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Canadian Journal of Plant Science

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Effects of postharvest deficit irrigation on sweet cherry (*Prunus avium*) in five Okanagan Valley, Canada, orchards: I. Tree water status, photosynthesis, and growth

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Abstract

The timing and availability of water supply are changing in the Okanagan Valley, and the availability of irrigation water in the late summers is a growing concern. Postharvest deficit irrigation (PDI) is a strategy that can be used to reduce water demands in sweet cherry orchards; previous studies in this region have reported no change in plant physiology or tree growth with irrigation volume reductions of up to 25%, postharvest. However, the effects of more severe postharvest reductions in irrigation volume remain unknown. We compared the effects of full irrigation (100% of conventional grower practice through the growing season) with 27%–33% reductions in irrigation postharvest (∼70% of conventional grower practice) and 47%–52% reductions in irrigation postharvest (∼50% of conventional grower practice) over a 3-year period (2019–2021) in five commercial sweet cherry orchards that ranged in elevation and latitude across the Okanagan Valley, BC, Canada. In the growing season following treatment application, PDI had no effect on stem water potential or photosynthesis in any year and at any site; there were also no effects of PDI treatment on tree growth. Findings from this study suggest that postharvest stem water potentials from −0.5 to −1.3 MPa, and one-time stem water potentials as low as −2.0 MPa, have no lasting effects on future plant water status, rates of photosynthesis, or plant growth. PDI shows potential as an effective water-saving measure in sweet cherry orchards in the Okanagan Valley.

Key words: postharvest deficit irrigation, stem water potential, sweet cherry, tree growth, water-use efficiency

Introduction

The Okanagan Valley is a semi-arid region in the interior of British Columbia (BC), Canada, that is located in the rain shadow of the Coast Mountains. This area is important for fruit crops and sweet cherry production, and the area has rapidly expanded over the past several years. Sweet cherry is one of the dominant tree fruit commodities in BC (BC Ministry of Agriculture, Food, and Fisheries 2020). An estimated 4138 acres of commercial cherry are planted within the Okanagan Valley, accounting for 86% of cherry acreage in BC. The Okanagan Valley experiences low levels of precipitation (average annual precipitation of 300–400 mm in the valley bottom), given that sweet cherry crops require ∼550–700 mm to produce a viable crop each year, and therefore irrigation is required (Summit 2010; Neilsen et al. 2017). However, the availability of sufficient water for irrigation is a growing concern, especially in the late summers when water reservoirs and stream flow are typically low and agricultural, nonagricultural, and ecosystem water demands can be high. Overall, annual water use and irrigation water demand are projected to increase in this region due to climate change, population growth, and expanding agriculture (Cohen et al. 2006; Neilsen et al. 2006). Therefore, it is important to consider research and adopt irrigation practices that will reduce water consumption while minimizing adverse effects on crop production. Postharvest deficit irrigation (PDI) is a strategy that can be used to reduce agricultural water demands by reducing irrigation during the period postharvest (Wang et al. 2020). For fruiting trees, certain developmental stages, such as the postharvest nonfruit bearing stage, may also be less sensitive to water stress, making it an ideal time to apply deficit irrigation (DI) (Fereres and Soriano 2007). Additionally, postharvest is often the preferred period to apply DI because it can reduce overall vegetative growth and the associated pruning requirements (Samperio et al. 2015*b*). Studies on PDI as an irrigation best management practice have been completed to observe its impact on cherry fruit yield, quality, and physiology (Dehghanisanij et al. 2007; Marsal et al. 2009, 2010; Blanco et al. 2018, 2019*a*, 2019*b*; Carrasco-Benavides et al. 2020), but limited work has been done in the Okanagan Valley (Gebretsadikan et al. 2022).

When applying PDI, stem water potential (Ψ_{stem}) is a good indicator of tree water stress (Livellara et al. 2011; Blanco et al. 2019*a*). Stem water potential represents the potential

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Fig. 1. Experimental layout showing an example of one block including three plots, one of each irrigation treatment, with guard trees and measurement trees (x) represented by each cell.

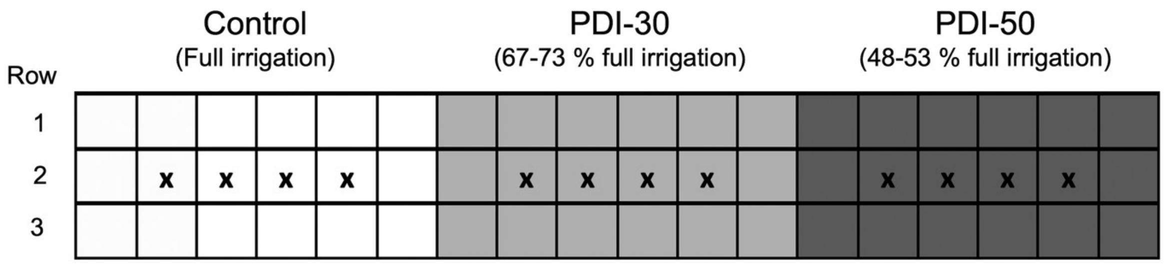

Table 1. Commercial harvest dates and dates of PDI application each year.

	2019	2020		2021		2022
Site	Start of PDI	Harvest	Start of PDI	Harvest	Start of PDI	Harvest
1	Aug. 23	Aug. 10	Aug. 12	Aug. 18	Aug. 22	Aug. 16
2	Aug. 16	July 31	Aug. 4	Aug. 20	Aug. 20	Aug. 10
3	Aug. 7	Aug. 8	Aug. 12	Aug. 6	Aug. 12	Aug. 20
4	July 30	Aug. 2	Aug. 3	Aug. 10	Aug. 10	Aug. 10
5	Not applied	Aug. 2	Aug. 4	July 30	July 30	Aug. 6

Table 2. Estimated June–September precipitation (mm) in 2019, 2020, and 2021 and June–August in 2022 at sites 1, 2, 4, and 5.

	Total precipitation (mm)		
Year	Site 1	Site 2	Sites 4 and 5
2019			
June	40	25	25
July	53	36	39
Aug.	19	15	37
Sept.	48	41	85
2020			
June	72	57	62
July	16	22	12
Aug.	13	12	17
Sept.	9	9	9
2021			
June	18	10	14
July	0	1	6
Aug.	27	27	16
Sept.	22	24	11
2022			
June	92	73	58
July	51	14	6
Aug.	2	4	7

Note: Data are taken from Environment Canada weather stations (Government of Canada 2021*a*). Site-specific precipitation data were not available for site 3, but this orchard is located closest to sites 4 and 5.

for water movement from one part of the plant to another, within the xylem (Taiz and Zeiger 2003). As water stress increases, Ψ_{stem} becomes more negative. Few studies have measured Ψ_{stem} in sweet cherry under DI. The lowest Ψ_{stem} at which DI is proposed to have no negative effects in sweet cherry is ranged between −1.3 and −1.6 MPa (Marsal et al. 2009; Carrasco-Benavides et al. 2020) although a threshold of −0.5 MPa has also been proposed to prevent vegetative growth from being impacted (Livellara et al. 2011). The influence of PDI on sweet cherry has been reported to decrease plant photosynthesis (Marsal et al. 2009; Blanco et al. 2018, 2019*b*), improve water-use efficiency (Dehghanisanij et al. 2007; Blanco et al. 2019*b*; Carrasco-Benavides et al. 2020), and decrease vegetative growth (Dehghanisanij et al. 2007; Blanco et al. 2019*b*, 2020; Carrasco-Benavides et al. 2020). Improving our understanding of the influence of PDI on these aspects of cherry trees in the Okanagan Valley may help contribute to more sustainable irrigation management practices to support the expansion of the cherry industry in this region and possibly to other semi-arid cherry-producing regions globally.

This project builds on an earlier 2-year study conducted in three Okanagan cherry orchards, which demonstrated that reducing postharvest irrigation by approximately 25% had no detrimental effects on tree water stress, fruit yield, or fruit quality in the subsequent growing season (Gebretsadikan et al. 2022). The objective of this work was to examine the effects of two PDI strategies: PDI-30 (27%–33% reduction in irrigation, relative to conventional grower practice, postharvest) and PDI-50 (47%–52% reduction in irrigation, relative to conventional grower practice, postharvest) over three seasons (2019, 2020, and 2021) on plant water stress, photosynthesis rate, and tree growth in five commercial "Sweetheart"/Mazzard cherry orchards in the Okanagan Valley, BC. In control treatments, 100% of conventional grower practice was applied, postharvest. We hypothesized that the PDI treatments would have no effect on Ψ_{stem} or rates of photosynthesis (A_n), transpiration (E), or stomatal conductance (g_s) in the following growing season; however, Ψ_{stem} would become more negative and A_n, E, and g_s would be reduced during

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Table 3. Average monthly temperatures at each study site with extreme heat dome temperatures bolded.

	Site 1		Site 2		Site 3		Site 4		Site 5	
Year	Mean T (°C)	Max T (°C)	Mean T (°C)	Max T (°C)	Mean T (°C)	Max T (°C)	Mean T (°C)	Max T (°C)	Mean T (°C)	Max T (°C)
2019										
June	16.8	31.0	17.1	32.2	16.8	31.3	18.5	33.5	—	—
July	18.4	31.6	19.3	34.4	18.4	32.6	20.6	32.6	—	—
Aug.	19.6	35.3	20.5	37.0	19.4	35.4	20.6	35.6	—	—
Sept.	13.8	30.7	14.5	30.2	12.5	28.4	14.3	28.5	—	—
2020										
June	14.9	27.9	15.6	29.0	14.3	28.5	16.2	29.1	—	—
July	18.6	35.4	19.4	34.9	18.2	34.4	20.1	35.0	—	—
Aug.	19.2	36.6	19.3	34.2	18.9	36.0	20.7	36.1	—	—
Sept.	15.9	30.6	16.8	31.6	15.2	32.0	16.6	32.2	—	—
2021										
June	20.2	**42.9**	20.1	**42.2**	18.9	**41.1**	20.8	**40.6**	21.3	**44.5**
July	23.7	36.0	23.6	35.6	22.7	36.0	24.3	36.7	25.2	39.3
Aug.	19.5	35.4	19.2	34.8	18.4	34.5	19.9	36.6	20.8	38.3
Sept.	13.9	28.5	14.4	27.4	13.2	27.7	15.0	27.8	15.7	28.4
2022										
June	15.5	31.9	16.0	31.5	14.2	31.1	16.2	31.8	16.4	31.3
July	21.5	36.3	22.1	37.5	20.3	35.5	22.6	38.5	22.8	38.6
Aug.	21.7	34.3	22.1	34.8	19.9	32.6	22.6	35.7	23.1	36.3

Note: Site 5 temperature measurements are missing for 2019 and 2020; however, site 5 was located approximately 2.2 km from site 4 at an elevation of 95 m a.s.l. lower for comparison.

the application of PDI treatments. We also hypothesized that water-use efficiency would increase with increasing levels of PDI and that overall tree growth, as indicated by trunk cross-sectional area (TCSA), new wood pruning weight, and leaf area, would be lower in the PDI treatments than in the control.

Materials and methods

Study sites

The study sites were located at five commercial sweet cherry orchards that varied in both elevation and latitude across the Okanagan Valley, BC. All sites were established on sections of the cultivar "Sweetheart" (*Prunus avium* L.) grafted on Mazzard (*P. avium*) rootstock. Site 1 (50°14′N/119°08′W, 615 m a.s.l.), site 2 (49°53′N/119°22′W, 507 m a.s.l.), site 3 (49°42′N/119°48′W, 755 m a.s.l.), site 4 (49°37′N/119°42′W, 510 m a.s.l.), and site 5 (49°38′N/119°40′W, 415 m a.s.l.) were established in 2015, 2013/2014, 2016/2017, 2006, and 2017, respectively. The soil type at site 1 was loam, at sites 2, 3, and 4 it was sandy loam, and at site 5 it was silt. Organic matter content (% loss on ignition) was the highest at site 1 (10%), intermediate at site 4 (5.3%), and lowest at sites 2, 3, and 5 (2.7%, 3.2%, and 2.2%, respectively).

Experimental design and treatments

Irrigation treatments were applied to sites 1–4 in 2019 and to sites 1–5 in 2020 and 2021. This study was not conducted in site 5 in 2019 due to the young age of the orchard, which limited plant and flower bud material. Irrigation scheduling was managed by the growers at each study site, and PDI treatments were imposed by reducing emitter flow rate but not irrigation frequency or duration. In general, site 1 received short cycles (1 h) of irrigation twice weekly in the spring, increasing to daily applications of water for most of the summer and then gradually reducing irrigation frequency in the postharvest period. Site 2 received approximately 0.5 h of daily irrigation from April to mid-May, 1 h of daily irrigation from mid-May until harvest (with an additional 0.5 h if temperatures approached 32 °C), and 1 h of irrigation three or four times a week postharvest. At both of these sites, irrigation was usually applied using microsprinklers (Micro Sprays, Maxijet, Dundee, FL, USA) with a flow rate of 39.75 litres per hour (LPH) postharvest, and PDI treatments were imposed by reducing microsprinkler flow rate to 29.15 LPH (PDI-30) or 21.20 LPH (PDI-50) except in 2020 at site 1, when drip lines (emitter spacing 0.6 m) were also used to irrigate postharvest. In this case, PDI treatments were applied by sealing every fourth (PDI-30) or second (PDI-50) emitter, using waterproof tape.

In general, sites 3, 4, and 5 were managed differently than sites 1 and 2. At site 3, irrigation was applied in short cycles (1.5–3.5 h) several times a week (2–7 times), with shorter and less frequent irrigation postharvest. At site 4, irrigation was applied in longer cycles (3–10 h) approximately every 4–7 days preharvest, and approximately weekly postharvest. At site 5, irrigation was applied approximately weekly in 3–6 h cycles both before and after harvest. At these sites, irrigation was usually applied using microsprinklers (AquaMaster 2005,

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Table 4. Estimated annual water requirements (calculated using the BC Agricultural Water Calculator) and % of estimated annual water requirements applied as irrigation and precipitation in 2020.

2020	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Total
Site 3								
Water requirements (mm)	12	17	107	171	132	75	56	570
Precipitation (mm)	8.4	59.6	61.8	12.3	17	8.5	51.9	219.5
Control irrigation (mm)	0	70	141	141	123	70	26	571
PDI-30 irrigation (mm)	0	70	141	141	106	47	18	523
PDI-50 irrigation (mm)	0	70	141	141	96	34	13	495
Irrigation + precipitation % of requirements								
Control	**70**	**762**	**190**	**90**	**106**	**105**	**140**	
PDI-30	**70**	**762**	**190**	**90**	**93**	**74**	**125**	
PDI-50	**70**	**762**	**190**	**90**	**86**	**57**	**116**	
Site 4								
Water requirements (mm)	29	41	135	185	152	87	62	691
Precipitation (mm)	8.4	59.6	61.8	12.3	17	8.5	51.9	219.5
Control irrigation (mm)	0	50	120	170	170	90	0	600
PDI-30 irrigation (mm)	0	50	120	170	113	60	0	513
PDI-50 irrigation (mm)	0	50	120	170	81	43	0	464
Irrigation + precipitation % of requirements								
Control	**29**	**267**	**135**	**99**	**123**	**113**	**84**	
PDI-30	**29**	**267**	**135**	**99**	**86**	**79**	**84**	
PDI-50	**29**	**267**	**135**	**99**	**64**	**59**	**84**	
Site 5								
Water requirements (mm)	40	61	143	185	151	89	61	730
Precipitation (mm)	8.4	59.6	61.8	12.3	17	8.5	51.9	219.5
Control irrigation (mm)	0	51	107	102	118	51	0	429
PDI-30 irrigation (mm)	0	51	107	102	79	34	0	373
PDI-50 irrigation (mm)	0	51	107	102	56	24	0	340
Irrigation + precipitation % of requirements								
Control	**21**	**181**	**118**	**62**	**89**	**67**	**85**	
PDI-30	**21**	**181**	**118**	**62**	**64**	**48**	**85**	
PDI-50	**21**	**181**	**118**	**62**	**48**	**37**	**85**	

Note: All precipitation values are based on the closest Environment Canada weather station (Government of Canada 2021*a*) located in Summerland, BC. Sites 1 and 2 irrigation data are missing due to water meter malfunctions. https://bcwatercalculator.ca/agriculture/

NaanDanJain Irrigation, Israel) with a flow rate of 105 LPH postharvest, and PDI treatments were imposed by reducing microsprinkler flow rate to 70 LPH (PDI-30) or 50 LPH (PDI-50) except in 2021 at site 3, when drip lines (emitter spacing 0.6 m) were used to irrigate postharvest; again, PDI treatments were applied by sealing every fourth (PDI-30) or second (PDI-50) emitter, using a waterproof tape.

Treatments were applied in a randomized complete block design with six replicates treatment^{-1} site^{-1}. Each block consisted of a single row of 18 trees, divided into three 6-tree treatment plots with four measurement trees and a guard tree located at each end; treatments were randomly assigned to one of the three treatment plots in each block. Tree rows with treatment plots were separated by two rows of guard trees (Fig. 1). Distance between trees and rows was 2.1 and 4.6 m at sites 1 and 2, 2.4 and 4.9 m at sites 3 and 5, and 2.4 and 4.3 m at site 4. PDI treatments were applied right after commercial harvest; dates of harvest and application of PDI treatments can be found in Table 1.

Meteorological data and water requirement estimates

A HOBO® data logger (Onset®, Bourne, MA, USA) installed at a height of 1.3 m above the ground in sites 1 and 3–5, and within 1 km of site 2 was used to record hourly ambient air temperatures. To compare average annual irrigation water requirements for each site with actual volume of water ap-

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Table 5. Estimated annual water requirements (calculated using the BC Agricultural Water Calculator) and % of estimated annual water requirements applied as irrigation and precipitation in 2021.

2021	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Total
Site 3								
Water requirements (mm)	12	17	107	171	132	75	56	570
Precipitation (mm)	13.6	6.9	14	5.9	16.2	11.2	48.7	116.5
Control irrigation (mm)	0	26	97	154	145	0	0	422
PDI-30 irrigation (mm)	0	26	97	154	107	0	0	384
PDI-50 irrigation (mm)		26	97	154	72	0	0	349
	Irrigation + precipitation % of requirements							
Control	**113**	**196**	**104**	**93**	**122**	**15**	**87**	
PDI-30	**113**	**196**	**104**	**93**	**93**	**15**	**87**	
PDI-50	**113**	**194**	**104**	**94**	**67**	**15**	**87**	
Site 4								
Water requirements (mm)	29	41	135	185	152	87	62	691
Precipitation (mm)	13.6	6.9	14	5.9	16.2	11.2	48.7	116.5
Control irrigation (mm)	15	98	153	195	60	82	0	603
PDI-30 irrigation (mm)	15	98	153	195	47	55	0	563
PDI-50 irrigation (mm)	15	98	153	195	39	39	0	539
	Irrigation + precipitation % of requirements							
Control	**99**	**256**	**124**	**109**	**50**	**107**	**79**	
PDI-30	**99**	**256**	**124**	**109**	**42**	**76**	**79**	
PDI-50	**99**	**256**	**124**	**109**	**36**	**58**	**79**	
Site 5								
Water requirements (mm)	40	61	143	185	151	89	63	732
Precipitation (mm)	13.6	6.9	14	5.9	16.2	11.2	48.7	116.5
Control irrigation (mm)	0	98	154	143	62	56	0	513
PDI-30 irrigation (mm)	0	98	154	143	41	38	0	474
PDI-50 irrigation (mm)	0	98	154	143	29	27	0	451
	Irrigation + precipitation % of requirements							
Control	**34**	**172**	**117**	**80**	**52**	**76**	**77**	
PDI-30	**34**	**172**	**117**	**80**	**38**	**55**	**77**	
PDI-50	**34**	**172**	**117**	**80**	**30**	**43**	**77**	

Note: All precipitation values are based on the closest Environment Canada weather station (Government of Canada 2021*a*) located in Summerland, BC. Sites 1 and 2 irrigation data are missing due to water meter malfunctions. https://bcwatercalculator.ca/agriculture/

plied by irrigation and precipitation, annual irrigation water requirements were estimated for each site using the BC Agricultural Water Calculator (https://bcwatercalculator.ca/agriculture/irrigation), which calculates average water demand using crop, irrigation, soil, and climate parameters, adjusted for site-specific irrigation infrastructure, soil texture, and crop type (Van der Gulik et al. 2010). These estimates are made using average historical climate data from 2001 to 2010 and do not vary from year to year (Tam and Anslow 2018). For sites 1 and 2, actual applications of irrigation water could not be calculated because grower records were not sufficiently accurate and water meters were not functional. For sites 3, 4, and 5, actual volumes of applied irrigation water were estimated using grower records (irrigation timing, frequency, duration), emitter flow rates, and emitter density. Daily precipitation data were obtained from the Environment Canada weather station located closest to each site and accessed through the Government of Canada's online historical weather and climate database: https://climate.weather.gc.ca/index_e.html (Government of Canada 2021*a*).

Soil moisture

Soil moisture probes (5TE or TEROS 12, Decagon Devices, Pullman, WA, USA) were installed at a depth of 30 cm (Olson and Al-Kaisi 2015), 30 cm out from the centre of the tree row in three of the six treatment replicates at each site. Probes were installed at sites 1–4 in August 2019 and at site 5 in July

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Table 6. AICc-based model selection of GLS models with Gamma distributions and log links fitted with preharvest (pre) or postharvest (post) soil moisture (SM) as response variable and Site and Treatment (Trt) as interacting fixed effects.

Response	Top models' fixed effects	AICc	ΔAICc
2020 SM pre	1. Trt × Site	−749.2	0
	2. Site + Trt	−680.5	68.7
2021 SM pre	1. Trt × Site	−812.2	0
	2. Site	−770.2	42.0
2022 SM pre	1. Trt × Site	−654.1	0
	2. Site	−624.8	29.3
2019 SM post	1. Trt × Site	−300.1	0
	2. Site	−289.5	10.6
2020 SM post	1. Trt × Site	−592.8	0
	2. Site + Trt	−554.5	38.3
2021 SM post	1. Trt × Site	−640.9	0
	2. Site	−591.0	50.0

2020. Probes were connected to ZL6 automated data loggers (Decagon Devices, Pullman, WA, USA); volumetric soil moisture data were recorded hourly.

Stem water potential

Stem water potential (Ψ_{stem}) was measured at mid-day approximately every 2 weeks from June through September in 2020 and 2021 and from June through to harvest (Table 1) in 2022, at all sites. Measurements were conducted in four (of six) randomly selected replicates treatment^{-1} and two (of four) randomly selected trees plot^{-1} at each site. Measurement trees were randomly selected on each sample date. One hour prior to conducting measurements, two shaded leaves tree^{-1} (16 leaves treatment^{-1} site^{-1} on every sample date) were wrapped in black plastic and aluminum foil (Shackel et al. 1997). Leaves were excised from the tree and a Scholander pressure chamber (Model 3005: Soilmoisture Equipment Corp., Santa Barbara, CA, USA) was used to measure Ψ_{stem}.

Photosynthesis and water-use efficiency

Net rates of photosynthesis (A_n), transpiration (E), and stomatal conductance (g_s) were measured approximately every 2 weeks from June through September in 2020 and 2021 and from June through to harvest (Table 1) in 2022, at all sites. Measurements were conducted around mid-day on the dates and the same trees as the Ψ_{stem} measurements using an LCi T photosynthesis meter fitted with a white light unit (ADC BioScientitic Ltd., Hoddesdon, Herts, UK). The white light unit was set to deliver 1500 μmol m^{-2} s^{-1} to the leaf surface in 2020 and 1300 μmol m^{-2} s^{-1} in 2021 and 2022. The white light unit settings differed in 2020 due to human error. Water-use efficiency ($WUE_{intrinsic}$) was calculated as A_n/g_s (Pascual et al. 2013).

Tree growth

Plant growth was assessed by measuring annual TCSA, new wood pruning weight, and average leaf area. Trunk diameter (30 cm above graft union) was measured in October 2019 at sites 1–4 and October 2020 and 2021 at sites 1–5, using digital calipers (Absolute AOS Digimatic, Mitutoyo Corporation, Kawasaki, Japan). Two measurements, one perpendicular and one parallel to the tree row, were taken from every measurement tree (72 trees site^{-1}). Tree trunks were assumed to be circular, and TCSA was calculated using the average of the two diameter measurements for each tree.

The pruning weight of wood 2 years or younger (new wood) was measured in the winters of 2020–2021 at sites 1–4 and 2021–2022 at sites 1 and 3–5. Site 2 was pruned in the 2021–2022 season; however, material collection was missed. Pruning was conducted by commercial growers according to industry standards. At sites 1 and 2, trees were typically pruned twice during the dormant season, once in late autumn to remove older, larger branches and then again later in the dormant season to remove young upright and overabundant shoots. Sites 3, 4, and 5 were typically pruned once in the dormant season in a multileader system/open centre structure. One tree plot^{-1} was randomly selected from all six replicates at each site; all freshly pruned new wood was collected from each selected tree and weighed in the field, to determine fresh weight. A subsample of freshly pruned new wood from each treatment was taken to the lab, weighed, dried at 65 °C for 72 h (Heratherm™ OMH180, Thermo Scientific™, Cleveland, OH, USA), and reweighed (dry weight) to determine moisture content. The total dry weight of pruned new wood was calculated for each plot after correcting for moisture content (Samperio et al. 2015*a*).

To determine average leaf area, 5 leaves per measurement tree (20 leaves plot^{-1}) were sampled from four randomly selected replicates treatment^{-1} at each site in August 2020 and 2021. Leaves were sampled from the middle third section of a segment of new growth, on a limb growing at a 30°–60° angle from the ground located on any side of the tree. Total leaf area was measured using a leaf area meter (LI-3000, LI-COR Inc., Lincoln, NE, USA).

Statistical analyses

Generalized least squares (GLS) models and linear mixed-effects models (LMMs) were used to test for significant effects of irrigation treatment and site on tree water status, rates of photosynthesis, transpiration, stomatal conductance, and tree growth. LMMs are appropriate for nested designs with repeated measures (Yang 2010). GLS models with Gamma distributions and a log link function were fitted with average weekly volumetric soil water content from June 1 to the approximate date that growers stopped irrigation in the fall (usually in late September to mid-October). A Gamma distribution was used because it is appropriate for models fit with variables ranging from 0 to ∞ and can improve the accuracy of significance testing (Medici et al. 2022). Each measurement period (preharvest or postharvest) and year was then modelled independently, with Treatment × Site as a fixed effect.

Average Ψ_{stem}, A_n, E, g_s, and $WUE_{intrinsic}$ measurements preharvest and postharvest were analyzed separately for each year using LMMs with Treatment × Site as fixed effects but with crossed random effects for Block and Date. Hierarchi-

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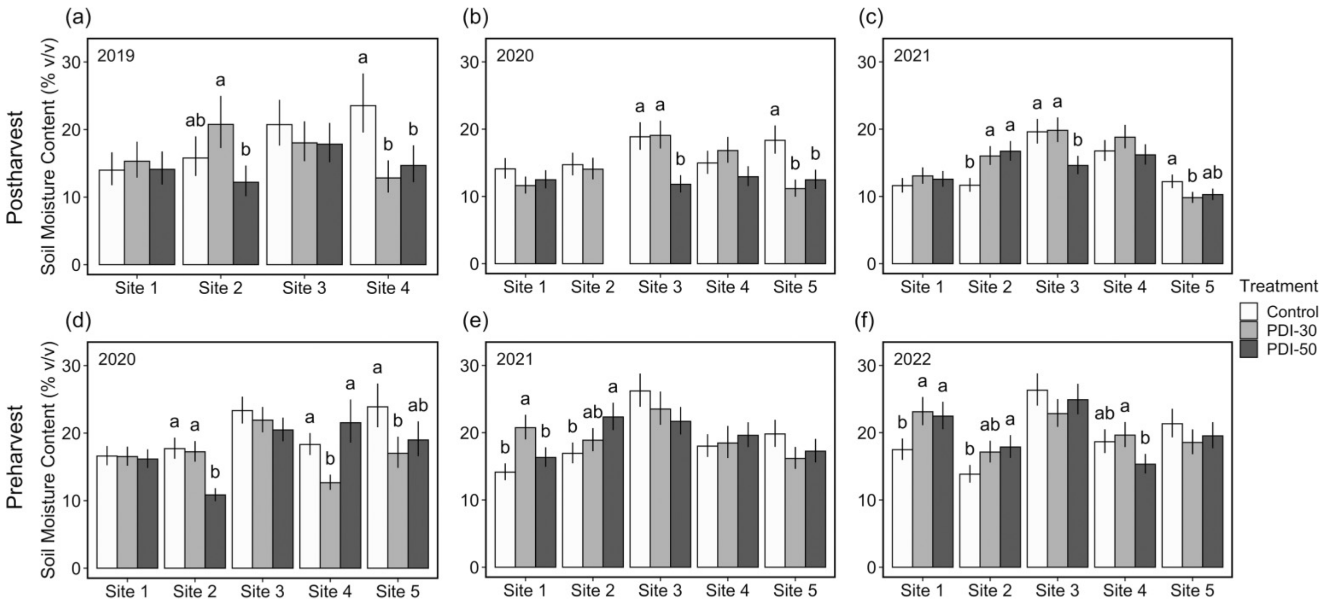
Fig. 2. Estimated marginal mean average weekly soil moisture ((*a*) 2019 postharvest soil moisture, (*b*) 2020 postharvest soil moisture, (*c*) 2021 postharvest soil moisture, (*d*) 2020 preharvest soil moisture, (*e*) 2021 preharvest soil moisture, (*f*) 2022 preharvest soil moisture). The preharvest and postharvest periods were analyzed separately. Error bars indicate 95% confidence levels of estimated marginal means. Values within the same parameter and site that share the same letter or have no letters do not differ significantly ($p \leq 0.05$). Data from site 2 in the postharvest period in 2020 are missing due to soil moisture sensor failures.



cal random effects were employed to account for the clustered data structure (Schabenberger and Pierce 2001). Data from the 2020 season from site 5 were excluded from the analysis because, unlike sites 1–4, PDI treatments had not been applied the previous year. The relationship between Ψ_{stem} and A_n, E, g_s, and $WUE_{intrinsic}$ was also explored using LMMs. Each parameter was modelled with Ψ_{stem} as a fixed effect and nested Site, Year, and Date as a random effect.

To determine the effect of irrigation treatment on each year's growth, LMMs were fitted with TCSA and new wood winter pruning weight as response variables, Treatment × Site as fixed effects, and Block as a random effect. The TCSA and new wood pruning weight were log transformed to improve model residual normality. GLS models were also fitted with leaf area as the response and Treatment × Site as fixed effects.

Analysis of variance (ANOVA) using the "lmerTest" package (Kuznetsova et al. 2017) was completed on the LMMs and the information theoretic approach (Burnham et al. 2011), using Akaike's information criterion adjusted for small sample sizes (AICc), was used to identify fixed effects that improved model fit for GLS models fitted using maximum likelihood. Tukey's-adjusted pairwise comparisons between treatments, sites, and years were completed on the estimated marginal means and the 95% confidence intervals using the "emmeans" function from the "emmeans" package (Lenth et al. 2022). Estimated marginal means are provided on the response scale. Gaussian model assumptions of normality and homoscedasticity were validated. Statistical analyses were performed using the "lme4" (v1.1.27.1; Bates et al. 2015), "lmerTest" (v3.1.3; Kuznetsova et al. 2017), "nlme" (v3.1.149; Pinheiro et al. 2020), and "emmeans" (v1.5.4; Lenth et al. 2022) packages in RStudio (v1.3.1093; R Core Team 2020). *p* values of ≤ 0.05 were considered significant.

Results

Climate, irrigation, and soil moisture

There was substantial interannual variability in precipitation and temperature over the postharvest period in 2019, 2020, and 2021 (Tables 2 and 3). In 2019, higher than average precipitation fell in August and September (15–85 mm) (Table 2). In 2020 and 2021, more seasonal precipitation fell over the same period (9–17 mm and 11–27 mm, respectively). All sites experienced similar monthly mean temperatures from June to September each year (Table 3). Mean monthly temperatures were similar in 2019 and 2020, but in 2021, western North America experienced an extreme temperature event referred to as a "heat dome" (Government of Canada 2021*b*). In the Okanagan Valley, this heat dome began by the end of June and brought extreme maximum daily temperatures (40.6–44.5 °C) to all study sites. Commercial growers increased irrigation frequency at all sites to mitigate heat stress during this period.

When expressed relative to annual irrigation water requirements (estimated using BC's Agricultural Water Calculator (https://bcwatercalculator.ca/agriculture/irrigation)), the amount of water (irrigation + precipitation) applied to cherry trees at sites 3, 4, and 5 in 2020 (Table 4) and 2021 (Table 5) showed variability among sites and months. Estimations

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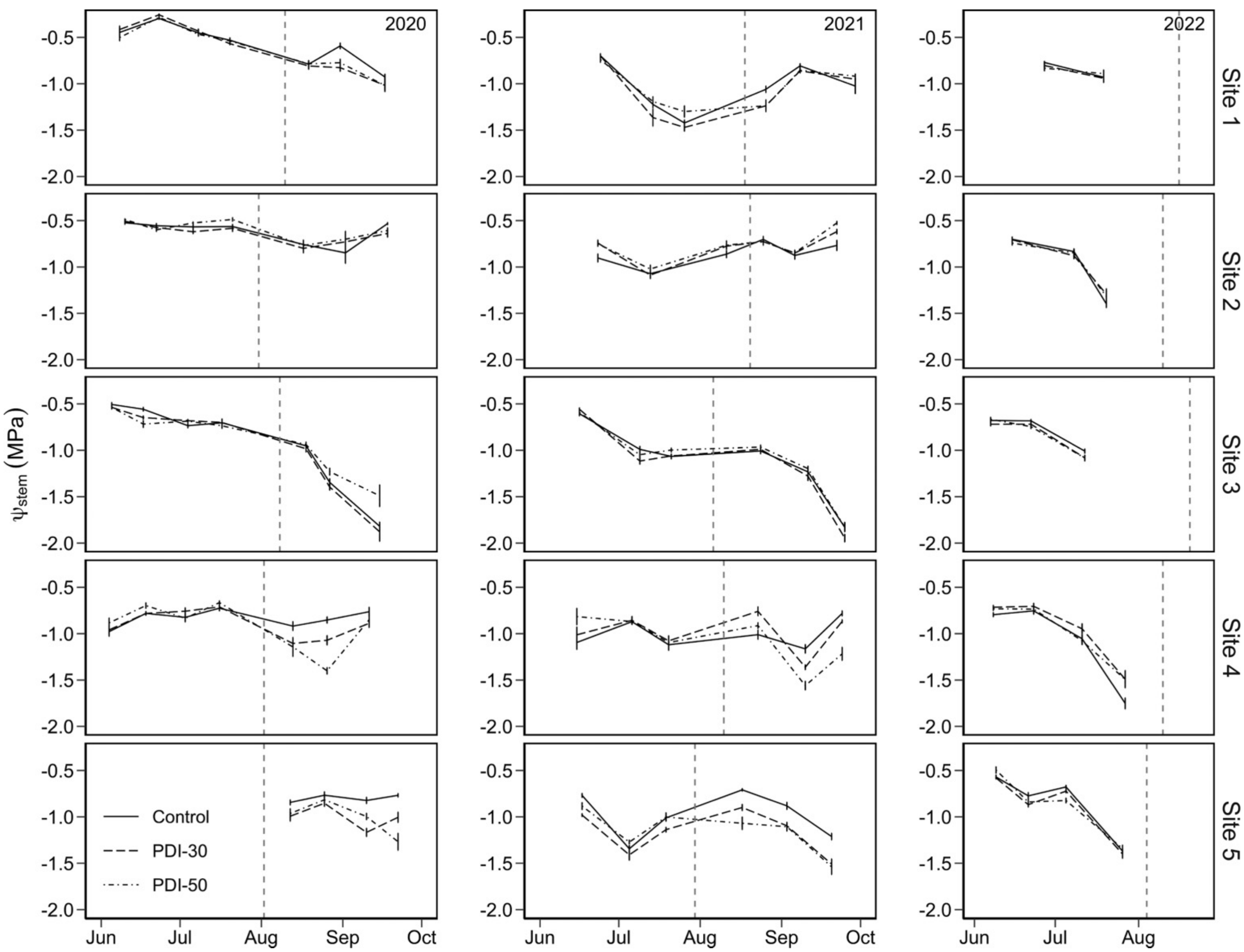
Fig. 3. Stem water potential measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. Each value is the mean of $n = 4 \pm$ the standard error (SE). The dashed vertical lines indicate the commercial harvest date.



for sites 1 and 2 were not made as the applications of irrigation water could not be calculated for this period. In general, irrigation supplied more water than required in May and June, and similar to or less than required in subsequent months. During the postharvest irrigation period (August and September), the control plots (growers practice) received between 50% and 123% of estimated water demand. Notably, approximately 50% of estimated water requirements were applied in August 2021 in the control treatments at sites 4 and 5. Only 15% of estimated water requirements were applied in September 2021 at site 3, which relies on a private reservoir that ran dry that year. Consequently, while 30% and 50% reductions in water use relative to grower practice were applied each year, postharvest deficits relative to irrigation demand ranged between 37%–93% in 2020 and 15%–93% in 2021.

Soil moisture was measured postharvest in 2019 at sites 1–4, preharvest and postharvest in 2020 and 2021 at all sites, and preharvest in 2022 at all sites. In the postharvest period, average weekly soil moisture ranged from 13% to 21%, 12% to 19%, 10% to 27%, 14% to 20%, and 10% to 16% at sites 1–5, respectively. Significantly lower mean weekly soil moisture contents in response to reduced irrigation treatments were observed at site 4 in 2019; sites 3 and 5 in 2020; and sites 3 and 5 in 2021 (Table 6; Fig. 2). However, significant treatment differences in mean weekly soil moisture were also observed over the preharvest period, when treatments were uniformly irrigated, at sites 2, 4, and 5 in 2020, sites 1 and 2 in 2021, and sites 1, 2, and 4 in 2022. These results indicated a variability in soil moisture content, which could not be attributed to postharvest treatments. In general, soil moisture content was higher in the preharvest period than the postharvest period with an across site and year weekly average of 19% and 15%, respectively.

Stem water potential

The Ψ_{stem} of cherry trees was measured at both preharvest and postharvest periods in 2020 and 2021 and at the preharvest period in 2022 at all study sites (Fig. 3). Stem water potential was used as an indicator of tree water stress; more negative Ψ_{stem} values indicate an increase in water stress. Average Ψ_{stem} measurements across sites and years ranged from -0.3 to -1.8 MPa preharvest and from -0.5 to -2.0 MPa postharvest. Higher Ψ_{stem} values typically occurred in mid to

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Table 7. *p* values of ANOVAs based on LMM preharvest and postharvest stem water potential (Ψ_{stem}), photosynthesis rate (A_n), transpiration (E), stomatal conductance (g_s), and water-use efficiency (WUE) as unique response variables, with Treatment and Site as interacting fixed effects and Block and Date as crossed random effects.

Preharvest 2020			Postharvest 2020		
Response	Fixed effect	*p*	Response	Fixed effect	*p*
Ψ_{stem} R^2: 0.73	Trt	0.7226	Ψ_{stem}	Trt	**<0.0001**
	Site	**0.0004**	R^2: 0.74	Site	**0.0377**
	Trt × Site	**0.0009**		Trt × Site	**<0.0001**
A_n	Trt	0.1103	A_n R^2: 0.66	Trt	**0.0002**
R^2: 0.47	Site	0.4741		Site	0.4260
	Trt × Site	0.4847		Trt × Site	**0.0307**
E	Trt	0.0942	E	Trt	**<0.0001**
R^2: 0.78	Site	0.2866	R^2: 0.55	Site	**0.7911**
	Trt × Site	0.1352		Trt × Site	**<0.0001**
g_s	Trt	0.1394	g_s	Trt	**<0.0001**
R^2: 0.63	Site	0.1131	R^2: 0.68	Site	0.2182
	Trt × Site	0.5122		Trt × Site	**0.0012**
WUE	Trt	0.9135	WUE	Trt	**0.0118**
R^2: 0.56	Site	**0.0118**	R^2: 0.58	Site	0.2192
	Trt × Site	0.7426		Trt × Site	**0.0010**
Preharvest 2021			Postharvest 2021		
Ψ_{stem}	Trt	**<0.0001**	Ψ_{stem}	Trt	**<0.0001**
R^2: 0.75	Site	0.7126	R^2: 0.82	Site	0.1817
	Trt × Site	**0.0002**		Trt × Site	**<0.0001**
A_n	Trt	0.2352	A_n	Trt	**<0.0001**
R^2: 0.33	Site	0.5987	R^2: 0.56	Site	**0.0329**
	Trt × Site	0.0974		Trt × Site	**0.0174**
E	Trt	**0.0043**	E	Trt	**<0.0001**
R^2: 0.71	Site	0.0749	R^2: 0.81	Site	0.2732
	Trt × Site	**0.0049**		Trt × Site	**<0.0001**
g_s	Trt	**0.0078**	g_s	Trt	**<0.0001**
R^2: 0.72	Site	0.9537	R^2: 0.70	Site	0.1062
	Trt × Site	**0.0034**		Trt × Site	**<0.0001**
WUE	Trt	**0.0310**	WUE	Trt	**<0.0001**
R^2: 0.72	Site	0.9965	R^2: 0.63	Site	0.0816
	Trt × Site	0.3521		Trt × Site	**0.0001**
Preharvest 2022					
Ψ_{stem}	Trt	0.6543			
R^2: 0.87	Site	0.9267			
	Trt × Site	**0.0011**			
A_n	Trt	0.6154			
R^2: 0.74	Site	0.3974			
	Trt × Site	0.0625			
E	Trt	0.3930			
R^2: 0.67	Site	0.1099			
	Trt × Site	0.0549			
g_s	Trt	0.8687			
R^2: 0.75	Site	0.1472			
	Trt × Site	0.0770			
WUE	Trt	0.1211			
R^2: 0.30	Site	0.1080			
	Trt × Site	0.3382			

Note: *p* values in bold < 0.05. R^2: coefficients of determination of LMMs.

late June at each site, suggesting the trees were experiencing less water stress at these times. Lower Ψ_{stem} values were often measured in late August and early September, indicating increased tree water stress.

A series of LMMs were used to determine whether PDI treatment significantly affected Ψ_{stem} at preharvest and postharvest periods. The Ψ_{stem} measurements from the preharvest and postharvest periods from each year were analyzed separately; all sites were combined. There were significant Treatment × Site effects on Ψ_{stem} at both preharvest and postharvest periods in 2020 and 2021 (Table 7). Contrary to expectations, some treatment differences in Ψ_{stem} were observed preharvest, i.e., when irrigation was the same across treatments (Fig. 4). At site 5 in 2021, mean preharvest Ψ_{stem} in the PDI-30

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Fig. 4. Estimated marginal mean Ψ_{stem} ((*a*) preharvest 2020 Ψ_{stem}, (*b*) preharvest 2021 Ψ_{stem}, (*c*) preharvest 2022 Ψ_{stem}, (*d*) postharvest 2020 Ψ_{stem}, (*e*) postharvest 2020 Ψ_{stem}). Error bars indicate 95% confidence levels of estimated marginal means. The preharvest and postharvest periods were analyzed separately. Values within the same parameter and site that share the same letter or have no letters do not differ significantly ($p \leq 0.05$).

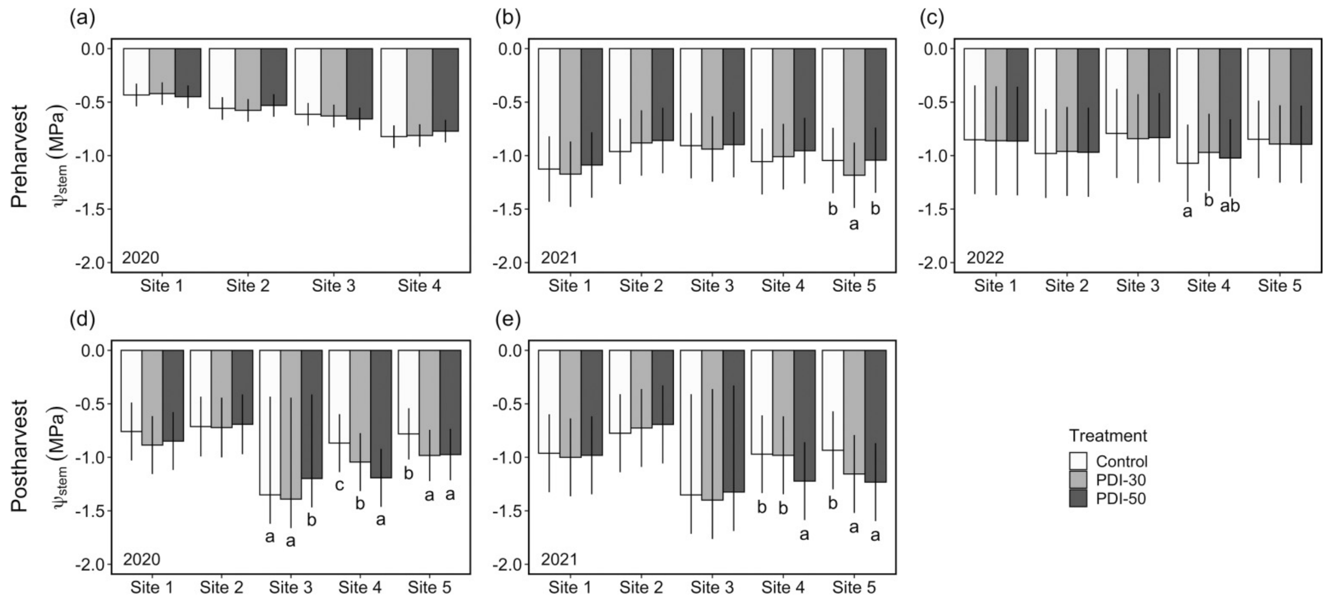

Fig. 5. Photosynthetic rate (A_n) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of $n = 4 \pm$ the standard error (SE).

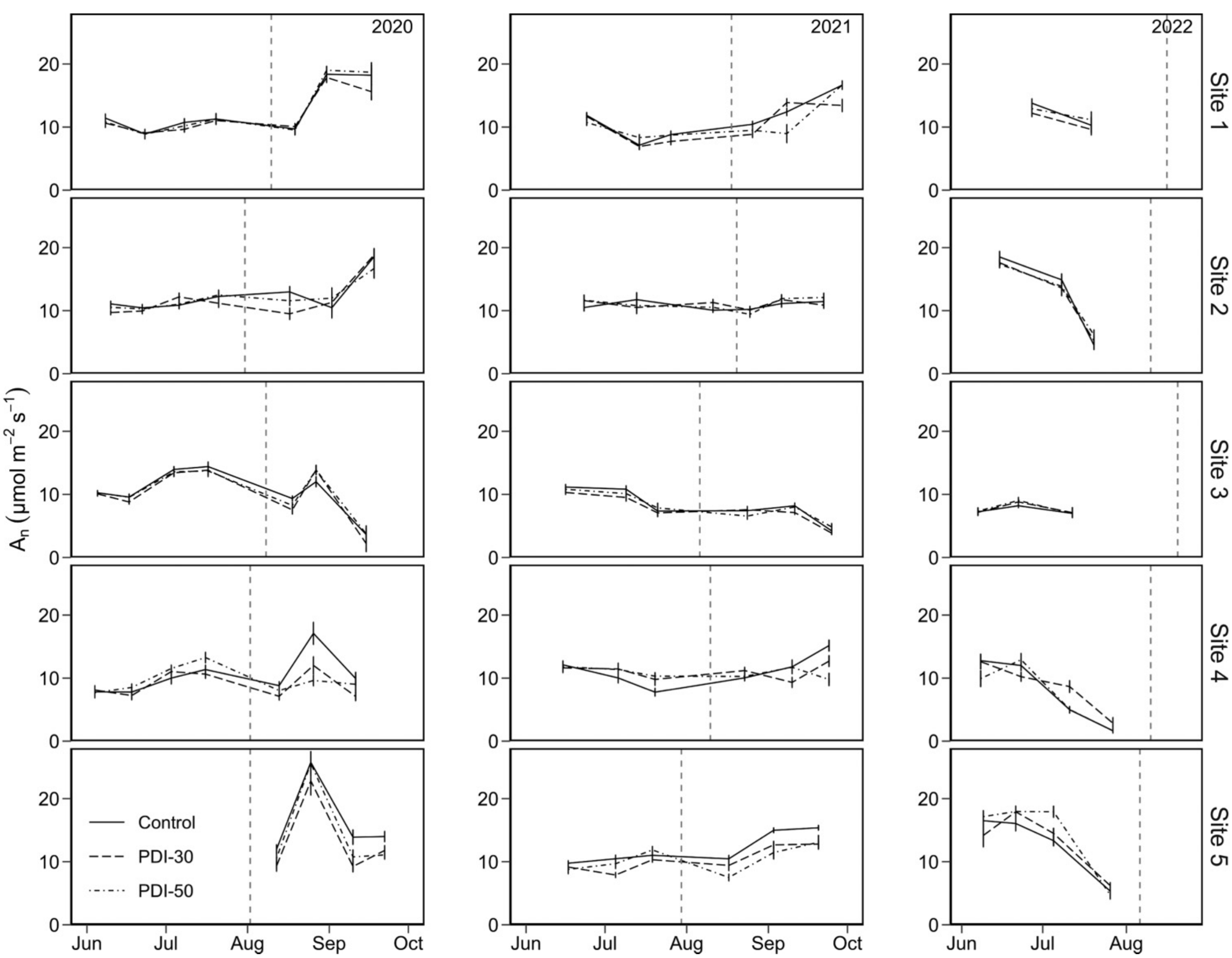

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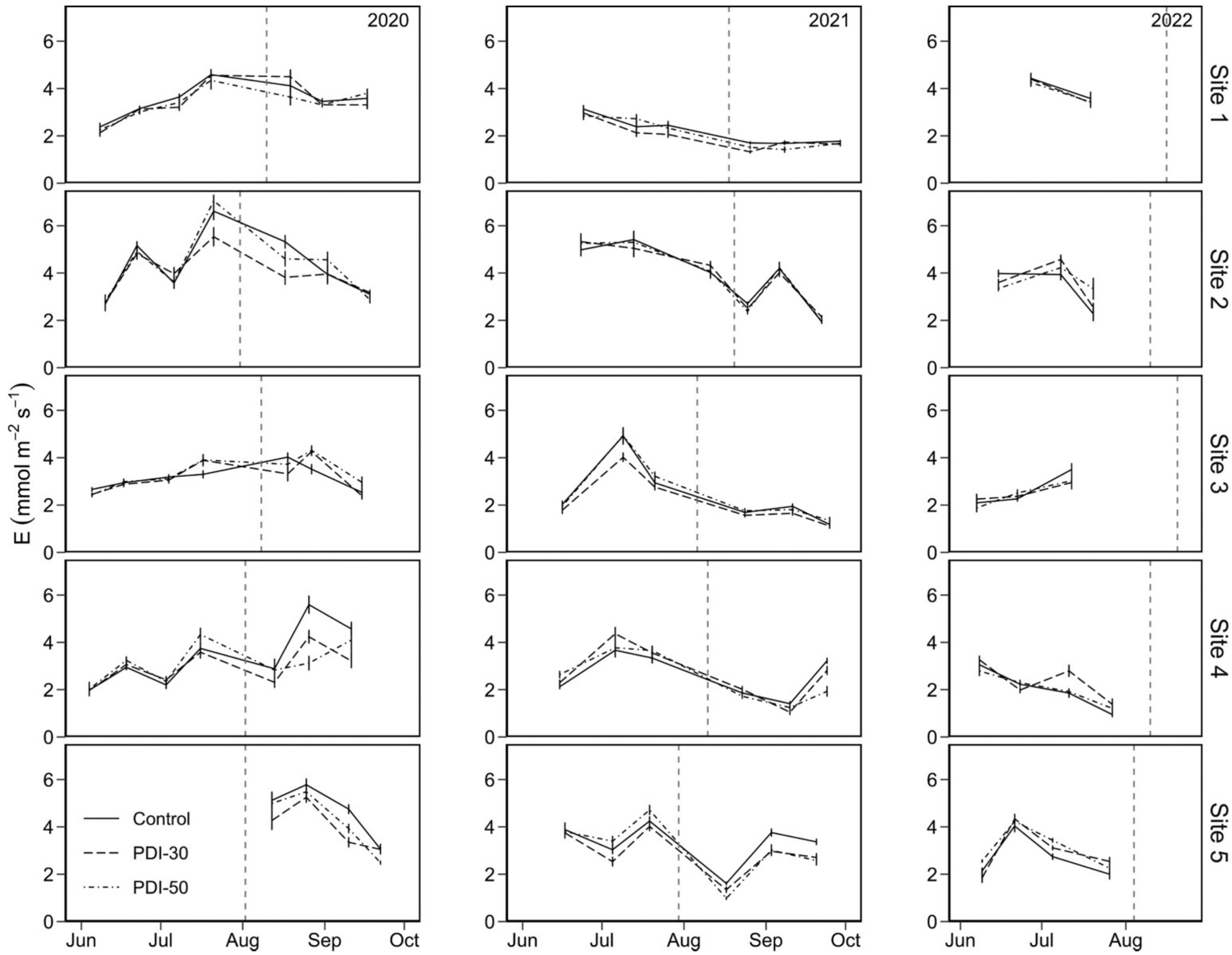
Fig. 6. Transpiration rate (E) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of $n = 4 \pm$ the standard error (SE).



treatment was significantly lower (suggesting greater water stress) than in the control or PDI-50 treatments. At site 4 in 2022, mean preharvest Ψ_{stem} in the PDI-30 treatment was significantly higher (suggesting lower water stress) than in the control treatment.

In the postharvest period, when PDI treatments had been applied, more treatment differences were observed. At site 3 in 2020, mean Ψ_{stem} in the PDI-50 treatment was significantly higher (suggesting lower water stress) than in the control or PDI-30 treatment; treatment differences disappeared in 2021. At site 4 in 2020, mean Ψ_{stem} was the highest in the control, followed by the PDI-30 treatment; mean Ψ_{stem} was the lowest in the PDI-50 treatment; and, in 2021, mean Ψ_{stem} in the PDI-50 treatment was significantly lower than in the control or PDI-30 treatment. At site 5, mean Ψ_{stem} was significantly lower in the PDI-30 and PDI-50 treatments than in the control in both years. In 2021, at site 3, all plots received the same low water applications postharvest and were equally stressed. There were no treatment effects on mean Ψ_{stem} at sites 1 or 2 postharvest in either year.

Photosynthesis and water-use efficiency

Preharvest, when irrigation applied was the same across treatments, the mean values of A_n, E, g_s, and $WUE_{intrinsic}$ ranged from 0.6 to 18.5 μmol m^{-2} s^{-1}, 0.9 to 7.1 mmol m^{-2} s^{-1}, 0.02 to 0.3 mol m^{-2} s^{-1}, and 36.1 to 116.9, respectively, across treatments and years (Figs. 5–8). Postharvest, when PDI treatments were applied, mean values of A_n, E, g_s, and $WUE_{intrinsic}$ ranged from 2.2 to 25.6 μmol m^{-2} s^{-1}, 1.0 to 5.8 mmol m^{-2} s^{-1}, 0.03 to 0.5 mol m^{-2} s^{-1}, and 47.2 to 123.5, respectively, across treatments and years. Models fit with A_n, E, g_s, and $WUE_{intrinsic}$ as response variables and Ψ_{stem} as a fixed effect indicated that there was a positive relationship between A_n, E, or g_s and Ψ_{stem} and a negative relationship between $WUE_{intrinsic}$ and Ψ_{stem} (Table 8).

In the preharvest period, treatment had a significant effect on $WUE_{intrinsic}$ in 2021 (Table 7); however, no significant difference between treatment estimated marginal means within each site was observed (data not shown). Treatment × Site had a significant effect on preharvest E and g_s in 2021 (Table 7), where at site 5 only, PDI-30 had significantly lower E and g_s than the control and the PDI-50 treatment (data not shown).

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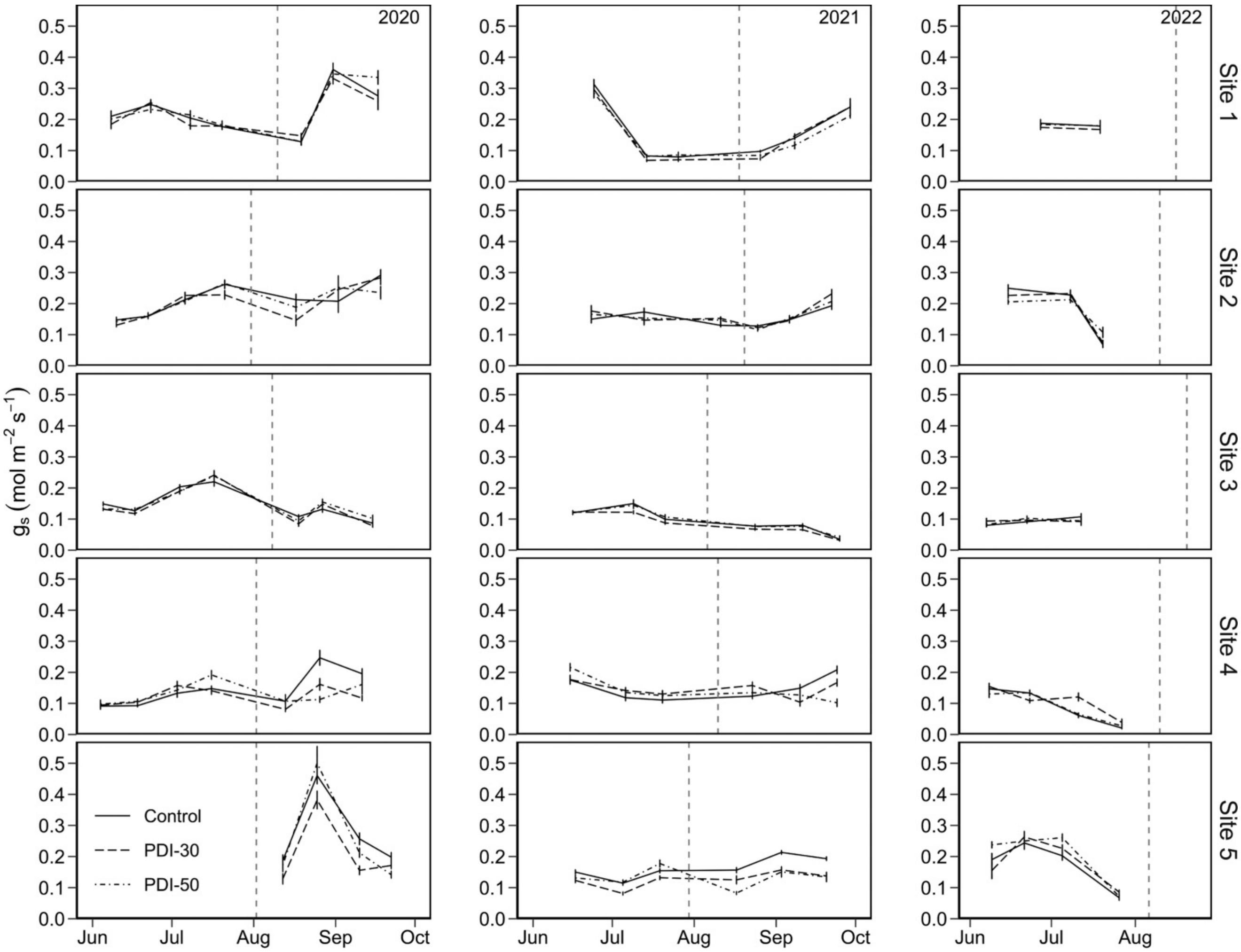
Fig. 7. Stomatal conductance (g_s) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of $n = 4 \pm$ the standard error (SE).



In the postharvest period, after PDI treatments had been applied, there were significant Treatment × Site effects on A_n, E, g_s, and $WUE_{intrinsic}$ in both years (Table 7; Figs. 9 and 10). There were no effects of PDI treatment on A_n, E, g_s, and $WUE_{intrinsic}$ at sites 1, 2, or 3 in 2020 or 2021. At site 4 in 2020, however, A_n, E, and g_s in the control were significantly higher than in the PDI-30 or PDI-50 treatments; $WUE_{intrinsic}$ in the control was significantly lower than in the PDI-50 treatment. At site 4 in 2021, E in the control and PDI-30 treatment was significantly higher than the PDI-50 treatment; g_s in the control was significantly higher than in the PDI-50 treatment, while $WUE_{intrinsic}$ in the control was significantly lower than in the PDI-50 treatment. At site 5 in 2020, A_n and E and g_s in the control were significantly higher than in the PDI-30 treatment; there were no treatment differences in $WUE_{intrinsic}$. At site 5 in 2021, E and g_s in the control were significantly higher than in the PDI-30 and PDI-50 treatments; A_n in the control was significantly higher than in the PDI-50 treatment; and $WUE_{intrinsic}$ in the control was significantly lower than in the PDI-50 treatment.

Tree growth

The average TCSA range was 74.3–117.0 cm^2 at sites 1–4 in 2019, and 63.2–127.1 cm^2 in 2020 and 89.2–133.6 cm^2 in 2021 across sites 1–5 (Table 9). Average dry new wood pruning weight measured from winter pruning range was 0.13–1.65 kg at sites 1–5 after the second and third year of PDI application, and average leaf area range was 59.31–101.98 cm^2 (Table 9). Overall, irrigation treatment did not significantly affect any measured indicators of growth, including annual measures of TCSA during the dormant season, new wood pruning weight, or leaf area at all study sites (Table 10; Fig. 11). The interaction between treatment and site was significant for leaf area in 2020; however, no significant differences between the estimated marginal mean leaf area within each site were observed. Overall differences between measures of growth between sites can likely be attributed to differences in orchard age where sites 3 and 5 are the youngest, established in 2016/2017 and 2017, respectively, and sites 2 and 4 are the oldest, established in 2013/2014 and 2006, respectively.

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Fig. 8. Water-use efficiency ($WUE_{intrinsic}$) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of $n = 4 \pm$ the standard error (SE).

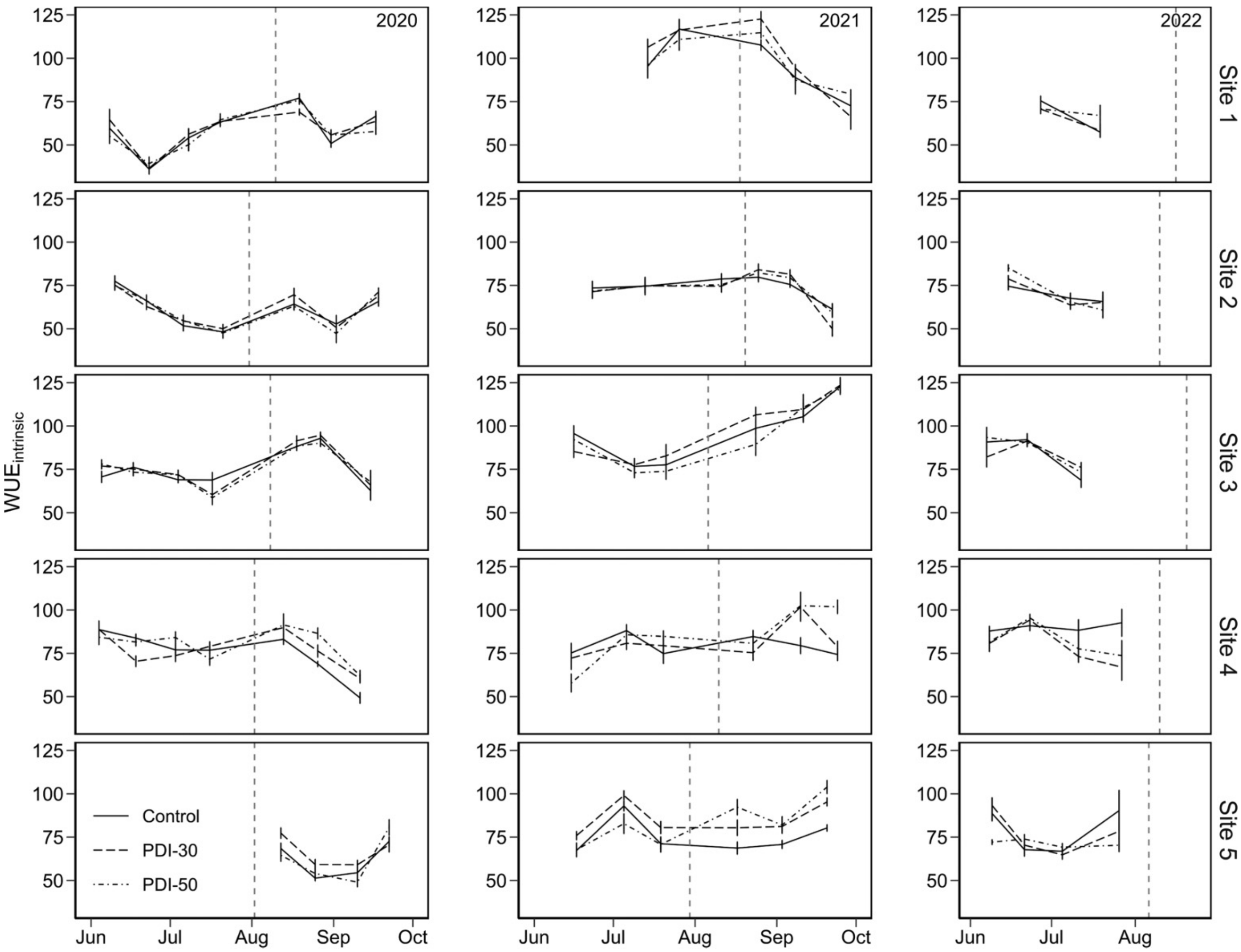

Table 8. LMM parameter coefficient and *p* values of ANOVAs based on models fit, with photosynthetic rate (A_n), transpiration rate (E), stomatal conductance (g_s), or water-use efficiency ($WUE_{intrinsic}$) as the response, Ψ_{stem} as a fixed effect, and Site, Year, and Date as nested random effects.

Response	ψ_{stem} coefficient sign	*p* value
A_n[a]	+	<0.0001
E[a]	+	<0.0001
g_s[a]	+	<0.0001
$WUE_{intrinsic}$	−	<0.0001

[a]These parameters were log transformed.

Discussion

Overall, the findings of this study supported the hypothesis that reducing the postharvest irrigation applied to "Sweetheart"/Mazzard trees would have no significant effect on Ψ_{stem}, A_n, E, or g_s in the season after PDI application, but during PDI application would result in more negative Ψ_{stem} values and reduced A_n, E, and g_s. The findings also support the hypothesis of increased water-use efficiency in response to PDI as greater water-use efficiency was observed during the third application of PDI in both PDI-30 and PDI-50 treatments. In contrast, no significant effect of PDI on any measured indicators of tree growth was noticed. This may be due to the deep and more extensive root system of Mazzard rootstock, which can make the trees less susceptible to drought stress (Hrotkó and Rozpara 2017).

Soil volumetric moisture content has been used as an indicator of soil water status in DI studies on peach, apricot, and sweet cherry orchards (Girona et al. 2005; Pérez-Sarmiento et al. 2016; Blanco et al. 2018). In the current study, lower soil moisture contents in the PDI treatments during the postharvest period at site 4 in 2019, and at sites 3 and 5 in 2021 and 2020 suggest that the reductions in applied irrigation were significant enough to reduce soil moisture at some sites. However, similar differences at site 5 were present during the preharvest period in 2020, when the DI was not yet imposed, and preharvest measurements were not obtained in 2019 to determine whether these differences were also present before DI

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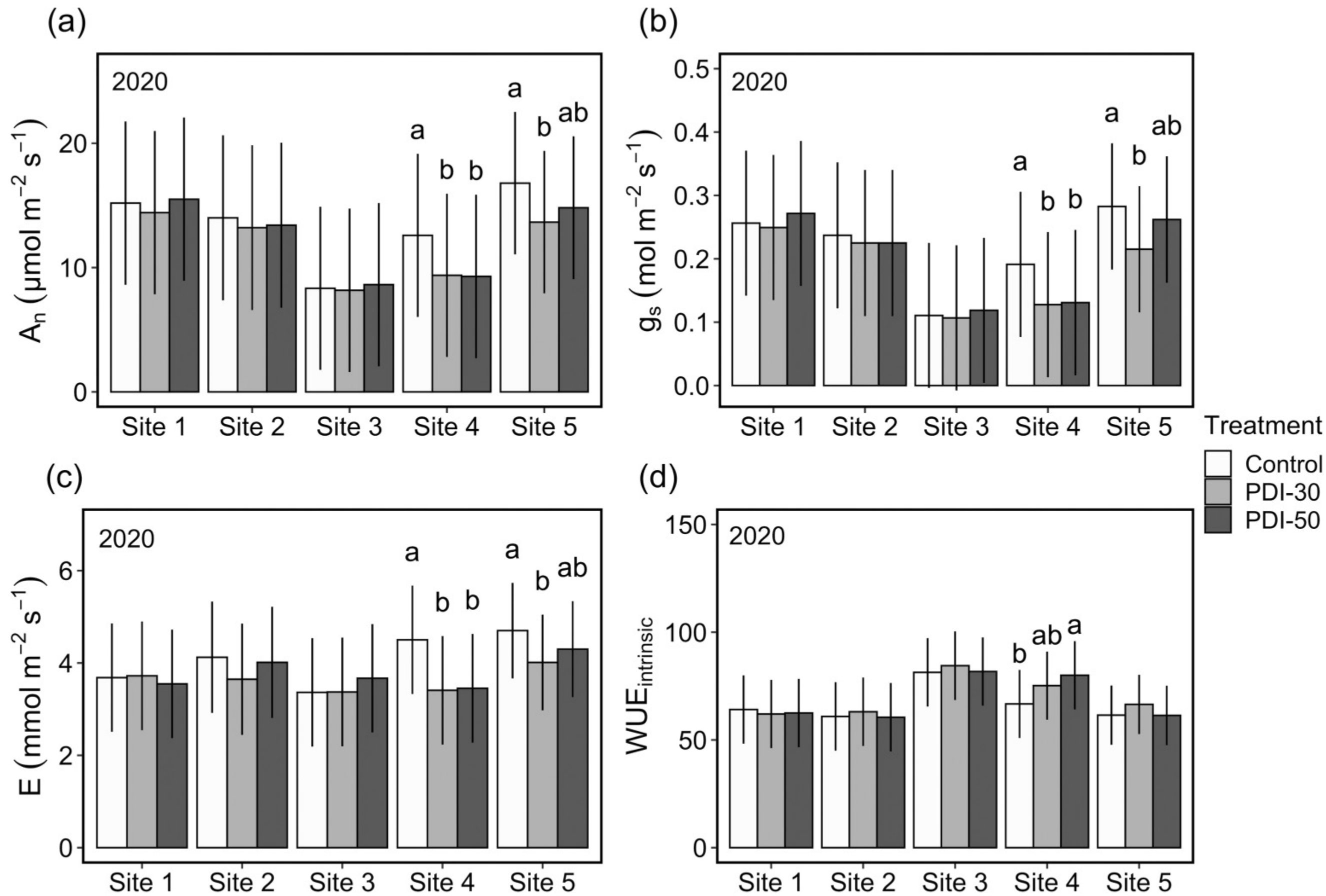
Fig. 9. Estimated marginal mean postharvest photosynthetic rate (A_n), stomatal conductance (g_s), transpiration rate (E), and water-use efficiency ($WUE_{intrinsic}$) in 2020 ((*a*) A_n, (*b*) g_s, (*c*) E, (*d*) $WUE_{intrinsic}$). Error bars indicate 95% confidence levels of estimated marginal means. Values within the same parameter and site that share the same letter or have no letters do not differ significantly ($p \leq 0.05$).



application. Therefore, it cannot be concluded that the reductions in soil moisture resulted from PDI application at site 4 in 2019 or whether the existence of preharvest soil moisture differences indicates that these differences may be instead an artifact of other factors such as soil moisture sensor location (e.g., differing proximity to microsprinklers) or soil textures in individual plots. Significant treatment differences in preharvest and postharvest Ψ_{stem} did not always correspond with the observed significant differences in average weekly soil moisture content. The differing results between sites are likely a factor of the variability between orchards including soil type, texture, organic matter content, depth, drainage, and water holding capacity; slope and aspect; temperature as well as precipitation (Waterman 2002). Additionally, these differences may also result from differences in growers' practice in terms of water application duration and frequency.

Stem water potential has been used as a reference water stress indicator in fruit trees and was used to evaluate PDI influence on plant water stress in the current study (McCutchan and Shackel 1992; Naor and Peres 2001; Remorini and Massai 2003; Dichio et al. 2004; Girona and Marsal 2006; Jones 2006). Significant decreases in Ψ_{stem} (suggesting greater water stress) were observed in the PDI treatments during their application at sites 4 and 5 in 2020 and 2021. Observed differences between treatments for Ψ_{stem} measurements at sites 4 and 5 may be explained, in part, by the fact that the applied water was much less than the calculated water requirements in August and September of 2020 and in August of 2021. The water use estimates suggest that the trees were already receiving less water than they required in the control during the postharvest period, so further reductions in irrigation likely led to the significant increase in plant water stress observed. Significant reductions in Ψ_{stem} in the PDI treatments were not observed at site 3 in 2020 or 2021. In 2020, this may have been a result of water application being more similar to water requirements in all treatments in August. In 2021, it is likely that no differences were observed as all treatments experienced high levels of water stress resulting from site 3 running out of irrigation water during the late summer. Based on measures of Ψ_{stem} and soil moisture content at sites 1 and 2, it is not clear whether the water reductions imposed resulted in true deficits at these orchards. Due to the lack of detailed irrigation records at sites 1 and 2 and the malfunctioning water meters, it was hard to make comparisons of the water applied in terms of estimated water requirements.

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Fig. 10. Estimated marginal mean postharvest photosynthetic rate (A_n), stomatal conductance (g_s), transpiration rate (E), and water-use efficiency ($WUE_{intrinsic}$) in 2021 ((*a*) A_n, (*b*) g_s, (*c*) E, (*d*) $WUE_{intrinsic}$). Error bars indicate 95% confidence levels of estimated marginal means. Values within the same parameter and site that share the same letter or have no letters do not differ significantly ($p \leq 0.05$).

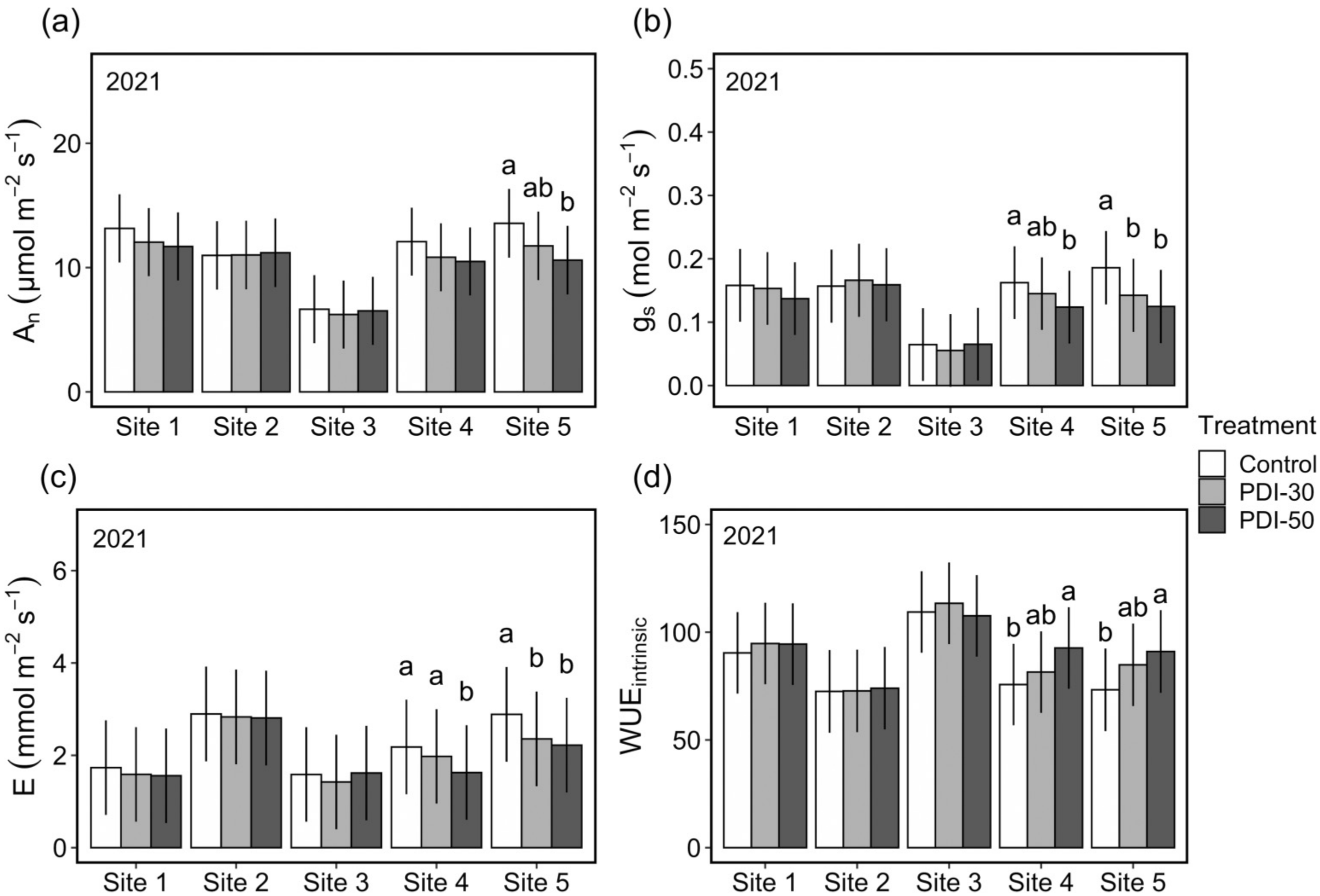

Table 9. Average measurements of tree growth (TCSA ($n = 72$), dry new wood pruning weight (n indicated in brackets), and leaf area ($n = 20$)) and standard error (SE) at all study sites.

	Average TCSA (cm^2)			Average dry new wood pruning weight (kg)		Average area per leaf (cm^2)	
Site	2019	2020	2021	2020–21	2021–22	2020	2021
1	74.3 ± 1.3	98.2 ± 1.6	105.2 ± 2.1	1.31 ± 0.11 (18)	1.27 ± 0.12 (18)	95.15 ± 2.03	72.43 ± 1.44
2	98.3 ± 3.4	118.0 ± 3.9	122.4 ± 4.0	0.13 ± 0.02 (18)	—	101.98 ± 1.63	68.99 ± 1.43
3	54.8 ± 1.0	75.3 ± 1.4	96.2 ± 1.7	0.31 ± 0.03 (9)	0.44 ± 0.03 (18)	76.99 ± 1.20	59.91 ± 1.37
4	117.0 ± 5.7	127.1 ± 6.0	133.6 ± 6.4	1.06 ± 0.20 (18)	0.76 ± 0.19 (17)	77.19 ± 1.71	59.31 ± 2.65
5	—	63.2 ± 2.1	89.1 ± 2.8	—	1.65 ± 0.23 (16)	—	80.11 ± 1.49
Mean	86.1 ± 2.2 (288)	96.4 ± 2.0 (360)	109.3 ± 1.9 (360)	0.70 ± 0.29 (63)	1.0 ± 0.27 (69)	87.82 ± 1.80 (320)	68.15 ± 1.27 (400)

When considering the heat stress induced by the heat dome experienced in 2021, the findings suggest that it did not lead to lasting effects on plant physiology. Stem water potential was not measured during the heat wave event; however, mean Ψ_{stem} measurements taken within 4–14 days of the extreme temperatures were all above −1.4 MPa, suggesting that there was no lasting damage to the vascular tissues in the trees resulting from these extreme temperatures. These findings are supported by Romero et al. (2004), who reported that almond trees (*Prunus dulcis*) recovered from severe water stress (−2.0 MPa) within 15 days. The lowest average values of Ψ_{stem} experienced at sites 1–5 were −1.4, −1.4, −1.9, −1.6, and −1.4 MPa, respectively. These values are close to −1.5 MPa, which has been proposed to indicate that the cherry tree is not suffering severe water stress and it has no long-term negative effects on tree vascular function (Marsal et al. 2009; Carrasco-Benavides et al. 2020). The deep and extensive root system of Mazzard rootstock may have reduced the

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Table 10. *p* values of ANOVAs based on LMMs of TCSA and new wood pruning weight (PW) and GLS models of leaf area (LA) with interacting Site and Treatment as fixed effects.

Response	Fixed effect	*p*
TCSA 2019	Trt	0.6830
R^2: 0.50	Site	**<0.0001**
	Trt × Site	0.4235
TCSA 2020	Trt	0.6859
R^2: 0.48	Site	**<0.0001**
	Trt × Site	0.2951
TCSA 2021	Trt	0.9412
R^2: 0.24	Site	**<0.0001**
	Trt × Site	0.3586
PW 2020–21	Trt	0.7322
R^2: 0.78	Site	**<0.0001**
	Trt × Site	0.8306
PW 2021–22	Trt	0.5040
R^2: 0.51	Site	**<0.0001**
	Trt × Site	0.1903
LA 2020	Trt	0.6578
	Site	**<0.0001**
	Trt × Site	**0.0236**
LA 2021	Trt	0.1193
	Site	**<0.0001**
	Trt × Site	0.5233

Note: TCSA and PW models included block as a random effect. *p* values in bold < 0.05. R^2, coefficients of determination of LMMs.

tree's susceptibility to water stress during this time (Hrotkó and Rozpara 2017). The overall lack of differences between Ψ_{stem} during PDI application at sites 1 and 2 and the lack of lasting differences in Ψ_{stem} between treatments in the season following deficit application suggest that although slightly lower Ψ_{stem} resulted from the PDI-30 and PDI-50 treatments at some sites, the water stress experienced was not extreme enough to affect the tree's ability to conduct water through its vascular system in the following growing season.

Few studies have looked at the effect of PDI on photosynthetic measurements in cherry orchards (Marsal et al. 2009; Blanco et al. 2018, 2019*b*). In the current study, significant reductions in A_n, E, and g_s were observed in the PDI treatments at sites 4 and 5 only. This agrees with the current findings of decreased Ψ_{stem} values in the PDI treatments at these sites. Overall, no lasting effect of PDI treatment was observed in the season following application. These results are supported by similar trends observed in the Ψ_{stem} measurements. Remarkably, the heat dome that occurred at the end of June 2021 did not appear to have any lasting effect on leaf gas exchange measurements (Figs. 5–8). Romero et al. (2004) found that the A_n and g_s of almond trees (*P. dulcis*) took approximately 30 days to recover from severe drought stress (<−2.0 MPa). As Ψ_{stem} and photosynthetic measurements were not taken during the heat dome, it is not possible to know the extent of the impact of the heat stress on plant water stress and photosynthesis during these unprecedented temperatures. $WUE_{intrinsic}$ was significantly higher in the PDI-50 treatment at site 4 in 2020, during the second application of PDI, and at sites 4 and 5 in 2021 during the third and final deficit applications. The increased water stress experienced at postharvest period in the PDI-50 treatment in 2020 and the compounding conditions of increased water stress experienced at postharvest period at sites 4 and 5 in 2021 as a result of PDI, and possibly the warmer conditions the trees were exposed to during this season, resulted in the trees using water more efficiently.

Ψ_{stem} had a significant effect on $A_{n,}$ E, $g_{s,}$ and $WUE_{intrinsic}$ throughout the season. Ψ_{stem} had a positive relationship with $A_{n,}$ E, and g_s. This is similar to results published by Blanco et al. (2018, 2019*b*) and Marsal et al. (2009). Blanco et al. (2018) found that A_n and g_s were positively correlated with Ψ_{stem}, indicating that as water stress decreases, the trees have their stomata open more and fix more carbon. Marsal et al. (2009) found similar results with A_n. No other studies were found that measured DI and leaf E in cherries; however, studies in almond (Romero et al. 2004) and peach (Guizani et al. 2019) have observed decreases in E with increasing water stress, consistent with results found in the current study. Additionally, Ψ_{stem} had a significant negative relationship with $WUE_{intrinsic}$. When cherry trees are water stressed, they reduce their stomatal aperture, and thereby transpiration rate, which increases their water-use efficiency (Taiz and Zeiger 2003). Similar findings in sweet cherry (Blanco et al. 2019*b*) and peach and plum (Razouk et al. 2013), where trees exposed to DI had higher WUE, have also been observed. Romero et al. (2004) also found that $WUE_{intrinsic}$ increased with increasing water stress, up to a Ψ_{stem} of −2.5 MPa in almond trees. In the current study, mean daily Ψ_{stem} values (by irrigation treatment) always remained above −1.9 MPa in 2020 and −2.0 MPa in 2021.

Water stress can reduce overall vegetative growth by inhibiting cell expansion and growth (Kozlowski and Pallardy 1997). However, the water reductions imposed in the PDI treatments had no significant effect on all indicators of tree growth (TCSA, new wood pruning weight, and leaf area) suggesting levels of water stress that inhibit cell expansion in sweet cherry were not reached. Many studies have found that PDI has a negative correlation with vegetative growth in other *Prunus* fruit trees such as peach, plum, and apricot (Intrigliolo and Castel 2010; Samperio et al. 2015*b*; Pérez-Sarmiento et al. 2016). Several studies have also been conducted on the effect of PDI on tree growth in sweet cherry (Nieto et al. 2017; Blanco et al. 2018, 2019*b*; Carrasco-Benavides et al. 2020; Gebretsadikan et al. 2022). The current results are comparable with findings by Gebretsadikan et al. (2022), who observed no significant effect of a PDI of 24%–28% volumetric water reductions on TCSA or leaf area at three Okanagan sweet cherry orchards. Additionally, further volumetric reductions of 27%–33% (PDI-30) and up to 47%–52% (PDI-50) also had no impact on these growth parameters. As well, in line with the TCSA results, Blanco et al. (2018) observed that sweet cherry irrigated with 100% crop evapotranspiration (ET_c) during the preharvest period and in the first 15–20 days of flower differentiation and with 55% ET_c during the postharvest period showed no significant differences in TCSA over 4 years. In contrast to the current findings, Blanco et al. (2019*b*) observed that this treatment significantly reduced pruning weight, canopy volume, shaded area, and shoot growth during the second year of the study. Carrasco-Benavides et al. (2020) observed that irrigation re-

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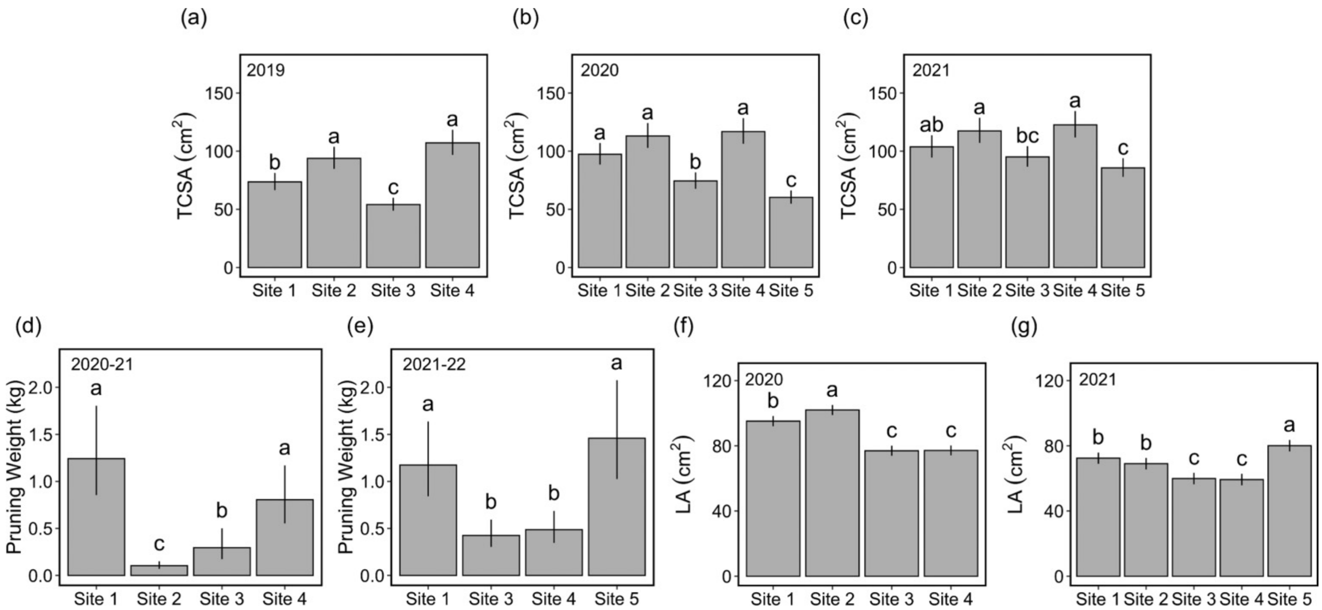
Fig. 11. Estimated marginal mean TCSA, pruning weight, and leaf area ((*a*) 2019 TCSA, (*b*) 2020 TCSA, (*c*) 2021 TCSA, (*d*) 2020–21 dry new wood winter pruning weight, (*e*) 2021–22 dry new wood winter pruning weight, (*f*) 2020 leaf area, (*g*) 2021 leaf area). No significant differences among irrigation treatments were found for all three indicators of growth. Values within the same parameter and year that share the same letter do not differ significantly ($p \leq 0.05$).



ductions of 50% resulted in significantly lower TCSA, which also contrasts with the results of the current study.

The current findings indicated that an opportunity exists to define a threshold level of Ψ_{stem} that may cause lasting damage to sweet cherry trees. Thresholds have been suggested in the literature between −1.3 and −1.6 MPa (Marsal et al. 2009; Livellara et al. 2011; Carrasco-Benavides et al. 2020); however, these studies were conducted in the Mediterranean and Chile regions and on different variety–rootstock combinations than the ones used in the current study. Results also indicated that postharvest Ψ_{stem} between approximately −0.5 and −1.3 MPa, and one-time mean Ψ_{stem} as low as −2.0 MPa postharvest, appeared to have no lasting effects on the future plant water status and photosynthesis measurements of "Sweetheart" sweet cherry on Mazzard rootstock. However, the effects of further increases in water reduction on Ψ_{stem}, leaf gas exchange measurements, and tree growth in "Sweetheart" sweet cherry grown in the Okanagan are still unknown.

Average estimated postharvest water savings of 519 000 L ha^{-1} year^{-1} by adopting PDI-30 and 838 000 L ha^{-1} year^{-1} by adopting PDI-50 were achieved through this study. These estimates were made from the calculations of irrigation application at sites 3–5 in 2020 and 2021. The patterns of water application as a percentage of water requirements suggest that growers could benefit from refining their irrigation scheduling. The estimates of the current study indicate that overall irrigation applications from April to June may be able to be reduced. During these months, sites 3–5 were often found to receive well over their water requirements. Water allocation could be redistributed and growers may benefit from increasing applications in July by irrigating with quantities that result in applications closer to the requirements. This is a critical time for rapid fruit cell expansion (Herrero et al. 2017), so applying quantities to maximize Ψ_{stem} and photosynthesis may be beneficial. Furthermore, no lasting effects from the PDI-30 or PDI-50 treatments were found highlighting the potential for further irrigation refinement during the postharvest period. Overall, further advances in water savings may be achieved by improving grower's irrigation practice to match better plant demand.

Conclusion

The application of PDI with reductions of 27%–33% and 47%–52% in the volume of water applied in five Okanagan sweet cherry orchards over 3 years had minimal effect on tree water status and photosynthesis during application and overall, no lasting effects in the seasons following application. Additionally, at sites where increased water stress was observed, trees responded with improved $\text{WUE}_{\text{intrinsic}}$ during PDI application by the final year of the study, while having no significant effect on tree growth. This study was completed over seasons with highly contrasting weather conditions (extreme temperatures and high levels of rain fall) giving insight to effects of PDI over a variety of conditions in the Okanagan Valley. Longer term studies evaluating the effects of postharvest reduction would contribute to our understanding of the compounding effect of water deficits over time as well as further variability resulting from seasonal differences. Additionally, the current study was conducted at orchard sites with a range of management practices, tree ages, and site conditions. As such, future research to be conducted in a more controlled setting to corroborate these findings may be beneficial. These

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findings support the use of PDI as an effective water saving technique for sweet cherry orchards in the Okanagan Valley of BC and provide insight on current irrigation practices of commercial cherry growers in this region. We estimated that some growers overirrigated their trees during the months of May and June and during the postharvest period. Growers at these sites may be able to reduce the volume of water applied postharvest by up to 50% without causing significant lasting increases in tree water stress or significantly impacting plant photosynthesis and tree growth. However, caution must be taken when generalizing these findings to different cultivar/rootstock combinations and to orchards with irrigation management practices that vary significantly from these studied sites. Overall, the results of this study have the potential to contribute to the improvement of sustainable irrigation management practices in the Okanagan Valley and other semi-arid tree fruit-producing regions.

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Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Competing interests

The authors declare that there are no competing interests.

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