

Suction Cup Samplers for Estimating Nitrate-Nitrogen in Soil Water in Irrigated Sugarbeet Production

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Abstract

Efforts have increased to measure nitrate losses from farmland under different management practices due to environmental and public concerns over levels of nitrate-nitrogen ($\text{NO}_3\text{-N}$) in surface and ground waters. This study evaluated the effect of conventional tillage (CT) and strip tillage (ST) practices and three N application rates on $\text{NO}_3\text{-N}$ concentrations in soil water at a 76 cm depth under irrigated sugarbeet (*Beta vulgaris* L.) in a clay loam soil. Nitrogen rates were applied as dry urea at 120, 150, 180 kg N ha⁻¹ in 2006; 130, 160, 190 kg N ha⁻¹ in 2007; and 110, 140, 170 kg N ha⁻¹ in 2008. Soil water volumes were measured weekly during each growing season using three ceramic suction cup samplers per plot placed at a 76 cm depth below the soil surface under each tillage. Results indicated that $\text{NO}_3\text{-N}$ concentrations at the 76 cm depth in the soil profile were not significantly affected by either tillage practice or by N application rate due to soil variability across the field and due to suction cup samplers' biased estimate of soil water. The three N rates under CT and ST practices maintained $\text{NO}_3\text{-N}$ concentrations below the root zone to levels exceeding the 10 mg L⁻¹ safe drinking water maximum level in all three years. There were large variations in $\text{NO}_3\text{-N}$ concentrations among replicates within each tillage and N rate that were likely caused by variability in soil physical, hydraulic and chemical properties that impacted water movement through the soil profile, N dynamics and leaching below the root zone of sugarbeet. In conclusion, suction cup samplers are point water measurement devices that reveal considerable variability among replicates within each treatment due to the heterogeneity of field soils. Further, these samplers are not recommended in heterogeneous soils with preferential flow characteristics.

Keywords

Suction Cup Samplers, Nitrate-Nitrogen, Sugarbeet, Strip Tillage, Conventional Tillage

1. Introduction

Contamination of surface and ground waters with nitrate-nitrogen ($\text{NO}_3\text{-N}$) from farmland is a major environmental issue and an important public health concern. Nitrate-N levels at and above 10 mg L^{-1} have been shown to pose health risks to humans and particularly to infants, causing a condition called methemoglobinemia [1]. Consequently, the United States Environmental Protection Agency [2] has designated the maximum contamination limit for $\text{NO}_3\text{-N}$ in drinking water at 10 mg L^{-1} (10 ppm). This issue has received increasing attention nationally and internationally over the past several decades. With these growing public and environmental concerns, researchers are diligently working to develop farm management practices that will reduce $\text{NO}_3\text{-N}$ leaching loss from agricultural production lands.

Nitrogen (N) in soil is dynamic and is susceptible to leaching, denitrification, volatilization, and immobilization processes within the soil ecosystem. Nitrate-N leaching losses from agricultural production depends on N fertilizer application practices, soil type, tillage systems, N transformations due to changes in the soil ecosystem and irrigation practices.

The effect of tillage on $\text{NO}_3\text{-N}$ leaching is viewed by many researchers as a controversial matter. Research has shown higher $\text{NO}_3\text{-N}$ leaching losses under conventional tillage due to increased N mineralization [3] [4].

Randall and Iragavarapu [4] found that average flow-weighted $\text{NO}_3\text{-N}$ concentrations were 13.4 and 12.0 mg L^{-1} for conventional and no-tillage practices, respectively, under corn (*Zea mays* L.) production. Although the differences were small, their results suggested a trend toward greater $\text{NO}_3\text{-N}$ leaching losses with conventional tillage than no-tillage in their 6-yr study. Conversely, other researchers reported higher $\text{NO}_3\text{-N}$ leaching losses with no-tillage as compared to tillage due to an increase in soil infiltration rate and internal drainage under no-tillage practices [5]-[7]. Other researchers have found little evidence of a relationship between tillage practices and risk of nitrate leaching. Randall and Mulla [8] concluded that nitrate leaching losses from agricultural fields is minimally affected by different tillage practices compared with N management practices. Al-Kaisi and Licht [9] concluded in a 2-yr study that strip tillage, chisel plow, and no-tillage systems did not cause significant differences in $\text{NO}_3\text{-N}$ concentration in water leachate collected at the 1.2 m depth in loam and silty clay loam soils in corn.

Nitrogen fertilizer application rate is one of the primary causes of nitrate losses to surface and ground waters. Therefore implementing better and more site-specific N and irrigation management practices with an appropriate tillage system is essential to minimize nitrate leaching to the environment from fertilized farms while sustaining crop productivity. Zvomuya *et al.* [10] compared the effect of 140 and 280 kg N ha^{-1} rates on potato yield and $\text{NO}_3\text{-N}$ leaching on a loamy sand soil. In their 3-yr study, they found that nitrate leaching increased rapidly with increased fertilizer N application rate on coarse-textured soils.

Little is known about the effects of different tillage systems, particularly, the strip tillage practice in conjunction with N input rates on $\text{NO}_3\text{-N}$ concentration below the root

zone under irrigated sugarbeet production in the northern Great Plains (NGP) region. We hypothesized that 1) strip tillage would reduce the leached amounts of $\text{NO}_3\text{-N}$ compared to conventional tillage due to immobilization process of soil N (not measured) in ST plots as a result of presence of crop residue, and 2) a positive correlation would exist between N input rates and amounts of $\text{NO}_3\text{-N}$ leached below the root zone of irrigated sugarbeet under a given tillage system. Therefore the objective of this study was to evaluate and compare the effect of conventional tillage (CT) and strip tillage (ST) practices and three N input rates on $\text{NO}_3\text{-N}$ concentrations in soil water measured by suction cup samplers below the root zone of sugarbeet under irrigated conditions in a clay loam soil.

2. Materials and Methods

2.1. Experimental Layout and Field Methods

A 3-yr field study was established in spring 2006 at the Montana State University, Eastern Agricultural Research Center (EARC) located in Sidney, MT, USA (latitude 47.7255 N, longitude 104.1514 W, elevation 650 m). The field site is on a Savage clay loam (fine, smectitic, frigid VerticArgiustoll). The experimental location consists of deep well-drained soil formed in alluvial parent material, and is nearly level (<1% slope). The amount of soil organic matter in the upper 30 cm averaged 2.67% with a CV = 34.9% (n = 24).

Two cropping system treatments were implemented, namely CT-sugarbeet/CT-malting barley and ST-sugarbeet/CT-malting barley with each phase of each rotation present each year. Sugarbeet was planted following malting barley (*Hordeum vulgare* L.) in each of the three study years and all barley residues remained on the field following barley harvest. Nitrate-N concentrations in soil water were monitored the sugarbeet phase of the rotation only.

Plots were irrigated with a self-propelled overhead linear-move sprinkler irrigation system (Valmont Industries, Inc., Valley, NE, USA) fitted with mid-elevation spray application (MESA) heads (Rotator with D6-12° R3000 plate, Nelson, Walla Walla, WA, USA) suspended about 1 m above the sugarbeet canopy, spaced 3 m apart that delivered water at approximately $24 \text{ L min}^{-1} \text{ head}^{-1}$. Total amounts of seasonal rainfall were 194, 227, and 142 mm in 2006, 2007, and 2008 growing seasons, respectively. Total irrigation amounts applied to sugarbeet plots during 2006, 2007, and 2008 growing season were 212.3, 284.5, and 270.8 mm, respectively. The amount of water lost by evaporation from soil surface and transpiration from the sugarbeet plants (evapotranspiration, ET) were 553.9, 640.8, and 587 mm for the 2006, 2007, and 2008 growing seasons, respectively.

2.2. Tillage Practices Description

Conventional tillage consisted of six separate operations using different implements following the harvest of malt barley. Plots were fertilized, disked 12 cm deep and then tilled with a soil ripper (Case IH, Racine, WI, USA) to a depth of 30 cm. Conventional

tillage was completed by making two passes with a rolling mulcher (Brillion Inc., Brillion, WI), and two passes with a leveler (Eversman, Denver, CO, USA).

Strip tillage was performed using a single operation with a modified ST machine (SchlagelMfg, Torrington, WY, USA) that provided alternating 30-cm wide strips of tilled and untilled soil. The ST implement also applied fertilizer in a band in the center of the tilled zone. Strip tillage and the associated fertilizer application were performed in the fall of previous year.

The preceding malt barley crop was harvested in August of each year using a combine harvester equipped with straw spreaders that uniformly distributed chaff and straw across each plot under both CT and ST systems. Dates of sugarbeet planting were 01 May 2006, 23 April 2007, and 25 April 2008. Dates of sugarbeet hand harvest were 21 September, 2006, 27 September 2007, and 26 September 2008.

Further information regarding tillage operations and dates, fertilizer applications and dates, irrigation system and experimental design were described in detail by Evans *et al.* [11] [12]; Stevens *et al.* [13] and Jabro *et al.* [14].

2.3. Fertilizer Application Rate

Urea and mono-ammonium phosphate were applied based on soil test results estimated on composite soil samples collected the fall preceding the sugarbeet crop. Nitrogen was applied as dry urea at 120, 150, 180 kg N ha⁻¹ in 2006; 130, 160, 190 kg N ha⁻¹ in 2007; and 110, 140, 170 kg N ha⁻¹ in 2008 with the middle rate representing the recommended N application for each year. Monoammonium phosphate was applied at 56 kg P₂O₅ ha⁻¹. The same amount of N and P fertilizer was applied to both CT and ST treatments. Fertilizer was broadcast and incorporated into the top 7.5 cm of soil on CT plots and was banded about 7.5 cm under the seed row on ST plots as described by Stevens *et al.* [13]. Dates of tillage and fertilizer applications were 13 September 2005, 13 September 2006, and 4 September 2007 for 2006, 2007, and 2008 growing seasons, respectively.

2.4. Description of Ceramic Suction Cup Samplers, Soil Water Sampling and Processing

Soil water volumes were measured weekly during the growing season using three ceramic suction cup water samplers per plot placed at a 76 cm depth below the soil surface under each tillage system. Suction cup samplers were located in the fourth crop row (61-cm row spacing) from each respective plot edge [14]. Suction cup water samplers or lysimeters consisted of a cylindrical porous ceramic cup (20 kPa high flow model with an outside diameter of 4.826 cm, inner diameter of 4.034 cm and 6.045 cm long) sealed to the lower end of a polyvinyl chloride (PVC) pipe using epoxy glue (Soilmoisture Equipment Corp, Goleta, CA, USA). The surface area of the ceramic cup in contact with the soil was approximately 74.74 cm². The total PVC tubing length including the ceramic cup was approximately 88 cm. Two small polypropylene tubes were inserted through a size 10 rubber stopper in the above-ground end of each PVC tube. The long tube was extended to the base of the ceramic cup to extract the volume of drainage soil water (soil solution). The short tube, which consists of a 15 cm long rigid

tube with a vacuum hose attached on the outside of the rubber stopper, was used to apply vacuum. Holes 5.08 cm in diameter were drilled into the soil to a depth of 85 cm using a truck-mounted probe. Mud slurry was poured into each hole prior to vertical insertion of a suction cup sampler to ensure good cup-to-soil contact. Any space along the outside of the water sampler casing was sealed with soil slurry to prevent preferential flow along the sides [14].

Samples of soil water were collected by creating a partial vacuum of –50 kPa with a hand operated syringe connected to the smaller inside tube. Soil water samples were stored in an ice cooler. The volume of soil water in each container was later measured in the laboratory, where a small soil water sample was filtered using Q2 filter paper (porosity: fine, flow rate: slow; Fisher Scientific, Pittsburgh, PA, USA), then stored frozen in a small container until analyzed for NO₃-N using an automated flow analyzer (QuikChem 8000; Lachat Instruments, Milwaukee, WI, USA).

Suction cup samplers were reinstalled each year after planting then removed prior to harvest each year.

Seasonal average NO₃-N concentration in soil water (\overline{CN}) values for each replication or plot under each N rate and tillage practices were calculated as:

$$\overline{CN} = \frac{\sum_i^n CN_i}{n}$$

where CNi is concentration of NO₃-N (mg L⁻¹) in the soil water sample for each sampling interval or week, i , $i = 1, 2, 3, \dots, n$ that corresponds to sampling events which were 14, 10, and 11 for 2006, 2007, and 2018, respectively.

2.5. Soil Physical and Hydraulic Properties

Particle size distribution for each soil sample was determined using the hydrometer method. Mean and coefficient of variation (CV %) results of sand, silt, and clay in the soil are given in **Table 1**.

Table 1. Mean soil particle size distribution and coefficient of variation (CV, %) at 0 - 10, 10 - 20, 20 - 40, and 40 - 60 cm depths for Savage clay loam soil.

Depth (cm)	Statistics ^a	Sand	Silt	Clay	Textural class
			(%)		
0 - 10	Mean	21	42	37	Clay Loam
	CV (%)	29	5	16	
10 - 20	Mean	19	44	37	Silty Clay Loam
	CV (%)	41	5	17	
20 - 40	Mean	12	49	39	Silty Clay Loam
	CV (%)	10	20	26	
40 - 60	Mean	16	42	42	Silty Clay
	CV (%)	10	25	18	

^aNumber of observations is 12.

Undisturbed soil samples were collected using a stainless steel core of 50 mm internal diameter and 50 mm length from each plot at 0 - 10, 10 - 20, and 20 - 30 cm depths under CT and ST practices in 2007. Soil cores were used to measure bulk density as mass of oven dried soil per volume of core (Mg m^{-3}) and gravimetric moisture content as mass of water in the soil sample per mass of the oven dried soil (g g^{-1}). Soil cores were extracted from within the crop row for each tillage treatment (**Table 2**).

Soil saturated hydraulic conductivity (Kfs) measurements for the surface layer (0 - 10 cm) were determined using the single head pressure ring infiltrometer method [15] while Kfs measurements for the two subsurface layers (10 - 20, 20 - 30 cm) were assessed using a constant head well permeameter [16]. Soil Kfs measurements were made within the row of sugarbeet at each layer for each tillage treatment (**Table 2**). Soil cores

Table 2. Mean and coefficient of variation (CV) of soil bulk density (BD), moisture content (MC), and saturated conductivity (Kfs) at 0 - 10, 10 - 20, and 20 - 30 cm depths for Savage clay loam soil under conventional (CT) and strip tillage (ST) practices near Sidney, MT, 2006.

Tillage	Depth, cm	Soil Property ^a	Mean	CV (%)
CT	0 - 10	BD (Mg m^{-3})	1.405	6.5
		MC (g g^{-1})	0.205	4.0
		Kfs (mm h^{-1})	37.20	104.5
	10 - 20	BD (Mg m^{-3})	1.520	4.9
		MC (g g^{-1})	0.219	9.5
		Kfs (mm h^{-1})	4.86	97.9
	20 - 30	BD (Mg m^{-3})	1.49	6.1
		MC (g g^{-1})	0.215	9.6
		Kfs (mm h^{-1})	8.28	166.6
ST	0 - 10	BD (Mg m^{-3})	1.324	2.9
		MC (g g^{-1})	0.224	7.2
		Kfs (mm h^{-1})	76.21	58.5
	10 - 20	BD (Mg m^{-3})	1.433	3.6
		MC (g g^{-1})	0.249	6.0
		Kfs (mm h^{-1})	3.524	105.8
	20 - 30	BD (Mg m^{-3})	1.437	5.3
		MC (g g^{-1})	0.241	5.3
		Kfs (mm h^{-1})	8.414	

^aNumber of observations (n) per treatment and per each depth is 4.

and Kfs measurements were taken within approximately 1 m of the suction cup water samplers.

2.6. Statistical Analysis

The experimental design was a randomized complete block with individual main 14.6 m × 24.4 m plots arranged as a split plot with eight replications in 2006 and 2008 and six replications in 2007. Sub plots (3.7 × 12.2 m) were arranged randomly within the outer margins of the main plots. Nitrate-N data were analyzed using the SAS mixed model procedure [17]. Method of tillage was treated as fixed main plot effect, with N rate as a fixed split plot effect and replication as the random effect. All statistical comparisons were performed at $P < 0.05$.

3. Results and Discussion

3.1. Effect of Tillage

Seasonal average $\text{NO}_3\text{-N}$ concentrations in soil water below a 76 cm depth under sugarbeet did not differ significantly between CT and ST practices for all three N application rates in 2006, 2007, and 2008, respectively, due to considerable variability in soil physical and hydraulic properties among plots (Figures 1-3). There were large variations in $\text{NO}_3\text{-N}$ concentrations among replicates or plots under each tillage for each N rate treatment used in this study as are indicated by two standard errors of the mean and displayed in Figures 1-3 for 2006, 2007, and 2008, respectively. The spatial variability in the field's soil among replicates within each tillage treatment had a major impact on soil physical and chemical properties that influenced water movement, N dynamics, transformation and leaching.

To explain variation among plots within each tillage treatment some possible reasons were considered. Soil across the field was not uniform but rather was heterogeneous

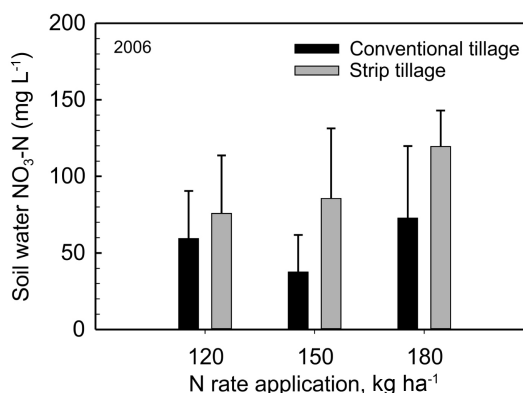


Figure 1. Effect of conventional tillage (CT) and strip tillage (ST) on average seasonal $\text{NO}_3\text{-N}$ concentration at a 76 cm depth under 120, 150, and 180 kg N ha^{-1} application rates in sugarbeet near Sidney, MT, 2006. Error bars represent two standard errors of the mean.

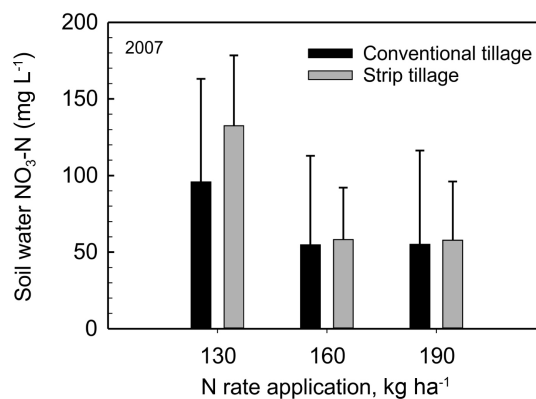


Figure 2. Effect of conventional tillage (CT) and strip tillage (ST) on average seasonal $\text{NO}_3\text{-N}$ concentration at a 76 cm depth under 120, 150, and 180 kg N ha⁻¹ application rates in sugarbeet near Sidney, MT, 2007. Error bars represent two standard errors of the mean.

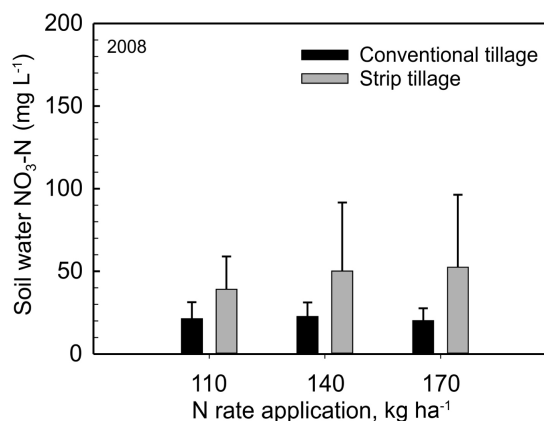


Figure 3. Effect of conventional tillage (CT) and strip tillage (ST) on average seasonal $\text{NO}_3\text{-N}$ concentration at a 76 cm depth under 120, 150, and 180 kg N ha⁻¹ application rates in sugarbeet near Sidney, MT, 2008. Error bars represent two standard errors of the mean.

and exhibited great spatial variability in soil physical and hydraulic properties among plots within each tillage treatment (Table 1 and Table 2). Most soil properties which influence the transport of $\text{NO}_3\text{-N}$ through natural field soils varied substantially at different locations, even at short separation distances (Table 1 and Table 2). For instance, soil Kfs measurements in Table 2 showed large spatial variation among plots under each tillage practice attributed to variability in soil morphology in the field. The variability of soil Kfs among plots within the study site was classified as high ($\text{CV} > 75\%$) under both tillage systems according to classification described by Dahiya *et al.* [18].

Research conducted on Savage clay loam soils showed that these soils exhibited cracks and a high potential of preferential water flow throughout the soil profile [19]. Therefore, another reason for inconsistency of suction cup samplers for measuring

$\text{NO}_3\text{-N}$ concentration in soil water among replicates within each treatment was related to preferential flow that mainly affected water movement and nitrate transport through cracks and worm holes that bypassed most of the soil matrix (microporous medium) and ceramic cups directly to the lower portion of the soil profile in the Savage clay loam used in this study [19].

The effect of tillage on water movement into and through the soil profile is inconsistent as both CT and ST practices can either increase or decrease Kfs [20] [21]. Changes in soil Kfs across a field and among plots within the same tillage treatment can affect water movement, which in turn affects $\text{NO}_3\text{-N}$ concentrations and transport through the soil profile. Therefore, knowledge of the soil spatial variability across a field is critical to the success of site-specific water and N management practices.

3.2. Effect of Nitrogen Application Rate

Average seasonal $\text{NO}_3\text{-N}$ concentrations in soil water below the root zone of sugarbeet from three N application rates under CT and NT practices for 2006, 2007, and 2008 are presented in **Figures 4-6**, respectively. Statistical results showed that average seasonal $\text{NO}_3\text{-N}$ concentrations within CT and ST practice did not differ significantly among N rates for all three years. Nitrate-N concentration exhibited considerable variation among plots within each N application rate as shown by two standard errors of the mean (**Figures 4-6**). Our results did not follow the paradigm that $\text{NO}_3\text{-N}$ concentrations in the soil profile increase with an increase of N application rate except in 2006 under ST, though these trends were not significant.

Zvomuya *et al.* [10] reported that nitrate leaching increased rapidly with increasing fertilizer N rate on coarse-textured soils. This paradigm may only apply to uniform and coarse textured soils that have homogeneous morphologies but not to heterogeneous field soils, clayey soils, soils with high spatial and vertical variability, and soils with preferential flow patterns and macroporous characteristics.

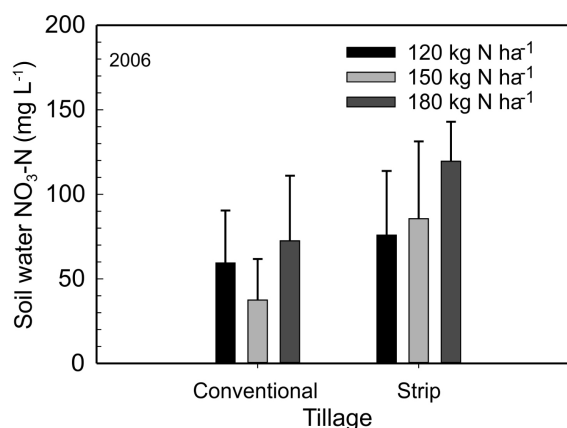


Figure 4. Effect of N application rates on average seasonal $\text{NO}_3\text{-N}$ concentration in soil water at a 76 cm depth under sugarbeet conventional tillage (CT) and strip tillage (ST) practices in 2006.

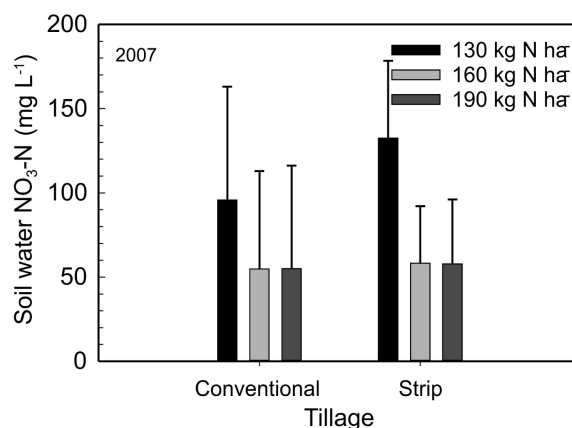


Figure 5. Effect of N application rates on average seasonal $\text{NO}_3\text{-N}$ concentration in soil water at a 76 cm depth under sugarbeet conventional tillage (CT) and strip tillage (ST) practices in 2007.

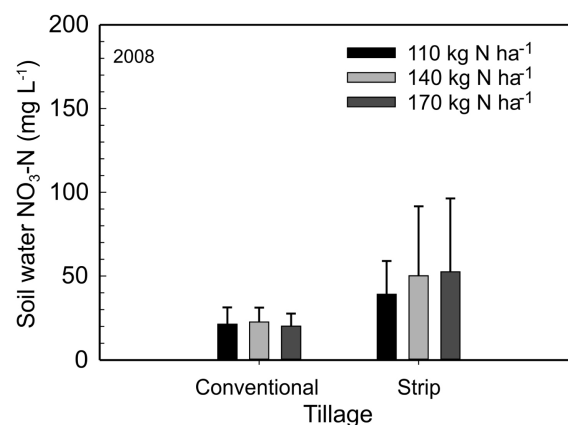


Figure 6. Effect of N application rates on average seasonal $\text{NO}_3\text{-N}$ concentration in soil water at a 76 cm depth under sugarbeet conventional tillage (CT) and strip tillage (ST) practices in 2008.

The soil variability among plots for each N rate likely had an impact on soil physical, chemical and biological properties that influenced water movement, N dynamics, and N transformation and losses. Variations in soil texture, internal drainage, water content, and porosity (Table 1 and Table 2) among field plots likely significantly impacted soil temperature and microbial activity which in turn affected soil N dynamics, N transformation and leaching.

Another possible reason of variability in $\text{NO}_3\text{-N}$ concentration in soil water could be associated with distribution of residue and organic matter from previous crops among plots across the field. Soil N mineralization tends to be higher in plots with high organic matter which in turn produce higher $\text{NO}_3\text{-N}$ transport than plots with lower soil organic matter. The amount of soil organic matter in the upper 30 cm averaged 2.67% with a CV = 34.9% ($n = 24$). The variability of soil organic matter among plots within

the study site was classified as medium ($CV = 15\% - 75\%$) according to Dahiya *et al.* [18].

Another possible factor that contributed to variability of NO_3 -N concentrations in soil water among plots within the same treatment is that NO_3 -N under each tillage system can be moved below the majority of the sugarbeet root zone with excess irrigation regardless of N application rate. Our overhead linear move sprinkler irrigation is a cutting-edge technology system with a high efficiency of 85% - 90% that applies water uniformly over an entire soil surface compared to furrow irrigation. Despite the uniformity of the irrigation system used in this study, some suction cup samplers could have received more water than others that resulted in spatially variable water applications that affected the transport of NO_3 -N by mass flow processes within the soil profile at the 76 cm depth.

Previous research revealed that suction cup water samplers provided useful data on solute concentration in soil water at various depths within the soil profile [22] [23]. However, those studies indicated that large variations existed in NO_3 -N concentrations in soil water among replications, illustrating the effect of soil variability when using suction cup lysimeters. Wang *et al.* [23] concluded that suction cups gave inconsistent and biased results of NO_3 -N concentrations in two of three soils used in their study, and they also showed that suction cups only worked well in fairly homogeneous soils.

Our results were in agreement with those summarized by Weihermuller *et al.* [22] and found by Wang *et al.* [23] who used suction cup lysimeters for measuring NO_3 -N concentrations in different soil types. Thus, suction cup lysimeters are likely unsuitable for measuring solute concentrations and transport in heterogeneous and heavy clayey soils that show high degrees of variability and preferential flow patterns.

4. Conclusions

Seasonal average NO_3 -N concentrations in soil water at the 76 cm depth under irrigated sugarbeet did not differ significantly between CT and ST practices for all three N application rates in 2006, 2007, and 2008 due to soil variability and heterogeneity across the field.

Soil variability among plots within each tillage treatment had a major impact on soil physical, chemical and biological properties that influenced water movement, N dynamics and concentrations of NO_3 -N in soil water at the 76 cm depth.

Variations in soil texture, internal drainage, water content, porosity, plant residues and other properties among field plots can significantly impact soil temperature and microbial activity which sequentially affect soil N dynamics, NO_3 -N concentrations and losses.

The findings from this study concur with those from previous research studies that illustrate the limited capabilities of suction cup lysimeters used for monitoring and quantifying NO_3 -N concentration in soil water at various depths in the profile of heterogeneous soils with preferential flow and macropore characteristics. Further research is needed to evaluate the use of suction cup samplers in a broader range of soil types

and cropping systems.

The three N rates used in this study under CT and ST practices for three growing seasons maintained NO₃-N concentrations in soil water below the root zone to levels exceeding the EPA safe drinking water standard of 10 mg L⁻¹.

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Statement

Mention of a trademark, vendor or proprietary product does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that may also be suitable. This type of information is solely provided to assist the reader in better understanding the scope of the research and its results.

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