Journal of Agricultural Science; Vol. 9, No. 6; 2017
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Above Ground Drip Application Practices Alter Water Productivity of Malbec Grapevines under Sustained Deficit

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Received: March 17, 2017 Accepted: April 16, 2017 Online Published: May 15, 2017

doi:10.5539/jas.v9n6p1 URL: https://doi.org/10.5539/jas.v9n6p1

This research was partially financed by a grant from the Northwest Center for Small Fruits Research and the Agricultural Research Service project 5358-21000-034-00D.

Abstract

An objective of this study was to identify above ground drip application practices for winegrape that increase water productivity and mitigate water deficit-associated loss of yield. The influence of irrigation frequency on water productivity under two severities of sustained deficit irrigation was evaluated in field grown Malbec grapevines (*Vitis vinifera* L.) over three growing seasons. A weekly amount of water was delivered in a single irrigation event (1X) or apportioned into thirds and delivered in three irrigation events per week (3X). The least severe deficit (STD) had a 3-yr average maximum duty cycle (ratio of irrigation duration to irrigation interval) of 0.3, and vines irrigated 3X relative to 1X had higher water productivity each year due to a decrease in pruning weight. The most severe deficit (STD50) had a 3-yr average maximum duty cycle of 0.02 and vines irrigated 1X relative to 3X had higher water productivity due to a reduction in pruning weight in 2012 and an increase in yield in 2013. The fruit produced from vines irrigated at the frequency with highest water productivity under each deficit severity contained a lower concentration of anthocyanins. While treatment combinations did not alleviate a water-stress associated reduction in yield, results provided new information about grapevine water use efficiency that can be used to select combinations of irrigation frequencies and duty cycles with potential for increasing water productivity.

Keywords: irrigation, *Vitis vinifera* L., water productivity, water stress, winegrape

1. Introduction

A majority of global winegrape (*Vitis vinifera* L.) production is located in semi-arid regions where sustainability relies upon efficient use of limited water resources (Medrano et al., 2015). In wine-producing regions that experience summer drought, irrigation is commonly used to optimize vine balance and manage fruit quality (Chaves et al., 2010). However, irrigation for crop production will increasingly take place under water scarcity due to climate change and competition for water with industrial and domestic users (Costa, Ortuño, & Chaves, 2007; Fereres & Soriano, 2007; Davies, Zhang, Yang, & Dodd, 2011). Deficit irrigation is the practice of supplying an amount of water to a crop that is a fraction of the crop's estimated water demand (ET_c). Deficit irrigation is widely used as a method to sustain crop productivity under water scarcity. Sustained (SDI) and regulated (RDI) deficit irrigation and partial root-zone drying (PRD) are deficit irrigation strategies used in winegrape production to improve water use efficiency (Fereres & Soriano 2007; Medrano et al., 2015). Water productivity is the amount of marketable product produced per unit of supplied water and it is a measure of water use efficiency at the crop level (Fereres & Soriano, 2007; Davies et al., 2011; Medrano et al., 2015). The marketable product produced from winegrapes is the harvested fruit so seasonal water productivity in winegrape can be measured as the relationship between the Ravaz index (ratio of yield to pruning weight) and the amount of supplied water (Davies et al., 2011; Shellie, 2014).

A practical difference between SDI and RDI is the fraction of ET_c supplied during the growing season. The supplied fraction of ET_c remains constant under SDI, whereas it is altered at particular phenological stages under

RDI (Shellie, 2014; Munitz, Netzer, & Schwartz, 2017). A similar level of water productivity can be attained using SDI or RDI; however, reduced water usage is usually associated with a reduction in yield (Davies et al., 2011; Shellie, 2014). The PRD irrigation strategy evolved from studies with potted grapevines where it was observed that water use efficiency could be increased without reducing berry size by alternating the wet and dry portions of the root zone to induce root-to-shoot signaling of abscisic acid (ABA) (Stoll, Loveys, & Dry, 2000). A consistent response to PRD can be induced under controlled conditions; however, under field conditions, vine response to PRD has frequently been undistinguishable from that of other deficit irrigation strategies and response has been found to vary according to the supplied percentage of ET_c (Dodd, 2009; Davies et al., 2011; Sadras, 2009; Chaves et al., 2010; Puértolas, Alcobendas, Alarcón, & Dodd, 2013; Romero et al., 2015).

When above ground drip is used to supply water for irrigation, the drip emitters create a heterogeneous wetting pattern in the vine row beneath the drip line (Goldberg, Rinot, & Karu, 1971; Davenport, Stevens, & Whitley, 2008; Bowen, Bogdanoff, Usher, Estergarrd, & Watson, 2011). The configuration of the drip system, interval between irrigation events and irrigation amount will alter the spatial and temporal distribution of the wetting pattern in the soil profile (Sinai, Zur, & Haramati, 2007). The ideal irrigation application should recharge the soil profile in minimum time at a maximal application rate that does not cause water logging or runoff at the soil surface. The different drip irrigation application practices used under field conditions in deficit irrigation trials may partially explain the inconsistent results on vine drought response found in the literature (Sadras, 2009). In the few studies that have investigated the influence of irrigation intervals on water productivity under field conditions, results have been confounded by differing amounts of plant available water in the root zone due to different deficit irrigation treatment amounts (Hepner, Bravdo, Loinger, Cohen, & Tabacman, 1985) or irrigation frequencies with duty cycles, defined as the ratio of irrigation duration to irrigation interval, that caused excessive drainage or aeration stress from water logging at the soil surface (Goldberg et al., 1971; Selles et al., 2004). The objective of this study was to delineate the influences of above ground drip emitter configuration and irrigation event frequency on water productivity, yield components, and berry maturity in field grown Malbec grapevines under two severities of SDI. A practical goal of the study was to identify water-use-efficient, above ground drip application practices that increase water productivity under deficit irrigation by mitigating water deficit-associated loss of yield.

2. Materials and Methods

2.1 Trial Site and Experimental Design

The study was conducted in an experimental vineyard located at the University of Idaho Parma Research and Extension Center in Parma, ID (lat. 43°37′7.9716″N, long. 116°12′54.1″W, 750 m asl.) during the 2011, 2012 and 2013 growing seasons. The climate at this location was a Köeppen classification of BSk, meaning that plant growth was limited by water availability. Soil texture at the trial site was a sandy loam with an available water-holding capacity of 0.14 cm/cm soil. Water for irrigation was sourced from a ground well located at the trial site. The wine grape cultivar Malbec was planted in 2007 on its own roots in rows oriented north to south with a row and vine spacing of 2.4 m and 1.8 m, respectively. The vines were double-trunked and each trunk was trained to form one side of a bilateral cordon. Canes were spur-pruned annually to 16 buds/m of cordon. Shoots were vertically positioned on a two-wire trellis with moveable wind wires. Disease, weed and pest control were managed according to local commercial practices.

The experimental design was a 2 × 3 factorial, split-split plot with six replicate blocks. Irrigation amount was the main factor. Drip line emitter spacing/delivery rate was split within each irrigation amount. Irrigation event frequency was split within each drip line configuration subplot. A block was comprised of 12 adjacent vine rows with 12 vines per row. Six consecutive vines across the 12 adjacent rows of each block were deficit irrigated from fruitset until harvest with 70 (STD) or 35% (STD50) of estimated weekly ET_c. The STD irrigation amount was intended to induce a sustained, mild water deficit, similar to standard industry practice (Keller, Smithyman, & Mills, 2008). Weekly ET_c was calculated by multiplying the value for reference crop evapotranspiration (ET_r), acquired from a weather station located within 3 km of the study site (http://www.usbr.gov/pn/agrimet/wxdata.html), by the value of a crop coefficient that was increased from 0.3 to 0.7 during the growing season (Allen, Pereira, Raes, & Smith, 1998; Keller et al., 2008). Different spacing between in-line emitters with different delivery rates were used to create spatially different soil wetting patterns. Six adjacent rows within each irrigation subplot had above ground drip with an emitter spacing/delivery rate of 45 cm/16.7 ml/min or 90 cm/33.4 ml/min. Both emitter spacing/delivery rate configurations delivered the same amount of water per hour. Plots with 45 cm emitter spacing had four emitters per vine (4E) and plots with 90 cm emitter spacing had two emitters per vine (2E). Each drip line configuration was used to supply a weekly amount of water as a single weekly event (1X) or apportioned into thirds and delivered as three irrigation events per week (3X). Three adjacent rows (6 vines per row) with the same drip emitter configuration were irrigated 1X or 3X. Vines located in outer rows and at either end of the interior row of each plot were treated as guard vines. Data were collected from vines located in the interior of the middle row of each plot. The trial perimeter had a two-vine deep border. Allocation of irrigation amount, emitter spacing/delivery configuration and irrigation event frequency treatment levels was randomized within each replicate block and the same treatment level was applied to all plots in each successive year of the study. The six replicate blocks for each treatment level were connected to one of eight, independently controlled, water supply manifolds. The manifolds were equipped with a programmable solenoid and a flow meter. All plots were irrigated to field capacity prior to budbreak. There were no subsequent irrigations until the start of treatment applications. The irrigation treatments were initiated after fruitset, when berries were ~7 mm in diameter and vines were at growth stage 31 of the modified E-L grapevine growth stage system (Coombe, 1995).

2.2 Soil Moisture and Vine Water Status

Soil moisture was recorded hourly using a time domain reflectometry (TDR) data-logging system (Moisture Point; Environmental Sensors Inc. Sydney, Canada). Each probe was 91-cm long and had measurement sensors located at soil depths of 30, 46, 61, 76, and 91 cm. One probe was permanently installed at a standard distance from the vine trunk and drip emitter, as described by Bowen, Bogdanoff, and Estergaard (2012), in a single replicate of each subplot.

Vine water status was monitored weekly by measuring leaf water potential at midday (Ψ_{lmd}) using a pressure chamber (model 610; PMS Instruments; Corvallis, OR) as described by Shellie (2014). Weekly Ψ_{lmd} was measured on the sixth day after a weekly irrigation event. In 2013, the $^{13}C/^{12}C$ ratio ($\delta^{13}C$) of juice at harvest was measured following the method of Herrero-Langreo, Tisseyre, Goutouly, Scholasch, and Van Leeuwen (2013).

2.3 Yield Components and Berry Composition

Fruit were harvested when a composite sample of randomly collected clusters had a target soluble solids concentration (SS) of ~24% and a juice titratable acidity (TA) of 4 to 6 g/L. All plots were harvested on the same day. On the day of harvest, a basal cluster was removed from either side of two main shoots from the center two data vines in each plot (n = 8/plot). The sampled clusters were immediately placed into a cooler and transported to the lab on the day of harvest. The remaining clusters on each data vine were counted as they were removed from the vine and their weight was added to the weight of sampled clusters to determine yield per vine. Sampled clusters were individually weighed and used to calculate average cluster weight. Average berry fresh weight and number of berries per cluster were determined by counting the number of berries per cluster and dividing the weight of the cluster by the number of berries per cluster (2011 and 2012) or by dividing average cluster weight by the average weight of 100, randomly sampled berries (2013). Samples of 100 berries were stored at -80 °C for analysis of total berry anthocyanins following the method of Iland, Bruer, Edwards, Weeks, & Wilkes (2004), and for $\delta^{13}C$ analysis by isotope-ratio mass spectrometry at the Stable Isotope Facility (UC Davis, University of California Davis, CA).

The remaining berries from the 8-cluster sample were used to measure juice SS, pH and TA following methods of Iland et al. (2004) using equipment previously described by Shellie (2006). The same vines harvested for yield and berry measurements were pruned to two bud spurs during dormancy and pruned canes from each vine were weighed. The ratio of yield to pruning weight (Ravaz index) was calculated as an indicator of vine balance. Water productivity was expressed as the relationship between the Ravaz index and seasonal irrigation amount.

Seasonal cumulative growing degree days (GDD) were calculated from daily maximum (no upper limit) and minimum temperatures from 1 Apr to 31 Oct using a base threshold of 10 °C. Temperature data were obtained from the same weather station used for ET_r.

2.4 Statistical Analysis

Data were analyzed by year using a mixed model analysis of variance with a 2 × 3 factorial and split-split plot treatment structure (SAS version 8.02; SAS Institute, Cary, NC). Fixed effects were irrigation amount, emitter configuration, and irrigation frequency. Weekly Ψ_{lmd} were analyzed by phenological stage of the vine. Probability of a significant difference among fixed effect treatment levels ($p \leq 0.05$) was determined using the Tukey-Kramer adjusted t-test. The significance of interaction effects was determined using the LSMEANS slice statement at $p \leq 0.05$. Graphs presented in figures were generated using Sigmaplot 11.2 (Systat Software, San Jose, CA).

3. Results

3.1 Environmental Conditions and Irrigation Amounts

In 2011, seasonal GDD accumulation and ET_r were lowest of the three study years and were 14 and 7% lower than the 11-yr average for the location (Table 1). In 2012, GDD and seasonal ET_r were similar to the 11-yr site average. In 2013, seasonal GDD was similar to the 11-yr site average but ET_r was 6% higher than the 11-yr site average. The amount of seasonal precipitation was similar to the 11-yr site average in each study year. The onset of bloom and the day of harvest in 2011 were 20 and 27 days later than in 2013. In 2011, 2012 and 2013 the day of year for bloom was 175, 167, and 155; for veraison was 241, 233 and 224; and for harvest was 293, 284 and 266, respectively. The elapsed number of days between bloom and veraison was 66 (2011 and 2012) and 69 (2013); and between veraison and harvest was 51 (2011 and 2012) and 42 (2013).

Irrigation treatments were initiated on day of year 173, 179 and 184 and were applied for 15, 14 and 12 weeks in 2011, 2012 and 2013, respectively. The amount of water supplied to vines under the STD irrigation amount was 37, 45 and 35% of seasonal ET_r in 2011, 2012 and 2013, respectively (Table 1). Vines under the STD50 irrigation amount were supplied 50 (2011), 43 (2012) and 50% (2013) of the STD irrigation amount. The amount of water actually delivered to 3X plots was from 2 to 7% less than 1X plots. The amount of water delivered to plots with 4E drip line configuration was ~1 to 5% less than plots with 2E drip line configuration.

Table 1. Growing season (1 Apr through 31 Oct) environmental conditions at the field trial site and irrigation treatment amounts

	2011	2012	2013	2000-2010 Average[a]
GDD[b] (°C)	1488	1710	1757	1733±162
Pcp[b] (mm)	105	76	102	95±33
ET_r[b] (mm)	1155	1270	1321	1243±46
Seasonal irrigation treatment amount (mm)[c]				
STD	423	571	468	
1X	439	579	472	
3X	407	562	464	
2E	434	574	475	
4E	411	567	461	
STD50	210	244	234	
1X	214	251	238	
3X	206	237	231	
2E	215	245	235	
4E	205	243	233	

Note. [a]Average and standard deviation for years 2000 through 2010. [b]Heat unit accumulation (GDD), precipitation (Pcp) and reference evapotranspiration (ET_r) from the Bureau of Reclamation AgriMet system [(www.usbr.gov/pn/grimet/), latitude 43°48′00″, longitude 116°56′00″, elevation 700 m] PMAI weather station. GDD calculated as simple average with no upper limit and a base threshold of 10 °C. ET_r from 1982 Kimberly-Penman equation for well-watered alfalfa with 30-50 cm top growth (Jensen et al., 1990). [c]Amount of water supplied to Malbec grapevines to satisfy 70 (STD) or 35 (STD50) percent of estimated water demand. Weekly estimated irrigation amount was delivered in a single weekly event (1X) or apportioned into thirds and delivered as three events per week (3X) using above ground drip with in-line emitter spacing/delivery rate configurations of 45 cm/16.7 ml/min (4E) or 90 cm/33.4 ml/min (2E).

3.2 Soil Moisture

Irrigation amount, drip line configuration and irrigation event frequency influenced the vertical depth of water penetration after an irrigation event. Water penetration was deeper under STD (72 to 91 cm) than under STD50 (46 to 61 cm) and deeper in plots with 2E than 4E drip configuration. The average depth of water penetration in plots under STD with 2E drip configuration was 91 cm when irrigated 1X and 76 cm when irrigated 3X. Plots under STD50 with 2E drip configuration had an average depth of water penetration of 61 cm when irrigated 1X and 46 cm when irrigated 3X. In plots with 4E drip configuration, the average depth of water penetration was 76 cm under STD and 46 cm under STD50, and was similar when irrigated 1X or 3X.

3.3 Leaf Water Potential and $^{\delta}$13C

Weekly Ψ_{lmd} was measured eight (2011 and 2012) or six (2013) times between fruitset and veraison and five times (all years) between veraison and harvest. The influence of irrigation event frequency on Ψ_{lmd} was different under each irrigation treatment amount (Figure 1). Under STD, vines irrigated 3X had significantly less negative Ψ_{lmd} than vines irrigated 1X, during the period from fruitset to veraison in 2011 and 2012, and during the period from veraison to harvest in 2012 and 2013. In all three years, the Ψ_{lmd} of vines under STD50 irrigated 3X was similar, during the period from fruitset to veraison, and significantly different, during the period from veraison to harvest, as vines irrigated 1X. In 2013, irrigation frequency had no influence on δ^{13}C; however, vines under STD50 had a lower δ^{13}C (-24.13) than vines under STD irrigation (-26.65). Emitter configuration had no significant influence on Ψ_{lmd}.

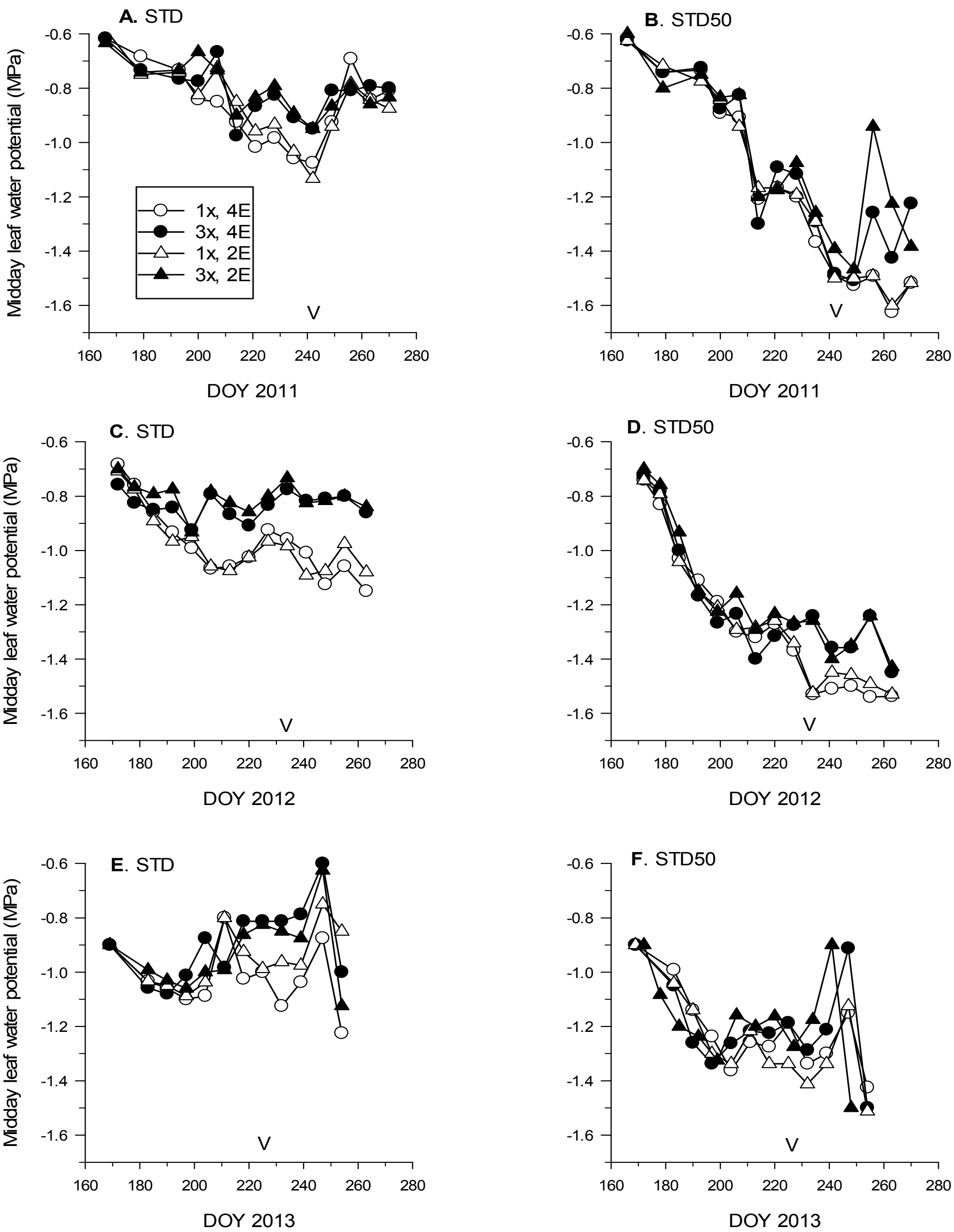

Figure 1. Weekly midday leaf water potential of Malbec grapevines under sustained deficit irrigation that were supplied 70 (STD) or 35 (STD50)% of estimated vine water demand as a single weekly event (1X) or apportioned into thirds and applied as three events per week (3X) and delivered with above drip that had an emitter spacing/delivery rate of 45 cm/16.7 ml/min (4E) or 90 cm/33.4 ml/min (2E) in 2011 (A and B), 2012 (C and D), and 2013 (E and F). The day of veraison is indicated with the letter "V"

3.4 Vine Balance and Water Productivity

There was a significant interaction between irrigation frequency and irrigation amount on pruning weight each year and on yield in one out of two years (Figure 2). In each respective year, vines under STD irrigated 3X had 19, 11, and 16% lower pruning weight than vines irrigated 1X. The only year that irrigation frequency had a significant influence on yield under STD was in 2012, when vines under STD irrigated 3X had 21% higher yield than vines irrigated 1X (Figure 2). In 2012, the berry fresh weight of vines under STD irrigated 3X was greater than that of vines irrigated 1X (Table 2). Vines under STD irrigated 3X had greater cluster weight in 2011 and 2013 and lower berry weight in 2011 than vines irrigated 1X (Table 2); however, these differences had no detectable influence on yield in 2011 or 2013 (Figure 2).

Under STD50, irrigation frequency influenced pruning weight only in 2012 when vines irrigated 1X had 24% lower pruning weight than vines irrigated 3X (Figure 2). In 2013, vines under STD50 irrigated 1X had higher yield than vines irrigated 3X. In 2013, vines under STD50 irrigated 1X had greater cluster weight and a greater number of berries per cluster than vines irrigated 3X (Table 2).

The dormant pruning weight of vines under STD50 was 34 (2011) or 50% (2012 and 2013) less than that of vines under STD (Figure 2). Vines under STD50 had 43 and 31% lower yield than vines under STD in 2012 and 2013, respectively, and similar (5.5 kg) yield per vine in 2011 (Figure 2). In 2012 and 2013, vines under STD50 had ~26% fewer clusters than vines under STD (Table 2). Vines under STD50 had lower cluster weight and berry fresh weight than vines under STD in each respective year of the study; although the difference in cluster weight in 2013 was not of statistical significance. Drip line configuration had no consistent main or interactive effect on pruning weight or yield (data not shown) or yield components (Table 2).

Table 2. Yield components for Malbec grapevines supplied with 70 (STD) or 35 (STD50) percent of estimated weekly water demand in a weekly event (1X) or apportioned into three events per week (3X) using above ground drip tubing with emitter spacing/delivery rate configurations of 90 cm/33.4 ml/min. (2E) or 45 cm/16.7 ml/min (4E) over three growing seasons in Parma, ID

Treatment	Cluster number per vine			Cluster weight (g)			Berry weight (g)			Berry number per cluster		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
I[a]												
STD	33	41a	42a	180.3a	152.7a	134.8	2.0a	1.6a	1.4a	68	87	94
STD50	36	30b	32b	147.8b	115.5b	118.0	1.7b	1.3b	1.2b	73	99	101
*I*F*[b]												
STD-1X	35	41	43	163.2a	148.1	127.0a	2.2a	1.6a	1.4	69	84	90a
STD-3X	30	40	41	197.4b	157.2	142.8b	1.9b	1.7b	1.4	66	90	99a
STD50-1X	35	31	31	145.6a	119.6	130.8a	1.7a	1.3a	1.2	74	91	110a
STD50-3X	36	28	34	150.0a	111.4	105.3b	1.8a	1.3a	1.1	73	107	93b
p value[c]												
Irrigation (I)	ns	**	**	**	**	ns	**	**	**	ns	ns	ns
Emitter (E)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
I × E	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Frequency (F)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
I × F	ns	ns	ns	*	ns	**	*	*	ns	ns	ns	**
E × F	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
I × E × F	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns

Note. [a]Different lower case letters indicate significant difference between treatment levels within a given year ($p \leq 0.05$ determined by Tukey-Kramer adjusted t-test). [b]Least square mean values followed by a different letter between subplot treatment level rows within a year column are significantly different ($p \leq 0.05$) according to LSMEANS slice statement using a mixed model analysis of variance. [c]*, $p \leq 0.05$; **, $p \leq 0.01$; ns, not significant.

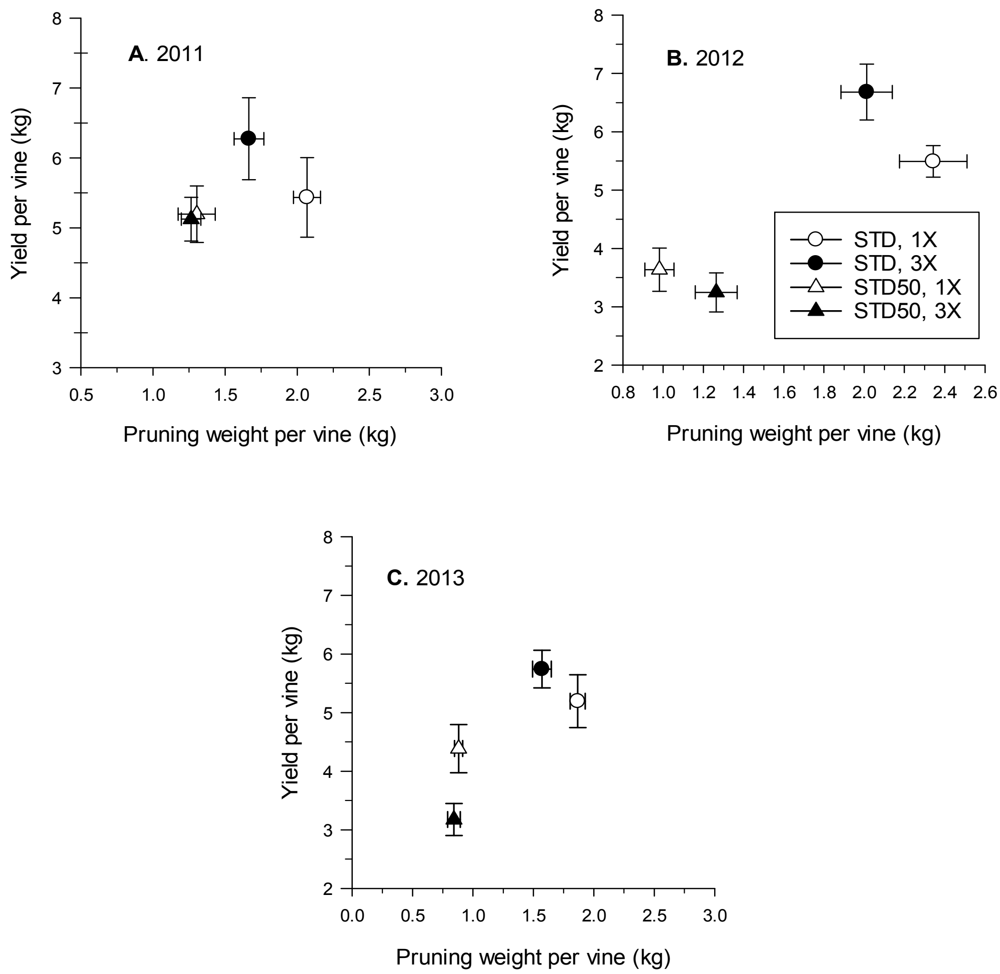

Figure 2. Relationship between pruning weight and yield in Malbec grapevines under sustained deficit irrigation that supplied 70 (STD) or 35 (STD50)% of estimated vine water demand as a single weekly event (1X) or apportioned into thirds and applied as three events per week (3X). Error bars represent the standard error of the mean

Irrigation frequency had a significant influence on the Ravaz index and the effect differed by irrigation amount (Figure 3). More frequent irrigation significantly increased the Ravaz index of vines under STD in all years, but decreased the Ravaz index of vines under STD50 in two out of three years. Vines under STD irrigated 3X had a higher Ravaz index than that of vines irrigated 1X by 37, 31 and 26% in each respective year. Vines under STD50 irrigated 3X had a lower Ravaz index than vines irrigated 1X by 28 and 23% in 2012 and 2013, respectively. Irrigation amount had no significant effect on the Ravaz index in 2011 or 2012. In 2013 the Ravaz index was significantly higher in vines under STD50 (4.6) than in vines under STD (3.4). In 2011 and 2012, the Ravaz index was 3.9 and 3.2, respectively. Drip line configuration had no consistent influence on the Ravaz index.

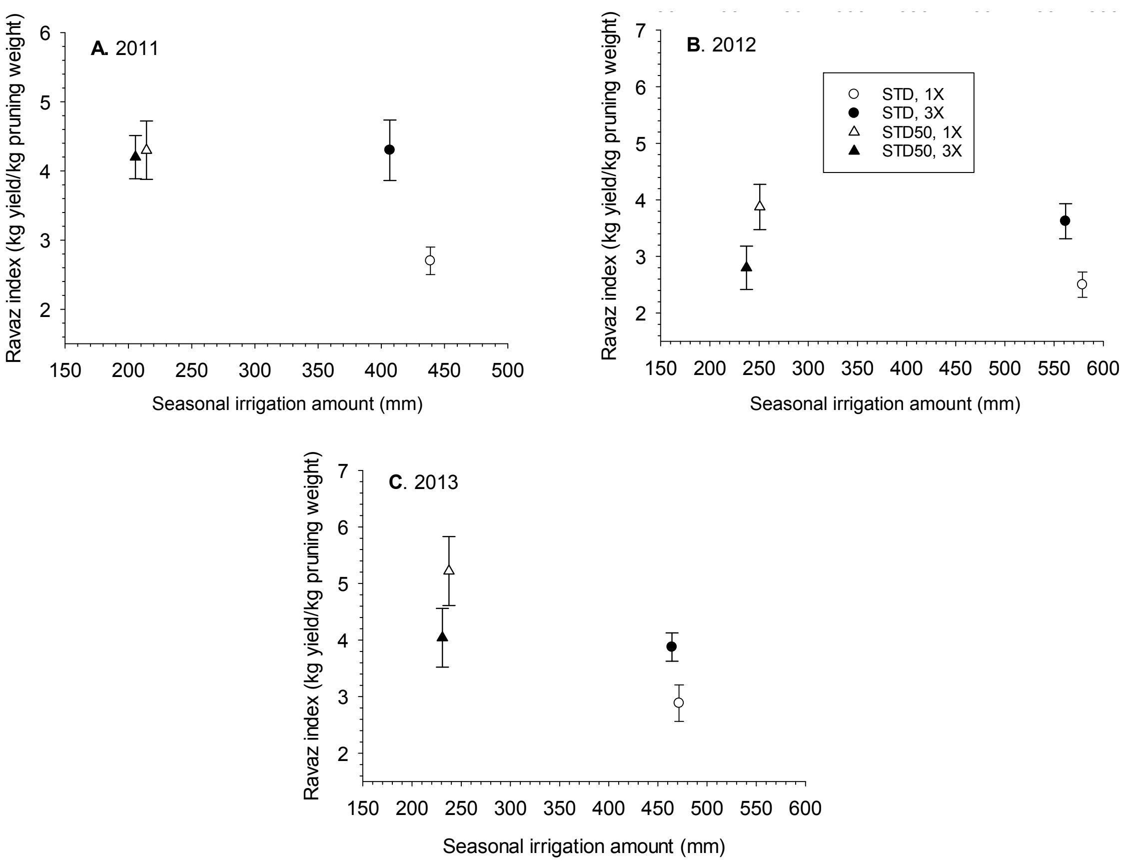

Figure 3. Water productivity of Malbec grapevines under sustained deficit irrigation that supplied 70 (STD) or 35 (STD50)% of estimated vine water demand as a single weekly event (1X) or apportioned into thirds and applied as three events per week (3X). Error bars represent the standard error of the mean

3.5 Berry Composition

The SS and pH of juice at harvest were similar among all treatments (data not shown). In each respective year, SS was 23, 25, and 22% at the time of harvest; and pH was 4.0, 3.9, and 3.7. Irrigation event frequency and drip emitter configuration had no consistent main or interactive effects on juice TA; however, the TA of juice from vines under STD50 was lower each year than vines under STD (Table 3).

The influence of irrigation event frequency on the concentration of anthocyanins and phenolics was inconsistent among years and differed by irrigation amount (Table 3). In vines under STD, the concentration of anthocyanins in berries irrigated 3X was lower in 2011 and 2012 than that of vines irrigated 1X. The concentration of phenolics in vines under STD irrigated 3X was similar in 2011 and 2013 and lower in 2012 than vines irrigated 1X. Under STD50, the concentration of anthocyanins and phenolics in berries from vines irrigated 3x was higher than that of vines irrigated 1X in each year of the study, though the difference in anthocyanins was not of statistical significance in 2012. Berries from vines under STD50 had a higher concentration of anthocyanins and phenolics in 2012 and 2013 than that of vines under STD (Table 3).

Table 3. Berry composition of Malbec grapevine at fruit maturity. Vines were supplied with 70 (STD) or 35 (STD50) percent of estimated weekly water demand as a single weekly irrigation event (1X) or apportioned into three events per week (3X) and delivered using above ground drip tubing with emitter spacing/delivery rate configurations of 90 cm/33.4 ml/min. (2E) or 45 cm/16.7 ml/min (4E) over three growing seasons in Parma, ID

	Titratable acidity			Total anthocyanins			Total phenolics		
	2011	2012	2013	2011	2012	2013	2011	2012	2013
	------------- g/L ------------			--- mg/g berry fresh weight ---			-- mg/g berry fresh weight --		
Irrigation (I)[a]									
STD	9.41a	7.02a	6.26a	1.92	2.01a	1.65a	1.42	1.44a	1.59a
STD50	6.35b	4.82b	5.07b	1.92	2.24b	1.86b	1.46	1.65b	1.82b
*I*Frequency*[b]									
STD-1X	9.47	7.17	6.49a	1.98a	2.12a	1.53a	1.41a	1.50a	1.58a
STD-3X	9.36	6.87	6.03b	1.87b	1.89b	1.77a	1.42a	1.38b	1.60a
STD50-1X	6.17	4.94	4.86a	1.85a	2.22a	1.79a	1.43a	1.63a	1.75a
STD50-3X	6.53	4.71	5.28a	1.99b	2.27a	1.92b	1.49b	1.68b	1.89b
p value[c]									
Irrigation (I)	**	**	**	ns	**	**	ns	**	**
Emitter (E)	ns	ns	ns	**	ns	ns	ns	ns	ns
I × E	ns	ns	ns	**	ns	ns	*	ns	ns
Frequency	ns	ns	ns	ns	ns	ns	ns	**	*
I × F	ns	ns	*	**	**	*	**	**	**
E × F	ns	ns	*	ns	**	ns	ns	**	ns
I × E × F	ns	ns	ns	**	**	ns	**	**	**

Note. [a] Different lower case letters indicate significant difference between main effect treatment levels within a given year ($p \leq 0.05$ determined by Tukey-Kramer adjusted t-test). [b]Least square mean values followed by a different letter between subplot treatment level rows within a year column are significantly different ($p \leq 0.05$) according to LSMEANS slice statement in mixed model analysis of variance. [c]*, $p \leq 0.05$; **, $p \leq 0.01$; ns, not significant.

4. Discussion

A practical goal of this study was to identify water use efficient, above ground drip application practices that mitigate undesirable, water deficit-associated loss of yield in winegrape. The irrigation event intervals evaluated in this study under each severity of deficit irrigation alleviated water stress-associated yield reduction in only one out of three years; however, the observed interaction between irrigation amount and event frequency on water productivity provides new information about irrigation frequency and duty cycle combinations that influence water productivity under SDI.

In this study, irrigation amount and event frequency influenced the vertical depth of moisture in the soil profile. The distribution of soil moisture under drip irrigation has been described as mainly two dimensional, with soil moisture content highest beneath the drip line and decreasing laterally (Goldberg et al., 1971; Selles et al., 2004; Davenport et al., 2008; Bowen et al., 2012). A model using irrigation frequency and irrigation duty cycle, defined as the ratio of irrigation duration to irrigation interval, was used by Sinai et al. (2007) to predict maximum depth of water penetration under drip irrigation. Depth of water penetration was shown to increase with less frequent irrigation or with increasing duty cycle values (Sinai et al., 2007). In this study, plots irrigated 1X and 3X under each irrigation amount had similar duty cycle values. The 3-yr average maximum duty cycle value under STD was 0.30 and under STD50 was 0.02. The different duty cycle values for STD and STD50 and different irrigation frequency in 1X and 3X plots explain the greater depth of water penetration observed under STD relative to STD50 and in plots irrigated 1X relative to 3X.

The author found three published field studies with winegrapes in which above ground drip irrigation interval was evaluated as a treatment (Goldberg et al., 1971; Hepner et al., 1985; Selles et al., 2004). In the study of Hepner et al. (1985), the main effect of irrigation frequency could not be evaluated because it was confounded within different severities of SDI and RDI. In Goldberg et al. (1971) and Selles et al. (2004), an amount of water equal to estimated demand (well-watered) was delivered at irrigation frequencies similar to the 1X and 3X frequencies evaluated in this study. In both of these studies, depth of water penetration increased with less frequent irrigation. Goldberg et al. (1971) and Selles et al. (2004) found that irrigation frequency influenced water productivity and that higher productivity was due to an increase in yield that was proportionally greater than the increase in pruning weight. Goldberg et al. (1971) found that water productivity increased as irrigation frequency increased, whereas Selles et al. (2004) reported an inverse relationship between water productivity and irrigation frequency. The contrasting results of these two studies could be due to different soil textures and/or the amount of supplied water relative to actual vine water demand.

The influence of irrigation frequency on water productivity in this study differed according to deficit irrigation amount. An interaction between irrigation amount and application timing on drought response has also been noted by Romero et al. (2015). Under the least severe water deficit (STD), more frequent irrigation increased water productivity each year and the increase was due to a decrease in pruning weight. An explanation for the reduction in pruning weight of vines under STD irrigated 3X is not readily apparent from Ψ_{lmd} values. Reduction of shoot growth is usually associated with a Ψ_{lmd} value ≤ -1.0 MPa (Shellie, 2006). However, in this study, vines under STD irrigated 3X had values of Ψ_{lmd} more negative than -1.0 MPa only in 2013. Under STD, the fruit produced from plots with highest water productivity had a lower concentration of anthocyanins in 2011 and 2012. The lower concentration of anthocyanins could be attributed to the higher values of Ψ_{lmd} between fruitset and veraison in 3X relative to 1X irrigated plots.

Under the most severe water deficit (STD50), less frequent irrigation was associated with increased water productivity in 2012 and 2013. The increase in 2012 was due to a decrease in pruning weight and the increase in 2013 was due to an increase in yield. The decrease in pruning weight in 2012 was most likely due to the more negative Ψ_{lmd} of vines irrigated 1X relative to 3X. The greater number of berries per cluster observed in 1X plots under STD50 in 2013 might have been related to the less negative Ψ_{lmd} in the first weeks after fruitset which could have reduced the amount of water stress-associated berry abscission (May, 2004). Under STD50, the irrigation frequency with highest water productivity had the lowest concentrations of anthocyanins and phenolics. This lower concentration was not due to a lack of vine water stress, as vines irrigated 1X had lower Ψ_{lmd} than vines irrigated 3X. The concentration of phenolics may have been lower in vines under STD50 irrigated 1x relative to 3X because of more frequent exposure to high temperatures. An increase in canopy temperature under deficit irrigation has been associated with lower anthocyanin accumulation (Shellie & King, 2013). The cumulative duration of exposure to damaging high temperatures may have been greater under 1X than 3X due to the longer interval between irrigation events.

Under each irrigation amount, increased water productivity was accompanied by an increase in yield in only one out of three years. An increase in yield and decrease in pruning weight occurred only under STD in 2012 in plots irrigated 3X. This was also the only year when a significant difference in Ψ_{lmd} was maintained throughout berry development between vines irrigated 1X and 3X. The increase in berry fresh weight in 2012 in vines under STD irrigated 3X was likely attributed to higher vine water status. The general lack of yield response to the irrigation frequencies and duty cycles evaluated in this study suggests that the pattern of soil moisture distribution associated with the treatment combinations evaluated in this study did not induce the same drought response observed in potted vines under partial root-zone drying (Stoll et al., 2000; Sadras, 2009).

The influence of deficit irrigation severity on yield components, berry maturity and berry composition observed in this study were similar to that reported by others (Shellie, 2006; Shellie, 2014; Romero et al., 2015; Munitz et al., 2017). The irrigation intervals evaluated in this study did not alleviate a water-stress associated reduction in yield under either severity of deficit irrigation; however, study results provide new information about water use efficiency that can be used to identify combinations of irrigation frequencies and duty cycles with potential for increasing water productivity.

Acknowledgements

This research was partially funded by a grant from the Northwest Center for Small Fruits Research and the Agricultural Research Service project 5358-21000-034-00D.The author thanks Alan Muir and Monte Shields for their technical assistance and the University of Idaho Parma Research and Extension Center for the use of their field resources and materials.

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