CLIMATE CHANGE
ADAPTATION PROGRAM

Postharvest Deficit Irrigation for Improved Resilience of Cherry to Climate Change

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Executive Summary

Climate change is altering the spatial boundaries of suitable growing regions for sweet cherry in the Okanagan Valley of British Columbia as a result of warmer temperatures and prolonged growing seasons. Sweet cherry orchards are now being established both further north and at higher elevations than ever before seen in the Okanagan Valley. As the sweet cherry industry expands into more extreme growing sites, there is increasing concern for the availability of a sufficient supply of water for irrigation and concern over risks for flower bud cold damage from fall and early spring frosts and winter cold snaps.

To address the first concern, the use of postharvest deficit irrigation (PDI) was investigated as a technique to conserve water and improve water use efficiency in commercial cherry orchards. Previous studies in this region have reported no change in plant physiology or tree growth with postharvest irrigation volume reductions of up to 25 %. 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 three-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 overall effect on stem water potential or photosynthesis; there were also no effects of PDI treatment on tree growth. Additionally, PDI did not significantly influence the timing of flower bud phenological stages in the spring, flower bud cold hardiness or moisture in the fall, winter, or spring period, or fruit yield and quality.

Findings from this study suggest that postharvest stem water potentials from -0.5 MPa to -1.3 MPa, and one-time stem water potentials as low as -2.0 MPa, have no lasting effects on future plant function or crop production. A cost-benefit analysis of adopting PDI in Okanagan cherry orchards was also completed and findings revealed the costs of implementing PDI are minimal but bring benefits for the grower and society in conserving water. This research demonstrates that commercial cherry growers in the Okanagan Valley can likely reduce the volume of water applied after harvest. These findings will contribute to improving sustainable irrigation practices to help conserve water in this region while improving the cherry industry's resilience to climate change through a better understanding of plant postharvest water requirements.

To help address the second concern of the risk of flower bud cold damage in the Okanagan Valley, sweet cherry cold hardiness models were developed that estimate the temperatures that cause 10 %, 50 % and 90 % cold damage to 'Sweetheart' and 'Lapins' sweet cherry from the fall to spring season. Additionally, an open-access web application based on these models was developed for use by growers and extension workers as a frost management decision support tool. These models may help estimate production risk prior to the establishment of new orchards in more extreme growing sites in the Okanagan Valley and could be used to improve our understanding and modelling of changing sweet cherry crop site suitability under present and future predictions of climate change.

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1.0 Introduction

British Columbia accounts for 96 % of Canada's sweet cherry (*Prunus avium* L.) production and within this province, the Okanagan Valley (latitude 41˚ 22' to 50˚ 12' ˚N) is the main production area (BC Ministry of Agriculture, Food, and Fisheries 2020; Agriculture and Agri-Food Canada 2021). Climate change is altering the spatial boundaries of suitable growing regions for many fruit crops, including sweet cherries, in the southern interior of British Columbia as a result of warmer temperatures and longer growing seasons (Quamme and Neilsen 2012). The Okanagan basin was once considered the northern boundary for cherry production and commercial cultivation of this fruit crop was also limited to lower elevation regions (Neilsen et al. 2017). Today, sweet cherry orchards are being established further north and at higher elevations than ever seen before in this region.

As the sweet cherry industry expands into higher elevations and latitude in the semi-arid climate of the Okanagan Valley, concern for the availability of a sufficient supply of water for irrigation arises. There is also concern for an increased risk of flower bud damage from fall and early spring frosts, as well as mid-winter cold snaps at these more extreme growing locations, as these buds are the most vulnerable part of the plant to frost damage(Salazar-Gutiérrez et al. 2014). Furthermore, climate change predicts greater weather variability and extremes. Postharvest deficit irrigation (PDI) is a method that can be implemented to address the concerns for sufficient irrigation water by reducing the water demands of stone fruit crop production (Pérez-Pastor et al. 2007; Marsal et al. 2009, 2010; Samperio et al. 2015a, 2015b; Pérez-Sarmiento et al. 2016; Gebretsadikan et al. 2022). For fruiting trees, certain developmental stages, such as the non-fruit bearing stage postharvest, may be less sensitive to water stress, making the postharvest period an ideal time to apply deficit irrigation (Fereres and Soriano 2007). Additionally, perennial crops, such as sweet cherry, are a good candidate for deficit irrigation (DI) regimes when compared to annual crops as they generally have more extensive root systems at a greater depth for water uptake (Goldhamer et al. 1999; Girona et al. 2005).

Although PDI has the potential to reduce the water demands of cherry production in the Okanagan Valley, the upper limit of PDI that can be applied without adversely impacting cherry tree phenology, cold hardiness and fruit yield and quality is not yet well understood. A study completed over a two-year period in the Okanagan Valley found that a 25 % reduction in postharvest watering in three sweet cherry orchards allowed for reduced water use without compromising fruit yield or quality (Gebretsadikan et al. 2022). Similar studies on sweet cherry crops in Spain (Marsal et al. 2009, 2010) and other stone fruit crops in the Mediterranean (Pérez-Pastor et al. 2007; Samperio et al. 2015b; Pérez-Sarmiento et al. 2016) demonstrated that postharvest deficits of up to 50 % do not affect the following year's fruit yield or quality. Limited research on the influence of PDI on spring phenology in *Prunus* has been completed but it has been observed that PDI regimes in the range of 30-60 % crop evapotranspiration (ET_c) do not significantly influence spring flower development (Samperio et al. 2015b; Blanco et al. 2020). To the authors' knowledge, no known studies on the influence of PDI on sweet cherry cold hardiness have been published to date.

This project consisted of three main objectives and built on earlier work by Gebretsadikan et al. (2022):

Objective 1: Investigate the overall effects of PDI with volumetric irrigation reductions of approximately 30 % and 50 %, compared to a control of full irrigation at conventional growers' practice, on 'Sweetheart' sweet cherry at five commercial Okanagan cherry orchards.

Objective 2: Complete a cost-benefit analysis (CBA) to determine what the costs and benefits of adopting PDI are in Okanagan cherry orchards.

Objective 3: Develop sweet cherry cold hardiness predictive models for the cultivars 'Sweetheart' and 'Lapins' applicable in the Okanagan Valley and an open-access web application for access to real-time model predictions that can be used as a frost management decision support tool.

The project objectives aim to contribute to the development of more sustainable irrigation management practices in sweet cherry production in the Okanagan Valley. Furthermore, this research will help improve the resilience of sweet cherry to climate change by both expanding our understanding of sweet cherry water requirements through the study of the effects of PDI on commercial sweet cherry orchards and improving our understanding of plant cold hardiness throughout the dormant season.

2.0 Research Methods

2.1 Objective I

Methods and results from Objective I can also be found in Houghton et al. (2023a), Houghton et al. (2023b), and Bevandick (2022).

Experimental sites

This research was conducted in five sweet cherry orchards established across a latitudinal and elevational gradient in the Okanagan Valley, BC (Fig. 1). It focussed on the sweet cherry cultivar ‘Sweetheart’ grafted on Mazzard rootstock. A more detailed description of each site and the site’s soil properties is provided in Table 1 and Table 2.

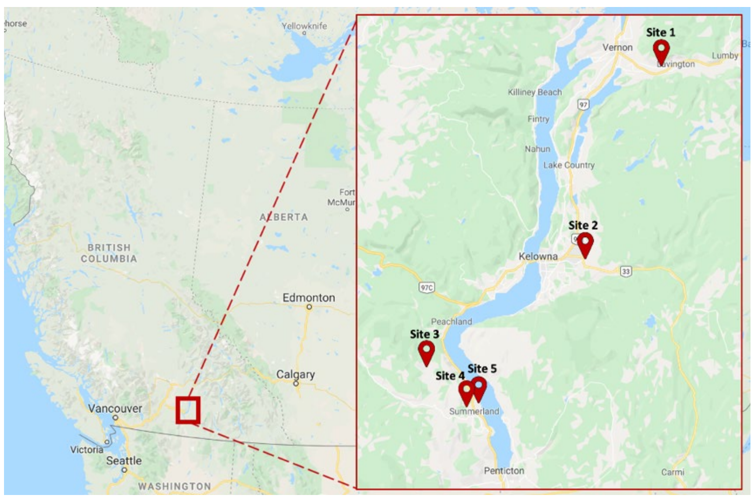


Figure 1. Map displaying the experimental site locations within the Okanagan Valley, BC

Table 1. Detailed description of experimental sites location and age

Site	Coordinates	Location	Elevation (m amsl)	Year Planted
1	50˚14’09”N 119˚08’16”W	Coldstream, BC	617	2015
2	49˚52’51”N 119˚22’02”W	Kelowna, BC	507	2013/2014
3	49˚41’31”N 119˚48’15”W	Meadow Valley, BC	755	2016/2017
4	49˚36’47”N 119˚41’44”W	Summerland, BC	510	2006
5	49˚37’32”N 119˚40’16”W	Summerland, BC	415	2017

Table 2. Site soil texture, organic matter, CEC, pH from control plots

Site	Sand (%)	Silt (%)	Clay (%)	Texture Classification	Organic Matter (% LOI)	CEC (cmol+/kg)	pH
1	48	38	14	Loam	10	41	6
2	60	30	10	Sandy Loam	2.7	11	5.5
3	53	34	13	Sandy Loam	3.2	17	6.9
4	57	33	10	Sandy Loam	5.3	26	7.2
5	6.9	75	18	Silt	2.2	22	7.8

Experimental design and treatments

At each of the five experimental sites, three different irrigation treatments were applied, including a control, with full irrigation at 100 % of growers' practice, and an approximately 30 % reduction (PDI-30) and 50 % reduction (PDI-50) in postharvest irrigation relative to growers' practice. The irrigation treatments were applied to randomized plots of four measurement trees surrounded by guard trees (Fig. 2). Six plots of each irrigation treatment were installed at each site for a total of 24 measurement trees per treatment at each site.

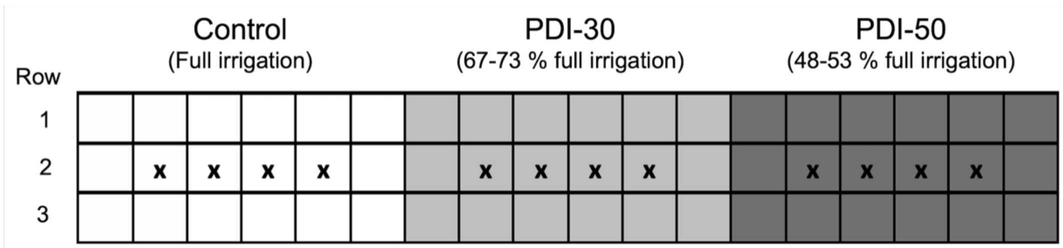


Figure 2. Example experimental layout showing layout of one replicate of guard trees and measurement trees (**x**), each represented by one cell

Postharvest deficit irrigation was started after fruit harvest in 2019 at Sites 1-4 and after harvest in 2020 and 2021 at Sites 1-5 (Table 3). The deficits were applied by replacing the microsprinkler emitters with ones that applied altered flow rates and by reducing emitter frequency using waterproof tape where needed. Flow rates used to impose PDI as well as irrigation set up for each study site and treatment are outlined in Table 4. A more detailed description of irrigation scheduling at each site can be found in Houghton et al. (2023a).

Table 3. Commercial harvest dates and dates of PDI application each year.

Site	2019	2020		2021		2022
	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 4. Microsprinkler flow rates and irrigation set up at each study site

Site	Flow Rate (l/h)			Irrigation		
	Control	25% PDI	50% PDI	Drip	Microsprinkler	Microsprinkler Brand
1	39.75	29.15	21.20	x	x	Maxijet
2	39.75	29.15	21.20		x	Maxijet
3	105	70	50	x	x	Aquamaster2005
4	105	70	50		x	Aquamaster2005
5	105	70	50		x	Aquamaster2005

Meteorological data and soil moisture

A HOBO® data logger (Onset®, Bourne, MA, USA) installed at a height of 1.3 m above the ground in site 1, 3-5 and within 1 km of site 2, was used to record hourly ambient air temperatures. If HOBO® failure occurred, temperature data from nearby weather stations was accessed from the Government of Canada's online historical weather and climate database. Daily precipitation measurements were also obtained from this database: https://climate.weather.gc.ca (Government of Canada 2021a). Soil moisture and temperature probes (5TE or TEROS 12, Decagon Devices, Pullman, WA) were installed in three of the six treatment replicates for all treatments at all sites. They were installed 30 cm from the middle of the fertilizer strip centered between measurement trees at a depth of 30 cm. At sites with microsprinklers between every other tree, sensors were placed between the trees without the microsprinkler. ZL6 (Decagon Devices, Pullman, WA, USA) automated data loggers recorded hourly probe measurements at each site.

Plant measurements

Stem water potential (Ψ_{stem})

Stem Water Potential (Ψ_{stem}) was used as an indicator of plant water status. Stem water potential was measured at midday using a Scholander Pressure Chamber (Model 3005: Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Stem water potential measurements were conducted approximately every two weeks from June – September in 2020 and 2021. On each sampling day, for each treatment, four of the six replicates were randomly selected for measurements. Within each of the four replicates, two leaves per tree were measured from two trees, for a total of 16 leaves sampled per treatment. Each of the leaves measured was wrapped in black plastic and tinfoil for 1 h and was located on the shaded side of the tree.

Photosynthesis and water use efficiency

Net photosynthesis (A_n), transpiration rate (E), and stomatal conductance (g_s) measurements were taken every two weeks around midday on the same days and trees that were used for measurement of Ψ_{stem} using a LCi T Photosynthesis Meter (ADC BioScientitic Ltd., Hoddesdon, Herts, UK). The photosynthesis meter was fitted with a white light unit. In 2020, the white light unit was set to deliver 1500 µmol m^{-2} s^{-1}. The amount of light actually delivered to the leaf surface was 1380 µmol m^{-2} s^{-1}. In 2021, the white light unit was set to deliver 1300 µmol m^{-2} s^{-1} (actual light delivered = 1131 µmol m^{-2} s^{-1}). Water use efficiency ($WUE_{intrinsic}$) was calculated as A_n/g_s (Pascual et al. 2013).

Tree growth

Plant vigor was assessed by measuring tree trunk cross sectional area (TCSA), new wood pruning weight, and leaf area. Annual measurements of tree diameter, measured once parallel and once perpendicular to the fertilizer strip, were taken in October each year using digital calipers (Absolute AOS Digimatic, Mitutoyo Corporation, Kawasaki, Japan) at a permanently marked height of 30 cm above the graft union. TCSA was measured in October 2019 at Sites 1-4 and October 2020 and 2021 at Sites 1-5.

The pruning weight of wood two years or younger (new wood) was measured when trees were trimmed according to industry standard in the second and third season of this study (2020-21 and 2021-22). One tree from each plot at each site was randomly selected and the fresh weight of the new wood was recorded. Following methods by Samperio et al. (2015a), subsamples of the new wood clippings from each PDI treatment were weighed, dried at 65 ˚C for 72 h (Heratherm™ OMH180, Thermo Scientific™, Cleveland, OH, USA) and reweighed to determine the dry weight. The total dry new wood pruning weight was calculated by applying the ratio of dry to fresh weight (measured on the subsample) to the total fresh weight of pruned new wood.

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).

Flower bud spring phenology

During the spring of each study year, flower bud developmental stages were determined weekly or biweekly from side-green to petal fall. One tree from each plot was randomly selected and the percentage of the entire tree in each growth stage was determined by visual inspection (Fig. 3). Spring phenological stage, expressed as an index between 0 (no flower buds at side green or beyond) and 1 (all flower buds at full bloom or beyond), was calculated for each tree on every measurement date. This index was calculated for selected trees by multiplying the proportion of flower buds at each developmental stage by a value between 1/7 and 7/7: side green (1/7), green tip (2/7), tight cluster (3/7), open cluster (4/7), first white (5/7), first bloom (6/7), full bloom or later (7/7), and then determining the sum of all seven values. The same tree was observed on each measurement date. Phenology was tracked at site 4 in 2020 and at all sites in 2021 and 2022.

Figure 3. Sweet cherry developmental stages (A) side green, (B) green tip, (C) tight cluster, (D) open cluster, (E) first white, (F) first bloom, (G) full bloom, (H) petal fall

Flower bud cold hardiness, moisture, and in-field cold damage

One flower bud spur from each measurement tree, for a total of 24 spurs per treatment, was collected weekly from each study site in the fall, beginning around October, and every other week during the winter months. Flower buds were also collected weekly in the spring of 2021. Buds were placed in a sealed plastic bag with a moist paper towel and transported to Agriculture and Agri-Food Canada's Summerland Research and Development Centre (AAFC SuRDC) in a cooler on ice. Cold hardiness was measured using differential thermal analysis (DTA) in the fall and winter months and controlled freezing tests in the spring.

To complete DTA, flower buds were excised from the spurs just below the bud base using a scalpel and placed on thermocouple plates with six buds per plate for each treatment (48 buds in total). The plates were placed in a Tenney Freezer Unit programmable freezer (Thermal Product Solutions, New Columbia, PA, USA) with an initial temperature of 3 ˚C, and subjected to artificial hardening at a rate of -4 ˚C h^{-1} for 9 h down to -36 ˚C. The peak identification software Bud Processor (v.1.8.0, Brock University, St. Catherines, ON, CA) was used to identify the temperature at which the LTEs occur.

To complete controlled freezing tests in the spring, methods modified from Salazar-Gutiérrez et al. (2014) were used on flower buds that were collected and prepared following the same methods as were used prior to DTA. Subsamples of 10 excised buds from each treatment were placed in sealed plastic bags and put in a programmable freezer initially cooled to 1 ˚C. One reference bud with a thermocouple inserted into the bud was placed in the freezer to be used as a reference temperature. The freezer temperature was lowered by 1 ˚C every 15 min, and one bag of buds for each treatment was removed once the reference bud had reached the target temperature. Target temperatures were selected based on the lethal temperatures measured during the previous week's lethal temperature analysis and aimed to capture the range of temperatures over which buds experience 0 % to 100 % damage. Buds were then refrigerated overnight and held at room temperature for at least two hours before being cut open longitudinally to visually assess cold damage, indicated by browning tissue.

One additional bud spur from one measurement tree per block was collected (6 spurs from each treatment at each site) on the same schedule as the cold hardiness measurements. One flower bud from each spur was excised at the base of the bud, just below the scales, and the collective fresh weight of the 6 buds was immediately measured. The buds were then dried in an oven at 65 ˚C for 72 h and reweighed to determine dry weight. The moisture content was calculated by dividing the difference in the dry and fresh weight by the dry weight.

In-field flower bud damage was evaluated if the recorded daily temperature approached or fell below the measured lethal temperature value. To determine damage, a subsample of 50 of the remaining flower buds from the spurs collected for cold hardiness measurements was assessed by cutting them open longitudinally and recording the number of buds and individual primordia that were damaged, indicated by browning tissue.

Fruit yield and quality

Yield assessments were conducted on the day of commercial harvest. All of the cherries from one tree from each of the plots were harvested and weighed. Yield (kg ha^{-1}) was calculated from the mean weight harvested from each tree/treatment, and the tree spacing

Fruit quality was assessed from 300 cherries sampled from each plot in 2020 and 2021 and 100 cherries in 2022. The fruit was collected from the top, bottom, and all sides of the four central trees one day before commercial harvest. In all years, one hundred cherries were assessed immediately after harvest. In 2020 and 2021, an additional 100 were stored for 6 weeks under commercial storage conditions prior to assessment. The remaining 100 cherries were stored for 6 weeks under commercial storage and then subjected to "shelf conditions" of 20 ˚C, for 5 days prior to reassessment. The cherries were assessed for the following quality parameters: fruit firmness (FF), size, weight, colour, stem pull force (SPF), soluble solids concentration (SSC), and titratable acidity (TA).

In 2020 and 2021, fruit firmness was first measured on 100 fruit $plot^{-1}$ using a FirmTechII (Bioworks, Stillwater, OK, USA) pressure tester. The FirmTechII pressure tester also records the row size of each fruit. In 2022, fruit firmness was measured using a hand-held durometer (type OO, Shore Instrument, Jamaica, NY, USA) which measured firmness on the Shore OO hardness scale; row size was measured manually using a cherry row size chart (row sizes 8-12) in 2022. All other fruit quality measurements were conducted using the same techniques in all years. Colour was assessed on 100 fruits $plot^{-1}$ using a Centre Technique Interprofessionnel des Fruits et Légumes (CTIFL) Colour Chart. The cherries were given a rating of one to seven based on this chart. Stem pull force (kg) was measured on 25 un-split cherries $plot^{-1}$, using a Dart FGV-5X (Nidec-Shimpo America Corporation, Itasca, IL, USA) digital force gauge. To measure SSC, juice was extracted by breaking the skin of 25 un-split cherries $plot^{-1}$ and placing the juice of each cherry onto the lens of a handheld digital refractometer (Model PR-101; AD Scientific Instruments, Keene, NM, USA). Titratable acidity (TA) was measured by completing a titration on the juice of 25 un-split cherries $plot^{-1}$ to an end point of 8.2, using the methods by Garner et al. (2020).

Statistical analysis

Soil moisture

Generalized least squares (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.

Stem water potential, photosynthesis, and water use efficiency

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). 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. Hierarchical 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.

Tree growth

LMMs were fitted with TCSA and new wood winter pruning weight as response variables, and Treatment×Site 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.

Flower bud spring phenology

Logistic regression was completed on the weighted spring phenology (0-1) of each measured tree measured over time using generalized linear models (GLM). The Julian day on which the inflection points of the logistic curves occurred (assumed to be at a probability of 0.5) was calculated using the model coefficients. To determine the effect of irrigation treatment on spring phenology, linear mixed effects models (LMMs) were then fitted with the Julian day on which the weighted spring phenology logistic inflection point occurred as the response variable and Treatment (for 2020) or Treatment×Site (for 2021 and 2022) as fixed effects and Block as a random effect for each year separately. Data were analyzed using mixed effects models as they are an appropriate choice for data with nested designs (Yang 2010; Harrison et al. 2018). This statistical approach was taken following modified methods by Guak et al. (2005) so an analysis considering the overall progression through flower bud phenological stages could be made.

Flower bud cold hardiness and moisture

For flower bud cold hardiness, the median LTE was calculated as the temperature that caused 50 % flower bud damage (LT_{50}) when DTA was used. Sampling dates with less than ten LTEs were omitted. When controlled freezing tests were completed, the proportion of new bud damage was assumed to be binomially distributed and modelled using a logit link (Zuur et al. 2009). Parameter estimates from these models were used to calculate the LT_{50} for each sampling date (at a probability of 0.5). LT_{50} and whole flower bud moisture measurements from each site were separated by season: fall (Sep. 1 – Dec. 1), winter (Dec. 2 – Mar. 5), and spring (Mar. 6- Apr. 30). Dates for each season were chosen based on approximate dates of observed acclimation in the fall and deacclimation in the spring. We modeled each season (fall, winter, or spring) and period (2019-20, 2020-21, 2021-22) separately using generalized least squares (GLS) models (Ugrinowitsch et al. 2004) with Treatment×Site as fixed effects. ANOVA tests were then performed on these models. GLS models were only fitted for a season and period if there were at least three LT_{50} or bud moisture measurements site^{-1}. Linear regression was also completed with the average LT_{50} and flower bud moisture content measured on each date at all sites.

Fruit yield and quality

Fruit yield was analyzed using LMMs with Treatment×Site as fixed effects and Block as a random effect. All fruit quality parameters (FF, size, colour, SPF, and SSC:TA) measured at harvest were analyzed in 2020, 2021, and 2022 separately using LMMs fitted with Treatment×Site as fixed effects and Block as a random effect. All fruit quality parameters measured at harvest, after storage, and after shelf-life conditions (storage type) in 2020 and 2021 were also analyzed by site separately using LMMs with Storage Type×Treatment as fixed effects and Block as a random effect. GLS models without the random effect of Block were used if the inclusion of Block resulted in an overfit model, as indicated by a singular fit (Bates et al. 2022).

Gaussian model assumptions of normality and homoscedasticity were validated and analysis of variance using the *lmerTest* package (Kuznetsova et al. 2017) or *nmle* package (Pinheiro et al. 2020) were completed. 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 (ML). Tukey-adjusted pairwise comparisons between treatments and sites were completed on the estimated marginal means (EMM) 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. Statistical analyses were performed using the "lmer4" (Bates et al. 2015), "lmerTest" (Kuznetsova et al. 2017), "nlme" (Pinheiro et al. 2020) and "emmeans" (v1.5.4, Lenth et al. 2022) package in RStudio v1.3.1093 (R Core Team 2020). P values of ≤ 0.05 were considered significant.

2.2 Objective II

To perform the cost-benefit analysis (CBA), the principles laid out by (Boardman et al. 2018) were followed. More detailed information on the CBA methodology can be found in Bevandick (2022). This methodology includes the following ten steps:

1. Explain the purpose of the CBA
2. Specify the set of alternative projects
3. Decide whose benefits and costs count
4. Identify the impacts categories, catalogue them, and select measurement indicators.
5. Predict the impacts quantitatively over the life of the project.
6. Monetize all impacts

7. Discount benefits and costs to obtain present values
8. Compute the net present value of each alternative
9. Perform sensitivity analysis
10. Make a recommendation

2.3 Objective III

Data acquisition

To develop and validate sweet cherry flower bud predictive models, historic measures of flower bud lethal temperature (LT) measured from orchards at AAFC SuRDC for the cultivar 'Sweetheart' (2013-17) and 'Lapins' (2013-17) as well as the cold hardiness data collected in Objective II at sites 3, 4, and 5 were used. Additionally, the LT of the cultivars 'Staccato' (2015-16), 'Sonata' (2015-16), and 'Skeena' (2015-16) measured from orchards at AAFC SuRDC was determined for cultivar comparisons.

Weather data

Weather data used in this study for plant material collected from AAFC SuRDC were obtained from the Government of Canada's online historical weather and climate database (Government of Canada 2021a). Hourly records of air temperature from the nearest weather station to the collected flower buds, located at AAFC SuRDC were used. For plant material collected from the high, mid-, and low elevation orchards in Summerland, BC, under Objective I, the HOBO® data logger hourly air temperature records were used.

Flower bud cold hardiness

To collect flower bud material and conduct cold hardiness measurements, the methods outlined in Objective I were used.

Statistical procedure

All statistical analyses were performed using RStudio (v1.3.1093; R Core Team 2020). When cold hardiness was measured using DTA, the 90th percentile, median, and 10th percentile of the identified LTEs were calculated as the lethal temperatures that damaged 10 %, 50 %, and 90 % of the buds (LT10, LT50, LT90), respectively. When lethal temperature was measured using controlled freezing tests, the proportion of new bud damage was assumed to be binomially distributed and was modelled using a logit link (Zuur et al. 2009) to determine the LT10, LT50, and LT90 values for each sampling date. Chill and heat accumulation (referred to here as forcing) were included as potential parameters for these LT models and chill unit (CU) and forcing unit (FU) accumulation were calculated using the 'Sweetheart' specific chilling and forcing equations developed by Neilsen et al. (2015).

Model selection and calibration

Six seasons of LT data were used to develop separate LT10, LT50, and LT90 models for 'Sweetheart' (four seasons of data collected from AAFC SuRDC [2013-2017] and two seasons collected from the mid-elevation orchard in Summerland, BC [2019-2020, 2021-2022]). Three seasons of LT data were used to develop separate LT10, LT50, and LT90 models for 'Lapins' (all data collected from AAFC SuRDC [2013-2015, 2016-2017]). Model development was separated into two stages for each cultivar and LT (10 %, 50 %, 90 %). Separate models were developed to estimate LT when the accumulated FU was less than 30 (T1) or greater than 30 (T2) for 'Sweetheart' and when accumulated FU was less than 25 (T1) or greater than 25 (T2) for 'Lapins'.

The predictor variables used for the lethal temperatures during T1 included daily mean air temperature from one, two, and three days prior, accumulated CU and log transformed accumulated FU. The predictor variables for T2 lethal temperatures included accumulated FU and bud stage (ranging from side green to first bloom).

The initial full models including all variables were fitted using generalized least squares technique (GLS) models and maximum likelihood (ML). Akaike's information criterion corrected for small sample sizes (AICc) was then used to determine the parameters that improved model fit and best explain the observed LT values.

Model evaluation and validation

The results of the best fit models for both T1 and T2 for each LT and cultivar were evaluated by the root mean square error (RMSE) (Janssen and Heuberger 1995), the Index of agreement (d) (Willmott 1981; Yang et al. 2014) , and through one-to-one regressions of the models' predicted values and the observed values.

To validate the final models, predictions were made and compared to additional seasons of LT data not included in model development. Additionally, model comparisons to LT data collected for the cultivar 'Staccato', 'Sonata', and 'Skeena' were made.

Interactive web application

Using the package Shiny (v1.6.0; Chang et al. 2021) in RStudio, an interactive web application was developed to allow for simplified and open access to the outputs of these models with the option for model application in real-time.

3.0 Results

3.1 Objective I

For this section, tables relating to statistical analysis and certain plant and fruit measurement values have been included in Appendix A.

Climate and soil moisture

Precipitation and temperature varied greatly over the postharvest period in 2019, 2020 and 2021 (Table 5 & Table 6). In 2019, higher levels of precipitation fell in August and September and in 2020 and 2021, more seasonal precipitation fell over the same period (Table 2). Similar monthly mean temperatures in the late summers (June to September) were experienced at all sites (Table 6). In 2021, an extreme temperature event referred to as a 'heat dome' occurred in western North America and abnormally high daily temperatures (40.6–44.5 ˚C) were experienced at all study sites at the end of June (Government of Canada 2021b). As a result of this temperature event, the commercial growers increased irrigation frequency at all study sites to mitigate heat stress during this period.

Table 5. Estimated June to September precipitation (mm) in 2019, 2020 and 2021 and June to August in 2022 at sites 1, 2, 4 and 5. Data are taken from Environment Canada weather stations (Government of Canada 2021a). Site specific precipitation data were not available for site 3 but this orchard is located closest to sites 4 and 5.

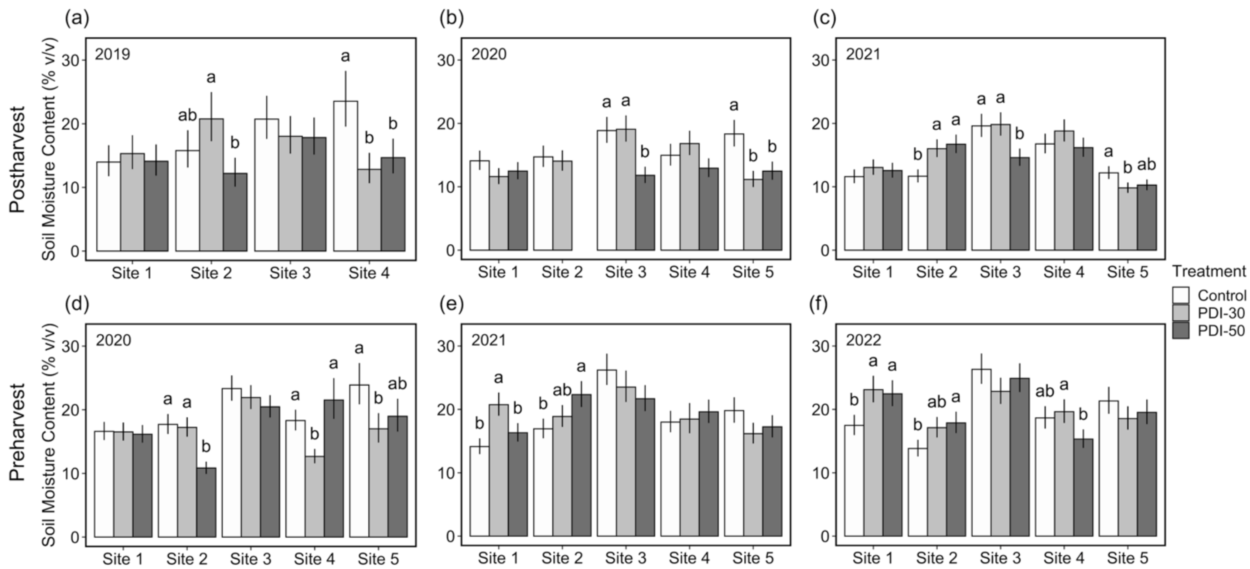
	Total Precipitation (mm)		
Year	Site 1	Site 2	Site 4 and 5
2019			
June	40	25	25
July	53	36	39
Aug	19	15	37
Sept	48	41	85
2020			
June	72	57	62
July	16	22	12
Aug	13	12	17
Sept	9	9	9
2021			
June	18	10	14
July	0	1	6
Aug	27	27	16
Sept	22	24	11
2022			
June	92	73	58
July	51	14	6
Aug	2	4	7

Table 6. Average monthly temperatures at each study site with extreme heat dome temperatures bolded. 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 95 m a.s.l. lower for comparison.

Year	Site 1		Site 2		Site 3		Site 4		Site 5	
	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

Soil moisture was measured at sites 1-4 in the postharvest in 2019, and at sites 1-5 preharvest and postharvest in 2020 and 2021 and preharvest in 2022. Average weekly postharvest soil moisture ranged from 13– 21 %, 12– 19 %, 10–27 %, 14–20 %, and 10–16 % at sites 1 to 5, respectively. Significantly lower mean weekly soil moistures 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 (Appendix A Table A1, Fig. 4). However, significant treatment differences were also observed in the preharvest period, when irrigation deficits had not yet been applied, at sites 2, 4 and 5 in 2020, sites 1 and 2 in 2021, and sites 1, 2, and 4 in 2022. These findings indicated soil moisture content variability that could not be attributed to the PDI 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.

Figure 4. 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.

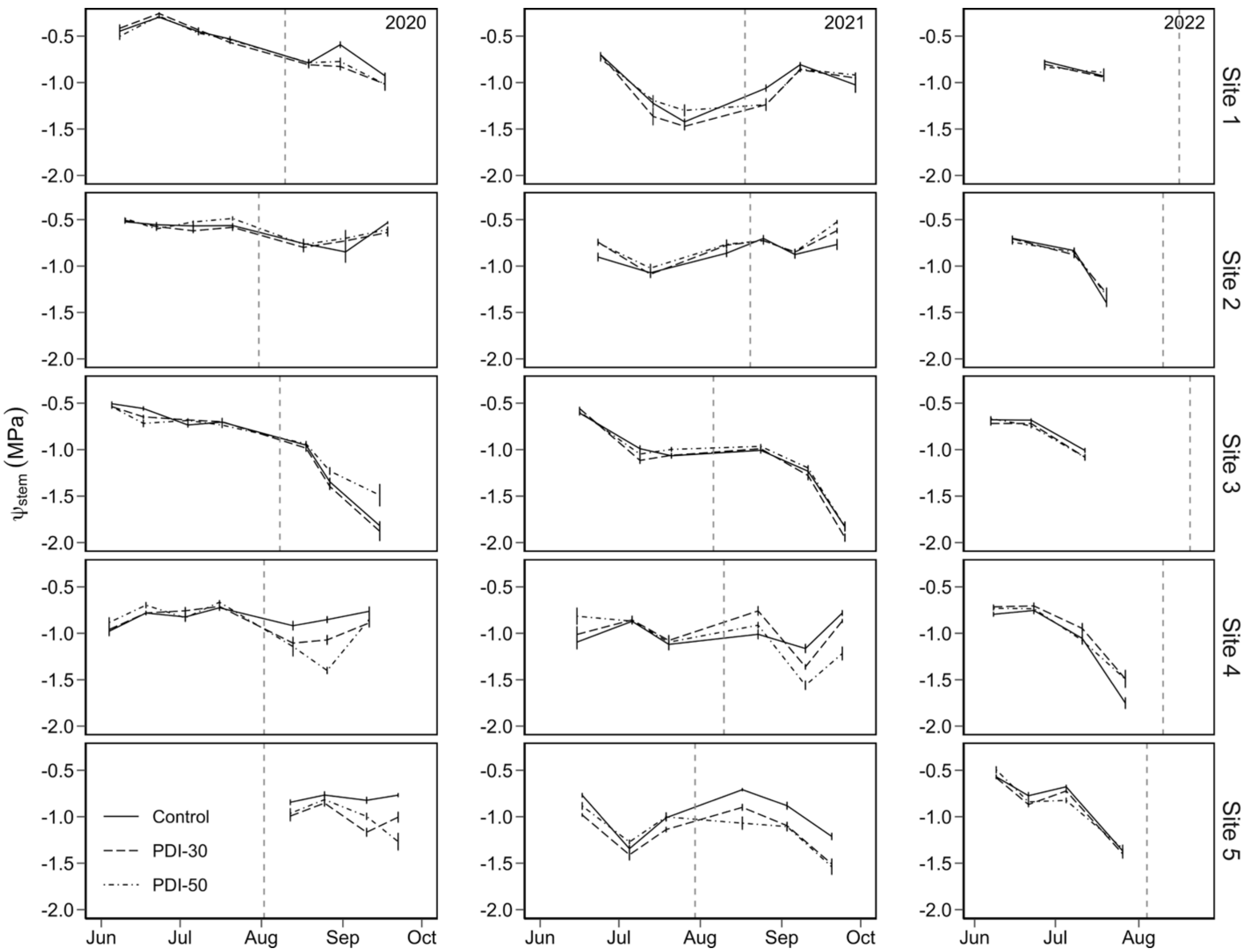


Stem water potential

The Ψ_{stem} of cherry trees, measured as an indicator of water stress, was measured preharvest and postharvest in 2020 and 2021 and preharvest in 2022 at all study sites (Fig. 5). More negative Ψ_{stem} values indicate an increase in water stress. Average Ψ_{stem} measurements across sites and years ranged from -0.3 MPa to -1.8 MPa preharvest and from -0.5 MPa to -2.0 MPa postharvest. Higher Ψ_{stem} values typically occurred in mid to 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.

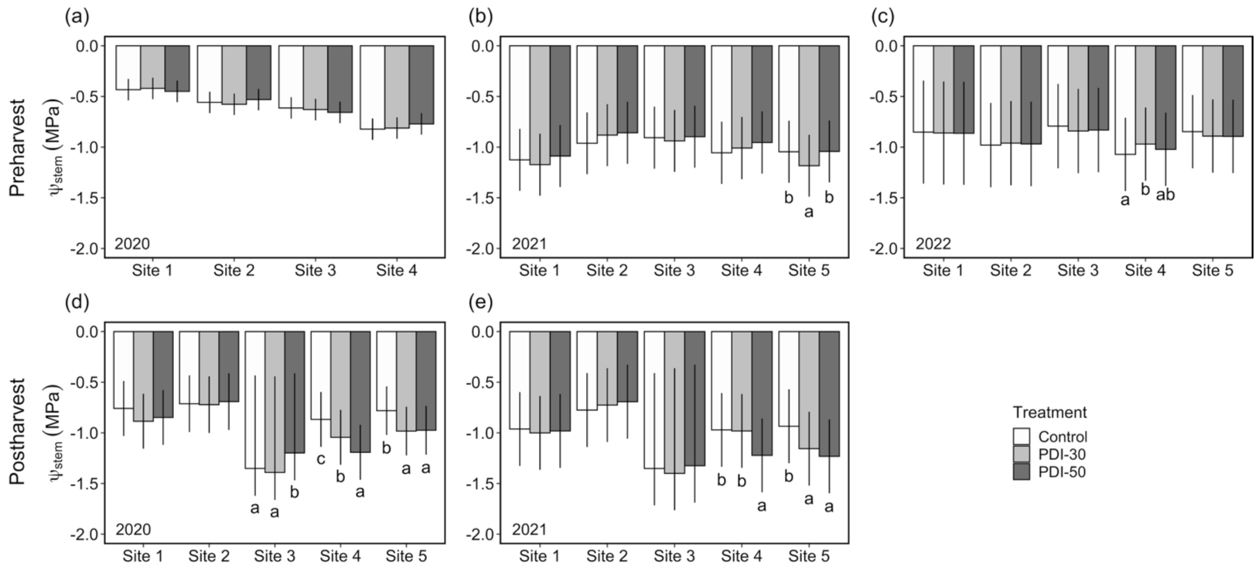
Treatment and site significantly affected Ψ_{stem} measurements both preharvest and postharvest in 2020 and 2021 (Table A2). Contrary to expectations, some treatment differences in Ψ_{stem} were also observed preharvest, i.e., when irrigation was the same across treatments (Fig. 6). At site 5 in 2021, mean preharvest Ψ_{stem} in the PDI-30 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.

Figure 5. 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.



During the postharvest period, during PDI treatments application, 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; 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.

Figure 6. 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 2021 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 ($p \leq 0.05$).



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. (Fig. A1-Fig. A4). 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 7).

Table 7. LMMs parameter coefficient and *p*-values of ANOVAs based on models fitted with photosynthetic rate (A_n), transpiration rate (E), stomatal conductance (g_s), or water use efficiency ($WUE_{intrinsic}$) as the response and Ψ_{stem} as a fixed effect and Site, Year, and Date as nested random effects. ^{x} Indicates parameters were log transformed.

Response	Ψ_{stem} coefficient sign	*p*-value
A_n ^{x}	+	< 0.0001
E ^{x}	+	< 0.0001
g_s ^{x}	+	< 0.0001
$WUE_{intrinsic}$	-	< 0.0001

In the preharvest period, treatment had a significant effect on $WUE_{intrinsic}$ in 2021 (Table A2); 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 A2) 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). 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 A2, Fig. 7 & Fig. 8). 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; $WUE_{intrinsic}$ in the control was significantly lower than in the PDI-50 treatment.

Figure 7. 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 ($p \leq 0.05$).

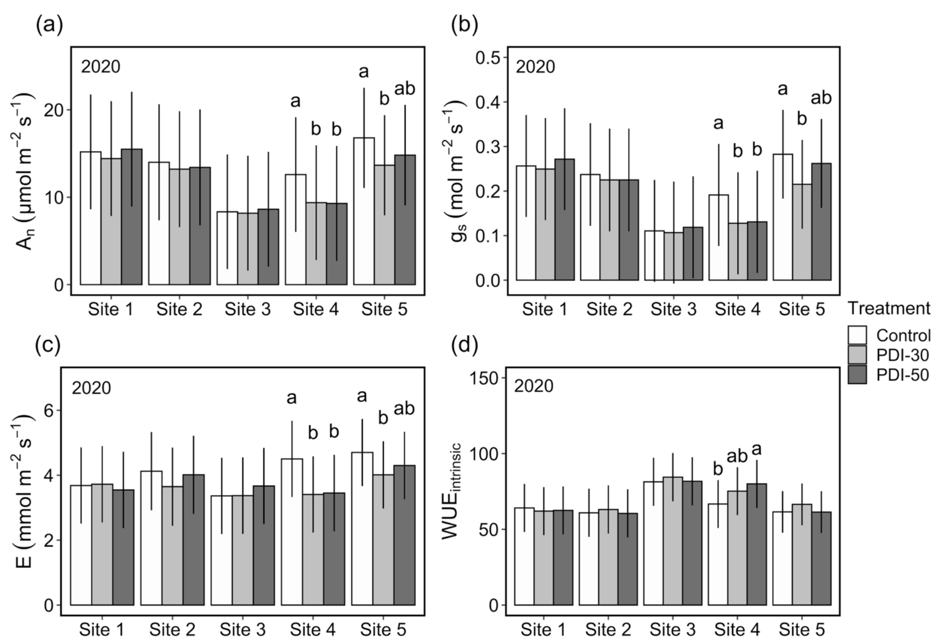
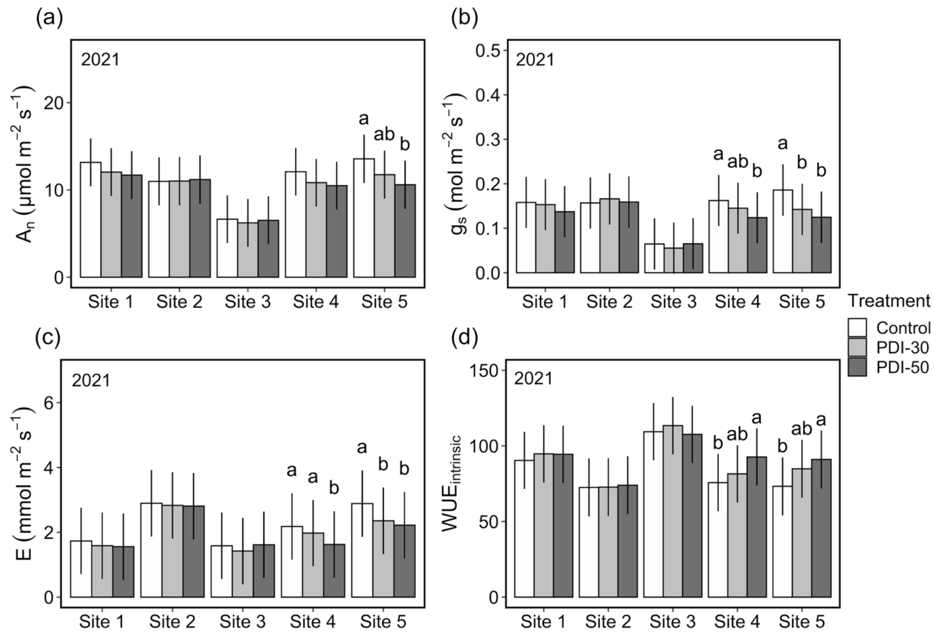


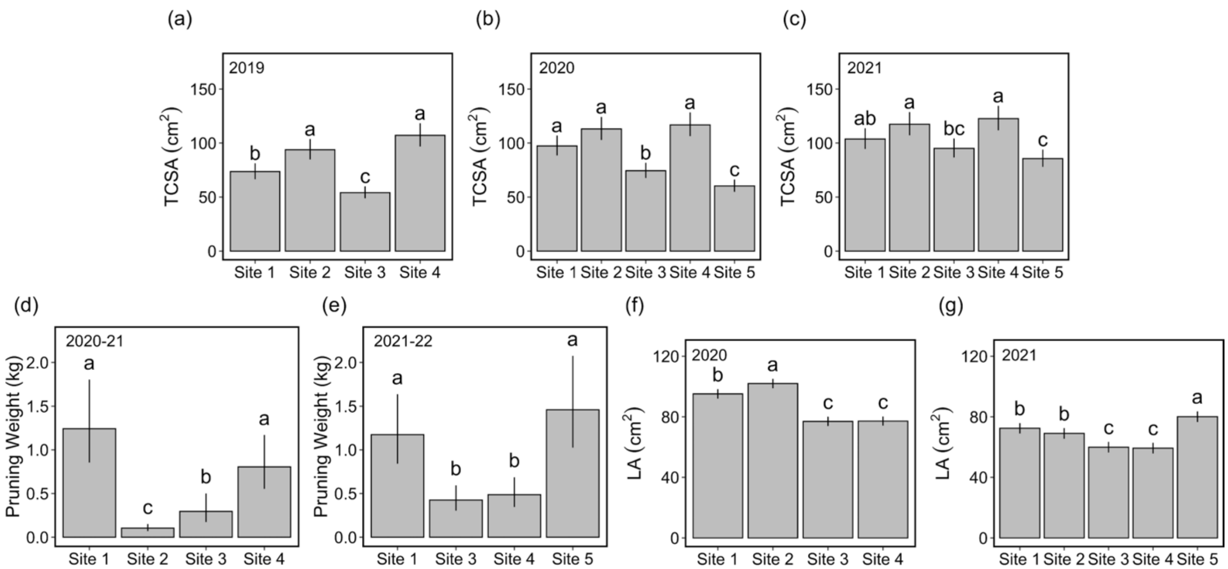
Figure 8. Estimated marginal mean postharvest photosynthetic rate (A_n), stomatal conductance (g_s), transpiration rate (E), and water use efficiency ($WUE_{intrinsic}$) in 2021 ((a) A_n, (b) g_s, (c) E, (d) $WUE_{intrinsic}$). Error bars indicate 95 % confidence levels of estimated marginal means. Values within the same parameter and site that share the same letter or have no letters do not differ significantly ($p \leq 0.05$).



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 A3). Average dry new wood pruning weight measured from winter pruning ranged from 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 A3). 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 A4, Fig. 9). The interaction between treatment and site was significant for LA in 2020; however, no significant differences between the estimated marginal mean LA 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.

Figure 9. 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 ($p \leq 0.05$).



Flower bud spring phenology

Treatment did not significantly affect weighted spring phenology in any year of this study at any site. Site significantly affected measurements taken in 2021 and 2022 with the progression from side green to full bloom occurring significantly later at the higher latitude and elevation orchards (sites 1, 2 and 3) than those at lower latitudes and elevations (Table A5, Table 7). The Julian day of the inflection point of the logistic regression of the weighted spring phenology ranged from 99.3 – 119.9 (April 9 – April 29) across all sites and years.

Table 7. Estimated marginal mean inflection point (in Julian days) of logistic regression of the progression of the weighted proportion of the tree in each bud stage and 95 % confidence levels. Values that do not share the same letter within the same year differ significantly ($p \leq 0.05$). Treatment did not significantly affect spring phenology.

Site	**Julian Day of Weighted Spring Phenology Logistic Inflection**		
	2020	**2021**	**2022**
1	106.6 [106.0, 107.2]	108.4 [107.5, 109.4]b	119.9 [119.4, 120.4]a
2	-	102.7 [101.8, 103.7]c	107.6[107.1, 108.0]c
3	-	114.5 [113.5, 115.4]a	116.8 [116.3, 117.3]b
4	-	99.3 [98.4, 100.2]d	102.1 [101.7, 102.6]d
5	-	99.8 [98.9, 100.8]d	101.4 [100.9, 101.9]d

Flower bud cold hardiness, moisture, and in-field cold damage

Average flower bud cold hardiness (measured as LT_{50}) ranged from -7.7 to -17.1 ˚C in the fall (Sept. 1 – Dec. 1), -12.1 to -22.4 ˚C in the winter (Dec. 2 – Mar. 5) and -4.2 to -9.6 ˚C in the spring (Mar. 6- Apr. 30) across sites and seasons (Fig. 10). The ANOVA tests of the treatment effect performed on the GLS models fitted with LT_{50} revealed no significant effect of treatment on LT_{50} at any site during any year or season (Table A6). Site significantly affected LT_{50} in all years and seasons except for the spring season of the 2020-21 measurement year.

Irrigation treatment also did not significantly affect whole flower bud moisture content (Table A7) in the fall, winter or spring season across all sites and years; site significantly affected whole flower bud moisture in all measured periods except for the winter of the 2021-22 season. A linear regression of LT_{50} and whole flower bud moisture content revealed a strong correlation between LT_{50} and bud moisture in the fall and winter and a weak correlation in the spring (Fig. 11). This relationship indicated that in the fall and winter season an increase in flower bud moisture content is correlated with a reduction in cold hardiness (higher temperature LT_{50}).

Figure 10. Flower bud cold hardiness as indicated by LT_{50} measured using DTA in the fall and winter months and controlled freezing tests in the spring (n= 3 where each value is the LT_{50} measured from 48-54 individual flower buds for DTA or from a subsample of 40-120 buds for the controlled freezing tests in the spring). Cold hardiness was measured after the first (2019-2020), second (2020-2021), and the third (2021-2022) year of PDI application.

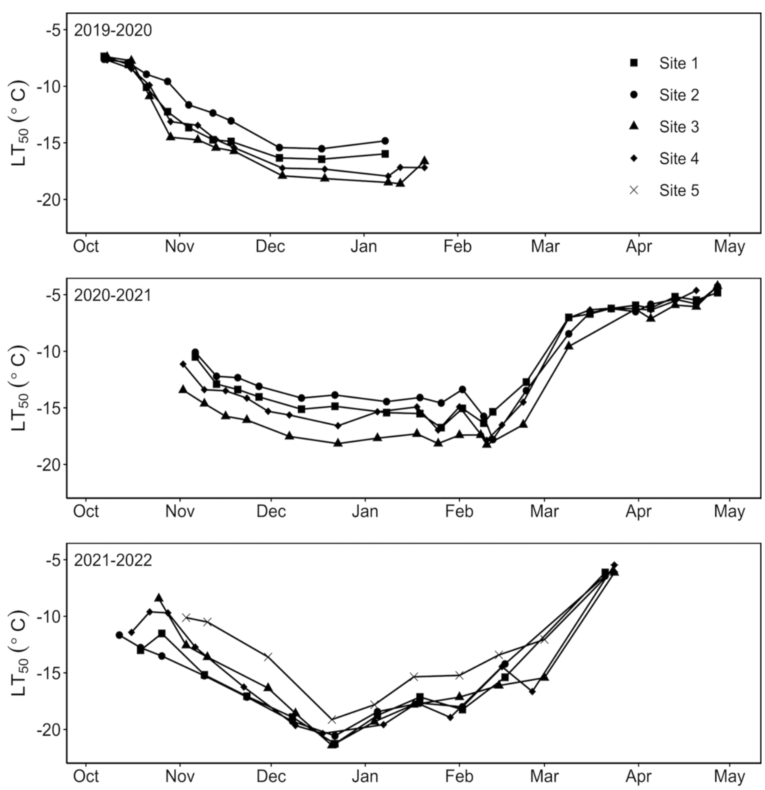
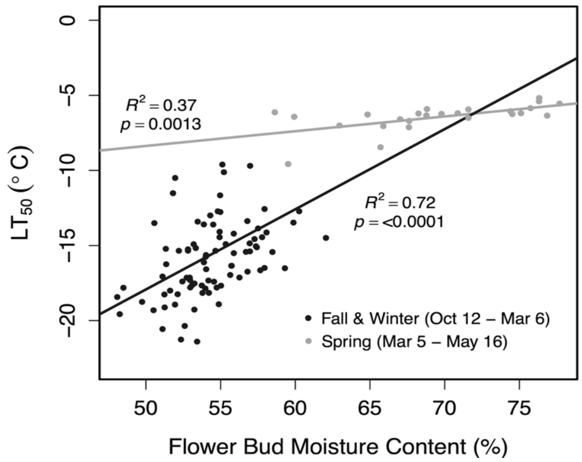


Figure 11. Correlation between flower bud cold hardiness (LT_{50}) and whole flower bud moisture in the fall and winter and spring seasons.



Observations of percent primordia cold damage in the field ranged from 26 %-95 % in the first season, 0.2 %-17 % in the second season, and 0 %-37 % in the final season (Table 8). In the first season, high levels of bud damage likely resulted from the rapid cold snap event that occurred in early January 2020 in the Okanagan Valley.

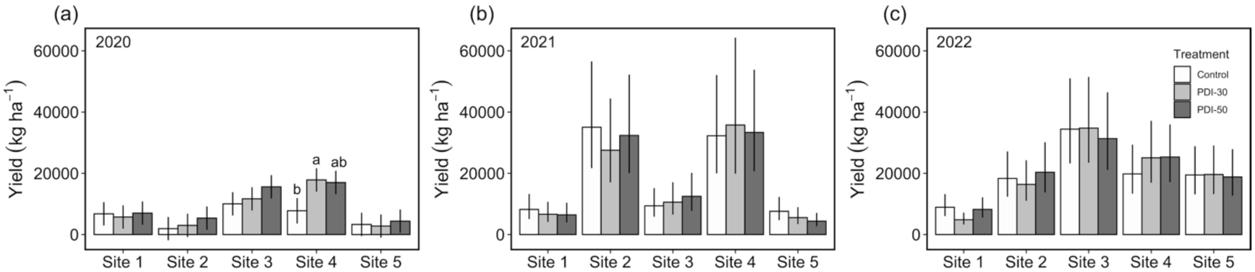
Table 8. Average flower bud cold damage, determined as the percent primordia damaged, between sites (n=3 on each date with each sample consisting of 50 to 120 individual flower buds) measured in the spring of each study with standard error (SE).

Site	**2020**		**2021**		**2022**	
	Damage (%)	Date	Damage (%)	Date	Damage (%)	Date
1	86 ± 1.7	Feb. 24	17 ± 3.0	Mar. 9	3.8 ± 1.7	Mar. 2
2	95 ± 1.7	Feb. 24	5.4 ± 2.1	Mar. 9	1.1 ± 0.6	Mar. 2
3	41 ± 2.9	Mar. 2	17 ± 1.8	Mar. 9	37 ± 0.7	Mar. 1
4	26 ± 2.9	Mar. 20	0.8 ± 0.7	Mar. 9	0.6 ± 0.6	Feb. 25
5	-	-	0.2 ± 0.2	Feb. 15	0.0 ± 0.0	Mar. 1

Fruit yield and quality

Fruit was harvested commercially on dates ranging from July 30 to August 20, depending on the season and site (Table 3). The higher latitude (site 1) and higher elevation (site 3) orchards were often harvested later in the season. Average fruit yields of 8543 kg ha^{-1}, 19,924 kg ha^{-1}, and 21,552 kg ha^{-1} were harvested in 2020, 2021, and 2022, respectively (Table A8). Treatment and site significantly influenced fruit yield in 2020 and site significantly influenced measures of yield in all years (Table A9, Fig. 12). In 2020, a significant difference in yield was observed between treatments only at Site 4; yield was significantly higher in the PDI-30 treatment than the control; however, the PDI-30 and PDI-50 treatment did not differ significantly (Fig. 12 a).

Figure 12. Estimated marginal means of the fruit yield (kg ha^{-1}) by year ((a) 2020, (b) 2021, (c) 2022). Error bars indicate 95 % confidence levels of estimated marginal means. Values within the same site and year that share the same letter, or do not have a letter, do not differ significantly ($p \leq 0.05$).



Treatment did not significantly affect any measures of fruit quality taken at harvest (FF, size, colour, SPF, or SSC:TA) in 2020, 2021, or 2022 (Table A10, Fig. 13). However, site significantly affected all measures of fruit quality at harvest. Average values of fruit quality parameters are provided in Appendix A (Table A11-Table A15).

LMMs and GLS models revealed a significant effect of irrigation treatment on some fruit quality parameters under different storage conditions at some sites (Table A16, Table A17). However, no significant difference in the estimated marginal means of any fruit quality parameter was observed with the exception of SSC:TA at site 1 in 2021 where the PDI-50 treatment under the shelf-life conditions had significantly lower SSC:TA (Table 9). Storage treatments were found to significantly influence most fruit quality parameters across sites. In general, fruit firmness was higher after cold storage than after harvest or shelf-life conditions, fruit size was smaller in 2021 in the cold storage and shelf-life treatments when compared to size at harvest, fruit colour was darker after storage and shelf-life conditions, SPF decreased with storage and shelf-life conditions and SSC:TA increased with cold storage and shelf-life conditions.

Figure 13. Estimated marginal means of the fruit quality parameters measured at harvest (fruit firmness as measured by a FirmTechII in 2020 (a) and 2021 (b) and a durometer (Shore OO hardness scale) in 2022 (c), row size in 2020 (d), 2021 (e), and 2022 (f) colour in 2020 (g), 2021 (h), and 2022 (i), stem pull force in 2020 (j), 2021 (k), and 2022 (l), SSC:TA in 2020 (m), 2021 (n), and 2022 (o)) Error bars indicate 95 % confidence levels of estimated marginal means. Values within the same year and parameter that share the same lower-case letter do not differ significantly ($p \leq 0.05$). Treatment did not significantly affect any measures of fruit quality at harvest.

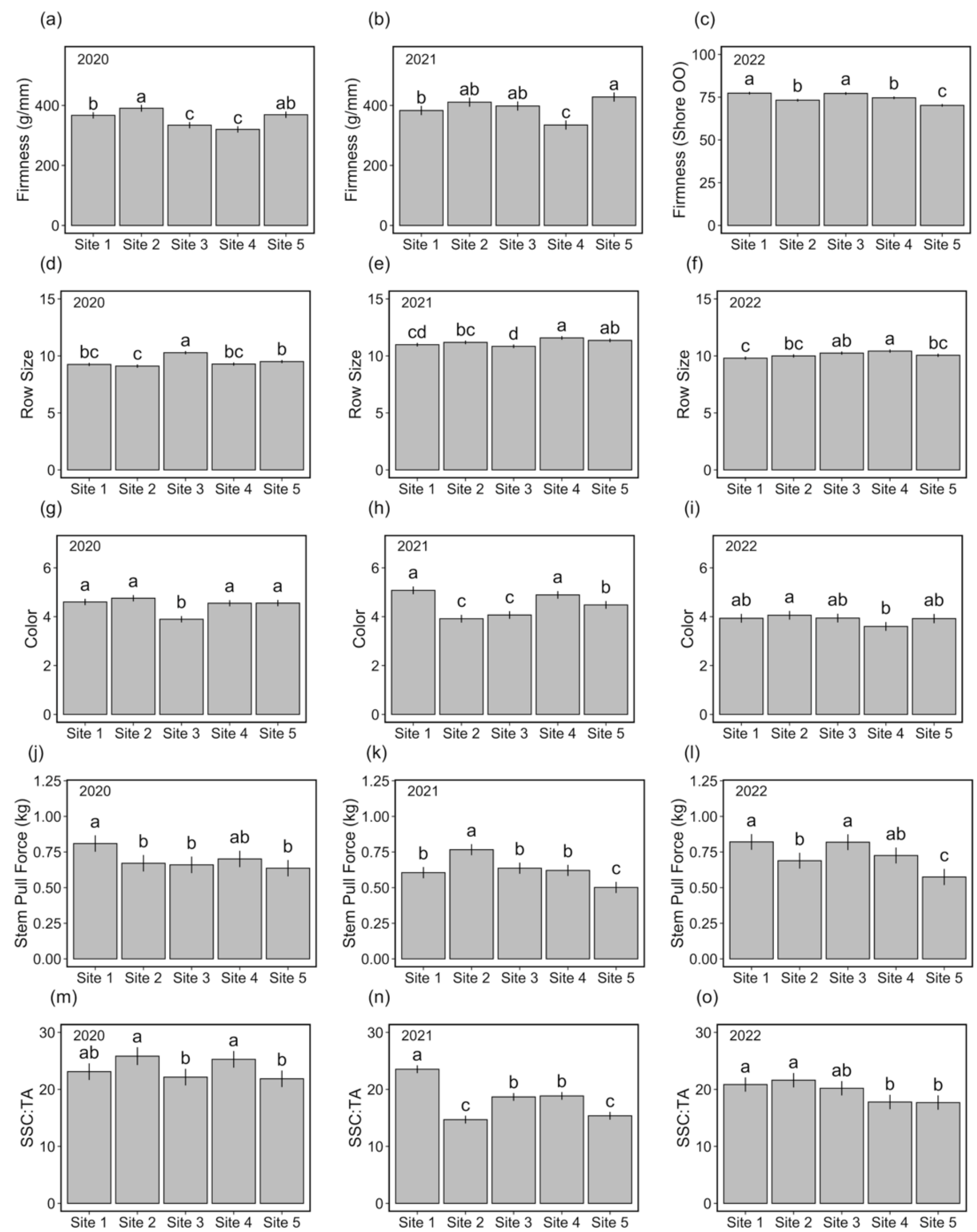


Table 9. Estimated marginal mean fruit quality parameters (firmness, size, colour, stem pull force [SPF], and SSC:TA) with 95 % confidence levels as measured at harvest, after cold storage conditions, and after cold storage and shelf-life conditions in 2020 and 2021. Values that do not share the same letter within the same year, site, and fruit quality parameter differ significantly ($p \leq 0.05$). Irrigation treatment did not significantly affect fruit quality except SSC:TA at site 1 in 2021.

Site	Storage Treatment	Fruit Quality Parameter Estimated Marginal Mean				
2020		**Firmness**	**Size**	**Colour**	**SPF**	**SSC:TA**
1	Harvest	367 [359, 375]b	9.3 [9.1, 9.4]a	4.6 [4.5, 4.7]b	0.809 [0.781, 0.838]a	23.1 [21.3, 24.9]c
	Cold Storage	411 [403, 419]a	9.2 [9, 9.4]a	4.9 [4.8, 5.0]a	0.417 [0.389, 0.446]b	30.9 [29.1, 32.6]b
	Shelf-Life	343 [335, 351]c	9.2 [9.1, 9.4]a	4.9 [4.8, 5.0]a	0.313 [0.285, 0.342]c	38.5 [36.8, 40.3]a
2	Harvest	391 [373, 409]b	9.1 [8.9, 9.4]a	4.8 [4.6, 4.9]a	0.671 [0.625, 0.718]a	25.8 [23.3, 28.3]b
	Cold Storage	436 [416, 456]a	9.1 [8.9, 9.4]a	4.3 [4.2, 4.5]b	0.38 [0.329, 0.431]c	33.9 [31.4, 36.5]a
	Shelf-Life	344 [319, 368]c	9.2 [9.0, 9.5]a	4.5 [4.3, 4.6]b	0.534 [0.473, 0.594]b	22.2 [21.1, 23.2]c
3	Harvest	334 [322, 346]a	10.3 [10.1, 10.4]a	3.9 [3.8, 4.0]c	0.66 [0.617, 0.703]a	31.6 [30.6, 32.7]b
	Cold Storage	349 [337, 361]a	10.3 [10.2, 10.5]a	4.5 [4.3, 4.6]b	0.448 [0.405, 0.491]b	36.0 [34.9, 37.0]a
	Shelf-Life	290 [277, 302]b	10.3 [10.1, 10.5]a	5.0 [4.9, 5.2]a	0.443 [0.4, 0.486]b	25.3 [24, 26.6]c
4	Harvest	320 [303, 338]c	9.3 [9.2, 9.4]a	4.6 [4.4, 4.7]b	0.701 [0.661, 0.742]a	27.8 [26.5, 29.1]b
	Cold Storage	394 [376, 412]a	9.3 [9.2, 9.4]a	4.4 [4.3, 4.6]b	0.516 [0.475, 0.556]b	33.1 [31.8, 34.3]a
	Shelf-Life	349 [332, 367]b	9.3 [9.2, 9.4]a	4.9 [4.7, 5.0]a	0.274 [0.233, 0.314]c	21.9 [20.5, 23.2]c
5	Harvest	369 [354, 384]b	9.5 [9.4, 9.6]a	4.6 [4.4, 4.7]b	0.635 [0.604, 0.667]a	29.3 [27.9, 30.7]b
	Cold Storage	459 [444, 474]a	9.5 [9.4, 9.7]a	4.6 [4.5, 4.7]b	0.353 [0.321, 0.385]b	31.7 [30.4, 33.1]a
	Shelf-Life	366 [350, 381]b	9.5 [9.4, 9.7]a	4.8 [4.7, 4.9]a	0.225 [0.197, 0.253]c	23.1 [21.3, 24.9]c
2021		**Firmness**	**Size**	**Colour**	**SPF**	**SSC:TA**
1	Harvest	383 [365, 401]c	11.0 [10.9, 11.1]a	5.1 [5, 5.2]b	0.605 [0.562, 0.649]a	23.5 [22.1, 25.0]d
	Cold Storage	501 [483, 520]a	10.6 [10.5, 10.7]b	5.9 [5.8, 6.0]a	0.460 [0.417, 0.503]b	32.3 [30.4, 34.4]c
	Shelf-Life	413 [395, 432]b	10.6 [10.5, 10.7]b	5.9 [5.8, 6.0]a	0.228 [0.184, 0.271]c	*Control:* 51.8 [47.9, 56.2]a *PDI-30:* 46.5 [42.9, 50.4]ab *PDI-50:* 43.3 [40, 46.9]b
2	Harvest	411 [394, 428]a	11.2 [10.9, 11.4]a	3.9 [3.8, 4.0]c	0.767 [0.721, 0.813]a	14.7 [13.7, 15.7]b
	Cold Storage	405 [386, 424]a	10.7 [10.5, 11]b	5.2 [5.1, 5.3]a	0.359 [0.311, 0.406]b	25.3 [24.3, 26.3]a
	Shelf-Life	408 [391, 425]a	10.8 [10.6, 11]b	4.8 [4.7, 4.9]b	0.238 [0.19, 0.285]c	26.0 [25.0, 27.0]a
3	Harvest	398 [390, 406]b	10.8 [10.7, 10.9]a	4.1 [3.9, 4.2]b	0.636 [0.598, 0.675]a	18.7 [17.9, 19.5]c
	Cold Storage	474 [466, 482]a	10.5 [10.4, 10.6]b	4.9 [4.7, 5]a	0.354 [0.316, 0.392]b	29.4 [28.6, 30.2]b
	Shelf-Life	462 [454, 470]a	10.5 [10.4, 10.6]b	4.9 [4.7, 5]a	0.257 [0.219, 0.295]c	32.4 [31.5, 33.2]a
4	Harvest	335 [311, 359]c	11.6 [11.3, 11.8]a	4.9 [4.6, 5.1]b	0.621 [0.575, 0.667]a	18.9 [17.3, 20.4]c
	Cold Storage	438 [414, 462]a	11.1 [10.9, 11.4]b	5.4 [5.2, 5.7]a	0.42 [0.374, 0.466]b	29.5 [28.0, 31.0]b
	Shelf-Life	400 [376, 424]b	11.0 [10.8, 11.3]b	5.5 [5.3, 5.8]a	0.281 [0.235, 0.327]c	33.4 [31.8, 34.9]a
5	Harvest	428 [415, 441]b	11.4 [11.2, 11.5]a	4.5 [4.4, 4.6]c	0.502 [0.479, 0.524]a	15.4 [14.4, 16.3]c
	Cold Storage	481 [468, 494]a	10.9 [10.8, 11.1]b	5.9 [5.7, 6.0]b	0.305 [0.282, 0.327]b	25.2 [24.3, 26.1]b
	Shelf-Life	489 [476, 502]a	10.9 [10.8, 11]b	5.3 [5.2, 5.4]a	0.256 [0.234, 0.278]c	27.5 [26.6, 28.5]a

3.2 Objective II

After all of the impacts of adopting PDI in the Okanagan Valley were monetized (Table 10), the estimated net present value (E[NPV]) and the equivalent annual net benefit (EANB) m^{-3} were calculated. In order to calculate the E[NPV] the sum of the benefits and costs along with the NPVs were calculated under various drought scenarios (Table 11). The EANB m^{-3} was also calculated to represent the annual benefit of adopting PDI versus the value over 20 years (net present value [NPV]). All values were calculated as 2021 CAD. The E[NPV] m^{-3} was $5.94 over the next twenty years. The EANB m^{-3} was $0.42 m^{-3}. The value of adopting PDI ha^{-1} was also dependent on the amount of water saved. E[NPV] ha^{-1} and EANB ha^{-1} values ranged from $2,366 m^{-3} (site 1) to $4,689 m^{-3} (site 4) and $166.44 m^{-3} (site 1) to $329.95 m^{-3} (site 4), respectively (Table 12). No value of E[NPV] was calculated for site 2 as the water meter data were unreliable and the amount of water consumed after harvest was unknown.

Table 10. The benefits and costs of adopting postharvest deficit irrigation in Okanagan cherry orchards. Values are presented on a m^{-3} basis and the value attributed to the benefit or cost for every m^3 saved by adopting PDI. The option values and non-use values were not monetized.

	Metric	Value per m^3 (2021 CAD)	Value per m^3 saved from PDI in the Okanagan (2021 CAD)
BENEFITS			
Benefits to the farmer			
Less maintenance and hardware replacement costs on irrigation infrastructure	Annual cost of microsprinkler irrigation X 6 %.	0.03	0.03
Option Use	This is accounted for by the "non-use" value of water.	+	+
Benefits to society			
Saving money on treatment cost	Chemical costs	0.07	0.07
Save money for pumping costs	Energy costs to pump groundwater	0.04	0.009
Water for other crops	WTP for irrigation	1.18	0.649
Water for golf courses	WTP for irrigation	1.18	0.059
Residential/ Institutional/ Municipal Water Use	Cost of domestic water in the Okanagan	2.1	0.714

Industrial/Commercial Uses (Manufacturing/Energy generation)	Total cost of water for manufacturing in the Okanagan/ Volume (Stats Canada, 2018)	1.29	0.077
Preservation/Existence/ Ecosystem Services/ Cultural Value	The value of water not used in agriculture, and delivered to the surrounding ecosystem.	+	+
COSTS			
Potential decrease in carbon sequestration	WTP for carbon sequestration X the potential decrease in C sequestration.	0.024	0.024

Table 11. Probability, sum of benefits, sum of costs, and NPV under each drought scenario.

Drought Stage	Probability of Drought Stage From Historical Data	Sum of Benefits ($ m^{-3})	Sum of Costs ($ m^{-3})	Net Present Value (Benefits – Costs) ($ m^{-3})	EANB ($ m^{-3})
Abnormally Dry (D0)	52.6%	0.10	0.005	1.47	0.10
Moderate Drought (D1)	21%	0.46	0.01	6.45	0.45
Severe Drought (D2)	15.8%	0.82	0.015	11.44	0.80
Extreme Drought (D3)	5.3%	1.17	0.019	16.41	1.15
Exceptional Drought (D4)	5.3%	1.53	0.024	21.39	1.51

*All $ values are presented in 2021 CAD

Table 12. E[NPV] and EANB values calculated by cubic meter and for each of the study locations ha^{-1}.

	E[NVP] (2021 CAD m^{-3})	EANB (2021 CAD m^{-3})
m^{-3}	$ 5.94	$ 0.42
Site 1 ha^{-1}	$ 2,366	$ 166.44
Site 2 ha^{-1}	-	-
Site 4 ha^{-1}	$ 4,689	$ 329.95
Site 3 ha^{-1}	$ 4,363	$ 306.95
Site 5 ha^{-1}	$ 3,863	$ 271.82
ha^{-1} (Average of the four sites)	**$ 3,820**	**$ 268.79**

The NPV and EANB increased dramatically with the drought scenario, indicating adopting PDI is more valuable in a year of extreme drought. For example, in years of no drought, EANB was calculated to be \$0.10 m^{-3} versus in an extreme drought year where the EANB was \$1.51 m^{-3}. The social benefit of adopting PDI is likely to increase in the future with an increase of drought incidence predicted for the Okanagan Valley (Merritt et al. 2006; Mirmasoudi et al. 2019; Tam et al. 2019; Bonsal et al. 2020).

3.3 Objective III

Model description

Final model parameters were selected by ranking the full models using AICc to determine which parameters improved model fit. All final models were the top models except for the 'Lapins' T1 LT10 model which was the second-best model. The equations for the best fit final models can be expressed as follows (Eq. 4-7):

$$LT_{SweetheartT1} = \hat{\beta}_{S0} + \hat{\beta}_{S1}T_{lag1} + \hat{\beta}_{S2}T_{lag3} + \hat{\beta}_{S3}CU + \hat{\beta}_{S4}logFU + \varepsilon_s \quad (4)$$

$$LT_{SweetheartT2} = \hat{\beta}_{S0.2} + \varepsilon_{s.2} \quad (5)$$

$$LT_{LapinsT1} = \hat{\beta}_{L0} + \hat{\beta}_{L1}T_{lag1} + \hat{\beta}_{L2}T_{lag2} + \hat{\beta}_{L3}CU + \hat{\beta}_{L4}logFU + \varepsilon_L \quad (6)$$

$$LT_{LapinsT2} = \hat{\beta}_{L0.2} + \varepsilon_{L.2} \quad (7)$$

where $LT_{SweetheartT1}$ and $LT_{LapinsT1}$ represent the LT of maximum injury at LT10, LT50, and LT90 for 'Sweetheart' and 'Lapins' at T1, respectively and $LT_{SweetheartT2}$ and $LT_{LapinsT2}$ represent the LT of maximum injury at LT10, LT50, and LT90 for 'Sweetheart' and 'Lapins' at T2, respectively. $\hat{\beta}_{S0}$ and $\hat{\beta}_{L0}$ are the intercepts, $\hat{\beta}_{S1}$ and $\hat{\beta}_{L1}$ are the coefficients for the first order lag mean daily air temperature (T_{lag1}), $\hat{\beta}_{L2}$ is the coefficient for the second order lag mean daily air temperature (T_{lag2}), $\hat{\beta}_{S2}$ is the coefficient for the third order lag mean daily air temperature (T_{lag3}), $\hat{\beta}_{S3}$ and $\hat{\beta}_{L3}$ are the coefficients for the accumulated chill units (CU), $\hat{\beta}_{S4}$ and $\hat{\beta}_{L4}$ are the coefficients for the log transformed accumulated forcing units (logFU). ε_s and ε_L are the error terms. $\hat{\beta}_{S0.2}$ and $\hat{\beta}_{L0.2}$ are the model intercepts at T2 and $\varepsilon_{s.2}$ and $\varepsilon_{L.2}$ represent the error terms at T2.

Model calibration

Unique models for 'Sweetheart' and 'Lapins' were developed for each period (T1 and T2) for every lethal temperature (LT10, LT50, LT90). Parameter estimates for all models are presented in Table 13.

Table 13. Estimated parameters coefficients, 95 % confidence limits in brackets, and *p* values for final, top 'Sweetheart' and 'Lapins' LT10, LT50, and LT90 models for T1 and T2.

Coefficient	LT10 Estimate	*p* value	LT50 Estimate	*p* value	LT90 Estimate	*p* value
'Sweetheart' T1						
$\hat{\beta}_{S0}$	-28.8 [-32.0, -25.6]	<0.0001	-28.2 [-31.2, -25.2]	<0.0001	-27.8 [-31.0, -24.7]	<0.0001
$\hat{\beta}_{S1}$	0.22 [0.12, 0.32]	<0.0001	0.21 [0.11, 0.30]	<0.0001	0.22 [0.12, 0.32]	<0.0001
$\hat{\beta}_{S2}$	0.16 [0.07, 0.25]	0.0006	0.18 [0.09, 0.26]	<0.0001	0.17 [0.08, 0.26]	0.0003
$\hat{\beta}_{S3}$	-0.003 [-0.004, -0.002]	<0.0001	-0.003 [-0.003, -0.002]	<0.0001	-0.003 [-0.003, -0.002]	<0.0001
$\hat{\beta}_{S4}$	8.1 [6.6, 9.6]	<0.0001	6.8 [5.3, 8.2]	<0.0001	5.5 [4.0, 6.9]	<0.0001
'Sweetheart' T2						
$\hat{\beta}_{S0.2}$	-4.3 [-4.8, -3.8]	<0.0001	-5.8 [-6.3, -5.3]	<0.0001	-7.4 [-8.1, -6.6]	<0.0001
'Lapins' T1						
$\hat{\beta}_{L0}$	-26.4 [-32.8, -20.0]	<0.0001	-29.9 [-35.6, -24.2]	<0.0001	-29.0 [-35.3, -22.7]	<0.0001
$\hat{\beta}_{L1}$	0.18 [-0.05, 0.42]	0.1296	0.19 [-0.02, 0.40]	0.0847	0.27 [0.04, 0.50]	0.0261
$\hat{\beta}_{L2}$	0.17 [-0.05, 0.38]	0.1384	0.25 [0.06, 0.45]	0.0127	0.23 [0.01, 0.44]	0.0418
$\hat{\beta}_{L3}$	-0.003 [-0.004, -0.002]	<0.0001	-0.003 [-0.004, -0.002]	<0.0001	-0.003 [-0.004, -0.001]	<0.0001
$\hat{\beta}_{L4}$	7.1 [4.0, 10.2]	<0.0001	7.2 [4.4, 10.0]	<0.0001	5.4 [2.4, 8.5]	0.0009
'Lapins' T2						
$\hat{\beta}_{L0.2}$	-4.1 [-4.7, -3.5]	<0.0001	-5.2 [-5.8, -4.5]	<0.0001	-6.3 [-7.2, -5.4]	<0.0001

Model evaluation

The RMSE and d values for the 'Sweetheart' and 'Lapins' T1 LT10, LT50, and LT90 models are presented in Table 14.

Table 14. Root mean square error (RMSE) and index of agreement (d) for final T1 and combined results from T1 and T2 models for 'Sweetheart' and 'Lapins' LT10, LT50, and LT90 predictions. RMSE and d were not calculated for T2 independently as these models were intercept only models.

Cultivar	Parameter	T1			T1 & T2		
		LT10	LT50	LT90	LT10	LT50	LT90
'Sweetheart'	RMSE	1.52	1.43	1.50	1.47	1.38	1.49
	d	0.96	0.96	0.96	0.97	0.97	0.97
'Lapins'	RMSE	1.92	1.71	1.89	1.84	1.64	1.83
	d	0.94	0.96	0.95	0.96	0.97	0.97

One-to-one regression of the combined predicted LT and the observed LT for all seasons of data used to develop these cultivar specific models reveal very good agreement as indicated by the high R^2 values and low RMSE values (Fig. 14). These statistics indicate a strong agreement between the predicted and observed values. This agreement is also evident when plotting the predicted against observed values (Fig. 15).

Figure 14. One-to-one regression of all season's predicted and observed LT10, LT50, LT90 for 'Sweetheart' and 'Lapins'.

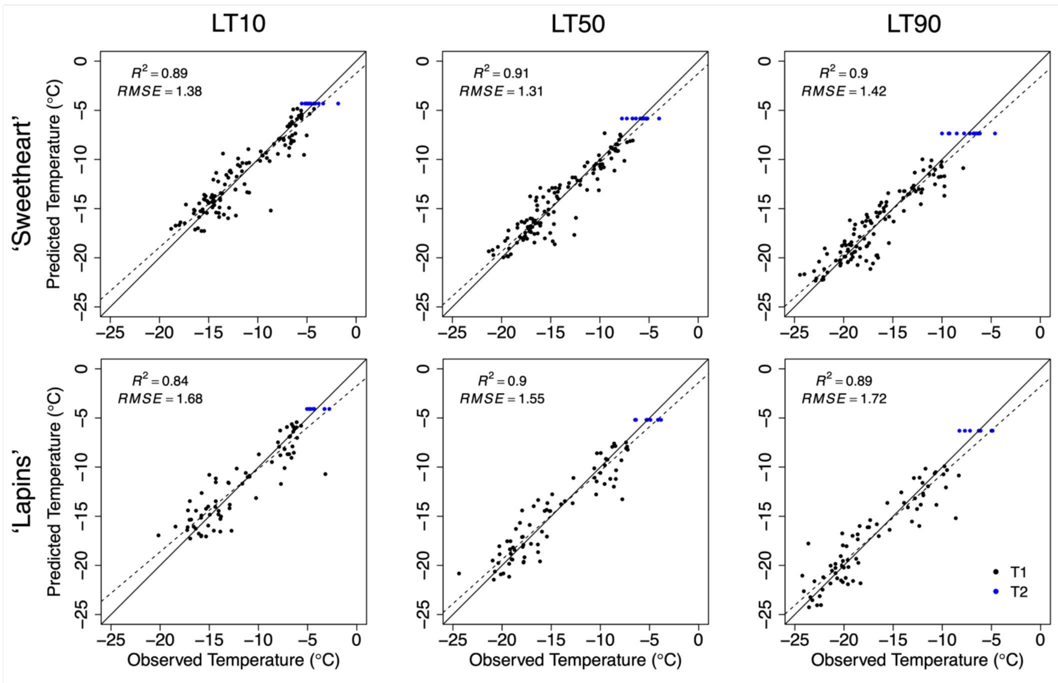
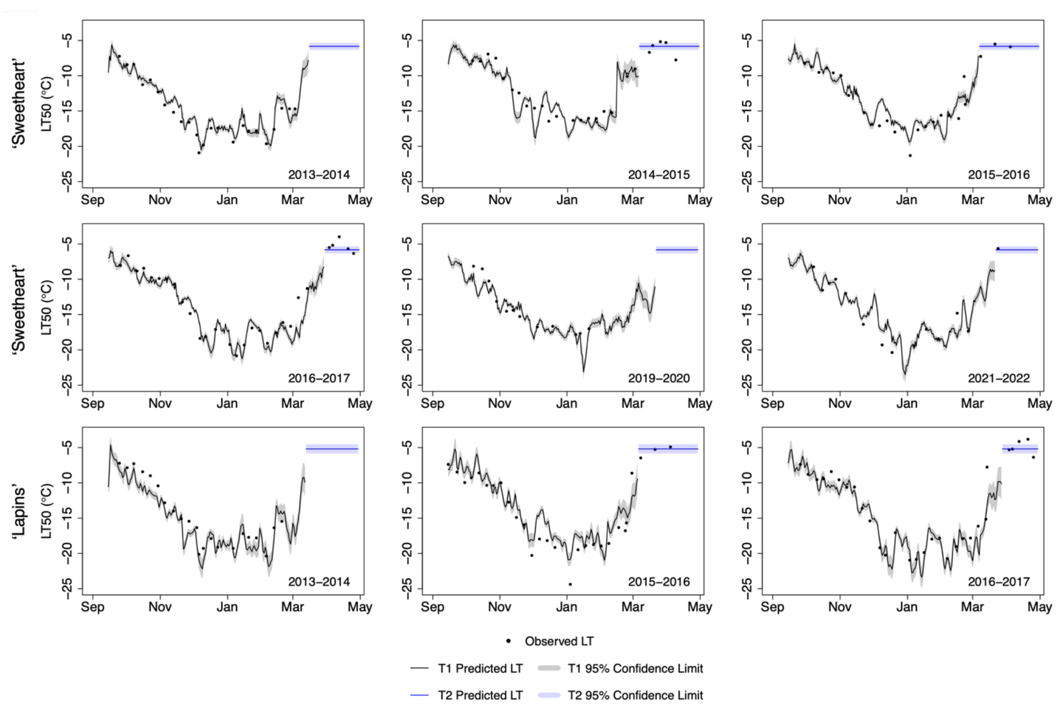


Figure 15. Predicted LT50 values plotted against the observed LT50 values for all seasons of data used to develop the 'Sweetheart' (6 seasons) and 'Lapins' (3 seasons) models.



Model validation

Model LT estimates were compared to three seasons of LT data not used in model development. The 'Sweetheart' models showed good agreement between the predicted and observed LT50 values in the T1 and T2 period (Fig. 16). Similar agreement between predicted and observed values for LT10 and LT50 was also observed (data not shown). The 'Lapins' LT estimates showed excellent fit to the observed LT values in the T1 period. However, model estimates in the T2 period were not as good (Fig. 17).

Figure 16. Examples of model LT50 estimates compared to data not included in model development at orchards varying in elevation in or near Summerland, BC. (a) high elevation orchard 2020-21, (b) mid-elevation orchard 2020-21, (c) low elevation orchard 2021-22.

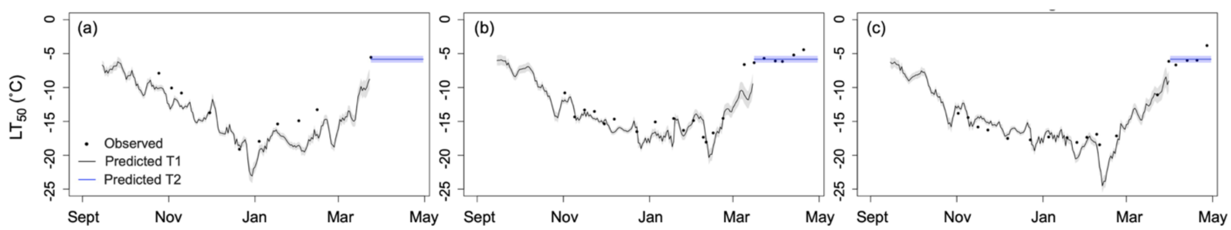
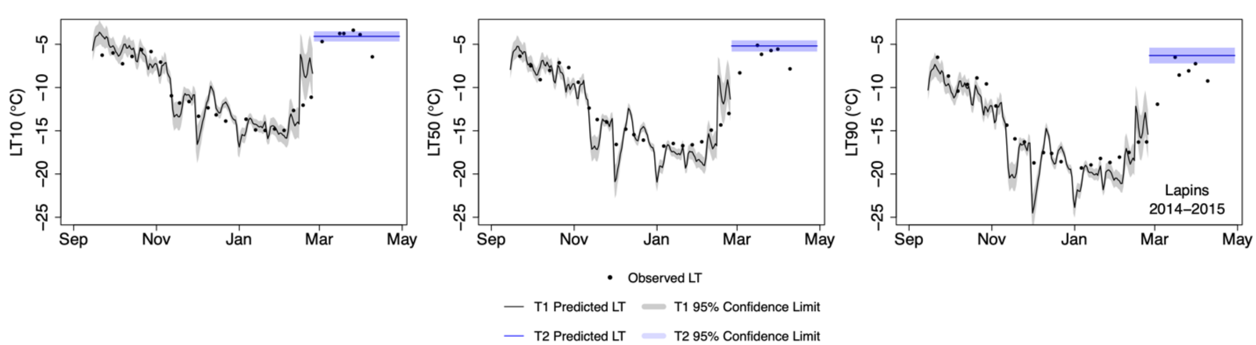
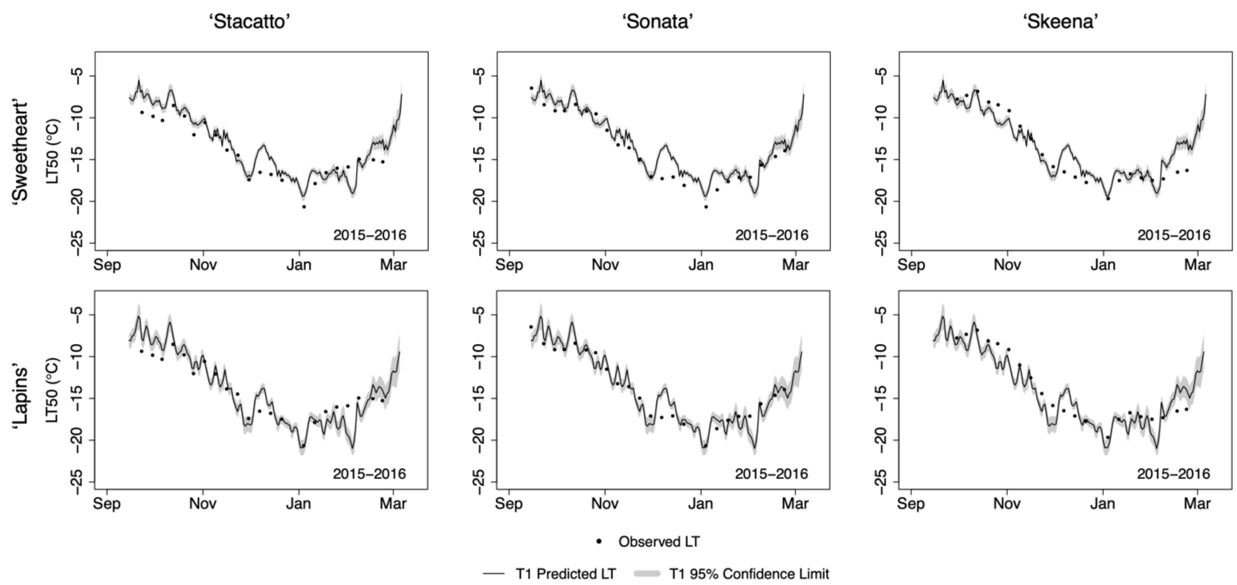


Figure 17. Predicted LT10, LT50, and LT90 values plotted against the observed LT values for one season of 'Lapins' data (2014-2015) that were not used in model development.



These models were also validated against three different sweet cherry cultivars including 'Staccato', 'Sonata', and 'Skeena' (Fig. 18). The LT of these additional cultivars was only measured during the T1 period and both 'Lapins' and 'Sweetheart' LT estimations did a reasonably good job at estimating these values during the T1 period.

Figure 18. Predicted 'Sweetheart' and 'Lapins' LT50 values in the T1 period plotted against observed 'Staccato', 'Sonata', and 'Skeena' cultivar LT50 values.



Interactive web application

The interactive web application provides the users with the background information required to understand and apply the developed 'Sweetheart' and 'Lapins' LT models, a description of the models and their performance, instructions on how to use the models as well as access to model outputs. Both graphical (Fig. 6) and downloadable numeric outputs from the models' LT10, LT50, and LT90 predictions are available on this website. On this website application, users can either input their own hourly temperature data or access the Government of Canada's Historic Climate database (Government of Canada 2021a) to automatically access and input weather data for select locations in the Okanagan Valley, BC. It also provides future lethal temperature estimates based on three days of weather forecasts accessed from OpenWeather (OpenWeather 2022) (https://openweathermap.org) for select locations in the Okanagan Valley, BC. The online hosted version of this application can be found at: https://sweetcherry.shinyapps.io/cherrycoldhardiness.

Figure 19. Interactive web application designed for simplified and open access to cold hardiness model estimations.

4.0 Discussion

4.1 Objective I

Overall, the results of this study indicate that reducing the volume of water applied after harvest by 27-33 % or 47-52 % had no significant effect on plant water stress, photosynthesis, tree growth, flower bud spring phenology, cold hardiness, or fruit yield and quality in the season after deficit irrigation was applied in five commercial cherry orchards in the Okanagan Valley. It should be noted that the reduction of postharvest irrigation based on a specific percentage of the control, which was irrigated to growers' standard practice at each commercial orchard, likely caused varying levels of water deficit conditions depending on the year and study site. This may help explain why the treatments imposed did not significantly affect the variables measured, even in the treatment with the greatest water reductions (PDI-50), as severe, extended periods of water stress were avoided throughout the duration of this three-year study.

The current findings indicated 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 MPa 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. Our results also indicated that postharvest Ψ_{stem} between approximately -0.5 MPa 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. 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.

4.2 Objective II

Given that the E[NPV] of the project alternative is positive and relatively low risk, we suggest that PDI be adopted in Okanagan cherry orchards. Very few costs are associated with the adoption of this practice; however, the majority of the benefits are for society and not for the farmers who are adopting this practice. Currently, most growers are allotted a base amount of water for a fixed price and are charged for over consumption. Most of the farmers in this study did not use their allotted amount of water, but given the current pricing structure, they received no financial reward.

In order to encourage the adoption of PDI, more should be done to incentivize the adoption of PDI and other water conservation practices. One possible option would be to charge for water by cubic meter. By moving to a charge per cubic meter, farmers who consume less water would save money. Structuring water pricing in this manner may help to act as a financial policy tool by helping users pay for the actual cost of water and an economic policy tool by encouraging efficient water use (Molle and Berkoff 2007). Accurate pricing will likely lead to irrigation efficiencies; however, the pricing should be reasonable as large price increases may have a negative effect on farm income and would in turn have negative effects on our food supply (Wichelns 2010). Correct pricing of water may also encourage growers to plant crops that are not only profitable, but also water efficient (Wichelns 2010).

4.3 Objective III

Through this project, the authors developed, evaluated, and validated models that successfully estimated the lethal temperature of the 'Sweetheart' and 'Lapins' sweet cherry in the Okanagan Valley, BC, Canada. Additionally, an online interactive web application for easy access and application of these models was developed. Overall, model performance was very good during the T1 period. However, these models do not predict changes in cold hardiness in the late winter and spring (after 30 and 25 accumulated FU [T2]) for either 'Sweetheart' or 'Lapins' as successfully. Additional data collected in the late winter and early spring will be needed to develop more capable models for estimating LT during these periods. These models show potential applications to other varieties (‘Stacatto’, ‘Sonata’, and ‘Skeena’) during the T1 period but application during the T2 period has not been validated.

5.0 Future Research Directions

In the current study (Objective I), postharvest deficits were applied in relation to growers’ standard practice. Although this greatly contributed to our understanding of irrigation practices in commercial orchards in the Okanagan Valley, it likely caused variable levels of water deficit conditions that were both year and study site dependent. As such, further research in which water reductions are applied in a more uniform manner, for example as a percentage of crop evapotranspiration (ET_c), is recommended. Additionally, 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. Furthermore, the current study was conducted at orchard sites with a range of management practices, tree ages, and site conditions. As such, future research conducted in a more controlled setting to corroborate these findings may be beneficial.

Results from Objective III indicate model performance could benefit from additional data collection in the late winter and early spring period during flower bud deacclimation. By collecting more data and then re-parameterizing models applicable during this critical period, we could improve the ability to estimate plant cold hardiness and create a stronger decision support tool for cherry growers in the Okanagan Valley.

6.0 Conclusion

6.1 Objective I

Reducing postharvest irrigation volume by 27-33 % and 47-52 % had no significant effect on plant water stress, photosynthesis, tree growth, flower bud spring phenology, cold hardiness, or fruit yield and quality in the season following application over a three-year period in five commercial Okanagan sweet cherry orchards. Additionally, at sites where increased water stress was observed, trees responded with improved $WUE_{intrinsic}$ 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 rainfall) giving insight to effects of PDI over a variety of conditions in the Okanagan Valley. To our current knowledge, this is the first published study that observed the effects of PDI on flower bud cold hardiness in sweet cherry. Therefore, according to our data, PDI is a viable approach to conserve water that safeguards tree function, crop production, and will not increase risk of flower bud frost damage in cherry orchards established in this semi-arid region. These findings support the use of PDI as an effective water saving technique for sweet cherry orchards in the Okanagan Valley of British Columbia and provide insight on current irrigation practices of commercial cherry growers in this region. 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.

6.2 Objective II

The adoption of PDI in Okanagan orchards has many benefits and very few costs. The value of adopting PDI comes from the value of water saved in the Okanagan. These savings can be divided into savings for the farmer and savings for the rest of society. The value of these savings is also dependent on the supply of water, which can fluctuate from year to year (Dupont and Renzetti 2008). The CBA showed that adopting PDI has more benefits in years of drought. The majority of the benefits from adopting PDI in the Okanagan are for society and not for the farmers. Incentives to encourage water saving practices in cherry production within the Okanagan Valley could prove beneficial. Additionally, the actual value of adopting PDI may be much higher, if the non-use value of saving water is included in the analysis.

6.3 Objective III

The purpose of Objective III was to develop and validate models to estimate the lethal temperature that could cause 10 %, 50 % and 90 % damage to the sweet cherry cultivars ‘Sweetheart’ and ‘Lapins’. These models have been made openly and easily accessible through an online interactive web application. These models may be used as a decision support tool to aid in frost management decision making and provide a tool to help estimate production risk prior to establishing new orchards in the Okanagan Valley, BC.

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Appendix A: Objective I Results

Table A1. 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

Table A2. *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. *p*-values in bold <0.05. R^2: coefficients of determination of LMMs.

Preharvest 2020			**Postharvest 2020**		
Response	**Fixed Effect**	***p***	**Response**	**Fixed Effect**	***p***
Ψ_{stem}	Trt	0.7226	Ψ_{stem}	Trt	**<0.0001**
R^2: 0.73	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	Trt	**0.0002**
R^2: 0.47	Site	0.4741	R^2: 0.66	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		
Response	**Fixed Effect**	***p***	**Response**	**Fixed Effect**	***p***
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		
Response	**Fixed Effect**	***p***
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

Figure A1. 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).

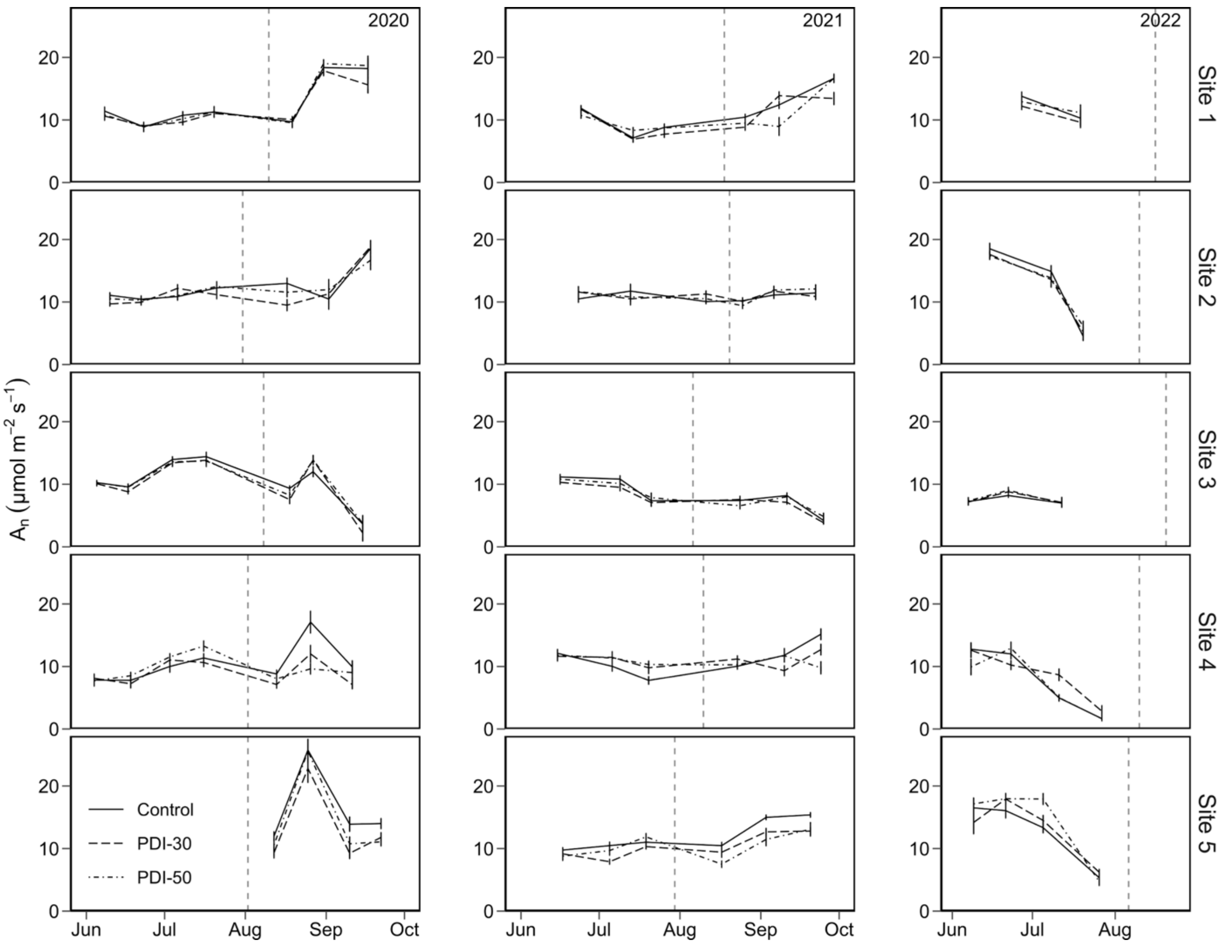

Figure A2. Transpiration rate (E) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of n=4 ± the standard error (SE).

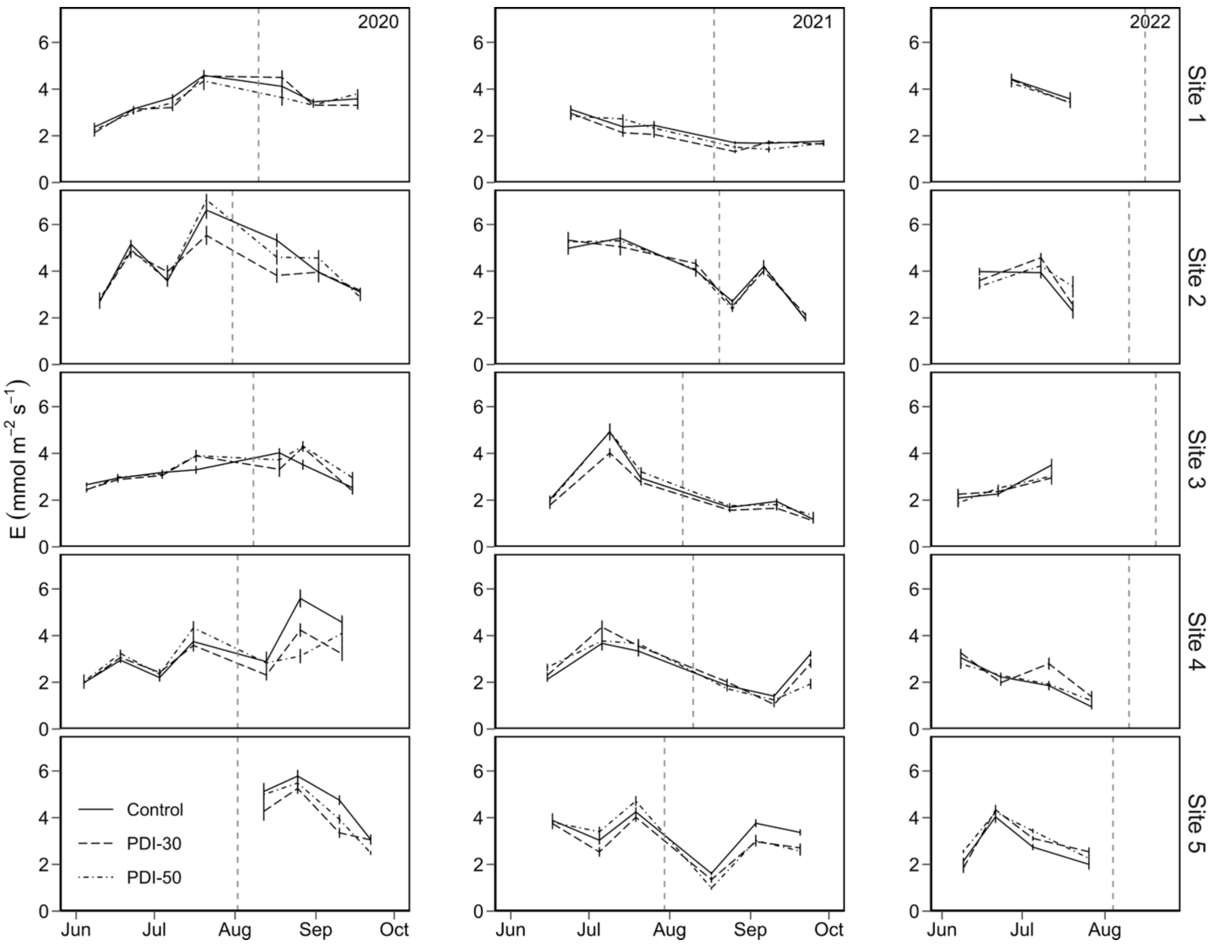

Figure A3. Stomatal conductance (g_s) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of n=4 ± the standard error (SE).

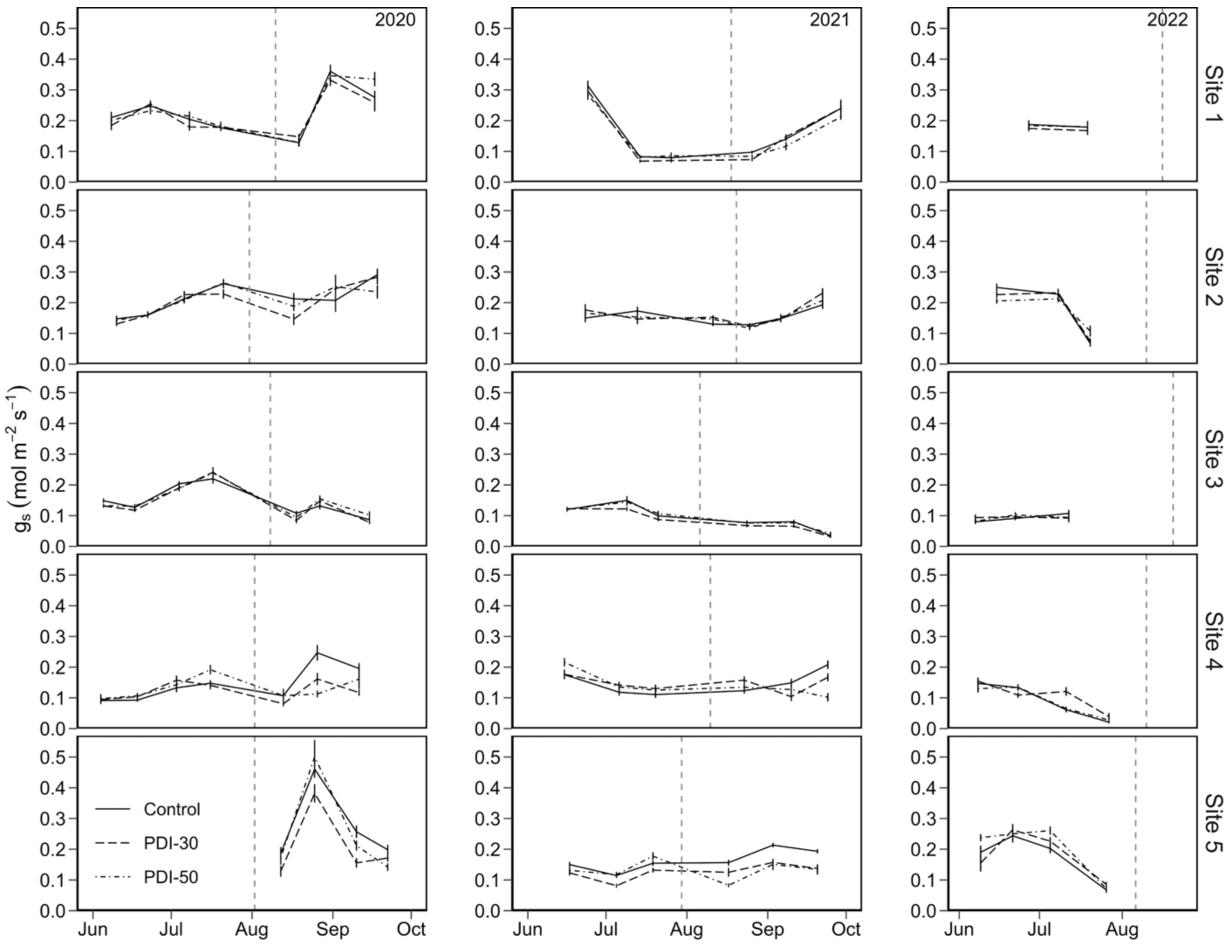

Figure A4. Water use efficiency ($WUE_{intrinsic}$) measurements at five Okanagan cherry orchards in 2020, 2021, and 2022. The dashed vertical lines indicate dates of commercial harvest. Each value is the mean of n=4 ± the standard error (SE).

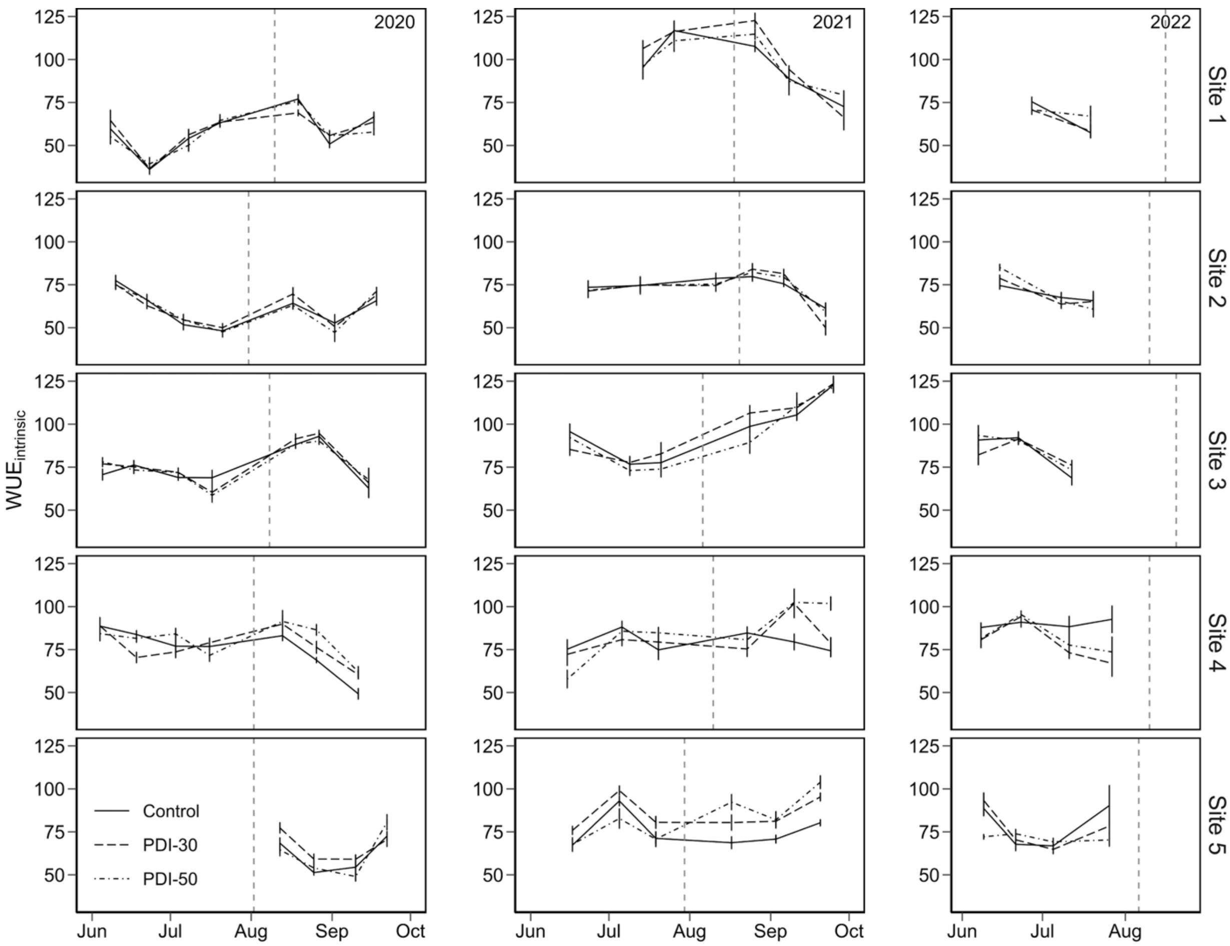

Table A3. Average measurements of tree growth (TCSA [n=72], dry new wood pruning weight [n indicated in brackets], and leaf area [n=20]) and standard error (SE) at all study Sites.

Site	Average TCSA (cm^2)			Average dry new wood pruning weight (kg)		Average area per leaf (cm^2)	
	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)**

Table A4. 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. TCSA and PW models included block as a random effect. *p*-values in bold <0.05. R^2: coefficients of determination of LMMs.

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

Table A5. *p*-values of ANOVAs based on linear mixed effects models (LMMs) with the Julian date of the inflection point of the logistic model of flower bud phenological development (SP) as the response variable, Treatment (Trt) or Trt×Site as fixed effects, and Block as a random effect. *p*-values in bold <0.05. R^2: Coefficients of determination (conditional) of LMMs.

Response	Fixed Effect	*p*	Response	Fixed Effect	*p*	Response	Fixed Effect	*p*
2020 SP	Trt	0.1392	2021	Trt	0.1127	2022	Trt	0.0706
R^2: 0.21			SP	Site	**<0.0001**	SP	Site	**<0.0001**
			R^2: 0.99	Trt×Site	0.5777	R^2: 0.99	Trt×Site	0.5790

Table A6. ANOVA table of the generalized least squares (GLS) models fit using restricted maximum likelihood (REML) with flower bud LT_{50} as the response variable and Site×Treatment (Trt) as fixed effects. Each season (fall, winter, spring) and year were modelled separately. *p*-values in bold <0.05.

Response	Fixed Effect	df	F-value	p-value
LT_{50} 2019-20				
Fall[a]	Trt	2	0.022	0.9780
	Site	3	4.020	**0.0113**
	Trt×Site	6	0.016	1.0000
Winter	Trt	2	1.622	0.2116
	Site	3	39.85	**<0.0001**
	Trt×Site	6	2.232	0.0622
LT_{50} 2020-21				
Fall	Trt	2	0.046	0.9551
	Site	3	9.402	**0.0001**
	Trt×Site	6	0.060	0.9990
Winter	Trt	2	0.506	0.6044
	Site	3	33.98	**<0.0001**
	Trt×Site	6	0.337	0.9157
Spring	Trt	2	1.056	0.3531
	Site	3	0.889	0.4511
	Trt×Site	6	0.127	0.9927
LT_{50} 2021-22				
Fall	Trt	2	0.233	0.7928
	Site	4	3.566	**0.0125**
	Trt×Site	8	0.100	0.9991
Winter	Trt	2	0.298	0.7434
	Site	4	4.335	**0.0032**
	Trt×Site	8	0.117	0.9984

[a]Values were cubed.

Table A7. ANOVA table of the generalized least squares (GLS) model fit using restricted maximum likelihood (REML) with whole flower bud moisture (BM) as the response variable and Site×Treatment (Trt) as fixed effects. Each season (fall, winter, spring) and year were modelled separately. *p*-values in bold <0.05.

Response	Fixed Effect	df	F-value	p-value
BM 2020-21				
Winter[a]	Trt	2	0.436	0.6476
	Site	3	6.780	**0.0003**
	Trt×Site	6	0.012	1.0000
Spring	Trt	2	0.008	0.9922
	Site	3	7.608	**0.0002**
	Trt×Site	6	0.121	0.9935
BM 2021-22				
Fall	Trt	2	0.192	0.8254
	Site	4	4.011	**0.0051**
	Trt×Site	8	0.126	0.9980
Winter	Trt	2	0.226	0.7982
	Site	4	1.206	0.3155
	Trt×Site	8	0.007	1.0000

[a]Values were log transformed.

Table A8. Yield (kg ha^{-1}) and standard error (SE). The final mean value is the average of all sites in each year.

Site	Fruit Yield (kg ha^{-1})		
	2020	2021	2022
1	6495 ± 878(18)	8302 ± 1138 (18)	8631 ± 1438 (18)
2	3420 ± 956 (18)	34792 ± 3230 (18)	19740 ± 1638 (18)
3	12427 ± 1196 (18)	11528 ± 965 (18)	34268 ± 1739 (18)
4	16890 ± 2960 (18)	37854 ± 4647 (16)	25788 ± 3125 (18)
5	3484 ± 562 (18)	7145 ± 1110 (18)	21579 ± 2429 (18)
mean	**8543 ± 1310 (18)**	**19924 ± 2218 (17.6)**	**22001 ± 2074 (18)**

Table A9. ANOVA table of the generalized least squares model (GLS) fit using restricted maximum likelihood (REML) with fruit yield as the response variable and Site×Treatment (Trt) as fixed effects. Each year was modelled separately. *p*-values in bold <0.05.

Response	Fixed Effect	df	F-value	p-value
Yield 2020	Trt	2	5.377	**0.0066**
	Site	4	21.17	**<0.0001**
	Trt×Site	8	1.558	0.1524
Yield 2021[a]	Trt	2	0.881	0.4186
	Site	4	33.38	**<0.0001**
	Trt×Site	8	0.483	0.8643
Yield 2022	Trt	2	0.530	0.5910
	Site	4	25.60	**<0.0001**
	Trt×Site	8	0.802	0.6026

[a]Values were log transformed

Table A10. ANOVA table of linear mixed effects models (LMMs) fit with fruit quality parameters (soluble sugar content to titratable acidity ratio [SSC:TA], colour, fruit firmness [FF], stem pull force [SPF], or row size) measured at harvest in 2020, 2021 and 2022 as response variables, Treatment (Trt)×Site as fixed effects, and Block as a random effect. *p*-values in bold <0.05.

Response	Fixed Effect	*p*	Response	Fixed Effect	*p*
SSC:TA			Colour		
2020	Trt	0.6847	2020	Trt	0.4410
R^2: 0.39	Site	**0.0020**	R^2: 0.72	Site	**<0.0001**
	Trt×Site	0.8788		Trt×Site	0.2957
2021	Trt	0.8426	2021	Trt	0.4197
R^2: 0.85	Site	**<0.0001**	R^2: 0.74	Site	**<0.0001**
	Trt×Site	0.0870		Trt×Site	0.5353
2022	Trt	0.6079	2022	Trt	0.1883
R^2: 0.52	Site	**0.0002**	R^2: 0.32	Site	**0.0047**
	Trt×Site	0.1113		Trt×Site	0.2716
FF			SPF		
2020	Trt	0.3853	2020	Trt	0.1210
R^2: 0.76	Site	**<0.0001**	R^2: 0.65	Site	**0.0018**
	Trt×Site	0.3843		Trt×Site	0.3033
2021	Trt	0.5779	2021	Trt	0.9537
R^2: 0.66	Site	**<0.0001**	R^2: 0.59	Site	**<0.0001**
	Trt×Site	0.5792		Trt×Site	0.4107
2022	Trt	0.1726	2022	Trt	0.4679
R^2: 0.81	Site	**<0.0001**	R^2: 0.68	Site	**<0.0001**
	Trt×Site	0.0735		Trt×Site	0.0736
Row size					
2020	Trt	0.3876			
R^2: 0.93	Site	**<0.0001**			
	Trt×Site	0.1035			
2021	Trt	0.7504			
R^2: 0.65	Site	**<0.0001**			
	Trt×Site	0.4389			
2022	Trt	0.5616			
R^2: 0.64	Site	**<0.0001**			
	Trt×Site	0.5478			

R^2: Coefficients of determination (conditional) of LMM.

Table A11. Average fruit SSC:TA and standard error for all three seasons of this study at all five sites with three different storage treatments.

Site	SSC:TA		
	2020	**2021**	**2022**
At Harvest			
1	21.1 ± 0.31 (18)	25.5 ± 0.3 (18)	19.4 ± 0.27 (18)
2	22.2 ± 0.29 (15)	19.4 ± 0.22 (18)	21.0 ± 0.34 (18)
3	20.4 ± 0.27 (18)	20.8 ± 0.12 (18)	17.2 ± 0.23 (18)
4	22.5 ± 0.28 (18)	22.6 ± 0.39 (18)	18.1 ± 0.33 (18)
5	20.9 ± 0.28 (18)	22.5 ± 0.26 (18)	18.5 ± 0.32 (18)
mean	**21.4 ± 0.29 (17)**	**22.2 ± 0.24 (18)**	**18.9 ± 0.3 (18)**
After Storage			
1	21.0 ± 0.22 (18)	24.2 ± 0.29 (18)	-
2	21.3 ± 0.49 (14)	19.1 ± 0.25 (18)	-
3	20.1 ± 0.22 (18)	19.7 ± 0.11 (18)	-
4	21.6 ± 0.25 (18)	20.8 ± 0.33 (18)	-
5	20.6 ± 0.30 (18)	21.0 ± 0.21 (18)	-
mean	**20.9 ± 0.3 (17)**	**21.0 ± 0.24 (18)**	**-**
After Storage and Shelf-Life Conditions			
1	20.6 ± 0.21 (17)	23.1 ± 0.39 (17)	-
2	21.5 ± NA (1)	17.9 ± 0.25 (17)	-
3	19.9 ± 0.23 (18)	19.0 ± 0.12 (18)	-
4	21.7 ± 0.27 (18)	20.1 ± 0.32 (18)	-
5	20.2 ± 0.19 (18)	20.5 ± 0.29 (17)	-
mean	**20.8 ± 0.23 (14)**	**20.1 ± 0.27 (17.4)**	**-**

Table A12. Average fruit firmness and standard error for all three seasons of this study at all five sites with three different storage treatments. Firmness was measured using a FirmTechII in 2020 and 2021 (g mm^{-1}) and a handheld durometer (Shore OO) in 2022.

Site	Firmness		
	2020 (g mm^{-1})	**2021 (g mm^{-1})**	**2022 (Shore OO)**
At Harvest			
1	395.77 ± 1.8 (1186)	410.8 ± 1.59 (1771)	73 ± 0.15 (1800)
2	334.23 ± 1.15 (1794)	398.11 ± 1.46 (1799)	77 ± 0.12 (1800)
3	320.15 ± 1.72 (1800)	334.89 ± 1.75 (1788)	75 ± 0.12 (1800)
4	370.45 ± 1.55 (1700)	428.07 ± 1.79 (1800)	70 ± 0.13 (1800)
5	357.52 ± 1.56 (1656)	390.97 ± 1.71 (1789)	75 ± 0.13 (1798)
mean	**367.00 ± 1.57 (1798)**	**382.96 ± 1.95 (1789)**	**77 ± 0.13 (1792)**
After Storage			
1	410.7 ± 1.83 (1795)	501.06 ± 2.02 (1757)	-
2	431.31 ± 2.76 (1249)	406.61 ± 2.11 (1258)	-
3	348.8 ± 1.71 (1799)	474.12 ± 1.75 (1783)	-
4	394.62 ± 2.05 (1598)	437.79 ± 1.98 (1783)	-
5	458.48 ± 2.09 (1686)	480.89 ± 2.06 (1781)	-
mean	**408.78 ± 2.09 (1625)**	**460.09 ± 1.98 (1672)**	**-**
After Storage and Shelf-Life Conditions			
1	343.03 ± 1.43 (1789)	414.13 ± 2.38 (1746)	-
2	342.98 ± 3.11 (649)	407.81 ± 1.99 (1780)	-
3	289.53 ± 1.21 (1793)	462.31 ± 1.94 (1787)	-
4	349.36 ± 1.71 (1800)	399.19 ± 2.04 (1787)	-
5	366.15 ± 1.76 (1600)	488.47 ± 2.12 (1778)	-
mean	**338.21 ± 1.84 (1526)**	**434.38 ± 2.09 (1776)**	**-**

Table A13. Average fruit colour (CTIFL colour chart) and standard error for all three seasons of this study at all five sites with three different storage treatments.

Site	Colour		
	2020	**2021**	**2022**
At Harvest			
1	4.6 ± 0.05 (1801)	5.1 ± 0.09 (1797)	4.0 ± 0.07 (1801)
2	4.8 ± 0.05 (1492)	3.9 ± 0.05 (1796)	4.0 ± 0.06 (1805)
3	3.9 ± 0.07 (1800)	4.1 ± 0.04 (1800)	3.9 ± 0.10 (1800)
4	4.6 ± 0.06 (1795)	4.9 ± 0.09 (1804)	3.6 ± 0.05 (1789)
5	4.6 ± 0.03 (1800)	4.5 ± 0.07 (1780)	3.9 ± 0.11 (1798)
mean	**4.5 ± 0.5 (1738)**	**4.5 ± 0.7 (1795)**	**3.9 ± 0.8 (1798)**
After Storage			
1	4.9 ± 0.05 (1783)	5.9 ± 0.03 (1794)	-
2	4.3 ± 0.07 (1382)	5.2 ± 0.05 (1791)	-
3	4.5 ± 0.05 (1802)	4.9 ± 0.03 (1787)	-
4	4.4 ± 0.07 (1801)	5.4 ± 0.07 (1786)	-
5	4.6 ± 0.06 (1805)	5.9 ± 0.04 (1786)	-
mean	**4.5 ± 0.06 (1715)**	**5.4 ± 0.04 (1789)**	**-**
After Storage and Shelf-Life Conditions			
1	4.9 ± 0.04 (1790)	5.9 ± 0.03 (1768)	-
2	4.5 ± 0.12 (682)	4.8 ± 0.06 (1813)	-
3	5.0 ± 0.05 (1784)	4.9 ± 0.05 (1793)	-
4	4.9 ± 0.06 (1800)	5.5 ± 0.08 (1788)	-
5	4.9 ± 0.10 (1775)	5.3 ± 0.06 (1778)	-
mean	**4.8 ± 0.07 (1566)**	**5.3 ± 0.6 (1788)**	**-**

Table A14. Average fruit SPF (kg) and standard error for all three seasons of this study at all five sites with three different storage treatments.

Site	SPF (kg)		
	2020	**2021**	**2022**
At Harvest			
1	0.810 ± 0.0107 (450)	0.606 ± 0.0093 (448)	0.821 ± 0.0094 (450)
2	0.673 ± 0.0128 (424)	0.753 ± 0.0106 (450)	0.689 ± 0.0112 (450)
3	0.660 ± 0.0092 (450)	0.637 ± 0.0061 (450)	0.819 ± 0.0089 (450)
4	0.702 ± 0.0109 (450)	0.622 ± 0.0080 (454)	0.720 ± 0.0080 (450)
5	0.635 ± 0.0114 (450)	0.502 ± 0.0076 (450)	0.572 ± 0.0060 (425)
mean	**0.696 ± 0.011 (445)**	**0.618 ± 0.0083 (450)**	**0.724 ± 0.0087 (445)**
After Storage			
1	0.417 ± 0.0086 (450)	0.460 ± 0.0083 (450)	-
2	0.384 ± 0.0108 (350)	0.359 ± 0.0089 (450)	-
3	0.448 ± 0.0070 (450)	0.354 ± 0.0064 (450)	-
4	0.516 ± 0.0104 (450)	0.420 ± 0.0078 (450)	-
5	0.353 ± 0.0080 (450)	0.305 ± 0.0060 (450)	-
mean	**0.424 ± 0.0216 (430)**	**0.379 ± 0.0075 (450)**	**-**
After Storage and Shelf-Life Conditions			
1	0.313 ± 0.0066 (450)	0.228 ± 0.0060 (450)	-
2	0.540 ± 0.0172 (217)	0.238 ± 0.0049 (450)	-
3	0.443 ± 0.0077 (450)	0.257 ± 0.0063 (450)	-
4	0.274 ± 0.0066 (450)	0.281 ± 0.0065 (450)	-
5	0.223 ± 0.0065 (438)	0.256 ± 0.0046 (450)	-
mean	**0.359 ± 0.0089 (401)**	**0.252 ± 0.0057 (450)**	**-**

Table A15. Average fruit row size and standard error for all three seasons of this study at all five sites with three different storage treatments.

Site	Row Size		
	2020	**2021**	**2022**
At Harvest			
1	9.3 ± 0.01 (1798)	11.0 ± 0.02 (1789)	9.8 ± 0.04 (1793)
2	9.0 ± 0.02 (1186)	11.2 ± 0.02 (1760)	10.0 ± 0.06 (1793)
3	10.3 ± 0.01 (1794)	10.8 ± 0.02 (1799)	10.3 ± 0.05 (1839)
4	9.3 ± 0.01 (1800)	11.6 ± 0.02 (1779)	10.4 ± 0.06 (1790)
5	9.5 ± 0.02 (1700)	11.4 ± 0.01 (1799)	10.1 ± 0.05 (1710)
mean	**9.5 ± 0.01 (1656)**	**11.2 ± 0.02 (1785)**	**10.1 ± 0.05 (1785)**
After Storage			
1	9.2 ± 0.01 (1795)	10.6 ± 0.02 (1757)	-
2	9.1 ± 0.02 (1249)	10.6 ± 0.02 (1235)	-
3	10.3 ± 0.01 (1799)	10.5 ± 0.01 (1782)	-
4	9.3 ± 0.01 (1598)	11.1 ± 0.02 (1780)	-
5	9.6 ± 0.02 (1686)	10.9 ± 0.01 (1781)	-
mean	**9.5 ± 0.01 (1625)**	**10.8 ± 0.02 (1667)**	**-**
After Storage and Shelf-Life Conditions			
1	9.2 ± 0.02 (1798)	10.6 ± 0.02 (1744)	-
2	9.1 ± 0.02 (649)	10.8 ± 0.02 (1765)	-
3	10.3 ± 0.01 (1793)	10.5 ± 0.02 (1783)	-
4	9.3 ± 0.01 (1800)	11.1 ± 0.02 (1786)	-
5	9.5 ± 0.02 (1600)	10.9 ± 0.01 (1778)	-
mean	**9.5 ± 0.02 (1528)**	**10.8 ± 0.02 (1771)**	**-**

Table A16. ANOVA table of linear mixed effects models (LMMs) or generalized least squares (GLS) models fit with fruit quality parameters (soluble sugar content to titratable acidity ratio [SSC:TA], colour, fruit firmness [FF], stem pull force [SPF], or row size) measured at harvest, after storage, and after shelf-life conditions in 2020 as response variables, Treatment (Trt)×Storage Type (Storage) as fixed effects, and Block as a random effect. Each site was analyzed separately. *p*-values in bold <0.05.

Response	Fixed Effect	*p*	Response	Fixed Effect	*p*
SSC:TA 2020			Colour 2020		
Site 1	Trt	0.0700	Site 1	Trt	0.1205
R^2: 0.81	Storage	**<0.0001**	R^2: 0.42	Storage	**<0.0001**
	Trt×Storage	0.4336		Trt×Storage	0.8815
Site 2[a]	Trt	0.8977	Site 2[b]	Trt	0.2811
R^2: 0.57	Storage	**<0.0001**		Storage	**0.0001**
	Trt×Storage	0.9623		Trt×Storage	**0.0361**
Site 3[b]	Trt	0.3001	Site 3	Trt	0.2432
	Storage	**<0.0001**	R^2: 0.83	Storage	**<0.0001**
	Trt×Storage	0.9735		Trt×Storage	0.5305
Site 4[b]	Trt	0.4757	Site 4	Trt	0.1137
	Storage	**<0.0001**	R^2: 0.51	Storage	**<0.0001**
	Trt×Storage	0.7929		Trt×Storage	0.6550
Site 5	Trt	**0.0076**	Site 5	Trt	0.0788
R^2: 0.80	Storage	**<0.0001**	R^2: 0.32	Storage	**0.0012**
	Trt×Storage	0.5721		Trt×Storage	0.8138
FF 2020			SPF 2020		
Site 1	Trt	0.6496	Site 1	Trt	0.9213
R^2: 0.76	Storage	**<0.0001**	R^2: 0.96	Storage	**<0.0001**
	Trt×Storage	0.4297		Trt×Storage	0.9248
Site 2	Trt	0.8878	Site 2	Trt	0.9006
R^2: 0.59	Storage	**<0.0001**	R^2: 0.72	Storage	**<0.0001**
	Trt×Storage	0.4100		Trt×Storage	0.6063
Site 3	Trt	0.5909	Site 3	Trt	0.3958
R^2: 0.67	Storage	**<0.0001**	R^2: 0.69	Storage	**<0.0001**
	Trt×Storage	0.3219		Trt×Storage	0.3795
Site 4	Trt	**0.0224**	Site 4	Trt	0.7069
R^2: 0.61	Storage	**<0.0001**	R^2: 0.84	Storage	**<0.0001**
	Trt×Storage	0.4762		Trt×Storage	0.5567
Site 5	Trt	**0.0259**	Site 5[b]	Trt	0.0045
R^2: 0.79	Storage	**<0.0001**		Storage	**<0.0001**
	Trt×Storage	0.9314		Trt×Storage	0.1600
Row size 2020					
Site 1	Trt	0.3585			
R^2: 0.70	Storage	0.4237			

	Trt×Storage	0.8156
Site 2 R^2: 0.84	Trt	0.4530
	Storage	0.0830
	Trt×Storage	0.8924
Site 3 R^2: 0.41	Trt	0.1420
	Storage	0.8249
	Trt×Storage	0.9533
Site 4 R^2: 0.53	Trt	**0.0253**
	Storage	0.7519
	Trt×Storage	0.9722
Site 5 R^2: 0.37	Trt	**0.0087**
	Storage	0.8287
	Trt×Storage	0.7539

[a]Shelf-life condition was missing for Site 2 2020 due to limited cherry production resulting from significant cold damage experienced in the winter of 2020

[b]The random effect of Block was omitted due to model overfitting and instead GLS models were used to analyze these data with Storage Type×Treatment as fixed effects

R^2: Coefficients of determination (conditional) of LMM.

Table A17. ANOVA table of linear mixed effects models (LMMs) or generalized least squares (GLS) models fit with fruit quality parameters (soluble sugar content to titratable acidity ratio [SSC:TA], colour, fruit firmness [FF], stem pull force [SPF], or row size) measured at harvest, after storage, and after shelf-life conditions in 2021 as response variables, Treatment (Trt)×Storage Type (Storage) as fixed effects, and Block as a random effect. Each site was analyzed separately. *p*-values in bold <0.05.

Response	Fixed Effect	*p*	Response	Fixed Effect	*p*
SSC:TA 2021			Colour 2021		
Site 1[a]	Trt	0.1615	Site 1	Trt	0.4954
R^2: 0.93	Storage	**<0.0001**	R^2: 0.74	Storage	**<0.0001**
	Trt×Storage	**0.0379**		Trt×Storage	0.4504
Site 2	Trt	0.1504	Site 2	Trt	0.1691
R^2: 0.88	Storage	**<0.0001**	R^2: 0.88	Storage	**<0.0001**
	Trt×Storage	0.8290		Trt×Storage	0.6535
Site 3[b]	Trt	0.0077	Site 3	Trt	0.3505
	Storage	**<0.0001**	R^2: 0.89	Storage	**<0.0001**
	Trt×Storage	0.1381		Trt×Storage	0.6760
Site 4[b]	Trt	0.1525	Site 4	Trt	0.5189
	Storage	**<0.0001**	R^2: 0.56	Storage	**<0.0001**
	Trt×Storage	0.9965		Trt×Storage	0.7457
Site 5	Trt	**0.0249**	Site 5	Trt	0.5758
R^2: 0.91	Storage	**<0.0001**	R^2: 0.84	Storage	**<0.0001**
	Trt×Storage	0.6992		Trt×Storage	0.6073
FF 2021			SPF 2021		
Site 1	Trt	0.8861	Site 1	Trt	0.9071
R^2: 0.76	Storage	**<0.0001**	R^2: 0.90	Storage	**<0.0001**
	Trt×Storage	0.3974		Trt×Storage	0.0577
Site 2	Trt	0.2190	Site 2[b]	Trt	0.5650
R^2: 0.27	Storage	0.8265		Storage	**<0.0001**
	Trt×Storage	0.4255		Trt×Storage	0.4749
Site 3[b]	Trt	0.7845	Site 3	Trt	0.5134
	Storage	**<0.0001**	R^2: 0.95	Storage	**<0.0001**
	Trt×Storage	0.2090		Trt×Storage	0.8551
Site 4	Trt	0.7753	Site 4	Trt	0.1551
R^2: 0.72	Storage	**<0.0001**	R^2: 0.87	Storage	**<0.0001**
	Trt×Storage	0.7985		Trt×Storage	0.3056
Site 5	Trt	0.7764	Site 5[b]	Trt	0.0608
R^2: 0.63	Storage	**<0.0001**		Storage	**<0.0001**
	Trt×Storage	0.7237		Trt×Storage	0.8589
Row size 2021					
Site 1[b]	Trt	**0.0238**			
	Storage	**<0.0001**			

	Trt×Storage	0.8541
Site 2 R^2: 0.65	Trt	0.1890
	Storage	**<0.0001**
	Trt×Storage	0.8926
Site 3 R^2: 0.66	Trt	0.5326
	Storage	**<0.0001**
	Trt×Storage	0.9763
Site 4 R^2: 0.67	Trt	**0.0076**
	Storage	**<0.0001**
	Trt×Storage	0.9884
Site 5 R^2: 0.64	Trt	0.7171
	Storage	**<0.0001**
	Trt×Storage	0.7758

[a]These data were log transformed

[b]The random effect of Block was omitted due to model overfitting and instead GLS models were used to analyze these data with Storage Type×Treatment as fixed effects

R^2: Coefficients of determination (conditional) of LMM.