Nitrogen Availability for Sugarbeet affected by Tillage System and Sprinkler Irrigation Method

W. Bart Stevens,* Robert G. Evans, Jay D. Jabro, and William M. Iversen

ABSTRACT

Many shank-type strip tillage (ST) implements band fertilizer below the seed without incorporating crop residue into the soil, potentially affecting N availability. Sprinkler irrigation method may also affect N availability due to its influence on water and NO$_3$–N movement in soil. A field study was conducted at Sidney, MT, to determine if sugarbeet (Beta vulgaris L.) petiole NO$_3$–N concentration and soil available (i.e., mineral) N distribution differ under (i) conventional tillage (CT) and ST systems and (ii) mid-elevation spray application (MESA) and low energy precision application (LEPA) irrigation methods. Mid-season petiole NO$_3$–N concentration was lower with ST than with CT in 1 of 3 yr. In-season mineral N concentration in the top 45 cm of soil was lower with ST than with CT. Postharvest mineral N was 10% lower with ST than with CT. There were few measurable effects of irrigation method except that in-season mineral N in the top 45 cm of soil was 10% greater with LEPA than with MESA. Root yield and sugar production were reported to be similar with the two tillage systems. It was concluded that differences in petiole NO$_3$–N concentration and soil mineral N content were not sufficient to justify altering N application rate based on the tillage systems or irrigation methods evaluated. However, there were indications that NO$_3$–N leaching may be reduced by combining LEPA, with which irrigation water is applied between alternating crop rows, with strip tillage, where N is banded beneath the crop row.

HIGHER FUEL COSTS, damage to seedlings caused by wind-blown soil, and declining soil quality have increased interest in reduced tillage practices for sugarbeet. Various reduced tillage approaches have been investigated, ranging from no-till to chisel-plow–based systems. Many researchers have reported similar root yield and quality regardless of tillage system (Overstreet, 2009; Cavalaris and Gemtos, 2002; Halvorson and Hartman, 1984; Sojka et al., 1980). Strip tillage, which is also referred to as zone tillage, loosens soil only in the seed row while leaving the inter-row soil and stubble undisturbed, thus offering a compromise between CT and no-till systems. Early research results with ST in sugarbeet were favorable (Halvorson and Hartman, 1984; Sojka et al., 1980) for a power-driven rotary ST implement, but slow ground speeds and high maintenance costs were disadvantages. Furthermore, fertilizer was typically broadcast before the ST operation resulting in only a portion of the fertilizer being incorporated into the soil. Halvorson and Hartman (1988) determined that N requirements for this approach did not differ from conventional practices when using ammonium nitrate (NH$_4$NO$_3$) fertilizer, which is less prone to volatilization loss than alternative N carriers, but this fertilizer is no longer commercially available in a dry form. Interest in ST among producers of large-seeded crops such as corn (Zea mays L.) and soybean (Glycine max [L.] Merr.) (Janssen et al., 2005; Al-Kaisi and Licht, 2004) has contributed to the development of a variety of equipment configurations consisting of a single-shank and a series of coulters and packer wheels. One advantage of the shank design is that fertilizer can be banded within the tilled zone at various depths below the seed row. Stevens et al. (2007) reported that banding N fertilizer near the seed row reduces the amount of N fertilizer required for furrow-irrigated, conventionally-tilled sugarbeet compared with broadcast N applications; however, some researchers have observed poorer seedling vigor with ST than with CT even though fertilizer is banded near the seed (Regtnig, 2008; Stevens et al., 2008). One possible explanation is that N availability and uptake is different for the two tillage systems.

Optimum N management may also be affected by irrigation method due to the potential for irrigation water to cause N movement in the soil profile (Spalding et al., 2001). Water application efficiencies of spray and LEPA sprinkler irrigation methods (Lyle and Bordovsky, 1981, 1983) exceed 80% in most field evaluations and are reported to be between 90 and 98% when runoff and deep percolation are minimized (Schneider, 2000). Highly efficient irrigation combined with careful N management should minimize the risk of N leaching. This hypothesis is supported by Guenzi et al. (1994), who concluded that, when properly managed, use of the LEPA irrigation method does not result in N leaching to groundwater; however, there is little information available on the effect of different high-efficiency sprinkler methods on in-season N availability for sugarbeet under different tillage systems.

A field study was conducted to test the hypothesis that tillage system and sprinkler irrigation method affect N uptake and...
Fig. 1. Layout of a 5-yr cropping systems study at Sidney, MT reported by Evans et al. (2010). Crop/tillage treatments were planted in continuous 125-m strips parallel to the sprinkler direction of travel. Odd-yr (2005 and 2007) crop/tillage treatments are indicated on the diagram with labels spanning the four affected subplots. In even years, sugarbeet was planted into odd-year barley plots and vice-versa. Irrigation treatments were applied to 14.6 by 24.4-m subplots. The low-energy precision application (LEPA) method was applied to crosshatched subplots while the mid-elevation spray application (MESA) method was applied to those with no background pattern. Data reported in this paper were from 2005, 2006, and 2007 sugarbeet plots.

soil N availability in sugarbeet production. Specific objectives were to determine if petiole NO$_3$–N concentration and soil mineral N distribution differ under (i) CT and ST systems or (ii) MESA and LEPA irrigation methods.

**MATERIALS AND METHODS**

A field experiment was conducted from 2005 to 2007 at the Montana State University Eastern Agricultural Research Center approximately 2 km north of Sidney, MT (47°43'32" N, 104°9'W). Data were collected from plots within an existing cropping systems study established in 2004 to evaluate ST and high-efficiency irrigation for sugarbeet production in a sugarbeet–malt barley (*Hordeum vulgare* L.) rotation. The soil is a deep, well drained, nearly level Savage clay loam (fine, smectitic, frigid Vertic Argustolls) with 209 g kg$^{-1}$ sand, 463 g kg$^{-1}$ silt, and 328 g kg$^{-1}$ clay; soil pH 7.8; organic C 8.9 g kg$^{-1}$; and total N 0.65 g kg$^{-1}$ in the top 20 cm. Growing season average monthly air temperatures range from 7.2 to 21.1°C and average annual rainfall is about 330 mm, with approximately 190 mm occurring during the growing season.

A 2-yr rotation of barley and sugarbeet was implemented in 2004 so that both CT and ST sugarbeet were planted following barley. Management of barley was the same regardless of whether CT or ST was used for the subsequent sugarbeet crop. All barley residues remained on the field following harvest, with some lying on the soil surface and the remainder standing 15 to 20 cm in height. Barley residues were spread as evenly as possible over the soil surface using straw and chaff spreaders attached to the combine.

A 4-ha field was divided into 14 strips 14.6 m wide running the entire 125 m length of the study area and planted uniformly with a given crop and tillage practice. Four 14.6 m wide by 24.4 m long plots were established along the length of each field-length strip to which two irrigation treatments (two replicates of each) were randomly assigned, yielding a total of 56 plots in an unbalanced striped block design with four blocks (Fig. 1). Each sugarbeet treatment combination was replicated eight (2005, 2007) or eight (2006) times according to the unbalanced design. Data from the barley component of the rotation were not included in this manuscript and will be discussed in other papers.

All plots were irrigated with a 244 m, 5 span, self-propelled electric linear move sprinkler irrigation system (Valmont Industries, Inc., Valley, NE). The customized overhead sprinkler system was interfaced with a programmable logic controller (PLC) and global position system (GPS) receiver to allow water application method for each of 14 nozzle banks to be independently and automatically toggled from spray to LEPA methods as the self-propelled machine traveled across the study area (Kim et al., 2008). Each 14.6 m wide plot was irrigated using either MESA (locally the most common sprinkler irrigation method) with heads suspended about 1 m above the canopy and spaced 3 m apart, or LEPA with heads spaced every 1.2 m that apply water in a low-pressure stream about 15 cm above the soil surface between every other crop row (60 cm row widths) with minimal wetting of the canopy. Irrigation applications were scheduled based on calculated crop water use data obtained from the North Dakota Agricultural Weather Network (NDAWN) website (http://ndawn.ndsu.nodak.edu/crop-water-use-table-form.html). Daily reference evapotranspiration (ET) values were automatically calculated by NDAWN using a modified Jensen-Haise equation (Burman et al., 1983). Reference ET values were multiplied by a crop water-use coefficient ($K_w$) for sugarbeet (Stegman et al., 1977) to estimate actual ET. The depth of irrigation water applied to each plot was based on the estimated ET adjusted for rainfall, soil moisture, and an assumed application efficiency of 85% that was selected based on average values from various field studies reviewed by Schneider (2000). The same application efficiency factor was applied to both irrigation methods because the objectives of the original cropping systems study required that the risk of drought stress be minimized and because the design of the

<table>
<thead>
<tr>
<th>Year</th>
<th>In-season rainfall†</th>
<th>Irrigation</th>
<th>Rainfall + irrigation</th>
<th>Seasonal ET‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>229</td>
<td>194</td>
<td>423</td>
<td>616</td>
</tr>
<tr>
<td>2006</td>
<td>184</td>
<td>212</td>
<td>396</td>
<td>569</td>
</tr>
<tr>
<td>2007</td>
<td>227</td>
<td>315</td>
<td>542</td>
<td>640</td>
</tr>
</tbody>
</table>

† In-season rainfall is the sum of daily values from 1 May to 30 September.
‡ Seasonal ET is the sum of daily ET values from emergence (12 May 2005, 22 May 2006, and 2 May 2007) to harvest (30 September). Daily ET values were obtained from the North Dakota Agricultural Weather Network (NDAWN) website (http://ndawn.ndsu.nodak.edu/crop-water-use-table-form.html).
control system made varying the application rate impractical. In-seaon rainfall, irrigation water applied, and seasonal ET amounts are presented in Table 1. Soil moisture was determined weekly to a depth of 1.2 m by neutron thermalization (Hignett and Evett, 2002). Data are reported to a depth of 0.9 m because water table encroachment into the 1.2 m depth was suspected in some plots.

Conventional tillage was performed in the fall after broadcasting fertilizer and consisted of a primary tillage operation with a ripper (Case IH, Racine, WI) to a depth of about 23 cm, two passes with a rolling mulcher (Brillion Inc., Brillion, WI), and two passes with a leveler (Eversman, Denver, CO). The following spring, a single pass was made with an S-tine cultivator equipped with rolling baskets (Kongskilde Mfg., Soro, Denmark) before planting.

Strip tillage was accomplished using a custom-built, six-row strip till machine (Schlagel Mfg., Torrington, WY) which was described in detail by Evans et al. (2010). The implement leaves alternating 30-cm strips of tilled and undisturbed soil, leaving standing crop residue in the undisturbed interrow areas. Any straw remaining in the tilled zone was mixed into the soil. Fertilizer was applied in a band during the tillage operation via a tube attached to the back of the tillage shank. Strip tillage and the associated fertilizer application were done in the fall. Urea (NH₂CO) and monoammonium phosphate (NH₄PO₄) were applied based on soil test results with typical application rates of about 123 kg N ha⁻¹ and 56 kg P₂O₅ ha⁻¹. The same amount of N and P fertilizer was applied to both tillage treatments. Fertilizer was broadcast and incorporated into the top 7.5 cm of soil on CT plots and was banded approximately 7.5 cm under the seed row on ST plots. Potassium and Zn fertilizers were broadcast regardless of soil tillage system when soil test levels were deficient (Jacobsen et al., 2003). Strip tillage was performed on 13 Sept. 2005, 13 Sept. 2006, and 4 Sept. 2007. Sugar beet seed (cultivar ACH 927 large bare, American Crystal Co., Eden Prairie, MN) was planted in the spring at 135,000 seeds ha⁻¹. The same instrument described for the analysis of soil extracts.

Data were analyzed using the MIXED procedure of SAS (SAS Institute, 2003) treating day and sampling depth as double-nested repeated measures. Year, day, sampling depth, tillage and irrigation method were considered fixed effects, while block, block interactions and strip (main tillage plot) were considered random effects. Year was considered fixed rather than random due to notable differences among the three study years. Moreover, all response variables exhibited interactions with year and were thus analyzed within years. Least squares means, with probability differences, were estimated to determine significant differences among treatments. Due to somewhat variable soil properties within the experimental site, treatment effects were considered significant if P was ≤0.05. Instances where statistical analysis indicated greater confidence (i.e., P ≤ 0.05) were indicated.

RESULTS AND DISCUSSION

Weather conditions between the time of fertilizer application in early September and the beginning of the rapid N uptake period in late June varied markedly among the three study years. The mean annual temperature was warmer than average all 3 yr, ranging from 1.6°C warmer in 2007 to 2.5°C warmer in 2006. Mean precipitation during this 8-mo period was 1.8 and 0.5 cm less than average in 2005 and 2007, respectively, and 2.9 cm more than average in 2006. Deviations from mean monthly precipitation values were <3 cm throughout the off-season in 2005. The same was true for 2006 and 2007, except for April 2006 and May 2007 when precipitation amounts were 10.5 cm (7.6 cm more than average) and 12.4 cm (7.1 cm more than average), respectively.

Tillage Effect

Plant Nitrogen Status

Ulrich and Hills (1990) suggested petiole NO₃⁻N concentration as an effective assay of plant N status. The effect of tillage system on petiole NO₃⁻N concentration was not significant
when data were pooled across years, but there was a significant sample date (SD) × tillage (T) interaction (Table 3). There were differences between tillage systems at some sample dates in 2 of 3 yr. In 2005, petiole NO$_3$–N concentration was lower with ST than with CT from 81 to 107 DAP (Fig. 2a) suggesting that N availability was lower with ST. Root sucrose concentration, which typically increases with low N availability (Carter and Traveller, 1981; Stevens et al., 2009), trended slightly higher with ST than with CT in 2005 (Table 2). This trend was also observed in 2004 (Table 2) suggesting that N availability was less with ST than with CT, though no petiole NO$_3$–N or soil NO$_3$–N is available to confirm this for 2004. Conversely, there was no difference between ST and CT in petiole NO$_3$–N concentration in 2006 or 2007 before the 100 DAP sample date (Fig. 2b, c). Petiole NO$_3$–N concentration was 1.29 g kg$^{-1}$ (44%) lower with ST than with CT 109 DAP in 2007 (Fig. 2c), but this was the only sample date in 2006 or 2007 when a difference was observed. Though there was a nonsignificant trend for root yield and root sucrose content to be higher with ST than with CT in 2006, mean values for these two yield parameters were nearly identical for the two tillage systems in 2007 and 2008 suggesting that N availability was not affected by tillage system in these years (Table 2).

Petiole NO$_3$–N concentration results correspond to visual observations of mid-season plant color in each year. There was no clear difference in N-deficiency chlorosis development between the two tillage systems in 2006, 2007, and 2008 but in 2005 N deficiency chlorosis developed earlier with ST than with CT, suggesting lower N uptake with the ST system. Stevens et al. (2008) reported a similar observation in 2004 along with apparent N deficiency early in the seedling growth stage. However, this early-season N deficiency was not observed from 2005 to 2007. A possible explanation for its occurrence in 2004 is that the fertilizer N band was placed 17.5-cm deep, causing the roots to grow through N-depleted soil before reaching the fertilizer band. Fertilizer was banded 7.5 cm deep from 2005 to 2007. Regitnig (2008) also observed reduced seedling vigor with ST as compared with CT. Only small differences in soil temperature and soil N availability were reported with the temperature being slightly higher for CT and soil N availability slightly higher for ST; however, the author concluded that neither of these factors accounted for the difference in seedling vigor and no other potential causes were proposed.

### Table 3. Probability ($P > F$) values for the effects of treatments and their interactions on soil in-season mineral N concentration, soil postharvest (fall) NO$_3$–N concentration, and petiole NO$_3$–N concentration.

<table>
<thead>
<tr>
<th>Source</th>
<th>Soil N in-season</th>
<th>Fall NO$_3$–N</th>
<th>Petiole NO$_3$–N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO$_3$–N</td>
<td>NH$_4$–N</td>
<td>(NO$_3$ + NH$_4$)–N</td>
</tr>
<tr>
<td>Sample date (SD)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Soil depth (D)</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SD × D</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Tillage (T)</td>
<td>&lt;0.001</td>
<td>0.221</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SD × T</td>
<td>&lt;0.001</td>
<td>0.433</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D × T</td>
<td>&lt;0.001</td>
<td>0.649</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SD × D × T</td>
<td>&lt;0.001</td>
<td>0.795</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Irrigation (I)</td>
<td>&lt;0.001</td>
<td>0.407</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SD × I</td>
<td>0.705</td>
<td>0.033</td>
<td>0.477</td>
</tr>
<tr>
<td>D × I</td>
<td>0.597</td>
<td>0.661</td>
<td>0.814</td>
</tr>
<tr>
<td>SD × D × I</td>
<td>0.809</td>
<td>0.018</td>
<td>0.899</td>
</tr>
<tr>
<td>T × I</td>
<td>0.344</td>
<td>0.929</td>
<td>0.353</td>
</tr>
<tr>
<td>SD × T × I</td>
<td>0.885</td>
<td>0.411</td>
<td>0.806</td>
</tr>
<tr>
<td>D × T × I</td>
<td>0.989</td>
<td>0.881</td>
<td>0.976</td>
</tr>
<tr>
<td>SD × D × T × I</td>
<td>0.954</td>
<td>0.783</td>
<td>0.960</td>
</tr>
</tbody>
</table>

Fig. 2. Petiole NO$_3$–N concentration for strip till (ST) and conventional till (CT) sugarbeet at Sidney, MT. Error bars show two standard errors of the mean and an * indicates significant differences ($P < 0.05$). The absence of a symbol indicates that means are not significantly different.
In-Season Distribution of Soil Mineral Nitrogen

Soil NH₄⁺-N concentration during the growing season generally declined as both sample date and soil depth increased (data not shown), but was not affected by tillage (Table 3). Concentrations of NH₄⁺-N were relatively low, averaging about 3.4 mg kg⁻¹ across year, sample date, and soil depth compared with 9.6 mg kg⁻¹ for NO₃⁻-N (Table 4). While NH₄⁺-N made up 20 to 30% of total available N (NO₃⁻-N + NH₄⁺-N), its inclusion has little impact on conclusions about the effect of tillage system on N availability (Tables 3 and 4).

Soil NO₃⁻-N concentration varied with both tillage system (T) and irrigation method (I), but there was no T × I interaction (Table 3). Averaged across years and sample dates, there was 12.2 mg NO₃⁻-N kg⁻¹ with CT and 7.0 mg NO₃⁻-N kg⁻¹ with ST in the top 45 cm of soil (Table 4). The higher NO₃⁻-N concentration observed with CT was consistent across all years and sample dates, but the magnitude of the difference varied with time and soil depth as indicated by significant interactions of tillage with soil depth, sample date (Table 3) and year (not shown). In 2005 there was more available NO₃⁻-N in the top 45 cm of soil with CT than with ST at 80 DAP (Fig. 3a). There was only about 5 mg NO₃⁻-N kg⁻¹ in each 15-cm depth increment with ST, indicating that fertilizer N may have moved below the sampling depth. With CT, there was more NO₃⁻-N at the 15- to 30-cm and 30- to 45-cm depths (14 and 18 mg kg⁻¹, respectively) than in the surface 15 cm (9 mg kg⁻¹). At 101 and 133 DAP, most fertilizer N had been removed by plant uptake, leached below 45 cm or lost to denitrification in both tillage systems (Fig. 3b, c).

While not as great as in 2005, differences in soil NO₃⁻-N concentration exhibited a similar pattern in 2006 with CT leading to higher overall concentrations than ST. With CT, some NO₃⁻-N was remaining at the 30- to 45-cm depth by 81 DAP, but with ST little remained in the top 45 cm (Fig. 3d). At subsequent sampling dates in 2006, NO₃⁻-N had been depleted in the top 45 cm under both tillage systems (Fig. 3e, f). Wet fall and spring conditions (160 and 126%, respectively, of average precipitation) and warm spring temperatures (113% of average) likely increased NO₃ leaching, denitrification, and early season N uptake, resulting in soil NO₃⁻-N concentrations 81 DAP that were lower than those at corresponding sampling dates in 2005 and 2007. Moreover, average growing season volumetric soil moisture at the 22.5 cm soil depth was greater with ST than with CT (Fig. 4), particularly under LEPA irrigation management, indicating that during the growing season, soil conditions in the top soil layer under ST management may have favored some N loss.

Low soil NO₃⁻-N concentrations observed at 81 DAP in 2005 suggested that an earlier sampling date may be necessary. Consequently, sampling commenced 59 DAP in 2007 in an effort to better document the effect of tillage system on early season N availability. At this earlier sample date, NO₃⁻-N concentration was greater with CT than with ST at all three sampling depths (Fig. 3g). Nitrate-N concentration increased from 9.1 to 11.9 mg kg⁻¹ and from 15.3 to 36.2 mg kg⁻¹ for ST and CT, respectively, as sampling depth increased suggesting that fertilizer N had moved downward in the soil. At 77 DAP, the distribution of soil NO₃⁻-N was very similar to that at 80 DAP in 2005 (compare Fig. 3a and 3h). Spring precipitation amounts were similar for these 2 yr, with the exception of one above-average rainfall event in May 2007. Conversely, soil NO₃⁻-N concentration remained significantly higher at all sampling depths 109 DAP in 2007, while differences were smaller 101 DAP in 2005 (compare Fig. 3b

![Fig. 3. Soil NO₃⁻-N concentration in a 45-cm soil profile as affected by placement/tillage system (ST, strip till/banded fertilizer; CT, conventional till/broadcast fertilizer) at Sidney, MT. Three sampling times are represented for each year in terms of the number of days after planting (DAP). Error bars show two standard errors of the mean. The symbols * and + indicate significant differences at P < 0.05 and P < 0.10, respectively. The absence of a symbol indicates that means are not significantly different.](image-url)
This is likely the result of substantially lower than average precipitation in July and August 2007.

**Postharvest Soil Nitrate-Nitrogen**

Only small amounts of residual NO$_3$–N remained following harvest in all 3 yr. Nitrate-N concentration decreased with increasing soil depth, ranging from about 4.8 mg kg$^{-1}$ at 0 to 15 cm to 1.5 mg kg$^{-1}$ at 90 to 120 cm (Table 5). Nitrate-N concentrations were 1.7 and 0.6 mg kg$^{-1}$ higher with CT than with ST in the 0- to 15-cm and 15- to 30-cm depth increments, respectively, but the total profile (0–120 cm) residual NO$_3$–N differed by only 4.4 kg ha$^{-1}$. These results are similar to the in-season soil NO$_3$–N concentration data discussed previously which shows slightly higher concentration below a sampling depth of 30 cm (Table 5).

Lower petiole NO$_3$–N, in-season soil NO$_3$–N and post-harvest soil NO$_3$–N concentrations with ST suggest that N availability may be somewhat less than with CT. The reason for this small but consistent difference remains unclear. It might be expected that since fertilizer N is banded with ST and broadcast with CT that N availability would be greater with the former. Stevens et al. (2007) reported enhanced N efficiency and a lower requirement for applied N when fertilizer was banded near the seed row than when it was broadcast. However, in that study fertilizer was applied in the spring and was accompanied by intensive tillage and alternate-furrow irrigation. Conversely, in the study reported herein fertilizer was applied in the fall, tillage was greatly reduced with the ST treatment and water was applied by sprinkler irrigation. Consequently, the reduction in petiole and soil NO$_3$–N concentrations with ST could be the result of differences between the two tillage systems in late fall or early spring N leaching, alterations of the mineralization-immobilization turnover (MIT) with ST due to reduced soil disturbance and residue incorporation, effects of residue on soil temperature and thus MIT and urea hydrolysis, or suboptimal fertilizer band placement with ST. Additional research is needed to determine if these or other factors may be contributing to the reduced NO$_3$–N concentrations observed with ST.

Despite the apparent difference in N availability between ST and CT there were no differences in yield and quality when data were pooled over 5 yr (Table 2) indicating that production can be maintained with ST using the same N application rate as is recommended for CT. This agrees with the conclusions of Halvorson and Hartman (1988) who concluded that N response was similar for the two tillage systems. The lower concentrations of petiole and soil NO$_3$–N suggest that N application rate should not be reduced with ST based on an assumption that banding N will lead to higher N-use efficiency. Further research is needed to determine if production with ST can be further enhanced by increasing the N application rate or altering the fertilizer band placement to compensate for the apparent decrease in N availability.

### Irrigation Effect

**Plant Nitrogen Status**

Irrigation method (I) did not affect plant N status as measured by petiole NO$_3$–N concentration nor was there a significant sample date (SD) × I interaction (Table 3). This suggests that N uptake by sugarbeet is the same whether water is applied using MESA or LEPA methods, provided equal amounts of water are applied. Colaizzi et al. (2004) observed that when grain sorghum [Sorghum bicolor (L.) Moench] was irrigated at <75% of ET, yield with LEPA was greater than with MESA; however, when irrigated at 75 or 100% of ET, yield with LEPA was greater than with MESA. They also observed that when 75 or 100% of ET was applied, there was greater deep profile soil moisture with LEPA than with MESA and suggested that there may have been more nutrients leached below the root zone with LEPA than with MESA; at least partially explaining the yield differences observed. There are several reasons that irrigating with LEPA to meet 100% of ET may cause more deep percolation than with MESA. First, predictions of ET include an estimate of evaporation that assumes the entire soil surface is wetted, but with LEPA a substantial portion...
of the soil surface remains dry. For sugarbeet planted in 60-cm rows without ridges, approximately 50% of the soil is wetted. Second, if irrigation water is concentrated on only half of the soil surface, the effective water application rate in the wetted portion of the row is approximately 200% of ET. Third, less water is lost to evaporation with LEPA than with MESA due to larger droplet size, shorter distance of travel from the nozzle to the soil surface, and less wetting of the crop canopy. These factors combine to potentially produce a water application efficiency of from 95 to 98% for LEPA compared with a maximum of about 90% with MESA (Schneider, 2000).

Average subsoil (45–90 cm) moisture readings were consistently higher in the present study with LEPA than with MESA, particularly under CT management (Fig. 4). This was likely the result of greater application efficiency with the LEPA system and may have caused greater percolation of water than the MESA system. It might be expected that the effect of deep percolation of water on N movement depends on N placement. Nitrogen fertilizer was broadcast with the CT system and was banded below the crop row with the ST system. Past research with corn (Zea mays L.) and sugarbeet has shown that placing the fertilizer band in a position where it is protected from percolating water reduces N leaching (Stevens et al., 2007; Jaynes and Swan, 1999; Waddell and Weil, 2006). There was no significant T × I interaction for petiole NO₃–N concentration (Table 3); however, there was a consistent but nonsignificant trend in all 3 yr for petiole NO₃–N concentration to be greater, respectively, with LEPA irrigation than with MESA when averaged across years and sample dates (Table 4). These results agree somewhat with the nonsignificant trend in petiole NO₃–N concentration under the ST system (Table 6), while results in the CT system were more variable.

In-Season Distribution of Soil Mineral Nitrogen

Soil NH₄–N was not affected by irrigation method (Table 3), but soil NO₃–N and NO₂–N + NH₄–N were 13 and 10% greater, respectively, with LEPA irrigation than with MESA when averaged across years and sample dates (Table 4). These results agree somewhat with the nonsignificant trend in petiole NO₃–N concentration under the ST system (Table 6), but the irrigation effect on soil mineral N was consistent across both tillage systems as suggested by the nonsignificant T × I interaction (Table 3). As with petiole NO₃–N concentration, the in-season concentration of soil mineral N suggests that less N is lost with LEPA than with MESA. These results seem to contradict those of Colaiuzzi et al. (2004) who found evidence for greater percolation and nutrient movement with LEPA than with MESA under center pivot irrigation; however, they suggested that LEPA is prone to deep percolation when irrigation water is applied to supply 75% of ET or greater. The irrigation application rate in the study reported herein was estimated to be about 70% replacement of ET despite efforts to base irrigations on soil moisture readings and visual evaluations of crop stress. We suspect that a seasonally (late summer) shallow water table may have affected crop water use and research is being conducted to quantify its effect. In addition, the application rates with a linear move system are lower than for the outer sections of center pivot systems such as the one used by Colaiuzzi et al. Consequently, the results from the present study agree with those of Colaiuzzi et al. (2004); however, under conditions where irrigation must meet >75% of ET or under the outer sections of center pivot systems, there may be a greater risk of N leaching with the LEPA method when used in combination with broadcast N applications.

Table 6. Petiole NO₃–N concentration as affected by irrigation method with either strip tillage (ST) or conventional tillage (CT) at Sidney, MT.

<table>
<thead>
<tr>
<th>Year</th>
<th>CT</th>
<th>LEPA</th>
<th>P &gt; F</th>
<th>ST</th>
<th>LEPA</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>4211</td>
<td>4479</td>
<td>ns†</td>
<td>2392</td>
<td>2737</td>
<td>ns†</td>
</tr>
<tr>
<td>2006</td>
<td>2168</td>
<td>1916</td>
<td>ns‡</td>
<td>2151</td>
<td>2400</td>
<td>ns‡</td>
</tr>
<tr>
<td>2007</td>
<td>6530</td>
<td>6385</td>
<td>ns‡</td>
<td>5740</td>
<td>6587</td>
<td>ns‡</td>
</tr>
</tbody>
</table>

† MESA, mid-elevation spray application; LEPA, low-energy precision application. ‡ ns, means within a row are not significantly different (P ≤ 0.1).

Postharvest Soil Mineral Nitrogen

Irrigation method did not affect the amount of postharvest residual NO₃–N at any depth within the 120-cm soil profile (Table 5). There was also no evidence that there was accumulation of NO₃–N within the 120-cm profile regardless of irrigation method. The presence of a gravel layer in the lower profile prevented deeper sampling so it is unknown how much, if any, NO₃–N leached beyond 120 cm. Research has shown that the deep-rooted sugarbeet extracts N from soil depths of at least 180 cm (Moraghan, 1985; Franzen et al., 2000) so any N that moved beyond 120 cm may have still been absorbed by the crop. The concentration of residual mineral N remaining in the profile following harvest suggests that N fertilizer application rate and irrigation management practices led to an efficient utilization of fertilizer and soil N under both MESA and LEPA irrigation methods.

SUMMARY AND CONCLUSIONS

Petiole NO₃–N concentration was lower for ST than CT for at least one sample date in 2 of 3 yr and in-season available N in the top 45 cm of soil was lower with ST than with CT, particularly at sampling dates 80 DAP and earlier, in all 3 yr. Postharvest residual NO₃–N was about 10% less with ST than with CT. Despite these differences, sugarbeet root yield and quality were similar for the two tillage systems. Plant N status and soil mineral N concentration were similar for MESA and LEPA irrigation methods. The only significant difference observed was a 10% increase in in-season soil mineral N with LEPA compared with MESA. This may be due in part to a possible reduction in NO₃ leaching when LEPA, in which irrigation water is applied between alternating crop rows, is combined with strip tillage, where N is banded directly underneath the crop row. With the combination of these two systems N fertilizer is spatially separated from the downward percolating irrigation water. It was concluded that, while some differences in plant N status and soil N content were observed, these differences do not appear to justify altering N application rate based on the tillage systems or irrigation methods evaluated in this study. In particular, N application rate should not be reduced with ST assuming that banding N will lead to higher N-use efficiency.

Because the two tillage systems evaluated employed different methods of fertilizer application, it is difficult to ascertain if the observed differences were due to differences in tillage intensity or N placement; however, it is most likely that the observed effects of ST on N response resulted from fertilizer placement. Optimum fertilizer band placement will ensure sufficient N availability to the sugarbeet at all growth stages while minimizing the risk of fertilizer-induced seedling injury. More research
is needed to determine optimum placement of the fertilizer band under various tillage and irrigation practices.

REFERENCES


