horticulturae

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Irrigation Management with a Field Water Balance and Virus Incidence in Dahlia Cut Flowers

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Highlights

What are the main findings?

- We determined crop coefficient (Kc) values for the vegetative and reproductive stages of dahlia cut flower production using the field water balance method.
- We documented the prevalence of dahlia mosaic virus and found cultivar-specific plant responses to multiple infections.

What are the implications of the main findings?

- Our guidelines for irrigation and virus management can be used to reduce water use, promote plant health, and improve the predictability of harvest timing and yield in cut flower production.

Abstract

Irrigation guidelines are needed for the field production of emerging specialty crops to support the sustainability and economic viability of small farms. The goal of this study was to establish crop coefficients (K_c) of dahlia (*Dahlia* × *hybrida*), a popular, profitable cut flower crop, while documenting virus infection. A two-year field study was conducted with two industry-important cultivars that vary in production timing and bloom: ‘Boom Boom White’, an earlier and mid-sized formal decorative, and ‘Café au Lait’, a later and large informal decorative bloom type. A field water balance was used to evaluate five irrigation rates (I), as a percentage of the estimated crop evapotranspiration, ET_c: 100% of ET_c (I_{100}), two deficit irrigation (DI) rates of 80 and 60% (I_{80} and I_{60}), and two regulated deficit irrigation (RDI) rates during the vegetative stage ($I_{80/100}$ and $I_{60/100}$). The K_c of both cultivars were 1.0 during the vegetative stage and 1.1 during the reproductive stage and estimated to be 0.7 during establishment. Both DI and RDI delayed and reduced yields, while virus infection led to cultivar-specific responses. ‘Café au Lait’ had greater sensitivity to viral infection and water stress, particularly when under co-infection with two or more viruses; this occurred for ‘Boom Boom White’ with three viruses.

Keywords: deficit irrigation; evapotranspiration; crop coefficient; dahlia mosaic virus; soil moisture

Academic Editor: Jinzhi Zhang

Received: 10 July 2026
Revised: 7 August 2026
Accepted: 19 August 2026
Published: 2 September 2026

1. Introduction

Agricultural irrigation accounts for up to 90% of the water use in the Western U.S. [1] where drought, interannual variability in precipitation, and intensifying urban demand for water and land add growing pressure on resources [2]. In this region, water conservation strategies and the adoption of high-value specialty crops are essential for farm economic viability [3,4]. Cut flower crops offer premium returns with limited land use and have surged in popularity [5]. U.S. production reached $800 million in 2022, a 13% increase over a five-year period [6], yet irrigation management remains largely undefined for field production [3].

Dahlia (*Dahlia* × *hybrida*) is one of the most profitable crops for small and urban farms because of its short post-harvest life, market demand, and pricing [7,8]. In a survey across North America, dahlia was the fifth most common cut flower field crop (74% of 194 respondents) [9]. In Utah, dahlia reached a reported gross income equivalent of $939,000 per hectare [10] and was the top crop to source locally for 89% of surveyed florists [11]. As neither crop coefficients (K_c) nor soil moisture thresholds are established for dahlia, farms primarily rely on their intuition, word-of-mouth with other farms, and basic guidelines from associations and Cooperative Extension. These general recommendations included moist, well-drained soil with 2.5 to 3.8 cm of water per week, and originated in low-elevation, humid regions with long growing seasons and soils with higher organic matter and low salinity (e.g., [12–14]). Establishing the physiological stages and associated K_c would increase the crop's sustainability while maintaining profitability.

Dahlia, a tuberous crop native to Mexico [15–17], may have three physiological stages relevant to irrigation management: (1) establishment, (2) vegetative, and (3) reproductive. From greenhouse trials, 5.5 °C is the base temperature for growth, 15 to 20 °C promotes tuber formation, and flowering is optimized at 25 °C and limited at 30 °C [18]. Reproductive and leaf tissues are damaged at supraoptimal temperatures of 35 °C or more [19,20]. Across ten field sites in southern Brazil (Hardiness Zone 10a, 50 to 700 m elevation, 1300 mm annual precipitation), the vegetative stage included establishment, defined as the period from shoot emergence to the appearance of the first floral bud [15]. This lasted up to 55 calendar days (in thermal time: 940 °C·days). The reproductive stage, from first bud to the opening of the first layer of petals, then lasted 11 to 29 calendar days (180 to 275 °C·days), depending on the cultivar and location [15]. In Orono, Maine [Hardiness Zone 5a, 45 m elevation, 1026 mm annual precipitation], thermal time was not calculated but the vegetative stage (emergence to first bud) lasted 57 calendar days, first bud to flower opening took 17 days, and the total reproductive stage (first bud to first frost) was 51 days for 'Blizzard', a mid-sized (8 cm diameter), white, formal decorative bloom type [21]. For 'Café au Lait', a large (20 cm diameter) and popular, blush, informal decorative bloom type associated with late-season maturity, the vegetative stage lasted 79 days, bud to flower opening took 24 days, and the total reproductive stage was 43 days [21]. These findings established baseline timing for the vegetative stage, which had the greatest effect on the onset of bloom production, differences between cultivars, and the limited duration of the reproductive stage in temperate climates.

Growth stages can become prolonged in regions with conditions outside of a crop's optimum range, reducing yield [21,22] and K_c [23]. In Northern Utah (lat. 41.77 N, long. 111.81 W, Hardiness Zone 6a, 1380 m elevation), the day/night temperature differentials are up to 16 °C during the freeze-free growing season (from the 30-year normal, 1991–2020, [24]). This results in hourly temperatures frequently outside of the optimal range for vegetative growth, tuber formation, and flowering of dahlia. For 'Café au Lait', an extended vegetative stage truncated the duration of the reproductive stage, decreasing yield potential, especially in years with additional temperature variability [7]. For example, the vegetative stage lasted 74 to 88 calendar days (thermal time: 955 to 1051 °C·days) depending on temperature, moisture conditions, and plant health [7]. The reproductive stage lasted 44 to 64 calendar days (488 to 642 °C·days), ending with the first freeze date, which can be as early as late August, for a minimum freeze-free growing season of 94 days [25]. Regions with limiting growing conditions underscore the need for refined irrigation strategies that balance crop stress without further delays to production.

Although not studied in dahlia, sensitivity to water stress through soil moisture depletion is crop-specific and can delay harvest and decrease yield by reducing transpiration [26–28]. In drip-irrigated loams, the soil potential threshold for shallow-rooted and tuberous crops ranged from −10 kPa in onion (*Allium cepa* L.) to −25 kPa in potato (*Solanum tuberosum* L.), while that for tomato (*Solanum lycopersicum* L.), a mid-sized and warm-season crop, was −50 kPa [29–31]. A form of deficit irrigation (DI), regulated deficit irrigation (RDI) restricts water only at growth stages that are less sensitive to soil moisture stress, which induces partial stomatal closure and root growth to increase water-use efficiency while minimizing yield loss [32,33]. For example, in potato, RDI at 80% and 70% during the establishment and vegetative stages, followed by full irrigation during and after bulking, had the greatest water-use efficiency and no significant yield differences from plants maintained with 110% irrigation [34]. For cauliflower (*Brassica oleracea* var. *botrytis* L.) and sunflower (*Helianthus annuus* L.), yield did not change with RDI during the vegetative stage, but decreased by 9 and 4%, respectively, when applied during the reproductive stage [35,36]. In tomato, water stress during the reproductive stage caused flower abortion [37,38] but 60% RDI during the vegetative stage resulted in a significant 4% increase in yield, compared to those fully irrigated or at 80% DI [38]. Although crop-specific, avoiding RDI after the vegetative stage avoided yield loss and may be a conservation strategy for water-limited regions.

The popularity and profitability of dahlia drive the need for research-based management to optimize production timing and yield with water use. Quantifying irrigation guidelines requires evaluating the timing of physiological stages of high-demand cultivars and bloom types, and assessing soil and environmental factors to determine actual crop evapotranspiration (ET_a) and K_c. This may be complicated by the prevalence of viruses in plant stock, which is asexually propagated. Across studies and states in the U.S., most plants tested positive for at least one of three dahlia mosaic viruses [7,39,40]. Symptoms included chlorosis, as well as deformed and stunted growth, with asymptomatic infections also occurring and increasing the spread of diseased plants [39,40]. While the yield and economic impacts were not quantified, the general decrease in plant productivity is likely to reduce yield [39]. Moreover, the interaction of virus infection with water stress is unknown. Therefore, field-based research on irrigation strategies and crop coefficients should be evaluated with cultivar response and virus status.

The goal of this study was to estimate ET_a and develop K_c with a field water balance method for the (1) establishment, (2) vegetative, and (3) reproductive stages of two industry-important dahlias, 'Café au Lait' and 'Boom Boom White', a mid-sized (10 cm diameter), white formal decorative bloom, similar to 'Blizzard'. The physiological stages are defined by Doorenbos and Kassam [41] for sunflower (*Helianthus annuus* L.), and are analogous to (1) initial, (2) development, and (3) mid-season in Pereira [23]. While identifying virus infection, crop response to DI, RDI, and soil moisture was also evaluated to establish the viability of water conservation strategies for dahlia cut flower production in the high elevation U.S. Intermountain West. Virus status was evaluated as an additional biological factor when interpreting irrigation responses. We hypothesized that bloom timing would be delayed and yield would decrease for dahlia irrigated with DI and RDI at 60% of the estimated crop evapotranspiration (ET_c), compared to those irrigated at 80% and 100% of

https://doi.org/10.3390/horticulturae12091093

ET_c. Because of the variability in dahlia response to virus infection, we hypothesized that the effects of irrigation would interact with virus infection status and cultivar, with virus-infected 'Café au Lait' showing a less predictable response to irrigation than virus-infected 'Boom Boom White'.

2. Materials and Methods

2.1. Site and Plant Stock Description

The field study was conducted from May to October in 2023 and 2024 at the Utah State University (USU)–Greenville Research Farm in North Logan, UT, USA (lat. 41.77 N, long. 111.81 W, 1382 m elevation, 135 freeze-free days, USDA hardiness zone 6a). The soil is classified as a Millville silt loam with 2% organic matter [42], a bulk density of 1.37 g cm^{-3}, and field capacity and permanent wilting point at volumetric water contents, θ_v, of 0.25 and 0.10 m^3 m^{-3}, respectively [43]. The field was 31.7 m × 18.2 m and consisted of 22 rows oriented north to south, each 0.5 m wide, 18.2 m long, and spaced 1.5 m on center with weed barrier fabric (116 g Weed Barrier, Dewitt, Sikeston, MO, USA) between rows. Up to three weeks prior to transplant each year, the field was tilled, and the soil was sampled for nutrient analysis. Primary macronutrients were applied based on soil tests [7,44] and two split applications of chelated iron totaled 1.4 kg EDDHA-Fe ha^{-1} (0-0-0-6, Ferriplus, Miller Chemical and Fertilizer LLC, Hanover, PA, USA) per season [45].

Drip irrigation was supplied by five headers oriented east to west across the field, subdividing each row into five 0.5 × 3.7 m plots for a total of 100 plots. Each plot had one line of drip tape (flow rate: 5.1 L min^{-1} at 30.5 m^{-1}, Aqua-Traxx, Toro, Bloomington, MN, USA) from the header with a valve to manually control the irrigation duration. Five irrigation treatments (I) were replicated ten times for each of the two cultivars, 'Boom Boom White' (B) and 'Café au Lait' (C), with each (I) represented per row in a completely randomized design. The field was maintained near field capacity during the establishment stage, which began at transplant (23 May 2023 and 30 May 2024) and lasted until 13 June 2023 and 20 June 2024 (approximately 22 calendar days each year). The irrigation treatments (I) began on 12 June each year and ended on 20 October 2023 and 11 October 2024. The average initial volumetric water content (θ_v) at 0.08 m depth at midnight on 12 June was 0.21 and 0.22 m^3 m^{-3} in 2023 and 2024, respectively. Irrigation events occurred three times per week (Monday, Wednesday, and Friday), beginning at 10:00 am local time, unless a precipitation event greater than 10 mm occurred.

Irrigation treatments followed percentages of estimated crop evapotranspiration (ET_c) that were calculated as $ET_r \times K_c$, with ET_r as the reference evapotranspiration for a tall crop, reported by the Greenville Farm weather station located 0.2 km from the field [25]. These included: 100% of ET_c (I_{100}) and DI of 80% (I_{80}) and 60% (I_{60}). The other two followed RDI through the vegetative stage at 80 and 60% and then increased to 100% of ET_c at the reproductive stage: $I_{80/100}$ and $I_{60/100}$. The onset of the reproductive stage was defined as the date when 50% of the plants reached first bud within each cultivar and lasted until the first freeze date, and hence the end of the growing season each year. From this, the durations of the vegetative stage were 14 June–29 July (46 calendar days) for B and 14 June–12 August (60 days) for C in 2023, and 21 June–18 August (59 days) for B and 21 June–20 August (61 days) for C in 2024. The reproductive stage lasted 30 July–27 October (90 days) for B and 13 August–27 October (76 days) for C in 2023, and 19 August–16 October (59 days) for B and 21 August–16 October (57 days) for C in 2024.

In 2023, K_c was conservatively assumed to be 1.0 throughout the field season. In 2024, K_c values were applied with I: 0.64 (12 June–7 July), 0.7 (8 July–14 July), 0.9 (15 July–18 July), 1.0 (19 July–11 August), and 1.1 (12 August–13 October). From this, the total measured water applied across cultivars with I_{100} was 645 mm, P was 210 mm, and ET_r was 722 mm from 12 June to 20 October 2023 (i.e., I_{100} was 90% of ET_r and I_{100} + P was 118% of ET_r). The total water applied with DI across cultivars was 516 mm with I_{80} and 387 mm with I_{60}. Based on differences in maturity timing by cultivar in 2023, RDI was 581 mm for B and 535 mm for C in $I_{80/100}$, and 517 and 425 mm for B and C, respectively, in $I_{60/100}$. In 2024, 664 mm of water was applied with I_{100}; P was 43 mm, and ET_r was 700 mm from 12 June to 13 October 2024 (i.e., I_{100} was 92% of ET_r and I_{100} + P was 97% of ET_r). The other I totaled 584 mm with $I_{80/100}$, 531 mm with I_{80}, 504 mm with $I_{60/100}$, and 398 mm with I_{60}.

Plant stock was propagated annually in the USU Research Greenhouse Complex at 21 to 22 °C with a 16 h photoperiod [18]. The outermost rows on the east and west sides of the field were guard rows; B was transplanted into the ten interior east rows, and C was in the ten interior west rows. The two cultivars were established as separate experiments because the objective was to evaluate irrigation response with virus status within each representative dahlia type, rather than compare cultivars. Given known differences in growth, bloom timing, bloom size, and yield, the field design also facilitated irrigation, harvest, and other management practices to be tailored to each cultivar. Plots had five plants spaced 0.6 m apart in-row, for a total of 50 plots and 250 plants per cultivar. As dahlia stock is prone to virus infection [7,10] and lab tests require several months, two approaches were used to reduce incidence. In 2023, B and C tubers were sprouted, grown for four weeks in the greenhouse, and hardened off for one week prior to transplant. This allowed for an initial screening through visual observation of the leaves [10]. Plants with visual symptoms of virus were culled, and asymptomatic plants were transplanted after the average last freeze date on 22 and 23 May 2023. After establishment in June 2023, a leaf sample was collected from each plant and tested for: Endogenous plant pararetroviral sequence (DvEPRS; formerly DMV-D10), Dahlia common mosaic virus (DCMV; formerly DMV-Holland), and Dahlia mosaic virus (DMV; formerly DMV-Portland) [7]. DNA was extracted from each leaf using the DNEasy Plant Mini kit (Qiagen, Germantown, MD, USA) following the manufacturer's instructions. Polymerase chain reaction (PCR) tests were conducted using the repliQa HiFi ToughMix (Quantabio, Beverly, MA, USA) and species-specific primers for each virus [40,46]. PCR products were visualized in a 1% agarose gel stained with ethidium bromide. Plants were considered positive when a PCR band of the expected size was obtained. In 2024, cuttings of B were sprouted from tubers that tested negative for DCMV and DMV in 2023, while certified virus-free cuttings were sourced for C (Syngenta Flowers, Gilroy, CA, USA). To produce plugs, cuttings were treated with rooting gel (Clonex, Lansing, MI, USA), grown for 10 weeks, hardened off for two weeks, and transplanted on 30 May 2024. Crop health was visually inspected and recorded weekly for every plant. This included visual virus symptoms, pest damage, and death.

2.2. Crop Parameters

During the vegetative stage, the weekly height (in mm) and canopy area (in %) of one plant per replicate (i.e., 10 plants per cultivar × I) were measured within I_{100}, I_{80}, and I_{60}, beginning on 14 June 2023 and 11 June 2024. The canopy area was measured at 1 m above the canopy, between 12:00 and 1:00 pm local time, with the Canopeo Application (Canopeo Software, Stillwater, OK, USA) [47].

Yield per plant was evaluated based on local farm and cooperative feedback regarding the stage of flower opening, bloom quality, minimum stem length, and corresponding florist market pricing [48]. For both cultivars, undamaged stems longer than 0.46 m were classified as M1, the highest quality and price grading. An M2 grade indicated stem lengths of 0.36 to 0.46 m for B and 0.25 to 0.46 m for C. Any shorter stems, or misshapen or damaged blooms, were culled. The wet mass of tubers was measured to the nearest 0.01 kg after each growing season. Dead plants were excluded from stem and tuber yield calculations, while plants having virus symptoms or with zero stem yield were included. The average total marketable stem yield (MT) per year was calculated as the sum of all M1 and M2 stems per plant and averaged within each cultivar × I. To assess harvest timing, the date of first harvest (FH) was recorded, and yield thresholds (Y) of 20%, 50%, and 80% (denoted Y20, Y50, and Y80, respectively) of the total seasonal marketable yield were also calculated per cultivar × I. These, as well as the duration of the physiological stages, with establishment grouped with the vegetative stage [15] were analyzed in thermal time. Hourly thermal time was calculated using the hourly reference air temperature, T_A in °C, at a 3 m height from the USU–Greenville Research Farm weather station [25], a base temperature (T_{BASE}) of 5.5 °C, and a maximum temperature for growth and flowering (T_{MAX}) of 30 °C [18]. If $T_{BASE} < T_A < T_{MAX}$, then daily accumulation (°C·days) was the 24 h sum [49]:

$$^{\circ}\mathrm{C{\cdot}days} = \sum \frac{T_A - T_{BASE}}{24}, \quad (1)$$

The statistical analysis was conducted for each cultivar and year using the PROC GLIMMIX function in SAS Studio (SAS 9.4, SAS Institute Inc., Cary, NC, USA) with a significance level of 0.1. The significance level was chosen to account for the relatively large biological variability known in dahlia crops (e.g., plant behavior and virus response), limitations with sample size, and the inherent environmental variability with field settings. In addition, this study was exploratory to determine trends that will be important for industry. Therefore, although some results may not be statistically significant at the $p = 0.05$ level, the observed trends may be relevant and impactful for growers, Cooperative Extension, consultants, and other industry stakeholders. The random effects in the mixed model were rows and plots within rows. The negative binomial distribution was used for MT, M1, and M2 response variables. The lognormal distribution was used for Y timing response variables, while wet tuber mass was log-transformed and used the normal distribution. The Tukey–Kramer method was used to adjust for multiplicity in the least squares means. With virus data only obtained for 2023, the interaction between the effects of I and virus infection, V, was tested in 2023, but not in 2024. Since all plants were infected with DvEPRS, plants with only DvEPRS were compared to plants with additional infections of either DCMV or DMV, or both DCMV and DMV.

2.3. Environmental Sensing and Water Balance

To estimate ET_a in mm on a daily time step, the following field water balance was used:

$$ET_a = P + I - \Delta S, \quad (2)$$

The weather station at the USU–Greenville Research Farm recorded P and calculated ET_r by the American Society of Civil Engineers Standardized Reference ET method [25]. Irrigation inputs, I, were measured with one flow meter per header (DLJSJ50C, Daniel L. Jerman Co., Hackensack, NJ, USA). The daily change in soil water storage, ΔS, of the root zone was calculated as the difference in hourly volumetric water content (θ_v) at midnight per day [50]. The θ_v and temperature of the soil (T_S) were measured at depths of 0.08 m and 0.2 m using time domain reflectometry sensors (TDR315 and TDR310, Acclima, Inc., Meridian, ID, USA), with three sensors at 0.08 m and one at 0.2 m installed per cultivar × I. Data loggers (CR1000 and CR300, Campbell Scientific, Inc., Logan, UT, USA) scanned every 2 min, from which hourly and daily averages were recorded. A surface layer with a thickness of 0.2 m was defined for θ_v at 0.08 m. Once in the reproductive stage, ΔS included a lower layer of 0.1 m thickness that was measured by θ_v at 0.20 m. There was no surface runoff, and deep percolation was determined to be negligible based on irrigation management and monitoring of soil moisture after precipitation events.

ET_a was then summed on a weekly time step by cultivar × I each year, defined as each Sunday to Saturday from 4 June to 8 October 2023 and 2 June–6 October 2024. The K_c was calculated for each cultivar × I from the cumulative weekly ET_a as:

$$K_c = \frac{ET_a}{ET_r} \quad (3)$$

Weekly K_c values were averaged within establishment, vegetative, and reproductive physiological stages by cultivar × I each year. Weeks with more than 20 mm of precipitation [50] or frost events were excluded from K_c calculations, resulting in only one measurement week (from 2023) used to calculate the establishment stage. A total of 14 measurement weeks were used for the vegetative stage (six measurement weeks in 2023 and eight weeks in 2024), while the reproductive stage had six weeks in 2023 and seven weeks in 2024, for a total of 13 measurement weeks. Note: here, K_c refers to $K_{c\ (alfalfa)}$, and we also report $K_{c\ (grass)}$, which is K_c relative to ET_o (short reference ET) in the standard climate (minimum relative humidity of 45%, wind speed at 2 m height of 2 m s^{-1}). This was calculated using the FAO 56 method for adjusting K_c values for climate [23].

3. Results

3.1. Environmental Conditions and Timing of Physiological Stages

From 1 May to 31 October 2023, the average daily minimum T_A was 10.1 °C and the maximum was 24.4 °C, near the 30-year normal, while 2024 had a lower average minimum T_A of 9.8 °C and a higher average maximum of 25.8 °C (Table 1). In May 2023, the average daily minimum and maximum T_A were 2 °C warmer than normal, while May 2024 was 2 °C lower than normal. Hourly T_A exceeded 30 °C for 223 h in July and August 2023, while in 2024, T_A exceeded this threshold for 381 h, beginning in June and lasting through September. Additionally, on 18 June 2024, the T_A was between 1.2 and 3.3 °C for 9 h, during which radiative frost occurred. This cool period was followed by maximum T_A between 25 and 34 °C each day from 20 to 30 June 2024, for a total of 125 h (52% of the time) at an average of 4 °C above normal. There were a total of 1780 °C·days accumulated during the 2023 growing season (23 May–27 October) and 1740 °C·days in 2024 (30 May–16 October). From 1 May to 31 October, cumulative precipitation was three times greater in 2023 (290 mm) than in 2024 (95 mm) (Table 1). The ET_r was 990 mm in 2023 and 1018 mm in 2024, with differences between years most pronounced in May and June (Table 1).

Table 1. The average monthly conditions in Logan, UT, from 1 May to 31 October, in 2023 and 2024 [25], with 30-year normals (1991–2020, [24]).

Month	T_A (°C)							P (mm)			ET_r (mm)	
	Min/Max			Hours < 15 °C		Hours > 30 °C						
	2023	2024	30-Yr	2023	2024	2023	2024	2023	2024	30-Yr	2023	2024
May	8.1/22.1	4.1/18.0	6.9/19.3	449	552	0	0	41	29	61	187	164
June	9.8/23.6	12.1/28.3	11.1/25.5	343	189	0	86	58	7	32	170	219
July	15.6/32.2	15.1/32.0	15.7/31.2	53	81	166	164	5	21	7	237	227
August	14.9/28.7	13.6/30.3	14.9/30.3	86	134	57	105	64	14	18	185	189
September	9.2/24.1	9.9/26.3	10.0/24.2	379	318	0	26	57	8	34	135	136
October	3.3/16.1	4.3/20.2	3.7/15.9	634	548	0	0	65	16	47	76	83
Avg or Total	10.1/24.4	9.8/25.8	10.4/24.4	1944	1822	223	381	290	95	199	990	1018

T_A: reference air temperature; P: cumulative precipitation; ET_r: tall reference evapotranspiration; Min: minimum; Max: maximum.

Peak T_S generally occurred in June and July each year (Figure 1). Within B in 2023, the daily maximum T_S of I_{80}, $I_{60/100}$, and I_{60} exceeded 30 °C for 24 to 26% of days from 10 June to 30 August, while I_{100} and $I_{80/100}$ did so for 9 to 13% of days (Figure 1). For C during the same period in 2023, the daily maximum T_S of I_{80}, $I_{60/100}$, and I_{60} exceeded 30 °C on 19 to 28% of days, while I_{100} and $I_{80/100}$ did for 7% to 18% of days. Across I and cultivars in 2023, the daily minimum T_S was below 15 °C from transplant until the end of June and from mid-September through the end of the season (Figure 1). In 2024, the percentage of days with a maximum T_S above 30 °C ranged from 4 to 47% across I and cultivars, and TS was below 15 °C only in October (Figure 1).

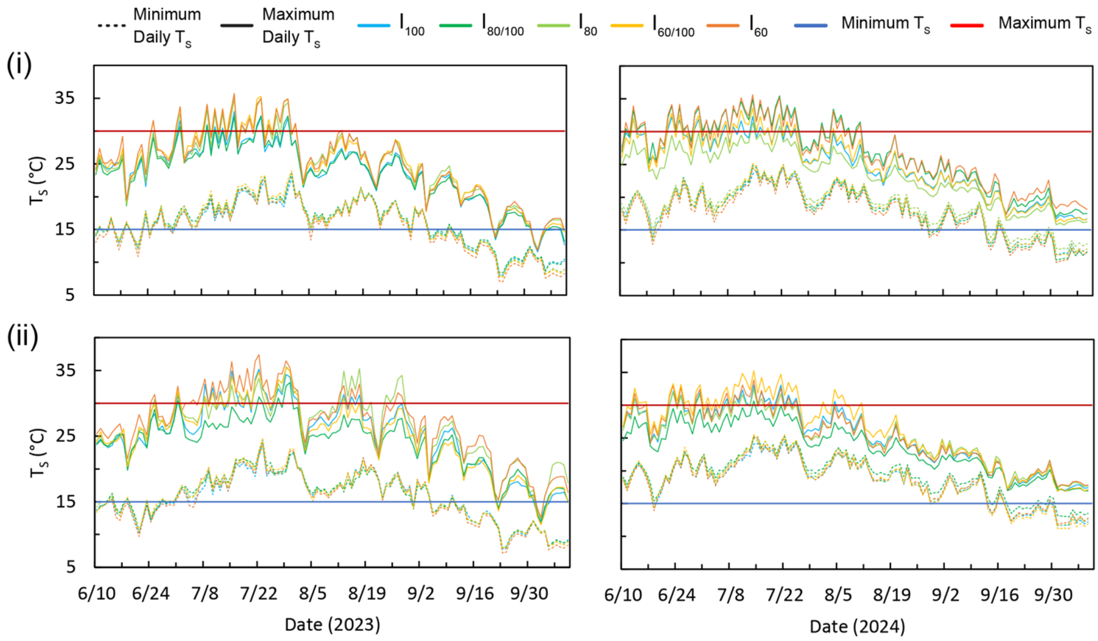

Figure 1. The average daily minimum (dashed lines) and maximum (solid lines) soil temperature, T_S in °C, at a 0.08 m depth by irrigation rate, I, and cultivar, **(i)** 'Boom Boom White' (B) and **(ii)** 'Café au Lait' (C), from 10 June to 5 October in 2023 and 2024.

The duration of the vegetative stage of B was 580 °C·days (46 calendar days) in 2023 and 780 °C·days (59 days) in 2024. At the end of the vegetative stage (i.e., onset of bloom), canopy coverage ranged from 25% in I_{60} to 27% in I_{80}, and 35% in I_{100} in 2023; this was 49% in I_{60}, 59% in I_{80}, and 62% in I_{100} in 2024. The reproductive stage of B lasted 940 °C·days (90 days) in 2023 and 680 °C·days (59 days) in 2024. For C, the duration of the vegetative stage was 780 °C·days (60 days) in 2023 and 810 °C·days (61 days) in 2024, and its reproductive stage lasted 730 °C·days (76 days) in 2023 and 650 °C·days (57 days) in 2024. The canopy reached 22% in I_{60}, 23% in I_{80}, and 24% in I_{100} in 2023, and 43% in I_{60}, 51% in I_{80}, and 61% in I_{100} in 2024.

3.2. Plant Health and Mortality

All tested B and C plants were positive for DvEPRS in 2023. The percentage of plants with DvEPRS-only and those with additional infections of DCMV, DMV, or all three ranged across cultivars and I (Tables 2 and 3). Of the 50 B plants transplanted within each I, 20 to 58% tested positive for DvEPRS-only, 22 to 56% had DvEPRS and DCMV, 0 to 28% had DvEPRS and DMV, and 6 to 20% had all three viruses (Table 2). No B plants died in 2023, but eight of the 250 total B plants were not tested for virus status and thus excluded from analysis (Table 4). In 2024, five of the 250 B plants died: two in I_{80}, and one in each of I_{100}, $I_{60/100}$, and I_{60}. Of the 50 C plants transplanted within each I, 20 to 44% tested positive for DvEPRS only, 14 to 40% had DvEPRS and DCMV, 0 to 10% had DvEPRS and DMV, and 2 to 12% had all three viruses (Table 3). In 2023, 61 of 250 C plants were excluded from analysis:

30 were not tested due to a handling error, and 31 plants died: seven in each of I_{100} and $I_{60/100}$, five in $I_{80/100}$, eight in I_{80}, and four in I_{60} (Table 4). Of these 31 plants, 14 died before leaf tissue could be sampled for virus testing, and the virus status of the 17 plants that died after sampling is reported in Table 4. No C plants died in 2024.

Table 2. The virus status of 'Boom Boom White' (B) in 2023, with the number of infected plants and crop production metrics given as means (standard error) of yield (stems/plant), timing (°C·days), and wet tuber mass (kg/plant) with significance by the main effects of irrigation rate (I) and virus (V) and their interaction (I × V).

Virus Status [1]	Metric	Significance [2]			Irrigation Rate				
		I	V	I × V	I_{100}	$I_{80/100}$	I_{80}	$I_{60/100}$	I_{60}
DvEPRS [3], *n* = 86	n_1, n_2	-	-	-	*29, 0*	*14, 0*	*19, 0*	*10, 0*	*14, 0*
	M1	*	-	-	12 [a] (1.4)	12 [ab] (2.0)	10 [ab] (1.5)	15 [a] (3.0)	7 [b] (1.2)
	M2	NS	-	-	11 (1.1)	13 (1.8)	13 (1.6)	10 (1.7)	10 (1.5)
	MT	NS	-	-	24 (1.6)	25 (2.4)	23 (1.9)	25 (2.8)	18 (1.8)
	FH	NS	-	-	1030 (40)	1040 (60)	1070 (60)	1140 (90)	1250 (70)
	Y20	NS	-	-	1270 [a] (30)	1300 [ab] (40)	1330 [ab] (40)	1370 [ab] (50)	1410 [b] (40)
	Y50	NS	-	-	1480 (20)	1460 (30)	1480 (30)	1490 (30)	1540 (30)
	Y80	NS	-	-	1660 (10)	1640 (20)	1670 (20)	1680 (20)	1680 (20)
	Tuber	NS	-	-	1.9 (0.20)	1.9 (0.20)	1.9 (0.20)	1.8 (0.30)	1.8 (0.20)
DvEPRS & DCMV, *n* = 101	n_1, n_2	-	-	-	*13, 0*	*24, 0*	*25, 0*	*28, 0*	*11, 0*
	M1	*	*	NS	9 (1.5)	10 (1.3)	8 (1.1)	9 (1.2)	10 (1.9)
	M2	NS	NS	NS	13 (1.4)	11 (1.0)	12 (1.0)	12 (1.0)	11 (1.4)
	MT	*	NS	NS	23 (2.1)	21 (1.5)	20 (1.4)	22 (1.4)	22 (2.2)
	FH	*	NS	**	1060 (60)	1140 (50)	1180 (50)	1070 (40)	1050 (60)
	Y20	*	NS	NS	1290 (40)	1330 (30)	1330 (30)	1350 (30)	1280 (40)
	Y50	NS	NS	NS	1450 (20)	1480 (20)	1460 (20)	1480 (20)	1490 (30)
	Y80	NS	NS	NS	1650 (20)	1620 (20)	1650 (20)	1650 (20)	1690 (30)
	Tuber	NS	NS	NS	2.0 (0.19)	1.7 (0.15)	1.7 (0.14)	1.7 (0.14)	1.6 (0.22)
DvEPRS & DMV, *n* = 22	n_1, n_2	-	-	-	*5, 0*	*0, 0*	*0, 0*	*3, 0*	*14, 0*
	M1	**	NS	NS	10 (2.3)	-	-	13 (3.7)	9 (1.5)
	M2	NS	NS	NS	12 (2.6)	-	-	9 (2.5)	11 (1.4)
	MT	*	NS	NS	22 (3.4)	-	-	22 (4.4)	20 (1.9)
	FH	NS	NS	NS	1010 (90)	-	-	1090 (110)	12009 (68)
	Y20	*	NS	NS	1300 (60)	-	-	1430 (80)	1400 (40)
	Y50	NS	**	NS	1420 (40)	-	-	1500 (50)	1430 (25)
	Y80	NS	NS	NS	1610 (30)	-	-	1700 (50)	1620 (21)
	Tuber	NS	NS	NS	1.7 (0.35)	-	-	1.6 (0.40)	1.7 (0.21)
DvEPRS, DCMV & DMV, *n* = 33	n_1, n_2	-	-	-	*3, 0*	*11, 0*	*5, 0*	*4, 0*	*10, 0*
	M1	*	*	NS	12 (4.1)	7 (1.4)	8 (2.2)	9 (2.7)	7 (1.4)
	M2	NS	NS	NS	7 (2.0)	9 (1.4)	13 (2.7)	9 (2.2)	11 (1.7)
	MT	NS	**	NS	19 (4.1)	17 (2.0)	21 (3.5)	19 (3.4)	18 (2.2)
	FH	NS	NS	NS	1220 (140)	1200 (80)	1050 (100)	1210 (120)	1110 (70)
	Y20	*	NS	NS	1270 (80)	1400 (50)	1380 (70)	1420 (70)	1370 (50)
	Y50	NS	NS	NS	1410 (50)	1550 (30)	1500 (40)	1510 (50)	1500 (30)
	Y80	NS	NS	NS	1630 (40)	1680 (20)	1680 (40)	1650 (40)	1690 (30)
	Tuber	NS	**	NS	1.7 (0.40)	2.0 (0.25)	1.6 (0.35)	1.2 (0.36)	1.2 (0.23)

M1: marketable yield grade 1; M2 marketable yield grade 2; MT: total marketable yield (the sum of M1 + M2); FH: timing to first harvest; Y20, Y50, Y80: timings to 20, 50, and 80% of harvest; Tuber: tuber mass; number of n: infected plants by virus status of the 250 plants per cultivar; n_1: infected plants by virus status of the 50 plants per I; n_2: living plants with zero total marketable yield of the 50 plants per I. [1] All 250 plants across the study tested positive for DvEPRS. [2] Significant results are indicated with asterisks, with one (*) and two (**) representing significance at α = 0.10 and 0.05, respectively. Means in the same row with the same letter are not significantly different (Tukey-adjusted, α = 0.10). NS: not significant. [3] Plants with DvEPRS-only were analyzed using one-way ANOVA, so there are no virus or interaction results.

Table 3. The virus status of 'Café au Lait' (C) in 2023, with the number of infected plants and crop production metrics given as means (standard error) of yield (stems/plant), timing (°C·days), and wet tuber mass (kg/plant) with significance by the main effects of irrigation rate (I) and virus (V) and their interaction (I × V).

Virus Status [1]	Metric	Significance [2]			Irrigation Rate				
		I	V	I × V	I_{100}	$I_{80/100}$	I_{80}	$I_{60/100}$	I_{60}
DvEPRS [3], *n = 78*	n_1, n_2	-	-	-	*11 , 0*	*22 , 2*	*10 , 0*	*13 , 1*	*22 , 1*
	M1	NS	-	-	3 (1.0)	4 (1.0)	3 (0.9)	3 (0.8)	2 (0.6)
	M2	**	-	-	8 ^{ab} (1.8)	9 ^{a} (1.7)	11 ^{a} (2.6)	7 ^{ab} (1.5)	5 ^{b} (0.9)
	MT	**	-	-	11 ^{ab} (2.3)	14 ^{a} (2.3)	13 ^{ab} (2.9)	10 ^{ab} (2.0)	7 ^{b} (1.2)
	FH	NS	-	-	1340 (70)	1410 (50)	1340 (70)	1440 (70)	1400 (50)
	Y20	NS	-	-	1500 (50)	1490 (40)	1400 (50)	1520 (50)	1520 (40)
	Y50	NS	-	-	1620 (30)	1630 (20)	1540 (30)	1610 (30)	1610 (20)
	Y80	NS	-	-	1660 (20)	1670 (20)	1660 (20)	1670 (20)	1680 (20)
	Tuber	NS	-	-	0.9 (0.09)	0.7 (0.06)	0.8 (0.09)	0.7 (0.08)	0.6 (0.06)
DvEPRS & DCMV, *n = 75*	n_1, n_2	-	-	-	*15 , 1*	*7 , 0*	*18 , 0*	*15 , 2*	*20 , 4*
	M1	NS	NS	NS	1 (0.5)	4 (1.4)	3 (0.8)	2 (0.7)	1 (0.4)
	M2	*	***	NS	4 (1.0)	6 (1.8)	6 (1.1)	6 (1.3)	4 (0.8)
	MT	NS	***	NS	6 (1.3)	9 (2.7)	8 (1.6)	8 (1.8)	6 (1.1)
	FH	NS	NS	NS	1520 (70)	1490 (100)	1410 (60)	1310 (70)	1360 (60)
	Y20	NS	NS	*	1580 (50)	1510 (70)	1540 (40)	1440 (50)	1450 (40)
	Y50	NS	NS	*	1630 (30)	1570 (40)	1620 (30)	1560 (30)	1550 (30)
	Y80	NS	NS	NS	1680 (20)	1630 (30)	1670 (20)	1690 (20)	1640 (20)
	Tuber	NS	NS	NS	0.7 (0.09)	0.9 (0.13)	0.9 (0.08)	0.7 (0.09)	0.6 (0.08)
DvEPRS & DMV, *n = 17*	n_1, n_2	-	-	-	*5 , 0*	*4 , 0*	*5 , 0*	*0 , 0*	*3 , 0*
	M1	NS	NS	NS	1 (0.8)	1 (0.8)	5 (2.0)	-	1 (0.9)
	M2	**	NS	NS	6 (2.0)	7 (2.6)	12 (3.8)	-	7 (3.0)
	MT	**	NS	NS	7 (2.3)	8 (3.0)	16 (5.0)	-	9 (3.4)
	FH	NS	NS	NS	1550 (120)	1540 (150)	1280 (90)	-	1310 (120)
	Y20	NS	NS	NS	1570 (80)	1570 (100)	1360 (70)	-	1400 (90)
	Y50	NS	NS	NS	1650 (40)	1650 (50)	1510 (40)	-	1600 (50)
	Y80	NS	NS	NS	1710 (30)	1700 (40)	1640 (30)	-	1660 (40)
	Tuber	NS	NS	NS	0.8 (0.13)	0.6 (0.15)	0.9 (0.13)	-	0.9 (0.17)
DvEPRS, DCMV & DMV, *n = 19*	n_1, n_2	-	-	-	*3 , 0*	*4 , 0*	*6 , 0*	*5 , 1*	*1 , 0*
	M1	NS	NS	NS	6 (3.5)	4 (1.9)	2 (0.7)	1 (0.8)	2 (2.3)
	M2	**	NS	NS	10 (4.2)	8 (3.2)	7 (2.2)	4 (1.6)	4 (3.0)
	MT	*	NS	NS	16 (6.4)	12 (4.5)	9 (2.7)	5 (1.9)	6 (4.4)
	FH	NS	NS	NS	1090 (110)	1420 (130)	1300 (100)	1510 (120)	1470 (270)
	Y20	NS	NS	NS	1510 (120)	1520 (90)	1480 (70)	1650 (100)	1570 (170)
	Y50	NS	NS	NS	1550 (60)	1580 (60)	1630 (50)	1620 (50)	1630 (100)
	Y80	NS	NS	NS	1620 (40)	1740 (50)	1680 (40)	1650 (40)	1640 (60)
	Tuber	NS	NS	NS	1.0 (0.17)	1.0 (0.15)	0.9 (0.12)	0.8 (0.15)	0.7 (0.29)

M1: marketable yield grade 1; M2 marketable yield grade 2; MT: total marketable yield (the sum of M1 + M2); FH: timing to first harvest; Y20, Y50, Y80: timings to 20, 50, and 80% of harvest; Tuber: tuber mass; number of n: infected plants by virus status of the 250 plants per cultivar; n_1: infected plants by virus status of the 50 plants per I; n_2: living plants with zero total marketable yield of the 50 plants per I. [1] All 250 plants across the study tested positive for DvEPRS. [2] Significant results are indicated with asterisks, with one (*), two (**), and three (***) representing significance at α = 0.10, 0.05, and 0.01, respectively. Means in the same row with the same letter are not significantly different (Tukey-adjusted, α = 0.10). NS: not significant. [3] Plants with DvEPRS-only were analyzed using one-way ANOVA, so there are no virus or interaction results.

Table 4. Number of plants in 2023 by cultivar, 'Boom Boom White' (B) and 'Café au Lait' (C), and irrigation rate that were included and excluded from the irrigation × virus analysis, with reason for exclusion also given.

Cultivar	Analysis Status	Irrigation Rate					Total Plants
		I_{100}	$I_{80/100}$	I_{80}	$I_{60/100}$	I_{60}	
B	Included in analysis [1]	50	49	49	45	49	242
	Excluded from analysis [2]	0	1	1	5	1	8
	Not tested (8 total)						
	Handling error	0	1	1	5	1	8
C	Included in analysis [1]	34	37	39	33	46	189
	Excluded from analysis [2]	16	13	11	17	4	61
	Not tested (44 total)						
	Handling error	9	8	3	10	0	30
	Died before sampling	3	1	4	3	3	14
	Tested: Died before bloom (17 total)						
	DvEPRS only	3	0	2	1	1	7
	DvEPRS and DCMV	0	1	2	3	0	6
	DvEPRS and DMV	0	2	0	0	0	2
	DvEPRS, DCMV, and DMV	1	1	0	0	0	2

[1] Plants were included because they were laboratory tested for virus status and survived the vegetative and reproductive stages. [2] Plants were excluded from analysis for one of three reasons: not tested because of a sampling or laboratory error (handling error); not tested because the plant died during establishment and could not be tested (died before sampling); or was tested but died during the vegetative stage (i.e., died before bloom). For those that were tested and then died, their virus status is also reported.

3.3. Bloom Timing

For B that were infected with DvEPRS-only in 2023, the harvest timing thresholds were increasingly delayed with lower I, but no differences were significant ($p > 0.10$; Table 2). For example, FH occurred at 1030 °C·days in I_{100}, 1040 °C·days in $I_{80/100}$, 1070 °C·days in I_{80}, 1140 °C·days in $I_{60/100}$, and 1250 °C·days in I_{60}. The main effect of I was not significant for Y20, but I_{100} reached Y20 significantly sooner at 1270 °C·days than I_{60} at 1410 °C·days by pairwise comparison ($p = 0.09$). I_{100} also reached Y50 and Y80 the earliest, at 1480 and 1660 °C·days, respectively, compared to I_{60}, which took 1540 °C·days to reach Y50 and 1680 °C·days to reach Y80, respectively. B infected with DCMV had a significant interaction with FH ($p = 0.03$). Plants in the two lowest I (I_{60} and $I_{60/100}$) reached FH up to 200 °C·days sooner when infected with both DvEPRS and DCMV than those infected with DvEPRS-only (Table 2). The opposite was true in the three highest I (I_{100}, $I_{80/100}$, I_{80}): the FH of plants with DvEPRS and DCMV was delayed by 30 to 110 °C·days compared to plants with DvEPRS-only. For B with DvEPRS, DCMV, and DMV, the main effect of I was significant ($p = 0.10$) for Y20, with I_{100} reaching the threshold first at 1270 °C·days, followed by I_{60} and I_{80} at 1370 to 1380 °C·days, $I_{80/100}$ at 1400 °C·days, and $I_{60/100}$ at 1420 °C·days.

For C infected with DvEPRS-only in 2023, the harvest timing thresholds were also increasingly delayed with lower I, though not significantly ($p > 0.10$; Table 3). FH was 1340 °C·days after transplant for I_{100} and I_{80}, and 1410 to 1440 °C·days for $I_{80/100}$, I_{60} and $I_{60/100}$. Plants with the three largest I reached Y20 the earliest, at 1400 to 1500 °C·days, while those with the two lowest I took about 1520 °C·days. Y80 also occurred sooner with more water: I_{100} took 1660 °C·days, and I_{60} took 1680 °C·days. For C infected with both DvEPRS and DCMV, the time to FH had similar patterns to those observed for B; the three largest I took more time to reach FH, while the two lowest I took less time, compared to C with DvEPRS-only. The differences in yield timing were not significant for C plants infected with DvEPRS and DMV or all three viruses.

In 2024 (Table 5), I had a significant effect on all yield timing metrics for B ($p < 0.03$). By pairwise comparison with I_{60}, I_{80} reached FH sooner by 130 °C·days ($p = 0.0001$), Y20 by 100 °C·days ($p = 0.001$), Y50 by 80 °C·days ($p = 0.007$), and Y80 by 70 °C·days ($p = 0.03$). Harvest of C began earliest with I_{100}, but no differences were significant across I ($p > 0.10$). All I reached Y50 within 20 °C·days of each other.

Table 5. Crop production metrics of 'Boom Boom White' (B) and 'Café au Lait' (C) in 2024, given as means (standard error) of yield (stems/plant), timing (°C·days), and wet tuber mass (kg/plant) with significance by the main effect of irrigation rate (I).

Cultivar	Metric	Significance [1]	Irrigation Rate				
			I_{100}	$I_{80/100}$	I_{80}	$I_{60/100}$	I_{60}
B *n* = 245	n_1, n_2	-	*49 , 0*	*50 , 0*	*48 , 0*	*49 , 0*	*49 , 0*
	M1	NS	2 (0.4)	2 (0.3)	2 (0.3)	2 (0.3)	2 (0.3)
	M2	*	6 ^{a} (0.4)	6 ^{a} (0.4)	6 ^{ab} (0.4)	6 ^{ab} (0.4)	5 ^{b} (0.4)
	MT	**	9 ^{a} (0.7)	8 ^{ab} (0.7)	8 ^{ab} (0.6)	7 ^{ab} (0.6)	6 ^{b} (0.6)
	FH	***	1400 ^{ab} (20)	1370 ^{bc} (20)	1320 ^{c} (20)	1400 ^{ab} (20)	1450 ^{a} (20)
	Y20	***	1460 ^{ab} (20)	1430 ^{bc} (20)	1390 ^{c} (20)	1460 ^{ab} (20)	1490 ^{a} (20)
	Y50	***	1550 ^{abc} (20)	1520 ^{bc} (20)	1500 ^{c} (20)	1570 ^{ab} (20)	1580 ^{a} (20)
	Y80	**	1640 ^{ab} (20)	1640 ^{ab} (16)	1610 ^{b} (20)	1670 ^{a} (20)	1670 ^{a} (20)
	Tuber	***	1.1 ^{a} (0.05)	1.0 ^{ab} (0.05)	0.9 ^{bc} (0.05)	0.9 ^{bc} (0.05)	0.8 ^{c} (0.04)
C *n* = 250	n_1, n_2	-	*50 , 0*	*50 , 0*	*50 , 0*	*50 , 0*	*50 , 0*
	M1	NS	3 (0.3)	3 (0.3)	3 (0.3)	2 (0.3)	2 (0.3)
	M2	NS	8 (0.8)	8 (0.8)	7 (0.7)	7 (0.7)	6 (0.6)
	MT	**	11 ^{ab} (0.7)	11 ^{a} (0.8)	10 ^{ab} (0.7)	9 ^{ab} (0.7)	8 ^{b} (0.6)
	FH	NS	1500 (20)	1510 (20)	1510 (20)	1520 (20)	1520 (20)
	Y20	NS	1570 (20)	1580 (20)	1590 (20)	1590 (20)	1590 (20)
	Y50	NS	1680 (10)	1650 (10)	1680 (10)	1680 (10)	1670 (10)
	Y80	NS	1720 (10)	1710 (10)	1710 (10)	1730 (10)	1730 (10)
	Tuber	***	0.6 ^{a} (0.02)	0.5 ^{b} (0.02)	0.4 ^{bc} (0.02)	0.4 ^{cd} (0.02)	0.3 ^{d} (0.02)

M1: marketable yield grade 1; M2 marketable yield grade 2; MT: total marketable yield (the sum of M1 + M2); FH: timing to first harvest; Y20, Y50, Y80: timings to 20, 50, and 80% of harvest; Tuber: tuber mass; number of *n*: living plants of 250 per cultivar, n_1: living plants of 50 per I, n_2: living plants with zero total marketable yield of 50 plants per I. [1] Significant results are indicated with asterisks, with one (*), two (**), and three (***) representing significance at $\alpha = 0.10$, 0.05, and 0.01, respectively. Means in the same row with the same letter are not significantly different (Tukey-adjusted, $\alpha = 0.10$). NS: not significant.

3.4. Yield

For B in 2023 (Table 2), differences in M1 were significant across all virus statuses ($p < 0.10$). For plants with DvEPRS-only, $I_{60/100}$ produced the greatest M1 yield (standard error) at 15 (3.0) stems per plant, followed by I_{100} and $I_{80/100}$ at 12 (1.4, 2.0, respectively), I_{80} at 10 (1.5), and I_{60} at 7 (1.2), with $I_{60/100}$ and I_{100} significantly greater than I_{60} by pairwise comparison ($p = 0.07, 0.09$). Both main effects of I and V were significant ($p = 0.10, 0.09$), with M1 for plants with DvEPRS and DCMV showing that all I produced two to six fewer stems per plant than their counterparts with DvEPRS-only, except for I_{60}, which produced three additional stems per plant. Plants infected with all three viruses also showed significant main effects of I and V ($p = 0.07, 0.06$), with I_{80}, $I_{80/100}$, and $I_{60/100}$ producing two, five, and six fewer stems per plant than those with DvEPRS-only; I_{100} and I_{60} yields were not different. The MT was not significant between I for plants with DvEPRS-only ($p > 0.10$), and all I produced 23 to 25 stems per plant, except for I_{60}, which produced 18 (1.8). For plants with all three viruses, V had a significant effect on MT ($p = 0.03$), with I_{100}, $I_{80/100}$, I_{80}, and $I_{60/100}$ producing five, eight, two, and seven fewer stems per plant than plants with DvEPRS-only, though there was no difference in MT for I_{60}. The tuber weight of B infected with DvEPRS-only increased from 1.8 (0.2, 0.3) kg for I_{60} and $I_{60/100}$, respectively, to 1.9 (0.2) kg for I_{80}, $I_{80/100}$, and I_{100}, though differences were not significant ($p > 0.10$). For plants with all three viruses, V had a significant effect on tuber weight ($p = 0.05$), which generally increased with increasing irrigation, but remained lower than that of their counterparts with DvEPRS-only.

For C in 2023 (Table 3), differences were significant for M2 and, therefore, also MT, but not M1. For plants with DvEPRS-only, I had a significant effect on M2 ($p = 0.03$) and MT ($p = 0.06$), with I_{80} and $I_{80/100}$ producing up to 11 M2 stems per plant, which, by pairwise comparison, was significantly greater than I_{60} at five M2 stems per plant ($p = 0.04$, 0.05). For plants with both DvEPRS and DCMV, both I and V had a significant effect on M2 ($p = 0.08$, 0.001), with plants in all I producing one to five fewer stems per plant than plants with DvEPRS-only. Only V had a significant effect on MT for plants with DvEPRS and DCMV ($p = 0.008$). These plants had reduced MT, with I_{100}, $I_{80/100}$, and I_{80} producing five fewer stems, and $I_{60/100}$ and I_{60} producing two and one fewer stems per plant than plants with DvEPRS-only. The tuber weight of C infected with DvEPRS-only increased with I, ranging from 0.6 (0.06) to 0.7 (0.08) kg for I_{60} and $I_{60/100}$, 0.7 (0.06) to 0.8 (0.09) kg for $I_{80/100}$ and I_{80}, and 0.9 (0.09) kg for I_{100}, but differences were not significant ($p > 0.10$). Tuber production did not follow a predictable pattern for plants with additional virus infections.

In 2024 (Table 5), I was not significant for B production of M1 but was significant for M2 ($p = 0.06$). Similarly, differences among I for MT were significant ($p = 0.04$); I_{100} produced the most at nine (0.7) stems per plant and significantly more than I_{60} at six (0.6) stems per plant ($p = 0.03$). Irrigation had a significant effect on B tuber production ($p = 0.0002$). Through pairwise comparison, the tuber mass in I_{100} (1.1 kg) was significantly greater than the 0.9 kg produced in both I_{80} ($p = 0.08$) and $I_{60/100}$ ($p = 0.01$), or the 0.8 kg produced in I_{60} ($p = 0.0001$). Additionally, $I_{80/100}$ produced 1.0 kg of tubers, which was significantly greater than that in I_{60} ($p = 0.01$). For C, differences in M1 and M2 yields from I were not significant ($p > 0.10$), but MT was ($p = 0.04$), with $I_{80/100}$ producing the most at 11 (0.8) stems per plant, significantly more than I_{60} at 8 (0.6) stems per plant. For C, I significantly affected tuber mass ($p < 0.0001$), which increased with I. Through pairwise comparison, tubers produced in I_{100} (0.6 kg) were significantly greater than those produced in all other I ($p < 0.01$). The tubers in $I_{80/100}$ (0.5 kg) were also significantly ($p = 0.009$, 0.001) greater than those in $I_{60/100}$ at 0.4 kg ($p = 0.009$) and I_{60} at 0.3 kg ($p = 0.001$).

3.5. Water Balance and K_c

For B in 2023, the average antecedent θ_v in I_{80} was 0.20 $m^3\ m^{-3}$, and those in I_{100}, $I_{80/100}$, $I_{60/100}$, and I_{60} were 0.23 $m^3\ m^{-3}$ (Figure 2). From 10 June to 10 October 2023, differences in θ_v remained within 0.02 to 0.05 $m^3\ m^{-3}$ among all I. For C, the antecedent θ_v was greatest in I_{100}, $I_{80/100}$, and I_{80} at 0.27 to 0.29 $m^3\ m^{-3}$, followed by I_{60} at 0.23 $m^3\ m^{-3}$, and $I_{60/100}$ at 0.20 $m^3\ m^{-3}$, respectively. From 18 June to 9 August 2023, the average θ_v in I_{100} was lower than those in I_{80} and $I_{80/100}$ by 0.05 to 0.11 $m^3\ m^{-3}$ for 89% of days. In 2024, the average antecedent θ_v for B was 0.22 to 0.23 $m^3\ m^{-3}$ in I_{100}, $I_{80/100}$, I_{80}, and I_{60}, while that in $I_{60/100}$ was 0.20 $m^3\ m^{-3}$. The θ_v of I_{100} and I_{80} remained within 0.02 $m^3\ m^{-3}$ throughout 2024. For C, the average antecedent θ_v was 0.24 to 0.27 $m^3\ m^{-3}$ for all I. From 10 June to 12 September 2024, I_{100} had the greatest θ_v at 0.19 to 0.28 $m^3\ m^{-3}$, and I_{60} generally had the lowest θ_v at 0.13 to 0.22 $m^3\ m^{-3}$.

For weeks without precipitation, weekly ET_a during the vegetative and reproductive stages was greatest for both cultivars in I_{100} compared to those at lower I (Figure 3). Within I_{100}, the average weekly ET_a of B during the vegetative stage was 30 to 70 mm in 2023 and 2024, which was greater than the weekly mean of I_{80} by about 10 mm in both years, and I_{60} by about 20 mm in both years. During the reproductive stage of B, the average weekly

https://doi.org/10.3390/horticulturae12091093

ET_a in I_{100} was 10 to 60 mm in 2023 and 30 to 50 mm in 2024, which was greater than in I_{80} by less than 10 mm per week in both years, while I_{60} was about 10 mm lower in both years. For the vegetative stage of C in I_{100}, the weekly ET_a was 30 to 70 mm in both years, which was greater than the weekly mean of I_{80} by about 10 mm in both years and that of I_{60} by 20 mm in both years. During the reproductive stage of C, weekly ET_a in I_{100} was 20 to 70 mm in 2023 and 20 to 50 mm in 2024, which was greater than in I_{80} by less than 10 mm per week in both years, while I_{60} was about 10 mm lower in both years. For RDI of both cultivars, the differences in weekly ET_a were near zero mm during the reproductive stage.

In I_{100}, B and C had the same K_c at each physiological stage. During establishment, K_c was 0.7 during the week ending on 11 June 2023. During the vegetative stage, the average (+/− standard deviation) K_c of I_{100} was 1.1 (0.2) in 2023, which lasted six weeks (18 June to 29 July 2023, 290 to 820 °C·days), and 1.0 (0.3) in 2024, which lasted nine weeks (23 June to 17 August, 300 to 1050 °C·days), with an average across years of 1.0 (0.3). For the reproductive stage in both 2023 and 2024, the average K_c of I_{100} was 1.1 (0.1, 0.2) and lasted ten weeks in 2023 (30 July–7 October, 840–1670 °C·days) and seven weeks in 2024 (18 August–5 October 2024, 1060–1650 °C·days). Across cultivars and years, the lower I had an average K_c during the vegetative stage of 0.9 (0.2) in $I_{80/100}$ and I_{80}, and 0.7 (0.2) in $I_{60/100}$ and I_{60}. During the reproductive stage, the average K_c was 1.1 (0.2) in $I_{80/100}$ and $I_{60/100}$, while I_{80} and I_{60} remained at 0.9 (0.2) and 0.7 (0.1), respectively. The ET_o-based K_c adjusted to the standard climate was 0.8 for establishment, 1.2 for the vegetative stage, and 1.4 for the reproductive stage.

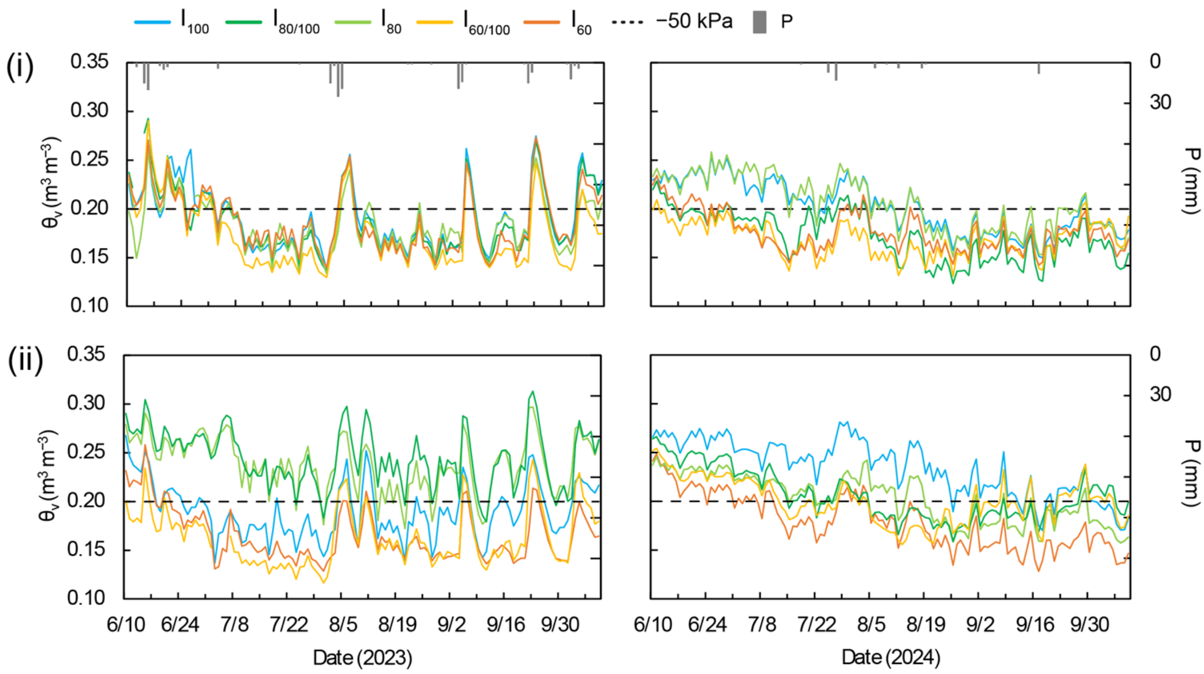

Figure 2. The average daily soil volumetric water content (θ_v, $m^3\ m^{-3}$) at a 0.08 m depth by irrigation rate, I, with total daily precipitation (P, mm, gray bar) from 10 June to 5 October in 2023 (left panels) and 2024 (right panels) by cultivar: (**i**) 'Boom Boom White' (B) and (**ii**) 'Café au Lait' (C). A θ_v of 0.20 $m^3\ m^{-3}$ (dashed black line) is the estimated soil moisture content at a matric potential of −50 kPa for the Millville silt loam [43].

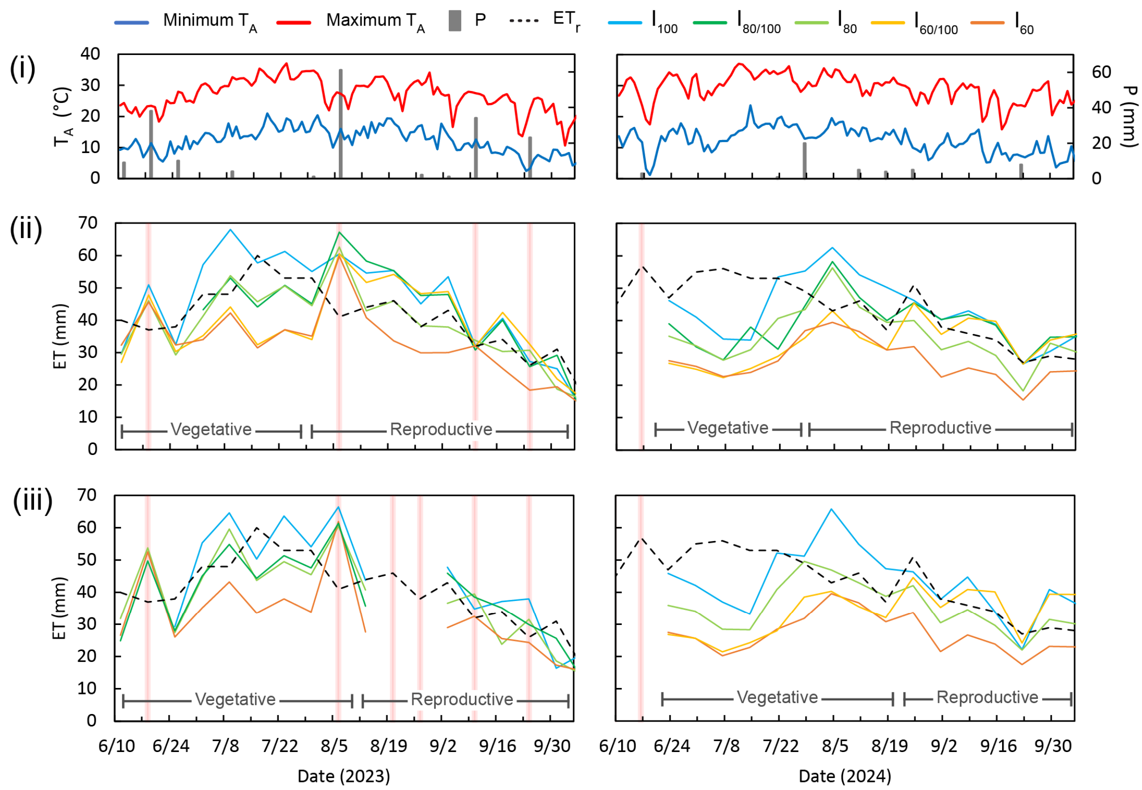

Figure 3. (**i**) Daily maximum and minimum air temperature (T_A, in °C) with the weekly cumulative precipitation (P, mm). (**ii**,**iii**) Weekly cumulative tall reference evapotranspiration, (ET_r, in mm) and weekly cumulative actual evapotranspiration (ET_a, in mm) of dahlia by irrigation rate, I, and cultivar, (**ii**) 'Boom Boom White' (B) and (**iii**) 'Café au Lait' (C). Pink bars denote weeks excluded from K_c calculations, either due to P > 20 mm or missing data. Data not available for C × $I_{60/100}$ in 2023, C × $I_{80/100}$ in 2024, and for C in the weeks of 20 and 27 August 2023 due to datalogger outages.

4. Discussion

Year-to-year production differences in both cultivars reflected the extreme environmental conditions in 2024, when near-freezing temperatures occurred two and four weeks after the average last freeze date, and were followed by above-normal highs that persisted into fall. Extreme temperatures delayed transplant and, especially for B, the onset of the reproductive stage in 2024. Similar effects of delayed reproduction and lower yield were established in muskmelon, after seedlings were exposed to 2 °C for three to nine hours, followed by 29 °C [51]. For dahlia, recovery from temperature stress is highly cultivar-specific, and even two days of supraoptimal temperatures were lethal for some decorative types [20]. For B, vegetative growth was 13 calendar days (200 °C·days) longer in 2024 than in 2023, while the later-maturing C was delayed by one calendar day (20 °C·days) in 2024. The reproductive stage was further truncated by a first freeze that was 11 days sooner in 2024 than in 2023, resulting in lower yields that were also reported across Northern Utah by commercial growers and enthusiasts alike [52,53] but were similar to or greater than those reported in Maine [21]. Stress caused by low, followed by high temperatures has been documented across grain and fruiting crops [51,54,55] and compounds with drought stress [56].

Plants with only DvEPRS, which may be part of the genome, were considered healthy [40] and were often asymptomatic by visual observation. For dahlia with DvEPRS and additional viruses in 2023, yield response was cultivar-specific, with C exhibiting greater sensitivity to infection than B. Plants are often bred or selected based on specific traits such as bloom color, bloom size or shape, or yield. These traits get priority over disease resistance or disease tolerance traits [57]. The resulting cultivars may not be the most vigorous plants, and in some cases, genes that conferred resistance or tolerance to a pathogen may be lost. The yield of B generally decreased with decreasing I, but yield was unchanged or increased when plants were infected with two viruses (DvEPRS and DCMV or DvEPRS and DMV) and irrigated at the lowest rate. Sadras [58] reported that virus infection may increase drought tolerance in some plants, or that water stress can increase virus tolerance. In response to drought stress or pathogen infection, plant signaling can lead to the production of reactive oxygen species (ROS). ROS, in turn, can trigger systemic acquired resistance (SAR) that makes plants more resistant to infections with plant pathogens [59]. If ROS are produced as a stress signal by an infection with a pathogen, they can also activate functional proteins and regulatory proteins that change the physiology of the plant, making them more resilient to drought stress [60]. It is possible that this mechanism applies to dahlias as well.

When B was infected with three viruses, however, the yield decreased across irrigation rates compared to plants with just two viruses, indicating that coinfection had an additive effect, as in 81% of studies sampled by Sadras [58]. For C, infection with two or more viruses generally reduced yield by irrigation rate, demonstrating the greater sensitivity of this cultivar to the combined effect of virus and water stress, which is known to be cultivar-dependent [58]. Virus infection also drove a cultivar-specific bloom timing response. For B, compared to plants with DvEPRS-only, harvest thresholds were generally reached sooner for plants with both DvEPRS and DMV, while plants with DvEPRS and DCMV reached thresholds later. For C, FH through Y80 were generally delayed with infection with DvEPRS and one other virus and accelerated with infection with all three viruses when well-watered, while the opposite was true with water stress.

With the high incidence of virus infections in addition to DvEPRS in 2023 and the cultivar-specific combined effects of infection and water stress, 2024 data were used to evaluate the effect of DI and RDI. In 2024, B irrigated at 100% of ET_c had greater height and canopy at the onset of bloom than those with DI and yielded one additional stem and greater tuber weights than the highest-yielding RDI and DI treatments, $I_{80/100}$ and I_{80}. As a popular bloom for wedding markets, the local wholesale pricing for B was $15 per bunch of five stems, while tubers are also sold by farms as an additional, post-season revenue source [8,48]. The loss of one stem, or $3 in gross receipts, and 0.1 kg of tuber per plant with DI or RDI scales to $25,995 per hectare in gross receipts from stems and 867 kg of tubers, assuming a density of 8,665 plants per hectare. The loss in tuber production was similar for C in DI and RDI, which also delayed FH and Y20, a concern for this premium but late-maturing cultivar that commands $5 per stem wholesale [8,21,48]. In addition to tuber mass, future research should quantify the number of tubers produced per plant for economic analysis of this loss, as dahlias are sold per tuber rather than by weight. Contrary to the gains in other crops with DI and RDI [32], reducing seasonal irrigation from 100% ET_c to 80/100% or 80% (i.e., by 80 to 130 mm of water) may result in economically meaningful revenue losses in dahlia, although differences were not statistically significant.

The weekly ET_a, and hence K_c, of DI and RDI plants remained consistently lower than that of plants irrigated at I_{100} across cultivars and years. Variations in soil moisture also contributed to differences in yield and tuber production each year, indicating high sensitivity to soil water depletion, particularly when θ_v approached 0.17 $m^3\ m^{-3}$ (−85 kPa). Compared to plants irrigated at I_{100} during the vegetative stage, the weekly ET_a averaged about 10 mm lower for both cultivars at I_{80} and $I_{80/100}$, and 20 mm lower for those at I_{60} and $I_{60/100}$. By the reproductive stage, weekly ET_a was 6 mm lower with I_{80} and 12 mm lower with I_{60}, while the RDI plants ($I_{80/100}$ and $I_{60/100}$) were within 1 to 2 mm of fully irrigated plants. Yield aligned with this for B in 2023 and C in 2024, but not when soil moisture was depressed with I_{100}.

Though C at I_{100} in 2023 should have received more water, soil moisture levels were at or below 0.20 m^3 m^{-3} (−50 kPa) for 75% of days during the vegetative stage, and 24% of days during the reproductive stage. By comparison, soils in I_{80} were below this threshold for 9% of days during the vegetative stage and 24% of days during the reproductive stage, and $I_{80/100}$ soils were below this threshold on 8% and 20% of days in each stage, respectively. Despite a water audit, fluctuations in pressure across the farm irrigation system during the growing season may have led to uneven water application. Each irrigation rate was replicated ten times per cultivar to account for the variability in plant health, particularly virus incidence, and production, which is especially documented in C [7]. As this present study identified soil moisture thresholds that induce water stress in dahlia, future management may include irrigating based on soil moisture depletion rather than ET_c, though the cost and availability of sensors can be a barrier to grower adoption.

The ET_r-based K_c values in this semi-arid location were 0.7 during establishment, 1.0 during the vegetative stage, and 1.1 during the reproductive stage for both cultivars at I_{100} in both years. The standardized K_c values (ET_o-based and adjusted to the standard climate) were 0.8, 1.2, and 1.4 during the establishment, vegetative, and reproductive stages, respectively. The estimated K_c of dahlia during establishment was similar to that of shallow-rooted, heat-sensitive crops like broccoli, lettuce, spinach, and celery, with $K_{c\ ini}$ values of 0.7 [23]. During the reproductive stage of dahlia, the standardized K_c value was greater than that of other crops harvested near flowering, such as broccoli and artichoke, with $K_{c\ mid}$ values that range from 1.0 to 1.1 [23]. Similarly, the standardized K_c of dahlia for the reproductive stage was higher than other tuberous but shorter-statured crops, such as potato and sweet potato, which have a $K_{c\ mid}$ of 1.1 [23]. Based on temperature conditions and visual observation, dahlia begins to develop tubers during the vegetative stage and to bulk during flowering. This, along with flowering, likely drove the increased and sustained water demand until the first freeze ended both the reproductive stage and growing season, rather than a tapered late-season decline in K_c.

5. Conclusions

Dahlia cut flower crops are sensitive to soil water depletion during both the vegetative and reproductive stages, as well as to temperature stress, which exacerbates delays and reductions in production in regions with short growing seasons. The onset of bloom for dahlia in the high-elevation U.S. Intermountain West can be expected between 840 and 1080 °C·days for mid-sized decorative bloom types, and 1040 to 1100 °C·days for large-sized decorative bloom types. Recommended crop coefficients are 1.0 for the vegetative (14 weeks of observation) and 1.1 for the reproductive (13 weeks of observation) stages, while establishment is estimated to be 0.7. Thresholds for irrigation should maintain soil moisture at a minimum of −50 kPa at a 0.08 m depth, and we recommend further research to target specific soil potential ranges. Deficit and regulated deficit irrigation practices are not recommended, as the total crop yield decreased by one to three stems and tuber mass decreased by 0.1 to 0.3 kg with these practices. The economic loss associated with these declines was estimated at $25,995 to $77,985 per hectare for 'Boom Boom White' and up to $86,650 per hectare for 'Café au Lait'. The use of K_c to schedule irrigation provides the first step for growers to balance production with optimized water use. Sufficient irrigation may also mitigate virus impacts for more sensitive cultivars, like 'Café au Lait'. Promoting healthy crop stock and virus testing are key to predictable yield, harvest timing, and plant vigor.

https://doi.org/10.3390/horticulturae12091093

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae12091093/s1, Figure S1: The average cumulative total marketable yield by irrigation rate, I, over thermal time (°C·days) for (i) 'Boom Boom White' and (ii) 'Café au Lait'. Inset: Total marketable yield by stem grade M1 and M2. Means for the same marketable grade and year with the same letter are not significantly different (Tukey-adjusted, $\alpha = 0.10$).

Author Contributions: Conceptualization, M.S. and C.N.; methodology, M.S., C.N., X.D. and B.B.; formal analysis, C.S., M.S., C.N., B.B. and C.A.; investigation, C.S., C.A., M.S., C.N. and X.D.; resources, M.S. and C.N.; data curation, C.S. and M.S.; writing—original draft preparation, C.S. and M.S.; writing—review and editing, M.S., C.N., B.B., X.D. and C.A.; visualization, C.S. and M.S.; supervision, M.S.; project administration, M.S. and C.N.; funding acquisition, M.S. and C.N. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the 2022 Utah Department of Agriculture and Food–Specialty Crop Block Grant (Award No. 204621) and the 2020 USDA NIFA—National Needs Fellowship (Award No. 2020-38420-30721), and the Utah Agricultural Experiment Station at Utah State University.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Acknowledgments: We thank Scott B. Jones for his input on soil physical properties; as well as Olive Stewart, James Frisby, Theresa Lara, Heather Warner, and Amanda Pratt for their field assistance; and Elliot Roberts, Savannah Gleeson, Katherine Michaels and Tim Miller for their laboratory assistance.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DI	Deficit irrigation
DCMV	Dahlia common mosaic virus
DMV	Dahlia mosaic virus
DvEPRS	Dahlia endogenous plant pararetroviral sequence
ET	Evapotranspiration
ET_r	Reference evapotranspiration for alfalfa
ET_c	Crop evapotranspiration
K_c	Crop coefficient
I	Irrigation
P	Precipitation
RDI	Regulated deficit irrigation
T_A	Reference air temperature
T_{BASE}	Base air temperature
T_{MAX}	Maximum air temperature
T_S	Soil temperature
°C·days	Degree Celsius days
θ_v	Volumetric water content

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https://doi.org/10.3390/horticulturae12091093