Direct Root-zone Delivery to Enhance Deficit Irrigation Application

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Abstract: *Direct root-zone (DRZ) is a sub-surface micro-irrigation application that delivers water directly into the plant root zone via plastic pipe placed vertically into the soil to depths of 2-feet (60 cm) or more. Field trials were initiated during 2015 in commercial vineyards to determine: 1) ability of DRZ to achieve grape production at or near commercial production goals with reduced irrigation amounts; 2) determine ideal depth at which to deliver the water; and 3) determine advantage of applying water in interrupted pulses versus continuous application. In 2016, we began to analyze grapes for quality attributes. After four years, we have concluded that: 1) DRZ can achieve grape production at or near full production levels while using only 60 percent the amount of water normally applied as surface drip; 2) grapes receiving reduced amounts of water via DRZ had progressively higher sugar content (% Brix), reduced levels of acidity, and higher total anthocyanin at reduced rates of water delivery; 3) no differences in yield were attributed to either a specific of water delivery depth or to use of pulse delivery.*

Keywords: Water conservation, Subsurface micro-irrigation, Deficit irrigation, Wine grape quality

Introduction

The Columbia Basin of Washington State is one of three areas within the United States capable of producing more than 300 different crops. This ability stems from irrigation from river systems that traverse through the major growing regions and provide irrigation to lands that would otherwise support native desert vegetation typical of the intermountain west. Underground aquifers are limited and not capable of supporting the current level of agricultural production derived from surface water. Additionally, ground water quality is often lower than the surface water, but varies by locale. Most importantly, most irrigation water has been adjudicated and water is demanded by many competing interests, including fisheries, energy production, and domestic use.

Against this backdrop scenario has emerged a profitable crop with an 8 percent annual growth in acreage, winegrapes, which has placed Washington State in second place only to California and quickly achieving an enviable recognition for high quality premium wines. The only factor currently threatening continued growth of this phenomenal industry is availability of water https://www.washingtonwine.org. Therefore, use of water must become more efficient, and new, cost-effective methods must become available for use by growers. Alternatively, acreage and water resources now committed to current crops may need to be converted to permit continued growth of winegrape acreage.

Irrigation is typically applied to wine grapes as surface drip which is considered an efficient and effective method. However, in the hot, dry region of Washington State, water is lost to both soil surface evaporation and weeds. Additionally, vine root systems become mostly concentrated in the upper 18-20 inches (0.5 m) of the soil profile under current irrigation strategies (Stevens and Douglas, 1994; Bauerle *et al*., 2008; Davenport *et al*., 2008). This condition is compounded by the fact that wine grapes in this region are mostly own-rooted from varieties that typically develop shallow to medium depth root systems (Keller *et al*., 2012). These growth patterns may be more susceptible to both cold intolerance and drought during infrequent, short-term climatic perturbations such as experienced in 2010 and 2015.

Deficit irrigation is known to enhance a number of compounds related to production of premium red wines and substantial literature has been published on this topic that is summarized in detail by Chaves *et al.* (2010). Likewise, subsurface drip irrigation has emerged as an effective water saving strategy in a number of row crops (Lamm *et al*., 2012; 2015). Some growers in Washington had attempted to use subsurface micro-irrigation applied through buried lines and many reported that this system failed their expectations because of soil clogging of emitters and chewing damage by burrowing rodents. Therefore, a newer form of subsurface water delivery was developed in our lab during 2013-2014 which we labeled direct root-zone (DRZ) micro-irrigation. In the following paper, we describe the design and application of this system in two phases (proof-of-concept and commercial application).

To investigate opportunities for increasing water use efficiency, we initiated a coordinated, trans-disciplinary research effort in 2014 with three broad objectives: 1) determine the potential and feasibility for use of a new form of sub-surface drip irrigation which might improve water conservation while improving the use of deficit irrigation in the production of high quality premium red wine grapes; 2) gain a better understanding of the potential advantages of developing deeper root systems of vines to obtain moisture from the available soil profile in the rhizosphere; and, 3) evaluate the potential of remote sensing to monitor water stress on the whole vineyard scale when applying direct root-zone micro-irrigation at rates much lower than used to meet commercial wine grape production goals.

Methods and Materials

To guide the approaches and methods used in the proof-of-concept phase, a stakeholder advisory group was established involving active growers and managers representing leading red wine grape producers in Washington. This group was convened quarterly to confer and advise the project Principal Investigator (PI) and team members on critical industry needs and opportunities. This group assisted in identifying collaborators to host research experiments in commercial vineyards, and they provided letters of support for grant proposals submitted to sponsoring agencies.

Research Site Description. Treatments were installed in a commercial block of Cabernet Sauvignon wine grapes located on Kiona Vineyards, Block 2 (46^{o}16'59" N, 119^{o}26'33" W) in the Red Mountain American Viticulture Area (AVA) near Benton City, WA in early 2015. Soil on the experimental site is of the Aridisol order and classified as a Hezel loamy fine sand (Xeric Torriorthents) on a terrace landform with parent materials being eolian sands over silty glacio-fluvial sediments deposited at the end of the most recent ice age. These soils are well-drained, subject to wind erosion, and relatively infertile, containing very low amounts of organic matter. Depth to nearest water table is more than 80 inches (>2 m). Normal annual precipitation is 8.83 inches (224 mm) and occurs mainly as rainfall during the dormant growing season. Summer temperatures average 70^{o}F (21^o C) with mid-day temperatures reaching 90^{o}F (32^{o}C) or higher and cooling during the night, typical of a desert climate. These conditions favor the development of high quality red wine grapes under irrigation. The research site was planted to Cabernet Sauvignon (Clone 2) of own-rooted vines on a spacing of 8’ (2.5 m) between rows and 6’ (1.8 m) between vines. The vineyard was 8 years old at the beginning of the 2015 growing season.

Experimental Design: During the Proof-of-Concept phase of the study (2015-2017), a randomized complete block with two main effect treatments, irrigation rate and depth of delivery sub-surface was used with a split plot super-imposed to compare pulse irrigation and constant delivery. Each treatment plot involved 15 vines (5 vines x 3 rows) with the center-most 3 vines designated for physiological measurements while being buffered by other vines receiving the same treatment. Each of 18 treatment plots was replicated 3 times (810 vines) and yields were compared with 12 plots (180 vines) receiving full commercial rate of irrigation via surface drip. Irrigation scheduling was determined by the vineyard manager according to long-standing guidelines used to meet commercial production goals. In 2017, pulse irrigation was discontinued and some of those plots were repurposed to allow direct comparisons of surface drip and DRZ (subsurface drip) delivery at equal rates on grape yield, vine stress levels, and fruit quality. Since no consistent differences in yield or grape quality were related to DRZ delivery depth during the first two years of the study, all DRZ treatments were delivered at the 2-ft. depth for the new phase of the project. Additionally, rates of water application to the treatments were raised to 80, 60, and 40 percent of full commercial rate. This modification to the original design permitted direct measurements between surface and subsurface (DRZ) and allowed relative water use efficiencies to be determined for grape production (yield) and grape quality (phenolic and other chemical components).

Direct root-zone delivery device. DRZ is designed to deliver water to deep within the root zone vertically through PVC pipes. This approach was used to avoid the two most common problems associated with use of buried driplines – clogging of emitters in contact with soil and chewing damage of buried lines. An additional advantage was the ease of installing within established plantings of perennial crops such as grapes.

To install this system, a 1 inch (25.4 mm) diameter hole was bored vertically to a depth of 1, 2, or 3 foot (30, 60, and 90 cm respectively) about 1.5 foot (45 cm) either side from the base of each vine and beneath the trellis wire and suspended irrigation dripline. A length of PVC tube was inserted into each hole. Each section of PVC pipe was previously cut to length to reach the desired depth while extending above ground for a given distance and then split about 6 inches (15 cm) from the lower end with a band saw to allow sufficient water passage to move into the soil to reduce the backing of water up the tube. A PVC cap, previously drilled to allow passage of a one foot (30.5 cm) length of ¼ inch (6.35 mm) diameter micro-tubing through the hole prior to attaching one end to a barbed connector and inserted into the main horizontal water line, and attaching a pressure compensating drip emitter at the other end of the feeder tube before placing the emitter snuggly into the top of the PVC tube beneath the drilled out cap. Emitters were selected to deliver 0.5 gallon (2 liter) per hour, thus delivering approximately 1.2 gallon (4 liters) per vine per hour.

Installation of all treatments involving 990 vines was completed prior to beginning of the 2015 growing season. Additionally, soil moisture access tubes containing electron capacitance sensors were installed in designated plots to monitor soil water dynamics both temporally and spatially across depths within the top 6.5 feet (2.0 meters). This technique measured soil moisture content (data not shown) continuously when using the SynTek EnviroSCAN https://www.sentek.com.au or by supplemental spot reading when using the SynTek Diviner. Irrigation events were monitored by data transmitted from the EnviroSCAN probes via cellphone transmitters to a base server AgriNET http://www.grovision.com .

Monitoring of plant water stress. Vine water stress was determined by periodically sampling the center three vines of direct root-zone treatments and control vines by measuring mid-day xylem water potential using the pressure bomb method (Scholander *et al.*, 1965). Leaves were selected on the east side of vines (most sun drenched prior to sampling), then covered with a plastic bag inside an aluminum foil exterior envelope and allowed to equilibrate for about an hour prior to sampling. The encased leaf was detached from the vine by severing the petiole with a razor blade, then quickly removed from the bag and inserted into the pressure chamber, while shielding the leaf from direct sunlight, then pressurized with nitrogen gas to the point of water movement from the cut petiole. Pressures were measured in pounds per square inch (psi), then converted to mega-pascals. These data were correlated with multi-spectral digital images obtained through aerial and ground-based platforms during both growing seasons as described and reported by Zuniga *et. al.* (2017; 2018). Visual observations of plant condition were documented with digital photos to document phenological impacts on vines from treatments as described by Keller (2005). Additionally, periodic measurements of gas exchange were taken with a field portable auto-porometer to gauge vine physiological activity.

Determination of grape production and quality. In 2015, grape clusters from designated vines were collected to determine estimates of production, as well as number and size of berries in each treatment and control block. Sampling was executed during two stages of maturity, early-*veraison* and mid-*veraison*. At the 2015 harvest date (September 26), all grapes were harvested at end of growing season from replicated rows of each treatment and weighed by individual vine. In 2016, cluster sampling was not repeated, but all vines in the treatment plots and a sample of commercially irrigated vines were harvested on September 24 and weighed. Samples of grapes from specific treatments were collected two weeks prior to harvest and submitted to a private commercial laboratory for analytical determination of a number of characteristics associated with quality red wines. Samples of clusters from each treatment were also taken at the date of harvest and submitted to the same commercial lab for juice and phenolics analyses. A similar sampling procedure was used in 2017 and 2018 to directly compare DRZ delivered at the 2-ft. (60 cm) depth with surface drip treatments, both applied as equally reduced rates in replicated plots during the second phase of the study.

Results and Discussion

Proof of Concept Phase: Treatments were successfully implemented during three consecutive growing season from 2015 through 2017. Direct root-zone treatments (DRZ) were effective in delivering water to the designated depths. The electronic controllers worked flawlessly, as did the small mechanical meters, except it was necessity to remove the meters over the winter months and reinstall prior to initiation of irrigation in the spring of the year. We discovered that the meters performed most accurately when placed face-up rather than to the side, owing to an internal design factor.

Comparison of pulse and constant irrigation delivery methods revealed no differences their relative contribution to either plant water stress or grape yield and these comparisons were terminated after 2016. Likewise, we found no consistent influences for delivery of water at any particular depth below the soil surface and no interaction was found between depth and amount of water applied.

Table 1. Seasonal irrigation delivery and water use efficiency based on grape production during 2015 and 2016 comparing commercial surface drip irrigation with season-long deficit irrigation imposed by direct root-zone micro-irrigation delivered subsurface at rates of 60, 30, or 15% the rate of surface drip irrigation.

	Commercial	**Irrigation Treatments**		
	(100 %)	60 %	30%	15%
2015 Water Use (acre ft.)	1.25	0.81	0.40	0.20
Grape production (tons/ac.)	4.54	4.08	3.40	3.18
Production Efficiency (tons/ac. ft. applied)	3.63	5.04	8.50	15.90
Relative Efficiency	1.0	1.39	2.34	4.38
2016 Water Use (acre ft.)	1.27	0.84	0.43	0.23
Grape production (tons/ac.)	8.16	5.02	4.19	3.52
Production Efficiency (tons/ac. ft. applied)	6.43	5.98	9.74	15.30
Relative Efficiency	1.0	0.93	1.51	2.38
2017 Water Use (acre ft.)	1.24	0.74	0.37	0.19
Grape production (tons/ac.)	4.64	4.43	4.06	3.52
Production Efficiency (tons/ac. ft. applied)	3.74	5.99	10.97	18.53
Relative Efficiency	1.0	1.60	2.93	4.95

Water use efficiency, determined as amount of fruit produced per unit of water applied, increased progressively with reduced rates of irrigation in 2015. This trend was repeated in 2016 and 2017, but was not as pronounced, largely owing to a much higher rate of grape production that occurred from the commercial plots in 2016 than in 2015 and high soil water content during the first half of 2017.

One of the objectives for the Proof-of-Concept phase was to ascertain the greatest degree of water conservation that could be achieved while maintaining health and productivity of the vine. The 2015 growing season was determined to be the hottest and driest on record for the area. Fruit production at the commercial irrigation rate and applied by surface drip averaged 10 pounds (4.5 kg) per vine, while DRZ irrigation applied 1-3 feet subsurface at reduced rates of ca. 60, 30, and 15% of full commercial rate produced an average of 9.0, 7.6, and 7.2 pounds per vine, respectively. By contrast, the 2016 growing season was one of the most productive on record with commercial production averaging almost 18 pounds per vine (8.16 tons/acre). DRZ treatments produced an average of 11.1, 9.2, and 7.8 pounds per vine (5.0, 4.2, and 3.5 tons per acre, respectively). There was wider disparity in fruit production between the commercial treatment plots and the DRZ plots than occurred during the previous growing season (Table 1) which we attribute to carryover effects on fruit set from the 2015 growing season and the levels of stress imposed from the reduced rates of water delivery.

Plant water stress, as measured by obtaining xylem pressure potentials among the treatment vines, showed obvious differences among the irrigation delivery rates when measured at 3 dates during the growing season (Table 2). Plant water stress increased proportionately with decreasing irrigation rate and progression of the growing season. Similar measurements were taken at only one date during 2015 and also showed progressively more stress with decreasing water application rates of DRZ irrigation (data not shown). Stress measurements continued on a more frequent basis during the subsequent years of study and consisted of both on plant water status measurement by xylem pressure method (Scholander, 1967) and remote sensing techniques (Zuniga *et. al.*, 2017; 2018).

Table 2. Plant water stress as determined by leaf stem xylem potential during 2016 growing season contrasting commercial surface drip irrigation with season-long deficit irrigation imposed by direct root-zone micro-irrigation delivered subsurface from 1-3' depths at rates of 60, 30, or 15% the rate of surface drip irrigation.

	Irrigation Treatments			
	Surface Drip (DI)	----------------------------DRZ------------------------		
	(100 %)	(60 %)	(30%)	(15%)
2016	Xylem Pressure Potential (-MPa)			
June 3	-0.529	-0.593	-0.641	-0.781
July 7	-0.635	-0.825	-0.925	-1.188
August 10	-0.869	-1.177	-1.522	-1.593

In 2015, cluster samples from the DRZ treatments showed that cluster weights were slightly lower, but grapes were more numerous, yet smaller in size than in the clusters from vines receiving the higher irrigation rate. These findings suggested that the grapes from the lower irrigation rates might have greater potential to produce higher quality red wine, owing to higher concentration of anthocyanins, tannins and sugars. In 2016, similar effects were noted for grapes receiving the DRZ treatments. Replicated cluster samples were obtained from the commercial and DRZ treatment plots and submitted to a private, commercial analytical lab for determination of a dozen components and ratios. Data summarized in Table 3 illustrates four of these components. Acidity became progressively reduced below the 60% irrigation rate, while sugars (Brix), tannins, and anthocyanins all trended higher with decreasing rate of irrigation. These results are in line with the findings of Casassa *et al.* (2015) who noted that efforts to derive benefits in grape quality and water savings through greatly reduced irrigation levels should recognize the potential for yield reductions and/or physiological impacts on vines. Results from our study provides evidence that use of efficient irrigation application such as DRZ could both sustain vines and produce grapes during drought conditions while yielding grapes with potential to produce premium quality red wines in the hands of skilled viticulturists and enologists.

Table 3. Comparison of selected chemical components influencing red wine quality. Analyses of Cabernet Sauvignon grapes grown under full and reduced rates of irrigation during 2016. Reduced irrigation rates were applied via direct root-zone micro-irrigation (DRZ) delivered 2 feet (61 cm) subsurface.

	Surface drip (DI)	DRZ		
	Control (100 %)	High (60 %)	Moderate (30%)	Low (15%)
2016				
pH	3.41	3.36	3.48	3.55
Brix (degrees)	25.5	27.1	27.6	28.6
Tannins (mg/L)	403	594	600	741
Anthocyanin (mg/L)	1015	1242	1298	1480
2017				
pH	3.38	3.55	3.50	3.47
Brix	25.1	25.3	26.5	25.0
Tannins	730	676	839	784
Anthocyanin	1185	1167	1447	1373

Treatment plots were harvested each year a few days prior to commercial harvest. Each vine was harvested and fruit was weighed on site. Yields within a given irrigation amount were not consistently influenced by depth of the water delivery within the soil profile. No significant differences were attributed to whether or not the water delivery was interrupted into hourly pulses or applied continuously at the selected rate. However, yields were impacted by the total amount of water applied. These rates were applied at the pre-selected rates throughout the entire growing season from start to finish. Under this regime, individual grape size was found to be reduced consistent with the declining amounts of water delivered. Approximately 6 clusters per treatment replication were selected for subsequent juice and phenolic panel analyses by a commercial analytical laboratory. These analyses revealed that pH and titratable acidity increased in proportion to amount of water applied, i.e. more acidic. Total anthocyanin, Brix, and tannins increased in proportion to increasing irrigation deficit, in response to greater plant stress.

Data obtained during the 2015 and 2016 growing seasons revealed that vines tended to show increasing levels of stress with lowering of the rates of water as anticipated; however, rates below 60 percent of commercial delivery resulted in less than 80 percent of commercial production and often led to berry shrivel at the lowest rate of delivery, regardless of depth of water delivery. Additionally, canopy cover at the low level of delivery was reduced to a level that was deemed less than acceptable.

Therefore, prior to the initiation of the 2017 growing season DRZ irrigation rates were adjusted to higher rates of irrigation on selected plots representing approximately 80, 60, and 40 percent the rate of surface drip irrigation used to achieve commercial production goals. In 2017, levels of soil moisture were exceedingly high from high amounts of winter snow moisture and cool, moist weather during spring that deferred the initiation of irrigation until July (Figure 1).

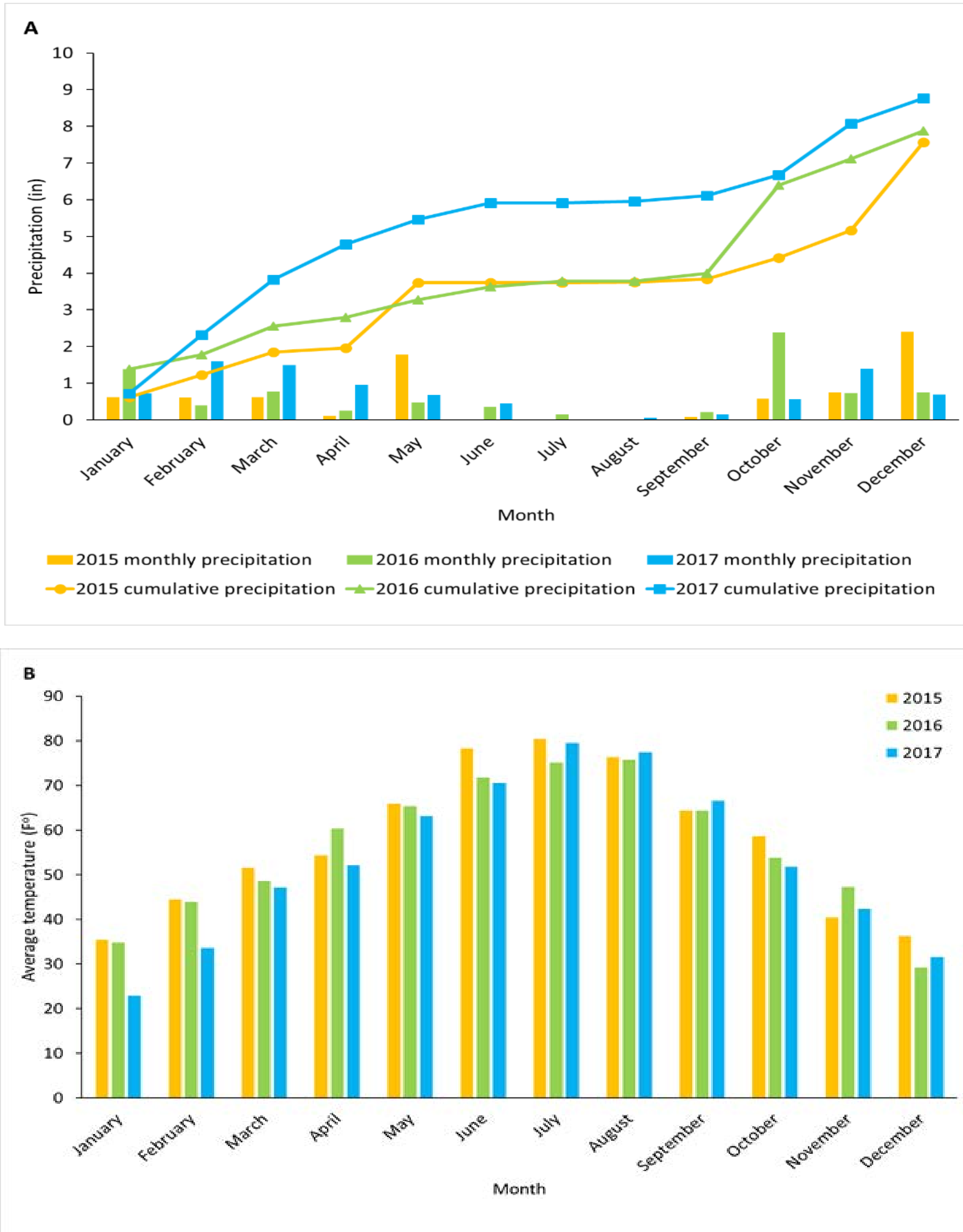

Figure 1. Average monthly and accumulated precipitation (A) and monthly temperature (B) during 2015, 2016, and 2017 at study site near Benton City, WA.

Grape yields from DRZ treatments during 2017 and 2018 proved to be largely statistically insignificant and generally in the same ranges of yield as grapes receiving the commercial rate of irrigation. Vines receiving DRZ subsurface delivery generally produced higher yields than vines receiving the same rate of water delivered as surface drip. Vines receiving DRZ delivery, including those reduced to 40 percent of full surface drip, also consistently produced higher yields than the vines which received full rates of surface drip irrigation. Grape quality factors such as Brix and anthocyanin increased progressively with decreased levels of water (data not shown).

Conclusions

A new form of subsurface micro-irrigation was developed to achieve direct root-zone (DRZ) subsurface delivery of drip irrigation to wine grapes in Washington State. During the concept phase of the project, vines were maintained at production levels with much reduced amounts of water than required by vines managed to meet production goals. In 2015, DZR water delivery reduced to 60, 30, and 15% of commercial irrigation rate produced ca. 90, 75, and 70% of the commercial grape production weight, respectively. Second year production rates were generally lower relative to the commercial grape yield, suggesting a carry-over effect from stress imposed during the previous year. No obvious advantages were found for using pulse irrigation delivery over continuous application sets. No consistent patterns were observed to favor a specific depth among 1, 2, or 3 ft. subsurface delivery points. Rates of deficit irrigation using DRZ delivery were raised to 80, 60, and 40 percent of commercial rate during 2017 and 2018. Comparison of DRZ delivered at the 2-ft. depth with surface drip irrigation consistently showed higher yields at each reduced rate and grape quality was improved over grapes produced with equal rates of surface drip irrigation. DRZ demonstrated the ability to achieve water savings up to 60 percent of the rate applied by surface irrigation to achieve commercial production goals while producing higher yields and quality of grapes than achieved with standard surface drip irrigation.

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