# Subirrigation System Performance and Evaluation in the Red River Valley of the North

X. Jia, T. F. Scherer, D. D. Steele, T. M. DeSutter

**Abstract.** *Using a subsurface drainage system, subirrigation (SI) applies water below the ground surface and raises the phreatic water to within or near the root zone. SI is relatively new to the Red River Valley (RRV) of the North in eastern North Dakota (ND) and west central Minnesota (MN). In 2011, two SI field sites in the RRV were installed and have shown promising results in optimal water management and increasing agricultural production. Unlike a surface irrigation system, SI supplies water below the ground surface over a long duration; water loss is generally through crop transpiration; and SI leads to negligible water loss via wind, surface runoff and evaporation. Therefore, a new method was developed to evaluate the SI system performance. Water application efficiency ($E_a$) was calculated through the soil moisture changes in the root zone before and after the SI application with known amounts of SI, precipitation, and evapotranspiration (ET). Uniformity coefficient (UC) and distribution efficiency of low quarter (DULQ) were estimated from the total depth of water stored in the root zone. The SI system performance in 2014 and 2015 showed that the $E_a$ was over 100% in 2014 and 78% for the ND 2015 site-year. The $E_a$ values were high, indicating that the SI system either performed better than typical surface irrigation systems with minimal water loss, or the SI system and/or the methods need improvement in accurate ET estimation to help close the water budget. The UCs were 67% to 86%, and the DULQs were 48% to 78%, much lower than typical sprinkler and surface irrigation systems, possibly due to the unique SI flow path. Overall, the evaluation indicated that a SI system is effective as a water supply, but the uniformity needs to be improved with a longer SI duration or smaller flow rate or an alternative SI system design.*

***Keywords.*** *Red River Valley of the North, Subirrigation, Uniformity, Water use efficiency.*

Subirrigation (SI) is defined as the "application of irrigation water below the ground surface by raising the water table to within or near the root zone" (*ASABE Standards*, 2015). In agriculture, SI is also known as seepage irrigation, which brings the water level to the root zone from below the soil surface through open surface ditches. Seepage irrigation is very common in Florida vegetable areas (Pitts and Clark, 1991). In greenhouse environments, SI is commonly applied to potted plants through capillary rise with a high uniformity and minimal nutrient loss (Schmal et al., 2011). In recent years, SI has become an important part of drainage water management strategies by irrigating fields using a subsurface drainage system and flow control devices. The combination of controlled drainage and subirrigation in a typical subsurface drained field provides an optimal soil water regime for better crop production. Yield increases of 11% for tomatoes (*Solanum lycopersicum*) and 64% for corn (*Zea mays*) were observed in a field study in Ontario, Canada (Tan et al., 1999), while Allred et al. (2003) saw yield increases of 34.5% and 38.1% for corn and soybeans (*Glycine max*), respectively, during drier growing seasons. Wetland reservoir SI systems in Ohio (USA) have the potential for yield increases, however SI is not widely used, possibly due to lack of an adequate water supply and difficulty in managing the SI system (Horntvedt et al., 2013; Kolars, 2016). While Kolars (2016) has developed a modified checkbook method to manage a SI field using a water balance approach, questions remain on how to evaluate an SI system, such as the application efficiency and distribution uniformity of the water in the field.

The uniqueness of an SI system makes it difficult to evaluate its performance using any of the existing methods applicable to above or below ground irrigation. In addition, once the water is delivered to the field through drain pipes, water movement from the pipe to the soil is much slower than surface irrigation water movement because water is flowing horizontally and upward through capillary forces. Therefore, as an irrigation method that has been practiced for several decades, it is still difficult to categorize the SI method into any of the existing irrigation methods, but more often, it is included in the subsurface drainage section as one way to manage the subsurface water. When the drainage system is in place, SI is less expensive and more efficient to

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irrigate a crop if a reliable water resource is available and the field is suitable for SI (Horntvedt et al., 2013). In general, SI is preferred for fields with less than 0.5% slope, has a drainage control, and a suitable water source [low soluble salts and sodium (Na)] (Belcher, 2005). Though SI may be needed for a short period of time during the growing season, the economic return is promising. SI has benefits such as reduced evaporation and salt accumulation in the root zone, zero runoff, less energy costs than a pressurized system, and low maintenance requirements compared to drip and center pivot sprinkler systems. Nevertheless, with all these benefits, SI is not widely utilized (Jia et al., 2016).

There are multiple ways to evaluate an irrigation system depending on the purpose of the evaluation. For the SI system in our study, our concerns are on improving crop production and profitability after the water is delivered into the field. With no previous studies on evaluating the SI system performance, we attempted to use any existing methods to fit what is appropriate for the SI system. This incorporates the understanding of where the water goes and how much is used by crops for production purposes. Once the water is delivered into the field, the majority of it was assumed to be used for crop water consumption and soil water storage, with minimal seepage and deep percolation and no runoff. Because of the additional water applied to the crop, the crop water consumption should be enhanced, or at least higher than fields without irrigation. If the evapotranspiration rate is measured in the irrigated field, it can be used to represent the field water usage. However, when actual ET was not measured, if other data, such as soil moisture or water table data were measured, the water consumption can be estimated indirectly (Yang et al., 2007; Kolars, 2016).

Considering the entire soil profile as a control volume in the soil, one can evaluate system performance through a water balance approach. For this approach, seepage and runoff portions can be ignored and the evapotranspiration can be used to assess system performance using the soil water changes before and after an SI event. In this article, we will examine the application of the water balance method to determine SI application efficiency and distribution uniformity for two SI systems in the Red River Valley (RRV) of the North in eastern North Dakota and west central Minnesota.

## Materials and Methods

### Locations

The experiments were conducted in two fields in the RRV; one located in west central MN (46°59’15.80”N, 96°41’1.95”W), the other in southeast ND (46°00’38.27”N, 96°35’56.80”W) (fig. 1). At the MN location, the field area was 16.6 ha, with a Bearden silt loam (fine-silty, mixed, superactive, frigid Aeric Calciaquolls; 50% of the total area, 0-0.1% slope), an Overly silty clay loam (fine-silty, mixed, superactive, frigid Pachic Hapludolls; 27% of the area, 0-0.1% slope), and a Colvin silty clay loam (fine-silty, mixed, superactive, frigid Typic Calciaquolls; 23% of the area, 0-0.1% slope). At the ND location, the field area was 21.8 ha, with Antler silt clay loam (fine-loamy, mixed, superactive, frigid Aeric Calciaquolls,; 48% of the total area, 0-0.1% slope,), Antler-Mustinka silty clay loams (Antler: fine-loamy, mixed, superactive, frigid Aeric Calciaquolls; Mustinka: fine, smectitic, frigid Typic Argiaquolls; 42% of the total area, 0-0.1% slope), and Doran clay loam (fine, smectitic, frigid Aquertic Argiudolls; 10% area, 0-0.1% slope). The impermeable layer at the MN site was at a depth of about 3 m, while at the ND site, the impermeable layer depth was at 2 m. The field slopes were obtained from topographic maps and the soil coverage area from the Web Soil Survey (NRCS, 2016).

### Field Layouts

The tile drainage and SI systems in the MN field were installed in fall 2009 with 12.2 m spacing, tile depth of 0.91 m on a 0.1% grade, and a drainage coefficient of 9.5 mm/day. The design was a modification from a standard SI system by using a 7.6 cm diameter rather than a typical 10.2 cm diameter drain tile in order to lower the installation cost (Horntvedt

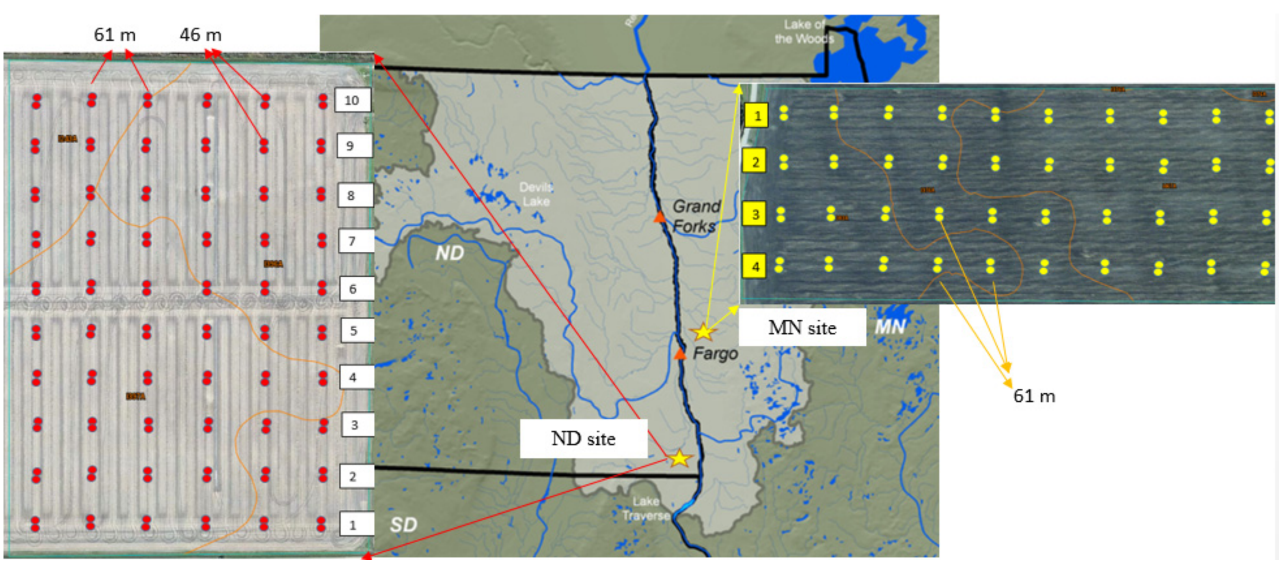


**Figure 1. Experimental locations at the ND and MN sites in 2014 and 2015. The red dots at the ND site indicate the sampling locations at 61 × 46 m grid. The yellow dots at the MN site indicate the sampling locations at 61 × 61 m grid. The curved orange lines represent soil types.**

et al., 2013). Due to the smaller size of the lateral and flat topography that resulted in smaller and slower flow, a second main was installed at the higher elevation (east) end of the field for SI water delivery purposes only. Therefore, the SI and the drainage water followed the same flow path and direction, but at different times of the season. The tile drainage system was laid out in an east-west direction, and the main for drainage was on the west edge of the field. A controlled drainage structure was installed near the northwest corner of the field, next to a legal drainage ditch. The irrigation water delivery main on the east side of the field was 15.2 cm diameter corrugated non-perforated pipe. The irrigation delivery main was 0.6 m higher in elevation from the north to south. A storage tank
3.6 m tall and 2.6 m in diameter with a 20 $m^3$ capacity was installed to provide enough head for water delivery and served as a temporary storage for the SI water. During a subirrigation event, the water level in the tank was maintained at 2.1 m above ground level. This was enough head to overcome the elevation and pipe friction loss for the required flow rate (12.6-25.2 L/s).

The tile drainage system for the ND field was installed in 2002. With potential SI in mind, the sump pump was designed to carry the water for the entire 44 ha field with typical 18.3 m tile drainage space. From our preliminary studies (Scherer and Jia, 2010; Jia et al., 2012; Rijal et al., 2012), it was concluded that it was challenging to subirrigate the entire field with one main drain due to the high surface elevation difference across the field and the layout of the tile drainage system. As indicated by Jia et al. (2012), the sump pump and the main were located at higher elevations than the laterals because of the outlet location. In addition, the wide tile spacing created a wave growth pattern for soybean in 2010 as reported by Horntvedt et al. (2013). Therefore, the entire field was converted in fall 2011 to SI with the addition of a lateral with a diameter of 10.2 cm, drain depth 1.1 m on a 0.14% grade, spaced 9.1 m apart. In addition, a second main and lift station were installed for the west half of the field (Horntvedt et al., 2013). During SI, well water was pumped directly into the sump. Water levels in the sump came to approximately 1.13 m below ground surface where it then flowed by gravity into the main and laterals from east to west. With a 0.14% slope on the laterals, the water flowed about 325 m into the field. Water was uniformly distributed across the field according to the measured water table data when a proper water level in the sump was maintained for SI requirement (Jia et al., 2012).

### Subirrigation Systems

Water supply for the SI system at the MN site was obtained from the legal drainage ditch that collected and transported surface and subsurface runoff water from a 36 $km^2$ area east of the site. The water was pumped from the bottom of the ditch. A float device turned off the pump if the water level in the ditch dropped too low, about 1.0 m from the bottom of the ditch. The elevation difference from the bottom of the ditch to the top of the tank was 10.4 m. The flow rate to the field was controlled by the water level in the tank, which normally was held at about 2.1 m above the ground surface. The flow rate and total volume delivered to the field were measured with a propeller meter (McCrometer, Hemet, Calif.) located in the delivery pipe. A current sensor in the pump control panel measured pump activity for the entire irrigation period.

The SI water for the two sumps at the ND site was supplied by four wells, two wells for one sump, pumping rate was 6.3 L/s (100 gpm) for each well (Jia et al., 2012). The total flow rate supplied to each sump was 12.6 L/s (200 gpm). The flow rate of the SI was measured with an inline flowmeter and water level sensors. In general, the water level in the sump (higher ground surface) was maintained between 1.13 and 1.44 m below the soil surface in order to keep the water table between 0.61 and 0.92 m below the soil surface at the lower corner of the field (lower ground surface) due to a 0.72 m surface elevation difference between the sump and the field. In addition, due to concerns about secondary soil salinity and potential enhanced evaporation, the water table was kept below 0.61 m near the soil surface (Kruse et al., 1993).

### Soil Water Content Sampling

Soil samples were collected on a grid (61 × 61 m for the MN site and 46 × 61 m for the ND site) across the entire field (fig. 1). Two soil sampling sites were in each grid, one over the tile line and the other at the midpoint between two tile lines. Three soil samples were taken (15, 46, and 76 cm depth) at each grid location, one day before and one to two days after completion of the SI event. For the MN site, 480 soil samples were collected in 2014, and for the ND site, 720 soil samples were taken in both 2014 and 2015. To avoid human error, the same two-person team sampled soil at the same locations before and after the SI event. The mass based soil water contents were measured at three depths, 15, 46, and 76 cm at each location. Considering the sampling point as the middle point of the soil samples, with 30.5 cm depth representing each of the three layers, the total depth for three soil samples came to 91.5 cm. This depth was slightly shallower than the actual root zone, particularly for the ND site where the drain depth is about 1.1 m. However, it is the maximal depth that a manual auger can reach for clayey soils in our situation. The soil samples were sealed in double plastic bags and kept in a cooler before determination of gravimetric soil water content (g/g). Soil bulk density was obtained from Web Soil Survey data for the major soils in the field (NRCS, 2016). The mass based soil water content was multiplied by the bulk density of the soil layer to obtain volumetric water content ($cm^3/cm^3$).

### Subirrigation System Evaluation Methods

#### *Water Application Efficiency*

Surface irrigation water application efficiency ($E_a$) is defined as water stored in the soil root zone after irrigation versus water delivered to the area being irrigated (Huffman et al., 2011). The water application efficiency equation for the surface irrigation method is:

$$E_a = \frac{W_s}{W_d} 100 \tag{1}$$

where

$W_s$ = depth of water stored in the soil root zone due to irrigation,

$W_d$ = depth of water delivered to the area being irrigated.

In this equation, the $W_s$ term has already accounted for water loss through deep percolation or runoff for a surface irrigation event. However, to complete a SI event, it takes several days to weeks. The loss of water through ET cannot be ignored as in the surface irrigation system. If we assume that ET is lost from the soil water storage, the calculated depth of water stored in the root zone, $W_s$, can be estimated as soil water storage plus ET. Similarly, the $W_d$ term should consider precipitation amounts during the SI application. Therefore, equation 1 is modified for the SI $E_{a+ET}$ calculation as:

$$E_{a+ET} = \frac{(S_2 - S_1) d_z + ET}{I + P} 100 \tag{2}$$

where

$S_2$ = soil moisture content after the SI application ($cm^3/cm^3$),

$S_1$ = soil moisture content before the SI application ($cm^3/cm^3$),

$d_z$ = root zone depth in mm for where the soil moisture content was measured,

ET = total depth of evapotranspiration in mm during the SI period,

I = SI amount in mm delivered to the field,

P = precipitation amount in mm during the SI period.

The actual ET was either measured directly in the SI fields, or obtained from crop water usage based on location, crop type, and the emergence date (NDAWN, 2016), or adjusted from reference ET but based on water table and soil moisture changes in the field using procedures proposed in Kolars (2016) and Yang et al. (2007). The precipitation was measured by a standard rain gage at the site.

If we consider the ET as a loss from the precipitation and subirrigation, equation 1 can be written as:

$$E_{a-ET} = \frac{(S_2 - S_1) d_z}{I + P - ET} 100 \tag{3}$$

If the efficiency is 100%, there will be no difference between equation 2 and 3. However, equation 2 considers ET as a loss of water from the root zone storage, while equation 3 considers ET as a loss of effectiveness of water from reaching root zone.

### *Uniformity*

After the water is delivered into the field, it is important to understand its uniformity across the field. The uniformity coefficient (UC) is typically used for sprinkler irrigation, but modified here to represent the depth of water stored plus the ET in the field while assuming that ET is uniform across the field. It is expressed as:

$$UC = 1 - \sum_{i=1}^{n} \frac{|y_i - d|}{n} / d \tag{4}$$

where

$y_i$ = measured $[(S_2 - S_1)d_z + ET]$ depth of water stored due to SI plus ET (mm),

d = average $[(S_2 - S_1)d_z + ET]$ depth of water stored in the root zone due to SI plus ET (mm),

n = number of samples collected.

For surface irrigation, distribution uniformity low quarter (DULQ) can be calculated as:

$$DULQ = \text{average low-quarter depth} / \text{average depth} \tag{5}$$

The average $[(S_2 - S_1)d_z + ET]$ depth of water is the amount of water stored in the root zone due to SI, plus ET during the SI event, while the low quarter are the lowest ¼ values among all the samples plus ET. Since the soil sampling took an entire day to accomplish, half of the ET on the first day and last day between soil water measurements were used as the ET for the calculations.

### Evapotranspiration

Corn was grown at the ND site and soybeans at the MN site in 2014. In 2015 soybeans were planted at the ND site. Crop emergence was on 26 May 2014 and 18 May 2015 at the ND site, and 29 May 2014 for the MN site. From the available information, the crop water use (or ET) for the SI testing period was estimated as 49 mm at the MN site in 2014 (beginning pod to full pod stages for soybean), and 50 mm in 2014 (12$^{th}$ to 13$^{th}$ leaf stages for corn) and 52 mm in 2015 (beginning seed to full seed stages for soybean) at the ND site based on the procedures listed in NDAWN (2016). The ET was calculated using the modified Jensen-Haise equation (Jensen and Haise, 1963) and crop coefficient curves developed by Stegman et al. (1977). Practically, the SI was not required in 2015 at the ND site, but was applied for the SI testing purpose.

## Results and Discussion

### Climate Conditions

SI testing was conducted for 10 days (8-18 July) in 2014 and for 20 days (21 August - 10 September) in 2015 at the ND site. At the MN site, the field was subirrigated for 9 days from 28 July to 6 August in 2014. The weather conditions during the testing are shown in table 1. Data collected by the North Dakota Agricultural Weather Network (NDAWN, 2016) was taken from the Fargo, ND station for the MN site, and the Wahpeton, ND, station for the ND site.

### Soil Bulk Density

Soil bulk density and total available water for the soil layers were obtained from the Web Soil Survey and the results are listed in table 2 (NRCS, 2016).

The corresponding bulk density was used for each soil sample according to its location and depth during the calculation of volumetric water content from mass based water content. The orange lines behind the sampling grids on figure 1 separate the soil types and delineate the area of the bulk density for each soil sample.

Table 1. Weather conditions during the subirrigation evaluation period at the ND site in 2014 and 2015, and the MN site in 2014.[a]

| | Dates | $T_{max}$ (°C) | $T_{min}$ (°C) | $T_{avg}$ (°C) | $T_{soil}$ (°C) | Wind (m/s) | $R_s$ (MJ/m$^2$) | PET (mm) | P (mm) | $T_{dew}$ (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| ND, 2014 | 7/8 – 7/18 | 31.8 | 8.1 | 19.6 | 23.2 | 3.9 | 23.6 | 60.6 | 4.1 | 11.8 |
| ND, 2015 | 8/21 – 9/10 | 33.3 | 4.6 | 19.6 | 21.9 | 3.2 | 16.0 | 76.9 | 13.5 | 15.0 |
| MN, 2014 | 7/28 – 8/6 | 30.0 | 10.7 | 20.2 | 23.1 | 2.0 | 20.0 | 47.9 | 2.9 | 13.8 |

[a] The parameters are average or total values for the entire sampling period, with $T_{max}$ = maximum daily air temperature, $T_{min}$ = minimum daily air temperature, $T_{avg}$ = average daily air temperature, $T_{soil}$ = bare soil temperature, Wind = average daily wind speed, $R_s$ = average daily incoming solar radiation, PET = total potential evapotranspiration amount by Jensen-Haise method, P = total precipitation amount, and $T_{dew}$ = average daily dew point temperature.

Table 2. Soil bulk density ($\rho_b$) and total available water (TAW) in the soil layer (NRCS, 2016).

| | | 0-30 cm | | 30-60 cm | | 60-90 cm | |
|---|---|---|---|---|---|---|---|
| Site | Soil Type | $\rho_b$ (g/cm$^3$) | TAW(cm) | $\rho_b$ (g/cm$^3$) | TAW (cm) | $\rho_b$ (g/cm$^3$) | TAW (cm) |
| | Bearden silt loam | 1.32 | 6.6 | 1.35 | 5.4 | 1.35 | 5.4 |
| MN | Overly silty clay loam | 1.31 | 6.0 | 1.35 | 5.4 | 1.35 | 5.4 |
| | Colvin silty clay loam | 1.25 | 6.0 | 1.34 | 5.4 | 1.37 | 5.4 |
| | Antler silt clay loam | 1.35 | 5.1 | 1.4 | 5.4 | 1.43 | 4.8 |
| ND | Antler-Mustinka silty clay loam | 1.35 | 5.1 | 1.4 | 5.4 | 1.43 | 4.8 |
| | Doran clay loam | 1.37 | 5.4 | 1.48 | 4.8 | 1.55 | 4.5 |

### SOIL WATER STORAGE

Soil water contents results for each sampling date ($S_1$ or $S_2$) were comprised of averages from three layers at two spots, for each grid location. The changes in soil moisture ($S_2$-$S_1$) are shown in figure 2a for the MN site in 2014, figure 2b for the ND site in 2014, and figure 2c for the ND site in 2015.

Changes in soil water did not go in one direction spatially across the entire field, i.e., some spots became drier and others wetter after the SI application. We initially thought this might be due to topographic differences where lower elevation spots resulted in higher moisture conditions. However, statistical analysis of the points in relation to elevation showed no correlations. Therefore, the differences may be

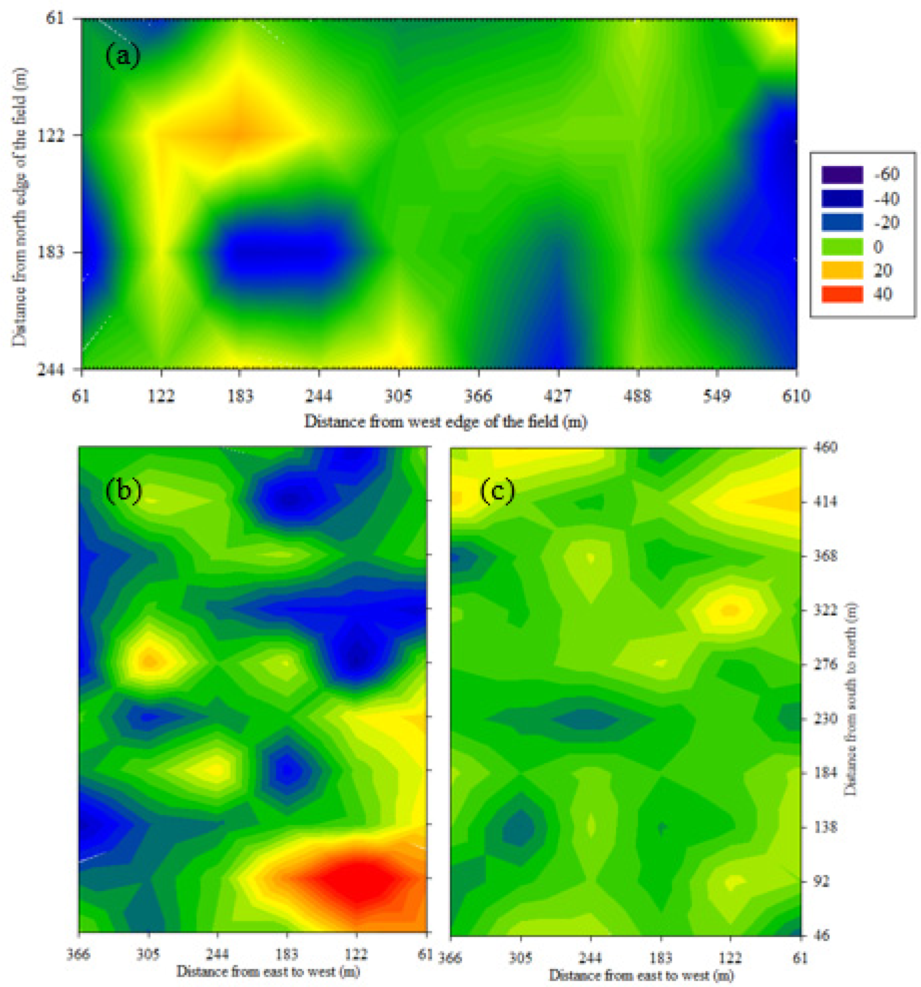


Figure 2. Average change in soil water storage ($S_2$-$S_1$) as depth of water in millimeter in the root zone for (a) the Minnesota site in 2014, (b) the North Dakota (ND) site in 2014, and (c) the ND site in 2015.

caused by the distance on the flow path; however, areas closer to the source of irrigation water, such as the east side of both fields, did not result in higher soil water conditions after the SI. Instead, the downstream end of the SI system showed a slightly higher soil water content increase, which implied that the water moves faster inside the pipe than water movement from the drain line to the soil.

### WATER APPLICATION EFFICIENCY

The water application efficiency was calculated from equation 2 and 3 for different ways to consider the ET effects. The results for the three site-years are summarized in table 3.

The results showed that using equation 2, the $E_{a+ET}$ was 103%, 122%, and 78% for the MN 2014, ND 2014, and ND 2015 site-years, respectively (table 3). In general, a higher $E_{a+ET}$ implied a better water delivery system. However, $E_{a+ET}$ above 100% indicates possible inaccurate measurements. This could be due to overlooking the upward flux from the shallow ground water (Yang et al., 2007), overestimation of crop ET (Rijal et al., 2012), or non-uniformity of ET and rain distribution in the field. This could also be caused by inaccurate measurement of soil bulk density and soil water contents.

If no change in soil water between the two sampling periods occurs, $E_a$ can have negative values when using equation 3. We may need more precise soil water measurement methods or need to do the uniformity test before or after the growing season so that ET and upward moisture flux do not interfere with the calculations. In 2015, the ND site was subirrigated when the soil water was initially high and precipitation occurred during the SI period, which would lead to less $E_{a+ET}$ while water loss through deep seepage or runoff were not measured. $E_{a-ET}$ values using equation 3 were 88%, 50%, and -42% for the MN 2014, ND 2014, and ND 2015 site-years, respectively (table 3). The $E_{a-ET}$ for the ND 2015 site-year was a negative value, implying a probable source of error in the calculation. As we know that the SI duration was much longer for the ND site in 2015, the $E_{a+ET}$ also showed a reasonable and dissimilar value (78%) compared to the other two site-years (103% and 122%, respectively), similar to the $E_{a-ET}$ method.

The soil water storage was measured to 0.91 m depth for the root zone. This is valid for surface irrigation method in which irrigation water would wet the top of the root zone first. However, the SI flow path was completely different from any existing irrigation method. When SI flows into the field, it comes from a point source, then flows into a main tile line and later into the laterals. From the small holes along a lateral tile line, water can either flow into the soil in vertical and horizontal directions, or be drawn out to the soil through capillary rise and crop root uptake. The water would flow downward and fill up the soil layer below the tile first, and then bring the moisture to the root zone. To consider all water storage due to SI, soil sampling down to the restrictive layer might be needed, but in reality, it would be difficult to obtain by hand. Since the contribution from a shallow water table to the root zone did occur, the measurement of water table changes and its contribution to the storage and ET should also be included in the future studies. We may have to calculate $E_a$ for each day between the soil sampling dates to account for the rise of the water table during the irrigation event. Estimating the efficiency of application for SI is difficult and we may have to reexamine how it is calculated or reformulate the equation.

**Table 3. Water balance components used in subirrigation performance evaluation.**

| | Site and Year | | |
|---|---|---|---|
| Water Balance Component<br>Measurement Period | MN 2014<br>28 July to<br>6 Aug | ND 2014<br>8 to<br>18 July | ND 2015<br>21 Aug to<br>10 Sept |
| Evapotranspiration (mm) | 49 | 50 | 52 |
| Precipitation (mm) | 0 | 0 | 9 |
| Subirrigation (mm) | 38 | 35 | 52 |
| Application efficiency (%) (eq. 2) | 103 | 122 | 78 |
| Application efficiency (%) (eq. 3) | 88 | 50 | -42 |
| Uniformity coefficient (%) (eq. 4) | 72 | 67 | 86 |
| Distribution uniformity low quarter (%) (eq. 5) | 53 | 48 | 78 |

### UNIFORMITY COEFFICIENT

The uniformity coefficient was calculated from equation 4, in which the average depth of water stored in the root zone was calculated from the average of two locations. The SI UC was 72%, 67%, and 86% for the MN 2014, ND 2014, and ND 2015 site-years, respectively (table 3). The SI system UC was close to the acceptable range (water was applied from below the surface). A sprinkler system is considered acceptable with a UC of 80% (Huffman et al., 2011). There was no observed difference in crop growth due to lower uniformity coefficient. A longer SI duration in ND in 2015 led to a higher UC, which implied that a longer time is needed for the soil water to equilibrate itself across the drains during an SI application.

### DISTRIBUTION UNIFORMITY LOW QUARTER

The DULQ was calculated using equation 5, where water depth totals taken in the root zone were averaged for the two locations, in each grid location (over the drain and equidistant between two drains). The DULQ was 53%, 48%, and 78% for the MN 2014, ND 2014, and ND 2015 site-years, respectively (table 3). For a surface irrigation system, 70% DULQ is considered an acceptable value (Huffman et al., 2011). Our measurements showed the DULQ was below the acceptable range when the SI duration was short. However, with the longer SI duration through the ND 2015 site-year, the DULQ was 78% and above the acceptable range.

Comparison of Water Application, Uniformity, and DULQ efficiencies indicates that when the $E_{a+ET}$ (eq. 2) was low in the ND 2015 site-year, the UC and DULQ (using depth of water stored values plus ET) were high. The reverse is true for the other two site-years, where a higher $E_{a+ET}$ resulted in lower UC and DULQ values using the depth of water stored plus ET. An optimal SI system should have a higher $E_a$ and higher UC and DULQ. When the SI application was too fast, there would not be a sufficient amount of water to meet the ET demand.

### ACCURATE ET ESTIMATES

With limited measured ET data for all three site years, the MN 2014 site-year was used as an example to examine whether an accurate ET estimate can improve the SI performance evaluation. Three additional methods for the ET estimates, namely Rijal et al. (2012), Kolars (2016), and eddy covariance, were used to evaluate the SI system performance. Table 4 shows the details of the performance with different ET estimates.

New corn and soybean crop coefficients were developed for southeastern ND by Rijal et al. (2012) using eddy covariance calculated ET and ASCE-EWRI alfalfa reference method for reference ET (Allen et al., 2005). Total ET was estimated to be 34 mm using the monthly soybean crop coefficients of 0.76 and 0.66 from the July and August testing period. This ET is 15 mm less than the ET of 49 mm from the NDAWN method, and resulted in values of 65%, 56%, and 25% for $E_{a+ET}$, UC, and DULQ, respectively. An eddy covariance system was installed in the testing field (Kolars et al., 2013; Kolars, 2016). Using the measured ET, 52 mm, during the testing period, the SI system had values of 111%, 74%, and 56% for $E_{a+ET}$, UC, and DULQ, respectively.

Kolars (2016) used procedures proposed in Yang et al. (2007) to estimate the ET based on soil water content and water table changes. Soil water content was measured up to 0.9 m, water table was measured every 30 min (1.28 m below surface at the beginning and 1.03 m at the end of the SI process), ET was estimated to be 46 mm. Using this ET value of 46 mm, the SI system had values of 96%, 70%, and 50% for $E_{a+ET}$, UC and DULQ, respectively.

The eddy covariance method used as a standard method for ET estimates overcomes the difficulty of ground measurement of ET, particularly in areas with shallow water tables (Farahani et al., 2007; Jia et al., 2009). When the application efficiency exceeds 100%, one can expect to balance the water budget to obtain 100% efficiency by either mathematically increasing the SI amount, or by mathematically lowering the ET rate to a hypothetical or preferred value. In this site-year, the preferred ET value was 48 mm as seen in table 4.

One may consider the upward flux from the shallow water table as another source of water for crop consumption. However, Kolars (2016) only considered the upward flux equivalent to the subirrigation amount instead of two separate sources (upward flux plus subirrigation). The total SI amount was measured as 38 mm, while the upward flux based on water table and soil moisture changes was 32 mm for the 28 July to 8 August MN 2014 testing period. The 6 mm difference is probably due to measurement errors or location points of measurement, since SI was measured at the pipe inlet before entering the field, whereas upward flux was estimated at the center of the field. With the similarity between the two values, we believe that using only one water source, such as the SI value measured at the inlet, is relevant for the study.

# Conclusion

Subirrigation is a relatively new irrigation method, which has potential to be applied in major subsurface drained areas. Its system performance was evaluated on two fields in ND and MN using measured soil water storage in the root zone from a subirrigation event. The results showed that water application efficiency calculated from the soil water storage plus ET was 103%, 122% and 78%, the uniformity coefficient was 72%, 67%, and 86%, and the distribution uniformity of low quarter was 53%, 48%, and 78% for the MN 2014, ND 2014, and ND 2015 sites, respectively. The high water application efficiency implied that the crop used all subirrigation water. However, some measurement errors, such as overestimation of ET and ignoring upward flux from shallow ground water, should be addressed in future studies. The formula to calculate the water application efficiency may have to be reformulated to account for the influence of water table depth changes during an irrigation event. The lower uniformity and distribution coefficients were not surprising because subirrigation water was supplied from a point to a line source. In summary, detailed evaluations indicate that subirrigation systems are an effective water supply, and uniformity can be improved if longer irrigation durations or slower flow rates are used.

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**Table 4. Subirrigation performance evaluation for MN 2014 site year (28 Jul-6 Aug 2014) calculated by four evapotranspiration (ET) methods: North Dakota Agricultural Weather Network (NDAWN), Rijal et al. (2012), Kolars (2016), Eddy Covariance, and preferred ET.**

| | ET Method | | | | |
|---|---|---|---|---|---|
| Evaluation | NDAWN[a] | Rijal et al. | Kolars | Eddy Covariance | Preferred[b] |
| Evapotranspiration (mm) | 49 | 34 | 46 | 52 | 48 |
| Application efficiency (%) (eq. 2) | 103 | 65 | 96 | 111 | 100 |
| Application efficiency (%) (eq. 3) | 88 | -215 | 117 | 70 | 100 |
| Uniformity coefficient (%) (eq. 4) | 72 | 56 | 70 | 74 | 71 |
| Distribution uniformity low quarter (%) (eq. 5) | 53 | 25 | 50 | 56 | 51 |

[a] NDAWN values were used in the efficiency calculations.

[b] Preferred ET = ET value required to achieve both $E_a$ values in equation 2 and 3 equal to 100%.

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