# SUBSURFACE DRIP IRRIGATION SYSTEMS FOR SPECIALTY CROP PRODUCTION IN NORTH DAKOTA

D. D. Steele, R. G. Greenland, B. L. Gregor

**ABSTRACT.** *Subsurface drip irrigation (SDI) systems offer advantages over other types of irrigation systems for specialty crop production, including water savings, improved trafficability, and a drier canopy. This study was conducted to evaluate the performance of SDI, placed at 1.2-m (4-ft) lateral spacing and buried at 0.28-m (11-in.) depth, in a subhumid climate with severe winters. Effects on crop yield and crop quality of tape design (from five manufacturers) and position along 152-m (500-ft) lateral runs were investigated for three consecutive years on a sandy loam soil near Oakes, N. Dakota. In 1993, marketable and total sweet corn yields averaged 13.9 and 14.9 Mg ha*$^{-1}$ *(6.20 ton ac*$^{-1}$ *and 6.65 ton ac*$^{-1}$*), respectively. In 1994, U.S. No. 1, U.S. No. 2, and total yields for winter squash were 17.7, 6.8, and 31.9 Mg ha*$^{-1}$ *(7.90, 3.03, and 14.23 ton ac*$^{-1}$*), respectively. In 1995, the cabbage yield averaged 98 Mg ha*$^{-1}$ *(43.7 ton ac*$^{-1}$*). Yields were measured at three transects [approximately 17, 76, and 136 m (56 ft, 250 ft, and 446 ft) from the upstream ends of the drip laterals] to determine effects of tape design on water distribution and corresponding yield. Yields did not differ statistically between designs for any transect in any year. Measured emitter discharge rates decreased dramatically with distance downstream from the start of the tape. This was attributed to friction losses in the tape, deformation of the normally circular cross-section of the tape by winter conditions, soil compaction from tillage operations, and calcium deposits. Subsurface drip irrigation tape appears durable enough to withstand winters in the northern Great Plains for multiple-season use, provided proper installation and maintenance procedures are followed.*

***Keywords.*** *Trickle, Sweet corn, Winter squash, Cabbage.*

Properly designed and installed drip irrigation systems can apply water more efficiently and uniformly than surface and sprinkler irrigation methods. This is partly because in a drip irrigation system, the distance from the point of water discharge to the point of water consumption is smaller than that for either surface or sprinkler irrigation systems. Hence the losses and inefficiencies associated with surface and sprinkler systems, such as atmospheric conditions and the macroscopic spatial variability of soil infiltration rates, are reduced or eliminated (Keller and Bliesner, 1990).

By providing dry soil surface and crop canopy conditions, subsurface drip irrigation (SDI) systems have disease prevention advantages for certain crops (Brown et al., 1991), when compared to sprinkler and above-ground drip irrigation systems. The drier soil surface associated with SDI systems also offers the advantages of smaller evaporative water losses; higher infiltration rates for natural precipitation, thereby reducing runoff and erosion; and improved trafficability.

The characteristics, design, installation, operation, and maintenance of drip irrigation systems have been extensively documented in the literature (e.g., Howell et al., 1983; Cuenca, 1989; Karmeli and Keller, 1975; Keller and Bliesner, 1990; James, 1988). Much literature is also available on the management of irrigation systems (e.g., Hoffman et al., 1990). The literature on irrigated production of vegetable crops is also extensive (e.g., Stanley and Maynard, 1990) for other states, but relatively little information has been compiled on the production of vegetable crops, or more generally, *high-value* crops, for North Dakota (Lee et al., 1995). Irrigation will be required for profitable production of many high-value crops in North Dakota due to the climate and soil types present. Drip irrigation may be a viable method of irrigation for North Dakota.

Conversion to drip irrigation from other irrigation methods may save water, which is in short supply in some areas of North Dakota (Scherer, 1995). Despite this advantage, little drip irrigation is used in North Dakota. Irrigation statistics (Anon., 1995) show that North Dakota has about 65 700 ha (162,400 ac) of sprinkler irrigation and about 18 400 ha (45,500 ac) of surface irrigation, but only about 40 ha (100 ac) of drip irrigation [26 ha (65 ac) of surface and 14 ha (35 ac) of subsurface drip installed]. If drip irrigation of windbreaks in western North Dakota is included, the drip irrigation total is still less than about 81 ha (200 ac) (Scherer, 1995).

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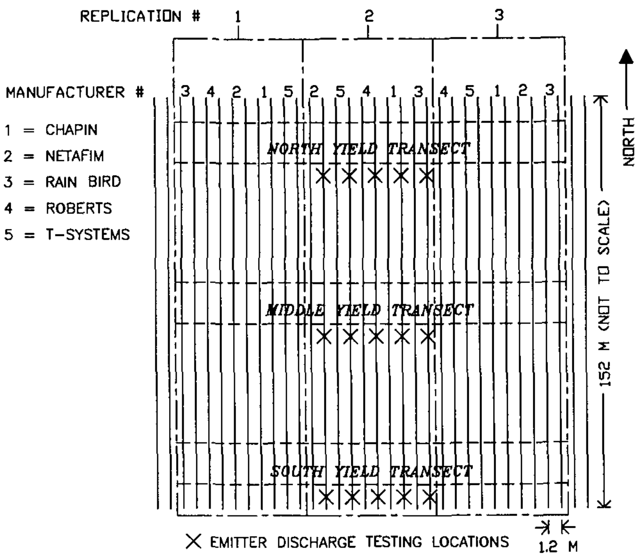

**Figure 1–Experimental layout of the subsurface drip irrigation system. Yield measurements were taken within each of the yield transects.**

Factors contributing to the low use of drip irrigation in North Dakota include: lack of exposure to drip irrigation systems; uncertainty about costs, durability, life span, installation, management practices, etc.; the management and maintenance intensity; and the lack of information for North Dakota on crop yield, water use, and pest problems. In order to address these issues, an SDI experiment was initiated in 1993 with the following objectives to: (1) determine the agronomic and engineering feasibility of using buried drip irrigation systems in North Dakota for multiple cropping seasons; (2) test the durability, uniformity of water distribution, and ease of handling of currently available drip irrigation tape products from several manufacturers when used for SDI in North Dakota and left in the soil for several seasons; (3) develop a demonstration site for drip irrigation; (4) determine the effects of using SDI with various horticultural crops on crop yield and quality.

## MATERIALS AND METHODS

A three-year field experiment was started in 1993 at the south end of the Oakes Irrigation Field Trials Site near Oakes, North Dakota (46°04′N Lat, 98°06′W Long, and 401 m M.S.L.; Enz et al., 1995). The climate is classified as sub-humid. Soil is a fine sandy loam topsoil approximately 0.30 m (1 ft) thick, underlain by a fine sand. The experimental area was 152 m (500 ft) long (north-south) and 41 m (136 ft) wide (fig. 1), for a total of 0.62 ha (1.54 ac), and had a 1% average slope from north (higher) to south (lower). The area was fallow prior to 1993 and was prepared for drip tape installation by moldboard plowing, disking (twice) and field cultivating. Irrigations were scheduled by water balance methods (Lundstrom and Stegman, 1988) in 1993, using field capacity water contents of 77, 127, and 229 mm for the top 0.30, 0.61, and 1.22 m, respectively. Water in the soil profile that is available to the crop, i.e., between field capacity and wilting point, was assumed one-half of field capacity, based on prior experience at the site (E. C. Stegman, 1992, personal communication). Irrigations were scheduled based on tensiometer information in 1994 and 1995 (discussed below).

### SYSTEM DESIGN

A randomized complete block statistical design was used for the experiment (fig. 1). Five different drip tape products (table 1) were installed as treatments and were replicated three times and blocked to minimize the effect of field variability. Each block was 12 m (40 ft) wide x 152 m (500 ft) long (fig. 1). For a 1% downhill slope, the lateral length of 152 m (500 ft) is within manufacturers' recommendations for tape length for each tape type (R. Lah, 1996, personal communication). Each plot consisted of two drip tapes installed 1.2 m (4 ft) apart at a 0.28 m (11 in.) depth below the ground surface with emitters on top, i.e., facing up toward the soil surface. The 0.28 m (11 in.) depth was selected to place the drip tape below tillage depth while keeping the drip tape within the fine sandy loam topsoil to maximize the upward capillary movement of water from the emitters. Drip tapes were installed using a three-point hitch mounted drip tape plow (fig. 2). Two drip tapes were installed on each edge (east and west) of the experimental area to provide an irrigated border.

**Table 1. Drip tape specifications and characteristics**

| | | Manufacturer | | | | |
|---|---|---|---|---|---|---|
| Specification or Characteristic* | Units | Chapin | Netafim | Rain Bird | Roberts | T-Systems |
| Emitter spacing | m (in ) | 0.30 (12) | 0.46 (18) | 0.30 (12) | 0.30 (12) | 0.30 (12) |
| Flow rate | L s$^{-1}$ (100 m)$^{-1}$<br>(gpm/100 ft) | 0.104<br>(0.5) | 0.087<br>(0.42) | 0.093<br>(0.45) | 0.083<br>(0.40) | 0.093<br>(0.45) |
| Thickness | mm (mil) | 0.38 (15) | 0.41 (16) | 0.23 (9) | 0.38 (15) | 0.38 (15) |
| Pressure† | kPa (psi gauge) | 69 (10)$^{nom}$ | 97 (14)$^{max}$ | 55 (8)$^{nom}$<br>21 (3)$^{min}$<br>110 (16)$^{max}$ | 55 (8) | 55 (8)$^{nom}$ |
| Handling durability‡ | – | 1 | 1 | 3 | 2 | 1 |
| Repairs§ | – | 1 | 2 | 3 | 2 | 1 |
| Connector sealing effort‖ | – | 3 | 1 | 1 | 2 | 3 |
| Overall handling# | – | 2 | 1 | 3 | 3 | 2 |

* Characteristics here are based on impressions of field technicians and are not intended to be quantitative, but are given for information only Users should consult manufacturers for current product specifications

† Abbreviations: "nom" is nominal, "max" is maximum, and "min" is minimum

‡ "Handling Durability" rated the drip tapes' resistance to abrasion while installing and repairing: 1 = resistant to damage, 3 = susceptible to damage

§ "Repairs" rate the overall ease of performing repairs in the field: 1 = repaired easily, 3 = not as easily repaired

\# "Connector Sealing Effort" rated the physical effort required to seal the spin-lock fittings: 1 = hand tighten, 3 = required use of tools

‖ "Overall Handling" rated the field technicians' preference based on overall handling: 1 = first choice, 2 = second choice, 3 = third choice.

Grassed turning areas were provided on the ends of the irrigated area to accommodate mechanized operations without damaging the drip tapes or header assemblies. In the north grassed turn-around area, 6.1-m (20-ft) long sections of 13-mm (0.5-in.) diameter poly tubing were buried approximately 0.15 m (6 in.) deep (fig. 3) and connected to the drip tape laterals. The other ends of the poly tubes were brought to the surface and connected to a 1.2-m (4-ft) section of 19-mm (0.75-in.) poly tubing to construct a low-pressure header. Water pressure in each poly header was regulated to 69 kPa (10 psi gauge pressure) by a low pressure regulator (Ag Products PENN-700-SN). One pressure regulator was used for each pair of drip tapes, rather than the whole treatment, to insure uniform water pressure at the drip tape inlet. The low pressure regulator was connected to high pressure headers by a 19-mm (0.75-in.) poly riser. At the south end of the experimental site, the terminal ends of the tapes were connected to 1.5-m (5-ft) lengths of 13-mm (0.5-in.) poly tubing, and the latter were brought to the surface and sealed with removable caps. The caps were used to periodically flush the drip tapes and check water flow and pressure.

Five high pressure headers made of 6.35-cm (2.5-in.), Class 160, PVC pipe were buried along the north end of the site. Although a commercial crop production setting may employ only one high pressure header for this size system, we used five for two reasons. First, flow must be accurately quantified as it was pumped to tapes with different flow ratings in this research setting. Second, the flow-pressure characteristic of the well and pump at the site did not permit irrigation of the entire 0.62 ha (1.54 ac) field simultaneously, i.e., as a single irrigated zone. The ends of the headers were sealed with removable plugs (for drainage prior to winter) that were accessed through drop boxes located on each corner of the north end of the experimental area. All drip tapes for a treatment were connected to the same high pressure header which was controlled by a supply manifold (figs. 3 and 4). Solenoid-activated valves in the supply manifold could be operated by both manual and automated switches to control water flow. The solenoid valves were 38-mm (1.5-in.), normally closed, 120-V bronze body valves. A vacuum relief valve was installed immediately downstream from each solenoid valve to prevent soil and foreign materials from being pulled into the drip emitters while the laterals were draining.

Figure 2–Installation of the subsurface drip irrigation tape.

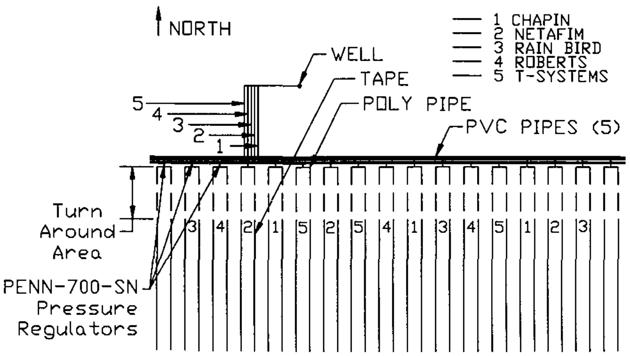

Figure 3–Detail of header area. The PENN-700-SN regulators were directly above the PVC pipes, but here are shown offset for clarity.

Irrigation water was supplied by groundwater. System capacity was desired to meet maximum 8-mm (0.3-in.) daily demand of corn and potatoes (Lundstrom and Stegman, 1988) and was based on 100% system efficiency. Water demand for the subsurface system was expected to be smaller, since the potential for evaporation losses is reduced relative to sprinkler or surface irrigation water application.

The irrigation water supply system consisted of a 100-mm (4-in.) stainless steel submersible pump (Goulds Model 35LD), a reduced-pressure-zone (RPZ) backflow prevention device (Watts Series 009), a 155-mesh nylon screen filter (Wade Rain 39-290-155, replacement element 39-11-7), a pressure regulator (Watts U-5), and a totalizing flow meter (Omega FTB-6115-PT) with switch closure output. The RPZ backflow prevention device was required to comply with chemigation requirements under North Dakota state law. The pressure regulator was needed to limit the water pressure in the supply manifold and high pressure headers to 276 kPa (40 psi gauge pressure). The solenoids in the headers allowed water to be routed to individual replications, and thus one flow meter was used for the entire experiment.

A CR10 data logger (Campbell Scientific, Logan, UT) was used in 1994 and 1995 to start and stop the pump, open and close solenoids to route water to each type of tape, measure irrigation amounts, and record tensiometer measurements. The CR10 was programmed to apply irrigations in 2.5 mm (0.1 in.) amounts up to three times daily when tensiometer readings at 0.3-m (1-ft) depth exceeded predetermined values (see crop culture below). Note that a simpler, timer-based control system would be

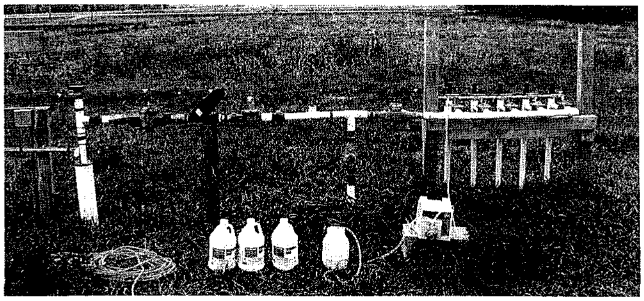

Figure 4–Irrigation water supply system. Acid is being injected immediately upstream from the five-way manifold used to direct water to individual treatments. This view faces south.

sufficient to irrigate zoned areas in a commercial crop production setting.

### CROP CULTURE: 1993

Supersweet sweet corn, 'Crisp 'N Sweet 711,' was planted on 14 May in rows that were 0.6 m (2 ft) apart. Before planting, 134 kg N ha$^{-1}$ (120 lb N ac$^{-1}$), 112 kg $P_2O_5$ ha$^{-1}$ (100 lb $P_2O_5$ ac$^{-1}$), 22 kg S ha$^{-1}$ (20 lb S ac$^{-1}$), and 5.6 kg Zn ha$^{-1}$ (5 lb Zn ac$^{-1}$) were broadcast and incorporated. Weeds were controlled with 1.75 L ha$^{-1}$ (1.5 pt ac$^{-1}$, 1.5 lb Metholachlor ac$^{-1}$) Dual + 1.68 kg ha$^{-1}$ (1.5 lb ac$^{-1}$, 1.35 lb Cyanazine ac$^{-1}$) Bladex 90 DF sprayed preemergence and by cultivation. Insects were controlled by 4.7 L ha$^{-1}$ (4 pts ac$^{-1}$, 5 lb Chlorpyrifos ac$^{-1}$) Lorsban (applied preplant incorporated) and by an aerial application of 3.5 L ha$^{-1}$ (3 pts ac$^{-1}$, 0.75 lb Methyl Parathion ac$^{-1}$) Penncap-M on 23 July. One sidedress nitrogen fertilizer application of 112 kg N ha$^{-1}$ (100 lb N ac$^{-1}$) in liquid form (28-0-0) was manually applied with the irrigation water using a venturi injection system.

Irrigation scheduling was based on field corn crop water use estimates using the checkbook method (Lundstrom and Stegman, 1988) which was initialized to field capacity at the date of crop emergence. The first irrigation was applied on 22 July, shortly after the system was readied for full-capacity delivery of water in a manual operation mode. At this time, the available soil moisture depletion level was approximately 50% in the top 0.6 m (2 ft) of the soil profile. The irrigation system was operated in a manual mode for the 1993 season. Irrigations were commenced when the estimated available water in the top 0.61 m (2 ft) of the profile were 50% depleted. Irrigation amounts were typically 25 mm (1.0 in.) for each irrigation event. We intentionally *did* not refill the soil profile to field capacity with each irrigation. It is generally not prudent to refill the root zone to field capacity in subhumid climates, since rainfall cannot be accommodated after the soil profile is at field capacity. That is, if rainfall occurs immediately after the soil profile has been irrigated to field capacity, some or all of the irrigation is wasted, being forced out of the profile by the rainfall.

### CROP CULTURE: 1994

The area was disked on 13 May. Fertilizer in 21-0-0-24 form (N - $P_2O_5$ -$K_2O$ - S) was broadcast at a rate of 103 kg ha$^{-1}$ (92 lb ac$^{-1}$) and incorporated with a field cultivator on 16 May. A barley cover crop was seeded on 16 May and was killed with Poast at 1.75 L ha$^{-1}$ (1.5 pt ac$^{-1}$, 0.28 lb Sethoxydim ac$^{-1}$) on 6 June. 'Burgess' buttercup squash was planted in 1.2-m (4-ft) rows on 27 May. Planting rate was one seed per 0.3 m (1 seed ft$^{-1}$). Plants were later thinned to one plant every 1.2 m (4 ft). Weeds were controlled by cultivation and hand weeding. On 20 July, liquid N (28-0-0) was applied through the drip irrigation system at a rate of 67 kg N ha$^{-1}$ (60 lb N ac$^{-1}$) in 5 mm (0.18 in.) of irrigation water. A positive-displacement pump was used for fertilizer injection. Squash were harvested during 11 to 14 October.

Irrigation scheduling was based on tensiometer readings at 0.3 m (1 ft) depth. Four tensiometers were located in crop rows and were placed near the north yield transect (fig. 1). Irrigations were commenced when the average of four tensiometer readings reached 30 kPa (30 cbar or 4.4 psi). Irrigations were typically applied in 25-mm (1-in.) amounts, which is less than one-third the 77 mm of available water at field capacity for the top 0.3 m (1 ft) and equal to one-half the 50 mm of available water at field capacity for the 0.3- to 0.6-m depth in the soil profile. The irrigation system was operated in a manual mode for most of the 1994 season, with a CR10 datalogger (Campbell Scientific, Logan, Utah) used for the last irrigation.

### CROP CULTURE: 1995

The area was disked on 5 May followed by nitrogen fertilizer application of 67 kg N ha$^{-1}$ (60 lb N ac$^{-1}$) and barley cover crop planting on 11 May. Cabbage was planted on 0.41-m (16-in.) row spacings on 11 to 12 May 1995. Due to seed availability constraints, replication 1 was planted with the variety 'Bravo' and replications 2 and 3 were planted with the variety 'Cheers'. Planting different varieties in different replications is analogous to having different soil types in different replications (see fig. 1), and, statistically speaking, both are accounted for in the randomized block design. Chemical applications included Treflan at a rate of 1.2 L ha$^{-1}$ (1 pt ac$^{-1}$, 0.5 lb Trifluralin ac$^{-1}$) and Dacthal at 9 kg ha$^{-1}$ (8 lb ac$^{-1}$, 6 lb Chlorthal-dimethyl ac$^{-1}$) for weed control; Sevin XLR Plus at 1.75 L ha$^{-1}$ (0.75 qt ac$^{-1}$, 0.75 lb Carbaryl ac$^{-1}$) to control flea beetle; Poast + Crop Oil Concentrate (COC) at 1.75 + 2.3 L ha$^{-1}$ (1.5 + 2 pt ac$^{-1}$; Poast applied at 0.28 lb Sethoxydim ac$^{-1}$; COC is a paraffinic spray oil; Fusilade + Penetrate at 1.17 + 0.88 L ha$^{-1}$ (1 + 0.75 pt ac$^{-1}$; Fusilade applied at 0.25 lb Fluazifop-butyl ac$^{-1}$; Penetrate is a surfactant) to kill the cover crop in June; and Asana XL at 585 mL ha$^{-1}$ (0.5 pt ac$^{-1}$, 0.041 lb Esfenvalerate ac$^{-1}$) and Biobit at 4.1 L ha$^{-1}$ (3.5 pt ac ac$^{-1}$, 3.2 × $10^{10}$ International Units *bacillus thuringiensis* var. *kurstaki* gal$^{-1}$) for insect control. Nitrogen fertilizer was applied through the drip irrigation system at a rate of 112 kg N ha$^{-1}$ (100 lb N ac$^{-1}$) in a single application that started on 29 June. Plants were hand thinned to an average of 44 500 plants ha$^{-1}$ (18,000 plants acre$^{-1}$) on 19 June. The south, middle, and north transects (explained in the next section) were harvested on 8 September, 18 September, and 2 October, respectively. Irrigations commenced when soil matric potential reached 25 kPa (25 cbar or 3.6 psi) and were applied in 2.5 mm (0.1 in.) amounts in response to output from transducer-equipped tensiometers (Irrometer Co., Riverside, Calif ).

### YIELD MEASUREMENTS

In each year of the study, yield data were collected from three transects across each plot. The transects are designated north, middle, and south (fig. 1) and correspond to the upstream, middle, and downstream ends of the SDI system, respectively. This method of yield data collection allowed direct evaluation of how evenly the water and nutrients were being distributed in the plots. The ease of communication with growers provided by this method better addresses the objective of using the system as a teaching tool than the more intensive, random sampling method that corresponds to the ASAE method for testing emitter discharge variation (ASAE, 1989), which is described below.

Yields were analyzed using analysis of variance techniques (Minitab, 1994) for differences due to tape manufacturer and replications. We do not present two-way analyses of variance in which position along the tape was a factor, since tape (manufacturer) locations were not independently randomized at each transect. Unless otherwise noted, all comparisons reported here refer to the $\alpha = 0.05$ level of significance and use of the word "significant" and its derivatives is in their statistical sense, according to the general linear model used in the analysis of variance.

Sweet corn yield data were taken from 7.6 m (25 ft) of two rows and yield measurements consisted of ear counts and harvested weights of marketable and nonmarketable ears for each plot. Winter squash yield data were taken from 15.2 m (50 ft) of two rows and yield measurements consisted of squash fruit numbers and harvested weights for U.S. No. 1, U.S. No. 2, immature, and cull squash from each plot. Cabbage yield data were taken from 5.2 m (17 ft) of two rows and yield measurements consisted of head counts and harvested weights for each plot. All yields and counts were adjusted to per ha bases. We caution that the small areas represented by the harvest plots in this research may have exhibited more variability than desired and that larger plot sizes would have been desirable. However, larger plot sizes were beyond the scope of this study.

### System Maintenance

Spring maintenance involved reinstalling equipment that was removed for the winter and repairing damaged drip tapes and fittings. Drip tape damage was primarily the result of burrowing rodent activity. When rodents encountered a drip tape, they tended to follow and chew on the tape. In 1994, repairs of up to 3 m (10 ft) were made to five drip tapes due to extensive gopher activity. Most of the spring repairs in 1994 were within 15 m (50 ft) of the downstream (south) ends of the tape. In 1995, four tapes had to have lengths of up to 0.3 m (1 ft) of drip tape replaced because of rodent damage. In all cases, the damage to fittings was the direct result of inattentive operation of tillage, mowing, and harvesting equipment.

Spring maintenance was efficiently accomplished using a two-man team. In 1994, spring maintenance required 36 man-hours, while the 1995 maintenance required 7 man-hours of labor. The reduction in repair time was primarily the result of an improved ability to locate and repair leaks, and secondly a reduction in the number of damaged fittings needing repair. The improved ability to locate leaks is the direct result of experience and familiarity with the physical experimental area.

Summer maintenance involved controlling rodents, chlorinating treatments, and acid shock treatments. Rodents were poisoned after the initial drip tape installation, and thereafter when signs of rodent activity were observed. Drip lines were injected with chlorine (household bleach) immediately after nitrogen fertilizer injection in 1993 to inhibit microorganism growth. With bicarbonate levels above 2.0 meq $L^{-1}$ and pH greater than 7.5, the well water could cause emitter plugging due to calcium (Ca) precipitation (Keller and Bliesner, 1990). On 2 August 1994, we injected muriatic acid (HCl) into the system to lower the pH and prevent Ca precipitation. The acid was injected (fig. 4) for approximately 20 to 25 min in each set of lines. The pH was measured at the downstream end of the tapes with a handheld meter. We injected sufficient acid to hold the pH below 3.0 for 20 to 25 min. The water applied as a carrier for the acid amounted to 1 mm (0.04 in.). A shock treatment method of acidification of the water was selected over a continuous acidification for two reasons. First, time and cost constraints limited the feasibility of continuous acid treatment to limit Ca precipitation. Second, a shock treatment may have the additional benefit of retarding root growth near the emitters to minimize root intrusion.

Fall maintenance consisted of an end-of-season acid treatment and winterization. The end-of-season acid treatment was intended to clean Ca precipitation from the emitters and to prevent microorganism growth in the off season. Winterization involved removing the RPZ backflow prevention device, water filter, water meters, and all pressure regulators and draining the manifold and high pressure headers. The water in the high pressure headers and supply manifold was drained using a 0.038-$m^3$ $s^{-1}$ (80 cfm) air compressor to push the water out of the headers through the plugs in the drop boxes. After draining the headers, all open ends were capped to keep soil, insects, and rodents out.

### Uniformity of Water Application

The ASAE method for testing emitter discharge variation (ASAE, 1989) requires at least 18 randomly located sampling points, but is difficult in SDI systems (Phene et al., 1992). Due to labor and time constraints, and because random sampling would have destroyed parts of the yield test strips described above, we employed a simplified test of the system for its water distribution. We note that the testing reported here gives only a rough picture of the distribution characteristics of the system and is not intended to be the basis for statistical comparisons. It does convey basic drip irrigation concepts to new users, the latter being an objective of the study.

The flow distribution tests were performed on 10 August 1994 and 9 August 1995. All PENN-700-SN pressure regulators were set to 69 kPa (10 psi). Three yield transects were marked and plants were removed adjacent to the yield transects to enable excavation around the drip tape. The testing locations were 4.6 m (15 ft) south of the yield transects (fig. 1). Soil around one drip tape from each manufacturer in replication number two, starting from the downstream (south) end of the field, was excavated by hand. Approximately 0.6 m (2 ft) of the tape was exposed so that a small trough could be used to catch water from two emitters for each tape (see table 1 for emitter spacing). Water was pumped through the line being tested until a uniform flow rate was established, usually about 10 min. Water was collected from two emitters for 3 min and measured in a graduated cylinder. The collection was repeated for another 3 min and the collected volumes were averaged. The tests were repeated for all five manufacturers at the south transect [148 m (485 ft) from headers] before moving upstream to repeat the process at the 88-m (290-ft) location and then the 29-m (95-ft) location. The experiment proceeded upstream to preserve undisturbed conditions upstream from the sampling location. Based on emitter spacing and rated flows (table 1), the average collected volumes were converted to an equivalent flow rate (e.g., L $min^{-1}$ 30 $m^{-1}$ or gallons per minute per 100 ft) and expressed as a percent of manufacturers' rated flow at the upstream ends of the tapes. In 1994, 38 man-hours of field labor were required for this testing, including one man for

**Table 2. Sweet corn yield and ear count averages for 1993**

| | Marketable Yield | | Total Yield* | | Marketable Count | | Total Count | |
|---|---|---|---|---|---|---|---|---|
| Position | (Mg ha$^{-1}$) | (ton ac$^{-1}$) | (Mg ha$^{-1}$) | (ton ac$^{-1}$) | (1000s ears ha$^{-1}$) | (1000s ears ac$^{-1}$) | (1000s ears ha$^{-1}$) | (1000s ears ac$^{-1}$) |
| North | 14 9 | 6.65 | 15 5 | 6 91 | 68.1 | 27.5 | 76.6 | 31.0 |
| Middle | 14 4 | 6.42 | 15 4 | 6 87 | 66 8 | 27.0 | 76.5 | 31 0 |
| South | 12 4 | 5.53 | 13 8 | 6 16 | 61 1 | 24 7 | 73.6 | 29 8 |
| Average | 13 9 | 6 20 | 14 9 | 6 65 | 65 3 | 26.4 | 75 6 | 30.6 |

* Total yields and counts consist of marketable plus nonmarketable ears Data for nonmarketable ears are not reported

6 h to prepare the area for sampling and 8 h of a four-man team to conduct the sampling and restore the soil to its original condition. In 1995, 33 man-hours were required, using a four-man team.

**Table 3. Winter squash yield averages for 1994**

| | No 1 Yield | | No 2 Yield | | Total Yield* | |
|---|---|---|---|---|---|---|
| Position | (Mg ha$^{-1}$) | (ton ac$^{-1}$) | (Mg ha$^{-1}$) | (ton ac$^{-1}$) | (Mg ha$^{-1}$) | (ton ac$^{-1}$) |
| North | 13 6 | 6 07 | 6.6 | 2.9 | 28 9 | 12 9 |
| Middle | 20.5 | 9 14 | 5.5 | 2 5 | 33 5 | 14 9 |
| South | 19 1 | 8 52 | 8 3 | 3 7 | 33 3 | 14 9 |
| Average | 17 7 | 7 90 | 6.8 | 3 0 | 31 9 | 14 2 |

* Total yields include cull and immature squash Yields for cull and immature squash are not reported

**Table 4. Cabbage yield and head count averages for 1995**

| | Yield | | Head Count | |
|---|---|---|---|---|
| Position | (Mg ha$^{-1}$) | (ton ac$^{-1}$) | (1000s Heads ha$^{-1}$) | (1000s Heads ac$^{-1}$) |
| North | 97 | 43 3 | 42 3 | 17 1 |
| Middle | 117 | 52 2 | 54 5 | 22.1 |
| South | 81 | 36 1 | 36 7 | 14.9 |
| Average | 98 | 43 7 | 44.5 | 18.0 |

## RESULTS AND DISCUSSION

### PRECIPITATION AND IRRIGATION

The 30-year average (1951-1980) rainfall for 1 May through 30 September was 329 mm (12.97 in.) (U.S. Dept. Comm., 1982). Corresponding precipitation totals were 445, 340, and 314 mm (17.52, 13.38, and 12.36 in.) for 1993, 1994, and 1995, respectively. Seasonal irrigation totals were 171, 255, and 302 mm (6.75, 10.02, and 11.90 in.) for 1993, 1994, and 1995, respectively.

In 1993, adequate moisture was available for seed germination and no surface or sprinkler irrigation was needed to aid germination.

In 1994, a hand-move irrigation system was used temporarily (labor requirements not available) to apply about 25 mm (1.0 in.) of water on 3 June to aid germination of the squash; the SDI system was not able to wet the soil around the seeds. In 1994, operator error resulted in slight differences [standard deviation 5 mm (0.21 in.)] in applications across tape manufacturers. The data logger was used in a 22 to 23 August application of 7 mm (0.29 in.) to all treatments.

In 1995, adequate moisture was available for seed germination. The irrigation system was operated in a manual mode to apply 55 mm (2.15 in.) of water before datalogger installation. The CR10 was used to apply water in 2.5-mm (0.1-in.) increments, up to three times daily, for the remainder of the 1995 season.

### YIELD MEASUREMENTS

Yield summaries are presented in tables 2, 3, and 4 for sweet corn, winter squash, and cabbage, respectively. In 1993, sweet corn yields averaged 13.9 and 14.9 Mg ha$^{-1}$ (6.20 and 6.65 ton ac$^{-1}$) for marketable and total yields, respectively. Yields for marketable ears were 14.9, 14.4, and 12.4 Mg ha$^{-1}$ (6.65, 6.42, and 5.53 ton ac$^{-1}$) for the north, middle, and south transects, respectively, when averaged across manufacturers and replications (table 2). Yields decreased with distance from the upstream end of the irrigation system; we later discuss decreasing water delivery rates with distance from the upstream end of the irrigation system. When averaged across position and replication, yields of marketable ears ranged from 13.4 to 15.0 Mg ha$^{-1}$ (5.98 to 6.69 ton ac$^{-1}$) for various manufacturers' tapes. There were no significant differences in yields or ear counts for the marketable or total yield categories due to manufacturer at the north, middle, or south transects. Both yields and ear counts for the marketable and total yield categories were significantly affected by replication at all transects, which indicates that the blocking was effective.

In 1994, squash yields averaged 17.7, 6.8, 1.8, 5.5, and 31.9 Mg ha$^{-1}$ (7.90, 3.03, 0.80, 2.45, and 14.23 ton ac$^{-1}$) for U.S. No. 1s, U.S. No. 2s, culls, immature, and total yields, respectively. Yields for U.S. No. 1s were 13.6, 20.5, and 19.1 Mg ha$^{-1}$ (6.07, 9.14, 8.52 ton ac$^{-1}$) for the north, middle, and south transects, respectively, when averaged across manufacturers and replications (table 3), and the corresponding yields for U.S. No. 2s were 6.6, 5.5, and 8.3 Mg ha$^{-1}$ (2.94, 2.45, and 3.70 ton ac$^{-1}$). When averaged across position and replication, U.S. No. 1 yields ranged from 16.4 Mg ha$^{-1}$ to 20.0 Mg ha$^{-1}$ (7.32 to 8.92 ton ac$^{-1}$) for various manufacturers' tapes. There were no significant differences in yields or fruit numbers of squash, in any yield category, due to manufacturer at the north, middle, or south transects. Moreover, there were no significant differences in yields or numbers of U.S. No 1s, U.S. No. 2s, and total yields due to manufacturer or due to replication at the north, middle, or south transects.

In 1995, cabbage yields averaged 98 Mg ha$^{-1}$ (43.7 ton ac$^{-1}$). Yields were 97, 117, and 81 Mg ha$^{-1}$ (43.3, 52.2, and 36.1 ton ac$^{-1}$) in the north, middle, and south transects, respectively, when averaged across manufacturers and replications (table 4). When averaged across position and replication, yields ranged from 94 to 105 Mg ha$^{-1}$ (41.9 to 46.8 ton ac$^{-1}$) for various manufacturers' tapes. Neither cabbage yields nor numbers (head count) exhibited significant differences due to manufacturer at the north, middle, or south transects. There were no statistical differences in cabbage numbers due to replication at any transect. The yields for the 'Bravo' variety (replication 1) at the south transect were significantly lower, at the $\alpha = 0.01$ level of significance, than for the 'Cheers' variety (replications 2 and 3) at the south transect (data not shown). The problem appeared to be related to stand. 'Cheers' produces a larger head and compensates better for a low stand than does 'Bravo,' even under the best conditions. At the south transect, both replications 1 ('Bravo') and 3 ('Cheers') had 32 800 heads $ha^{-1}$ (13 300 heads $ac^{-1}$), but the yield for 'Cheers' was 93 Mg $ha^{-1}$ (41.5 ton $ac^{-1}$) compared to 55 Mg $ha^{-1}$ (24.5 ton $ac^{-1}$) for 'Bravo.'

### UNIFORMITY OF WATER APPLICATION

In 1994, the results of the flow rate testing (fig. 5) indicated a large decrease in the water application with distance along the length of the tape. We attribute the large decrease in discharge with distance to excessive pressure decreases along the tape. From fluid mechanics principles, deformation of the normally circular cross-section of the tape into an elliptical or essentially flat shape would cause relatively large pressure decreases with distance. That is, for the 16-mm (5/8-in.) diameter tape used here, and rated flow rates as shown in table 1, Reynolds number (**R**) calculations indicate turbulent flow (**R** ≈ 11,000) near upstream ends of the tape — hence hydraulic radius concepts apply (Vennard and Street, 1982). The hydraulic radius of the tape approaches zero as the tape is compressed from a circular to a flat cross-section, greatly increasing friction losses along its length. Causes of tape deformation (flattening) include soil compaction, frozen soil conditions during North Dakota winters, freeze-thaw cycles during spring and fall, tillage operations on the soil surface, or combinations thereof. A thermocouple tree installed at the site during the winter of 1993-1994 indicated that the 0.30-m (1-ft) soil temperature was below 0°C (32°F) for approximately 90 consecutive days, with frost depths just reaching 0.91 m (3 ft).

Caution should be used when comparing the discharge uniformities of tape placed above the ground to SDI. Above-ground tape has an undeformed, circular cross-section, while SDI is subject to deformation by the surrounding soil. Further, depth of burial affects the additional vertical pressure experienced by buried tape under surface loading, such as that due to tractors and tillage equipment. Pressure decreases with depth below applied surface loads on soil (Wong, 1978). Therefore, deeper placement of buried drip irrigation tape makes it less susceptible to deformation due to surface loading. For comparison, Phene et al. (1992) reported burial of tape at 0.45-m (18-in.) depth, whereas our soil texture and soil horizons indicated an optimal placement at 0.28 m (11 in.). On the other hand, overburden pressure, i.e., the pressure exerted at depth by the soil itself, increases with depth, which favors shallow placement of tape to prevent deformation.

In 1995, the results of the flow rate testing (fig. 6) again indicated a decline in emitter discharge with distance along the flow pathways. For example, the pressure at the ends of the Chapin tape in replication 2 averaged 37.9 kPa (5.5 psi) on 15 August 1995. The very low discharges at the south transect for the Rain Bird tape were attributed to nearly complete plugging of the two emitters tested. The flows much above rated values (e.g., 140% at the north transect) could be attributed to emitter damage, but emitter damage was not observed.

When the average rated flows for each year are compared (fig. 7), it appears that system performance improved, since higher average flow rates occurred in 1995 than in 1994. The improvement could be due to increased on-off cycling in 1995 compared to 1994. In 1994, the system was operated manually and irrigations were applied in 25-mm (1.0-in.) increments in response to tensiometer readings. In 1995, the system was operated by a data logger and irrigations were applied in 2.5-mm (0.1-in.) increments, up to three times daily, in response to output from transducer-equipped tensiometers. In both years, the water was applied to the five treatments in succession prior to rechecking the tensiometers. The system was thus cycled on and off perhaps one or two times per week in 1994, while in 1995, the system could be cycled on and off up to 21 times per week. The increased cycling of the system may be better at preserving or restoring the circular cross-section of soil in which the buried tape lies.

Calcium precipitation and subsequent emitter plugging may have been more prevalent in 1994 than 1995 due to drier soil conditions between irrigations in 1994 than 1995. That is, the dryness of the soil around the tape increases with the interval between irrigations. Moreover, irrigations were scheduled at tensiometer readings of 30 kPa (4.4 psi) in 1994 and at 25 kPa (3.6 psi) in 1995, since cabbage is more

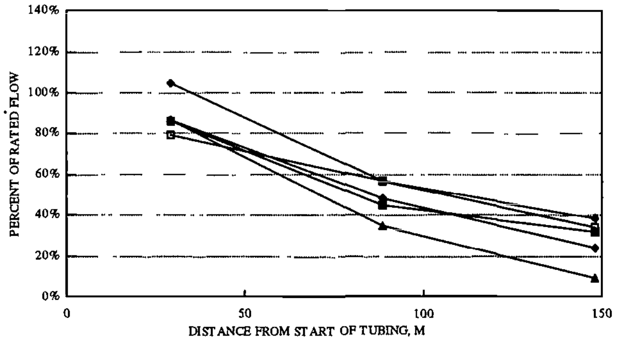

**Figure 5–Water distribution testing results. Testing was performed on 10 August 1994 at three locations for one tape of each manufacturer. The start (upstream) end of the tape was on the north end of the field site. Flows are expressed as a percent of rated flows that would be expected at the upstream ends of the tapes.**

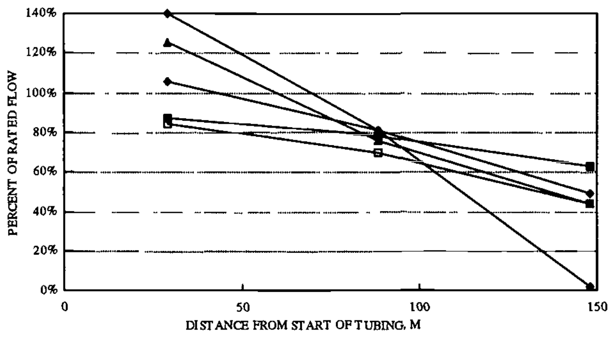

**Figure 6–Water distribution testing results. Testing was performed on 9 August 1995 at three locations for one tape of each manufacturer. The start (upstream) end of the tape was on the north end of the field site. Flows are expressed as a percent of rated flows that would be expected at the upstream ends of the tapes.**

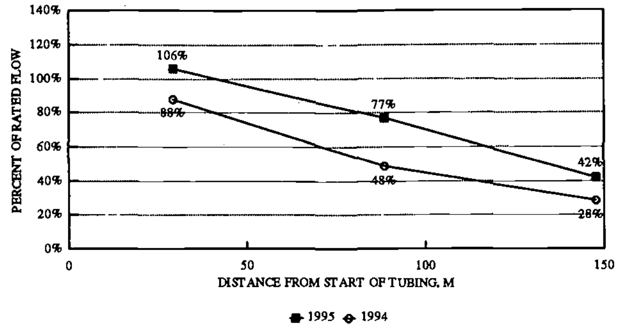

Figure 7–Average water distribution results for 1994 and 1995. The start (upstream) end of the tape was on the north end of the field site. Flows are expressed as a percent of rated flows that would be expected at the upstream ends of the tapes.

drought-sensitive than winter squash. The wetter soil in 1995 may have kept more Ca in solution around the tape, preventing emitter plugging (Scherer, 1995). That is, as the soil water content decreases due to ET, the Ca remaining in the soil is present in higher concentrations. If the Ca concentrations exceed the saturation capacity of the soil water, Ca will precipitate and may cause emitter plugging.

The performance improvement in 1995 may also have been due to a second acid treatment in the fall of 1994, indicating the need for more frequent acid treatments in this setting. The system was treated with muriatic acid (HCl) to lower the pH below 3.0 at the downstream ends of the tape for at least 20 min. The ground water supply used had pH values of 7.6 and 7.8 and $HCO_3$ values of 4.36 and 3.90 meq $L^{-1}$ in 1993 and 1995, respectively.

The yield variability from north to south (see tables 2, 3, and 4) generally followed the flow distribution patterns discussed above for 1993 and 1995, but not 1994. Timely rainfalls at the site may have masked or attenuated yield dependence on the delivery patterns of the SDI system. In 1993, the decreases between the north and south transects were 16% for marketable yield, 11% for total yield, 11% for marketable ear count, and 4% for total ear count. These patterns follow the water distribution patterns found by subsequent (1994 and 1995) testing of the system.

In 1994, the average squash yields in the south transect exceeded the north by 41% for U.S. No. 1 and 26% for U.S. No. 2 (table 3). The higher yields in the south transect are in direct contrast to the lower water distribution in the south. Average fruit counts for U.S. No. 1s and U.S. No. 2s were 32% and 10% higher, respectively, in the south than the north transect and we attribute the yield differences to fruit counts. Yields for U.S. No. 1s, U.S. No. 2s, and total yields were highly correlated to fruit counts for the respective categories, regardless of position, manufacturer, or replication (fig. 8). When data from all plots were pooled (i.e., grouped together regardless of manufacturer, replication, or position) linear regression of yield vs. fruit count produced an $r^2$ of 0.976. This indicates that management of plant population for the production of a large number of fruits is critical in this agronomic setting. We noted that the north end of the field has lighter soil, dried out faster in the spring, and plant stand was poorer than in the south. With an adequate stand we may not have seen the yield difference between the north and south.

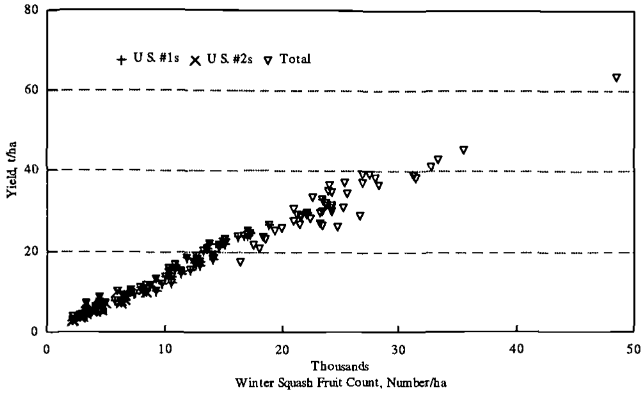

Figure 8–Winter squash yield dependence on fruit counts. Regression of yield vs. count for this pooled data set, pooled across treatments, replications, and positions, yielded $r^2 = 0.976$.

In 1995, the average cabbage yields and head counts in the south transect were 17% and 13% less than in the north transect, respectively. When data from all plots were pooled, yields were not highly correlated to head count for cabbage ($r^2 = 0.289$). However, when averaged across position, yields showed some correlation to head count: yields in the middle and south transects were 121% and 83% of the yield in the north transect, respectively, while head counts in the middle and south transects were 129% and 87% of the head count in the north transect, respectively. Linear regression of total yield vs. head count for 'Bravo' yielded $r^2 = 0.940$, while similar regression for 'Cheers' yielded $r^2 = 0.816$. Thus we conclude that 'Cheers' compensates for low plant populations better than 'Bravo.'

## SUMMARY AND CONCLUSIONS

An SDI system was installed in 1993 and successfully used to irrigate 0.62 ha (1.54 ac) of sweet corn in 1993, winter squash in 1994, and cabbage in 1995. Supplemental irrigation via a hand-move sprinkler system was required in 1994 to aid squash germination; in 1993 and 1995, no supplemental irrigation was required. In 1993, sweet corn yields averaged 13.9 and 14.9 Mg $ha^{-1}$ (6.20 and 6.65 ton $ac^{-1}$) of marketable and total yield, respectively. In 1994, yields of U.S. No. 1, U.S. No. 2, and total yield for winter squash were 17.7, 6.8, and 31.9 Mg $ha^{-1}$ (7.90, 3.03, and 14.23 ton $ac^{-1}$), respectively. In 1995, cabbage yields averaged 98 Mg $ha^{-1}$ (43.7 ton $ac^{-1}$). Yields were measured in plots defined by one of three positions (top, middle, bottom) along the 152-m (500-ft) tape runs and by tape manufacturer. Yields did not differ statistically between tape manufacturers for any year or position. Water discharge rates from the tape were measured at three positions in 1994 and 1995 and found to decrease with distance from upstream ends. Statistical analyses of yield vs. distance downstream were not conducted due to the randomization incorporated in the experimental design. Sweet corn yields roughly followed the system's water discharge patterns, with yields and ear counts decreasing with distance from the upstream ends of the tape. Yields for winter squash and cabbage did not correspond to position and appeared more sensitive to plant or fruit populations than to position along the tape.

Based on the results of this study, SDI systems are a viable irrigation option for producers in North Dakota. Careful attention must be paid to standard installation and management techniques for SDI, including correct installation, operation, and maintenance techniques; water management; and rodent control. In this 0.62-ha (1.54-ac) study, spring maintenance required 36 man-hours in 1994 and seven man-hours in 1995.

Aspects of SDI needing further study in North Dakota include: the economics of SDI, the yield response of additional crops to SDI, appropriate water management techniques, optimizing the system design (tape spacing, depth, flow rate, etc.) for crop rotations suited to the region, and additional data regarding yield versus flow distribution.

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