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Research Article

Optimizing Irrigation for Mechanized Concord Juice Grape Production

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Key words: fruit composition, irrigation, juice grapes, yield components

Abstract

Background and Goals: Economic considerations and water shortages associated with climate change are driving the conversion of many hand-pruned and furrow- or sprinkler-irrigated juice grape vineyards in arid eastern Washington to mechanical pruning and drip irrigation. However, juice grape producers have traditionally avoided plant water deficits, fearing a decline in vineyard productivity.

Methods and Key Findings: We conducted a 6-year field trial to test the impact of eight drip-irrigation treatments on large, mechanically-pruned Concord grapes. We found an estimated

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crop coefficient of 1.05 between fruit set and harvest. Replacing 75% of crop evapotranspiration (ET_c) from fruit set through harvest reduced annual irrigation water supply by 20% compared with the 100% ET_c control without altering canopy size, yield, and juice composition. Decreasing the water supply from 100% to 50% ET_c at veraison saved only 8% irrigation water, while irrigating at 50% ET_c from fruit set through veraison and 100% ET_c thereafter reduced irrigation water use by 30% but decreased canopy size and reduced yield by 14%. Replacing 150% of ET_c between fruit set and veraison increased seasonal water use by 20% but did not alter yield or juice composition.

Conclusions and Significance: Deficit irrigation does not impact crop yield and juice composition, so long as vines experience only mild water stress (midday stem water potential > -1 MPa) before veraison. Irrigating at 75% ET_c to impose mild preveraison water stress and mild to moderate postveraison stress optimally balances the goals of water conservation and yield and quality sustainability in juice grape production.

Introduction

Depending on the year and market conditions, between one-third and one-half of the juice grape production in the United States is concentrated in eastern Washington, much of it in the Yakima Valley. This region is characterized by an arid desert climate with warm but relatively short (<180 days) growing seasons and cold winters (Badr et al. 2018, Beck et al. 2018). Because the annual precipitation is only ~200 mm, adequate irrigation water supply is essential for vineyard establishment and sustained vine productivity. Consequently, the changes in precipitation patterns that are associated with global climate change are of some concern for the region, where irrigation relies on snow melt in the Cascade mountains. Like elsewhere in the western U.S., the water stored

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in those mountains' snowpack in early spring correlates strongly with water supply during the summer (Elsner et al. 2010). Because of a decreasing trend in snowpack and earlier snowmelt, peak river flows are shifting from May/June to February/March, and irrigation water availability in summer is declining (Elsner et al. 2010, Wagner et al. 2021). The decrease in water supply, coupled with the ongoing rise in temperature and evapotranspiration, is a challenge for juice grape production, because most growers in the region strive to apply ample irrigation water to avoid plant water stress. Although many vineyards are being converted from furrow or overhead sprinkler irrigation to more water-conserving drip irrigation, it is uncertain whether productivity can be maintained under drier conditions. The large canopy of well-watered juice grapes uses substantially more water than does the smaller canopy of deficit-irrigated wine grapes (Dragoni et al. 2006, Tarara and Ferguson 2006). However, contrary to the abundance of research into deficit irrigation of wine and table grapes (reviewed by Costa et al. 2016, Permanhani et al. 2016, Scholasch and Rienth 2019, Mirás-Avalos and Araujo 2021), little research has addressed the question of how limited water supply impacts fruit yield and composition of juice grapes (Morris et al. 1983, Reynolds et al. 2005, Stout et al. 2017). Indeed, in their recent comprehensive review, Mirás-Avalos and Araujo (2021) emphasized both the difficulty of generalizing optimal irrigation strategies across cultivars and regions, and the need for long-term studies.

The importance of the irrigation question is accentuated by the shift towards light mechanical pruning of much of the juice grape acreage in the region, which is driven by the increasing scarcity of labor paired with the need to cut production costs and maximize vineyard productivity. Because lower pruning severity increases canopy size and hence transpiration (Gómez del Campo et al. 1999, Lakso and Dunst 1999), lightly pruned vines may be more

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vulnerable to water stress (Keller et al. 2004, 2015). Heavy crop loads typical of such vines might further exacerbate the vines' vulnerability to water stress (Poni et al. 1994). In addition to its impact on shoot growth and leaf photosynthesis, water stress during the preveraison berry development phase restricts berry size, and postveraison water stress can lead to undesirable berry weight loss or delayed fruit maturity (Hardie and Considine 1976, Keller et al. 2006, Zhang and Keller 2015). Unlike wine grape growers, juice grape growers therefore have been reluctant to adopt deficit irrigation strategies.

Because mechanical pruning could exacerbate problems associated with water shortages, this labor-saving practice calls for careful irrigation management. The present study was conducted to test a range of irrigation treatments in a drip-irrigated, mechanically pruned juice grape vineyard in the Yakima Valley. Our hypothesis was that the large canopy of machine-pruned vines requires ample water supply to maximize and stabilize crop yield in the long-term. The field trial described here evaluated both the amount and timing of water supply and their influence on canopy development, plant water status, yield formation, and juice composition. Our goal was to identify one or several optimal irrigation strategies that may conserve valuable irrigation water while maximizing the production of high-quality juice grapes over multiple years.

Materials and Methods

Vineyard site and management. Own-rooted Concord grapes (an interspecific hybrid cultivar with *Vitis labrusca* L. and *Vitis vinifera* L. ancestry) were planted in 2003 in a 3.2-ha vineyard block at Washington State University's Irrigated Agriculture Research and Extension Center (46.29°N, 119.74°W, 360 m a.s.l.). The soil type is Warden silt loam with pH 7.2, <1% organic matter, volumetric water content (θ_v) at field capacity (FC) of 22.7% (v/v), and θ_v at

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permanent wilting point (PWP) of 7.1% (https://websoilsurvey.sc.egov.usda.gov). A caliche layer over basalt at depths varying from 50 to 120 cm limits rooting depth. The vines are planted at 2.74 m between rows and 1.83 m within rows oriented north–south down a <2% south-facing slope. They are trained to a single cordon wire at 1.83 m with no foliage wires; the shoots hang under the weight of the developing fruit. The vineyard has been mechanically pruned by a cooperating grower since 2007 as described in Keller and Mills (2021), and the canopy is not managed during the growing season. A permanent midrow cover of resident vegetation is maintained between rows; it is mowed as needed and generally goes dormant in the summer. A 1.2-m herbicide strip is maintained in the rows during the growing season, but other pesticides are not applied in this vineyard. Nitrogen fertilizer, in the form of UAN-32, is applied by fertigation through the drip irrigation system at a rate of 66 kg N/ha split equally between the six-leaf stage, bloom, and fruit set. Drip irrigation is applied weekly as needed, using 18-mm driplines with 3.4-L/h emitters spaced at 0.91 m. To compensate for the low winter precipitation in this region (<80 mm on average; see Table 1), the vine rows are usually irrigated to near FC around budbreak. Limited soil drydown is tolerated through bloom to maximize fruit set and cluster initiation and control canopy growth. Irrigation to near FC is applied after harvest to minimize winter cold injury to the roots.

We used a neutron probe (503 DR Hydroprobe, CPN International) to measure θ_v. One access tube was installed near the center of each treatment replicate, between two data vines, to a depth of 90 cm. Readings were taken weekly the day before irrigation started and used to calculate the required irrigation water amount for each week. Data are expressed as θ_v and as relative extractable soil water [$\theta_e = (\theta_v - PWP)/(FC - PWP)$], averaged over the top 60 cm of soil. The

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dimensionless θ_e normalizes the influence of soil texture on θ_v ($\theta_e = 0$ at PWP and $\theta_e = 1$ at FC) and permits comparison of soil water deficit across different soil types (Zhang et al. 2012).

Treatments and experimental design. An irrigation trial was conducted from 2011 through 2016. Irrigation treatments were designed to replace various fractions of water lost to crop evapotranspiration (ET_c) between fruit set and harvest. Instead of applying a crop coefficient (K_c), the amount of water to be applied under full irrigation (100% ET_c), which served as the control, was estimated based on maintaining θ_v in the soil's top 60 cm constant near 18% ($\theta_e = 0.7$). Differences in water supply for the remaining treatments were achieved by retrofitting the irrigation system to accommodate pressure-compensating drip emitters with different flow rates; emitters were changed at key phenological stages as required by the different treatments. Those treatments were: mild early deficit (75% ET_c from fruit set to veraison and 100% ET_c thereafter); moderate early deficit (50% ET_c from fruit set to veraison and 100% ET_c thereafter); mild late deficit (100% ET_c from fruit set to veraison and 75% ET_c thereafter); moderate late deficit (100% ET_c from fruit set to veraison and 50% ET_c thereafter); mild full-season deficit (75% ET_c from fruit set to harvest); moderate full-season deficit (50% ET_c from fruit set to harvest). In response to industry requests, the mild early deficit treatment was replaced in 2014 with abundant early irrigation at 150% ET_c through veraison and 100% ET_c thereafter. The other two mild (late and full-season) deficit treatments were not applied in 2016 because vine responses did not differ from the control in the first 5 years (see Results section). Each treatment was applied to 12 consecutive vines in 3 adjacent rows and replicated in 4 randomized blocks that were 48 vines long and 6 rows wide. Flow meters were installed in each block in 2013 to estimate irrigation water supply by treatment.

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Weather data and plant measurements. Daily weather data were obtained from the WSU-Roza AgWeatherNet station (http://weather.wsu.edu), located at the same elevation and ~500 m to the east of the vineyard. Growing degree days (GDD) for the period 1 April through 31 Oct were calculated from daily maximum and minimum temperatures, using a base temperature of 10°C. Vine phenology was monitored regularly, and dates of 50% budbreak, bloom, and veraison, as well as the harvest date were recorded.

Four consecutive data vines were designated in the middle row of each treatment replicate. Beginning at fruit set and on days that θ_v was measured, we also measured midday stem water potential (Ψ_s) to determine irrigation effects on vine water status. Recently mature, sun-exposed leaves were enclosed in aluminum-coated plastic bags for ≥2 hr and measured in a pressure chamber (model 615, PMS Instrument Company) between 13:00 and 15:00 local time. Canopy dimensions (average height from top to bottom of pendant shoots and width across the fruit zone) were measured at veraison and before harvest to estimate the external canopy surface area and the canopy volume, assuming a rectangular canopy cross section (Keller and Mills 2021). Within 30 min of solar noon on the same days, light penetration into the fruit zone was estimated using a ceptometer (AccuPAR LP-80, Decagon Devices) as described by Keller and Mills (2021). In 2013, 2014, and 2016, the trunk diameter was measured at the height of the dripline 45 cm above the vineyard floor as a proxy for vine size, since pruning weight is not a suitable indicator of vine vigor or size for mechanically pruned grapevines. Trunk diameter (and hence cross-sectional area) correlates strongly with both above-ground and whole-vine structural biomass (Miranda et al. 2017).

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All data vines were harvested manually on the same day once the vineyard exceeded an overall total soluble solids (TSS) target of 16 Brix except in the cool 2011 season, when this target was not reached and grapes were harvested at 15 Brix. The vineyard was then machine-harvested by a cooperating grower. Yield and its components (clusters per vine, cluster weight, berries per cluster, berry weight) were determined at harvest. A random 100-berry sample was collected at harvest from each treatment replicate to measure fruit composition. Juice TSS, titratable acidity (TA), pH, and red color intensity were determined as described elsewhere (Keller et al. 2004).

Because of an unusually heavy crop in 2014, we measured bud cold hardiness and cane phloem and xylem hardiness during the subsequent winter. Measurements were conducted by differential thermal analysis (Mills et al. 2006) in mid-Oct, early and late Nov, early Jan, early and late Feb, and late March on four replicates of five buds or two cane internodes in the control, mild full-season deficit, and moderate full-season deficit treatments.

Data analysis. Data were analyzed using Statistica version 14 (TIBCO Software). The pH values were converted to H^+ concentrations for data analysis, and means were converted back to pH for presentation. Because some irrigation treatments changed during the experiment, data were first analyzed by ANOVA for the control and the three moderate deficit treatments over all 6 years. Then all pertinent treatments were analyzed across the years in which they were applied. In each case, the year effect was tested using a repeated measures design. Though year × treatment interactions were rarely significant (exceptions: θ_v and Ψ_s), treatments were also analyzed by one-way ANOVA for each year to account for the changing treatments resulting in an unbalanced design over time. Duncan's test was used for post-hoc means comparisons when treatment effects

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were significant within years. Associations between key response variables were tested using Pearson product moment correlation analysis.

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Results

Phenology and weather. The timing of phenological stages of our Concord vines varied widely among years, depending on seasonal weather conditions (Table 1). The date of budbreak ranged from 1 April (2015) to 30 April (2011), bloom occurred between 15 May (2016) and 20 June (2011) with fruit set typically 1 to 2 weeks later. Veraison occurred between 13 Aug (2015) and 14 Sept (2011), and the date of harvest varied from 16 Sept (2015) to 28 Oct (2011). The Yakima Valley, where the study vineyard is located, is considered one of eastern Washington's cooler grape growing regions (https://wine.wsu.edu/extension/weather). Compared with the long-term average of 1409 GDD and mean growing season temperature of 16.5°C, the 2011 growing season was unusually cool and 2015 was unusually warm (Table 1). The 2012 and 2013 seasons were close to the average, while 2014 and 2016 were also warmer than average. The seasonal GDD accumulation is shown in Figure 1, and daily maximum and minimum temperatures and rainfall are shown in Supplemental Figure 1. Spring frosts were fairly common through mid-April, and the latest frost (-1.7°C) occurred on 1 May 2013, 16 days after budbreak. Annual precipitation varied from 125 mm in 2011 to 241 mm in 2012. Rainfall during the growing season ranged from 50 mm in 2015 to 128 mm in 2012, which was far below the seasonal grass reference evapotranspiration (ET_0) that varied from 924 mm in 2011 to 1057 mm in 2015 (Table 1). The daily ET_0 (range: 0–10.5 mm) correlated strongly with daily solar radiation ($r = 0.83$, $p < 0.001$, $n = 1284$), maximum temperature ($r = 0.80$, $p < 0.001$), and average relative humidity ($r = -0.79$, $p < 0.001$). Multiple regression analysis showed that these three variables accounted for 88% of the variation in ET_0 (multiple $R = 0.94$, $p < 0.001$).

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Irrigation water supply. Flow meters installed from 2013 through 2016 showed that the control treatment (irrigation at 100% ET_c) received between 689 mm and 826 mm irrigation water per year (Figure 2A). Flow meter readings, as a proxy for ET_c of the 100% ET_c vines, combined with ET_0 accumulated between weekly irrigation events permitted the estimation of a K_c (= ET_c/ET_0) for the fruit set to harvest period. The K_c was rather consistent at 1.05 ± 0.09 (mean ± SE) during this period and over the four years. On average across years and irrigation treatments, 10% (58 mm) of irrigation water was applied from budbreak to fruit set, 53% (345 mm) from fruit set to veraison, 19% (117 mm) from veraison to harvest, and 18% (112 mm) after harvest (Figure 2B, Supplemental Table 1). The average water supply between fruit set and veraison ranged from 201 mm at 50% ET_c irrigation to 391 mm at 100% ET_c and 632 mm at 150% ET_c. Similarly, water supply during fruit ripening varied from 74 mm at 50% ET_c to 147 mm at 100% ET_c. Because we attempted to even out differences in θ_v at budbreak and after harvest by irrigating the deficit treatments more heavily, postharvest water supply ranged from 157 mm in the 50% ET_c treatment down to 48 mm in the 150% ET_c treatment. On an annual basis, reducing irrigation to 50% ET_c from fruit set through harvest decreased water supply by 31% compared with the 100% ET_c control; restricting the 50% ET_c treatment to the preveraison period resulted in 30% water savings. The next most water-conserving strategy was 75% ET_c from fruit set to harvest (-20%); this treatment required less irrigation water after harvest than the 50% ET_c treatments. Irrigating at 150% ET_c before veraison, however, increased overall water supply by 20% compared with the control.

Soil and plant water status. Seasonal trends of θ_v and Ψ_s are shown in Figure 3, and Ψ_s data, averaged for the preveraison and postveraison periods, are summarized in Supplemental

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Table 2. In most years, θ_v declined through fruit set or somewhat later, then changed depending on the irrigation treatment, and finally increased to prebloom levels following postharvest irrigation. Irrigating at 75% ET_c and, especially, 50% ET_c generally led to soil drying, irrigating at 100% ET_c kept θ_v, constant, whereas irrigating at 150% ET_c steadily increased θ_v (Figure 3). Thus, the preveraison θ_v was highest in the 150% ET_c treatment (applied from 2014) and lowest in the 50% ET_c treatment. Moreover, the vines irrigated at 150% ET_c the previous year started out with the highest θ_v the following spring, and although θ_v decreased somewhat through fruit set, it then increased and remained near or above FC through harvest. The other treatments were irrigated after harvest and near budbreak to increase θ_v to within 3-5% of FC.

Each year, the average preveraison θ_v (or θ_e) was a nearly linear function of the irrigation water applied during that period ($0.72 < r < 0.95$, $p < 0.001$; see also Figure 4A). The correlation between postveraison θ_v and water applied during ripening was not as strong ($0.31 < r < 0.77$, $p < 0.11$) due to carryover effects from the preveraison irrigation treatments. The average preveraison Ψ_s correlated strongly with irrigation water supply during that period in all years ($0.74 < r < 0.87$, $p < 0.001$) but reached a plateau ($\Psi_s \approx -0.4$ MPa) at ~400 mm of applied water (Figure 4B). As in the case of θ_v, correlations were weaker for postveraison Ψ_s and water supply ($0.31 < r < 0.79$, $p < 0.11$). Moreover, θ_v (and hence θ_e) and Ψ_s were positively correlated. Figure 4C shows the Ψ_s vs. θ_e relationship for the 0 to 60 cm depth, but the correlation coefficients were nearly identical for the 0 to 30 cm and 0 to 90 cm depths, indicating that roots were taking up water over the entire measured soil profile. Except in 2016, when more irrigation water was applied than in the other seasons, Ψ_s generally declined to -1.2 to -1.4 MPa when θ_v reached ~12% and $\theta_e \leq 0.3$ (Figure 3). While deficit irrigation, especially at 50% ET_c, clearly resulted in lower plant water status, there

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was no further rise in Ψ_s at $\theta_v \geq 16\%$ and $\theta_e \geq 0.6$ (Figure 4C). Even irrigating at 150% ET_c, which raised θ_v above FC (i.e., $\theta_e > 1$), did not increase Ψ_s significantly above -0.4 MPa.

Canopy size and light exposure. The canopy dimensions measured at veraison were generally similar to those measured preharvest, and changes in postveraison irrigation had negligible effects on canopy size; thus only the harvest data are presented here (Figure 5, Supplemental Table 3). Before veraison of 2014, the canopy was accidentally hedged ~70 cm above the vineyard floor, which decreased its surface area and volume compared with the other years. In general, the preveraison moderate deficit irrigation treatments led to slightly smaller canopies (i.e., lower surface area and volume) compared with the other treatments (Figure 5A, B). The canopy size rarely differed among the remaining treatments, and the 150% ET_c treatment did not increase canopy size above that of the control. Although statistically significant, the difference between the lowest and highest water supply was only 10% in terms of canopy surface area and 25% in terms of canopy volume. The irrigation-related differences in canopy size were accompanied by an 11% difference in trunk diameter (thinner at 50% ET_c irrigation), which increased by 8% (3.7 cm to 4 cm) from 2013 through 2016 ($p < 0.001$). The trunk diameter in 2016 correlated positively with the average preveraison Ψ_s ($r = 0.64$, $p = 0.003$).

The proportion of sunlight that reached the fruit zone decreased from an average of 8% in 2011 to 4% in 2012 and then to 2% thereafter. Moderate deficit irrigation before veraison generally more than doubled the amount of light in the fruit zone compared with the control (Figure 5C). Changing the irrigation rate at veraison did not alter light penetration. Each year except 2011, fruit zone light correlated inversely with the average preveraison Ψ_s ($-0.75 < r < -0.40$, $p < 0.05$). The

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cold hardiness of buds as well as cane phloem and xylem remained unaffected by the irrigation treatments between mid-Oct 2014 and late March 2015 ($p > 0.3$).

Yield and its components. Crop yields varied from 17 t/ha in 2012 to over 55 t/ha in 2014 (Table 2, Supplemental Table 3). Alternate bearing did not account for yield fluctuations; no negative correlations were observed between prior-year yield and current-year yield of the 112 data vines (Supplemental Figure 2). The low crop in 2012 was a result of 38% fewer clusters per vine, 37% fewer berries per cluster, and 4% smaller berries than in 2011 (Table 2, Figure 6A, B). Yields recovered in 2013, mostly because of high cluster numbers per vine, whereas cluster weights remained low following the late frost that year. The heavy crop in 2014 was mostly due to larger than usual clusters (i.e., more berries per cluster). The 2015 crop was significantly lower than in other years except 2012, mostly as a result of lower cluster numbers. The 2016 crop was the second highest among the six years, resulting from a combination of above-average cluster numbers, cluster weights, and berry weights (Table 2). Within years, between 22% and 59% of the yield variation could be attributed to the variation in cluster number per vine ($0.47 < r < 0.77$, $p < 0.001$), whereas the cluster weight contributed only between 1% and 14% to that variation ($0.08 < r < 0.37$, $p < 0.001$). The main driver of the variation in cluster weight was the number of berries per cluster, while berry weight was comparatively unimportant. The average berry number per cluster ranged from 17 ± 1 in 2013 to 28 ± 1 in 2011 ($p < 0.001$).

Compared with the yield variability due to other sources, irrigation effects on yield were small. On average, irrigating at 50% ET_c before veraison decreased the harvest yield by 14% compared with the 100% ET_c control (Figure 6A). However, preveraison irrigation at 75% or 150% ET_c did not alter yield relative to the control, and differences in postveraison irrigation had

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no effect on yield. Irrigation influenced crop yield mainly by altering berry weight (Figure 6C). Moderate deficit irrigation before veraison led to a 6% decrease in berry weight compared with the control (p = 0.017), but the other treatments rarely impacted any yield components. The magnitude of the irrigation effect seemed to increase over time, with virtually no significant effects in the first two years, when θ_v was not as well differentiated among treatments. In 2016, moreover, preveraison moderate deficit irrigation also reduced clusters per vine by 18% (p = 0.002). Except in 2011, the average berry weight correlated positively with the average preveraison Ψ_s, and the correlation gradually increased from 2012 (r = 0.46, p = 0.016) through 2016 (r = 0.76, p < 0.001). A similar correlation was also found between berry weight and average preveraison θ_v (0.41 < r < 0.82, p < 0.03). Correlations between berry weight and average postveraison Ψ_s and θ_v were also significant, but only if the preveraison 50% ET_c treatments were included in the analysis, indicating that any apparent effects of postveraison water status resulted from differences established before veraison.

In four of the six years, the canopy volume correlated positively with yield per vine (0.40 < r < 0.52, p < 0.05). Fruit yield also increased in a curvilinear fashion as the annual irrigation water supply increased, but the relationship was different each year (Figure 7A), again demonstrating the dominant influence of seasonal weather over irrigation. Adding the sparse rainfall to the water supply did not change this relationship in any year. When the irrigation water supply was broken down by phenological phase, only the correlations for the period from fruit set to veraison were significant (Figure 7B). Therefore, the irrigation water use efficiency (yield per unit water applied; mean 6.9 ± 0.2 t/ML) was entirely dependent on preveraison irrigation, decreasing successively from 50% ET_c to 150% ET_c (p < 0.001). The irrigation water footprint

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(water applied per unit yield; 158 ± 5 m^3/t) and the total water footprint (rainfall plus irrigation water per unit yield; 199 ± 6 m^3/t) showed the opposite trend of increasing from 50% ET_c to 150% ET_c ($p < 0.001$). Data by year and treatment are shown in Supplemental Table 4.

Fruit composition. Like yield, fruit composition was dominated by the influence of the growing season rather than the irrigation treatment. The least mature fruit was harvested in the cool 2011 season, and the most mature fruit was harvested in the warm 2015 season (Table 2). The very high yield in 2014 did not prevent the fruit from reaching adequate maturity, albeit with low color density, by the time of harvest in mid-Oct. The irrigation treatments did not impact juice TSS, TA, pH, and red color in three of the six years (Supplemental Table 5). In 2013 and 2016, the only effect was a small decrease in TA with moderate preveraison deficit irrigation compared with the other treatments. Nevertheless, each year except 2015 there was a positive correlation between TA and the average preveraison Ψ_s ($0.38 < r < 0.85$, $p < 0.05$). In 2015, the low yield in the 50/100% ET_c treatment was associated with higher TSS and color, and irrigating at 150% ET_c before veraison reduced juice color. Differences in postveraison irrigation did not alter fruit composition in any year.

Higher TSS correlated with more intense juice color, both within years ($0.58 < r < 0.82$, $p \leq 0.001$) and between years ($r = 0.69$, $p < 0.001$, range 13.6–21.1 Brix). Berry size, however, did not correlate with color density in any year ($p > 0.1$). Despite the high variation in crop yield within and between years, yield was generally not an important driver of fruit composition. The strongest correlation between yield (range 17.5–28.5 kg/vine) and TSS was found in 2011 ($r = -0.55$, $p = 0.003$), when vines cropped at >45 t/ha had lower TSS and color density than vines with <45 t/ha. High-yielding vines that were irrigated at 50% ET_c were just as likely to have fruit with low TSS

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and color as were vines that were irrigated at 100% ET_c. Despite similar or even higher yields in 2014 (23.4–32.0 kg/vine) and 2016 (20.3–29.5 kg/vine), yield did not correlate with TSS in those warmer years ($p > 0.2$). Nevertheless, higher yields were associated with higher TA in the last three years ($0.43 < r < 0.75$, $p \leq 0.02$), higher pH in 2011 only ($r = 0.43$, $p = 0.02$), and lower color only in the warm 2015 season ($r = -0.71$, $p < 0.001$).

Discussion

The present study, conducted over six years in a mechanically pruned, high-yielding Concord juice grape vineyard in Washington's arid Yakima Valley, which is dependent on irrigation for crop production, demonstrated that (i) moderate (i.e., irrigation at 50% ET_c, $\Psi_s < -1$ MPa) but not mild (i.e., irrigation at 75% ET_c, $\Psi_s > -1$ MPa) water deficit between fruit set and veraison limits canopy size, berry size and yield; (ii) moderate water deficit after veraison has no effect on canopy size, berry size and yield; (iii) compensation for inadequate preveraison water supply is not possible by applying more water after veraison; (iv) moderate, but not mild, water deficit before veraison slightly decreases juice acidity; (v) mild water deficit from fruit set to harvest can conserve 20% of the total annual irrigation water with no reduction in yield; and (vi) water savings of ≥30% are possible with moderate water deficit but reduce yield by >10%.

In general, θ_v remained constant under vines that were irrigated at 100% ET_c, while irrigating at lower rates led to soil drying, and irrigating at 150% ET_c increased θ_v. These temporal changes in θ_v resemble those observed for Thompson Seedless (*V. vinifera*) grapes irrigated at fractions of ET_c varying from 20% to 140% (Williams and Trout 2005). Moreover, θ_v (and θ_e) correlated with midday Ψ_s, indicating that deficit irrigation led to lower plant water status, which is a common finding for wine and table grapes as well (Permanhani et al. 2016, Scholasch and

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Rienth 2019, Mirás-Avalos and Araujo 2021). In most years, Ψ_s reached a minimum of -1.2 to -1.4 MPa when θ_v declined to ≤12% ($\theta_e \leq 0.3$), which typically occurred with moderate deficit irrigation (replacing 50% ET_c). These results indicate that Concord vines experience moderate to severe water stress (*sensu* Mirás-Avalos and Araujo 2021) below 30% extractable soil water. The correlation between preveraison Ψ_s and trunk diameter and the thinner trunks of the 50% ET_c vines are consistent with findings for wine and raisin grapes and suggest that the water-stressed vines produced fewer and/or narrower xylem vessels (Williams et al. 2010b, Munitz et al. 2018). At the other end of the spectrum, and even with irrigation at 150% ET_c, Ψ_s plateaued near -0.4 MPa at θ_v ≥ 16% ($\theta_e \geq 0.6$), indicating that the water status of Concord is insensitive to soil moisture above 60% relative extractable water. The curvilinear relationship between θ_v and Ψ_s looks much like that reported for Thompson Seedless by Williams and Trout (2005), who also found that increasing irrigation from 100% to 140% ET_c did not raise Ψ_s. Midday Ψ_s values above -0.6 MPa have been reported to indicate no vine water stress (Mirás-Avalos and Araujo 2021). The Ψ_s variability at any given θ_v likely resulted from fluctuations in vapor pressure deficit and light intensity (Williams and Baeza 2007, Suter et al. 2019), as plant water status is determined by the interplay between soil water supply and evaporative demand driving canopy transpiration. Therefore, irrigating to keep θ_v close to FC wastes irrigation water even for large, mechanically pruned and heavily cropped juice grapes. Excess irrigation also favors excessive canopy and weed growth (Williams et al. 2010b, Keller et al. 2016), whereas allowing the soil to dry down somewhat facilitates vineyard access and weed control.

Over the four years that we monitored water supply, and averaged across irrigation treatments, the vineyard received between 586 and 731 mm of irrigation water per year (689–826

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mm for the 100% ET_c vines). This amount is similar to values obtained for mature, fully-irrigated Thompson Seedless grapes in central California (Williams et al. 2010a) but substantially higher than the ~300 mm that are applied in deficit-irrigated Cabernet Sauvignon wine grapes in eastern Washington (Keller et al. 2016). Wine grapes often have similar planting densities but much smaller canopies than juice and raisin grapes, and canopy size is a main driver of vineyard water use. The effect of canopy size is reflected in the K_c estimated here for the fruit set to harvest period; application of irrigation water at amounts different from 100% ET_c precluded estimation of a K_c outside of this period. The estimated K_c of 1.05 ± 0.09 is similar to that found for Thompson Seedless in California (Williams and Ayars 2005) but higher than those estimated for wine grapes in eastern Washington (Evans et al. 1993). Nevertheless, because of the high crop yield of our juice grapes, their irrigation water use efficiency was 2.5-times greater, while the irrigation water footprint and the total water footprint were more than 2.5-times lower than those of wine grapes in the same region (cf. Keller et al. 2016).

Our results indicate that deficit irrigation can be successfully applied in large juice grapes with no detrimental effects on crop yield and quality, so long as the preveraison deficit is only mild and the postveraison deficit is mild to moderate. Irrigating at 75% ET_c from fruit set through harvest reduced whole-season water use by 20% compared with the 100% ET_c control, but decreasing the water supply from 100% to 50% ET_c at veraison saved only 8% water on a seasonal basis. Both deficit treatments generally kept Ψ_s above -1 MPa (indicating mild water stress; Mirás-Avalos and Araujo 2021), and neither treatment altered canopy size, yield components, and fruit composition. By contrast, the 30% irrigation water savings achieved by irrigating at 50% ET_c from fruit set through veraison (31% if the deficit continued through harvest) was associated with a Ψ_s

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decrease below -1 MPa (indicating moderate water stress; Mirás-Avalos and Araujo 2021), a somewhat smaller and more open canopy, and a 14% reduction in yield compared with the control. In another study, conducted from 2011 through 2014 in a Concord vineyard in the same region, a comparable decrease in preveraison irrigation water supply reduced yield only in the second year (Stout et al. 2017). However, irrigation generally improved yield after the first year when nonirrigated Concord vines were compared with irrigated vines in Arkansas over four years or in Ontario over five years (Morris et al. 1983, Reynolds et al. 2005).

Because the period from fruit set to veraison, when days are long and warm and the canopy reaches its full size, dominates the total seasonal irrigation water demand in arid climates (53% in this study), this is the period during which deficit irrigation potentially results in the greatest water savings. However, moderate water deficit at this time limits canopy size, berry growth and, consequently, crop yield, as found elsewhere (Williams et al. 2010a, Intrigliolo et al. 2012, Junquera et al. 2012, Levin et al. 2020) and confirmed here by the curvilinear relationship between preveraison irrigation water supply and yield. The optimal deficit irrigation strategy must strive to balance water conservation and yield sustainability. We propose that the irrigation strategy that accomplishes this balance in highly productive juice grapes in eastern Washington is 75% ET_c, applied from fruit set through harvest. While severe water stress after veraison can lead to berry weight loss (Hardie and Considine 1976, Keller et al. 2006), none of our postveraison irrigation treatments induced severe stress, and berry size remained unaltered.

Crop yields were variable both within and between years, and much of this variability was driven by differences in cluster numbers per vine. Variable cluster numbers could have been partly a result of the mechanical pruning strategy that did not control for bud numbers per vine; however,

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we did not count buds or shoots in this experiment. Extending observations over the prior 6-yr period in the same vineyard block (Keller and Mills 2021), bigger vines were more productive, as suggested by the correlation between canopy volume and yield per vine, and alternate bearing did not explain the interannual yield variation. While differences in water supply accounted for some of the yield variation, climate variability clearly induced higher variation in clusters per vine and berries per cluster from year to year. For example, the unusually light crop in 2012 mirrored that in another irrigation study in a nearby Concord vineyard (Stout et al. 2017). The low cluster numbers in 2012 might have been caused by low bud fruitfulness due to reduced inflorescence initiation during the cool 2011 summer or by the early soil water deficit in 2011 (Vasconcelos et al. 2009, Levin et al. 2020). In addition, there was about 1 wk of unusually cool temperatures (T_{mean} < 15°C) during bloom in 2012, which likely reduced fruit set (Keller et al. 2022). In 2016, the decrease in clusters per vine under moderate preveraison deficit irrigation might have been a consequence of lower bud fruitfulness or lower shoot numbers resulting from long-term water stress (Williams et al. 2010a, Levin et al. 2020).

Although moderate preveraison water deficit (and lower preveraison Ψ_s) decreased berry size, fruit composition varied primarily as a result of seasonal differences and secondarily with crop load, similar to long-term irrigation studies with wine and raisin grapes (e.g. Intrigliolo and Castel 2010, Williams et al. 2010a, Junquera et al. 2012). Irrespective of the irrigation treatment, higher TSS, but not smaller berry size, was associated with more intense juice color. Up to the relatively low TSS (15–18 Brix) at which Concord grapes are typically harvested, anthocyanin production is linked to sugar accumulation (Hernández-Montes et al. 2021). Irrigation effects on fruit composition were minor and inconsistent, though lower preveraison Ψ_s was associated with

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higher fruit-zone light and lower juice TA at harvest. The smaller canopy of the 50% ET_c vines allowed greater light penetration into the fruit zone, which would have increased cluster temperatures and malate catabolism during ripening (Sweetman et al. 2014, Keller et al. 2016).

Conclusions

Though juice grape producers have traditionally tried to avoid plant water stress, the present study demonstrated that deficit irrigation can be successfully applied in large, mechanically-pruned Concord juice grapes ($K_c \approx 1$ between fruit set and harvest), so long as the irrigation strategy induced only mild plant water stress ($\Psi_s > -1$ MPa) during the preveraison period. Whereas moderate water stress (-1 MPa $> \Psi_s >$ -1.4 MPa) before veraison decreased canopy size, berry weight, crop yield, and juice acidity compared to nonstress conditions, moderate water stress after veraison, or mild water stress during either period, did not alter any of these variables. Our results suggest that presumed impacts of moderate postveraison water stress may often be due to carryover effects from stress that started before veraison. Trying to compensate for preveraison water stress by applying more irrigation water after veraison proved to be ineffective at preventing yield losses. Among the eight drip-irrigation treatments tested over up to six years, replacing 75% of ET_c from fruit set through harvest was the optimal strategy; it reduced annual irrigation water use by 20% compared with the 100% ET_c control without altering yield and fruit composition. Reducing irrigation to 50% ET_c increased water savings but incurred a yield penalty with no gain in juice quality. While prebloom and postharvest water supply in arid climates should aim to avoid soil and plant water deficit to maximize vine productivity, mild preveraison water deficit and mild to moderate postveraison deficit are desirable for juice grape production.

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Table 1 Summary of weather conditions and key phenological stages for the Washington State University Concord research vineyard in southeastern Washington from 2011 through 2016. Data were obtained from an AgWeatherNet station located ~500 m from the trial site.

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**Long-term[g]**
Seasonal GDD (°C)[a]	1221	1420	1492	1659	1828	1545	1409
Mean GST (°C)[b]	15.2	16.2	16.6	17.7	18.4	17.1	16.5
Preveraison T_{max} (°C)[c]	29.1	30.2	29.2	31.2	32.4	27.8	
Postveraison T_{max} (°C)[d]	19.2	25.7	27.3	25.2	27.3	24.9	
Seasonal ET_0 (mm)[e]	924	953	926	968	1057	986	879
Seasonal precipitation (mm)	70	128	101	71	50	107	97
Annual precipitation (mm)	125	241	131	150	176	211	174
Budbreak (DOY)[f]	120	116	105	118	91	99	
Bloom (DOY)	171	159	149	149	143	136	
Fruit set (DOY)	181	173	157	162	150	144	
Veraison (DOY)	257	242	238	236	225	230	
Harvest (DOY)	301	270	267	289	259	279	

[a]GDD = Growing degree days (base 10°C) accumulated from 1 April to 31 Oct.
[b]GST = Growing season temperature.
[c]Average daily maximum temperature for the fruit set to veraison period.
[d]Average daily maximum temperature for the veraison to harvest period.
[e]Grass reference evapotranspiration.
[f]DOY = Day of year for 50% occurrence of phenological stages.
[g]Average for 1989–2016.

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Table 2 Effect of growing season on yield and its components and on harvest fruit composition of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington.

	2011	**2012**	**2013**	**2014**	**2015**	**2016**
Yield (t/ha)	45.5 ± 0.7[a]	17.1 ± 0.4	36.4 ± 0.5	55.3 ± 0.7	30.1 ± 0.7	49.3 ± 1.0
Crop level (kg/vine)	22.8 ± 0.4	8.6 ± 0.2	18.3 ± 0.3	27.8 ± 0.3	15.1 ± 0.4	24.7 ± 0.5
Clusters per vine	307 ± 6	190 ± 5	446 ± 8	454 ± 8	263 ± 6	386 ± 10
Cluster weight (g)	75.9 ± 1.2	46.2 ± 0.8	41.7 ± 0.7	62.6 ± 1.0	58.6 ± 1.1	65.7 ± 1.2
Berries per cluster	28 ± 0.5	18 ± 0.3	17 ± 0.3	25 ± 0.5	22 ± 0.4	25 ± 0.8
Berry weight (g)	2.75 ± 0.03	2.65 ± 0.03	2.50 ± 0.02	2.55 ± 0.03	2.68 ± 0.03	2.68 ± 0.04
TSS (Brix)	15.0 ± 0.2	18.4 ± 0.1	17.0 ± 0.1	16.2 ± 0.2	18.1 ± 0.2	16.9 ± 0.1
Sugar (mg/berry)	413 ± 7	487 ± 5	425 ± 5	413 ± 8	487 ± 6	453 ± 8
Titratable acidity (g/L)	11.3 ± 0.1	11.1 ± 0.1	10.1 ± 0.1	9.2 ± 0.1	10.8 ± 0.1	9.6 ± 0.1
pH	3.23 ± 0.01	3.26 ± 0.01	3.21 ± 0.01	3.38 ± 0.01	3.41 ± 0.01	3.27 ± 0.01
Red color (A520)	n.d.[b]	7.0 ± 0.2	6.5 ± 0.3	2.7 ± 0.2	11.1 ± 0.5	4.5 ± 0.2

[a]Means ± SE (n = 20–28); the year effect was always significant at $p < 0.001$.
[b]Not determined.

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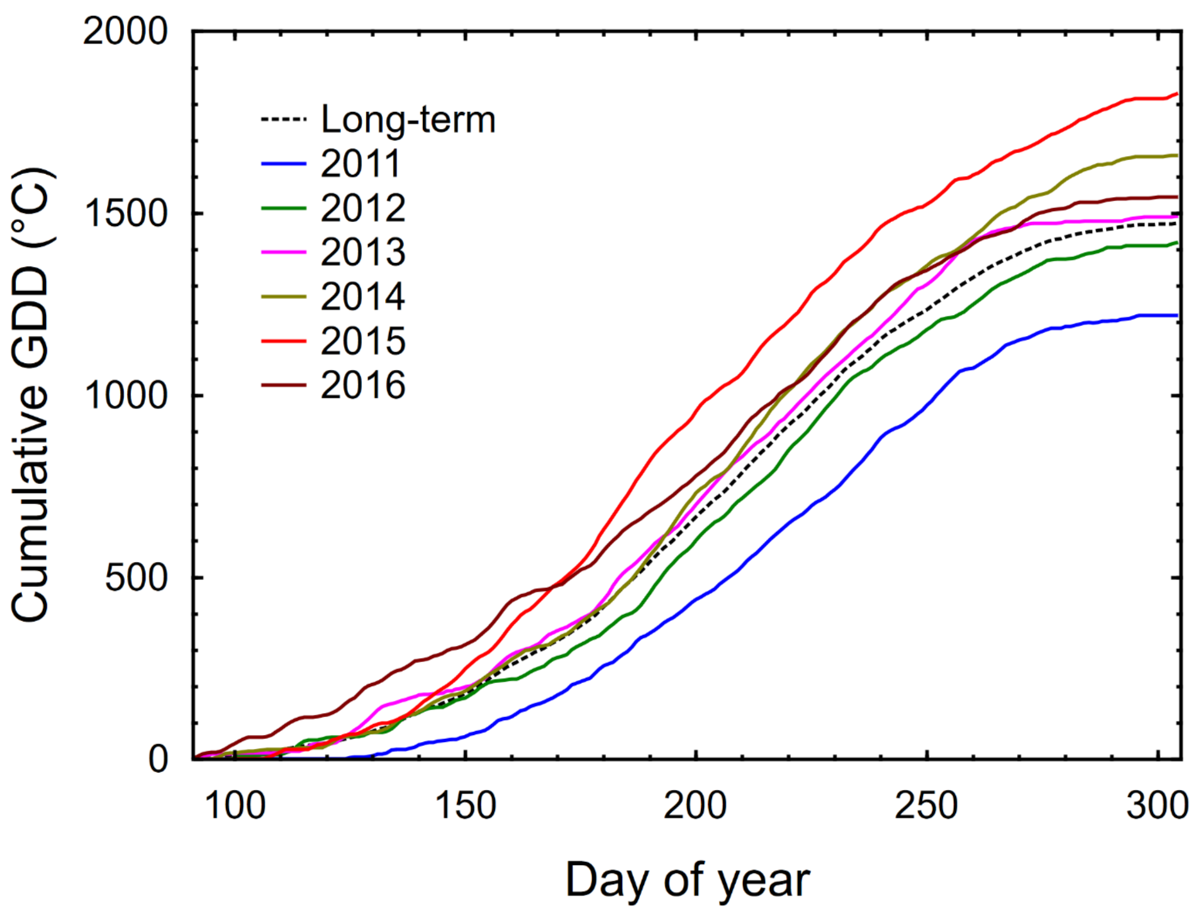

Figure 1 Seasonal trends of growing degree days (GDD, base 10°C) in a Concord juice grape vineyard in southeastern Washington over 6 years.

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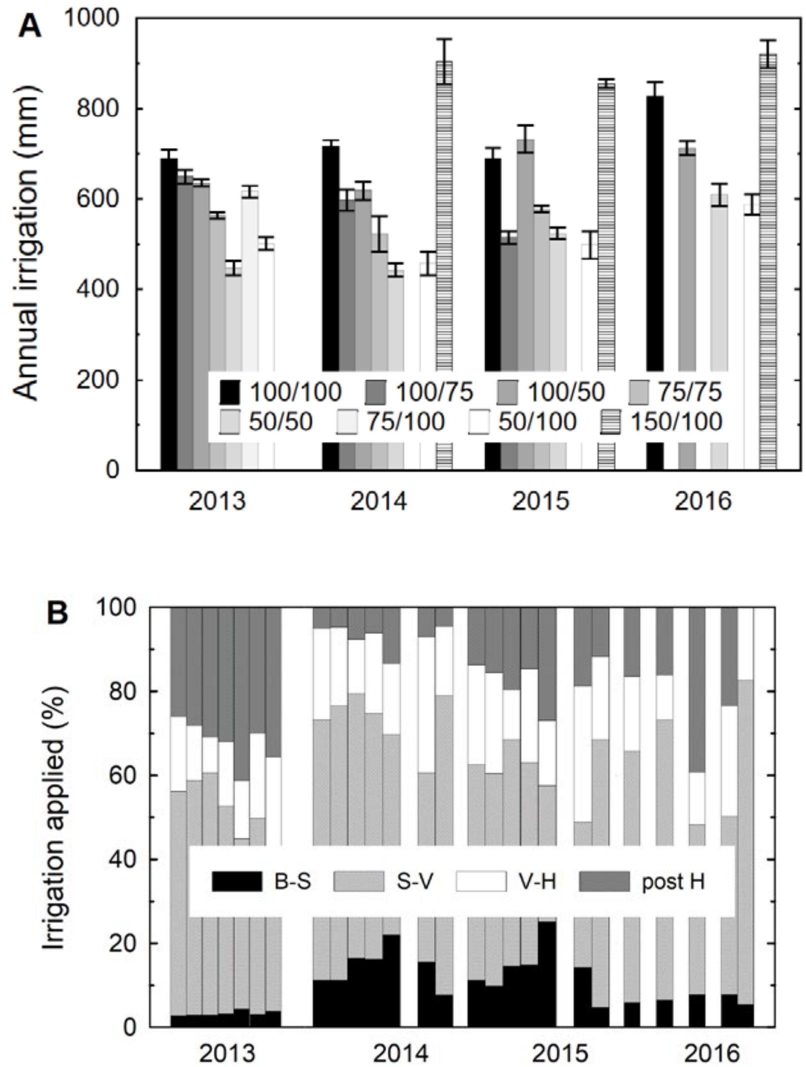

Figure 2 Annual irrigation water supply (**A**) and proportion of water supply by phenological period **(B)** for mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington and irrigated at various fractions of crop evapotranspiration (ET_c preveraison/postveraison). The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016. Bars in **A** show means ± SE; the sequence of treatments is identical in **A** and **B** (B = budbreak, S = fruit set, V = veraison, H = harvest).

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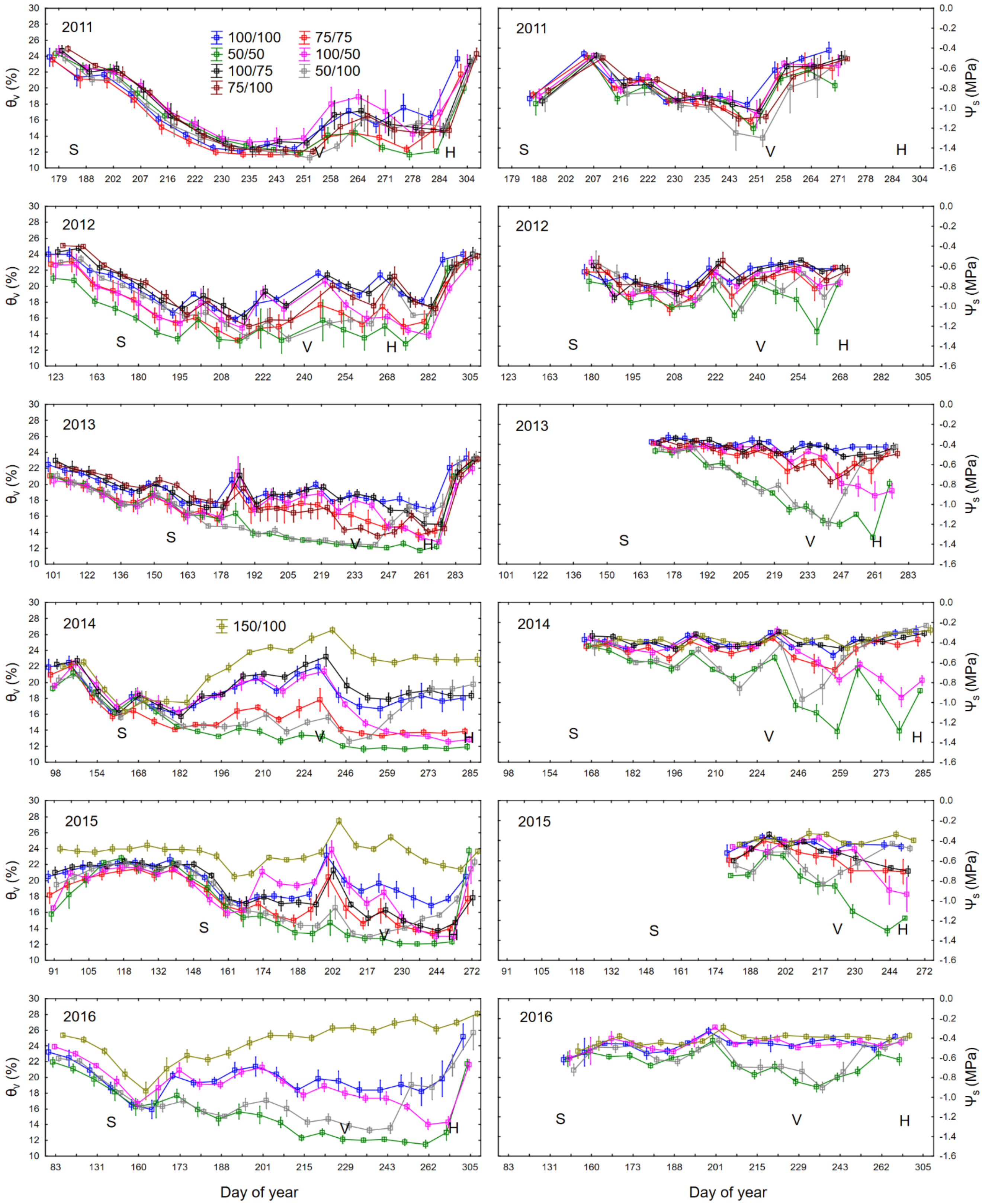

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Figure 3 Seasonal trends over 6 years of volumetric water content (θ_v) in the soil's top 60 cm and midday stem water potential (Ψ_s) of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington and irrigated at different fractions of crop evapotranspiration (% ET_c) applied preveraison/postveraison (S = fruit set; V = veraison; H = harvest). Data show means ± SE.

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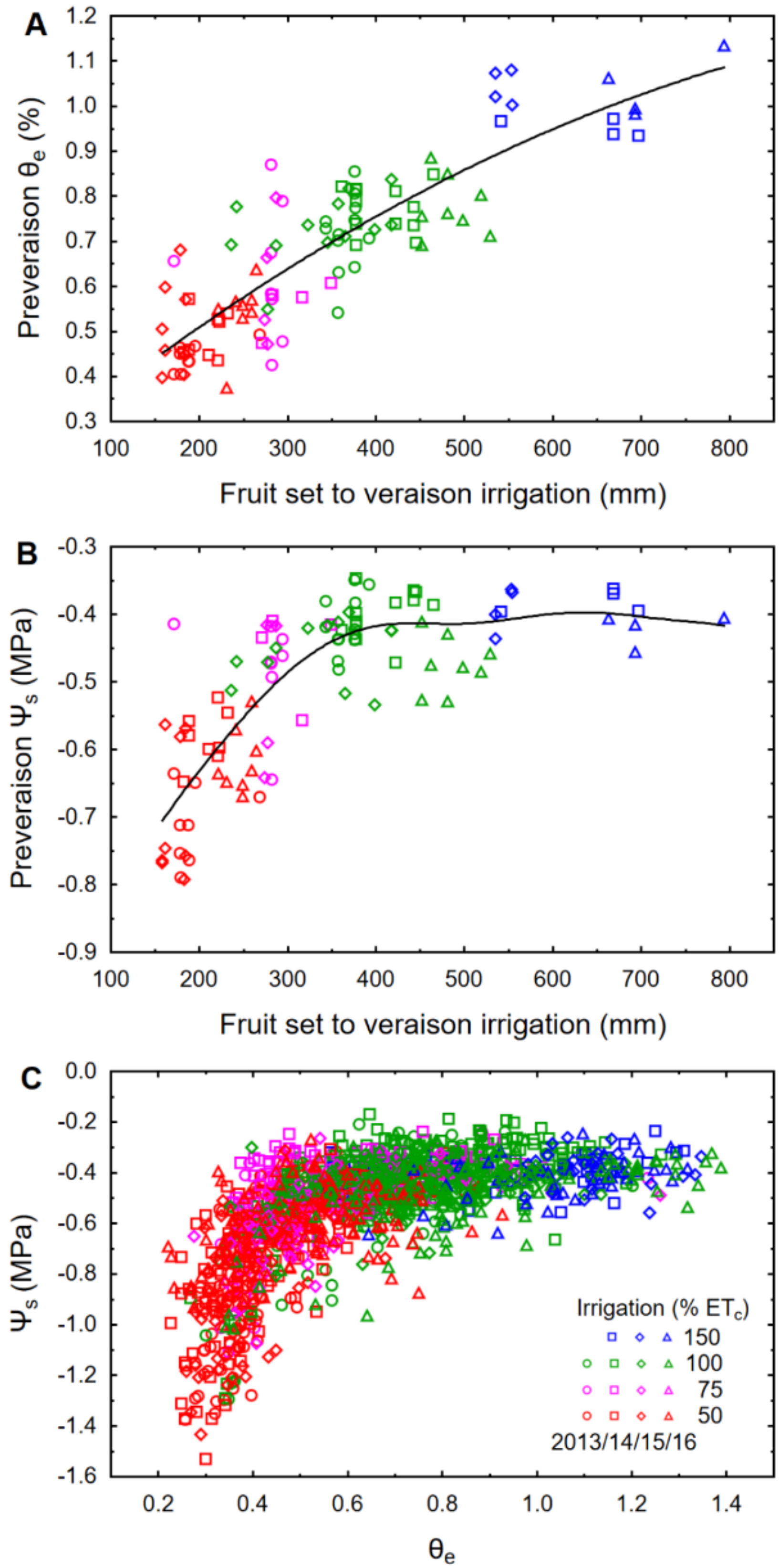

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Figure 4 Associations over 4 years between irrigation water amount applied from fruit set to veraison and average preveraison relative extractable soil water (θ_e; r = 0.86) in the soil's top 60 cm (**A**) and average preveraison midday stem water potential (Ψ_s; r = 0.67) (**B**), and between instant θ_e and Ψ_s (r = 0.62) over the fruit set to harvest period (**C**) of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington and irrigated at various fractions of crop evapotranspiration (ET_c). Symbol color indicates ET_c and symbol shape indicates year (all $p < 0.001$).

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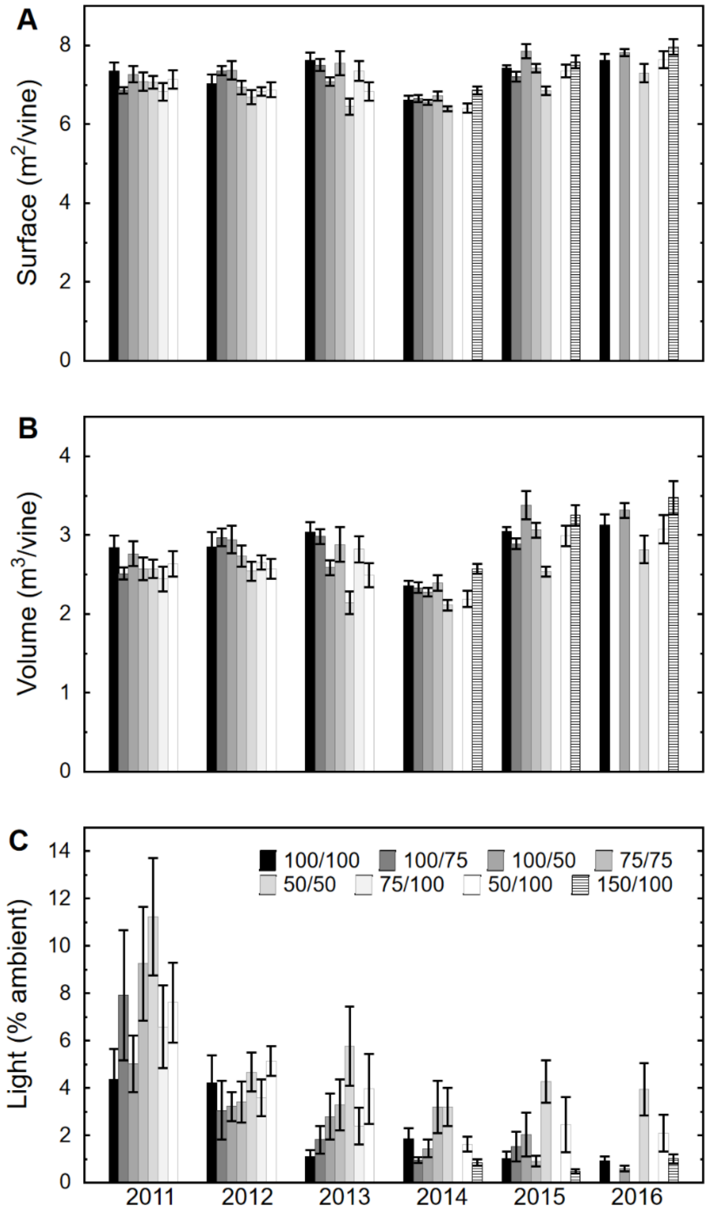

Figure 5 Effects of irrigation treatment (in % ET_c preveraison/postveraison) and growing season on preharvest canopy surface area (**A**), canopy volume (**B**), and fruit-zone light (**C**) of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington. Bars show means ± SE. The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.

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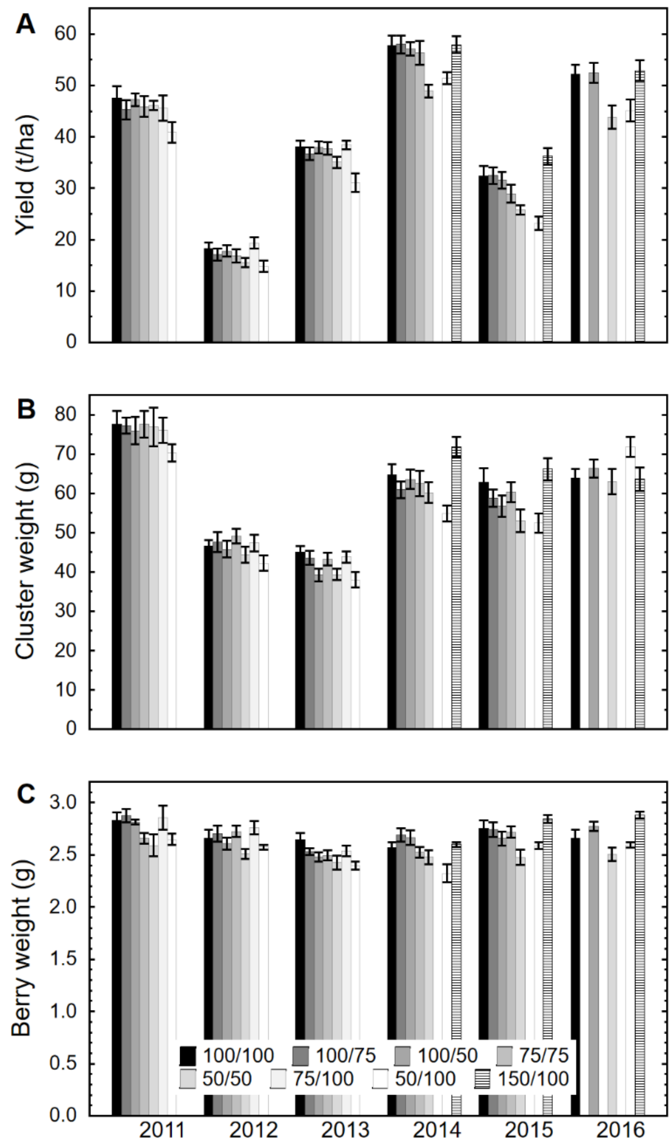

Figure 6 Effects of irrigation treatment (in % ET_c preveraison/postveraison) and growing season on crop yield (**A**), cluster weight (**B**), and berry weight (**C**) in mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington. Bars show means ± SE. The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.

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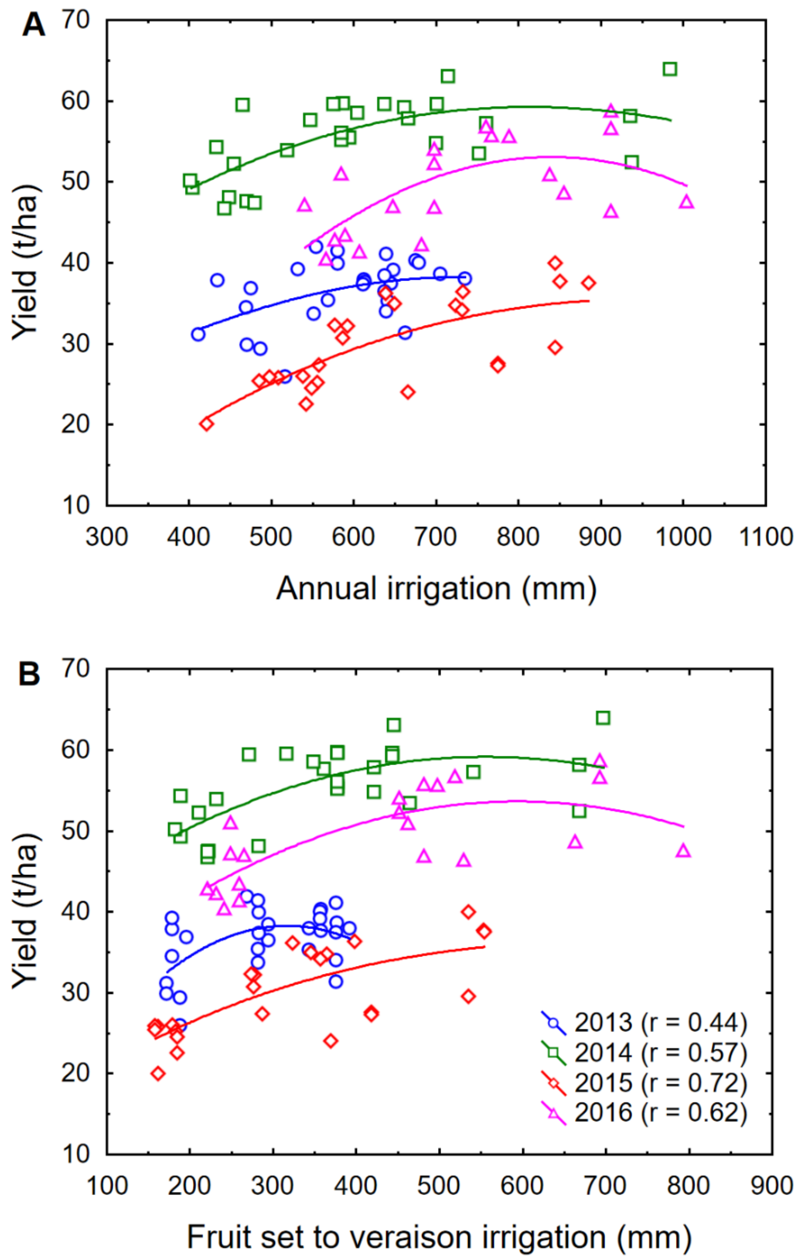

Figure 7 Association over 4 years between annual irrigation water supply and crop yield (**A**) and between irrigation water supply from fruit set to veraison and crop yield (**B**) of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington (all $p < 0.02$).

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Supplemental Table 1 Effect of irrigation treatment (in % ET_c preveraison/postveraison) on irrigation water supply to mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington.

Year	Treatment[a] (pre-/post-veraison)	Total (mm)	Budbreak to fruit set (mm)	Fruit set to veraison (mm)	Veraison to harvest (mm)	Postharvest (mm)
	100/100	689 ± 20 a[b]		367 ± 11 a	123 ± 2 a	
	100/75	650 ± 14 ab		363 ± 8 a	85 ± 5 b	
	100/50	635 ± 7 b		367 ± 5 a	54 ± 5 c	
2013	75/75	563 ± 7 c	19 ± 1[d]	279 ± 3 b	86 ± 6 b	184 ± 3
	50/50	448 ± 15 e		181 ± 5 c	62 ± 1 c	
	75/100	616 ± 13 b		288 ± 3 b	124 ± 2 a	
	50/100	501 ± 14 d		182 ± 4 c	122 ± 2 a	
	100/100	717 ± 12 b		444 ± 9 b	157 ± 3 a	36 ± 5 bc
	100/75	598 ± 24 cd		390 ± 18 b	113 ± 7 b	28 ± 3 c
	100/50	619 ± 20 c		389 ± 11 b	79 ± 4 c	47 ± 3 ab
2014	75/75	524 ± 39 de	82 ± 4	305 ± 18 c	101 ± 12 b	32 ± 5 bc
	50/50	443 ± 14 e		211 ± 8 d	75 ± 2 c	60 ± 10 a
	150/100	905 ± 49 a		644 ± 35 a	149 ± 7 a	41 ± 2 bc
	50/100	458 ± 26 e		206 ± 12 d	148 ± 8 a	33 ± 5 bc
	100/100	689 ± 23 b	78 ± 16 bc	353 ± 10 c	163 ± 6 a	95 ± 3 bc
	100/75	514 ± 14 d[c]	50 ± 10 cd	260 ± 13 d	124 ± 6 b	80 ± 4 d
	100/50	732 ± 30 b	107 ± 7 ab	394 ± 17 b	88 ± 2 c	143 ± 4 a
2015	75/75	578 ± 8 c	86 ± 12 b	278 ± 3 d	129 ± 3 b	85 ± 2 cd
	50/50	524 ± 13 cd	132 ± 7 a	170 ± 6 e	82 ± 3 c	141 ± 6 a
	150/100	855 ± 10 a	41 ± 7 d	544 ± 5 a	169 ± 1 a	101 ± 1 b
	50/100	499 ± 30 d	73 ± 16 bcd	172 ± 7 e	161 ± 5 a	93 ± 4 bc
	100/100	826 ± 32 b		492 ± 14 b	148 ± 7 a	137 ± 16 b
	100/50	713 ± 16 c		476 ± 16 b	77 ± 4 b	114 ± 4 b
2016	50/50	610 ± 25 d	48 ± 2	245 ± 6 c	76 ± 5 b	241 ± 24 a
	150/100	920 ± 31 a		710 ± 28 a	160 ± 2 a	0 ± 0 c
	50/100	588 ± 22 d		248 ± 10 c	155 ± 9 a	138 ± 18 b

[a]The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.

[b]Means ± SE ($n \geq 4$) followed by different letters within years differ significantly according to Duncan's test ($p < 0.05$).
[c]In 2015 the 100/75 treatment was accidentally irrigated like the 75/75 treatment.
[d]Values are listed by irrigation treatment only if the treatment effect is significant.

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Supplemental Table 2 Effects of irrigation treatment (in % ET_c preveraison/postveraison) and growing season on midday stem water potential (Ψ_s) and preharvest canopy characteristics of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington.

Year	Treatmenta (pre-/post-veraison)	Preveraison Ψs (MP[a])	Postveraison Ψs (MP[a])	Canopy surface (m^2/vine)	Canopy volume (m^3/vine)	Fruit-zone light (% ambient)
	100/100					4.4 ± 1.3 b
	100/75					7.9 ± 2.8 ab
	100/50					5.0 ± 1.2 ab
2011	75/75	-0.84 ± 0.02[b]	-0.57 ± 0.03	7.09 ± 0.07[c]	2.62 ± 0.05	9.3 ± 2.4 ab
	50/50					11.2 ± 2.5 a
	75/100					6.6 ± 1.8 ab
	50/100					7.6 ± 1.7 ab
	100/100	-0.71 ± 0.03 a[c]	-0.60 ± 0.01 a	7.03 ± 0.23 ab		
	100/75	-0.73 ± 0.02 ab	-0.60 ± 0.01 a	7.36 ± 0.16 a		
	100/50	-0.78 ± 0.03 ab	-0.73 ± 0.04 a	7.37 ± 0.23 a		
2012	75/75	-0.80 ± 0.03 abc	-0.69 ± 0.07 a	6.93 ± 0.18 ab	2.74 ± 0.08	3.9 ± 0.3
	50/50	-0.89 ± 0.05 c	-0.99 ± 0.07 b	6.69 ± 0.17 b		
	75/100	-0.72 ± 0.01 ab	-0.66 ± 0.03 a	6.84 ± 0.11 b		
	50/100	-0.81 ± 0.02 bc	-0.74 ± 0.04 a	6.87 ± 0.19 ab		
	100/100	-0.39 ± 0.02 a	-0.43 ± 0.03 a	7.62 ± 0.19 a	3.04 ± 0.13 a	1.1 ± 0.3 b
	100/75	-0.41 ± 0.02 a	-0.49 ± 0.04 ab	7.50 ± 0.16 a	2.98 ± 0.09 a	1.8 ± 0.6 b
	100/50	-0.45 ± 0.01 ab	-0.76 ± 0.09 bc	7.08 ± 0.11 abc	2.59 ± 0.10 ab	2.8 ± 1.0 ab
2013	75/75	-0.55 ± 0.06 bc	-0.81 ± 0.17 bc	7.55 ± 0.31 a	2.88 ± 0.22 ab	3.3 ± 1.1 ab
	50/50	-0.64 ± 0.08 cd	-1.02 ± 0.17 c	6.45 ± 0.21 c	2.14 ± 0.14 c	5.8 ± 1.7 a
	75/100	-0.47 ± 0.01 ab	-0.63 ± 0.04 ab	7.35 ± 0.25 ab	2.50 ± 0.15 ab	2.4 ± 0.8 ab
	50/100	-0.72 ± 0.03 d	-0.80 ± 0.04 bc	6.83 ± 0.23 bc	2.82 ± 0.16 bc	4.0 ± 1.5 ab
	100/100	-0.40 ± 0.03 ab	-0.39 ± 0.03 ab	6.63 ± 0.10 abc	2.36 ± 0.07 ab	1.9 ± 0.4 ab
	100/75	-0.39 ± 0.02 ab	-0.39 ± 0.02 ab	6.65 ± 0.09 abc	2.33 ± 0.07 bc	1.0 ± 0.1 b
	100/50	-0.41 ± 0.01 ab	-0.71 ± 0.03 d	6.55 ± 0.06 bc	2.28 ± 0.05 bc	1.4 ± 0.4 ab
2014	75/75	-0.45 ± 0.03 b	-0.50 ± 0.05 bc	6.72 ± 0.12 ab	2.39 ± 0.10 ab	3.2 ± 1.1 a
	50/50	-0.59 ± 0.01 c	-1.03 ± 0.04 e	6.40 ± 0.06 c	2.11 ± 0.07 c	3.2 ± 0.8 a
	150/100	-0.38 ± 0.01 a	-0.35 ± 0.01 a	6.86 ± 0.10 a	2.57 ± 0.06 a	0.8 ± 0.1 b
	50/100	-0.57 ± 0.03 c	-0.52 ± 0.05 c	6.41 ± 0.11 c	2.19 ± 0.10 bc	1.6 ± 0.3 ab
	100/100	-0.44 ± 0.03 a	-0.45 ± 0.02 a	7.42 ± 0.07 b	3.05 ± 0.06 abc	1.0 ± 0.3 b
	100/75	-0.48 ± 0.01 a	-0.65 ± 0.04 bc	7.21 ± 0.12 bc	2.89 ± 0.07 c	1.5 ± 0.6 b
	100/50	-0.45 ± 0.03 a	-0.77 ± 0.11 c	7.86 ± 0.17 a	3.38 ± 0.18 a	2.0 ± 0.9 b
2015	75/75	-0.52 ± 0.06 a	-0.71 ± 0.11 bc	7.43 ± 0.11 b	3.06 ± 0.09 abc	0.9 ± 0.2 b
	50/50	-0.72 ± 0.05 b	-1.20 ± 0.04 d	6.85 ± 0.11 c	2.54 ± 0.06 d	4.3 ± 0.9 a
	150/100	-0.39 ± 0.02 a	-0.39 ± 0.03 a	7.58 ± 0.17 ab	3.25 ± 0.13 ab	0.5 ± 0.1 b
	50/100	-0.66 ± 0.06 b	-0.51 ± 0.03 ab	7.35 ± 0.16 b	2.99 ± 0.13 bc	2.5 ± 1.2 ab
	100/100	-0.49 ± 0.02 a	-0.43 ± 0.02 a		3.13 ± 0.14 ab	0.9 ± 0.2 b
	100/50	-0.46 ± 0.03 a	-0.46 ± 0.01 a		3.31 ± 0.09 ab	0.6 ± 0.1 b
2016	50/50	-0.63 ± 0.02 b	-0.74 ± 0.04 c	7.67 ± 0.09	2.82 ± 0.17 b	3.9 ± 1.1 a
	150/100	-0.42 ± 0.01 a	-0.39 ± 0.02 a		3.48 ± 0.21 a	1.0 ± 0.2 b
	50/100	-0.60 ± 0.03 b	-0.60 ± 0.03 b		3.07 ± 0.18 ab	2.1 ± 0.8 b

[a]The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.
[b]Values are listed by irrigation treatment only when the treatment effect is significant.

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[c]Means ± SE ($n \geq 4$) followed by different letters within years differ significantly according to Duncan's test ($p < 0.05$).

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Supplemental Table 3 Effects of irrigation treatment (in % ET_c preveraison/postveraison) and growing season on yield and its components in mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington.

Year	Treatmenta (pre-/post-veraison)	Yield (t/ha)	Clusters per vine	Cluster weight (g)	Berries per cluster	Berry weight (g)
2011	All[b]	45.5 ± 0.7[c]	307 ± 6	76 ± 1	28 ± 0.5	2.75 ± 0.03
	100/100	18.2 ± 1.2 ab[d]				
	100/75	17.1 ± 1.2 ab				
	100/50	17.8 ± 1.1 ab				
2012	75/75	16.9 ± 1.3 ab	190 ± 5	46 ± 1	18 ± 0.3	2.65 ± 0.03
	50/50	15.5 ± 1.0 b				
	75/100	19.3 ± 1.1 a				
	50/100	14.8 ± 1.1 b				
	100/100	38.1 ± 1.2 a		45 ± 1 a		2.65 ± 0.06 a
	100/75	36.7 ± 1.2 a		44 ± 2 ab		2.53 ± 0.03 ab
	100/50	38.0 ± 1.2 a		39 ± 1 bc		2.48 ± 0.04 b
2013	75/75	37.7 ± 1.3 a	446 ± 8	43 ± 2 ab	17 ± 0.3	2.52 ± 0.05 ab
	50/50	35.1 ± 1.1 ab		39 ± 1 bc		2.42 ± 0.05 b
	75/100	38.4 ± 0.8 a		44 ± 1 ab		2.54 ± 0.05 ab
	50/100	31.1 ± 1.8 b		38 ± 2 c		2.40 ± 0.04 b
	100/100	57.7 ± 2.0 a		65 ± 3 ab		2.57 ± 0.05 ab
	100/75	58.0 ± 1.7 a		64 ± 2 bc		2.69 ± 0.06 a
	100/50	57.1 ± 1.3 a		64 ± 2 b		2.66 ± 0.07 ab
2014	75/75	56.4 ± 2.3 a	454 ± 8	62 ± 3 b	25 ± 0.5	2.53 ± 0.05 ab
	50/50	48.9 ± 1.2 b		60 ± 3 bc		2.48 ± 0.08 bc
	150/100	57.9 ± 1.6 a		72 ± 3 a		2.60 ± 0.02 ab
	50/100	51.4 ± 1.2 b		55 ± 2 c		2.32 ± 0.09 c
	100/100	32.3 ± 2.0 ab		63 ± 3 ab		2.76 ± 0.07 ab
	100/75	32.5 ± 1.7 ab		59 ± 2 abcd		2.74 ± 0.07 ab
	100/50	31.2 ± 1.6 b		57 ± 3 bcd		2.66 ± 0.07 abc
2015	75/75	28.9 ± 1.8 bc	263 ± 6	60 ± 3 abc	22 ± 0.4	2.72 ± 0.05 ab
	50/50	25.8 ± 0.9 cd		53 ± 3 cd		2.48 ± 0.07 c
	150/100	36.2 ± 1.6 a		66 ± 3 a		2.85 ± 0.04 a
	50/100	23.2 ± 1.3 d		52 ± 2 d		2.59 ± 0.03 bc
	100/100	52.2 ± 1.9 a	415 ± 18 ab			2.66 ± 0.08 bc
	100/50	52.5 ± 2.0 a	402 ± 18 ab			2.77 ± 0.05 ab
2016	50/50	43.8 ± 2.3 b	359 ± 22 bc	66 ± 1	25 ± 0.8	2.51 ± 0.06 c
	150/100	52.9 ± 2.0 a	433 ± 26 a			2.88 ± 0.03 a
	50/100	45.1 ± 2.1 b	322 ± 19 c			2.60 ± 0.03 c

[a]The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.
[b]Neither yield nor any of its components were significantly affected by irrigation treatment in 2011.
[c]Values are listed by irrigation treatment only if the treatment effect is significant.
[d]Means ± SE ($n \geq 4$) followed by different letters within years differ significantly according to Duncan's test ($p < 0.05$).

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Supplemental Table 4 Effect of irrigation treatment (in % ET_c preveraison/postveraison) on irrigation water use efficiency (WUE) and water footprint of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington.

Year	Treatment[a] (pre-/post-veraison)	Irrigation WUE (t/ML)	Irrigation water footprint (m^3/t)	Total water footprint (m^3/t)
	100/100	5.5 ± 0.2 c[b]	181 ± 5 a	216 ± 6 a
	100/75	5.7 ± 0.3 c	179 ± 11 a	215 ± 13 a
	100/50	6.0 ± 0.2 bc	168 ± 7 ab	203 ± 8 a
2013	75/75	6.7 + 0.3 b	150 ± 7 bc	185 ± 9 ab
	50/50	7.8 + 0.3 a	128 ± 5 c	166 ± 6 b
	75/100	6.3 + 0.3 bc	161 ± 7 ab	195 ± 8 ab
	50/100	6.2 + 0.3 bc	164 + 13 ab	207 ± 17 a
	100/100	8.1 ± 0.4 d	125 ± 6 b	151 ± 7 b
	100/75	9.7 ± 0.4 bc	103 ± 4 cd	129 ± 4 c
	100/50	9.3 ± 0.2 cd	108 ± 2 c	134 ± 2 bc
2014	75/75	10.9 ± 0.7 ab	93 ± 5 cd	120 ± 6 c
	50/50	11.1 ± 0.5 ab	91 ± 4 cd	121 ± 4 c
	150/100	6.5 ± 0.4 e	157 ± 9 a	183 ± 10 a
	50/100	11.3 ± 0.7 a	89 ± 6 d	119 ± 6 c
	100/100	4.7 ± 0.4 b	218 ± 21 a	
	100/75	6.3 ± 0.4 a	159 ± 10 b	
	100/50	4.4 ± 0.5 b	238 ± 26 a	
2015	75/75	5.0 ± 0.4 b	204 ± 16 ab	272 ± 8[c]
	50/50	4.9 ± 0.1 b	203 ± 6 ab	
	150/100	4.2 ± 0.3 b	239 ± 16 a	
	50/100	4.7 ± 0.2 b	216 ± 10 a	
	100/100	6.4 ± 0.5 ab	160 ± 13 ab	
	100/50	7.4 ± 0.2 a	136 ± 4 b	
2016	50/50	7.2 ± 0.5 a	141 ± 10 b	192 ± 6
	150/100	5.8 ± 0.4 b	176 ± 12 a	
	50/100	7.7 ± 0.3 a	130 ± 5 b	

[a]The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.
[b]Means ± SE ($n \geq 4$) followed by different letters within years differ significantly according to Duncan's test ($p < 0.05$).
[c]Values are listed by irrigation treatment only if the treatment effect is significant.

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Supplemental Table 5 Effects of irrigation treatment (in % ET_c preveraison/postveraison) and growing season on harvest fruit composition of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington.

Year	**Treatment[a] (pre-/post-veraison)**	**Total soluble solids (Brix)**	**Titratable acidity (g/L)**	**pH**	**Color density (A520)**
2011	All[b]	15.0 ± 0.2[c]	11.3 ± 0.1	3.23 ± 0.01	n.d.[e]
2012	All	18.4 ± 0.1	11.1 ± 0.1	3.26 ± 0.01	7.0 ± 0.2
	100/100		10.5 ± 0.1 a		
	100/75		10.5 ± 0.2 a		
	100/50		10.1 ± 0.1 a		
2013	75/75	17.0 ± 0.1	10.3 ± 0.3 a	3.21 ± 0.01	6.5 ± 0.3
	50/50		9.3 ± 0.2 b		
	75/100		10.3 ± 0.2 a		
	50/100		9.4 ± 0.2 b		
2014	All	16.2 ± 0.2	9.2 ± 0.1	3.38 ± 0.01	2.7 ± 0.2
	100/100	17.7 ± 0.5 bc[d]			10.6 ± 1.0 ab
	100/75	18.3 ± 0.3 bc			10.5 ± 0.9 b
	100/50	17.9 ± 0.2 bc			11.7 ± 0.7 ab
2015	75/75	18.6 ± 0.3 b	10.8 ± 0.1	3.41 ± 0.01	12.5 ± 1.1 ab
	50/50	17.5 ± 0.3 bc			11.1 ± 1.2 ab
	150/100	17.4 ± 0.4 c			7.5 ± 0.8 c
	50/100	19.7 ± 0.5 a			13.5 ± 0.1 a
	100/100		9.7 ± 0.2 ab		
	100/50		9.7 ± 0.2 ab		
2016	50/50	16.9 ± 0.1	9.2 ± 0.1 b	3.27 ± 0.01	4.5 ± 0.2
	150/100		10.1 ± 0.2 a		
	50/100		9.3 ± 0.1 b		

[a]The 75/100 treatment was replaced with the 150/100 treatment in 2014; the 100/75 and 75/75 treatments were not applied in 2016.
[b]None of the measures of fruit composition was significantly affected by irrigation treatment in 2011, 2012, 2014.
[c]Values are listed by irrigation treatment only if the treatment effect is significant.
[d]Means ± SE ($n \geq 4$) followed by different letters within years differ significantly according to Duncan's test ($p < 0.05$).
[e]Not determined.

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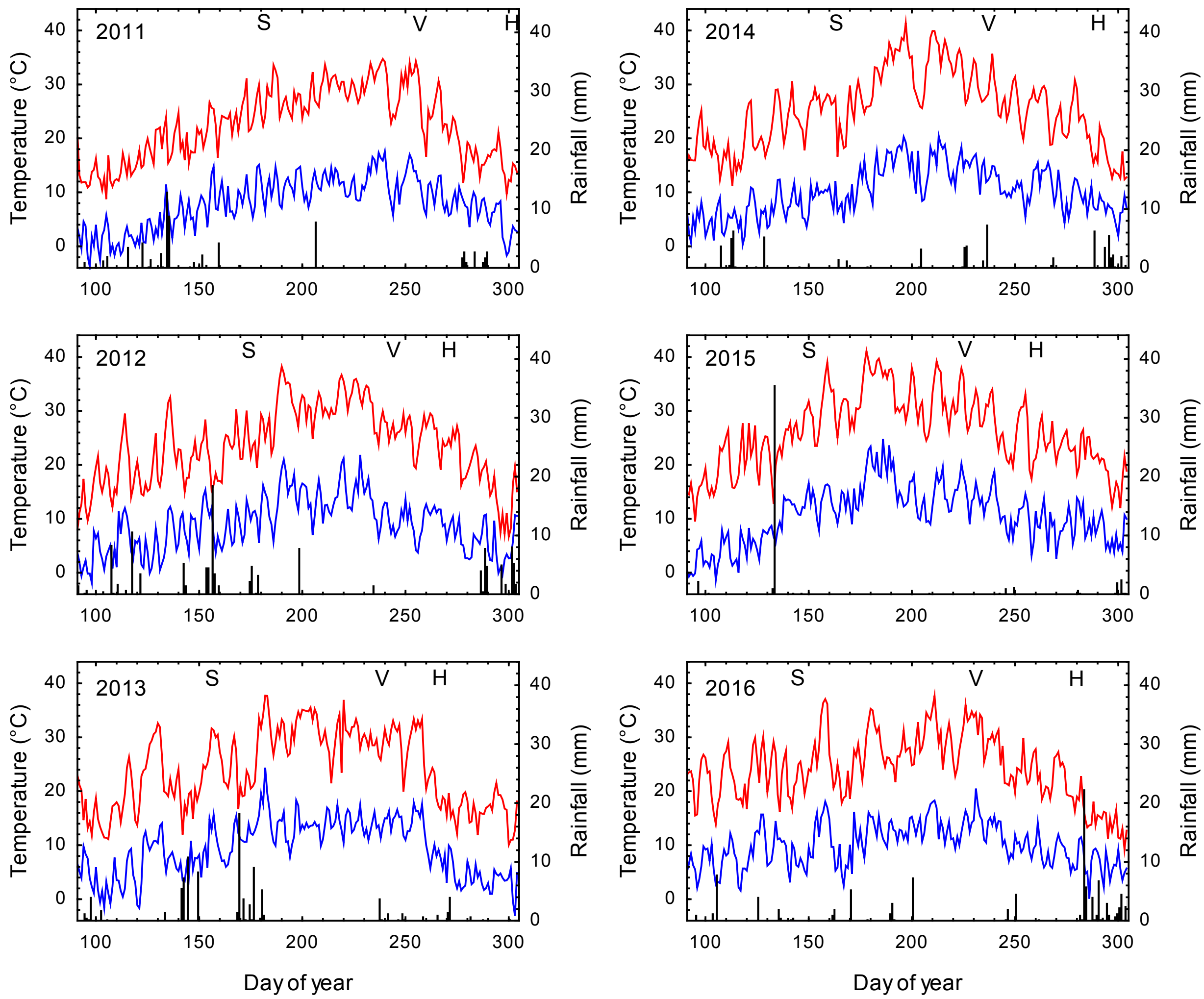

Supplemental Figure 1 Daily maximum and minimum temperatures (lines), and rainfall (bars) during the April–Oct growing season over 6 years in a Concord juice grape vineyard in southeastern Washington (S = fruit set; V = veraison; H = harvest).

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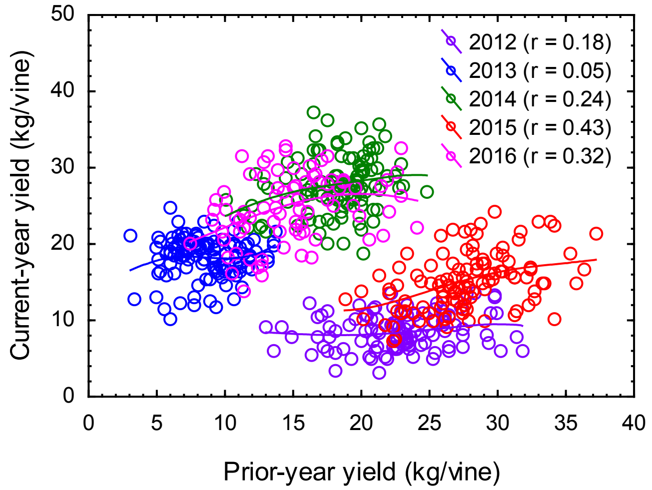

Supplemental Figure 2 Association over 6 years between crop yield in the previous year and the current year of mechanically-pruned Concord juice grapes planted in 2003 in southeastern Washington (all $p < 0.001$).