Reduced Irrigation during Orchard Establishment Conserves Water and Maintains Yield for Three Cider Apple Cultivars

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Abstract. Irrigation water productivity is a priority for sustainable orchard management as water resources become more limiting. This study evaluated reduced irrigation (RI) as a management strategy for cider apple (*Malus domestica* Borkh.) production in 2019 and 2020 in northwestern Washington, which has a Mediterranean climate and averages 14.1 cm of precipitation from June to September. RI was evaluated on three cider apple cultivars, Dabinett, Porter's Perfection, and Golden Russet, in their third and fourth leaf. Stem water potential (stem ψ) was measured weekly throughout the growing season to monitor water stress and implement the RI treatment: irrigation would be applied when stem ψ values dropped below -1.5 MPa, a threshold indicative of moderate water stress in apples. Soil water potential was monitored throughout the season, vegetative growth was assessed by measuring shoot length and non-destructive imaging of the plant canopy using lateral photography, and yield, fruit quality, and juice quality were measured at harvest. Moderate water stress as indicated by stem ψ did not occur either year, thus irrigation was never applied to the RI treatment plots. There was a negative relationship between average stem ψ and both yield and air temperature ($P < 0.0001$ for each); as yield increased by 5.9 kg per tree or temperature increased by 3.3°C , stem ψ decreased by 0.1 MPa. The juice quality attributes of the three cultivars in this study were similar to their historic measures at this site and there were no differences due to irrigation treatment, likely because trees did not reach the threshold to induce physiological stress. Both years, trees in the RI treatment did not differ from the control treatment in vegetative growth, fruit yield, juice yield, or any juice quality attribute, but weight per fruit decreased by 7 g, and fruit firmness (measured only in 2020) increased by 2 N. Results from this study indicate that fruit yield and quality in an establishing orchard can be maintained when irrigation is reduced relative to crop water requirements that are estimated from a calculated water balance or relative to conventional grower practices for this region. This finding highlights the benefits of using plant water status to schedule irrigation.

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on irrigation districts or municipal providers that hold water rights, the purchase or transfer of a water right, or the lease of excess or banked water rights. Senior water right holders generally have the least expensive access to irrigation water and the greatest reliability of access, with new farmers therefore facing higher water prices and higher risk of water loss at critical times in the growing season (Wichelns, 2010). The average cost of irrigation water across the United States is estimated at only \$131–167 per ha after adjusting for inflation (U.S. Department of Agriculture, Economic Research Service, 2006). However, costs may be significantly higher depending on the access pathway, particularly for options more readily available to beginning farmers. For example, the cost of municipal water in the Skagit Public Utility District in northwestern Washington, where this study was carried out, was \$3.36 per 2.83 m^3 (100 ft^3) in 2021 or \$550–1001 per ha for typical orchard irrigation requirements in the region, with additional system development fees and fixed monthly costs for water meters of \$34–1800 for 5/8–8 inch meters, respectively (Skagit Public Utility District, 2021). Furthermore, variable irrigation costs for a cider apple orchard also include labor and irrigation system maintenance, which can add an additional \$1309 per ha (Galinato et al., 2014). Thus, irrigation options are either cheaper with a higher likelihood of losing access or more expensive with more reliable access, and in the former case irrigation costs can still be significant. Therefore, reducing irrigation water use is an important strategy for growers to minimize risk and reduce costs.

One of the most common ways to reduce irrigation water use is regulated deficit irrigation (RDI), an irrigation conservation technique that purposefully maintains a plant in a water deficit for specific horticultural benefits such as reduced vegetative growth (Chalmers et al., 1986). Plants experience a water deficit when total water loss via transpiration exceeds total water absorption. RDI application in fruit trees was first evaluated in peach (*Prunus persica*) and pear (*Pyrus communis*) for the purpose of reducing shoot growth and subsequent pruning costs while maintaining yield (Chalmers et al., 1981; Mitchell et al., 1984). In apple production, RDI has been shown to reduce the photosynthetic rate compared with a fully irrigated control, leading to a reduction in leaf area, trunk diameter, and shoot growth in 'Braeburn' apples (Mills et al., 1996). While vegetative growth was reduced, fruit yield reduction was minimal, which the authors attributed to higher water retention in fruit than in leaves due to the latter's higher rate of transpiration. High resistance to movement of water in fruit suggests that moderate water stress implemented late in the growing season affects vegetative growth before fruit quality is impacted (Mills et al., 1996).

The physiological responses to RDI in apples include impacts on fruit quality in addition to reduced vegetative growth, such as reduced fruit size and increased fruit polyphenolic compounds, total soluble solids

Cider production in the United States has increased almost 16-fold over the last decade (Alcohol and Tobacco Tax and Trade Bureau, 2021), and anecdotal evidence suggests that new orchards and beginning farmers have played a role in this expansion despite the significant barriers they face. Notably, water availability and/or access in the arid west was the top agricultural concern of young farmers in a recent survey (Greenberg et al., 2016), and may be a considerable hurdle to entry into cider apple (*Malus domestica* Borkh.) production. Irrigation water access in the western United States typically requires a water right, and as such, agricultural producers must rely

(TSS), firmness, and titratable acidity (TA) (Chenafi et al., 2016; Ebel et al., 1993; Mills et al., 1996; Mpelasoka et al., 2001a, 2001b; Neilsen et al., 2016). Many of these changes can be neutral or positive impacts for cider apple fruit and juice quality, even if they may represent deleterious changes for table apple production. For example, fruit size of 'Braeburn' and 'Gala' has been shown to decrease in response to RDI (Chenafi et al., 2016; Mpelasoka et al., 2001b). While fruit size is often directly related to the value of table apples, cider apples are not sold based on their size, but rather based on total weight and the quality of juice they produce. Positive impacts of RDI on fruit and juice quality in table apples may similarly be positive impacts for cider apples, albeit for different reasons. Increased firmness, as observed with RDI in table apples (Chenafi et al., 2016; Mills et al., 1996; Neilsen et al., 2016), is also a desirable characteristic for cider apples because when firmer fruit are milled, they produce particles with a greater surface area to volume ratio, which provides for a more efficient pressing in the cider production process (Barrett et al., 2005). The increased TSS concentration observed with RDI in table apples can be favorable for cider apples as more sugar equates to a higher potential alcohol by volume percentage in the final fermented product, potentially eliminating the need to add sugars in the fermentation process to achieve the desired alcohol content (Chenafi et al., 2016; Ebel et al., 1993; Mills et al., 1996; Mpelasoka et al., 2001b). Increases in TA from RDI are also an important potential impact on cider apple fruit quality as TA is responsible for the flavor characteristic referred to as 'sharp' in cider apple classification (Barker and Burroughs, 1953). While no studies to date have measured the impact of RDI on cider apple cultivars, Miles et al. (2017) attributed lower measured tannin levels of three cider apple cultivars grown in Washington State vs. Bristol, England to greater water and nutrient applications in the U.S. study's orchard than in the U.K. study's orchard. This suggests that irrigation management can be used to manipulate fruit quality in cider apples.

To implement RDI, several methods for monitoring or estimating plant water status to schedule irrigation can be used. Weather-based methods using a water balance are the simplest approach and can be fairly robust (Osroosh et al., 2016), though limitations include the theoretical nature of estimating crop evapotranspiration (ET_c), which is often derived from the Penman–Monteith equation and relies on crop coefficients (K_c) (Allen et al., 1998). There are many environmental variables that can influence K_c values, and tree fruit canopy structures, groundcover, and the vigor of apple scion and rootstock combinations may differ from orchards in which K_c values were established (Snyder et al., 2000; Zanotelli et al., 2019). Monitoring soil moisture is another common method of scheduling irrigation in orchards (Black et al., 2008). However, continuous monitoring requires in situ equipment in representative locations, must assume relative

uniformity of site conditions, and works best with knowledge of soil-specific available water-holding capacity and soil water potential (soil ψ) thresholds for plant water stress (Shock and Wang, 2011). A primary limitation of both weather-based and soil-based irrigation scheduling strategies is that neither can directly reflect plant water status.

In RDI studies, midday stem water potential (stem ψ) has been used as an effective method for determining plant water status and for scheduling irrigation treatments (Shackel, 2011). Interpretation of stem ψ values can depend on climatic factors such as air temperature and relative humidity (De Swaef et al., 2009), with higher air temperatures and lower relative humidity (or a high vapor pressure deficit) increasing evaporative demand and increasing stem ψ even if the tree is adequately watered. Nevertheless, stem ψ is a very informative measure of plant water status if interpreted in the context of these environmental conditions. Irrigation thresholds for stem ψ have been established for multiple crops, including grapes (*Vitis vinifera*) (Choné et al., 2001), pecans (*Carya illinoensis*) (Othman et al., 2014), and prunes (*P. domestica*) (McCutchan and Shackel, 1992). Many studies have measured stem ψ in unstressed and water-stressed apples (Auzmendi et al., 2011; Chenafi et al., 2016; De Swaef et al., 2009; Girona et al., 2010; Naor et al., 1995, 2008; Neilsen et al., 2016; Reid and Kalcsits, 2020), and several RDI studies observed yield loss at stem ψ values more negative than -1.5 MPa (Auzmendi et al., 2011; Girona et al., 2010; Naor et al., 2008; Neilsen et al., 2016), suggesting that this is an appropriate irrigation threshold to achieve moderate water stress with no impact on yield.

Despite the positive effects of reduced irrigation (RI) demonstrated for many fruit crops and the importance of maximizing irrigation water productivity for cider apple production, to our knowledge, the impacts of restricting irrigation have not been formally evaluated in cider apples. Thus, the objective of this study was to determine whether restricting irrigation could meaningfully reduce water usage for cider apple production while maintaining fruit yield and increasing fruit quality. In the present study, we hypothesized that RI for cider apples would increase irrigation water productivity, decrease vegetative growth, maintain fruit yield, and improve juice quality.

Materials and Methods

Orchard description and experimental design. The study was carried out in a cider apple research orchard planted in 2017 at the WSU Northwestern Washington Research and Extension Center located in Mount Vernon at 48°44'N, 122°39'W and 6 m above sea level. The orchard was in its third and fourth leaf in 2019 and 2020, respectively. The area has a Mediterranean climate that is well suited to apple production, similar to European cider apple orchard sites (Kottek et al., 2006). The soil is a poorly drained Skagit silt loam (fine-silty, mesic Fluvaquentic

Endoaquepts) (Natural Resources Conservation Service, 2021), with a pH of 6.3 and 3.4% organic matter. The study included three cultivars: Dabinett, Golden Russet, and Porter's Perfection, grafted onto Geneva.202 semi-dwarfing rootstock. Two irrigation treatments were applied, RI and a control (CI) based on conventional grower irrigation practices (2019) or a calculated water balance (2020). The experiment was set up as a randomized complete block design with split plots replicated four times with cultivar as the main plot and irrigation as the split plot treatment. The trees were spaced 1.2 m apart in the row with 4.6 m spacing between rows. All trees per plot were harvested, main plots consisted of 18 to 24 trees, and split plots consisted of 8 to 12 trees. Plots differed in the number of trees due to wind and disease damage, and number of trees per plot was taken into account when calculating yield by dividing plot yield by number of trees per plot to present yield per tree. The orchard was managed according to guidelines laid out in Moulton et al. (2010). Monthly pesticide sprays were applied during the growing season except during harvest (August to October), and a spray rotation of protectant and systemic fungicides was applied monthly year-round except during harvest, primarily for the control of apple anthracnose canker (caused by *Neofabraea malicorticis*). A 1.2 m herbicide strip was maintained in-row. Fruit were hand thinned to two to three fruit per cluster, and clusters were thinned to 15 cm apart.

Irrigation treatments. Irrigation was applied via a surface drip irrigation system (Landscape Products, LP 710, 1.8 cm diameter, 0.61 m emitter spacing, drip rate of $0.56 \text{ mL}\cdot\text{s}^{-1}$). Two irrigation lines ran the length of each row, one dedicated to the CI plots and one to the RI plots. For the RI treatment, the preset threshold when irrigation was applied was when the midday stem ψ dropped to -1.5 MPa. In 2019, the CI treatment was based on an informal survey of regional grower practices, which suggested CI plots should be irrigated twice a week for 4 h per application with adjustments made for any significant rain events within a 24-hour period of a scheduled irrigation. A calculated water balance for the CI treatment in 2019 revealed that irrigation may have been in excess of plant requirements. In 2020, CI was based on a calculated water balance using the decision-support tool Irrigation Scheduler Mobile (ISM), developed by Washington State University (AgWeather-Net, 2021). For ISM, precipitation and reference evapotranspiration data were obtained from an onsite weather station, site-specific soil characteristic data were obtained from Web Soil Survey (Natural Resources Conservation Service, 2021), and custom K_c values were used based on two studies of similar orchards (Volschenk, 2017; Zanotelli et al., 2019) that were adjusted for tree age using a multiyear study that measured evapotranspiration using a weighing lysimeter (Marsal et al., 2013). ISM incorporates changing K_c values throughout the season as plant water use changes from bud burst through leaf fall;

key phenological dates corresponding to these changes for each cultivar were based on the average historical data (Miles, 2019). Plots were irrigated to 100% of field capacity when ISM estimated the available water content had dropped to 70% to 80% of the available water-holding capacity.

Total applied water. Applied water per treatment was measured with a FM150B water meter (Rain Bird Corporation, Azusa, CA) and verified by calculating water application based on the total duration subplots were irrigated throughout the season and the drip emitter flow rate. Emitter flow rates and distribution uniformity were verified by collecting the output in catch cans over a fixed time interval during a single event in 2019.

Soil moisture. Soil ψ was measured with granular matrix sensors (Watermark 200SS, Irrrometer Company, Inc., Riverside, CA) placed in three replicates in 2019 and all four replicates in 2020.

Stem water potential. Midday stem ψ was measured weekly between the hours of 12:00 PM and 4:00 PM on two randomly selected trees from the center of each subplot using a pressure chamber (PMS Instrument Company, Albany, OR) and following the protocols reported in Shackel (2011) and Fulton et al. (2014). For each tree, a foil bag was placed around one shaded leaf, leaves were left enclosed for 15 min, and then leaves were removed and the stem ψ reading was taken.

Vegetative growth. In 2019, vegetative growth was assessed by measuring three random shoots at the beginning and end of the season on each side of the row (west and east) for two randomly selected representative trees in each subplot (six shoots per tree, 12 shoots per subplot). Shoots were measured twice from base to tip, and total vegetative growth was calculated as average end of season shoot length minus beginning of season shoot length per plot. In 2020, vegetative growth was measured for three randomly selected trees in each subplot using digital photographs and the Canopeo application (Canopeo, Stillwater, OK) developed by the Soil Physics Research Group at Oklahoma State University (Patrignani and Ochsner, 2015). Profile photographs were taken 2.1 m away from the trunk using a digital camera mounted onto a 1.2 m tall tripod, and a backdrop was positioned behind the trees to eliminate background content from the images. Total vegetative growth was calculated as the average percentage of foliage in the image, which represented end of season canopy development per plot.

Yield and fruit quality. Apples were harvested in 2019 when a random sample from the four quadrants of the tree canopy of representative trees in each subplot reached a minimum average Cornell Starch Iodine Index value of 5 (scale is 1 to 8 where 8 is maximum maturity) (Blanpied and Silsby, 1992). In 2020, apples were harvested when a random sample (from the four quadrants of the tree canopy) from representative trees in each subplot reached the target TSS levels (reported as °Brix) indicative of full maturity based on

historical cultivar information (Golden Russet 15.4°Brix, Dabinett 13.5°Brix, Porter's Perfection 13°Brix) (Miles, 2019), and when each cultivar had a rating of 7–8 on the 8-point Cornell Starch Iodine Index (Blanpied and Silsby, 1992). In 2020, fruit were picked when they reached full maturity as this is more desirable for cider. In both years, all four replicates of each cultivar were harvested on one day and the fruit were pressed on the same date as harvest. First, 40 representative apples were selected and picked from the center 6 to 10 trees in each subplot. For subplots that had 12 trees, one apple per quadrant (upper east, upper west, lower east, lower west) was harvested per tree from the center 10 trees. For plots that had 8 to 11 trees, the center 6 to 9 trees were harvested, one apple per quadrant per tree, plus four additional random apples (one from each quadrant) per randomly selected tree to attain 40 representative apples. The weight of the 40 select apples was recorded for each subplot. The remaining apples in each subplot were then harvested into labeled totes, fruit weight was recorded, and total fruit weight for each subplot was calculated. In 2020, after the 40 selected apples were harvested, fruit weight was recorded separately for the trees that received stem ψ measurements to compare yield with stem ψ values.

The 40 selected fruit were lined up on a measuring tape side by side, total diameter was recorded, and average diameter per fruit was calculated. In 2020, fruit firmness was measured for each subplot. Five representative apples were selected from the 40 fruit per subplot, a spot on the widest part of the apple was peeled, and firmness (Newtons) was measured with a fruit hardness tester (FR-5120; QA Supplies LLC, Norfolk, VA) fixed with a 11.1 mm cylindrical blunt-end tip using the settings Peak H (the meter was set to stop reading at the maximum hardness) and Fast (the meter was set to read values at a high relative speed). The 40 selected apples per subplot, including the fruit evaluated for firmness in 2020, were then washed, milled (MuliMax 30; Zambelli Enotech, Camisano Vicentino, Italy), and pressed (bladder press; Enotechnica Pillan, Camisano Vicentino, Italy). The amount of time to press the apples was recorded in 2020. Timing started when the water was turned on to fill the bladder and was stopped when the pressure release valve automatically opened to release the water from the bladder at 345 kPa (50 psi), and the juice was no longer flowing from the sides of the press. Both years, juice volume was measured for the selected apples, and a 250 mL composite sample was collected per plot and frozen for later analysis. Juice yield per kg fruit was calculated.

Juice quality. Juice quality attributes were measured for all subplots in both years after thawing. Juice samples were thawed to room temperature (23 °C) and hand shaken for homogenization. TSS were measured with a digital refractometer (Palm Abbe model #PA201; MISCO, Cleveland, OH). For each subplot, two to three drops of juice from the 250 mL sample were placed on the

refractometer sensor making sure no bubbles were present, allowed to adjust to room temperature for 30 s, and the value was recorded as °Brix. In 2019, pH was measured for each subplot using a digital pH meter (Ohaus Starter 5000; Ohaus Corporation, Parsippany, NJ) by submersing the probe in 5 mL of juice. In 2020, pH was measured using a hand-held pH meter (Orion 3 Star; Thermo Scientific, Pittsburgh, PA). TA (percent malic acid) was measured for each subplot using titration with 0.1 N sodium hydroxide (NaOH) to an endpoint of 8.2. TA was calculated as grams of malic acid per 100 mL, using the conversion factor mL NaOH $\times$ 0.536 (a constant based on sample volume and normality). In 2019, titration was done manually (Digitate Titrette; Jencons Scientific Ltd., Lutterworth, UK). Titrant was added incrementally to a 5 mL sample diluted with 20 mL distilled water until the pH reached the endpoint, and the volume of titrant added was recorded. In 2020, titration was carried out using an auto-titrator (HI932; Hanna Instruments, Woonsocket, RI). Percent tannin (expressed as tannic acid equivalents) was measured using the Löwenthal Permanganate Titration method (Burroughs and Whiting, 1960; Lea, 2008; Löwenthal, 1877). A blank control was calculated for each batch of potassium permanganate solution by titrating the solution into an indigo carmine indicator without juice. The volume of titrant required to turn the indicator solution yellow was recorded as the 'Q' value for that batch. For each subplot, the potassium permanganate was titrated into 1 mL juice samples mixed with 5 mL of indicator solution until the reference color (yellow) was reached, and the volume of titrant was recorded as the P value. Percent tannin was calculated by (P-Q)/10. Specific gravity (SG) was measured using a precision hydrometer [SG range 1.000–1.070 (Bellwether; VeeGee Scientific, Kirkland, WA)] suspended in $\approx$ 200 mL of juice. Temperature was measured with a glass thermometer (VWR brand Cat. No 61-66-104, by H-B USA, Radnor, PA) submersed in $\approx$ 200 mL of juice from each subplot to provide a correction factor for SG.

Statistical analysis. A post-hoc analysis was conducted to determine the sample size necessary to capture the true mean of each plot to within $\pm$ 5%. Data were analyzed as a randomized complete block design with split plots using ANOVA carried out in RStudio (version 1.2.5033; R Studio, Boston, MA). A linear mixed effects model was used with cultivar and treatment as fixed effects (and year or date where appropriate) and block as a random effect using the "nlme" package (Pinheiro et al., 2020), interactions were tested, and significance was reported at $\alpha = 0.05$. Where the ANOVA indicated a significant difference, a post-hoc means separation was carried out using Tukey's honestly significant difference with the "lsmeans" command in the "emmeans" package (Lenth, 2020). Assumptions of homogeneity of variance and normality were tested using a Levene's test and a Shapiro–

Wilk test, respectively. When assumptions weren't met, data were transformed by taking the square root so that the assumptions were satisfied; however, in all cases transformed data gave the same conclusions as the original data, and thus the original data are presented to aid interpretation. The relationship between stem ψ and yield or stem ψ and temperature was analyzed with simple linear regression. Relative humidity and soil ψ were considered as additional potential predictor variables in the analysis of stem ψ and temperature but were found to have no significant effect on stem ψ based on an ANOVA to compare models with and without these potential predictors.

Results

Irrigation treatments. The CI plots were irrigated twice per week for 4 h in 2019, from 11 June to 6 Sept., and a total of seven times in 2020, from 14 July to 11 Sept. for 8 to 10 h each application. The RI plots were not irrigated in either year because trees never reached the predetermined stem ψ threshold of -1.5 MPa. The total amount of irrigation applied to the control treatment was $843 \text{ m}^3 \cdot \text{ha}^{-1}$ (8.4 cm) in 2019, and $463 \text{ m}^3 \cdot \text{ha}^{-1}$ (4.6 cm) in 2020. The difference in the amount of irrigation between years was primarily due to the difference in the irrigation scheduling methodology. The change in irrigation scheduling method from a calendar-based schedule (with adjustment for precipitation) to a calculated water balance was made based on preliminary data from 2019 that showed irrigation in the control treatment (which was initially based on an informal grower survey) was in excess of plant requirements. Additionally, midseason precipitation was greater in 2020 than in 2019 (Fig. 1).

Soil moisture. Differences in soil ψ between irrigation treatments were observed within a week of the onset of irrigation in the CI subplots (Fig. 2). RI subplots had lower soil ψ throughout the growing season, and soil ψ values in the CI subplots were extremely responsive to irrigation events (Fig. 2). Differences between treatments persisted until the last irrigation event, when fall rains began. During the summer months, the CI subplots

Fig. 1. Cumulative precipitation (cm) at WSU Mount Vernon NWREC during the 2019 and 2020 growing seasons, and the 25-year average (AgWeatherNet, 2021). The shaded regions represent the ranges based one (dark) and two (light) standard deviations from the 25-year average.

Fig. 2. Soil water potential (kPa) of control and reduced irrigation treatments from 3 June to 16 Oct. 2019 (A), and 1 June to 30 Sept. 2020 (B). The control treatment was fully irrigated to 80% to 100% soil available water-holding capacity based on a water balance calculation, and the reduced irrigation treatment received no irrigation applications based on stem water potential values. Error bars represent the standard error of the mean.

averaged -52 kPa and -69 kPa with lows of -107 kPa and -123 kPa in 2019 and 2020, respectively. The RI plots averaged -109 kPa and -101 kPa with lows of -168 kPa and -157 kPa in 2019 and 2020, respectively. Greater differences between years in the CI subplots

Fig. 3. Stem water potential of control and reduced irrigation treatments (A) and of cider apple (*Malus domestica* Borkh.) cvs. Dabinett, Golden Russet, and Porter's Perfection (B) from 15 May to 18 Sept. 2019. Stem water potential of control and reduced irrigation treatments (C) and of cider apple cvs. Dabinett, Golden Russet, and Porter's Perfection (D) from 15 May to 15 Oct. 2020. Note that the direction of the primary y-axis is reversed to aid comparison with temperature; that is, higher values on the y-axis are increasingly negative or increasingly water-stressed. The control treatment was fully irrigated to 80% to 100% soil available water-holding capacity based on a water balance calculation, and the reduced irrigation treatment received no irrigation applications based on stem water potential values. Asterisks represent a significant difference at $\alpha = 0.05$. Error bars represent the standard error of the mean.

Fig. 4. (A) Average stem water potential (MPa) and temperature (°C) at each timepoint for all cider apple (*Malus domestica* Borkh.) trees in the control irrigation treatment, which was irrigated to 80% to 100% soil available water-holding capacity based on a water balance calculation. Data are combined from 15 May to 18 Sept. 2019, and from 15 May to 15 Oct. 2020. (B) Average stem water potential (MPa) of all timepoints from 15 May to 15 Oct. 2020 and yield per tree (kg) for individual cider apple trees. Regression lines are the linear model from the relevant data with the shaded area representing the 95% confidence interval.

are likely due to the change in irrigation frequency.

Stem water potential. Midday stem ψ in 2019 did not show any meaningful differences in response to irrigation treatment (Fig. 3A) or cultivar (Fig. 3B) throughout the growing season. While there were differences between the two irrigation treatments on some dates, both treatments remained well above the irrigation threshold for the RI treatment (-1.5 MPa). In 2019, average stem ψ in the RI plots reached a minimum of -0.98 MPa on 26 July. In 2020, stem ψ did not differ significantly due to irrigation treatment (Fig. 3C), and the average in the RI plots reached a minimum of -0.73 MPa on 29 July. Stem ψ did differ by cultivar for the majority of the year in 2020. However, the values for all cultivars were far above the threshold value (Fig. 3D). The cultivar

Dabinett experienced the lowest stem ψ of -0.98 MPa on 29 July 2020 and 'Porter's Perfection' experienced the highest stem ψ of -0.19 MPa on 7 Oct. 2020. A negative relationship ($P < 0.0001$, $R^2 = 0.33$) was observed between midday stem ψ of the well-watered control trees of all cultivars considered together and temperature during the 2-hour data collection time (12:00 PM–2:00 PM) (Fig. 4A). As temperature increased by 10°C , stem ψ values decreased by 0.3 MPa. A negative relationship ($P < 0.0001$, $R^2 = 0.45$) was also observed between stem ψ and yield in 2020 (the yield from individual stem ψ trees was not recorded in 2019) (Fig. 4B). As yield increased by 10 kg per tree, stem ψ values decreased by 0.2 MPa. 'Dabinett' had the lowest stem ψ and the highest yield while 'Porter's Perfection' had the highest stem ψ and the lowest yield.

Table 1. Vegetative growth as measured by shoot growth (cm) from 27 June to 8 Aug. 2019 and canopy area (%) on 1 Oct. 2020 for three cider apple (*Malus domestica* Borkh.) cultivars grown with control and reduced irrigation treatments.^z

Cultivar	2019	2020
	Shoot growth (cm)	Canopy cover (%)
Dabinett	13.2 (2.1) a ^y	54.5 (2.1) a
Golden Russet	2.3 (0.6) b	31.0 (1.9) b
Porter's Perfection	2.8 (0.7) b	22.0 (1.5) c
P value	<0.0001	<0.0001
Irrigation		
Control	6.8 (1.9)	36.5 (2.9)
Reduced irrigation	5.5 (1.7)	35.2 (2.7)
P value	0.43	0.63
Interaction		
Cv. $\times$ Irrigation	0.97	0.87

^zThe control treatment was fully irrigated between 80% and 100% soil available water-holding capacity based on a water balance calculation, and the reduced irrigation treatment received no irrigation applications based on stem water potential values.

^yTreatments compared using Tukey's honestly significant difference at $\alpha = 0.05$. Treatment means followed by the same letter within a column are not significantly different. Values in parentheses are the standard error of the mean.

Vegetative growth. Late season cumulative vegetative growth as measured by the difference in midseason shoot length and end of season shoot length in 2019 showed no difference due to irrigation treatment (Table 1). There was a difference based on cultivar, with 'Dabinett' having a larger increase in shoot length (≈ 13 cm) from the beginning to the end of the measurement period than 'Golden Russet' and 'Porter's Perfection' (≈ 2.5 cm). Total vegetative growth as measured by end of season (1 Oct.) percent canopy in a lateral profile in 2020 also showed no difference due to irrigation treatment but there were differences due to cultivar (Table 1). 'Dabinett' had the largest lateral percent canopy cover (55%) compared with 'Golden Russet' (31%), and 'Porter's Perfection' (22%). There was no interaction of cultivar and irrigation in either measure of vegetative growth.

Fruit quantity and quality. For both years, fruit yield (kg/tree) and apple diameter (cm), and juice yield ($\text{mL}\cdot\text{kg}^{-1}$) did not differ due to irrigation treatment. However, there was a difference in individual fruit weight, with the CI treatment apples weighing 7 g more on average than RI treatment apples (Table 2). Fruit yield differed due to year and was greater in 2019 than 2020. Fruit yield and diameter also differed due to cultivar and both were greatest for 'Dabinett', intermediate for 'Golden Russet', and lowest for 'Porter's Perfection'. There was an interaction between cultivar and year in fruit yield, where only 'Dabinett' differed significantly in yield from the other cultivars in 2019 but the three cultivars differed significantly from each other in 2020. Fruit weight also differed due to cultivar and year, and there was an interaction between cultivar and year. Fruit weight was greater for 'Porter's Perfection' and 'Dabinett' in 2019, while 'Golden Russet' fruit weight was similar both years. Juice yield differed due to cultivar, with 'Dabinett' having the lowest yield (478 $\text{mL}\cdot\text{kg}^{-1}$) compared with 'Golden Russet' and 'Porter's Perfection' (558 $\text{mL}\cdot\text{kg}^{-1}$ for both). In 2019, fruit firmness was only measured on 'Golden Russet' and there was no difference due to irrigation treatment (32.1 N). In 2020, firmness differed due to irrigation and cultivar, but there was no significant interaction between irrigation and cultivar. Apples treated with RI were firmer (38.2 N) than the control treatment (36.2 N).

Juice quality. Both years, no juice quality parameter [TA, TSS, % Tannin, pH, SG] differed due to irrigation, while all parameters differed due to cultivar, and there was an interaction between cultivar and year for % tannin and TA (Table 3). 'Porter's Perfection' had higher % tannin and TA in 2020 than in 2019. TA in the RI trees (0.43 $\text{g}\cdot\text{L}^{-1}$) appeared lower than in the CI trees (0.49 $\text{g}\cdot\text{L}^{-1}$) though this difference was not statistically significant ($P = 0.054$). 'Porter's Perfection' had the highest tannin content both years (0.35% to 0.66%), and 'Dabinett' (0.33%) and 'Golden Russet' (0.16% to 0.24%) had the lowest. Both years 'Porter's Perfection' had the highest TA (0.67 – 0.83 $\text{g}\cdot\text{L}^{-1}$) and the lowest pH (3.17), followed by 'Golden Russet' with the next

Table 2. Fruit yield (kg per tree), weight per fruit (g), fruit diameter (cm), juice yield (mL·kg⁻¹), and firmness (N) (2020 only) for three cider apple (*Malus domestica* Borkh.) cultivars grown with control and reduced irrigation treatments.^z

	Yield per tree (kg)		Wt per fruit (g)		Fruit diam (cm)	Juice yield (mL·kg ⁻¹)	Firmness (N) (2020)
	2019	2020	2019	2020			
Cultivar							
Porter's Perfection	2.7 (0.2) b A ^y	0.7 (0.3) c B	66.7 (1.9) b A	53.1 (5.1) b B	5.0 (0.1) c	558.0 (6.7) a	43.5 (1.5) a
Golden Russet	4.3 (0.3) b A	3.9 (0.4) b A	129.3 (3.7) a A	132.4 (3.2) a A	6.6 (0.1) b	558.0 (7.8) a	37.6 (0.6) b
Dabinett	12.6 (0.9) a A	6.4 (0.6) a B	138.8 (7.3) a A	120.7 (2.3) a B	7.0 (0.1) a	478.0 (15.2) b	30.5 (0.7) c
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation							
Control		5.2 (0.9)		110.7 (7.5) a	6.2 (0.2)	522.5 (12.5)	36.2 (1.6) b
Reduced irrigation		4.9 (0.7)		103.4 (7.3) b	6.1 (0.2)	537.9 (10.3)	38.2 (2.0) a
P value		0.70		0.02	0.13	0.17	0.04
Interactions							
Cv. × Year		<0.0001		0.02	0.09	0.31	NA
Cv. × Irrigation		0.43		0.72	0.69	0.66	0.11
Year × Irrigation		0.42		0.39	0.53	0.34	NA

^zThe control treatment was fully irrigated between 80% and 100% soil available water-holding capacity based on a water balance calculation, and the reduced irrigation treatment received no irrigation applications based on stem water potential values.

^yTreatments compared using Tukey's honestly significant difference at $\alpha = 0.05$. The influence of cultivar on yield and fruit weight was only analyzed within each year, and the influence of year on these variables was only analyzed within each cultivar. Treatment means followed by the same lowercase letter within a column or by the same capital letter within a row are not significantly different. Values in parentheses are the standard error of the mean.

highest TA (0.46–0.50 g·L⁻¹) and next lowest pH (3.43), and 'Dabinett' had the lowest TA (0.13–0.15 g·L⁻¹) and the highest pH (4.47). 'Golden Russet' had higher SG (1.077 SG) and TSS (16.4°Brix) than 'Dabinett' and 'Porter's Perfection' (1.054–1.057 SG, 12.1–13.1°Brix).

Discussion

Moderate summer temperatures, soils with high available water-holding capacity, young trees, and summer precipitation all likely contributed to the lack of water stress experienced by trees in the RI treatment that received no irrigation for the two years of this study. Total precipitation during the summer months of this study (1 June to 30 Sept.) was 17.9 cm on average, which was slightly higher than the 25-year average at this site (14.1 cm) (AgWeatherNet, 2021). However, in 2019 precipitation June through August was lower than average and the site received

13.3 cm of precipitation in September, which was nearly three times the average September precipitation (4.5 cm) (Fig. 1). Despite these differences in precipitation, no substantial differences in stress were observed between treatments either year. This result indicates that irrigation may not be necessary for an establishing cider apple orchard at the third and fourth leaf stage in these climate conditions and this soil type. As trees reach maturity at this site, it is unclear whether this trend would continue. For example, larger differences in stem ψ values between cultivars in 2020 may be due to changes in maturation by the fourth leaf vs. the third leaf, as full production is generally achieved between the fifth and seventh leaf for dwarfing rootstocks planted at high densities (Crassweller, 2018; Heinicke, 1975; Parker et al., 1998). As trees mature, the differences in vegetative growth and yield between cultivars observed in this study could become more pronounced.

However, it is possible that differences in early-season vigor in 'Golden Russet' and 'Porter's Perfection' were not captured in our sampling window of 27 June to 8 Aug. in 2019. Differences in cultivar vigor are apparent in all measured variables, but the absence of an interaction between cultivar and irrigation treatment indicates that responses to imposed water deficit (based on soil moisture and the calculated water balance) were consistent. A decrease in yield in two of the three cultivars in 2020 compared with 2019 regardless of treatment was likely due to the natural biennial bearing habit of the cultivars. Fruit weight decreased similarly in 2020, which is surprising as yield and fruit weight are often negatively related (Elfving and Schechter, 1993; Treder, 2008). The absence of this relationship could be due to late thinning in 2020 since the effect of crop load on fruit size can be determined early in the season (Racskó, 2006). Given the observed relationship

Table 3. Juice quality attributes (% tannin), titratable acidity (g·L⁻¹), specific gravity (SG), total soluble solids (TSS, measured as Brix), and pH for three cider apple (*Malus domestica* Borkh.) cultivars grown with control and reduced irrigation treatments.^z

	Tannin (%)		TA (g·L ⁻¹)		SG	TSS (°Brix)	pH
	2019	2020	2019	2020			
Cultivar							
Dabinett	0.33 (0.03) ab A ^y	0.33 (0.02) b A	0.13 (0.02) c A	0.15 (0.01) c A	1.057 (0.001) b	13.1 (0.4) b	4.47 (0.03) a
Golden Russet	0.24 (0.01) b A	0.16 (0.01) c A	0.50 (0.04) b A	0.46 (0.02) b A	1.077 (0.001) a	16.4 (0.7) a	3.43 (0.03) b
Porter's Perfection	0.35 (0.02) a B	0.66 (0.06) a A	0.67 (0.07) a B	0.83 (0.04) a A	1.054 (0.001) b	12.1 (0.6) b	3.17 (0.03) c
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation							
Control		0.34 (0.03)		0.49 (0.06)	1.063 (0.002)	14.1 (0.6)	3.69 (0.13)
Reduced irrigation		0.35 (0.04)		0.43 (0.05)	1.063 (0.002)	13.6 (0.6)	3.70 (0.12)
P value		0.71		0.05	0.82	0.32	0.39
Interactions							
Cv. × Year		<0.0001		0.03	0.17	0.38	0.54
Cv. × Irrigation		0.35		0.30	0.83	0.63	0.14
Year × Irrigation		0.12		0.24	0.92	0.35	0.32

^zThe control treatment was fully irrigated between 80% and 100% soil available water-holding capacity based on a water balance calculation, and the reduced irrigation treatment received no irrigation applications based on stem water potential values.

^yTreatments compared using Tukey's honestly significant difference at $\alpha = 0.05$. The influence of cultivar on yield and fruit weight was only analyzed within each year, and the influence of year on these variables was only analyzed within each cultivar. Treatment means followed by the same lowercase letter within a column or by the same capital letter within a row are not significantly different. Values in parentheses are the standard error of the mean.

between stem ψ and yield (Fig. 4B), water stress may be more pronounced in trees experiencing a high crop load due to biennialism. This relationship agrees with studies that have observed that stomatal conductance and transpiration rates in apple are influenced by crop load (Naor et al., 1997, 2008). Overall, the lack of substantial differences in stem ψ between treatments led to few differences in fruit and juice quality. While there were small differences observed in fruit quality—firmness in 2020 and average fruit weight both years—post-hoc determination of the appropriate sample size using firmness data in 2020 suggests that larger sample sizes (179 fruit per treatment vs. 60) would have been required to estimate the true mean within $\pm 5\%$. Thus, whether RI can positively influence fruit and juice quality remains to be seen, especially in climates with higher evaporative demand and/or in mature orchards.

While RI can theoretically be scheduled with a calculated water balance, soil moisture monitoring, or many other methods, the results of this study highlight the importance of directly measuring plant water status (e.g., stem ψ) when implementing RI. Using a theoretical water balance, ISM estimated that plant available water in the RI plots was consistently below 50% of the available water-holding capacity between 14 June and 9 Sept. 2019 and between 27 July and 12 Oct. 2020. Further, plant available water in the RI plots reached a minimum of 24% in 2019 and 13% in 2020, which suggested water stress and thus that irrigation should be applied in this treatment. Similarly, soil ψ in the RI plots averaged less than -100 kPa in both years between June and September and dropped well below this level in both years. This soil ψ was below thresholds associated with inadequate irrigation for table apples in silt loam soils in Washington (Osroosh et al., 2016), and also suggested water stress. However, by using stem ψ as the trigger for irrigation in this study, it was clear that trees were not experiencing meaningful water stress, and irrigation application was eliminated with no impact on fruit yield and only minor impacts on fruit quality.

The relationship between temperature and the midday stem ψ of the well-watered control indicates a higher evaporative demand as temperature increases, which is intuitive and similar to a relationship observed in ‘Honeycrisp’ apples treated with RDI (Reid and Kalcsits, 2020). This relationship can provide reference values for well-watered cider apple trees to help growers schedule irrigation based on stem ψ , which has been done on grapevines and various tree fruits (De Swaef et al., 2009; Fulton et al., 2014; Suter et al., 2019). However, the use of midday stem ψ to schedule irrigation in commercial cider apple orchards is unlikely unless careful irrigation management to impose moderate water stress based on stem ψ results in economically relevant changes in fruit and juice quality and/or the ongoing development of microchip tensiometers to measure stem ψ

(e.g., Pagay et al., 2014) lowers the labor costs associated with this measurement.

A significantly higher tannin concentration in ‘Porter’s Perfection’ (0.66%) compared with other cultivars in 2020 was more than twice historic values at our site (Miles, 2019). This is potentially due to the low yield of ‘Porter’s Perfection’ in 2020 where some plots had very few fruit. A relationship between crop load and polyphenolic content has been observed in several other studies of cider cultivars (Guillermin et al., 2015; Karl et al., 2020). Similar to wine grapes, the skins of cider apples have the highest concentration of polyphenols such as tannins and anthocyanins (Lata et al., 2009), which provide for the highly desired cider sensory attributes of astringency and bitterness (Barker, 1903). Reduced irrigation has been used to increase tannin and anthocyanin concentration in the skins and seeds of grapes, partially due to a reduction in fruit size (Casassa et al., 2015; Matthews and Anderson, 1988; Roby et al., 2004), though it is unknown if the same result could be expected in apples. Further, as the skin of apples is typically not macerated in cider production, only an increase in phenolic compounds in the flesh would affect cider juice quality. The high pH of ‘Dabinett’ (4.47), similar to historic values at our site, prohibits its fermentation as a single varietal cider, as a low pH (< 3.3) is necessary to limit risk of microbial contamination during fermentation (Lea, 2008). While the three cultivars in this study differed from each other in fruit and juice quality attributes, these differences were similar to their historic measures and not due to irrigation treatment (Miles, 2019).

Conclusions

In summary, irrigation may not be necessary for establishing third and fourth leaf cider apple orchards in climates and soils similar to those in this study. While RI influenced some fruit quality components at our site (average fruit weight and firmness), these differences were small, likely due to the threshold for plant water stress not being met in either year. Positive impacts on fruit quality with RI may be observed in mature orchards and/or climates with higher evaporative demand or less precipitation. Cultivar differences for each variable were consistent with historic cultivar descriptions for this site. Based on water costs in the region where this study took place, cost savings from irrigating based on stem ψ were \$1001 per ha in 2019 and \$550 per ha in 2020. While the hypothesized benefits of RI for fruit and juice quality were generally not achieved, irrigation water productivity was increased, thereby increasing the feasibility of orchard establishment or expansion in regions with limited water availability and reducing the environmental impacts of cider apple production.

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