Effects of Tillage System and Nitrogen Supply on Sugarbeet Production

David D. Tarkalson[1], Dave L. Bjorneberg[1], and Amber Moore[2]

[1]USDA-ARS Northwest Soils and Irrigation Research Laboratory, Kimberly, ID; [2]University of Idaho Twin Falls Research and Extension Center, Twin Falls ID
Corresponding Author: David D. Tarkalson
(david.tarkalson@ars.usda.gov)

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ABSTRACT

The sugarbeet industry in the Pacific Northwest is interested in strip tillage (ST) primarily due to the potential savings in tillage costs. This study was conducted to evaluate the use of ST in the Pacific Northwest compared to conventional tillage (CT) practices and to evaluate N requirements of sugarbeet under ST and CT. The effect of tillage method (ST, moldboard plow [MP] system, and chisel plow [CP] system) and N supply (5 levels) on sugarbeet production factors were investigated in Kimberly, ID from 2008 to 2010 on a Portneuf silt loam soil with barley as the previous crop. Root and estimated recoverable sucrose (ERS) yields were the same under all three tillage practices across N supply. There were no differences in N response across tillage systems. However, estimated tillage costs for ST were from 53% to 76% lower than other tillage systems tested. The CP treatment had a significantly lower harvest plant population compared to ST and MP, likely because residue inhibited seed-soil contact. Averaged across tillage practices, in 2008 and 2010, a significant quadratic relationship was observed between N supply and root and ERS yield. During 2008 and 2010, yields at the economically optimum N supply (EONS) ranged from 73.6 to 79.9 Mg roots ha^{-1} and 11,054 to 11,415 kg ERS ha^{-1} across tillage practice and N prices ranging from \$0.44 to \$2.20 kg^{-1} N. During 2008 and 2010, nitrogen use efficiency (NUE) at the EONS ranged from 50.1 to 67.9 kg sucrose kg^{-1} N supply over

all tillage practices and N prices. The N requirements at the EONS ranged from 2.4 to 3.0 kg Mg^{-1} in 2008 and 2.5 to 2.8 kg Mg^{-1} in 2010 over tillage practices and the range of N prices. Strip tillage can be used to obtain yields comparable to other common tillage practices and decrease tillage costs. Nitrogen requirements for all tillage practices could be reduced on heavier textured soils compared to past recommendations in the Pacific Northwest. However, adjusting N requirements based on sugarbeet production and quality history, soil type, and soil residual N should be evaluated.

Additional Key Words: strip tillage, strip till, moldboard plow, chisel plow, nitrogen, nitrogen use efficiency, nitrogen requirement.

Abbreviations: ST = strip tillage, CT = conventional tillage, CP = chisel plow, MP = moldboard plow, ERS = estimated recoverable sucrose, EONS = economic optimum nitrogen supply, NUE = nitrogen use efficiency, UAN = urea ammonium nitrate, ET = evapotranspiration, TDM = total dry matter, RTN = net return from N fertilizer application, EONR = economic optimum nitrogen rate, SE = standard error, MRYNS = maximum root yield N supply

Strip tillage (ST) and other conservation tillage practices are common in many areas of the Corn Belt region in the central Great Plains and Midwest U.S. to conserve soil and water through residue management and to reduce tillage costs in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production systems. However, in the irrigated production systems of the Pacific Northwest, ST is less common, and research on the use of ST in sugarbeet (*Beta vulgaris* L.) production is limited. Overstreet (2009) listed several potential advantages of ST use in sugarbeet production systems compared to full-width, CT practices: reduced soil erosion, increased soil moisture, optimum fertilizer placement, increased carbon sequestration, and reduced fuel use. In this paper, CT refers to any full-width tillage practice that results in the incorporation of crop residue from a variety of tillage implements (e.g. disc, moldboard plow [MP], roller harrow, and chisel plow [CP]). Often multiple passes using different implements are used in CT. In the Pacific Northwest and other sugarbeet production regions it is common for producers to make five or more passes over a field in preparation for planting a sugarbeet crop (Evans et al., 2010), whereas with ST, one pass is typical. Potential fuel and time savings with ST compared to CT are attractive to the sugarbeet industry. With the availability of genetically modified Genuity® RoundUp Ready® (Monsanto Company, St. Louis, MO) sugarbeet seed in 2008, the use of ST became attractive because weed control became more manageable in a reduced tillage system.

Current ST equipment designs typically incorporate a series of coulters and shanks to create a residue free zone where the crop can be planted and fertilizers placed below the seed (Overstreet, 2009). The tilled area is approximately 15 to 20 cm wide with the remaining area of the field left undisturbed with residue from the previous crop remaining on the soil surface (Overstreet, 2009).

No research has been published on the use of ST in sugarbeet production in the Pacific Northwest. Most research evaluating ST in sugarbeet production systems has taken place in north central U.S. and Canada. Overstreet et al. (2007 and 2008) and Regitnig (2007) found that sugarbeet root yield and quality parameters under ST were the same as under CT in rain-fed and irrigated systems, respectively. Research results from USDA-ARS in Sidney, Montana have indicated under ideal conditions ST and CT produced similar sugarbeet root yields, but in one year a wind storm reduced populations in the CT treatment relative to the ST treatment, which resulted in greater root yield and sugar recovery under ST (Evans et al., 2010).

Strip tillage is starting to be used in the sugarbeet industry in the Pacific Northwest U.S. Also, due to the high dairy cow populations in southern Idaho, the potential use of ST in corn production is increasing, making the need for research to evaluate ST use and develop ST management practices a high priority. Sugarbeet production area under ST in the Amalgamated Sugar Company production area has increased from 0 ha in 2007 to approximately 2,800 ha in 2009.

Many research studies have been conducted to evaluate N management in sugarbeet production under CT systems (Adams et al., 1983; Anderson and Petersen, 1988; Carter et al., 1974 and 1976; Halvorson and Hartman, 1975 and 1980; Halvorson et al., 1978; Hills and Ulrich, 1976; Hills et al., 1978 and 1983; Lamb and Moraghan, 1993; and Stevens et al., 2007). All of these studies, excluding Stevens et al. (2007), were conducted 17 to 35 years ago. Nitrogen management recommendations can change as yields and crop production efficiencies increase over time (Dobermann et al., 2011). With the advent of new tillage systems and varieties, in particular Genuity® RoundUp Ready® sugarbeets, research is needed to evaluate sugarbeet response to N supply under ST and CT practices cropped to modern varieties. Nearly all of the sugarbeets grown for the Amalgamated Sugar Company in the Pacific Northwest are Genuity® RoundUp Ready® sugarbeets.

The objectives of this study were to compare ST to CT systems, and evaluate the N response of sugarbeet grown under ST in the Pacific Northwest relative to CT systems.

MATERIALS AND METHODS

This study was conducted on three fields over a three-year period (2008 to 2010) at the USDA-ARS Northwest Irrigation & Soils Research Lab in Kimberly, ID on a Portneuf silt loam (coarse-silty mixed superactive, mesic Durixerollic Xeric Haplocalcids). The treatments included tillage system (strip tillage, moldboard plow system, and chisel plow system), and N fertilizer application rate. The N fertilizer rates in 2008 and 2009 were 0, 56, 112, 168, and 224 kg N ha^{-1} and in 2010 were 0, 62, 109, 156, and 227 kg N ha^{-1}. The tillage system descriptions are presented in Table 1. The treatments were arranged in a split plot design. Tillage system was the main plot and N fertilizer application rate was the subplot. Treatment combinations were replicated either three (2008) or four (2009 and 2010) times. Each plot was 4.5 m wide (eight-0.56 m rows) and 12.2 m long.

A Strip Cat tillage implement was used for ST (Twin Diamond Industries, LLC, Minden, NE) in the spring. Barley was grown the year previous to the study year at each site. Tillage passes for the MP and CP systems increased in 2010 compared to 2008 and 2009 due to greater barley residue. The number of tillage passes within each tillage method treatment was based on farmer knowledge and judgment to obtain suitable seedbed conditions.

Prior to N fertilizer application in spring, three soil cores (4.4 cm diameter) in 0.3 m increments to a depth of 0.6 m were taken in 2008, and to a depth of 0.9 m in 2009 and 2010 in each tillage system main plot of each replication. In 2008, the site had a root restrictive hard pan layer at 0.6 m. Within each tillage system main plot samples were composited by depth increment. Soil samples were 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) (Table 2). These data were used to determine the parameter Spring Soil Residual N (NO_3-N and NH_4-N). The 0 to 0.3 m soil samples were also tested for sodium bicarbonate extractable P and exchangeable K concentrations (Olson et al., 1954) to determine sugar beet requirements of these nutrients (Table 2).

In the spring of 2008 (April 25) and 2009 (May 13), N fertilizer (urea ammonium nitrate [UAN, 32-0-0]) was broadcast applied to the soil surface in a single application prior to planting. A nitrification inhibitor (Agrotain®, Saint Louis, MO) was applied at a rate of 3.5 L metric ton^{-1} of UAN prior to application to prevent significant NH_3 losses from the UAN as a result of microbial urease activity on the soil surface. The UAN was irrigated into the soil with 15 mm of irrigation water within three days after application using a solid set irrigation system. In 2010, UAN (32-0-0) was applied between sugarbeet rows on June 10 when the sugarbeet crop reached the four leaf stage, prior to the start of significant crop N uptake (Amalgamated Sugar Company, 2010). The UAN was immediately irrigated into the soil with 15 mm of water. Based on soil test P analysis, 83 kg

P ha^{-1} was applied to the surface as a band above each row over the entire study area prior to planting as fertilizer grade liquid phosphoric acid in 2008, and 98 kg P ha^{-1} as superphosphate in 2009. In 2010, no P fertilizer was applied as soil test P level was considered adequate based on the University of Idaho fertilizer recommendations for sugarbeet (Moore et al., 2009).

The study was planted to sugarbeet on April, 25 2008; June 18, 2009; and April 27, 2010 at rate of 128,000 plant ha^{-1}. In 2009, beets were re-planted on June 18 due to poor emergence across the entire study area after the May 5 planting. Seed varieties planted in 2008, 2009, and 2010 were BTS 25RR05, BTS 27RR10, and BTS 27RR10, respectively. The change in variety was due to unavailability of BTS 25RR05 in 2009 and 2010.

To promote emergence and good stands, 44, 89, and 69 mm of water was applied through irrigation + precipitation over an approximately two week period after planting in 2008, 2009, and 2010, respectively. Following emergence the sites were irrigated uniformly to meet estimated crop evapotranspiration (ETc) rates. The ETc rates were estimated using the Kimberly-Penman ET model (Wright, 1982) using data from an Agrimet weather station (U.S. Bureau of Reclamation, Boise, ID). In 2008, 2009, and 2010, growing season cumulative irrigation + precipitation depths were 874, 567, and 893 mm, respectively.

To determine soil water status for each tillage system treatment throughout the season, volumetric soil water was measured in all replications of each tillage system treatment with 168 kg N ha^{-1} at six depths (0-0.15, 0.15-0.3, 0.3-0.45, 0.45-0.6, 0.6-0.75, 0.75-0.9, 0.9-1.05, and 1.05-1.2 m) on selected dates in 2009 and 2010 using the neutron probe method (Evett and Steiner, 1995).

Glyphosate was applied at a rate of 0.84 kg acid equivalent (in the form of its isopropylamine salt) ha^{-1} on May 5, June 6, and July 16 in 2008, 1.12 kg acid equivalent ha^{-1} on July 9 in 2009, and 2.24 kg acid equivalent ha^{-1} on June 6 and June 28 in 2010.

Whole plant tops were harvested from 1.5 m sections of 2 rows in each plot on October 21, 2008, October 19, 2009, and October 6, 2010. The samples were dried at 65° C, weighed to determine total dry matter mass (TDM), ground 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).

Prior to harvest, beet tops were removed and root counts were obtained in the harvest area from each plot (4 rows × 9.1 m). Roots were harvested on October 23 and 24, 2008, October 22 and 23, 2009, and October 12, 2010. Total yield was determined from each plot using a load cell-scale on the plot harvester. From each plot, three 8-root samples were obtained and bagged. Two of the samples from each plot were sent to the Amalgamated Sugar Company tare lab for analysis of percent sugar 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 nitrate was measured using a Denver Instruments Model 250 multimeter (Denver Instruments, Denver, CO) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, NY). Recoverable sucrose yield per ton of roots was estimated by: [(extraction)(0.01)(gross sucrose/ha)]/(t/ha), where extraction = 250 + [[(1255.2)(conductivity) – (15000)(percent sucrose - 6185)]/[(percent sucrose)(98.66 – [(7.845)(conductivity)])]] and gross sucrose = (t/ha)(percent sucrose)(0.01)(1000 kg/t). The third 8-root sample was ground, dried at 93° C, and analyzed for total N by combusting a 25 mg sample using the FlashEA1112 CNH analyzer.

Statistical analysis was conducted separately for each year due to temporal variability, and differences in N supply and management practices over years. Analysis of variance was conducted for tillage and N rate treatment main effects and the interaction for selected production factors (root yield, ERS yield, root sucrose concentration, root brei nitrate concentration, harvest population, top dry mass yield, root total N concentration, root total N mass, top total N concentration, top total N mass, top C/N ratio, and N use efficiency) using a split plot design model in Statistix 8.2 (Analytical Software, Tallahassee, FL). For each factor, polynomial contrasts were conducted for N rate main effects to determine significance of linear and quadratic relationships. Nitrogen response functions were determined for N rate means by root yield and ERS yield using Sigma Plot 10.0 (Systat Software, Chicago, IL). Based on polynomial contrasts and examination of several models, the quadratic model was selected and fit to the data. The economically optimum N rate (EONR) was calculated based on the fitted quadratic function for a range of N fertilizer prices. The EONR was the N supply at which the net return from N fertilizer application (RTN) was maximized.

$$(1)\ \text{RTN} = (\text{Yield}_{+N} \times \text{Gross Return}) - (\text{Yield}_{-N} \times \text{Gross Return}) - (\text{Fertilizer N Amount} \times \text{N Price})$$

Gross return was calculated from a base return of \$44/Mg beets at 17.4% sugar. The base return was adjusted to the gross return ± \$0.30 for every ± 0.1% sugar. Nitrogen prices used were \$0.44, \$0.88, \$1.32, \$1.76, and \$2.20 kg^{-1} N. The RTN was calculated for every 1 kg increment increase in fertilizer N (1, 2…199, 200 kg N ha^{-1}). The EONR was converted to the economic optimum N supply (EONS) by summing the EONR and measured Spring Soil Residual N.

Nitrogen supply (fertilizer N + spring soil residual N [NO_3-N + NH_4-N]), N use efficiency (NUE), N recovery efficiency, and N removal efficiency were calculated at the maximum root and ERS yield, EONR and EONS for 2008 and 2010 based on the fitted models. Nitrogen use efficiency in sugarbeet production systems is the mass of sucrose produced per kg of N supply. Quadratic functions were not applied to 2009 data; refer to the Results and Discussion section for explanation.

(2) NUE = kg sucrose / kg N

(3) N Recovery Efficiency = fraction of total N supply in plant (tops + roots) = kg plant total N (tops + roots) / kg N supply (fertilizer N + spring residual soil N [NO_3-N + NH_4-N])

(4) N Removal Efficiency = fraction of total N supply in roots = kg root total N / kg N supply (fertilizer N + spring residual soil N [NO_3-N + NH_4-N])

Economic comparisons accounting for differences in tillage practices were also evaluated using custom tillage rates in southern Idaho estimated from surveys conducted by the University of Idaho Extension in 2010 and 2011 (Patterson and Painter, 2011). Tillage costs per ha were $72.43 for MP, $48.53 for CP, $43.34 for offset disk, $38.03 for tandem disk, $35.34 for roller harrow, and $46.70 for bedding. Only one survey respondent reported costs for ST and the cost was considered high relative to other tillage costs based on other states reported tillage costs. For example, Purdue University had custom ST rates at 95% of the cost of MP custom rates. Other reports of custom tillage rates have ST similar to or slightly lower than MP custom rates. Therefore, for this analysis we will use a custom rate for ST at the same rate as MP ($72.43).

RESULTS AND DISCUSSION

Spring Residual Soil NO_3-N and NH_4-N

There were no statistical differences in spring residual soil N among tillage treatments during all years of this study. In 2008, average spring residual soil N in the 0-0.6 m depth was 104 kg N ha^{-1}. In 2009 and 2010, average spring residual soil N in the 0-0.9 m depth was 240 and 67 kg N ha^{-1}, respectively.

Tillage

Strip tillage performed similar to MP and CP in most measured factors, including root and ERS yield. There were no differences in root and ERS yield among tillage treatments across N rates (Table 3). These results were similar to results found by Overstreet et al. (2007 and 2008), Regitnig (2007) and Evans et al. (2010), all of whom found no differences in sugarbeet yields between ST and conventional tillage (CT) practices. Conventional tillage practices differed from previously reported studies, but ST consisted of one pass in each study. For example, the CT from the study performed by Evans et al.

(2010) included a ripper pass, two passes with a rolling mulcher, two passes with a leveler, and one pass with an S-tine cultivator with rolling baskets. Strip tillage consisted of one pass with a custom ST machine from Schlagel Mfg (Torrington, WY). In four years of the 5-year study, there were no significant differences in sugar and root yields among the tillage practices. However, during one year of the Evans et al. (2010) study, ST yielded 17% higher in sugar and root yield compared to CT due to greater wind damage early in the spring to sugarbeet plants under CT. The surface stubble in the ST treatments provided protection to the young sugarbeet plants. In our study, we did not see seedling damage resulting from wind in any of the tillage treatments.

Because root and ERS yields were not different among tillage treatments across N rates, differences in production costs are based on tillage costs. Actual tillage costs will vary greatly depending on factors such as tillage implement ownership status. To compare tillage costs on a relative basis, published custom tillage rates were

Table 1. Tillage method treatment descriptions.

Year	Tillage Method Designation	Fall Activity	Spring Activity
2008 & 2009	Strip Tillage	—	Strip Tillage
	Moldboard Plow	—	Moldboard Plow Roller Harrow Bed
	Chisel Plow	Offset Disk	Chisel Plow Tandem Disk Bed
2010	Strip Tillage	—	Strip Tillage
	Moldboard Plow	—	Moldboard Plow Roller Harrow Roller Harrow Bed
	Chisel Plow	—	Offset Disk Offset Disk Chisel Plow Tandem Disk Tandem Disk Tandem Disk Bed

Table 2. Selected soil nutrient concentrations of study sites in 2008, 2009, 2010.

Soil Nutrient	2008	2009	2010
	-----------*mg kg^-1*---------		
NO_3-N†	7.7	12.3	2.5
NH_4-N†	3.2	5.5	2.5
P_2O_5‡	11.6	4.8	19.0
K_2O‡	114	114	205

† 0-0.6 m in 2008; 0-0.9 m in 2009 and 2010.
‡ 0-0.3 m.

used for this analysis. In both 2008 and 2009, tillage treatment costs for the ST, MP, and CP systems (Table 1) were \$72.43, \$154.47, and \$176.60, respectively. In 2010, tillage treatment costs for the ST, MP, and CP systems were \$72.43, \$189.81, and \$296.00 ha^{-1}, respectively. Reduction in tillage costs for ST compared to the MP and CP systems ranged from 53% to 76% over all years of this study. Differences in tillage costs were associated with the number of tillage passes and types of tillage (Table 1).

Factors that differed among tillage treatments were harvest populations in 2009 and 2010, TDM in 2010, and top total N mass in 2010. In 2009 and 2010, ST and MP had similar harvest populations (average = 190,300 plants ha^{-1} in 2009 and 135,900 plants ha^{-1} in 2010 averaged over N rate) and were significantly greater than CP (168,900 in 2009 and 108,400 in 2010 averaged over N rate). Residue mixed into the surface soil with CP likely reduced soil to seed contact, resulting in reduced emergence leading to reduced plant populations, while ST swept all surface residues aside and MP placed the surface residues approximately 25 cm below the soil surface resulting in good soil and seed contact. In 2010, ST had greater TDM (9,473 kg ha^{-1}) than CP (7,549 kg ha^{-1}); MP (8,816 kg ha^{-1}) and CP were not significantly different. In 2010, ST had greater sugarbeet top N mass (234 kg N ha^{-1} averaged over N rate; top N mass = N in TDM) than MP and CP (average = 185 kg N ha^{-1} averaged over N rate). The increased TDM under ST resulted in the top N mass differences.

In 2008, tillage treatment harvest populations were not different. Although not statistically compared, harvest populations in 2008 appeared lower than in 2009 and 2010. It is likely that the seed germination was lower in 2008 than in 2009 and 2010. However, the populations in 2008 were within recommended populations (Amalgamated Sugar Company, 2010).

Soil water

There were tillage and date (soil water sampling date) main effect

Table 3. Probability values (P>F) from analysis of variance for measured yield related factors during the three years of the study.

Year	Source	df[†]	Root Yield	ERS[‡]	Root Sucrose	Brei Nitrate	Harvest Population	TDM[§]
2008	Tillage (T)	2	0.166	0.138	0.387	0.148	0.373	0.141
	N Rate (N)	4	**0.043**[¶]	**0.041**	0.192	**<0.000**	**<0.001**	**<0.001**
	T × N	8	0.292	0.097	0.076	0.404	0.095	0.345
	N Linear	1	0.071	0.484	**0.027**	**<0.001**	**<0.001**	**<0.001**
	N Quadratic	1	**0.013**	**0.004**	0.316	0.026	0.456	0.114
2009	Tillage (T)	2	0.453	0.447	0.409	0.643	**0.005**	0.208
	N Rate (N)	4	0.992	0.738	0.379	**<0.001**	0.551	0.249
	T × N	8	0.972	0.967	0.943	0.170	0.817	0.989
	N Linear	1	0.797	0.786	0.307	**<0.001**	0.314	**0.027**
	N Quadratic	1	0.808	0.555	0.468	0.207	0.528	0.582
2010	Tillage (T)	2	0.094	0.057	0.089	0.890	**0.009**	**0.042**
	N Rate (N)	4	**<0.001**	**<0.001**	0.064	**0.001**	0.508	**<0.001**
	T × N	8	0.877	0.793	0.931	0.590	0.311	0.596
	N Linear	1	**<0.001**	**<0.001**	0.928	**<0.001**	0.782	**<0.001**
	N Quadratic	1	**<0.001**	**<0.001**	**0.007**	**0.014**	0.179	0.158

[†] Degrees of freedom.
[‡] Estimated Recoverable Sucrose
[§] Top dry matter.
[¶] Bolded probability values are significant at the 0.05 level.

differences in soil water depth in the 0 to 1.05 m root zone in 2009 and 2010 (Table 5). No soil water measurements were taken in 2008. In 2009, the order of soil water depth was CP>ST>MP, with water depths of 293, 284, and 274 mm, respectively, averaged over measurement date. In 2010, the order of soil water was CP>ST=MP, with soil water depths of 313, 299, and 299 mm, respectively, averaged over measurement date. The greater soil water in the CP treatment was likely due to reduced water usage by plants resulting from lower plant populations in CP compared to ST and MP (Table 3 and 6). In 2009, the residue remaining on the soil surface under ST likely resulted in greater soil water compared to MP, but in 2010, the residue under ST had no measurable effect on soil water compared to the lack of residue on the soil surface under MP. In 2010, the quantity of irrigation applied (893 mm) likely masked any decreased rates of evaporation at the soil surface associated with the surface residues in ST.

Table 4. Probability values (P>F) from analysis of variance for measured nitrogen related factors during the three years of the study.

Year	Source	df[†]	Root N Conc.	Root Total N Mass	Top N Conc.	Top Total N Mass	Top C/N Ratio	NUE[‡]
2008	Tillage (T)	2	0.230	0.251	0.660	0.398	0.338	0.188
	N Rate (N)	4	**<0.001**[§]	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	T × N	8	**0.049**	0.222	0.175	0.296	0.540	0.057
	N Linear	1	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	N Quadratic	1	0.172	0.355	0.006	0.877	0.065	**<0.001**
2009	Tillage (T)	2	0.874	0.568	0.197	0.146	0.178	0.452
	N Rate (N)	4	**<0.001**	**<0.004**	**<0.007**	**<0.049**	**<0.009**	**<0.001**
	T × N	8	0.859	0.912	0.707	0.999	0.644	0.948
	N Linear	1	**<0.001**	**<0.001**	**<0.001**	**<0.003**	**<0.001**	**<0.001**
	N Quadratic	1	0.677	0.950	0.647	0.598	0.238	**0.028**
2010	Tillage (T)	2	0.698	0.602	0.094	**0.038**	0.219	0.141
	N Rate (N)	4	**<0.001**	**<0.001**	0.091	**<0.001**	0.063	**<0.001**
	T × N	8	0.307	0.228	0.868	0.451	0.756	0.944
	N Linear	1	**<0.001**	**<0.001**	0.939	**<0.001**	0.311	**<0.001**
	N Quadratic	1	0.410	**0.051**	**0.030**	0.404	**0.029**	**<0.001**

[†] Degrees of freedom.
[‡] Nitrogen Use Efficiency.
[§] Bolded probability values are significant at the 0.05 level.

In 2009, 326 mm less irrigation was applied compared to 2010 due to a shorter growing season resulting from replanting in June.

Nitrogen Supply

In 2008 and 2010, N supply had a significant effect on most measured factors (Tables 3 and 4). Because of high spring residual soil N (240 kg N ha^{-1}) and a shortened growing season due to late re-planting date in 2009, N supply did not significantly influence root and ERS yields. Therefore, regression analysis and associated analyses were only conducted for the 2008 and 2010 data sets.

Brei Nitrate and Root Sucrose Concentration

Brei nitrate is a measure of N related impurities in sugarbeet roots that result in reduced sucrose concentration and decreased sucrose extraction efficiency. In the Amalgamated Sugar Company Sug-

Table 5. Analysis of variance effects of tillage, date and the tillage by date (soil water sampling date) interaction for soil water depth in the 0-1.05 m soil depth in 2009 and 2010.

	2009	**2010**
	P>F	
Tillage (T)	<0.001	0.003
Date (D)	<0.001	<0.001
T × D	0.0981	0.458

arbeet Growers Guide Book, it is stated that sucrose concentration decreases by approximately 0.5% for every 100 mg brei nitrate kg^{-1}, and above average sucrose concentrations are likely at brei nitrate concentration below 200 mg kg^{-1} (Amalgamated Sugar Company, 2010). High brei nitrate levels indicate that excessive N was available during the growing season.

In 2009, brei nitrate levels were elevated and root sucrose concentrations were reduced in the beet roots (Table 6), indicating N supply was excessive, providing added evidence that high N supply at all N fertilizer rates resulted in non significant N supply main effects during the shortened growing season. In 2008 and 2010 brei nitrate concentration ranged from 48 to 157 mg kg^{-1} and 197 to 345 mg kg^{-1}, respectively (Table 6). Considering that spring residual soil N was higher in 2008 compared to 2010 (Table 2), brei nitrate results indicate higher quantities of N mineralized from soil organic matter during the growing season in 2010 relative to 2008. For each year of this study, brei nitrate concentration ranges across N supply did not result in differences in root sucrose concentrations, likely due to fairly narrow ranges of brie nitrate concentrations.

ERS and Root Yield Response to Nitrogen

Because there were no differences in ERS and root yield response among tillage treatments (Tables 3 and 6), ERS and root yield at each N rate were averaged across tillage treatments prior to analyzing the relationship between ERS and N rate and root yield and N rate. This data shows that N application rates, when surface applied and irrigated into the soil, was similar for all tillage systems, making N management for growers easier among tillage systems. Stevens et al. (2010) concluded that N rate need not be changed based on tillage practice (CT vs. ST) when N was applied via a band for ST and broadcast for CT. Although N application methods differed between our study and Stevens et al. (2010), evidence suggests in a given growing area, N rates to achieve optimum yields can be similar across tillage systems. In 2009, N rate had no effect on root yield or ERS yield. This was a result of high spring residual soil N and a shorter growing season due to replanting. However, in 2008 and 2010 N rate did have

Table 6. Root yield, estimated recoverable sucrose (ERS) yield, root sucrose concentration, brei nitrate, harvest stand, and top dry matter (TDM) at N rates and supply in 2008, 2009, and 2010. Data are averaged over tillage treatments.

Year	N Rate†	N Supply‡	Root Yield	ERS	Root Sucrose	Brei Nitrate	Harvest Population	TDM
	kg ha⁻¹	*kg ha⁻¹*	*Mg ha⁻¹*	*kg ha⁻¹*	*%*	*mg ha⁻¹*	*Plants ha⁻¹ × 1000*	*kg ha⁻¹*
2008	0	104	67.1	10327	17.9	47.8	96.6	2375
	56	160	71.7	11047	17.9	63.7	94.4	3160
	112	216	75.7	11604	17.8	70.1	86.5	3791
	168	272	73.2	11062	17.7	79.1	77.6	4018
	224	328	71.8	10637	17.4	157.3	70.5	4295
2009	0	240	40.2	4669	14.7	1023.7	184.4	7403
	43	283	40.9	4914	14.9	961.0	187.2	7505
	102	342	40.5	4680	14.6	1125.6	181.8	7552
	157	397	41.2	4818	14.8	1151.9	179.6	7993
	230	470	40.7	4671	14.5	1337.0	182.8	8412
2010	0	67	53.8	7211	16.2	209.4	125.6	5372
	62	129	71.3	9766	16.4	196.7	130.6	8520
	112	179	74.7	10440	16.7	204.1	124.7	8023
	157	224	79.5	11012	16.5	242.9	130.4	10126
	230	297	80.7	10858	16.2	345.5	124.5	10841

† N applied in fertilizer.
‡ N applied in fertilizer + spring residual soil NO_3-N and NH_4-N.

a significant effect on root yield and ERS yield and displayed a highly significant quadratic relationship (Table 3). In 2008 and 2010, the quadratic models accounted for >90% of the variability in ERS and root yields associated with N rate (Table 8).

Delta yields are presented as the differences between maximum ERS and root yields (Tables 9 and 10) and the ERS and root yields with no N applied (Table 8) based on quadratic model data. In 2008 and 2010, delta yields for ERS were 1,099 and 3,819 kg ha^{-1}, respectively. In 2008 and 2010 delta yields for root production were 8.1 and 26.3 Mg ha^{-1}, respectively. The greater delta yields in 2010 compared to 2008 were not explained by differences in N supply during each year (224 and 230 kg ha^{-1}, in 2008 and 2010, respectively; Table 6). The reason for greater yield responses to N in 2010 compared to 2008 could be related to N mineralization and other soil related factors,

Table 7. Root N concentration, root total N mass, top N concentration, top total N mass, top C/N ratio, and N use efficiency (NUE) at N rates and supply in 2008, 2009, and 2010. Data are averaged over tillage treatments.

Year	N Rate†	N Supply‡	Root N Conc.	Root Total N Mass	Top N Conc.	Top Total N Mass	Top C/N Ratio	NUE
	kg ha⁻¹	*kg ha⁻¹*	*g kg⁻¹*	*kg ha⁻¹*	*g kg⁻¹*	*kg ha⁻¹*		*kg sucrose kg⁻¹ N*
2008	0	104	5.1	85.3	21.1	50.9	17.6	99.1
	56	160	5.6	100.2	21.2	67.0	17.6	69.0
	112	216	6.0	112.9	22.8	86.7	16.1	53.7
	168	272	6.5	118.5	24.8	100.5	14.7	40.6
	224	328	7.2	130.4	27.2	117.6	13.4	32.4
2009	0	240	9.1	92.1	29.8	219.7	11.3	19.5
	43	283	9.5	97.3	29.0	219.0	11.6	17.4
	102	342	10.1	101.8	30.5	231.0	11.2	13.7
	157	397	10.2	104.8	31.2	250.4	10.9	12.2
	230	470	11.1	112.9	31.9	268.7	10.6	10.0
2010	0	67	5.3	72.6	23.8	127.1	14.3	107.3
	62	129	5.7	102.2	23.6	207.1	14.9	75.8
	112	179	5.9	113.6	22.8	179.3	16.1	58.3
	157	224	6.1	115.2	21.9	231.1	15.3	49.2
	230	297	6.8	136.3	23.7	258.2	15.0	36.6

† N applied in fertilizer.
‡ N applied in fertilizer + spring residual soil NO_3-N and NH_4-N.

and climatic factors. It is possible that greater N mineralization occurred during the growing season after spring soil samples were collected in 2010 than in 2008. It is also possible that other site and climatic factors could have resulted in the difference in yield response rates between the two years. However, during 2008 and 2010, N fertilizer additions were critical to achieve maximum yields.

In 2008 and 2010, ERS yields at the EONS ranged from 11,310 to 11,415 kg ha^{-1} and 11,054 to 11,127 kg ha^{-1}, respectively, across N price (Tables 9 and 10). In 2008, the difference in maximum ERS yield and ERS yield at the EONS ranged from 12 kg at the N price of \$0.44 kg^{-1} N to 61 kg at \$2.20 kg^{-1} N. In 2010, the difference in maximum ERS yield and ERS yield at the EONS ranged from 1 kg at the N price of \$0.44 kg^{-1} N to 74 kg at \$2.20 kg^{-1} N.

In 2008 and 2010, root yield at the EONS ranged from 75.1 to 73.6

Table 8. Coefficients for quadratic functions ($y = y_0 + ax + bx^2$)† applied to root yield and estimated recoverable sucrose (ERS) yield in 2008 and 2010. Results from 2009 are not included because there was no significant response to N.

Year		y_0	a	b	SE‡	R2§
2008	Root Yield	67.03	0.1139	-0.0004	1.20	0.93
	ERS Yield	10324.6	18.42	-0.0772	192.6	0.92
2010	Root Yield	54.74	0.3013	-0.0009	2.29	0.98
	ERS Yield	7308.6	48.01	-0.1509	241.3	0.99

† y = root yield or estimated recoverable sucrose yield; y_0 = yield (kg ha^{-1}) at 0 kg applied N; a = constant; x = N rate (kg N ha^{-1}); b= constant.
‡ SE = Standard error of predicted root yield or estimated recoverable sucrose yield.
§ Square of the correlation coefficient.

Mg ha^{-1} and 79.9 to 79.1 Mg ha^{-1}, respectively, across N price (Tables 9 and 10). In 2008, the difference in maximum root yield and root yield at the EONS ranged from 0 Mg at the N price of \$0.44 kg^{-1} N to 1.5 Mg at \$2.20 kg^{-1} N. Across the same N price range, the difference in N supply to achieve maximum root yield (MRYNS) and EONS were 12 and 61 kg N ha^{-1}. In 2010, the difference in maximum root yield and root yield at the EONS ranged from 0.1 Mg at the N price of \$0.44 kg^{-1} N to 0.9 Mg at \$2.20 kg^{-1} N. Across the same N price range the difference in the MRYNS and EONS were 6 and 30 kg N ha^{-1}.

In 2008 and 2010, the MRYNS values based on quadratic models were 235 and 227 kg ha^{-1}, respectively. Nitrogen supply to achieve maximum sucrose yield (MSYNS) based on quadratic models were 212 and 219 kg ha^{-1}, respectively.

The economic analysis in this study was based on a set sugar price formula at the time of the study and changing N prices. Changes in economic related variables from this data set are related to both N price and sugar price. The ratio of these prices will result in changes in the economic related variables. Based on USDA-Economic Research Service data, 2012 average N fertilizer price based on UAN and urea was \$1.34/kg.

Economic Optimum Nitrogen Supply

The N prices used in this analysis cover a range encompassing current and estimated future prices. The EONS in 2008 over an N price range of \$0.44 to \$2.20 kg^{-1}, ranged from 223 to 174 kg N ha^{-1}. In 2010, the range was from 221 to 197 kg N ha^{-1} over the same N

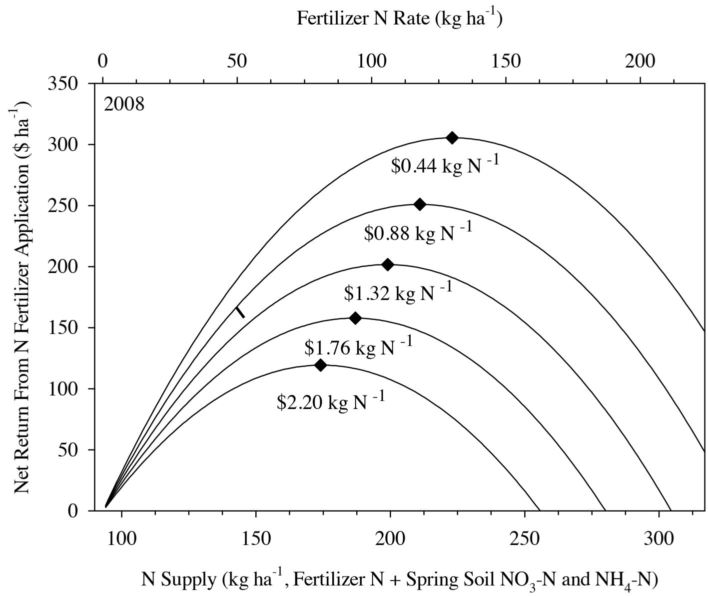
Table 9. Maximum root yield, maximum ERS, maximum root yield N supply (MRYNS; N supply that achieved maximum root yield), economically optimum nitrogen supply based on ERS (EONS), root yield at ENOS, ERS at EONR, returns to nitrogen (RTN) at MRYNS, RTN at EONS, root yield nitrogen supply requirement at EONS, ERS nitrogen supply requirement at EONS, N use efficiency (NUE) at MRYNS, and NUE at EONS for sugarbeet in 2008.

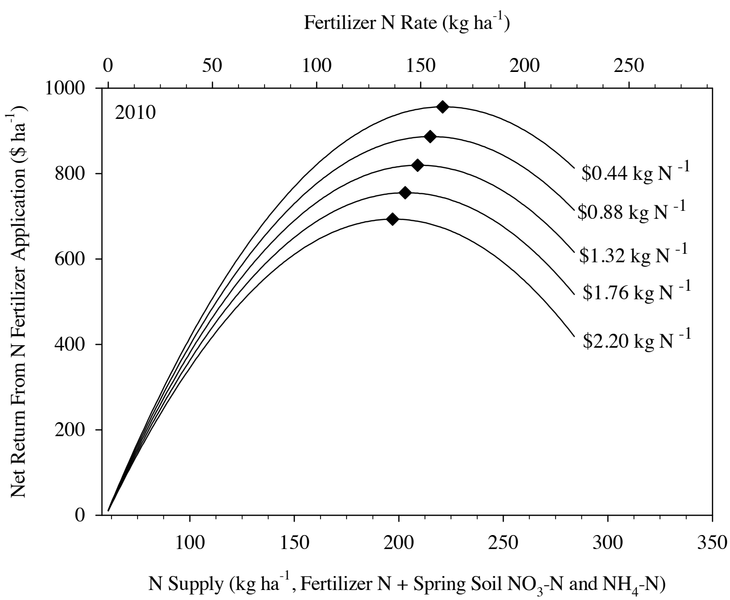
	Nitrogen Fertilizer Price ($ kg^{-1})				
	0.44	**0.88**	**1.32**	**1.76**	**2.20**
Maximum Root Yield (Mg ha^{-1})	75.1	75.1	75.1	75.1	75.1
Maximum ERS (kg ha^{-1})	11423	11423	11423	11423	11423
MRYNS (kg ha^{-1})	235	235	235	235	235
EONS (kg ha^{-1})	223	211	199	187	174
Root Yield$_{EONS}$ (Mg ha^{-1})	75.1	74.9	74.6	74.2	73.6
ERS$_{EONS}$ (kg ha^{-1})	11415	11423	11410	11374	11310
RTN$_{MRYNS}$ ($ ha^{-1})	303.08	240.60	178.12	115.64	53.16
RTN$_{EONS}$ ($ ha^{-1})	303.35	250.99	198.63	146.27	93.91
Root yield N Requirement$_{EONS}$ (kg N Mg^{-1} root yield)	3.0	2.8	2.7	2.5	2.4
NUE$_{MRYNS}$ (kg sucrose kg^{-1} N)	50.0	50.0	50.0	50.0	50.0
NUE$_{EONS}$ (kg sucrose kg^{-1} N)	52.9	56.1	59.6	63.4	67.9
N Recovery Efficiency$_{MRYNS}$ (kg whole plant total N kg^{-1} total available N)	0.88	0.88	0.88	0.88	0.88
N Recovery Efficiency$_{EONS}$ (kg whole plant total N kg^{-1} total available N)	0.91	0.94	0.97	1.00	1.04
N Removal Efficiency$_{MRYNS}$ (kg root total N kg^{-1} total available N)	0.45	0.45	0.45	0.45	0.45
N Removal Efficiency$_{EONS}$ (kg root total N kg^{-1} total available N)	0.47	0.50	0.52	0.55	0.58

Table 10. Maximum root yield, maximum ERS, maximum root yield N supply (MRYNS; N supply that achieved maximum root yield), economically optimum nitrogen supply based on ERS (EONS), root yield at ENOS, ERS at EONR, returns to nitrogen (RTN) at MRYNS, RTN at EONS, root yield nitrogen supply requirement at EONS, ERS nitrogen supply requirement at EONS, N use efficiency (NUE) at MRYNS, and NUE at EONS for sugarbeet in 2010.

	Nitrogen Fertilizer Price ($ kg^{-1})				
	0.44	**0.88**	**1.32**	**1.76**	**2.20**
Maximum Root Yield (Mg ha^{-1})	80.0	80.0	80.0	80.0	80.0
Maximum ERS (kg ha^{-1})	11128	11128	11128	11128	11128
MRYNS (kg ha^{-1})	227	227	227	227	227
EONS (kg ha^{-1})	221	215	209	203	197
Root Yield$_{EONS}$ (Mg ha^{-1})	79.9	79.8	79.7	79.4	79.1
ERS$_{EONS}$ (kg ha^{-1})	11127	11125	11112	11088	11054
RTN$_{MRYNS}$ ($ ha^{-1})	955.01	881.53	808.05	734.57	661.09
RTN$_{EONS}$ ($ ha^{-1})	956.16	886.47	819.41	754.99	693.20
Root yield N Requirement$_{EONS}$ (kg N Mg^{-1} root yield)	2.8	2.7	2.6	2.6	2.5
NUE$_{MRYNS}$ (kg sucrose kg^{-1} N)	48.9	48.9	48.9	48.9	48.9
NUE$_{EONS}$ (kg sucrose kg^{-1} N)	50.1	51.3	52.7	54.1	55.5
N Recovery Efficiency$_{MRYNS}$ (kg whole plant total N kg^{-1} total available N)	1.47	1.47	1.47	1.47	1.47
N Recovery Efficiency$_{EONS}$ (kg whole plant total N kg^{-1} total available N)	1.50	1.54	1.57	1.61	1.65
N Removal Efficiency$_{MRYNS}$ (kg root total N kg^{-1} total available N)	0.44	0.44	0.44	0.44	0.44
N Removal Efficiency$_{EONS}$ (kg root total N kg^{-1} total available N)	0.46	0.47	0.49	0.51	0.52

Figure 1. Net return from N fertilizer application versus N supply at selected N prices in 2008 and 2010. Symbols represent the net return from N fertilizer application at the economic N supply (RTN_{EONS}).





price range. The differences between the EONS and MSYNS are less for lower N prices and increase as N price increases (Table 9 and 10). This demonstrates the effect of N price relative to sugar price on economic return. There is a greater reduction in economic returns associated with applying N (return from N fertilizer, RTN) when N supply exceeds the EONS when N prices are high compared to when they are lower (Tables 9 and 10, Figure 1). Figure 1 demonstrates that as N prices increase, use of research and site-specific data to optimize N supply is more critical than when N prices are low at a given sugar price. Figure 1 also demonstrates the negative effect of under-supplying N relative to the optimum supply at all N fertilizer prices.

Nitrogen Use Efficiency and Nitrogen Requirement

For all three years of this study, there were no statistical differences in NUE among tillage treatments (Table 4). Nitrogen supply significantly affected NUE during all three years of the study (Table 4). As N supply increased, NUE decreased (Table 7). In 2008, 2009, and 2010, the variation in NUE from the lowest to the highest N supply were 67, 49, and 66%, respectively. In 2008 and 2010, NUE at the MSYNS and EONS were very similar (Tables 9 and 10), at 50.0 and 48.9 kg sucrose kg N supply^{-1}, respectively. The NUE at the EONS ranged from 50.1 to 67.9 kg sucrose kg N supply^{-1} over all N prices. In 2009, the high overall N supply and lower yields (result of decreased growing season from a late planting) resulted in lower NUE compared to 2008 and 2010 (Table 7).

The unit quantity of N required to produce a unit mass of sugarbeet (Nr) is a parameter commonly used to recommend N for sugarbeet production within the industry (in the U.S. lbs N ton^{-1} beets is often used). This allows producers to use an estimated root yield goal based on field records to fine-tune N fertilizer needs. For example, historically, Amalgamated Sugar Company has used a value of 4 kg N supply Mg^{-1}. Nitrogen supply includes fertilizer N and spring residual soil residual N. Research conducted by Amalgamated Sugar Company has indicated that this value could be reduced in many sugarbeet fields (personal communication). In 2008 and 2010, the Nr found in our study at the EONS ranged from 2.4 to 3.0 kg Mg^{-1} in 2008 and 2.5 to 2.8 kg Mg^{-1} in 2010 over the range of N price, suggesting that producers should evaluate reducing their N rates, particularly on heavier textured soils like the ones used in this study. The data presented here are not meant to provide N fertilizer recommendations, but do suggest that it is possible to optimize yield and profits at lower N requirements under some conditions; farmers could use historic root yield and quality data to fine-tune their N applications. A review of reported research from 1972 to 2011 assessing N management in sugarbeet production reported Nr values (based on achieving maximum sucrose yield) ranging from 2.2 to 8.9 kg Mg^{-1} (Tarkalson et al. 2012). This wide range of Nr values demonstrates variability that can exist from site to site.

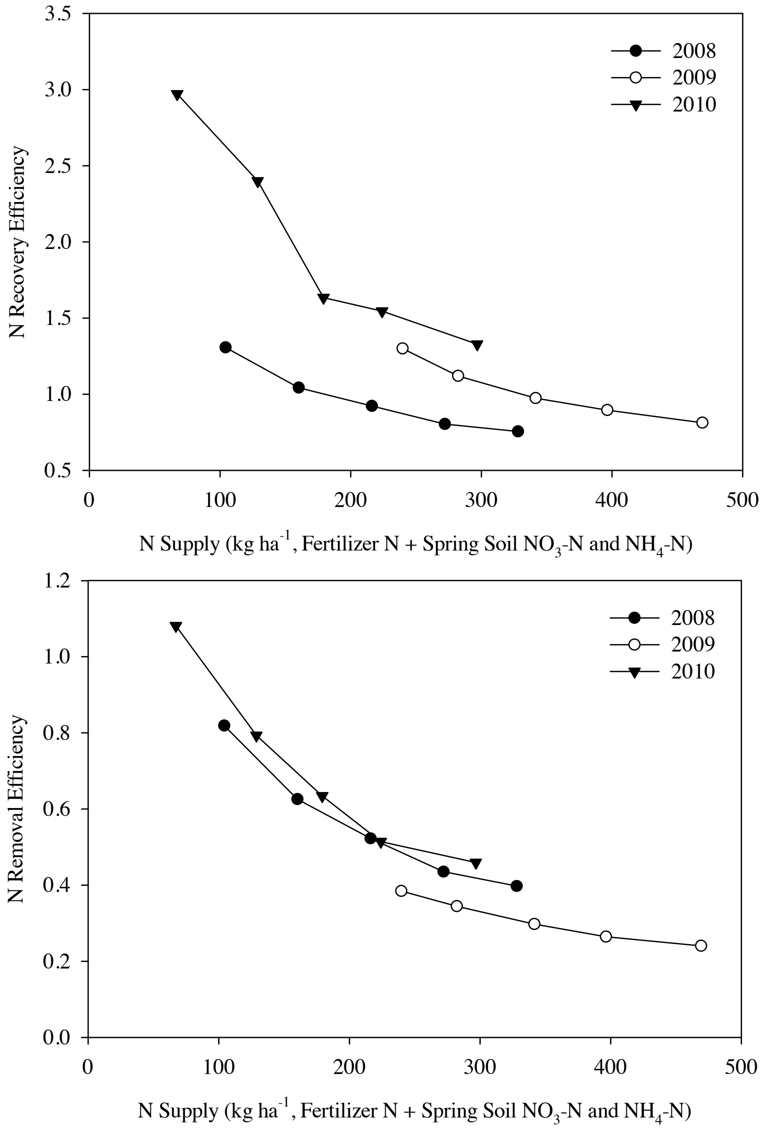
Nitrogen Uptake and Removal

Except for top N mass in 2010, there were no statistical differences among tillage treatments for root N concentrations, root total N masses, top N concentrations, top total N masses, and top C/N ratios in 2008, 2009, and 2010. In 2010, ST had significantly greater top N mass than CP (235 and 179 kg N ha^{-1}, respectively). The top N mass for MP treatment (191 kg N ha^{-1}) was not different than ST or CP. The lower top N mass for CP was likely a result of a lower plant population at harvest compared to ST (Table 3).

Nitrogen supply significantly influenced root N concentrations, root N masses, top N concentrations, top N masses and top C/N ratios. For all years, root N concentration, root N mass, top N concentration, and top N mass increased with increasing N supply (Table 7). Tables 9 and 10 present the N recovery and removal efficiency values at the MRYNS and EONS. The data in this study show that sugarbeet plants are very efficient in acquiring N. Reported N uptake and removal efficiency values do not account for available N not measured with the spring soil test and applied N such as N mineralized during the season and N below maximum sampling depth. In 2008, at the EONS over the range of N prices, 91 to 104% of spring available soil N (spring residual N and applied fertilizer) was accounted for in the total plant (tops and roots) at harvest. In 2008, at the EONS over the range of N price, the roots accounted for 47 to 58% of spring available soil N. The remaining balance (approximately 50%) was returned to the soil in the tops. In 2010, at the EONS over the range of N price, 150 to 165% of spring available soil N was accounted for in the total plant (tops and roots) at harvest. In 2010, at the EONS over the range of N price, the roots accounted for 46 to 52% of spring available soil N. The remaining balance (approximately 100%) was returned to the soil in the tops. During all years of this study, N recovery and removal efficiency values decreased with increasing N supply (Figure 2). During the N responsive years of 2008 and 2010, N removal efficiency values were similar over the range N supply, but there was more N in tops in 2010 than 2008, although the N supply was slightly greater in 2008 due to higher spring residual soil N. These data corroborate the brei nitrate and yield data and suggest greater quantities of N were mineralized in 2010 compared to 2008. Collectively, these data reiterate that understanding N mineralization and incorporating available N from mineralization into N recommendations for sugarbeet is important but difficult, due to an inability to predict N mineralization quantity and timing during the growing season as a result of many factors (climate, microbial processes, etc.). Continued research is vital to better understand N mineralization dynamics in soils.

In 2008 and 2010, top C/N ratios were below 20 (Table 7) which indicates that there will likely be net N mineralization from the sugarbeet tops as they decompose. A general rule is that a C/N ratio of 20 is the dividing line between N immobilization and N mineraliza-

Figure 2. Nitrogen recovery efficiency (fraction of total N supply in plant (tops + roots) = kg plant total N (tops + roots) / kg N supply [fertilizer N + spring residual NO_3-N and NH_4-N]) and N removal efficiency (fraction of total N supply in roots = kg root total N / kg N supply) versus N supply in 2008, 2009, and 2010.



tion (Tisdale et al., 1985). The N in the tops returned to the soil from this study will likely be available for the subsequent crops grown the following year, especially if tops are incorporated into the soil in the fall and precipitation is minimal after N is converted to NO_3-N. In the Pacific Northwest sugarbeet growing area, fall tillage following sugarbeet is common.

CONCLUSIONS

There were no differences in N response across tillage systems, suggesting N rates to obtain optimum yields will be similar for ST, MP, and CP systems when N is surface applied and irrigated into the soil. Strip tillage can be used to obtain yields comparable to other common tillage practices and decrease tillage costs. Estimated tillage costs for ST were from 53% to 76% lower than other tillage systems tested in this study. The N requirements at the EONS ranged from 2.4 to 3.0 kg Mg^{-1} in 2008 and 2.5 to 2.8 kg Mg^{-1} in 2010 over tillage practices and the range of N prices. Nitrogen requirements for all tillage practices could be reduced on heavier textured soils compared to past recommendations in the Pacific Northwest (historically, Amalgamated Sugar Company has used a value of 4 kg N supply Mg^{-1}).

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