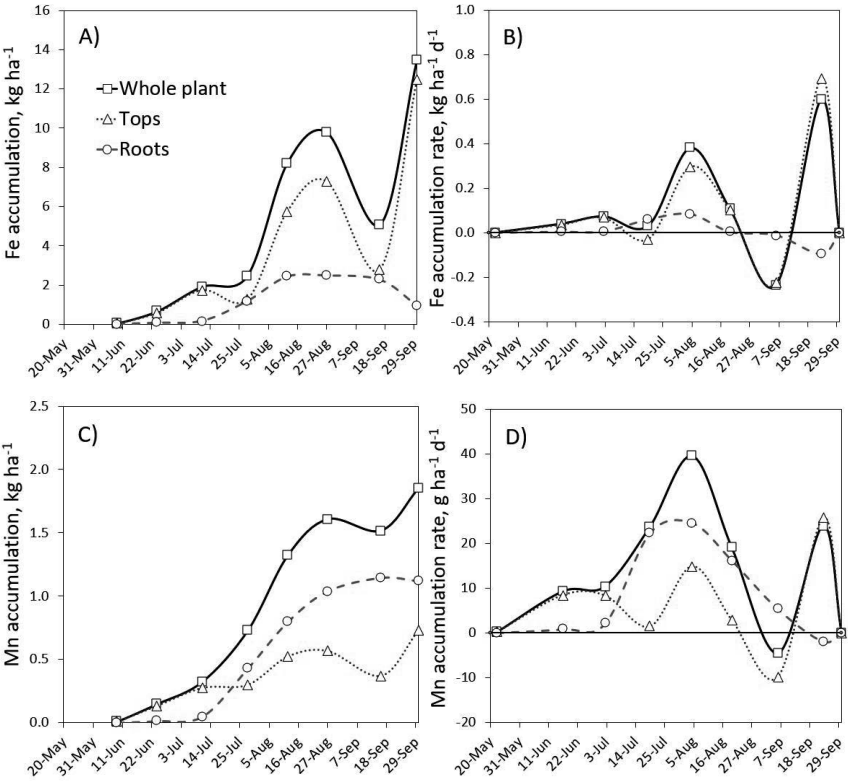
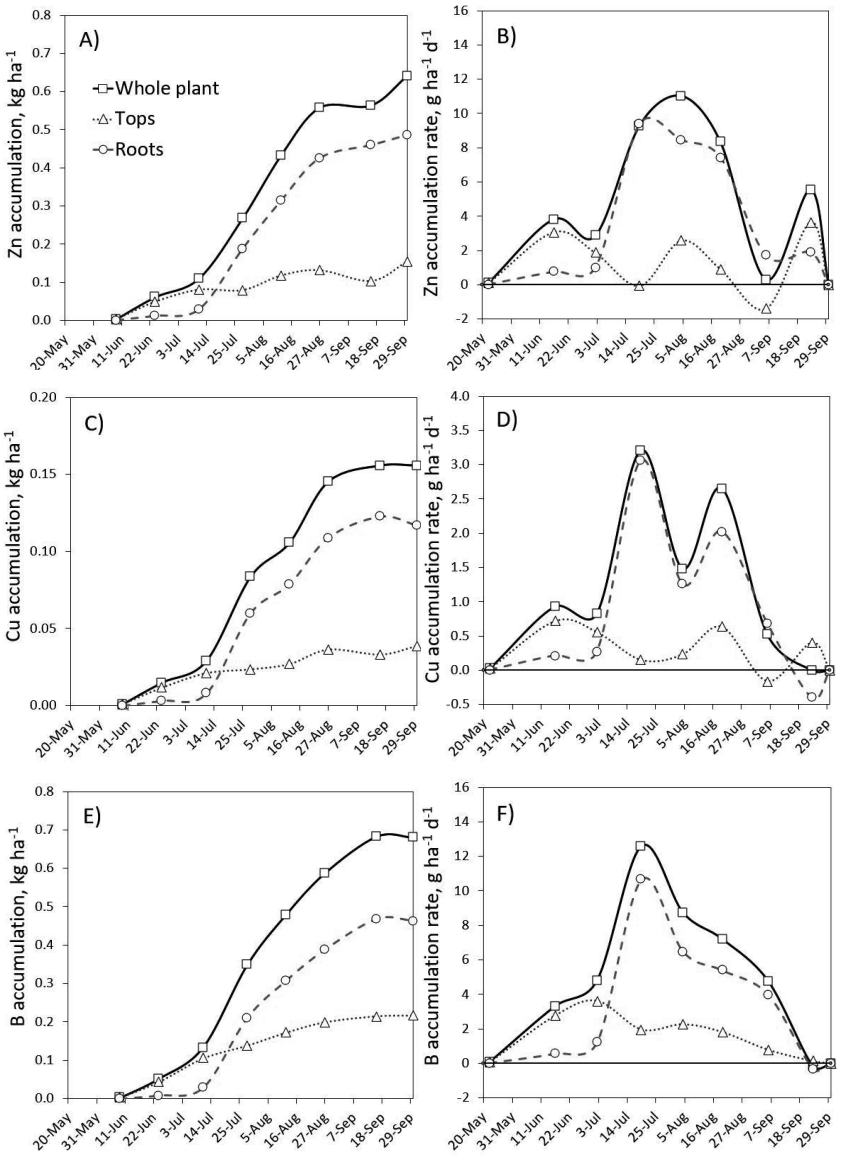


Figure 6. Partitioned plant tissue zinc (Zn), copper (Cu), and boron (B) accumulation over time for glyphosate resistant sugar beet variety (BTS-21RR25) which was grown under irrigated conditions on a Portneuf silt loam in Kimberly, Idaho in 2014. Data points represent mean (n = 4) value by sampling event. Individual graphs represent: A) cumulative Zn accumulations, B) daily Zn accumulation rate, C) cumulative Cu accumulations, D) daily Cu accumulation rate, E) cumulative B accumulations, and F) daily B accumulation rate.



Mean Zn accumulation at harvest was 0.64 kg ha^{-1}, with 0.49 and 0.16 kg Zn ha^{-1} in the roots and tops, respectively (Fig. 6A; Table 3). The Zn accumulation distribution in the plant was similar to those reported previously (Draycott and Christensen, 2003), even though total accumulation was more than tripled in the current study. Whole plant Zn accumulations followed a linear pattern from germination to harvest. Peak accumulation rates in the roots and tops fractions were approximately 9.4 and 3.7 g Zn ha^{-1} d^{-1}, respectively (Fig. 6B).

Mean Cu accumulation at harvest was 0.16 kg Cu ha^{-1}, with 0.12 and 0.04 kg Cu ha^{-1} in the roots and tops, respectively (Fig. 6C; Table 3). The Cu tissue concentrations were similar to reported values, while Cu uptake more than doubled (Draycott and Christensen, 2003). Peak accumulation rates for roots and tops were 3.1 and 0.7 g ha^{-1} d^{-1}, respectively (Fig. 6D). During 11 July to 27 August 2014 (67-114 DAP), daily Cu accumulation rates were dominated by two peaks in the roots. The first peak occurred at 84 DAP (28 July 2014) at a rate of 3.1 g ha^{-1} day^{-1} and the second peak occurred at 114 DAP (27 August 2014) at a rate of 2.0 g ha^{-1} day^{-1}. At harvest (30 September 2014 or 148 DAP), a likely translocation of equal rates of Cu (0.4 g ha^{-1} day^{-1}) to tops from the roots was observed as was indicated by negative accumulation rates in the roots and a simultaneous increase in the tops.

Mean B accumulation at harvest was 0.68 kg B ha^{-1}(Fig. 6E; Table 3). Distribution among plant fractions at harvest showed 68 and 32% in the roots and tops, respectively, with a root:top ratio of 2.1:1. Boron concentrations at harvest in the root and tops fractions were similar to values reported by Draycott and Christensen (2003), although B uptake in the current study was two times greater than what they had reported. Peak accumulation rates for tops and roots were 3.6 (11 July 2014; 67 DAP) and 10.6 g B ha^{-1} d^{-1} (28 July 2014; 84 DAP), respectively (Fig. 6F).

CONCLUSIONS

The amount and rate of dry matter, macro- and micro-nutrient accumulations was evaluated for a typical irrigated sugar beet crop produced in Southern Idaho. Mean total accumulation at harvest was approximately 50.2 Mg ha^{-1}, 268, 69, 529, 200, 122, 109, 28, 13, 1.85, 0.64, 0.16, and 0.68 kg ha^{-1} for dry matter, N, P, K, Na, Ca, Mg, S, Fe, Mn, Zn, Cu, and B, respectively. The order of whole plant nutrient accumulations at harvest were as follows: K > N > Na > Ca > Mg > P > S > Fe > Mn > B > Zn > Cu. Dry matter, P, Cu, Mg, Mn, and Fe mean accumulations at harvest were between two-fold and seven-fold greater than previously reported. In contrast, N, K, S, Na, Ca, Zn, and B mean accumulations were within range of previously reported values. During the late season (16-30 September 2014), K, Ca, Mg, Fe, Mn, and Cu translocated from roots to tops, and N and S translocated from tops to roots. The phenomena of nutrient translocation in sugar beet during the

late season was hypothesized in the current study and needs further investigation. To build on the findings discussed in this publication, further research is necessary to have a better understanding of nutrient uptake, accumulation and partitioning when compared over multiple years, soil types, varieties, and agro-climatic locations.

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