Journal of Horticulture
Smucker et al., J Hortic 2018, 5:4
DOI: 10.4172/2376-0354.1000246
Research Article
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# Increasing Vegetable Production on Transformed Sand to Retain Twice the Soil Water Holding Capacity in Plant Root Zone

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## Abstract

A new soil water retaining technology, designed to increase vegetable production and improve water use efficiency (WUE), was field tested on sand soil. Green bell pepper (*Capsicum annuum*) and cucumber (*Cucumis sativus*) were planted on previously installed U-shaped troughs of impermeable membranes designed to double soil water content in plant root zones. These soil water retention technology (SWRT) membranes significantly increased volumetric water content (VWC) in plant root zones promoting both crop production and improved water use efficiency (WUE). Greater vegetable production was attained when SWRT membranes significantly increased the low 9% to 10% water holding capacity by control sands. Membrane improved VWC to 15% and 18% increased yields of green bell pepper by 20% and cucumber by 24%. These newly optimized root zone water contents also increased WUE 19% and 41% for cucumber and bell pepper crops grown on SWRT transformed sands. SWRT membrane installations also provide an early return on investment (ROI) for the sand soils that auto control optimal soil water contents in plant root zones. This new technology offers new opportunities for establishing greater profits for the long-term vegetable production on sand soils. Anticipated positive impacts by SWRT on natural resource management and crop production offers new opportunities for enhanced profitability while protecting the environment in rural America.

These SWRT improvements for vegetable production including greater yields, higher WUE, and very brief ROI should encourage adoption of this technology across irrigated vegetable production located on highly permeable sand and loamy sand soils.

**Keywords:** Optimum soil moisture; Soil water retention membrane; Plant water deficits

## Introduction

Increasing water regulations and competition are requiring growers to improve irrigation water use efficiency (IWUE) in temperate and arid regions. Competition for and cost of irrigation water are also discouraging current vegetable producers to expand onto sand and loamy sand soils. A new auto-regulating soil water content technology offers the potential for expanding production onto sand soils while using less water than current practices [1] identified how impermeable water retainers, strategically placed in sand columns, retained twice as much water compared to naturally drained sand columns. SALUS models of the soil-plant-atmosphere, programmed to maintain constant optimal soil water in plant root zones, predicted enormous plant production increases [2]. Using HYDRUS soil water models [3] confirmed designs of SWRT U-shaped membranes, tested in greenhouse lysimeters [4], maintained optimal soil water in the plant root zone.

Continued testing of the modeled results with greenhouse lysimeter studies identified the establishment and maintenance of 15% to 18% volumetric water content (VWC) to provide optimal water conductivity to roots resulting in the highest plant production. Greater water holding capacities in sands, appeared to provide optimal plant available water that could be transformed into commercialized sustainable agriculture for prolonged periods of time for millions of sandy acres in the US and billons of acres globally [4]. Amount and distribution of precipitation in Michigan and the Midwestern United States are uneven during the growing season and vary greatly from year to year. Therefore, most growers have invested in supplemental irrigation to reduce the risks associated with irregular natural rainfall patterns. Drip tape irrigation is commonly used for fresh market pepper and cucumber production in Michigan as these crops are very susceptible to drought stress [5]. However, excess irrigation leads to nutrient leaching and possible anaerobic stress [6,7]. Earlier studies have reported improved WUE by delaying drip irrigation of vegetables during different phenological stages of plant growth [5,8]. Incorporating SWRT membranes into highly permeable soils will equilibrate water contents of 15 to 18% by the engineered SWRT membranes that continue to drain excessive rainfall. Because most vegetable crops are heavily fertilized, as indicated by high residual N levels after harvest, over irrigation often increases the risk of groundwater contamination [9]. These membranes also retain more nutrients resulting in greater vegetable production with lower fertilizer applications [4]. A more highly balanced soil water content without leaching nutrients into groundwater provides added ecosystem stability of plant nutrients in the root zone [5]. Thin layers of fine silt and clay textures located 50 cm (20 in) below the soil surface of Berrien fine sand soils in Western Michigan [10] have also been observed to increase crop production. Heterogeneous depositions of thin natural E horizons, in regions of some sand fields, of historically glaciated soils required thousands of years and occupy less than 2% of the landscape. SWRT membranes are simply engineered U-shaped troughs designed to establish uniform optimal soil water retaining conditions across sand fields. Mechanical installation of these U-shaped SWRT membrane troughs require patented mechanical equipment [11] to precisely install spatially distributed U-shaped SWRT membranes reported here.

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**Received** August 31, 2018; **Accepted** September 21, 2018; **Published** September 28, 2018

**Citation:** Smucker AJM, Levene BC, Ngouajio M (2018) Increasing Vegetable Production on Transformed Sand to Retain Twice the Soil Water Holding Capacity in Plant Root Zone. J Hortic 5: 246. doi: 10.4172/2376-0354.1000246

| Crop<br>Field production (years) | Irrigated SWRT production over irrigated control CWT/a | Average unit price per CWT | Net gain/a by SWRT US$ per acre | ROI (years) when annual production costs of $750/a are subtracted |
|---|---|---|---|---|
| Green Pepper (2011-2012) | *56 (20%) | $37.00 | $2,072 | 1.5 |
| Cucumber (2012-2014) | *96 (24%) | $11.40 | $1,094 | 5.8 |

* Statistically significant SWRT increases by each crop across 2 and 3 years of field production by the least significant difference (LSD) at ($P \le 0.10$). N=8 for pepper and 12 for cucumbers (4 reps. 2 years of Green Pepper and 3 years for Cucumber.

**Table 1:** Return on investment (ROI) for cucumber and green pepper planted in beds covered with black polymer mulch. SWRT membranes installed into loamy sand at SWMREC near Benton Harbor, MI. Although the uniform loamy sand soils in SWRT membrane and control treatments were irrigated equally, root zone soils above SWRT membranes always retained higher seasonal average VWC than root zone soils of controls presented in Figures 5-8.

All membranes are engineered to retain optimal soil water contents without flooding when placed at two soil depths enabling maximum capillary distribution of low matric potential soil water surrounding the root zone with plant available water, (Figure 1). SWRT membranes are designed to double soil water content in root zones below vegetable beds when irrigated by a single drip tape line and covered by polymer surface mulch. This study was designed to quantify production and WUE increases by green bell pepper and cucumber fields on irrigated sands.

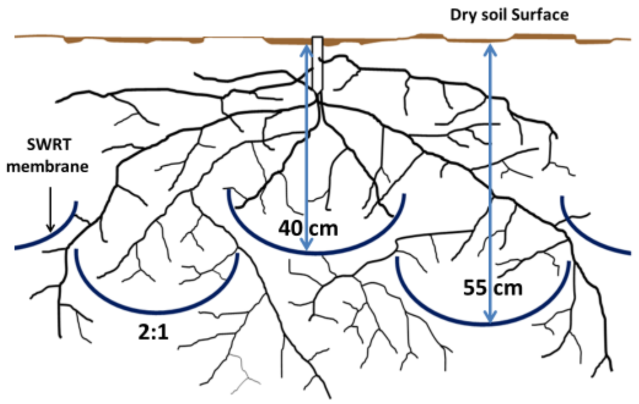


**Figure 1:** Two membrane depths; deeper at 55 cm (21.5 in.) and shallower 40 cm (15.6 in.) with aspect ratios of 2:1 SWRT membrane troughs significantly increase soil volumetric water content (VWC) in plant root zone across entire sand fields or sandy regions of larger fields of fine textured soil.

## Materials and Methods

Site of this study contained highly permeable Loamy sand with internal soil drainage rate exceeding 15 cm min$^{-1}$ (6 in min$^{-1}$), with, less than 2% organic matter, a pH of 6.5 and water holding capacity of 10% VWC (1 mm cm$^{-1}$) (5). The field location was at Michigan State University Southwest Michigan Research and Extension Center (SWMREC) near Benton Harbor, Michigan (42o 6'12" N, 86o21'32" W; 224 m above sea level). During the spring of 2011, two depths of parallel U-shaped troughs of SWRT membranes were mechanically installed into a Spinks loamy fine sand by the mechanical SWRT membrane installation chisel described by [11]. Each SWRT membrane trough installed across the field consisted of an impermeable 3 mil linear low-density polyethylene (LLDPE) film. Parallel installations of U-shaped deeper and shallower troughs, open in the upward position and immediately filled with displaced soil and leveled by the SWRT membrane installation chisel (MIC). SWRT membranes were installed at traveling rates approaching 3.3 km/h (2 mi/h). Deeper membrane troughs were installed first, with 30 cm (12 in) spaces between them. Shallower membranes were spatially between spaces of the deeper membranes by the same SWRT MIC, at soil depths 15 cm (6 in.) shallower than the deeper membranes as outlined in Figure 1. Soil depth of the deepest membrane is identified by capillary rise in sand filled columns described by [1]. These same capillary rise measurements can be completed by farmers in any machine shed. Membrane width to depth (aspect ratios) and depths of membrane troughs are adjusted depending on soil texture, 30-year rainfall records, and specific crops. SWRT membrane spacings are spatially distributed to intercept and retain all vertical flow of rain and irrigation water yet permit some aggressive root growth between the membranes into greater soil depths. During periods of excessive rainfall rates greater than 76 mm h$^{-1}$ (3 in h$^{-1}$) SWRT membranes are designed to drain VWC >21% to equilibrium contents of ranging between 15% and 18%. Two soil treatments were initiated during the early spring of 2011. 1) Control Treatment (CT) containing natural sand soil without tillage and 2) installed SWRT membranes. Size of each of the two soil and two crop treatments was 4.88 m (16 ft) wide by 27.43 m (90 ft). Four randomized replications were in the East/West direction. Each of the 16 plots containing two soil and two crop treatments were in a randomized complete block field design. After membrane installation and before each successive annual transplanting and seeding, the entire field containing replicated two soil treatments for both crops received a top dressing of 33 kg ha$^{-1}$ (29.5 lb a$^{-1}$) nitrogen (N);185 ha$^{-1}$ (165.2 lb a$^{-1}$) potassium (K), and 11 kg ha$^{-1}$ (9.8 lb a$^{-1}$) boron (B), respectively. Granular fertilizers were applied as 33N–0P–0K, 0N–0P–49.8K, and Solubor DF (U.S. Borax, Valencia, CA) containing 17.5% B. The field was then fumigated with 67% methyl bromide and 33% chloropicrin at 336 kg ha$^{-1}$ (300 lb a$^{-1}$). Rows of cucumber seeds and green bell pepper seedlings were planted in N and S direction, perpendicular to the installed SWRT membranes and covered with black polymer mulch. Details of the fertilizers, herbicides, and fungicides used are presented in Ngouajio et al. [8]. All treatments were fertigated every week via single line drip tape, from mid-June to the first week of September with 4N–0P–8K–2 Ca to achieve 4.5 kg N ha$^{-1}$ (4 lb N a$^{-1}$) each week. Rows of green bell pepper and cucumber were planted in three raised beds per plot, 1.5 m (5 ft) wide and 4.9 m (16 ft) long. Seven-week old seedlings of 'Paladin' bell pepper seedlings (*Capsicum annuum*) were transplanted on 4 June 2011 and 20 May 2012 in two rows 30 cm (12 in) apart at 45 cm (18 in) in-row spacing. 'Speedway' cucumber (*Cucumis sativus*) seeds were planted during the second week in early May of all years, in single rows with plant spacings of 45 cm (18 in) in each of three parallel raised beds, 4.9 m (16 ft) long. The experiment was set up as a randomized complete block factorial with four replications. Soil treatment (control and SWRT membrane) was the main plot factor and crop (pepper and cucumber) was the sub plot factor. Experimental units consisted of three beds with the middle bed used for data collection.

All beds were equipped with near soil surface drip tapes directly below the black plastic mulch. Both peppers and cucumbers were grown using recommended practices for fresh-market plasticulture production in southwestern Michigan [12]. Both cucumber and pepper seedlings received one-hour irrigation daily except on days with enough rainfall, through their final harvest. This practice is used by bell pepper and cucumber growers in the region. Pressure gauges were connected to each irrigation line for each center bed to calculate the amount of water delivered during each irrigation event. Natural rainfall was recorded at the site using a weather station (Model 012; Campbell Scientific, Logan, UT). Irrigation records along with rainfall measurements were collected to estimate the total amount of water available to the plants each season, (Figure 2). Due to the coarse nature of sand, considerable quantities of rainfall and irrigation water were lost from plant root zone of Control soils without SWRT membranes. Based on these values and the yield results obtained, estimated water use efficiencies for each year were calculated for each treatment according to the following equation [13] with IWUE kg acre$^{-1}$mm$^{-1}$.

$$\text{IWUE} = \frac{Y_I - Y_{XY}}{W_I - W_{XY}}$$

YI is pepper or cucumber yield of irrigated SWRT plots and YXY is crop yield in each irrigated control treatment. WI is the amount of irrigation water applied to pepper or cucumber SWRT and WXY is the water amount applied in control treatments for pepper or cucumber. Soil water probes, Decagon 5TE, (Matrix, formerly Decagon, Pullman, WA) were installed shortly after planting of both crops during each year. Probes were placed midway between plants of both crops at 15 and 25 cm soil depths in each of the four replications of each soil and crop treatment. Caution was taken to install the deeper probes at soil depths of at least 5 cm above SWRT membranes to diminish none soil interference of volumetric water content (VWC) errors. Each 5TE probe was connected to Em50 or Em50G data logger (Matrix, formerly Decagon, Pullman, WA) that recorded volumetric soil water contents, temperature and salinity at 4-hour intervals in 2011 and ten-minute intervals for 2012. The Em50G data loggers reported the observations regularly to a website providing continuous VWC information that could be utilized to remotely alter seasonal scheduling of one or two daily irrigation applications to all treatments when SWRT cultured soils approached the established minimum soil VWC range of 15-17%, for best plant available water and minimum large pore water loss by drainage [2,3]. Figure 2A-2D provides annual summations of precipitation and irrigation received during the four growing seasons reported in this paper.

Calculated ET is shown for the period between May 1st and mid-October annually. Plastic surface mulch dramatically improved water use efficiency for each irrigation event and planting dates were not always on May 1st. Therefore, the combination of rainfall and irrigation often appears to fall short of the ET each season. However, each year the objective for irrigation was to maintain the soil VWC% in the SWRT plots within a range where plant growth and yield were enhanced.

Equal volumes of water were applied to the control plots with each irrigation and soil moisture was monitored for differences in plant availability. Peppers were harvested four times from the middle of August to the first week in October in 2011, and five times in 2012 from July 23 to Oct. 6. Each harvested bed was located between two buffered single bed lines bordering each harvested area. Buffer zones between adjacent control and SWRT membrane treatments and blocks were ~150 cm (5 ft.). Pepper and cucumber fruits were graded according to market standards [14]. Reported large pepper standards included jumbo (240 g), extra-large (200–239 g), large (170–199 g), and medium (<170 g). The fruit number in each grade was counted and weighed. In this report, jumbo, extra-large, and large pepper fruit were combined as "large" marketable fruit, whereas medium and no. 2 fruits were identified as "medium" marketable fruit. The term "marketable fruit" was the combination of the "large" and "medium" designations. The quantity of cull fruit is also recorded in Figure 3.

Cucumbers were harvested five times from middle July to the first week in Sept. in 2012, 2013 and 2014. Each harvested bed was located between two buffered single bed lines bordering each harvested area. Buffer zones between adjacent control and SWRT membrane treatments and blocks were ~150 cm (5 ft). Cucumbers were graded as USDA No. 1 for long straight green cucumbers and USDA No. 2 when shorter somewhat curved with some green missing. Discards were the very short curved smaller pickle sizes [14]. These were not included in the cucumber production (Figure 4).

All yield data and measured soil water data at each depth, were subjected to analysis of variance, and significant differences among means and reported using Fisher's protected least significant difference (LSD) at ($P \leq 0.10$). All statistical analyses were conducted using the PROC GLM of SAS (version 9.4; SAS Institute, Cary, NC).

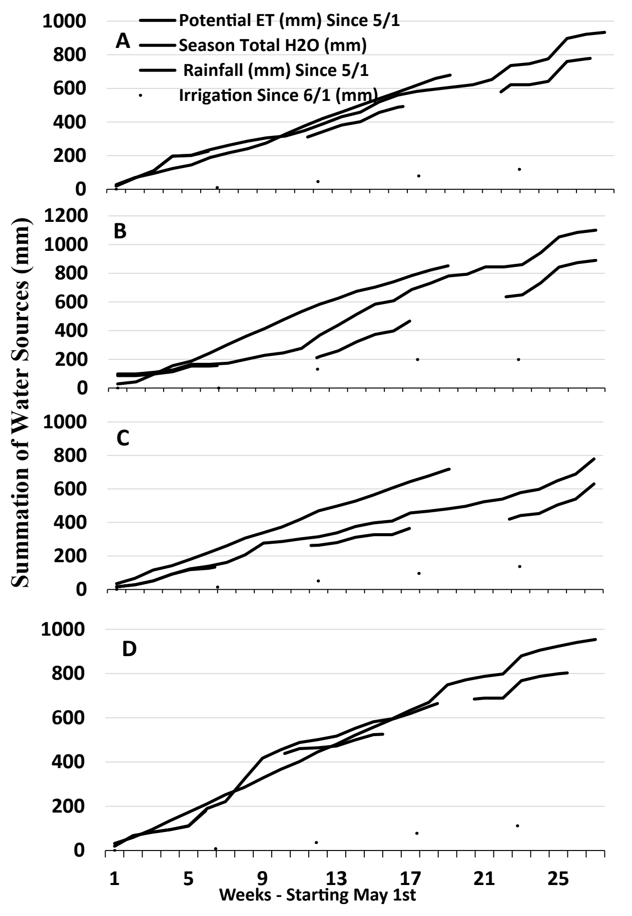


**Figure 2:** Accumulations of potential evapotranspiration (PET) water loss (25.4 mm = 1.0 in) compared to total water added by rainfall and equally applied irrigation to control and SWRT improved sands at SWMREC from May 1 through October 31, during four years from 2011 (A), 2012 (B), 2013 (C) and 2014 (D). Indices are the same in all four graphs.

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## Results

### Monitoring

Adjusting irrigation scheduling that retained VWC at 15 to 18% confirmed the importance of developing more prescriptive irrigation schedules to maintain optimal soil moisture in plant root zones during the entire vegetative stages through harvest during changing seasonal conditions from 2011 to 2014. Very low VWC of 11% to 13.5% in plant root zones of both the SWRT and control treatments during 2011 (Figure 5), resulted, in part, from the driest season in 35 years with only 272 mm (10.7 in.) of precipitation accompanied by optimal prescriptive rather than a traditionally adequate irrigation quantity of 127 mm (5 in). That six-week period of continuous plant water deficit condition of ≤ 10% VWC water contents was much too low for greater production of green bell pepper.

Total irrigation in 2012 was 307 mm (12.1 in) and better synchronized with 336 mm (13.2 in) of rainfall. Even as PET exceeded 1000 mm (39.4 in) (Figure 2B), the root zone VWC in plant root zones of SWRT improved sand remained between 16% and 20% for an optimal seasonal average of 17.5%, for both crops (Figure 6A and 6B). In contrast, VWC in the root zones of control sands vacillated between 7.4% and 17% for a seasonal average of 13.5% (Figure 7A and 7B). As VWC in sands drop below 10% soil water supplies to plant roots are drastically limited by leaf curling and prolonged plant water deficit stress. VWC of 7.4% for nearly a month, caused unrecoverable damage during longer durations of more severe plant drought stress coupled with high PET typical of Michigan summer [3].

### Crop yields

**5.2.1 Bell pepper:** Throughout this study, SWRT membranes placed in sands below vegetable crops always improved crop production by providing continuous supplies of plant-available water to plant root zones (Figures 6-8). There was a significant 31% greater total production by green bell peppers grown on SWRT improved sand in 2012 (Figure 3). The exception was during a severe drought the first year of testing SWRT. Conventional one-hour daily irrigation schedules maintained VWC between 13% and 15% in the root zones of SWRT peppers during the earlier vegetative growth stages. However, 11 and 12% VWC retained in root zones of control peppers (Figure 5), clearly diminished cucumber production. Early growing conditions in 2011 were cool with lowest ET among all four years (Figure 2A). The 8-week harvest began on August 12 as VWC dropped below 10% in both the SWRT and control soils and remained in the severe drought zone of <10% VWC from August 21 to the end of harvest in late September, Figure 5 resulting in suboptimal yields (Figure 3). In 2012, the weather conditions and the one-hour daily traditional irrigation scheduling more closely matched water needs of peppers growing on SWRT improved water retention in root zones of sand (Figure 6A). More stable and uniform VWC in crop root zones equipped with SWRT membranes improved the ability of plant maintained mid-day PET demands (Figure 2B), during the entire season. Throughout the season SWRT pepper root systems experienced better VWC between 15.5% and 18% with seasonal average of 17.5%. These consistently averaging 4% greater VWC than control sands contributed to significantly higher production. Additionally, control sand root zone VWC vacillated between 17.5% and 7.5% with seasonal average of 13.5%, four percent lower than in SWRT improved sands (Figure 6A). In sharp contrast, control plants experienced large vacillations of soil water content including 4 episodes of severe drought conditions below 10%, resulting in 31% yield reductions of large and medium weight, market grade peppers than SWRT grown peppers (Figure 3). Comparing the percentage increases between the years 2011 and 2012, SWRT root water retention conditions increased pepper production 126% while control peppers increased 100%. In 2012 the average yield of SWRT enhancement of USDA No. 1 large SWRT peppers, was 41% greater than controls. Medium peppers (USDA No. 2) were 14% greater for the SWRT treatment *vs.* controls. Identified "marketable" peppers were significantly greater for the SWRT treatment compared to controls in 2012 (Figure 3). Additionally, the average increase of marketable pepper on SWRT plots, across both years, was a significant 27% greater than controls. However, when combined with production

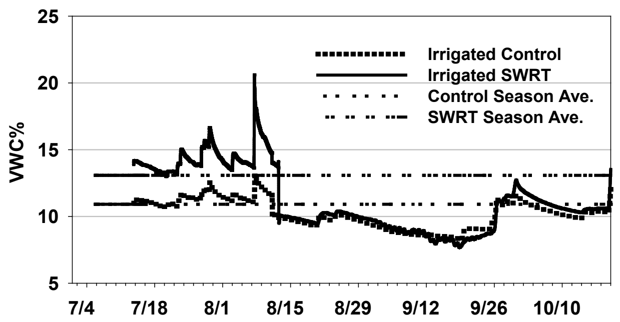


**Figure 3:** Average soil volumetric water content (VWC) at 15 cm (5.9 in) to 25 cm (10 in) depths in SWMREC Spinks loamy sand during 2011 for green bell peppers grown on and off SWRT membranes. Soil water contents are 12-hour averages of values samples at four-hour intervals for both depths in replicated positions across both controls and SWRT improved water holding capacity membranes. Although the uniform loamy sand soils in SWRT membrane and control treatments were irrigated equally, root zone soils above SWRT membranes retained seasonal average of 13.5% VWC while root zone soils of controls retained a seasonal average of 11% VWC.

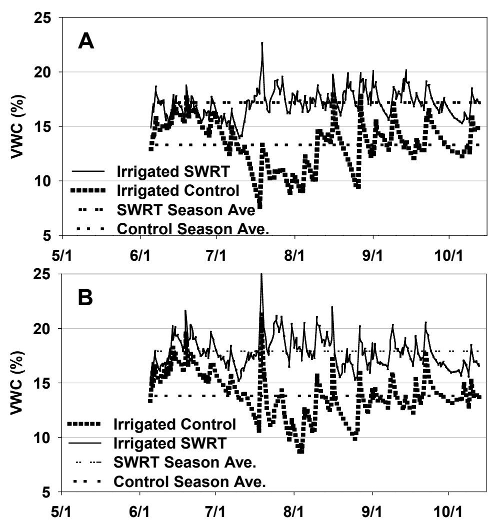


**Figure 4:** Average soil volumetric water content (VWC) at 15 cm (6 in) to 25 cm (10 in) depths in SWMREC Spinks loamy sand during 2012 for bell green peppers (A) and cucumbers (B) grown on and off SWRT membranes. Soil water contents are 12-hour averages of values sampled at ten- minute intervals for both depths near plants and replicated positions across the controls and SWRT improved water holding capacity membranes. Although the uniform loamy sand soils in SWRT membrane and control treatments were irrigated equally, root zone soils above SWRT membranes retained seasonal average of approximately 17.5% VWC while root zone soils of controls retained a seasonal average of 13.5% VWC for both the green peppers and cucumbers.

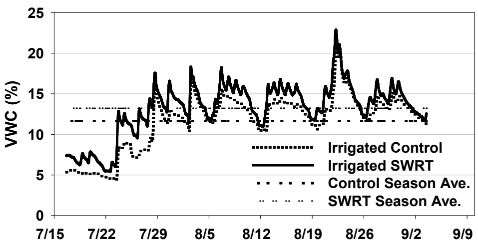


**Figure 6:** Average soil volumetric water content (VWC) at 15 cm (5.9 in) and 25 cm (9.8 in) depths in SWMREC Spinks loamy sand during 2014 for cucumbers grown on and off SWRT membranves. Soil water contents are 12-hour averages of values sampled at 10-minute intervals for both depths in replicated positions across both controls and SWRT improved water holding capacity membranes. Although the uniform loamy sand soils in SWRT membrane and control treatments were irrigated equally, root zone soils above SWRT membranes retained seasonal average of approximately 16% VWC while root zone soils of controls retained a seasonal average of 13.5% VWC.

increases of smaller peppers by SWRT treatments during both years, the average production of SWRT green bell peppers from 4 replicated field sites remained an impressive 22.5% higher than control peppers.

**Cucumber:** SWRT membrane increased plant root zone water holding capacity and cucumber yield by a significant average of 24% during the 2012-2014 field trials (Figure 4). Harvest for this crop was for fresh market distribution, therefore, multiple harvests were completed each of the three seasons from 2012-2014. Weights of different cucumber sizes were counted separately and designated as USDA No. 1 and No. 2 grades, and combined total "marketable grade" production is reported in Figure 4. Large and medium sized cucumbers produced significantly 38% and 14% greater yields when grown over irrigated SWRT improved sand than irrigated control plots. During the 2012 growing season a total of ten harvests were completed for the fresh market cucumbers. In 2013 only five harvests were completed. During the 2014 growing season, a total of eight harvests were completed for the cucumber SWRT field trials. There were consistent trends for the SWRT treatments to produce marketable yields well beyond the control plots across all 23 harvests from 2012 - 2014 as well as total yield produced during the different number of harvests during each season. Yield increases of No.1 and No. 2 cucumbers averaged 22% and 36% greater on SWRT than control treatments during this three-year study (Figure 4). However, variability in summation values of rainfall and supplemental irrigation scheduling (Figures 2B-2D), and the fluctuating soil VWCs in Figures 6-8, resulted in substantial variability in the individual harvest data lowering statistical significances. However, the three-year average of 24% improvements in irrigated cucumber yields was observed.

## Discussion

### Optimization of SWRT root zone VWC and WUE

Immediately following SWRT membrane installation in 2011, irrigation was applied to these transformed sands sometimes in excess to ensure maximum plant emergence of seedlings in moist sands. However, near the end of June the irrigation applications were reduced in quantity, primarily by tradition, to drip tape engineered application rates for one hour each day for both SWRT and control treatments. Figures 5-8 report VWC at 15 cm (5.9 in) to 25 cm (10 in) depths for years 2011-2014. These figures identify sand soils with SWRT membrane predominately retained greater soil VWC during periods of excessive soil water, originating from rainfall and equal subsequent supplemental irrigation to all treatments. SWRT membranes are also engineered to drain as they approach newly established field capacities 10% greater than control sands. Known saturation of these highly porous sands is 35%. These newly established field capacities of 22% by SWRT membranes can be identified by the most frequent peaking of soil water holding capacity that seldom exceeded 22% in Figures 6A and 6B. This new SWRT field capacity continues to maintain at least 13% (35%-22%) of open pore space to maintain optimal soil aeration of all SWRT root zones. When soil moisture is maintained within a range of 15-18% VWC, both pepper and cucumber plants avoided plant water deficits producing much higher yields of quality fruit. When soil moisture exceeded 20%, note two times in Figures 6A and 6B, soil water solutions containing dissolved nutrients were lost via gravitational macropore flow to soil depths below the main rooting zone [1,15,3]. Visual plant wilting symptoms were evident during daylight hours on both plant cultivars when VWC dropped below 10%. Vegetable crop harvests in 2011 were significantly lower for bell pepper and in 2013 for

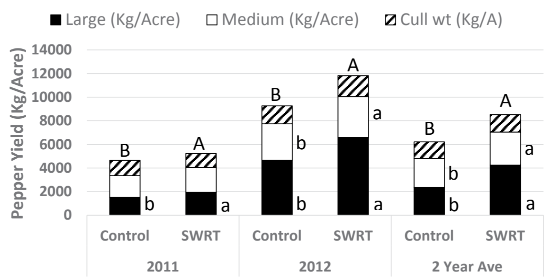


**Figure 7**: SWRT improved 'Paladin' green bell pepper production on loamy sand. Each vertical bar identifies total fresh weight yield of green bell pepper production on Control and SWRT soil treatments during both growing seasons, 2011 and 2012. Each bar is the sum of all three USDA market categories for each soil treatment within each year. Different capital letters above each bar during 2012 and two-year average and small letters beside each large, medium and cull market categories identify significant production differences between Control and SWRT treatments within each year and two- year average. Statistical differences were determined by the least significant difference (LSD) method at P ≤ 0.10, N=4. Useful conversions: (1 hectare =2.472 acres) and on (1 kg = 2.2 pounds).

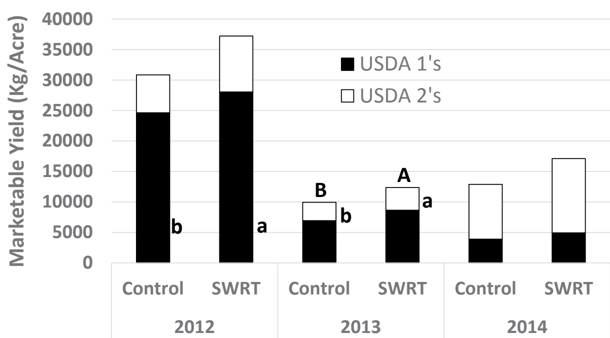


**Figure 8:** SWRT improvement of 'Speedway' cucumber production on loamy sand. Each vertical bar identifies total yield of cucumber production on Control and SWRT soil treatments during each of the three production seasons, 2012 - 2014. Each bar is the sum of USDA market grades 1 and 2 between soil treatments within each year. Total production bars, comparing Control and SWRT treatments, having different capital letters are statistically different by the least significant difference (LSD) at (P ≤ 0.10) within each year. Different small letters within different market grades are significant production differences by each soil treatment for each year, N=4. Useful conversions: (1 hectare = 2.47 acres) and on (1 kg = 2.2 pounds).

cucumber crops as potential evapotranspiration (PET) ranged between 830 mm (32.7 in) and 900 mm (35.4 in).

These two lowest production years occurred when root zone soil VWC dropped below 10% during harvest beginning in mid-August 2011 (Figure 5), or during the vegetative stages through most of July 2013, shown in Figure 7. Ideal maintenance of root zone VWC in 2012 produced the greatest overall yields of cucumber with IWUE of 298 Kg/mm for the SWRT and 272 Kg/mm. Similar WUE values match polymer covered cucumber studies in China (18). This small difference in the IWUE or total WUE avoids positive and negative contributions of timely rainfalls and disregards the frequencies and durations of plant water deficits. However, the total water retained in root zones of all plants can be used to compare plant root water uptake efficiencies on a daily or possibly each minute that provides contrasting resistances to drought for the same crop cultivar.

Statistically greater soil water retention enhancement by SWRT membranes, Figure 6A and 6B resulted in improved production for both crops (Figures 3 and 4). Seasonal water deficits occurred when total ET exceeded supplemental irrigation rates and the soil VWC approached 10% when conductivity of soil water to plant roots is at rates well below daily ET causing plant water deficit stress [3]. However, no account of the adverse effects of hourly, daily, or week-long plant water deficits during various phonologic stages. From early plant establishment through harvest, both the control and SWRT soil treatments were irrigated and fertigated the same throughout all cropping seasons. Consequently, greater plant production on SWRT water improved plant root zones are considered to be the primary contributors to greater vegetable production.

SWRT plots retained higher soil water contents between daily irrigations and rainfall events during the growing season (Figures 5-8). Consequently, plant root systems on SWRT sands avoided numerous periods of plant water deficits, experienced by controls, significantly increasing yields beyond control treatments (Figures 3 and 4). We should also note when rainfall was lower than PET and irrigation systems malfunctioned (Figure 5), August 15 to September 26 green pepper production was jeopardized more on control than SWRT treatments, Figures 3 and 4 in 2011 and 2013, especially when PET was greater than combined rainfall and irrigation resources. Drought physiologists have clearly identified accumulations of numerous, often detrimental, metabolites in frequently and long-term water deficit stressed plants, which cause productivity losses [16].

Most agree deep leaching of nutrients occurs during excessive soil water losses from plant root zones. Therefore, it is important to note that when SWRT membranes maintained 5% to 6% greater VWC in plant root zone than controls, the largest yield differences observed by both the bell pepper and cucumber growing on SWRT soil treatments (Figures 3 and 4), may result from both optimal soil water, no reductions of VWC below 10% and possibly greater quantities of nutrients in plant root zones. Soil nutrient losses on control sands are much greater than SWRT sands, for additional crops grown on control and SWRT sand in central Michigan.

Seasonal demands for moisture by different crops are generally described as ET losses. The closer the soil water contents can be maintained to meet PET, the greater crop growth and production, without exposure to drought stress. For this location and soil type, the optimum range of VWC was identified to be 15-18%. When soil moisture fell below 10%, a significant amount of root function was lost. The soil volumetric water content for both the bell peppers and cucumbers in the control treatments fell below 10% on four different dates during 2012, resulting in limited soil water absorption (Figure 6A and 6B). This dramatically reduced plant uptake of water and nutrients resulting in lower crop production [17]. Subsequent papers will address the importance of maintaining optimal soil water, nutrients, and aeration for maximizing plant production. This greater soil water retention study demonstrated the importance for maintaining optimal soil water for the duration of crop production. When leaching is reduced, greater production can be achieved improving IWUE. SWRT enablement of 20 and 24% greater production by peppers and cucumbers while increasing IWUE by 41% and 19% better than controls, respectively. These IWUE exceed [18] and establishes a new approach for expanding production while protecting the environment including conserving soil water resources.

Combining prescriptive irrigation water for best SWRT membrane retention and surface Polymer-mulch, offers additional opportunities for increasing water use efficiency for horticultural crops. As more abiotic stresses are removed from plant root zones, plant genetic potentials will be liberated to expand production to their fullest genetic potential while using less water on highly permeable sand, loamy sand and sandy loam soils.

### SWRT economics and return on investment

Cost estimates of SWRT membrane installation ranges between $1,800 and $2,000 per acre, depending on membrane thickness and depth of installation. Early SWRT MIC two chisel, model 1 used to install water retaining membranes of this study has been improved fast approaching installations at higher velocities with our current model 4. This four-chisel implement should reduce SWRT installation fees. Further developments in RTK-GPS precision installation of more uniform depths highly parallel to previous passages will bring new opportunities to apply SWRT conversions of established orchards and upgrade sand regions in irrigation fields to receive more uniform water and nutrient management practices.

Costs for installing SWRT membranes in highly permeable soils necessitate greater production for best return on investment (ROI). Phenomenal production increases by green bell peppers and cucumbers completely recovered installation costs in 1.5 years (2 crops) for peppers and 5.8 years (6 crops) for cucumbers (Table 1). The merits of incorporating SWRT membranes into vegetable production and coupled with prescriptive irrigation schedules, will significantly contribute to long-term farm income, as SWRT membranes require no maintenance for many decades.

## Conclusion

Multiple season testing of two vegetable crops growing on soil water retaining membranes with timely applications of the same prescription levels of irrigation water clearly promoted vegetable production on highly permeable loamy sands SWRT soil treatment maximized IWUE using less water than irrigating 10 to 20% lower rates than recent daily PET guided rates causing non-significant production reductions [19]. Irrigated vegetables grown on SWRT membrane improved soils irrigated to maintain a range of 15-18% volumetric water content (VWC), enabling vegetable plants to avoid plant water deficits producing at least 20% greater yields of higher quality fruit than controls. However, when soil VWC exceeded 18% soil water solutions containing dissolved nutrients will most likely be lost via gravitational macro pore flow to soil depths below the dominant rooting zone [1-3].

Plant wilting occurred when VWC dropped below 10% during daytime hours, resulting in projected accumulations of toxic metabolites contributing to lower yields by annual plants [16]. Well drained SWRT improved sands do not promote anaerobic bacterial and fungal communities [4]. Consequently, we believe neither nitrous oxide nor methane greenhouse gases evolve from these transformed sand soils. Michigan bell pepper production on 1,400 acres produced 364,000 hundred weights (CWT) with a crop value exceeding $13 million in 2016. During the same year, Michigan cucumbers grown on 40,400 acres produced 5,414,000 CWT with a crop value of $61 million (U.S. Dept. of Agriculture Crop Statistics).

Twenty-percent production increases by green bell pepper and twenty-four percent production increases by cucumbers growing on highly permeable sand equipped with SWRT membranes could generate additional $15.6 million annual farm gate incomes across Michigan. These production increases were achieved along with 41% and 19% greater IWUE than irrigated controls. Therefore, we can confidently report properly installed water retention membranes provide a new technology for transforming permeable sands into highly sustainable horticultural production areas than currently irrigated sands. SWRT provided a more constant 4% higher VWC soil water supply to these vegetable roots. We believe these results are applicable to a range of similar soils for commercial vegetable producers irrigating highly permeable sands.

### Acknowledgement

This work was supported in part by the Natural Resources Conservation Service, U.S. Department of Agriculture, under NRCS Conservation Innovation Grant number 69-3A75-13-093, John Deere Innovation Center, and MSU AgBioResearch. Research support and onsite field assistance by Ron Goldy, David Francis, and Sami Berhanu are gratefully acknowledged.

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