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Response of Riesling Grapes and Wine to Temporally and Spatially Heterogeneous Soil Water Availability

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Abstract

Background and goals

Regulated deficit irrigation (RDI) and partial rootzone drying (PRD) have produced divergent viticultural and enological outcomes when implemented in vineyard settings, with most research focused on red wine grape cultivars. The goal of this work was to assess the suitability of RDI and PRD for producing high-quality grapes for white wine production in arid climates.

Methods and key findings

We conducted a three-year field trial with Riesling winegrapes to compare RDI and PRD with a fully irrigated control in southeastern Washington. Irrigation scheduling was based on soil moisture thresholds depending on vine phenology. We measured irrigation water supply, soil and plant water status, canopy size and density, yield components, and fruit and wine composition. Both RDI and PRD conserved irrigation water but reduced yield. While RDI saved more water than PRD, it reduced canopy size relative to the control. The irrigation methods did not affect basic fruit composition, but small differences in preveraison plant water status attained through differential irrigation resulted in notable differences in wine volatile profiles and, to a lesser degree, phenolic composition.

Conclusions and significance

This study highlights the potential of different irrigation methods to shape wine style in the vineyard through temporal and spatial manipulation of soil water availability. The "optimum" irrigation approach for white wine grapes should integrate the trade-off between management complexity and costs, reductions in water supply and yield, and gains in wine quality or changes in wine style.

Key words: partial rootzone drying, regulated deficit irrigation, Riesling, *Vitis*, wine

Introduction

In regions with dry summers, strategically induced water deficit is often adopted in winegrape production for its beneficial outcomes. Regulated deficit irrigation (RDI) and partial rootzone drying (PRD) are deficit irrigation techniques that involve finely tuning water stress over time (specific timing of water application in RDI) or space (alternating dry and wet zones in PRD). With RDI, controlled water stress is deliberately imposed on grapevines after fruit set by providing irrigation water below the evaporative demand. This method is particularly effective in controlling shoot growth and berry size during the period from fruit set to veraison, but when compared to non-deficit irrigation, RDI may result in yield losses (Keller et al. 2016). Moderate water stress can alter canopy development and fruit composition by reducing vine vigor, which leads to an open canopy with increased sunlight penetration and airflow (Chaves et al. 2007, Keller et al. 2016, Keller 2023). Water deficit after fruit set also reduces berry size, increasing the skin-to-pulp ratio (Pérez-Álvarez et al. 2021, Torres et al. 2022). These advantages are particularly sought after for producing red wine grapes (Roubelakis-Angelakis and Kliewer 1986, Bucchetti et al. 2011, Casassa et al. 2015, Mirás-Avalos and Araujo 2021). However, the adoption of RDI may pose challenges for making white wine. Sunlight exposure has been observed to increase the concentration of skin flavonols in white grapes, which at high concentrations may contribute to the perceived astringency and bitterness of the resulting wines (Friedel et al. 2015, Bubola et al. 2019, Rustioni et al. 2023). Additionally, exposure to sunlight can subject grape clusters to higher temperatures than the ambient air, causing sunburn damage in severe cases (Peña-Quiñones et al. 2019, Ponce de León and Bailey 2021, Müller et al. 2023). These changes are especially relevant considering the scenarios of rising temperatures, increased aridity, and altered precipitation patterns, as projected by the Intergovernmental Panel on Climate Change (IPCC 2023).

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Although differences in the water needs of different winegrape cultivars are gaining more attention (Levin et al. 2020, Lamarque et al. 2023), there is still a need for site- and cultivar-specific irrigation guidelines. PRD, which has emerged as a promising alternative to RDI in dry regions, is a deficit irrigation technique that exposes the roots to alternate drying and wetting cycles. By generating spatial differences in water availability, a portion of the root system is always experiencing drying soil, triggering the production of abscisic acid (ABA) in the drying roots. In the leaves, ABA leads to partial stomatal closure as a drought avoidance mechanism. Hydraulic signals, the increase in ABA, and changes in other hormones and pH of the xylem sap alter shoot physiology (Stoll et al. 2000, Dodd et al. 2006, Romero et al. 2022). In theory, PRD saves irrigation water and increases water use efficiency without decreasing plant water status and fruit yield (dos Santos et al. 2003, 2005, du Toit et al. 2003, Antolín et al. 2006, Mirás-Avalos and Araujo 2021). Though PRD tends to decrease vigor compared with abundant water supply, the decrease has often been found to be less pronounced than that due to RDI (Dry et al. 2001, Antolín et al. 2006, De la Hera et al. 2007, Intrigliolo and Castel 2009, Romero et al. 2012).

The reduction in canopy density and higher sun exposure due to PRD irrigation compared with full irrigation has been reported to increase the concentration of anthocyanins and other phenolic compounds in the fruit (Dry et al. 2001, Bindon et al. 2008, Romero et al. 2022). However, the adoption of PRD in vineyards has yielded contrasting results in the literature. Several studies have reported no improvement in water relations, water use, yield, or fruit quality when compared to conventional drip irrigation at similar levels of water supply (dos Santos et al. 2003, Pudney and McCarthy 2004, Intrigliolo and Castel 2009, Gu et al. 2015). The diverse results may be caused by differences in the strength of chemical signaling during PRD, or by factors such as soil type or depth, rainfall patterns, evaporative demand, or the relative volumes of irrigation water applied to each rootzone (Dry et al. 2001, Medrano et al. 2015, Romero et al. 2022). Genetic differences in rooting patterns, ABA production or transport by the rootstock, or the response to ABA by the scion could also account for some of the diverse outcomes (Antolín et al. 2006, De la Hera et al. 2007).

To better understand the response of white wine grapes to different deficit irrigation techniques in arid climates, an irrigation trial was set up in eastern Washington, a region that receives only 200 mm annual precipitation and depends on irrigation for sustainable crop production. Using *Vitis vinifera* L. cv. Riesling, the study aimed to assess the influence of temporal (RDI) and spatial (PRD) differences in water availability on water use, vine size, yield components, and fruit and wine composition. In addition, the experiment served as a test bed to develop spectral imaging approaches for remote sensing of vine water status to map vineyard water status for precision irrigation management (Kang et al. 2023a, 2023b). Unlike previous studies that used fixed temporal intervals (e.g., 14 days) for switching irrigation sides (Stoll et al. 2000, De la Hera et al. 2007, Collins et al. 2010, Romero et al. 2014), we implemented PRD by monitoring soil moisture on both sides of the root system. The irrigation sides were switched when the dry side reached a lower soil moisture threshold. We hypothesized that PRD would effectively conserve irrigation water while maintaining an optimal vine water status and yield, and that PRD would limit canopy growth to a lesser extent than RDI, making it a more suitable irrigation approach for white wine grapes. We also hypothesized that larger canopies and reduced fruit sun exposure would reduce the concentration of undesirable phenolic compounds in the resulting wines.

Materials and Methods

Vineyard site and plant material

An irrigation trial was conducted from 2019 to 2021 in a vineyard at the Roza unit (46°18'N; 119°44'W, 364 m asl) of the Washington State University Irrigated Agriculture Research and Extension Center in Prosser, WA. The site is in the Yakima Valley American Viticultural Area, which is characterized by warm and very dry summers, moderately cold winters, and an average annual precipitation of 200 mm. The soil is a Warden silt loam with a pH of ~8 (https://websoilsurvey.sc.egov.usda.gov) and a caliche layer at variable depths (50 to 100 cm) that limits root growth. The volumetric water content (θ_v) is 26% (v/v) at field capacity (FC) and 8% at permanent wilting point (PWP) (Groenveld et al. 2023). Own-rooted *V. vinifera* cv. Riesling (clone FPS 09) vines, propagated from certified material, were planted in 2010. The between-row spacing is 2.74 m with a north-south row orientation, and the within-row spacing is 1.83 m. Vines were double-trunked, trained to bilateral cordons, spur pruned to 24 buds per vine, and vertically shoot-positioned. A permanent but summer-dormant volunteer cover crop was grown between rows, and 1.2-m herbicide strips were maintained in the rows. The vineyard was drip-irrigated using 2-L/hr emitters spaced 0.91 m apart. Irrigation water was applied throughout the growing season, as described in the "Treatments and experimental design" section. Nitrogen fertilizer in the form of UAN-32 was applied by fertigation at a rate of 30 kg N/ha, split into three applications: at the six-leaf stage, at full bloom, and at fruit set. In 2021, N was applied in the form of granular urea. Shoots were thinned on 6 June (fruit set) in 2019, 5 June (beginning of bloom) in 2020, and 27 June (berries pea size) in 2021. An additional shoot thinning pass was performed accidentally on 20 June 2020. Pest and disease control was applied homogeneously across the vineyard according to standard regional practices.

Treatments and experimental design

The experiment was set up in a randomized complete block design with four blocks and three treatments: a fully irrigated, no-stress control (FULL); RDI; and PRD. Each treatment was applied to 15 consecutive vines in four adjacent rows. Data were collected from four vines in the middle of each treatment replicate. Irrigation scheduling relied on predetermined soil moisture targets based on FC and PWP (Figure 1). To assess soil and plant water status and to schedule irrigation, θ_v and midday leaf water potential (Ψ_{leaf}) were measured weekly. Soil moisture was measured using a neutron probe (503 DR Hydroprobe, CPN International). One access tube was installed between two data vines near the center of each treatment replicate to a depth of 90 cm, except in three cases where the caliche layer limited the depth to 60 cm. With those three exceptions, the θ_v for the rooting zone was taken as the average of the readings at 30, 60, and 90 cm. Access tubes were installed on both sides of PRD vines to account for differences between the dry (PRD_{dry}) and wet (PRD_{wet}) sections of the soil. The measured θ_v was converted to relative extractable soil water content (θ_e = 100 × [θ_v − PWP]/[FC − PWP]) to normalize the influence of soil texture and enable comparisons across different soil types (Groenveld et al. 2023). Midday Ψ_{leaf} was measured with a pressure chamber (Model 615 D, PMS Instrument Company) after solar noon (1300 to 1400 hr). This time was chosen based on diurnal Ψ_{leaf} measurements under diverse temperature and θ_v conditions, indicating that the minimum Ψ_{leaf} was generally reached before 1200 hr and remained close to minimal until later in the afternoon (Supplemental Figure 1). Daily weather data were obtained from the Roza.2 AgWeatherNet meteorological station located ~550 m from the vineyard (https://weather.wsu.edu).

Weekly irrigation was scheduled to maintain θ_v within dynamic target ranges depending on vine phenological stages (Figure 1). For the FULL treatment, the goal was to keep θ_v at levels that maintained Ψ_{leaf} > -0.8 MPa (i.e., in the no-stress range; Rienth and Scholasch 2019). The FULL θ_v threshold was initially set at 14% in 2019, but adjusted to 16 to 18% in 2020 and 2021 based on Ψ_{leaf} and growth responses. For RDI and PRD, we used a θ_v threshold of 10 to 12% to induce mild-to-moderate water stress. This value was selected in 2019 and kept in subsequent growing seasons, as the midday Ψ_{leaf} was rarely below -1.4 MPa, which would indicate severe water stress (Rienth and Scholasch 2019). All treatments aimed to maintain θ_v close to the upper threshold from budbreak to fruit set. The FULL treatment maintained this target throughout the season, while RDI was applied from fruit set to veraison (with irrigation similar to FULL thereafter), and PRD was applied from fruit set to harvest. The PRD treatment alternated irrigation sides when the dry soil reached the lower θ_v threshold, regardless of the time taken to reach this point. If the dry side was above this threshold during a weekly measurement, it was left to dry, and the wet side was irrigated to the upper θ_v threshold. After harvest, θ_v was replenished to ≥17% in all treatments to prevent cold injury to roots during the winter. In 2019, heavy snowfall in late winter and the decision to withhold irrigation to stop shoot growth resulted in all irrigation treatments being delayed until 31 July, even though fruit set occurred on 12 June.

Field data collection

The total seasonal irrigation water supply for each treatment was estimated by multiplying the scheduled irrigation hours with the theoretical water delivery based on emitter rate, emitters per vine, and vine spacing. This estimation was highly correlated with flow meter readings (r = 0.99, Supplemental Figure 2), but flow meters were not operational for the entire trial duration. The length of four representative shoots per vine was measured at fruit set and veraison, and nodes per shoot, lateral shoots, and lateral leaves were counted. The shoot growth rate (vigor) between fruit set and veraison was estimated as change in shoot length over time. Sun exposure of the clusters was measured at veraison by inserting a ceptometer (AccuPAR LP-80, Decagon Devices) across the fruit zone (perpendicular to the canopy) at two locations on each vine. Ambient reference values were taken before and after canopy readings and used to estimate the percentage of fruit-zone light exposure. In winter, pruning weight was determined, and total canes and canes with ≤6 nodes were counted as a proxy for canopy density and to estimate the average cane weight as a proxy for vigor.

The fruit was hand-harvested on 8 Oct 2019, 29 Sept 2020, and 8 Sept 2021, as close to a target total soluble solids (TSS) content of 20 Brix as possible. This TSS threshold was determined based on periodic berry sampling across treatments and is considered desirable for a fresh, fruity Riesling wine style. Yield, yield components (cluster number per vine, cluster weight, berry weight), and basic fruit composition were determined. To measure berry weight, TSS, pH, and titratable acidity (TA), 100 randomly sampled berries per treatment replicate were used in 2019, and 200 berries were used in 2020 and 2021. Juice was obtained by crushing the berries manually and centrifuged for 1 min at 1500 g (centrifuge 5804R, Eppendorf). The TSS were measured with a digital refractometer (RE40D, Mettler-Toledo), pH was measured with a pH meter (MP225 General Purpose GLP pH/mV/T meter, Mettler-Toledo), and TA was measured with a titrator (G10 Compact Titrator, Mettler-Toledo) on the day of sample collection. The irrigation water use efficiency (WUE_i, t/ML)

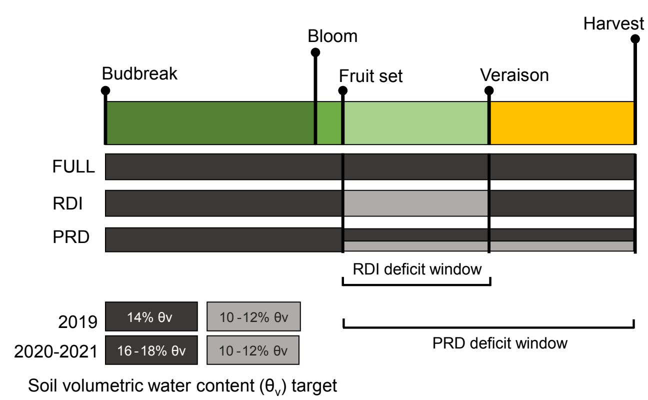

Figure 1 Schematic representation of the dynamic target soil moisture ranges by phenological period in an irrigation trial conducted in a Riesling vineyard in southeastern Washington. Soil moisture (θ_v) was measured weekly and irrigation hours were scheduled according to the dynamic targets. The period in which deficit irrigation was applied is indicated for each treatment. Treatments included a no-stress control (FULL), regulated deficit irrigation (RDI), and partial rootzone drying (PRD).

was calculated by dividing the yield (t/ha) by the total irrigation water supply (ML/ha). The irrigation water footprint (m^3/t) was similarly calculated as the amount of irrigation water applied per unit yield, and the total water footprint (m^3/t) was calculated as the amount of annual rainfall plus irrigation water per unit yield.

Winemaking

Approximately 135 kg of fruit from each of three field treatment replicates were transported on the day of harvest to the Washington State University Wine Science Center (Richland, WA) for winemaking. Wines were made in 2019 and 2021; equipment malfunction prevented winemaking in 2020. Whole clusters were pressed using a hydraulic press (Zambelli Enotech) to minimize phenolics extraction and wine bitterness (Sokolowsky et al. 2015). Each 100-L stainless-steel fermentation tank (Ghidi) received 50 mg/L of SO_2 and 0.25 g/L of bentonite before settling. The juice was settled in a cold room (0°C) for 24 hr before racking. GoFerm and VIN13 yeast (Scott Laboratories) were added the next day at a rate of 0.3 g/L, and yeast assimilable nitrogen (YAN) was adjusted to 225 mg/L by adding diammonium phosphate after a first dose of 0.25 g/L of Fermaid K (Scott Laboratories). The musts were held at 16°C throughout fermentation, and TSS were measured daily using an electric density/specific gravity meter (DMA 35, Anton Paar). Fermentation was considered complete when the wine contained less than 2 g/L of residual sugar. The wines were settled and stabilized in a cold room for approximately six months before racking and bottling. Wine was bottled into 750-mL green glass bottles using a four-spout bottling machine (XF4100, XpressFill Systems) at ambient temperature. Nitrogen was used as a sparging gas, and bottles were left with 15 mL of headspace. A Technovin TVLV semi-automatic capper was used to fix Saranex liner (30 × 60) screwcaps to the bottles. The highly acidic 2021 wines were deacidified by adding 2 g/L of potassium carbonate, following a benchtop trial to determine the adequate rate.

Basic juice and wine analysis

For juice composition, 50-mL juice samples were taken postpressing to be analyzed for TSS, pH, TA, and malic acid. Juice TSS were measured using a pocket refractometer (model 3810, Atago). Both pH and TA were measured using a T5 autotitrator (Mettler-Toledo). Malic acid (both years) and other organic acids (tartaric, lactic, and acetic acids) in 2021 were measured enzymatically using the Y15 automatic analyzer (BioSystems). Finished wines were analyzed for pH and TA (T5 autotitrator), as well as for malic, lactic (to ensure wines did not go through malolactic fermentation), and acetic acids; residual sugar; and free and total SO_2 (Y15 automatic analyzer). Alcohol was measured using a near-infrared Alcolyzer (Anton-Paar).

Wine phenolic composition analysis

Ellagic acid, ethyl gallate, gallic acid, methyl gallate, syringic acid, vanillic acid, ferulic acid, protocatechuic acid, *trans*-caffeic acid, *trans*-p-coumaric acid, (-)-catechin, (+)-epicatechin, (-)-epicatechin gallate, kaempferol, myricetin, quercetin, kaempferol-3-glucoside, quercetin-3-glucoside, *trans*-resveratrol, and tryptophol were used as standards (Supplemental Table 1). A 50-mL wine sample was concentrated to 15 mL under vacuum (model 2025, Welch) at 35°C in a rotavapor (R-205, Büchi). The concentrate was extracted three times with 15 mL diethyl ether and 15 mL ethyl acetate, as described (Fernández de Simón et al. 1990). The organic phases were combined, dried for 40 min with anhydrous magnesium sulfate, dried under vacuum, dissolved in 2 mL of 1:1 methanol/water, and filtered with a 0.45-µm plastic syringe filter. Concentrated samples were run on a high-performance liquid chromatograph (HPLC; Agilent 1290 Infinity II, Agilent Technologies) with a diode array detector coupled to a 6130 electrospray ionization single-quad mass spectrometer (MS). Phenolic compounds were measured according to Monagas et al. (2005) with the following changes: samples (10 µL) were injected into an Agilent Poroshell 120 EC-C18 (2.7 µm, 3.0 × 150 mm) column at 40°C. Solvent A (water:acetic acid, 98:2 v/v) and solvent B (water:acetonitrile:acetic acid, 78:20:2 v/v) were run at a flow rate of 0.5 mL/min with the following gradient: 0% B isocratic, 0 to 5 min; 0 to 10% B linear, 5 to 10 min; 10 to 80% B linear, 10 to 22.78 min; 80 to 100% B linear, 22.78 to 23.61 min; 100% B isocratic, 23.61 to 35 min. Each sample was followed by a 20-min 100% methanol wash, bringing total run time to 60 min (including 5 min for re-equilibration). Samples were run in selective ion mode (SIM) with a single SIM window, while standards were run in scan mode to identify retention times and the major (M-H)-ion to be targeted in the SIM method. Calibration curve and quantification data were evaluated using Agilent Quantitative Analysis software (ver. 10.0).

Wine volatile composition analysis

1-Hexanol, z-3-hexen-1-ol, isoamyl alcohol, phenethyl alcohol, hexyl acetate, isoamyl acetate, isoamyl octanoate, octyl acetate, 2-phenethyl acetate, propyl acetate, ethyl butyrate, ethyl heptanoate, ethyl hexanoate, ethyl isobutyrate, ethyl isovalerate, ethyl 2-methylbutyrate, ethyl nonanoate, ethyl octanoate, hexanal, octanal, phenylacetaldehyde, 3-(methylthio)-1-propanol, citronellol, corianderol, geraniol, linalool, α-terpinene, β-damascenone, 2,2,6-trimethylcyclohexenone, and 1,1,6-trimethyl-1,2,dihydronaphthalene (TDN) were used as standards (Supplemental Table 2). A 6890 gas chromatograph (GC, Agilent Technologies) coupled to a 5975 quadrupole MS and a multipurpose robotic sampler (Gerstel) were used to analyze wine organic volatiles. The wines were evaluated at different times (in 2022 for the 2019 wines and in 2023 for the 2021 wines). The robotic sampler dosed each wine with 5 µL of the internal standard (ISTD) 2-undecanone (Sigma-Aldrich) to an in-vial concentration of 50.9 µg/L (2019 wines) and 32.2 µg/L (2021 wines), which was used to convert compound area to a corrected area ratio. For each measured compound, its area was divided by the area of the ISTD, and data analysis used this ratio, rather than concentrations, as the response to improve precision.

The solid phase microextraction parameters and temperature ramp were adapted from Hjelmeland et al. (2013), though oak compounds were not considered in our analysis. A DB-wax capillary column (30 m, 0.25 mm i.d., 0.25 µm film thickness; Agilent Technologies) was utilized for separation. Wine samples (10 mL) were pipetted in duplicate into 20-mL brown glass vials with polytetrafluoroethylene-lined septa screwcaps (Restek) and run in untargeted scan mode without a sodium chloride addition. Samples were randomized in terms of sequence order. Data were analyzed in PARADISe deconvolution software (Department of Food Science, University of Copenhagen), which identified major volatile components using the NIST20 library included with the software.

Data analysis

All data were analyzed using Statgraphics Centurion XVIII (Statgraphics Technologies). Normality and homoscedasticity were checked with Shapiro-Wilks' and Levene's tests. One- and two-way analysis of variance (ANOVA) procedures were used to test irrigation and year effects (α = 0.05). Means were separated by Tukey's honest significant difference test. Non-parametric data were analyzed using the Kruskal-Wallis test, and the medians were separated using Bonferroni's multiple comparison test. Relationships between key variables were assessed by Pearson's correlation analysis. Each year was analyzed independently for HPLC and GC-MS data, as data were gathered at different times and with different levels of ISTD area correction. One-way ANOVA was performed on these data using XLSTAT (ver. 2022.5.1, Microsoft Excel). Significant area-corrected GC-MS data were analyzed using principal component analysis (PCA). Only significant attributes were included in the PCA biplot graphs.

Results

Weather

The 2019 growing season was characterized by late winter precipitation that left snow in the vineyard through March (Figure 2 and Table 1), which contributed to delayed pruning and other vineyard tasks, higher soil moisture, and increased vigor. The summer temperatures in 2019 were cooler and more consistent compared to recent years, without extreme heat waves, and lower evaporative demand. The average reference evapotranspiration (ET_o) of the growing season (April to October) in 2019 was 3.8 mm/day. 2020 had overall lower precipitation; late July and early August experienced more heat waves than in 2019, and the average ET_o was 4.6 mm/day. 2021 stood out as an exceptionally warm and dry growing season, with record-high temperatures across the region. Spring and summer were

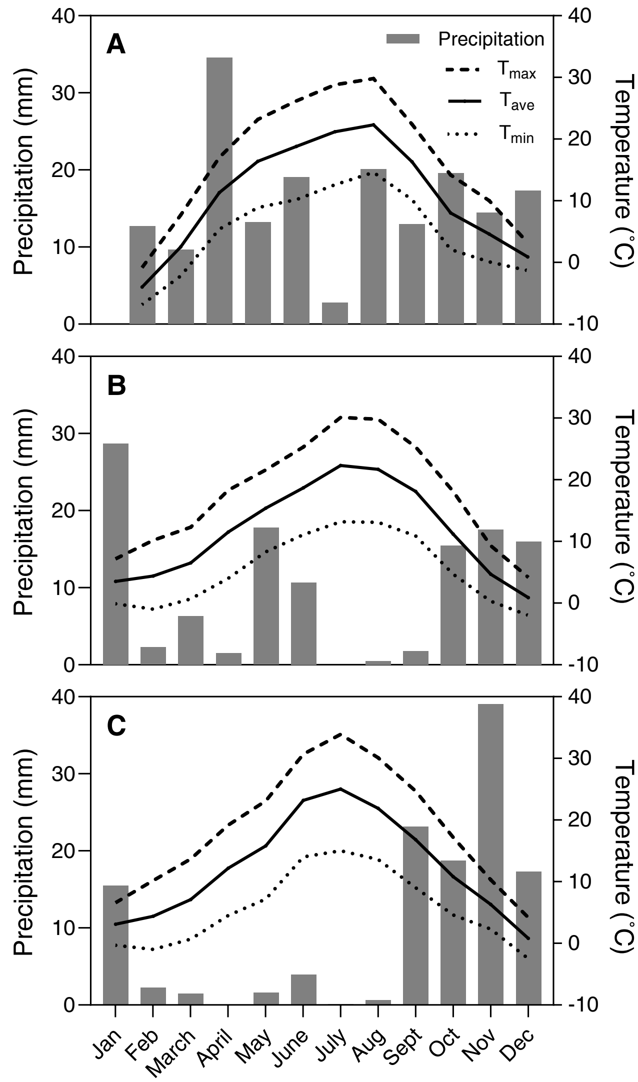

Figure 2 Trends of monthly mean maximum, minimum, and average temperatures (T_{max}, T_{min}, and T_{ave}, respectively) and monthly precipitation recorded in 2019 (**A**), 2020 (**B**), and 2021 (**C**) near the Washington State University Roza vineyard in southeastern Washington. Data were obtained from the AgWeatherNet Roza.2 station (https://weather.wsu.edu) located ~550 m from the trial site.

Table 1 Summary of weather conditions and key phenological stages for Riesling in the Washington State University Roza vineyard in southeastern Washington from 2019 through 2021. Data were obtained from the AgWeatherNet Roza.2 station (https://weather.wsu.edu) located ~550 m from the trial site. GDD, growing degree days (base 10°C); ET_o, reference evapotranspiration; DOY, day of year.

	2019	2020	2021	Long-term[a]
Annual precipitation (mm)	211	105	119	200
Seasonal[b] precipitation (mm)	85	37	42	90
Seasonal GDD (°C)	1627	1757	1845	1485
Seasonal ET_o (mm)	820	991	1028	886
Budbreak (DOY)	120	114	116	115
Fruit set (DOY)	163	170	164	166
Veraison (DOY)	232	235	230	233
Harvest (DOY)	281	273	251	274

[a]30 years for weather data, nine years for phenology data.
[b]Season: 1 April to 31 Oct.

particularly dry, with <10 mm of precipitation from February to August. Three successive, four-to-six-day heat waves (>35°C) between late June and mid-July led to temperatures as high as 44.2°C. The average seasonal ET_o in 2021 was 4.8 mm/day. All three years experienced higher temperatures and accumulated more growing degree days (GDD, base 10°C) than the 30-year average (Table 1 and Supplemental Figure 3).

Irrigation water use

On average across irrigation treatments, the total annual supply of irrigation water varied from 194 mm in the comparatively wet 2019 to 237 mm in 2020 and 479 mm in the hot and dry 2021 (Figure 3). The late snowfall coupled with snow drift due to wind in spring of 2019 resulted in high soil moisture, especially in some RDI plots. Consequently, only PRD received a small amount of irrigation water at budbreak to even out soil moisture differences. The water requirements during the deficit period (fruit set to veraison) accounted for ~45% of the total water supply across all treatments and years (Figure 3). This period coincided with the highest temperatures and ET_o (and thus, peak evaporative demand) of the growing season, when canopies were still growing but approaching their maximum size. All years combined, RDI resulted in average irrigation water savings per growing season of 32% relative to FULL, and PRD saved 21% water. In 2019, 2020, and 2021, RDI saved 43, 30, and 33%, respectively, of seasonal irrigation water compared to FULL, while PRD saved 13, 30, and 21%, respectively (Figure 3).

Soil and vine water status

Starting irrigation only after shoot growth had stopped, combined with the low θ_v thresholds used for irrigation in 2019, shortened the window for differential irrigation compared with 2020 and 2021. The decision to adjust the protocol for the subsequent years (Figure 1) was supported by the Ψ_{leaf} data gathered in 2019 (Figure 4): the vines did not experience water stress (Ψ_{leaf} > −0.8 MPa) when θ_v was above 17% (θ_e > 35%). Increasing the θ_v threshold for all non-deficit periods after 2019 generated significant differences in canopy size and yield, but introduced annual variability. In 2020 and 2021, timely initiation of θ_v differences from fruit set to veraison aligned with the intended targets (Figure 5). However, two irrigation leaks during the 2020 preveraison period disrupted the PRD irrigation pattern, which led us to exclude two PRD replicates from the data set. Across all years, θ_v was maintained above 16% for most of the budbreak-to-fruit-set period. During the preveraison deficit period, RDI and PRD_{dry} had significantly lower soil moisture than FULL and PRD_{wet}. After veraison, the θ_v of PRD_{dry} remained lower than that of the other treatments because PRD continued until harvest.

The seasonal changes in midday Ψ_{leaf} reflected the changes in θ_v (Supplemental Figure 4). RDI was associated with the lowest Ψ_{leaf} during the deficit period except in 2019, when PRD and RDI vines had similar Ψ_{leaf} (Figure 4). The transient maximum difference between FULL and RDI during the preveraison period was 0.25 MPa in 2019, 0.34 MPa in 2020, and 0.28 MPa in 2021. Consistent with

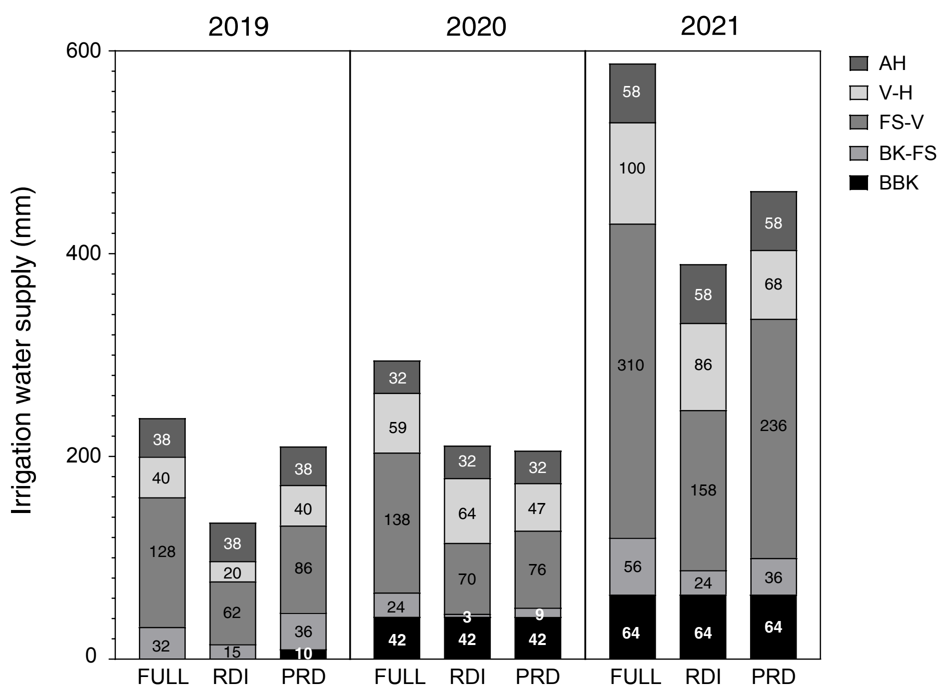

Figure 3 Annual irrigation water supply in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years. Treatments included a no-stress control (FULL), regulated deficit irrigation (RDI), and partial rootzone drying (PRD). Irrigation water supply is shown by phenological period in 2019, 2020, and 2021. AH, after harvest; V-H, veraison to harvest; FS-V, fruit set to veraison; BK-FS, budbreak to fruit set; BBK, before budbreak.

the irrigation protocol, no significant differences in Ψ_{leaf} between treatments were observed during fruit ripening in any year. Midday Ψ_{leaf} and θ_e were correlated (Figure 6; r = 0.53, $p < 0.001$); the θ_e for PRD_{wet} was used in this analysis. When each treatment was considered independently, the correlations for FULL (r = 0.55), RDI (r = 0.69), and PRD_{wet} (r = 0.47) were all highly significant ($p < 0.001$). Notably, while Ψ_{leaf} varied considerably around an average of -0.79 ± 0.01 MPa due to variation in evaporative demand, it remained unaffected by soil moisture until θ_e had declined to ~35% (Figure 6). As the soil dried below this threshold, Ψ_{leaf} dropped to values as low as -1.5 MPa. At the same level of θ_e > 35%, however, the Ψ_{leaf} of PRD vines was more variable than that of FULL and RDI vines. Using the average θ_e for the dry and wet sides of PRD-irrigated vines shifted the low PRD data points to the left and improved the correlation both overall (r = 0.63) and for PRD (r = 0.53), while decreasing the variability of Ψ_{leaf} at θ_e > 35% (Supplemental Figure 5).

Canopy size and cluster sun exposure

Implementing RDI reduced the canopy size compared to the FULL and PRD treatments across all years (Table 2). The irrigation methods had no effect on shoot length at veraison in 2019. Though the number of lateral shoots was higher for RDI than for FULL and PRD, no differences were found in the number of lateral leaves. In 2020 and 2021, irrigation significantly affected all measured vegetative data: FULL generally resulted in larger and denser canopies compared to RDI but had similar shoot length as PRD. Growth of lateral leaves was reduced in RDI, while in PRD it tended to be intermediate between FULL and RDI. Across all years, RDI reduced the shoot growth rate (vigor) between fruit set and veraison (0.23 cm/day, p = 0.01), while vigor was similar for FULL and PRD (0.48 and 0.42 cm/day, respectively). Compared with RDI and PRD, the FULL vines had lower fruit-zone sun exposure due to their higher canopy size and density (Table 2). Cluster sun exposure was lower in 2019, when late-winter and spring precipitation resulted in high vigor that led to irrigation treatment initiation being delayed and not altering canopy growth and density.

In agreement with the shoot measurements taken at veraison, no differences were found between the treatments regarding pruning weight and average cane weight in 2019 (Figure 7). In subsequent years, RDI notably reduced canopy size and cane weight, reflecting the RDI-induced reduction in vigor. The PRD vines produced a canopy size comparable to the control group in 2020 and 2021. The two shoot thinning passes in 2020 are reflected in the low cane numbers and pruning weights that year (Figure 7). Sun exposure of the fruit zone measured at veraison was inversely correlated with pruning weight (r = -0.85, $p < 0.001$; Supplemental Figure 6A) and total cane number per unit row length (r = -0.70, $p < 0.001$; Supplemental Figure 6B). Therefore, greater canopy size and higher canopy density were associated with lower fruit-zone sun exposure.

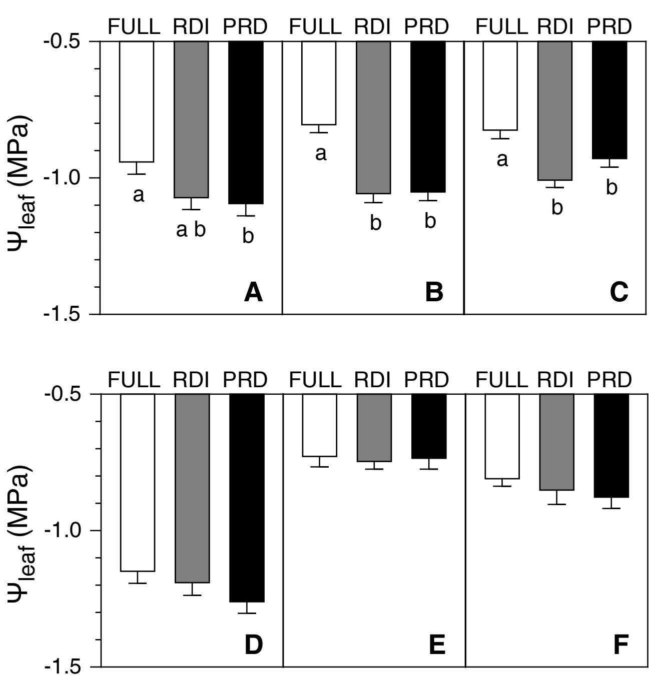

Figure 4 Average midday leaf water potential (Ψ_{leaf}) for three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) from fruit set to veraison in 2019 (**A**), 2020 (**B**), and 2021 (**C**), and from veraison to harvest in 2019 (**D**), 2020 (**E**), and 2021 (**F**), in a Riesling vineyard in southeastern Washington. Bars show means ± SE (8 ≤ n ≤ 32) of weekly measurements taken during each period; different letters indicate significant differences ($p < 0.05$) within years according to Tukey's honest significant difference test.

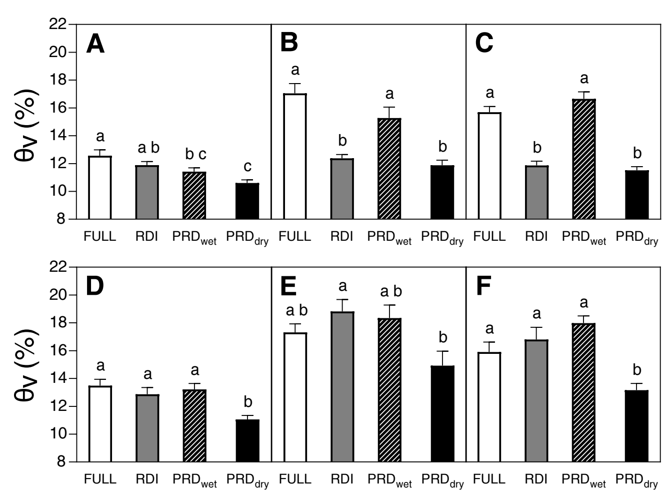

Figure 5 Average volumetric soil water content (θ_v) for three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) from fruit set to veraison in 2019 (**A**), 2020 (**B**), and 2021 (**C**), and from veraison to harvest in 2019 (**D**), 2020 (**E**), and 2021 (**F**), in a Riesling vineyard in southeastern Washington. The θ_v for PRD vines is separated into wet (PRD_{wet}) and dry (PRD_{dry}) sides. Bars show means ± SE (12 ≤ n ≤ 36) of weekly measurements taken during each period; different letters indicate significant differences ($p < 0.05$) within years according to Tukey's honest significant difference test.

Yield and its components

Regardless of the delivery method (RDI or PRD), deficit irrigation reduced fruit yield by ~20% compared with the control treatment (FULL). The three-year average yield was 16.7 t/ha with FULL irrigation, 13.5 t/ha with RDI, and 13.8 t/ha with PRD. In 2019, we did not observe differences in yield or its components among irrigation treatments (Figure 8). Though the exclusion of two PRD replicates in 2020 resulted in treatment effects not being significant, a trend to lower yields was observed for RDI and PRD (Figure 8A). Among the three years, 2020 also had the lowest cluster numbers and the lowest yields as a result of double shoot thinning. RDI significantly reduced yield in 2021. Unlike PRD, RDI resulted in lighter clusters than FULL in 2020 and 2021 (Figure 8B), but our berry sampling protocol failed to detect consistent differences in berry weight. The berry weights differed significantly in 2020 only: FULL and RDI had the largest and smallest berries, respectively, and PRD fell in between these weights (Figure 8C). Nevertheless, it seems likely that the lower cluster weight for RDI in 2021 was also a result of lower berry weights that year. Across years, the average cluster weight was correlated with the average preveraison Ψ_{leaf} ($r = 0.48$, $p = 0.004$; Supplemental Figure 7). The yield-to-pruning-weight ratio for FULL (12.4), RDI (11.3), and PRD (12.1) did not differ by treatment ($p = 0.31$) or year ($p = 0.07$; Supplemental Figure 8).

Water use efficiency

The three-year average WUE_i, calculated as crop yield per unit irrigation water applied, was 5.1 t/ML for FULL, 5.2 t/ML for PRD, and 7.2 t/ML for RDI. Data by year and treatment are shown in Supplemental Table 3. In 2019, the WUE_i for RDI was significantly higher (14 t/ML) compared to FULL (8.3 t/ML) and PRD (8.5 t/ML). This difference resulted from RDI only being implemented seven weeks after fruit set and thus not reducing yield. This pattern was not repeated in subsequent years, and no significant differences were found between irrigation treatments, as water savings with RDI and PRD were associated with yield reductions. Among years, 2019 had the highest WUE_i (10.3 t/ML) for all treatments. In 2020 (3.8 t/ML) and 2021 (3.4 t/ML), the marked decline in WUE_i reflected the higher θ_v threshold for irrigation scheduling compared with 2019. Similar patterns were observed for both the irrigation water footprint and the total water footprint (Supplemental Table 3).

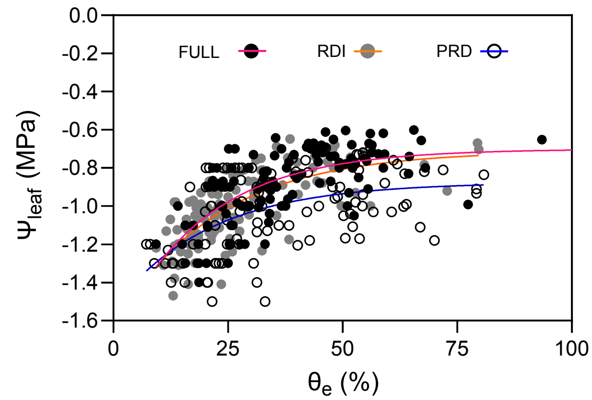

Figure 6 Associations over three years (2019 to 2021) between relative extractable soil water content (θ_e) of the top 60 to 90 cm of the soil profile and midday leaf water potential (Ψ_{leaf}), measured from fruit set through harvest in a Riesling irrigation trial conducted in southeastern Washington. Non-linear regression and curve fitting was applied to each of three irrigation treatments: a no-stress control (FULL; r = 0.55), regulated deficit irrigation (RDI; r = 0.69), and partial rootzone drying (PRD; r = 0.47).

Table 2 Effect of irrigation method (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) and growing season on canopy growth and cluster sun exposure relative to ambient light at veraison in a Riesling vineyard in southeastern Washington.

	Irrigation method			*p*
	FULL	**RDI**	**PRD**	
Shoot length (cm)				
2019 A[a]	131 ± 4.1[b]	134 ± 4.5	139 ± 4.3	0.41
2020 B	119 ± 6.8 a	90 ± 4.1 b	116 ± 7.8 ab	0.002
2021 A	137 ± 6.9 a	120 ± 5.3 b	132 ± 5.5 ab	0.01
Treatment				0.002
Year				<0.001
Treatment × year				0.06
Lateral shoots				
2019 B	12 ± 0.7 b	15 ± 0.7 a	12 ± 0.8 b	0.03
2020 B	14 ± 0.9 a	10 ± 0.5 b	13 ± 0.8 a	<0.001
2021 A	19 ± 0.9 a	16 ± 0.8 ab	13 ± 0.8 b	0.02
Treatment				0.03
Year				<0.001
Treatment × year				0.003
Lateral leaves				
2019 B	19 ± 1.3	23 ± 1.1	19 ± 1.3	0.06
2020 B	32 ± 4.3 a	20 ± 1.3 b	25 ± 2.0 ab	0.01
2021 A	53 ± 4.1 a	34 ± 3.0 b	40 ± 3.1 b	<0.001
Treatment				<0.001
Year				<0.001
Treatment × year				<0.001
Sun exposure (%)				
2019 C	27 ± 1.4	26 ± 1.4	27 ± 1.6	0.71
2020 A	39 ± 2.5 b	56 ± 1.8 a	48 ± 3.0 a	<0.001
2021 B	25 ± 1.6 b	35 ± 1.6 a	31 ± 1.5 a	<0.001
Treatment				<0.001
Year				<0.001
Treatment × year				<0.001

[a]Years followed by different capital letters differ significantly ($p < 0.05$) according to Tukey's honest significant difference (HSD) test.
[b]Means ± SE (n = 4) followed by different letters within rows differ significantly ($p < 0.05$) according to Tukey's HSD test.

Fruit and wine composition

The basic fruit composition at harvest showed no significant treatment effect in any year (Table 3). The overall variation in fruit composition was strongly dominated by seasonal differences. In 2020, the year with two shoot thinning passes and lowest yields, the fruit had the highest TSS, as harvest could not be scheduled in time for the 20 Brix target. While the fruit from 2019 and 2021 had similar TSS, 2019 fruit had low TA and high pH (along with some *Botrytis cinerea* bunch rot infection), and 2021 fruit had high TA and low pH. The juice data obtained after pressing in the winery confirmed the acidity differences between 2019 and 2021 (Table 4). In general, the irrigation treatments did not result in significant differences in juice composition; however, the 2021 measurements showed lower tartaric acid and higher malic acid in juice from FULL vines than in that from deficit-irrigated vines (Table 4). Juice from RDI vines had the lowest malic acid concentration.

At bottling, the 2021 wines had about three times as much malic acid as the 2019 wines, but the lower TA of the 2021 wines reflects the deacidification carried out that same year (Table 5). The 2019 wines from the FULL treatment had

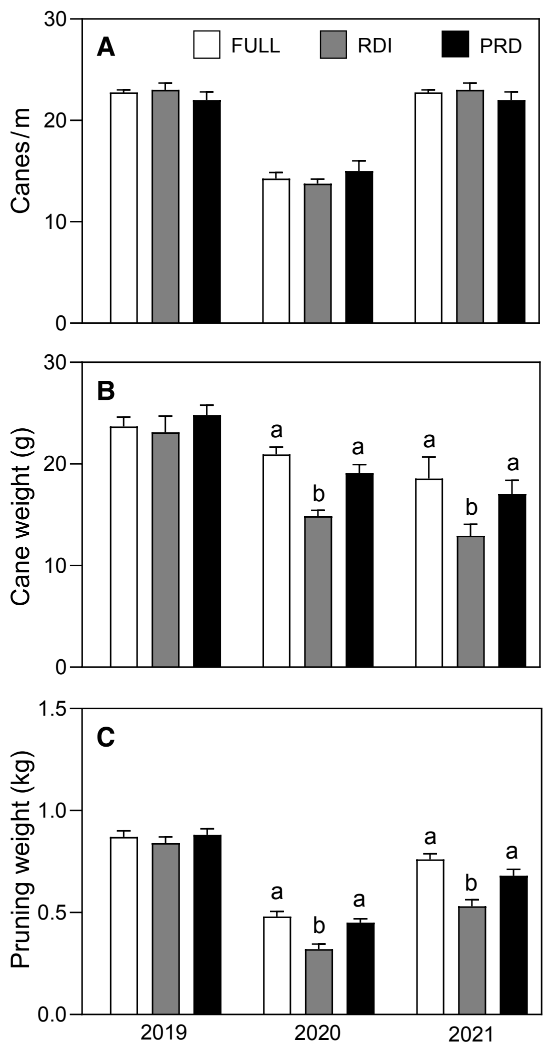

Figure 7 Effect of three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) on number of canes per meter of canopy (**A**), average cane weight (**B**), and pruning weight per vine (**C**) in a Riesling irrigation trial conducted in southeastern Washington from 2019 to 2021. Bars show means ± SE (n = 4); different letters indicate significant differences ($p < 0.05$) within years according to Tukey's honest significant difference test.

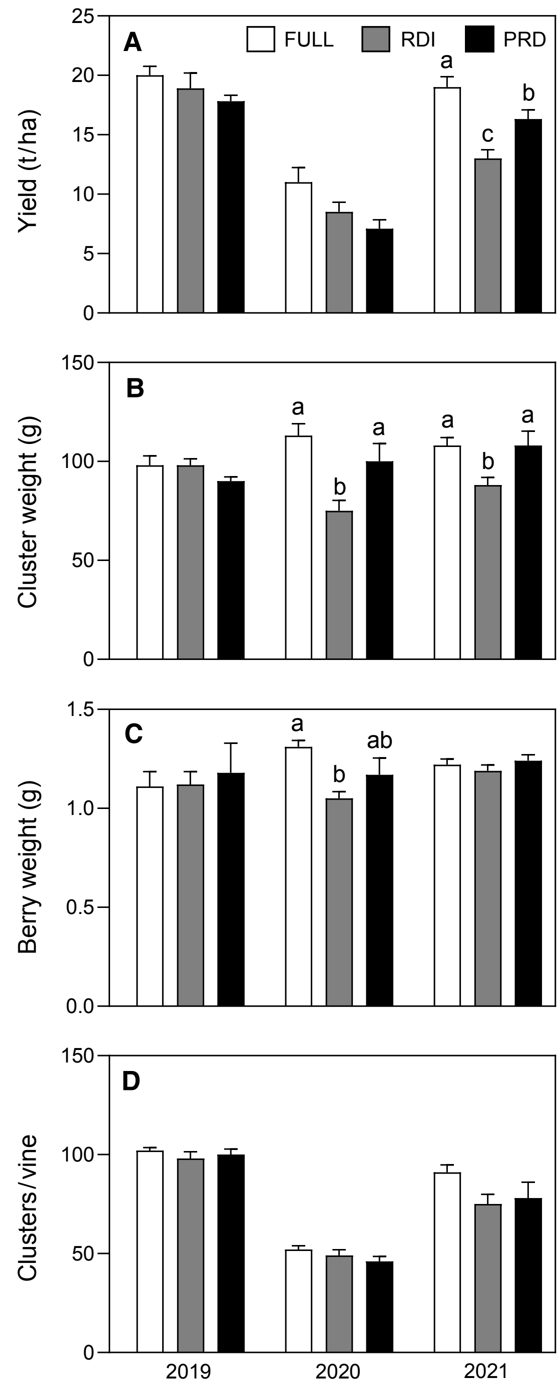

Figure 8 Effect of three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) on crop yield (**A**), cluster weight (**B**), berry weight (**C**), and clusters per vine (**D**) in a Riesling irrigation trial conducted in southeastern Washington from 2019 to 2021. Bars show means ± SE (n = 4); different letters indicate significant differences ($p < 0.05$) within years according to Tukey's honest significant difference test.

higher malic and acetic acid contents than the wines from the water deficit treatments. No wine was made in 2020. In 2021, the pH of the wines made from the RDI vines was higher than that of the FULL and PRD wines (Table 5). The RDI wines also had the lowest malic acid concentration.

The HPLC analysis showed that in 2019, protocatechuic acid was the only wine phenolic compound that was significantly affected by irrigation treatment. The wine produced from grapes in the FULL treatment had the lowest concentration, and the PRD-derived wines had the highest concentration of protocatechuic acid (Table 6). In 2021, the treatment effect was more pronounced, resulting in variations in the concentration of (-)-catechin, gallic acid, coumaric acid, and quercetin-3-glucoside. The RDI-derived wines had much higher levels of catechin and gallic acid than the wines made from the other treatments. The catechin concentration was particularly low in FULL wine. Conversely, coumaric acid was more abundant in FULL and PRD wines compared to RDI wine. Quercetin-3-glucoside was more prevalent in FULL, while PRD and RDI showed lower concentrations of this compound. Methyl gallate, kaempferol-3-glucoside, myricetin, and tryptophol were never detected. (+)-Epicatechin, (-)-epicatechin gallate, kaempferol, and resveratrol were also often below their detection limits, but the 2019 wines had measurable amounts of resveratrol (average 10.4 μg/L), which we attributed to bunch rot infection just before harvest. Phenolic components by treatment replicate and year are reported in Supplemental Table 4.

The GC-MS data showed that the three irrigation treatments resulted in wines with distinct organic volatile profiles in both 2019 and 2021. On the PCA plots, all wines separated from each other based on irrigation, while the three replicate wines from each treatment clustered together in each year (Figure 9). The first two dimensions (F1, F2) accounted for more than 81% (2019) or 90% (2021) of the variance observed. The fatty acid ethyl acetates and esters isoamyl acetate, 2-phenyl acetate, ethyl hexanoate, and ethyl octanoate were strongly associated with the FULL wines in both years, though somewhat less so in 2021. Hexyl acetate and ethyl butyrate as well as some higher alcohols and monoterpenes were predominantly associated with RDI wines, while ethyl-isobutyrate, ethyl isovalerate, ethyl 2-methyl butyrate, and the norisoprenoid TDN were consistently associated with the PRD wines. Wine volatile organic compounds are reported by treatment in Supplemental Tables 5 and 6 for 2019 and 2021, respectively.

Discussion

This study demonstrated that while different deficit irrigation methods such as RDI and PRD can effectively conserve irrigation water in arid climates, this benefit may come with a yield penalty. When implemented using soil moisture thresholds to schedule irrigation, PRD saved ~10% less water than RDI on an annual basis. Our study also showed that relatively minor changes in plant water status in Riesling grapevines can influence canopy size and architecture, fruit sun exposure, yield and its components, and wine composition. The three irrigation methods (FULL, RDI, PRD) tested in our field trial resulted in wines with distinct aroma profiles and differences in some phenolic compounds, even

Table 3 Effect of irrigation method (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) and growing season on basic fruit composition at harvest (means ± SE [n = 4]) in a Riesling vineyard in southeastern Washington.

	Irrigation method			*p*
	FULL	RDI	PRD	
Total soluble solids (Brix)				
2019 B[a]	20.0 ± 1.08	18.6 ± 0.70	19.2 ± 0.42	0.46
2020 A	21.6 ± 0.18	21.5 ± 0.36	21.6 ± 0.95	0.99
2021 B	20.1 ± 0.29	19.6 ± 0.13	19.9 ± 0.14	0.34
Treatment				0.33
Year				<0.001
pH				
2019 A	3.30 ± 0.04	3.30 ± 0.01	3.35 ± 0.02	0.40
2020 B	2.97 ± 0.03	3.07 ± 0.04	3.00 ± 0.01	0.19
2021 C	2.80 ± 0.01	2.77 ± 0.01	2.78 ± 0.01	0.32
Treatment				0.54
Year				<0.001
Titratable acidity (g/L)				
2019 C	7.8 ± 0.24	7.8 ± 0.12	7.5 ± 0.04	0.20
2020 B	9.5 ± 0.21	8.4 ± 0.12	8.9 ± 1.05	0.13
2021 A	10.9 ± 0.57	11.1 ± 0.49	10.9 ± 0.72	0.98
Treatment				0.67
Year				<0.001

[a]Years followed by different capital letters differ significantly ($p < 0.05$) according to Tukey's honest significant difference test. The treatment × year interaction was not significant for any variable.

though we found no significant differences in basic fruit composition at harvest. Our results highlight the potential of irrigation practices that induce temporal (RDI) or spatial (PRD) reductions in soil moisture as powerful tools for shaping wine styles in the vineyard. These differences were attained by RDI reducing preveraison vine water status by only 0.2 MPa on average over three years (midday Ψ_{leaf} = -1.03 MPa) compared to the nonstress control (Ψ_{leaf} = -0.85 MPa). The maximum difference between FULL and RDI during the preveraison period briefly reached ~0.3 MPa each year. On average, PRD maintained an intermediate plant water status (Ψ_{leaf} = -0.96 MPa). While RDI decreased the canopy size, PRD vines produced a canopy size comparable to the control, in agreement with several previous studies (see Introduction). Despite a trend in the "right" direction, however, our measurements failed to detect significant differences in fruit-zone sun exposure between PRD and RDI vines.

Yearly differences in weather patterns played a significant role in determining irrigation water supply and vine responses. 2019 was marked by more precipitation than the other years, increasing soil moisture availability early in the growing season. In addition, 2019 was cooler and had the lowest evaporative demand during the growing season. These factors contributed to the decision to delay irrigation to stop shoot growth, which shortened the window for applying differential irrigation by seven weeks. Consequently, preveraison water stress levels were greater and less variable across treatments, which resulted in no significant differences in canopy size, yield, or basic fruit composition in 2019. For 2020 and 2021, the irrigation scheduling target was altered to initiate differential irrigation treatments at fruit set regardless of the shoot growth status. This adjustment decreased vine water stress and resulted in significant differences in canopy size and density across treatments.

In our field trial, the water savings arising from PRD were lower than those found in previous research (Dry et al. 2001, dos Santos et al. 2003, du Toit et al. 2003). Except in 2020, the annual irrigation water savings obtained with PRD (~20% on average across the three years) were lower than savings obtained with RDI (~30%). We report water savings in terms of total seasonal irrigation water supply relative to FULL, including irrigation at budbreak and after

Table 4 Effect of irrigation method (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) and growing season on basic juice composition of fruit from a Riesling vineyard in southeastern Washington, after pressing in the winery.

	Irrigation method			*p*
	FULL	RDI	PRD	
Total soluble solids (Brix)				
2019	21.2 ± 0.68	19.1 ± 0.96	20.5 ± 0.28	0.18
2021	21.3 ± 0.31	21.9 ± 0.20	21.0 ± 0.08	0.06
Treatment				0.38
Year				0.02
Treatment × year				0.04
pH				
2019	3.41 ± 0.06	3.45 ± 0.02	3.51 ± 0.01	0.32
2021	2.73 ± 0.01	2.78 ± 0.01	2.76 ± 0.01	0.20
Treatment				0.16
Year				<0.001
Treatment × year				0.37
Titratable acidity (g/L)				
2019	9.2 ± 0.23	10.6 ± 0.64	9.1 ± 0.19	0.08
2021	14.1 ± 0.17	13.1 ± 0.27	14.3 ± 0.11	0.12
Treatment				0.87
Year				<0.001
Treatment × year				0.002
Tartaric acid (g/L)[a]				
2021	6.23 ± 0.06 b[b]	6.15 ± 0.01 b	6.54 ± 0.06 a	0.002
Malic acid (g/L)				
2021	3.93 ± 0.15 a	2.92 ± 0.05 c	3.52 ± 0.03 b	0.002
Lactic acid (g/L)				
2021	0.05 ± 0.01	0.05 ± 0.01	0.04 ± 0.01	0.18
Acetic acid (g/L)				
2021	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.99

[a]Organic acids were only analyzed in 2021.
[b]Means ± SE (n = 3) followed by different letters within rows differ significantly ($p < 0.05$) according to Tukey's honest significant difference test.

harvest. Unlike in regions with substantial winter precipitation, such early- and late-season irrigation is generally required in arid eastern WA (Keller et al. 2016, Keller 2023). The previously cited publications usually report water savings by comparing the relative WUE between treatments rather than the actual irrigation water supply. Such calculations can lead to overestimations, especially when only accounting for the deficit period. The calculation method and the definition of WUE vary, and our understanding of its underlying physiological regulation mechanisms remains incomplete. The WUE is affected by an intricate interplay of environmental and physiological factors, including stomatal regulation, photosynthetic capacity, and leaf and plant structure (Schultz and Stoll 2010). Reporting water savings should not solely rely on a comparison of this factor among treatments.

Vine water status was correlated with soil water content, but changes in θ_e explained only about one-third of

Table 5 Effect of irrigation method (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) and growing season on basic wine composition at bottling, with fruit obtained from a Riesling vineyard in southeastern Washington.

	Irrigation method			*p*
	FULL	**RDI**	**PRD**	
Alcohol (% v/v)				
2019	13.1 ± 0.67	10.8 ± 0.85	11.5 ± 0.07	0.09
2021	12.3 ± 0.18	13.0 ± 0.08	12.1 ± 0.07	0.06
Treatment				0.13
Year				0.08
Treatment × year				0.02
pH				
2019	2.70 ± 0.01	2.69 ± 0.01	2.71 ± 0.01	0.79
2021	3.02 ± 0.01 b[a]	3.08 ± 0.01 a	2.99 ± 0.01 b	0.01
Treatment				0.05
Year				<0.001
Treatment × year				0.01
Titratable acidity (g/L)				
2019	10.7 ± 0.37	10.5 ± 0.14	10.1 ± 0.10	0.20
2021	8.2 ± 0.36	7.8 ± 0.05	8.2 ± 0.10	0.41
Treatment				0.30
Year				<0.001
Treatment × year				0.20
Malic acid (g/L)				
2019	1.05 ± 0.01 a	0.69 ± 0.04 b	0.70 ± 0.02 b	<0.001
2021	2.94 ± 0.11 a	2.22 ± 0.08 b	2.66 ± 0.06 a	0.004
Treatment				<0.001
Year				<0.001
Treatment × year				0.01
Lactic acid (g/L)				
2019	0.01 ± 0.008	0.002 ± 0.002	0.005 ± 0.005	0.58
2021	0.003 ± 0.003	0.01 ± 0.01	0.00 ± 0.00	0.50
Treatment				0.73
Year				0.93
Treatment × year				0.36
Acetic acid (g/L)				
2019	0.15 ± 0.01 a	0.10 ± 0.02 b	0.08 ± 0.01 b	0.04
2021	0.14 ± 0.02	0.17 ± 0.01	0.16 ± 0.01	0.36
Treatment				0.34
Year				<0.001
Treatment × year				0.016
Glucose + fructose (g/L)				
2019	0.42 ± 0.14	0.23 ± 0.01	0.23 ± 0.01	0.27
2021	0.63 ± 0.41	0.25 ± 0.01	0.17 ± 0.01	0.39
Treatment				0.18
Year				0.68
Treatment × year				0.72

[a]Means ± SE (n = 3) followed by different letters within rows differ significantly ($p < 0.05$) according to Tukey's honest significant difference test.

the variability in midday Ψ_{leaf}. Notably, while other factors (e.g., temperature, vapor pressure deficit) also contributed to the variation in vine water status, Ψ_{leaf} remained unresponsive to soil moisture until the soil had dried to a θ_e of ~35%. A similar plateau-type response has been found for Concord grapes in eastern WA (Keller et al. 2023), and for Thompson Seedless in central California (Williams and Trout 2005). One might argue that in all these cases the vines behaved isohydrically at θ_e > 35% and anisohydrically at θ_e < 35%. From a practical standpoint, applying irrigation water to increase soil moisture above this threshold reduces WUE_i without improving vine water status. Nevertheless, RDI and PRD vines in our study showed signs of mild-to-moderate water stress (midday Ψ_{leaf} < -1.0 MPa) even at θ_e > 35% during hot summer days. We have no satisfactory explanation for the low Ψ_{leaf} values of some of the PRD vines, but it seems possible that roots growing across several drip emitter locations in these mature vines may have simultaneously experienced wet and dry soil and integrated the response to both conditions. Romero et al. (2012) observed that the preveraison Ψ_{leaf} declined as irrigation volumes decreased, with no significant differences between PRD and RDI. They only found a divergence in physiological response between PRD and RDI when the severity of water stress intensified, with both PRD and RDI receiving 50% less water than the control. One difference between their experiment and ours lies in the approach taken regarding water application. In their study, PRD and RDI vines were provided with the same volumes of water, while in our case, irrigation scheduling was guided by θ_v targets, leading to variable water inputs and variable intervals for switching the wet and dry sides in PRD. For this reason, letting the soil dry down to the lower θ_v threshold for PRD required more irrigation hours to reach the high θ_v target when sides were switched. Moreover, during the hot summer months the dry side of PRD vines often reached the low θ_v threshold within one week, which highlights the potential benefit of scheduling PRD irrigation based on soil moisture instead of predefined time intervals. Though not explored in our study, using θ_v targets for PRD (and RDI) scheduling has the potential for automation using soil moisture probes in conjunction with knowledge of local soil properties (e.g., FC, PWP). The problem of spatial variability in soil properties may eventually be overcome with the use of spectral imaging via remote sensing technology (Kang et al. 2023a, 2023b).

Unlike seasonal effects, our irrigation methods did not consistently alter the basic fruit composition at harvest. However, the juice and wine analysis revealed that FULL irrigation resulted in higher malic acid content compared to PRD and especially to RDI, likely as a result of the lower cluster sun exposure due to the larger canopy in FULL (Keller 2023). Malic acid catabolism is highly sensitive to temperature, but not to water deficit per se (Hewitt et al. 2023). Yet, although the ripening period was warmer in 2021 than in 2019, the 2021 wines had much more malic acid than the 2019 wines. Sugar accumulation may have outpaced malic acid degradation in 2021, since harvest at 20 Brix occurred one month earlier than in 2019, despite similar veraison dates.

While we did not collect grape skins for a comprehensive chemical composition analysis and our Riesling winemaking protocol deliberately minimized extraction of phenolics (Sokolowsky et al. 2015), the analysis of wine phenolics showed that only protocatechuic acid differed by treatment in 2019, in line with the lack of differences observed in vegetative growth, cluster sun exposure, and yield. In 2021, the higher catechin and gallic acid concentrations in RDI wines is consistent with our hypothesis of smaller canopy size and greater fruit-zone sun exposure resulting in white wines with a higher concentration of compounds associated with bitterness or astringency. Unexpectedly however, quercetin-3-glucoside and coumaric acid concentrations were higher in the FULL wines. It seems likely that higher sun exposure in the RDI vines increased the berry temperature, promoting degradation of these UV-sensitive compounds during hot days (Brillante et al. 2018, Torres et al. 2021, Keller 2023).

The three irrigation methods tested here resulted in wines with distinct profiles of aroma volatiles. The consistency of these differences in both years is remarkable, considering that the differences in vine water status were small (averaging 0.2 MPa) and mostly limited to the period from fruit set to veraison. The importance of preveraison water deficit for the accumulation of aroma volatiles and their bound precursors in grape berries was recently described for Sangiovese (Palai et al. 2023), and the irrigation-related changes in organic volatiles found in our study

Table 6 Effect of irrigation method (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) and growing season on the phenolic composition of wines made with fruit obtained from a Riesling vineyard in southeastern Washington. Only compounds that were significantly affected by the irrigation treatments are shown.

Year	Compound (μg/L)	Irrigation method			*p*
		FULL	RDI	PRD	
2019	Protocatechuic acid	89.7 ± 7.0 b[a]	93.5 ± 6.7 ab	109.6 ± 4.4 a	0.04
2021	(-)-Catechin	0.1 ± 0.1 b	73.6 ± 36.9 a	19.8 ± 19.8 b	0.001
	Gallic acid	46.2 ± 1.3 b	93.1 ± 20.4 a	70.0 ± 23.9 ab	0.026
	Coumaric acid	175.3 ± 9.4 a	120.9 ± 16.1 b	158.1 ± 20.1 a	0.002
	Quercetin-3-glucoside	53.2 ± 10.0 a	35.9 ± 5.8 b	36.3 ± 4.6 b	0.003

[a]Means ± SE (n = 3) followed by different letters within rows differ significantly (p < 0.05) according to Tukey's honest significant difference test.

are consistent with those described for deficit-irrigated Albariño (Mirás-Avalos and Araujo 2021). Most of the volatile compounds that differentiated our irrigation methods are derived from yeast metabolism of (grape) fatty acids, sugars, amino acids, and phenylpropanoids, in addition to some grape-derived monoterpenes and the carotenoid metabolite TDN (Robinson et al. 2014). Many of these compounds are characterized by fruity (especially apple, pear, pineapple, and citrus), floral (especially rose), or honey-like aromas, while the C6 alcohols and aldehydes have green-leaf and grassy aromas, and TDN is responsible for "kerosene" descriptive attributes in Riesling wine (Sacks et al. 2012, Robinson et al. 2014). Though we did not conduct a formal sensory analysis in this study, two independent blind tastings with wine industry professionals in Washington and Germany (30 < n < 300) revealed that differences among irrigation methods were perceived, but preference for one method over another was split roughly equally.

Investigating underlying causes for the observed differences in wine volatiles is a subject for future research. Additionally, given that our analytical method was originally designed for Sauvignon blanc, a Riesling-specific approach might identify more relevant wine volatiles to better describe and detect differences among irrigation treatments. Similar to earlier findings with Cabernet Sauvignon (Bindon et al. 2007), TDN was associated with PRD in both 2019 and 2021. While 2019 had higher levels of vine water stress, 2021 accumulated more GDD, and vines would have experienced more heat stress. Previous research suggested many factors play a role in determining the TDN concentration in Riesling wines, but fruit sun exposure is the most studied contributor to TDN accumulation (Kwasniewski et al. 2010, Schüttler et al. 2015). Fruit exposure to sunlight and warmer climates might increase the level of TDN precursors (Gerdes et al. 2001). Despite significant differences in canopy size, however, sun exposure was rather similar in our RDI and PRD vines. Other currently unknown factors may thus have contributed to the variation in wine TDN among our irrigation methods.

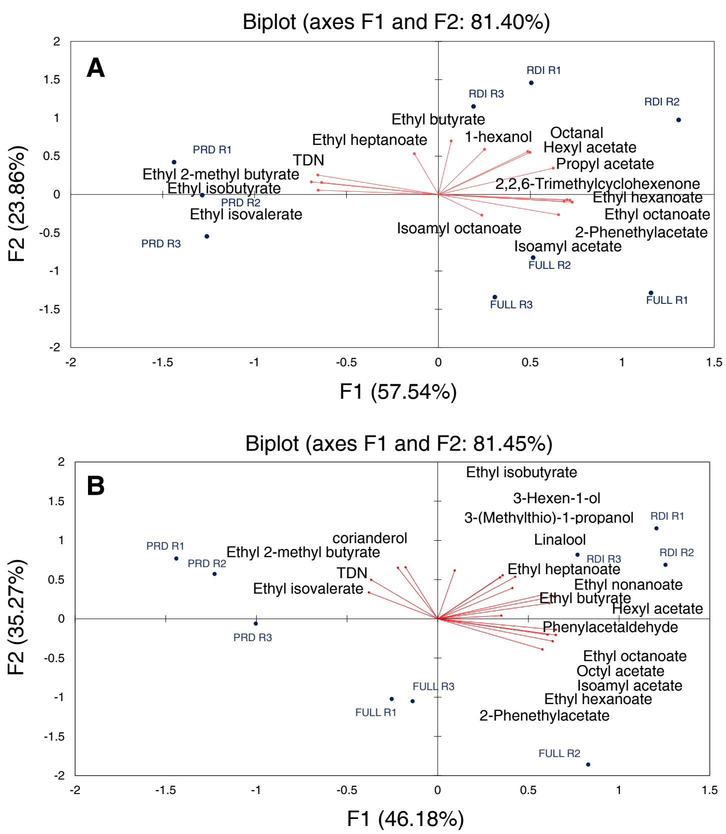

Figure 9 Principal component analysis biplots of the distribution of different volatile components measured in Riesling wines that were produced from grapes derived from three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) in an irrigation trial conducted in southeastern Washington in 2019 (**A**) and 2021 (**B**). Wine replicates R1, R2, and R3 were sourced from separate field replicates of each treatment. The means of two analytical replicates per treatment are shown. Only significant attributes were considered for the plot.

Conclusion

Adopting different deficit irrigation methods enables grapegrowers in dry climates to conserve irrigation water and manipulate grapevine canopy size and architecture, and ultimately, wine style. The data presented here demonstrate that relatively small changes in plant water status during the preveraison period can markedly alter the composition of the resulting Riesling wines. They also support the notion that PRD and RDI save irrigation water at the expense of crop yield. Unlike RDI, however, PRD maintained canopy growth at levels similar to fully irrigated vines. The effect of irrigation on white wine phenolic composition remains somewhat inconclusive, leading to challenges in providing practical recommendations. By contrast, the effect of minor preveraison water deficit on wine aroma volatile composition was pronounced, highlighting the importance of irrigation practices for shaping wine styles in the vineyard through temporal and spatial manipulation of soil water availability. Using soil moisture targets combined with knowledge of local soil properties for PRD (and RDI) scheduling has the potential for automation using soil moisture probes, perhaps in conjunction with remote sensing technology. However, growers must also consider the cost and management complexity of implementing specific deficit irrigation methods such as PRD. Our results suggest that the "optimum" irrigation approach needs to integrate the tradeoff between the expected reduction in canopy size, yield, and water supply, and the perceived gain in quality or change in wine style. Growers may consider adopting RDI if they aim to limit canopy size while maximizing fruit sun exposure and water conservation. They may choose PRD, however, if their priority is to minimize canopy size reductions while still conserving irrigation water.

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Supplemental Data

The following supplemental materials are available for this article at ajevonline.org:

Supplemental Table 1 List of chemical standards used to quantify the phenolic profile of Riesling wines made from fruit harvested in a vineyard in southeastern Washington. Each compound is accompanied by the chemical class, the commercial supplier, and the solvent used to prepare the high-performance liquid chromatography standards for calibration curves.

Supplemental Table 2 List of analytical standards used to semi-quantify the volatile composition of Riesling wines made from fruit harvested in a vineyard in southeastern Washington. Each compound is accompanied by commercial supplier and grouped by chemical class. For gas chromatography-mass spectrometry analysis, all analytical standards were prepared using methanol as solvent.

Supplemental Table 3 Effect of irrigation treatment (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) and growing season on irrigation water use efficiency, irrigation water footprint, and total water footprint of a Riesling vineyard in southeastern Washington over three years.

Supplemental Table 4 Phenolic compounds (µg/L) measured by high-performance liquid chromatography in Riesling wines obtained from three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) in a vineyard in southeastern Washington. Data are means of two technical replicates for each of three wine replicates in two years.

Supplemental Table 5 Volatile organic compounds (in internal standard response ratio) measured by gas chromatography-mass spectrometry in Riesling wines obtained from three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) in a vineyard in southeastern Washington in 2019. Data are means of two technical replicates for each of three wine replicates and include only compounds that were above the detection limit.

Supplemental Table 6 Volatile organic compounds (in internal standard response ratio) measured by gas chromatography-mass spectrometry in Riesling wines obtained from three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) in a vineyard in southeastern Washington in 2021. Data are means of two technical replicates for each of three wine replicates and include only compounds that were above the detection limit.

Supplemental Figure 1 Diurnal changes of leaf water potential (Ψ_{leaf}) measured in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years. Treatments included a no-stress control (FULL), regulated deficit irrigation (RDI), and partial rootzone drying (PRD). Data show Ψ_{leaf} during pretreatment drydown before (day of year [DOY] 198, T_{max} = 27.2°C) and during (DOY 204, T_{max} = 34.3°C) a heatwave in 2019 (**A**), Ψ_{leaf} for each treatment on preveraison DOY 218 in 2020 (**B**), and Ψ_{leaf} for two treatments and two additional treatments (irrigation to field capacity or no irrigation since budbreak) on postveraison DOY 239 in 2021 (**C**). Data show means ± SE (n = 6 in **A** and **B**; n = 4 in **C**); time is Pacific Daylight Saving Time.

Supplemental Figure 2 Irrigation water supply estimated from drip emitter number and flow rate against flow meter readings during two independent irrigation cycles in 2020 and 2021 in an irrigation trial conducted in a Riesling vineyard in southeastern Washington. Flow meters were installed in submains supplying water to the four replicates of each treatment.

Supplemental Figure 3 Seasonal growing degree day (GDD; base 10°C) accumulation from April through October near the Washington State University Roza vineyard in southeastern Washington. Data were obtained from the AgWeatherNet Roza.2 station (https://weather.wsu.edu) located ~550 m from the trial site.

Supplemental Figure 4 Seasonal changes in the volumetric soil water content (θ_v) in the top 60 to 90 cm of the soil profile and midday leaf water potential (Ψ_{leaf}) measured in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years. Treatments included a no-stress control (FULL), regulated deficit irrigation (RDI), and partial rootzone drying (PRD). For PRD, θ_v is plotted separately for the wet (PRD_{wet}) and dry (PRD_{dry}) sections. Data show means ± SE (n = 4) for 2019 (**A**, **B**), 2020 (**C**, **D**), and 2021 (**E**, **F**). Vertical dashed lines indicate phenological stages fruit set (FS), veraison (V), and harvest (H).

Supplemental Figure 5 Association between relative extractable soil water content (θ_e) of the top 60 to 90 cm of the soil profile and midday leaf water potential (Ψ_{leaf}), measured from fruit set through harvest in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years (2019 to 2021). Non-linear regression and curve fitting was applied to each of three irrigation treatments: a no-stress control (FULL; r = 0.55); regulated deficit irrigation (RDI; r = 0.69); and partial rootzone drying (PRD; r = 0.53). The θ_e for PRD is the average for the wet and dry sections.

Supplemental Figure 6 Association between cluster sun exposure relative to ambient light at veraison and pruning weight (**A**) or number of shoots per vine (**B**) in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years (2019 to 2021). Treatments included a no-stress control (FULL), regulated deficit irrigation (RDI), and partial rootzone drying (PRD).

Supplemental Figure 7 Association between average cluster weight and average midday leaf water potential (Ψ_{leaf}), measured from fruit set through veraison in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years (2019 to 2021). Treatments included a no-stress control (FULL), regulated deficit irrigation (RDI), and partial rootzone drying (PRD).

Supplemental Figure 8 Effect of three irrigation treatments (a no-stress control [FULL], regulated deficit irrigation [RDI], and partial rootzone drying [PRD]) on yield-to-pruning weight ratio in an irrigation trial conducted in a Riesling vineyard in southeastern Washington over three years. Bars show means ± SE (n = 4).

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Data Availability

The data underlying this study are available on request from the corresponding author.

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