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Feasibility of Using Pulse Drip Irrigation for Increasing Growth, Yield, and Water Productivity of Red Raspberry

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Abstract. **Pulse irrigation, the practice of applying water in small doses over time, is known to reduce deep percolation and runoff and, relative to irrigating in single continuous applications, can increase plant growth and production by supplying water and nutrients at an optimal rate. The objective of the present study was to determine whether pulse irrigation was beneficial in red raspberry (*Rubus idaeus* L. 'Wakefield'). Treatments included continuous or pulse drip irrigation and were evaluated for three growing seasons (2018–20) in a commercial field with silt loam soil. Continuous irrigation was applied up to 4 hours/day, whereas pulse irrigation was programmed to run for 30 minutes every 2 hours, up to eight times/day, using the same amount of water as the continuous treatment. Pulsing improved soil water availability relative to continuous irrigation and, by the second and third year, increased fruit production by 1210 to 1230 kg·ha^{-1}, which, based on recent market prices, was equivalent to \$2420 to \$2460/ha per year. Much of this yield increase occurred during the latter 3 to 4 weeks of the harvest season and was primarily due to larger fruit size during the second year and more berries per plant during the third year. In 1 or both years, pulse irrigation also produced more canopy cover, larger cane diameters, and higher concentrations of Mg and S in the leaves than continuous irrigation, but it reduced K and B in the soil and had variable effects on sugar-to-acid ratio in the berries. On the basis of these results, pulsing appears to be an effective means of irrigating raspberry plants in sandy or silty loam soils, but more research is needed to determine whether it is useful technique in heavier soil types.**

The majority of the processed red raspberry (*Rubus idaeus* L.) production in North America is in the maritime region west of the Cascade Mountains, extending from Salem, OR, north through Washington State, USA, into the Fraser Valley of British Columbia, Canada [US Department of Agriculture, National Agricultural Statistics Service (USDA NASS 2023)]. This region generally receives abundant rainfall from autumn through spring but is warm and dry during the summer (National Weather Service 2022). Irrigation is essential for many crops grown in this region, including raspberry. A mature raspberry field in the Pacific Northwest typically requires anywhere from 25 to 50 mm of water per week, which is often applied by irrigation from May through September (Strik et al. 2020).

Currently, most raspberry fields are managed using drip irrigation (Bryla 2023). Drip offers many advantages over other irrigation methods, including higher water use efficiency, fewer weeds, and lower incidence of fungal disease on the leaves and fruit (Dixon 2015; Evans and Sadler 2008). However, drip irrigation also restricts soil wetting and can limit outward development of the root system (Patten et al. 1988). As a result, irrigation must be applied frequently by drip, particularly when the plants are grown in light-textured soils. Raspberry plants are also usually grown on raised beds to reduce the risk of root infection by soilborne pathogens such as *Phytophthora* sp. (Maloney et al. 1993). Raised beds dry out more quickly than flat ground and therefore must be irrigated more frequently. To prevent water limitations, many growers will irrigate raspberry fields daily, especially when the plants are fruiting during the summer.

An important feature of drip irrigation is the ability to use small application rates (2 to 4 L·h^{-1}), proven to be desirable for optimal plant–soil–water relations (Shock 2006). However, due to technical limitations, application at low discharge rates is often problematic and can lead to emitter plugging at sites with poor water quality. To obtain lower rates, Karmeli and Peri (1974) suggested the use of pulse or intermittent application of irrigation water by drip. They defined pulse irrigation as a series of cycles, whereby each cycle is composed of an irrigation phase followed by a nonoperative resting phase. Recently, growers in Washington have expressed interest in using pulse irrigation in red raspberry. When managed properly, pulse irrigation reduces soil evaporation, runoff, and leaching (Cote et al. 2003; Mostaghimi and Mitchell 1983; Phogat et al. 2013), while supplying water and nutrients at an optimal rate for plant uptake (Elnesr et al. 2015; Segal et al. 2006). Lozano et al. (2020) recommended at least a 20-min pulse to reduce uneven water applications resulting from line pressurization, although others suggest that pulses should not exceed 1 h in length because longer discharge times may increase the movement of water downward rather than laterally (Elmaloglou and Diamantopoulos 2008a; Mostaghimi and Mitchell 1983; Phogat et al. 2013). In recent decades, pulse irrigation has been shown to increase yield in numerous crops, including green bean (*Phaselous vulgaris* L.) (El-Mogy et al. 2012), lettuce (*Lactuca sativa* L.) (Almeida et al. 2015; Xu et al. 2004), maize (*Zea mays* L.) (El-Abedin 2006), onion (*Allium cepa* L.) (Madane et al. 2018), orange (*Citrus ×sinensis*) (Abdelraouf et al. 2019), potato (*Solanum tuberosum* L.) (Bakeer et al. 2009), and soybean (*Glycine max* L.) (Eid et al. 2013). However, with the exception of strawberry (*Fragaria ×ananassa* Duch.) (Gendron et al. 2018; Létourneau and Caron 2019), pulse irrigation has not been well tested in small fruit crops such as red raspberry.

Red raspberry has unique growth and fruiting characteristics that can affect how irrigation is managed. The root system and crown are perennial, whereas the canes are biennial. New canes are produced from buds on the crown and older roots. These new canes are called primocanes the first year and floricanes the second year. Depending on the cultivar, fruit is produced either on both the primocanes and floricanes or on the floricanes only. Floricanes senesce after harvest and are normally pruned out in late summer or early fall (Barney et al. 2007). Once a raspberry planting is established, both primocanes and floricanes are present during the growing season. Consequently, irrigation is critical not only for fruiting in the summer, but also before and afterward when sufficient water is needed to sustain enough growth in the primocanes to achieve high yields the following year.

The objective of the present study was to assess the feasibility of using pulse drip irrigation to increase fruit production in red raspberry. The goal was to produce higher yields and better fruit quality. On the basis of results from other crops, we expected pulsing to reduce deep percolation relative to the standard practice of irrigating continuously for several hours, thus reducing water and nutrient limitations to plant growth and fruit development. Pulsing was tested in 'Wakefield' raspberry, which, in 2022, accounted for 38% of the total raspberry plant sales in Washington and Oregon, USA, and British Columbia, Canada (Northwest Berry Foundation 2023). 'Wakefield' produces fruit on floricanes only and is grown exclusively for the processed market.

Materials and Methods

Study site. The study was conducted in a mature field of 'Wakefield' raspberry established in Aug 2015 at a commercial farm in Lynden, WA, USA (lat. 48°59′N, long. 122°23′ W, 45 m elevation). Soil at the site is classified as a Kickerville silt loam (coarse-loamy, isotic, mesic Typic Haplorthods) with an average pH of 6.5. The plants were propagated from tissue culture and transplanted 0.78 m apart on rows of raised beds (0.3 m high × 1.2 m wide × 68.5 m long) that were centered 3.05 m apart. Trellis wires were installed at heights of ≈0.3, 1.4, and 1.5 m above the top of the beds. Primocanes were arc-trained and tied to the top two trellis wires after pruning out the weaker canes in mid-November (Barney et al. 2007). Irrigation was applied using a single lateral of drip tubing (Neptune; Toro, Bloomington, MN, USA) suspended from the lowest trellis wire in each row. The tubing was manufactured from polyethylene (15.8-mm internal diameter) and had integrated pressure-compensating emitters spaced every 0.5 m. The system was operated at a pressure of 103 kPa, which produced an average flow rate of 0.95 $L \cdot h^{-1}$ from each emitter.

The field was fertilized each spring with 60 $kg \cdot ha^{-1}$ N, 70 $kg \cdot ha^{-1}$ P, and 80 $kg \cdot ha^{-1}$ K from urea (46N–0P–0K), monoammonium phosphate (11N–52P–0K), K-mag (0N–0P–21.5K–10.8Mg–22S), and potassium sulfate (0N–0P–50K–17S). Dolomitic lime was also applied at a rate of 4480 $kg \cdot ha^{-1}$ in Spring 2019. The lime and fertilizer were broadcast along the top of the raised beds. Additional fertilizers, including three applications of calcium ammonium nitrate (17N–0P–0K–8.8Ca) each May and weekly applications of ammonium polyphosphate (10N–34P–0K) and potassium thiosulfate (0N–0P–25K–17S) from bloom to late June were applied by fertigation through the drip system for a total of 90 $kg \cdot ha^{-1}$ of N and P and 110 $kg \cdot ha^{-1}$ K per year. Water for fertigation was applied equally to the irrigation treatments in the present study.

New primocanes were chemically suppressed each spring (when they reached a height of ≈2.5 cm and again at 4 weeks after the initial burn) by spraying the base of the plant rows with carfentrazone-ethy (Aim, FMC, Philadelphia, PA, USA) and paraquat (Gramaxone, Syngenta Crop Protection, Greensboro, NC, USA). Diuron (DuPont Agricultural Products, Wilmington, DE, USA) and simazine (Ciba-Geigy Corp., Greensboro, NC, USA) were also applied during primocane suppression for weed control, and mefenoxam (Ridomil Gold SL, Syngenta Crop Protection) was applied to control *Phytophthora* sp. Fungicides, including cyprodinil + fludioxonil (Switch, Syngenta Crop Protection), iprodione (Rhone-Poulenc Ag. Co., Research Triangle Park, NC, USA), pyraclostrobin + boscalid (Pristine, BASF Corporation, Research Triangle Park, NC, USA), polyoxin D zinc salt (PH-D, Arysta, LifeScience, Cary, NC, USA), and cyprodinil + fludioxonil, were applied as a foliar spray each spring to control botrytis (*Botrytis cinerea*).

Experimental design. Treatments were applied for three growing seasons (2018–20) and included pulse or continuous irrigation arranged in a randomized complete block design with four replicates. Each replicate consisted of an entire 68.5-m-long row in the field and was randomized within each block for a total of eight rows. Continuous irrigation was scheduled by the grower and consisted of applying water once a day for a total of 4 h, as needed. Water was applied at the same rate throughout the growing season and only stopped when it rained, which is a common practice in raspberry. Pulsing was programmed to operate for 30 min every 2 h, up to eight times per day, using the same amount of water as applied to the continuous treatment. In this latter case, irrigation was scheduled using a wireless valve programmer (Model 2772-WVP; Hunter Industries, Inc., San Marcos, CA), which triggered electronic solenoid valves installed on the end of each treatment row. Both treatments were initiated in June each year and continued through mid-Sep 2018 and 2019 and late Aug 2020. Continuous and pulse irrigation was started at 0200 and 0600 HR, respectively. Each irrigation event was monitored using a water meter (Netafim Ltd., Tel Aviv, Israel) installed on the main line of each treatment and recorded using a data logger (Model CR-1000 with an AM16/32 channel relay multiplexer; Campbell Scientific, Inc., Logan, UT, USA). Due to issues with the water meters, irrigation was recorded as time (minutes) and calculated based on average flow rate of the drip emitters in the treatment rows.

Measurements. Fruit were machine harvested every 2 to 4 d from early July to mid-August during each year of the study. At each harvest, fruit were collected using an over-the-row harvester (Littau Harvester, Stayton, OR, USA) and weighed to determine the total yield in each treatment row. A random sample of 100 berries was also collected from each row and weighed to determine average berry weight in each treatment. On each date, the berries were sampled immediately after the row was harvested, collecting an equal number of berries from each flat coming off the row (e.g., if five flats were harvested, 20 berries were collected from each flat). Once weighed, the berries were frozen and later thawed and analyzed for soluble solids and titratable acidity. For each sample, ≈150 g of the berries was pureed in a blender, and soluble solids was measured by placing a drop of the puree on a digital refractometer (Palette PR-32; ATAGO C, Tokyo, Japan). Then, a 6-g sample of the puree was mixed with 50 mL of degassed, deionized water and used to determine titratable acidity. Each sample was titrated with 0.1 $mol \cdot L^{-1}$ NaOH to an endpoint pH of 8.1 using an autotitrator (DL12; Mettler-Toledo, LLC, Columbus, OH, USA). Titratable acidity was calculated as a percentage of citric acid. Sugar-to-acid ratios were calculated by dividing the concentration of soluble solids in the puree by its titratable acidity value.

Stem water potential was measured after each harvest in 2019 and 2020. On each date, measurements were taken at midday (1230–1330 HR) using a pressure chamber (Model 600; PMS Instrument Co., Albany, OR, USA), following the recommendations of Hsiao (1990). Readings were taken once or twice a week from 7 Jul to 15 Aug 2019 and 8 Jul to 15 Aug 2020. On each date, two recent, fully expanded primocane leaves, one from both sides of the row, were randomly selected from a representative plant in each treatment plot and equilibrated with the cane by enclosing them for at least 45 min in a heavy-duty, foil-laminated, ziplock bag before cutting them off at the base of the petiole with a razor blade. This procedure is effective for reducing variability in water potential of woody plants such as raspberry (McCutchan and Shackel 1992). Leaves selected for the measurements were free of disease, malformation, and any other damage and chosen from primocanes that were mostly shaded.

In 2019, soil moisture sensors (Model Meter Environment 10HS; Meter Group Inc., Pullman, WA, USA) were installed in groups of four at distances of 6.1, 12.2, and 18.3 m

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along one row each of the continuous and pulse treatments to measure volumetric water content. Within each group, two sensors were buried beneath a drip emitter at depths 15 and 30 cm, and one sensor each was buried 12.5 and 25 cm from the emitter at a depth 15 cm (in line with the drip tube). Each sensor was connected to a data logger (Model CR-1000 with an AM16/32 channel relay multiplexer; Campbell Scientific Inc.) and measured every 15 min from 18 Jun to 18 Sep in 2019 and from 4 Jun to 12 Aug in 2020. Although irrigation continued until 31 Aug 2020, the sensors were struck by a field implement on 13 Aug 2020, and therefore, readings were unavailable thereafter.

Thirty-five to 45, recent, fully expanded primocane leaves were collected randomly from each treatment row after harvest in mid-August each year. The leaves were oven-dried for 4 d at 73 °C, ground to pass through a 1-mm sieve, and analyzed for N using a combustion analyzer (model TruSpec CN; Leco Corp., St. Joseph, MI, USA) and for other nutrients, including P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn, using an inductively coupled plasma (ICP) optimal emission spectrophotometer (model Optima 3000DV; Perkin Elmer, Wellesley, MA, USA) after microwave digestion with 70% (v/v) nitric acid (Gavlak et al. 2005).

A composite of three soil samples were also collected from the center of the bed and under a drip emitter in each treatment row on 3 Oct 2020. Each sample was taken at a depth of 0 to 30 cm using a stainless steel, 2.5-cm-diameter soil corer (JMC Soil Samplers, Newton, IA, USA). Once collected, the samples were air-dried and sent to a commercial laboratory (Brookside Laboratories Inc., New Bremen, OH, USA) for analysis of nutrients. Available N (NH_4-N and NO_3-N) was extracted with 1 M KCl and determined using automated colorimetric methods (Dahnke and Johnson 1990). Phosphorus was extracted using the Bray 1 method (Bray and Kurtz 1945), and K, Ca, Mg, B, and Zn were extracted using the Mehlich 3 method (Mehlich 1984), and each nutrient was analyzed by ICP spectrometry.

From each row, a subplot of 13 plants was randomly selected on 3 Oct 2020 (i.e., before pruning) and counted to determine the total number of primocanes and floricanes on each plant. The diameter of three random primocanes and three floricanes at 0.3 m above the raised bed were also measured on each plant using a digital caliper. The primocanes were recounted and measured again on 15 Feb 2021 (after pruning, which occurred in mid-Nov 2020).

Canopy cover was measured remotely on 19 Sep 2019 and 30 Sep 2020 using an unmanned aerial system (AgBot; Aerial Technology International, Oregon City, OR, USA) equipped with a multispectral camera (RedEdge; Micasense, Seattle, WA, USA). Flights were conducted within 1 h of solar noon (1300 HR) at an altitude of 40 m. Imagery was stitched into an orthomosaic of each spectrum using geospatial software (Pix4D S.A., Prilly, Switzerland) and imported into ArcGIS for analysis (ESRI, Redlands, CA, USA). To distinguish the plants from the soil, a modified version of the normalized difference vegetation index (NDVI) was used, whereby the difference between the 40-nm-wide, near-infrared (NIR) spectral band centered at 840 nm and the 10-nm-wide, red spectral band centered at 668 nm was divided by their sum. Because shadows and glare can be a source of error in multispectral imagery (Leblon et al. 1996), the equation was modified by squaring NIR in the numerator to augment the signature of the plants. Subsamples of each treatment row were designated using a random point generator in ArcGIS. The images of each treatment row subplot were then categorized into two classes, plant and soil, using a threshold to ensure accurate classification of each category. To calculate canopy cover, the number of pixels occupying the plant class was multiplied by the ground sampling distance squared and divided by the plot area. The final values were multiplied by 100 and reported as the percentage of the soil surface shaded by the canopy at midday.

Each year, irrigation water use efficiency was calculated by the dividing yield ($kg \cdot ha^{-1}$) in each treatment by the total amount of water applied ($m^3 \cdot ha^{-1}$) by pulse or continuous irrigation (Howell 2000). Because raspberry requires irrigation for commercial production in Washington, yield under rain-fed conditions was set to zero.

Statistical analysis. Data were analyzed by analysis of variance using a mixed-model procedure when appropriate in R (R Core Team 2019). Repeated measures analysis was used when relevant (i.e., yield and berry weight). Fixed effects included irrigation, harvest date, and their interactions, and random effects included block. Data were assessed for normality and homogeneity of variance using the Shapiro–Wilk and Levene's test, respectively, and were transformed as needed. Transformed data were back-transformed after analysis to represent actual means. Means were separated at the 0.05 level using Tukey's honestly significant difference test. Soil moisture readings were not replicated due to financial constraints and therefore were not analyzed statistically.

Results and Discussion

Weather conditions and irrigation. In most cases, mean monthly air temperature measured near the site followed long-term averages for each growing season (Table 1). However, May was generally warmer than normal each year by an average of 1.1 to 2.2 °C. Precipitation also differed from normal each year, particularly from May through August, where the total each month was 10% to 89% below average during the first 2 years of the study and 18% to 95% above average during the third year. Consequently, irrigation was higher than usual in 2018 and 2019 and lower than usual in 2020.

Soil water content. Relative to continuous irrigation, pulse applications increased soil water content under the drip emitters as well as at 12.5 cm from the emitters, on average, but had no effect on soil water content at 25 cm from the emitters in 2019 and at all measurement locations in most of 2020 (Table 2). Soil water content declined quickly after each irrigation and was higher throughout the day with pulsing (Fig. 1). Pulsing did not appear to increase the movement of water horizontally. Continuous irrigation, on the other hand, increased soil water content by 1 to 2 $cm^3 \cdot cm^{-3}$ each day at 25 cm from the emitters. When horizontal water spreading is higher, system costs are reduced because fewer drip emitters are required along the irrigation lines. Skaggs et al. (2010) examined subsurface drip irrigation in a sandy loam soil in California and found that pulsing produced only minor increases in horizontal spreading at the end of each water application due primarily to longer irrigation times and not as a result of flow phenomena associated with pulsing. However, Ismail et al. (2014) found that pulse drip irrigation increased the width of the wetting front while reducing deep percolation when modeling continuous and pulse drip irrigation on sandy soils. Likewise, Elmaloglou and Diamantopoulos (2008b) investigated a model comparing continuous drip irrigation to pulse drip on loamy sand and silt loam soils and found that pulsing reduced water loss under the root zone.

Stem water potential. On average, pulse drip resulted in less negative stem water potential than continuous irrigation in 2019 (Table 3). However, the difference was small that year and only averaged 0.07 MPa. Furthermore, there was no difference in stem water potential the following year. Similarly, Coolong et al. (2011) found that increasing the frequency of daily irrigations had no effect on leaf water potential in tomato; however, it increased leaf relative water

Table 1. Weather conditions and the amount of irrigation applied each mo. to a mature field of 'Wakefield' raspberry in Lynden, WA, USA.

	Air temp (°C)[i]				Precipitation (mm)[i]				Irrigation (mm)[ii]		
Month	2018	2019	2020	Normal[iii]	2018	2019	2020	Normal[iii]	2018	2019	2020
Apr	9.9	10.1	9.7	9.5	67	98	40	60	0	0	0
May	15.5	15.1	14.4	13.3	6	34	80	54	0	0	0
Jun	16.0	16.7	15.6	16.1	30	26	74	38	64	70	16
Jul	19.9	18.3	17.9	18.5	18	19	33	21	234[iv]	243	84
Aug	18.1	18.6	17.5	18.0	18	15	27	24	190	156	60
Sep	14.4	15.2	16.3	14.8	76	112	49	60	20	24	0

[i] Obtained from a AgWeatherNet station located 5.9 km from the field site.

[ii] Irrigation was applied 19 Jun–6 Sep 2018, 18 Jun–10 Sep 2019, and 26 Jun–22 Aug 2020. The measurement does not include water applied during fertigation in May and June each year.

[iii] Calculated as the 20-year average from the weather station.

[iv] Pulse irrigation was initiated on 10 Jul 2018.

Table 2. Effects of continuous or pulse drip irrigation on average availability of soil water each mo. in a mature field of 'Wakefield' raspberry in Lynden, WA (n = 4).[i]

	Volumetric soil water content ($m^3·m^{-3}$)[ii]							
	Continuous irrigation				Pulse irrigation			
	Measured at a depth of 5–15 cm			Measured at a depth of 20–30 cm under a drip emitter	Measured at a depth of 5–15 cm			Measured at a depth of 20–30 cm under a drip emitter
Date	Under a drip emitter	12.5 cm from the emitter	25 cm from the emitter		Under a drip emitter	12.5 cm from the emitter	25 cm from the emitter	
2019								
Jun	0.255	0.250	0.201	0.242	0.313	0.283	0.203	0.319
Jul	0.285	0.269	0.229	0.251	0.332	0.305	0.224	0.328
Aug	0.272	0.251	0.233	0.228	0.346	0.322	0.245	0.334
Sep	0.260	0.244	0.229	0.227	0.329	0.312	0.250	0.318
Avg	0.268	0.253	0.223	0.237	0.330	0.305	0.230	0.325
2020								
Jun	0.289	0.266	0.230	0.242	0.289	0.284	0.235	0.319
Jul	0.292	0.298	0.253	0.260	0.330	0.334	0.259	0.349
Aug	0.330	0.296	0.271	0.259	0.340	0.335	0.265	0.363
Avg	0.298	0.285	0.248	0.253	0.316	0.315	0.251	0.340

[i] Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment.

[ii] Measured from 18 Jun to 18 Sep 2019 and 4 Jun to 12 Aug 2020.

content at midday, suggesting that more frequent irrigation led to an increase in plant available water. As water stress increases within a plant, stomata close on the leaves and prevent further water loss. This closure has been shown to reduce CO_2 assimilation quickly in many crops, including raspberry (Morales et al. 2013; Percival et al. 1998). Reductions in yield have been observed under mild water stress conditions in both red raspberry (Ortega-Farias et al. 2022) and grape (Basile et al. 2011). In Chile, Ortega-Farias et al. (2022) found that stem water potentials of 'Heritage' raspberry remained greater than –1.0 MPa when the plants were fully irrigated and ranged between –0.48 and –1.15 MPa when they were irrigated at 75% of the estimated daily water requirements. These readings were similar to those measured in the present study, as well as two previous studies on trailing blackberry (*Rubus* L. subgenus *Rubus* Watson) (Bryla and Strik 2008; Dixon et al. 2015).

Yield and fruit quality. Pulse drip had no effect on yield during the first year of the study (2018) but increased yield on multiple harvest dates the following 2 years (Fig. 2A–C). Relative to continuous irrigation, pulsing increased yield by a total of 1230 $kg·ha^{-1}$ in 2019 and 1210 $kg·ha^{-1}$ in 2020. On the basis of average market prices for processed raspberries at the time (USDA NASS 2021), yield increases with pulse drip were equivalent to $2420 to $2460/ha per year. Most of the increase occurred during the latter 3 to 4 weeks of the harvest season and was primarily due to larger fruit size in 2019 (Fig. 2E) and increased number of berries per plant in 2020 (data not shown). Others reported similar benefits to using pulse drip and found it increased production by an average of 2520 $kg·ha^{-1}$ in strawberry (Gendron et al. 2018), 335 $kg·ha^{-1}$ in green bean (El-Mogy et al. 2012), 6630 $kg·ha^{-1}$ in head lettuce (Almeida et al. 2015), 197 $kg·ha^{-1}$ in maize (El-Abedin 2006), 8382 $kg·ha^{-1}$ in onion (Madane et al. 2018), 5688 $kg·ha^{-1}$ in orange (Abdelraouf et al. 2019), 712 $kg·ha^{-1}$ in potato (Bakeer et al. 2009), and 118 $kg·ha^{-1}$ in soybean (Eid et al. 2013).

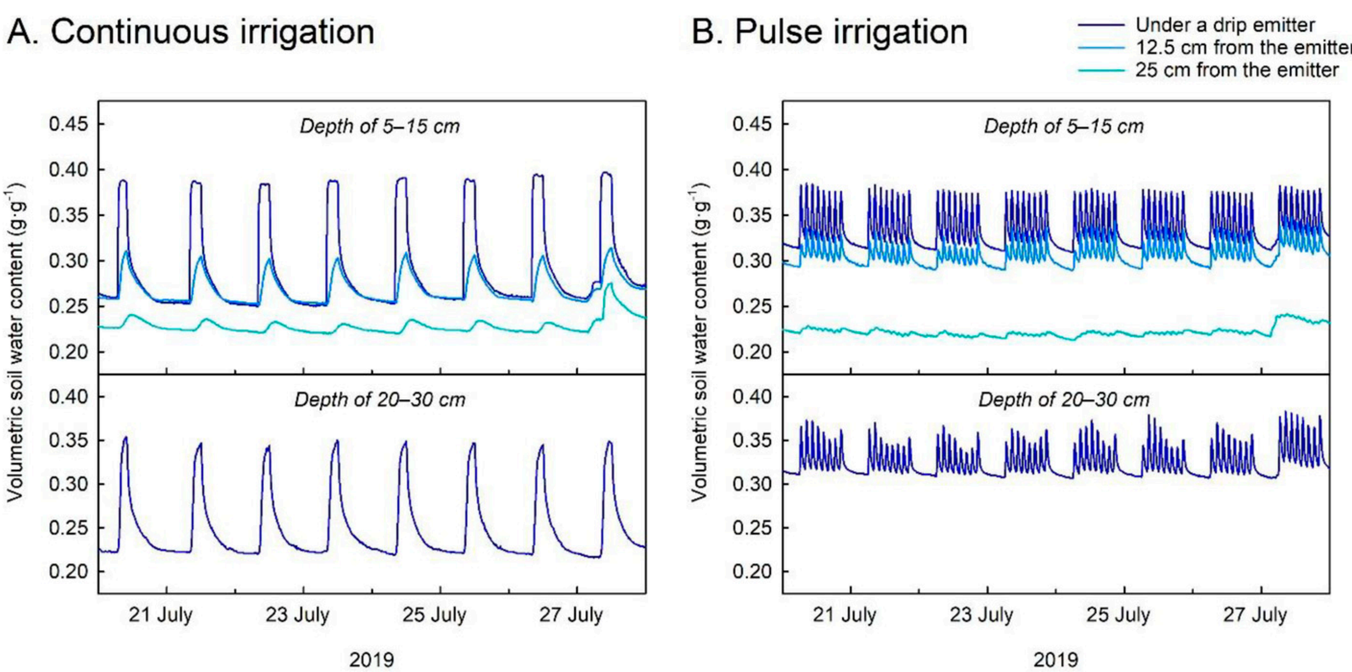

Fig. 1. Diurnal changes in volumetric soil water content with continuous (**A**) or pulse (**B**) drip irrigation in a mature field of 'Wakefield' raspberry in Lynden, WA, USA. Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment. Soil was measured at two depths (5–15 cm and 20–30 cm) under the drip emitters and at one depth (5–15 cm) at a lateral distance of 12.5 and 25 cm from the emitters.

Table 3. Effects of continuous or pulse drip irrigation on stem water potential of 'Wakefield' raspberry in Lynden, WA, USA (n = 4).[i]

	Stem water potential (MPa)	
	2019	2020
Irrigation[ii]		
Continuous	−0.76 b[iii]	−0.72
Pulse	−0.69 a	−0.71
Significance		
Irrigation	<0.001	0.239
Date	<0.001	<0.001
Irrigation × date	0.734	0.214

[i] Data were pooled across 14 sets of weekly or biweekly readings (7 Jul–15 Aug) in 2019 and 15 sets (8 Jul–15 Aug) in 2020.

[ii] Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment.

[iii] Means were separated at $P \leq 0.05$ (Tukey's honestly significant difference test).

In terms of irrigation water use efficiency, pulse drip increased productivity in the present study by ≈0.3 kg of fruit per m^3 of water applied in 2019 and by 1.3 kg of fruit per m^3 of water applied in 2020. Efficiency was much higher during the latter year due to more rain (Table 1) Pulsing resulted in similar increases in irrigation water use efficiency in other crops, including 0.3 $kg \cdot m^{-3}$ in maize (El-Abedin 2006), 0.8 $kg \cdot m^{-3}$ in orange (Abdelraouf et al. 2019), and 1.2 $kg \cdot m^{-3}$ in potato (Bakeer et al. 2009), but less increase than onion, which was 2.0 to 3.2 $kg \cdot m^{-3}$ higher with pulsing than with continuous irrigation (Madane et al. 2018). Each of these studies clearly indicate that pulsed drip irrigation has the potential to increase production while conserving water.

In addition to its influence on yield, pulsing also affected soluble solids and titratable acidity of the fruit in 2019 and 2020 (Table 4). However, the response differed between the years. In 2019, pulsing reduced soluble solids and increased titratable acidity, resulting in a lower ratio of sugars to acids in the berries than continuous irrigation. Pulsing slightly delayed fruit ripening that year (K. Berendsen, personal observations), which may account for the lower ratio. During ripening, sugars accumulate in the fruit and acids are degraded, resulting in a higher ratio of sugars to acids (Batista-Silva et al. 2018). Pulsing also increased berry weight in 2019 (Fig. 2D), which was likely due to more water in the berries. By the following year, pulsing increased soluble solids on multiple harvest dates but had no effect on titratable acidity or berry weight on any date (Table 4; Fig. 2E). Pulsing also increased the sugar-to-acid ratio at the later harvest dates, suggesting that although it had no effect on the size of the berries that year, it may have increased net assimilation in the leaves, resulting in higher transport of sucrose and other sugars into the fruit (Fernandez and Pritts 1994; Hubbard et al. 1990; Léchaudel et al. 2004; Roch et al. 2019). Recent work in grapevines found that less water-stressed plants had sufficient photoassimilates to meet C demands for sugar accumulation in the berries, whereas water-stressed plants were forced to mobilize starches within storage tissues located in the trunk and roots of the vines (Rossouw et al. 2017).

Soil and leaf nutrients. Pulse drip irrigation resulted in lower concentrations of K and B in the soil than continuous irrigation in 2020 (Table 5). Both nutrients are mobile in soil and therefore are readily leached by heavy rain and irrigation (Parker and Gardner 1982; Zeng and Brown 2000). Other nutrients in the soil, including available N, P, Ca, Mg, and Zn, were similar between the treatments during each year of the study (data not shown). Furthermore, apart from a slight increase in the concentration of Mg (0.32% vs. 0.35%; $P = 0.042$) and S (0.203% vs. 0.213%; $P = 0.021$) in the leaves in 2018, pulsing had little effect on other leaf nutrients in the plants during any year of the study (data not shown), and each nutrient was within the range recommended for red raspberry (Strik and Bryla 2015). In contrast, Xu et al. (2004) reported higher concentrations of P in the leaves when lettuce was irrigated by pulse drip and concluded the practice could compensate for shortages of P in the soil. Likewise, Assouline et al. (2006) found that pulse drip increased the concentration of N, P, and Mn in the leaves of bell pepper (*Capsicum annuum* L.), and El-Mogy et al. (2012) found that it increased N, P, and K in the shoots and pods of green bean. Because the plants in the present study were perennial,

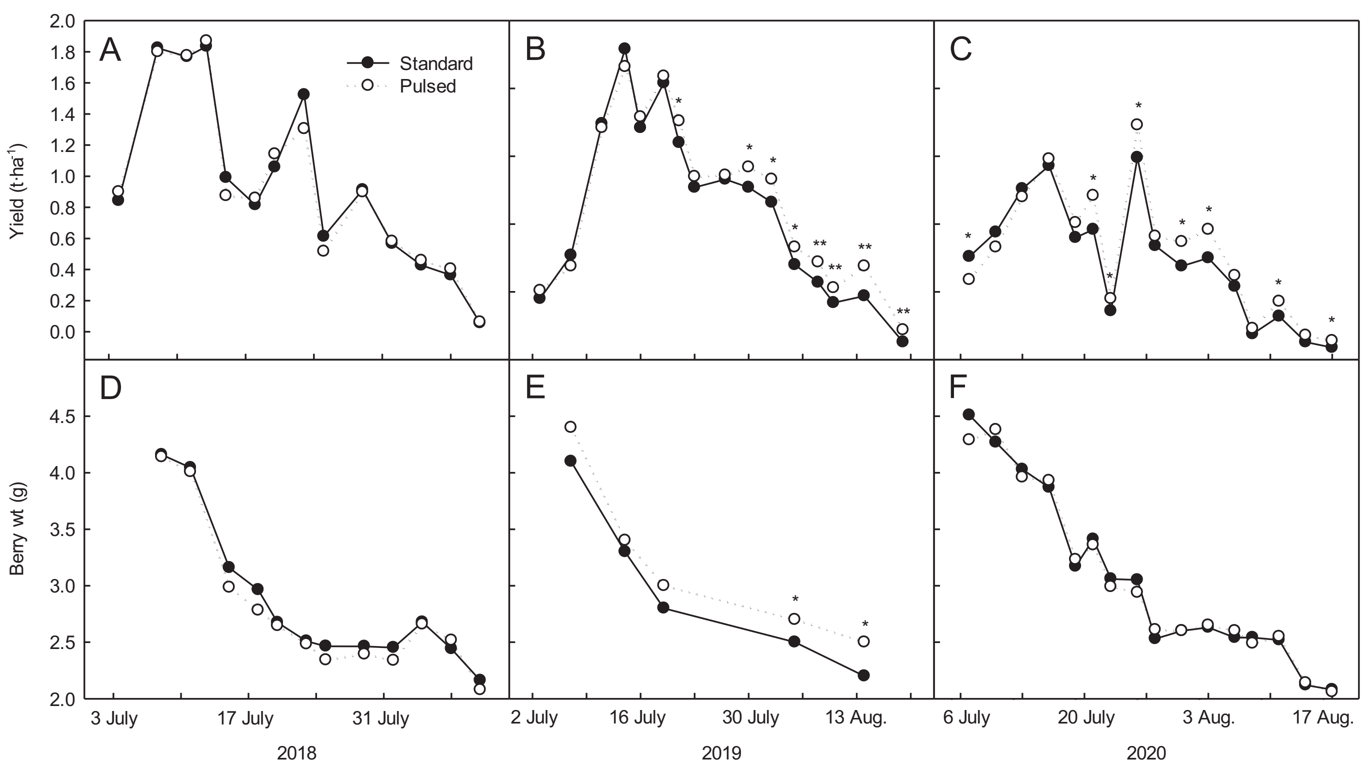

Fig. 2. Effects of continuous or pulse drip irrigation on yield (**A–C**) and berry weight (**D–F**) of 'Wakefield' raspberry in Lynden, WA, USA in 2018–20. Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment. Each symbol represents the mean of four replicates, and asterisks above the symbols indicate treatments are significantly different at $P \leq$ *0.05 or **0.01.

Table 4. Effects of continuous or pulse drip irrigation on soluble solids, titratable acidity, and the sugar:acid ratio of 'Wakefield' raspberries in Lynden, WA, USA (n = 4).

	Soluble solids (%)			Titratable acidity (%)		Sugar:acid ratio		
Factor	2019	2020		2019	2020	2019	2020	
Irrigation[i]								
Continuous	10.6 a[ii]	10.9 b		2.17 b	2.11	4.87 a	5.18 b	
Pulse	10.2 b	11.2 a		2.24 a	2.07	4.56 b	5.42 a	
Harvest		Continuous	Pulse				Continuous	Pulse
Early	10.8 a	10.5 bc y	10.5 c y	2.27 a	2.32 a	4.76 ab	4.54 d y	4.54 c y
Early-mid	9.6 b	10.0 c z	10.6 c y	2.13 b	2.00 cd	4.52 b	5.02 c y	5.24 b y
Mid	9.1 b	11.0 b y	10.5 c z	1.98 c	1.90 d	4.58 ab	5.67 a y	5.61 ab y
Mid-late	11.1 a	10.7 b z	11.6 b y	2.26 ab	2.01 c	4.94 a	5.55 bc z	5.89 a y
Late	11.2 a	12.3 a z	12.7 a y	2.36 a	2.21 b	4.77 ab	5.66 ab z	5.85 a y
Significance								
Irrigation	<0.001	0.004		<0.001	0.116	0.038	<0.001	
Harvest	0.007	<0.001		0.034	<0.001	<0.001	<0.001	
Irrigation × harvest	0.860	<0.001		0.955	0.394	0.902	0.005	

[i] Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment.

[ii] Means were separated at $P \leq 0.05$ (Tukey's honestly significant difference test). Letters a–d are used to compare means in a column, and letters y and z are used to compare means in a row.

Table 5. Effects of continuous or pulse drip irrigation on the concentration of K and B in a mature field of 'Wakefield' raspberry in Lynden, WA, USA (n = 4).[i]

Irrigation[ii]	Soil K ($mg \cdot kg^{-1}$)	Soil B ($mg \cdot kg^{-1}$)
Continuous	346 a[iii]	1.09 a
Pulse	283 b	0.79 b
Significance	0.029	0.049

[i] Soil was collected on 3 Oct 2020.

[ii] Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment.

[iii] Means were separated at $P \leq 0.05$ (Tukey's honestly significant difference test).

it is possible that nutrients stored in the crown and roots dampened the effects of pulsing on nutrients in the leaves. Furthermore, we did not measure nutrients in the fruit. A previous study in Oregon revealed that ripe raspberry fruit contains 2% to 27% of the total nutrients in the plant (Strik and Bryla 2015). Relative to daily continuous water applications, pulse drip irrigation increased nutrients in the fruit of some crops, including Mn in bell pepper (Assouline et al. 2006) and N in tomato (Bar-Yosef et al. 1980).

Production of new primocanes and floricanes. Pulse drip had no effect on plant growth in 2018 but increased canopy cover by a total of 6.5% in 2019 and 5.2% in 2020 (Table 6). Pulsing also increased the diameter of the floricanes and primocanes (before and after pruning) in 2020 and 2021. Larger cane diameter has been linked to higher yields and greater fruit weight in red raspberry (Dale 1986; Dale and Daubeny 1985). Crandall et al. (1974) also found that larger diameter canes contained more carbohydrates per node, which resulted in more berries per plant and a higher percent fruit set. Thus, pulse irrigation likely increased fruit production for at least a year after the season it was applied.

Conclusions

Pulse drip irrigation provided numerous benefits in red raspberry, including increased vegetative growth, higher yields, and greater water productivity than irrigating conventionally using single continuous applications. These benefits were largely related to changes in plant and soil water relations. For example, by increasing soil water content, pulsing also increased stem water potential in the plants during warmer and drier periods, coinciding with peak harvest in July during the second year of the study. Pulsing also increased cane diameters and canopy cover relative to continuous irrigation, which likely increased fruit production the following year. However, there were also a few negative effects of pulsing. Specifically, pulse drip irrigation reduced the sugar-to-acid ratio in the berries during the second year of the study but increased it the following year. Furthermore, pulsing reduced the concentrations of K and B in the soil but increased the concentrations of Mg and S in the leaves. In each case, the response was slight and occurred for only 1 year. All other nutrients in both the soil and leaves remained unaffected by pulsing during any year of the 3-year study. Overall, the results indicate that pulse drip irrigation could provide a means to maximize productivity in red raspberry and better prepare the industry against future water uncertainties.

Table 6. Effects of continuous or pulse drip irrigation on canopy cover and number and diameter of floricanes and primocanes in a mature field of 'Wakefield' raspberry in Lynden, WA, USA (n = 4).

						Primocanes			
	Canopy cover (%)[ii]			Floricanes[iii]		Before pruning[iii]		After pruning[iv]	
Irrigation[i]	2018	2019	2020	No./plant	Diam (mm)	No./plant	Diam (mm)	No./plant	Diam (mm)
Continuous	49.2	48.9 b[v]	53.0 b	5.3	9.9 b	10.4	10.7 b	7.7	10.0 b
Pulse	47.5	55.4 a	58.2 a	6.5	11.0 a	11.0	11.6 a	9.1	11.0 a
Significance	0.669	0.004	0.012	0.090	0.012	0.676	0.011	0.052	0.007

[i] Continuous irrigation was applied for up to 4 h per day, as needed. Pulse irrigation was applied 30 min every 2 h, up to eight times per day, using about the same amount water as the continuous treatment.

[ii] Measured on 26 Sep 2018, 18 Sep 2019, and 30 Sep 2020.

[iii] Measured on 3 Oct 2020 (before pruning).

[iv] Measured on 15 Mar 2021 (after pruning).

[v] Means were separated at $P \leq 0.05$ (Tukey's honestly significant difference test).

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