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# Diurnal irrigation timing affects fruit growth in late-ripening nectarines

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***Abstract***

**Little is known about the best diurnal irrigation timing for maximum fruit growth in stone fruit, despite fruit size being the most important focus for growers to achieve maximum marketable yield. This study investigated the effects of morning and afternoon irrigation on nectarine fruit growth in stage I (cell division) and stage III (cell expansion). In the 2017/18 season, 'September Bright' trees were subjected to morning ($I_{am}$) and afternoon ($I_{pm}$) irrigations. Fruit diameter was monitored continuously (15-min intervals) using fruit gauges and converted into fruit weight, relative growth rate (RGR) and fruit growth efficiency (FGE), with the latter representing RGR per unit of crop water supply (irrigation + rainfall). Irrigation timing affected FGE in opposite fashions during stage I and III. In stage I, maximum FGE occurred in days of $I_{am}$, whereas in stage III in days of $I_{pm}$. The different observations in the two stages were strongly influenced by the effect of crop evapotranspiration on FGE but were likely dependent on other factors such as stage-specific vascular activity, sugar and starch content and fruit advancement in phenology phases. Overall, this study suggests that optimal irrigation management needs to consider irrigation timing at sub-daily scales in conjunction with stage-specific irrigation strategies.**

**Keywords:** fruit size, precision irrigation, *Prunus persica* L. (Batsch), sustainability, water

## INTRODUCTION

Fruit size is one of the most important factors affecting final yield and it represents a key criterion for top-quality product value and grower profitability. Despite fruit size and growth being strictly dependent on genetic traits, they are also affected by environmental variables and agronomic practices. Fruit thinning and irrigation are the two key agronomic practices that influence fruit size (Berman and DeJong, 1996; Naor et al., 1997; Naor et al., 2000; Simões Grilo et al., 2019). In climate change scenarios, water productivity becomes crucial in light of predicted future water scarcity. The correct irrigation management in specific stages of fruit development is paramount for optimal fruit growth.

Fruit differ in the way they exchange water from and to their tissues along their development time window. Fruit containing pits, such as stone fruit, olive and avocado have a typical three-phase fruit development with an initial cell division stage (stage I), a subsequent pit-hardening stage (stage II) and a cell expansion stage (stage III) that lasts until physiological maturity. In these three phases, the main pathways of fruit water exchanges (i.e. phloem, xylem and transpiration) have different contributions to fruit growth (Morandi et al., 2007a; Corelli Grappadelli, et al., 2019). In addition, environmental parameters such as temperature, relative humidity, vapor pressure deficit (VPD) and crop evapotranspiration ($ET_c$) vary across the season. According to Morandi et al. (2007a) VPD

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drives fruit skin transpiration and consequently is very important for fruit growth dynamics (Morandi et al., 2010; Mossad et al., 2017). Sugar and starch concentration have also been associated with increased growth rate in peach fruit (Lo Bianco and Rieger, 2002). Considering the multitude of factors affecting fruit growth rates and their change over time, irrigation should not be equally managed in all the fruit developmental stages. In stone fruit, a reduction of irrigation in stage II has been widely associated with no effects on final fruit size and yield, as trees mainly focus on vegetative growth and pit-hardening (Li et al., 1989; Scalisi et al., 2019). Therefore, regulated deficit irrigation in stage II has been promoted as a viable agronomic practice (Mitchell and Chalmers, 1982; Naor, 2006). However, in stages I and III growers prefer to avoid deficit irrigation, as fruit size and yield are penalised.

To date, most of the studies on sustainable irrigation management of stone fruit have focused on reducing water volumes in specific phases, with nearly no interest on regulating water supply at specific times of the day. In the Goulburn Valley (Victoria, Australia), some growers target nocturnal irrigation to take advantage of low electricity prices. Falivene et al. (2018) suggested that water volumes can be reduced by 20 – 30% by irrigating citrus orchards at night, as evapotranspiration is reduced. However, this strategy is not always profitable, as in some crops the overall volume of water supplied at night is often greater than the amount plants would need if irrigation were scheduled at other times of the day, where maximum water use efficiency can be achieved. In loose soils, irrigation water can drain and become unavailable once stomata open and the transpiration pump becomes active early in the morning. Using higher volumes of water results in a loss of profit and water use efficiency; hence, targeting the most appropriate irrigation timing for each crop becomes paramount.

Torres-Ruiz et al. (2016) found that afternoon irrigation was beneficial for kiwifruit water status, although it did not significantly improve fruit size under full irrigation. Under optimal plant water status during stages I and III, the diel nectarine fruit growth follows a sigmoidal pattern, with steady or minimal increase in size from morning to early afternoon and a pronounced enlargement from late afternoon to late night (Scalisi et al., 2019). Stage-dependent effects of morning, afternoon and nocturnal irrigation on stone fruit growth patterns have been poorly investigated, despite xylem and phloem activity changing at different times of the day (Morandi et al., 2007a) and stage III being commonly warmer and drier than stage I. Therefore, the understanding of fruit growth responses to different irrigation timings may provide valuable information to improve water management and maximize profit.

This study aimed to assess the effects of morning and afternoon irrigation timing on nectarine fruit growth efficiency during stages I and III of fruit development in a temperate climate.

## MATERIALS AND METHODS

### Irrigation and environment

The experiment was conducted in 2017/18 at the stone-fruit experimental orchard of Agriculture Victoria, Tatura, Australia (36°26′7.2″ S and 145°16′8.4″ E, 113 m a.s.l.) on four-year old 'September Bright' nectarine trees trained to an open Tatura system (2,222 trees/ha) along North–South orientated rows. Within a deficit irrigation trial, a total of 36 trees (six trees per block) were subjected to full irrigation at 100% of $ET_c$ and irrigated at daily intervals. The experimental site has a clay loam soil texture, typical of the area.

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Conventional fertigation and thinning were carried out at the beginning of fruit developmental stage I, whereas summer pruning was done in stage II.

Irrigation was paused in days of significant rainfall. Only data from stages I and III were considered in this experiment, as irrigation in stage II (pit hardening) plays a minor role in fruit enlargement (Naor, 2006). Irrigation water was supplied at different times of the day at stages I and III of fruit development. Data of irrigation timing were pooled together and subdivided in two time-windows of 5 hours each: a morning irrigation ($I_{am}$) from 07.00 to 12.00 h, and an afternoon irrigation ($I_{pm}$) from 12.30 to 17.30 h. Days in which irrigation overlapped $I_{am}$ and $I_{pm}$ or exceeded the start and end time of either $I_{am}$ or $I_{pm}$ were classified as miscellaneous irrigation and not included in the data analyses. A buffer time of 30 minutes (from 12.00 to 12.30 h) was intentionally framed between $I_{am}$ and $I_{pm}$.

Meteorological data were collected using a weather station located next to the experimental orchard and $ET_c$ was calculated based on the tree canopy effective area of shade, as described by Scalisi et al. (2019). Crop water supply (CWS) was calculated by the summation of irrigation and precipitation water.

## Fruit growth efficiency

Fruit gauges based on linear potentiometers (Morandi et al., 2007b) connected to data loggers (CR1000, Campbell scientific, Inc., Logan, US) were used to determine fruit diameter variations at 15-min intervals during stages I and III. The gauges were mounted on two fruit per tree, and on two trees over 7 days at each stage. Fruit diameter (FD) was then converted to fruit weight (FW) using the cubic regression obtained after sampling FD and FW for 200 fruits across both fruit growth stages I and III [$FW = -4.90 + (0.49 \times FD) + (-0.006 \times FD)^2 + (0.0005 \times FD)^3$, $R^2 = 0.99$, $P < 0.001$]. The resulting gauge-derived FW data (n = 96) for each day (4 × 24 h) were then averaged to obtain a daily fruit weight. Daily fruit weight variations (ΔFW, g $d^{-1}$) were calculated by $FW_2 - FW_1$, which represent FW at day 2 and 1, respectively. Fruit relative growth rates (RGR, mg $g^{-1}$ $d^{-1}$) were obtained by $\Delta FW / FW_1 \times 1000$, to express growth relatively to initial size. Ultimately, fruit growth efficiency (FGE, mg $g^{-1}$ $mm^{-1}$ $d^{-1}$) was calculated as daily RGR / CWS.

## Statistical analysis

Analyses of covariance (ANCOVA) were used to test the effects of: (i) fruit growth stage on ΔFW, RGR and FGE, and (ii) irrigation timing on FGE. In both cases, daily $ET_c$ was used as covariate. A t-test was used to test the response of FGE to $I_{am}$ and $I_{pm}$. Statistical analyses were performed using SYSTAT procedures (Systat software Inc., Chicago, USA) and means were compared by Tukey's test. Least square means were reported to adjust for the effects of covariates. Sigmaplot procedures (Systat software Inc., Chicago, USA) were used for linear regression analyses to test the associations between FGE and $ET_c$ at stages I and III.

# RESULTS AND DISCUSSION

## Irrigation and environment

September Bright is a late-ripening nectarine cultivar with fruit set occurring at the beginning of October at the latitude of Tatura. Fruit growth stage I started after fruit set and lasted for a total of 36 days from 28 to 63 days after full bloom (DAFB). Stage III started after pit hardening and lasted for 59 days from 114 to 172 DAFB. Trees were subjected to $I_{am}$ and $I_{pm}$ for 10 and 12 days in stage I, and for 13 and 15 days in stage III, respectively (Fig. 1). Environmental conditions changed between stages, with stage III experiencing an average

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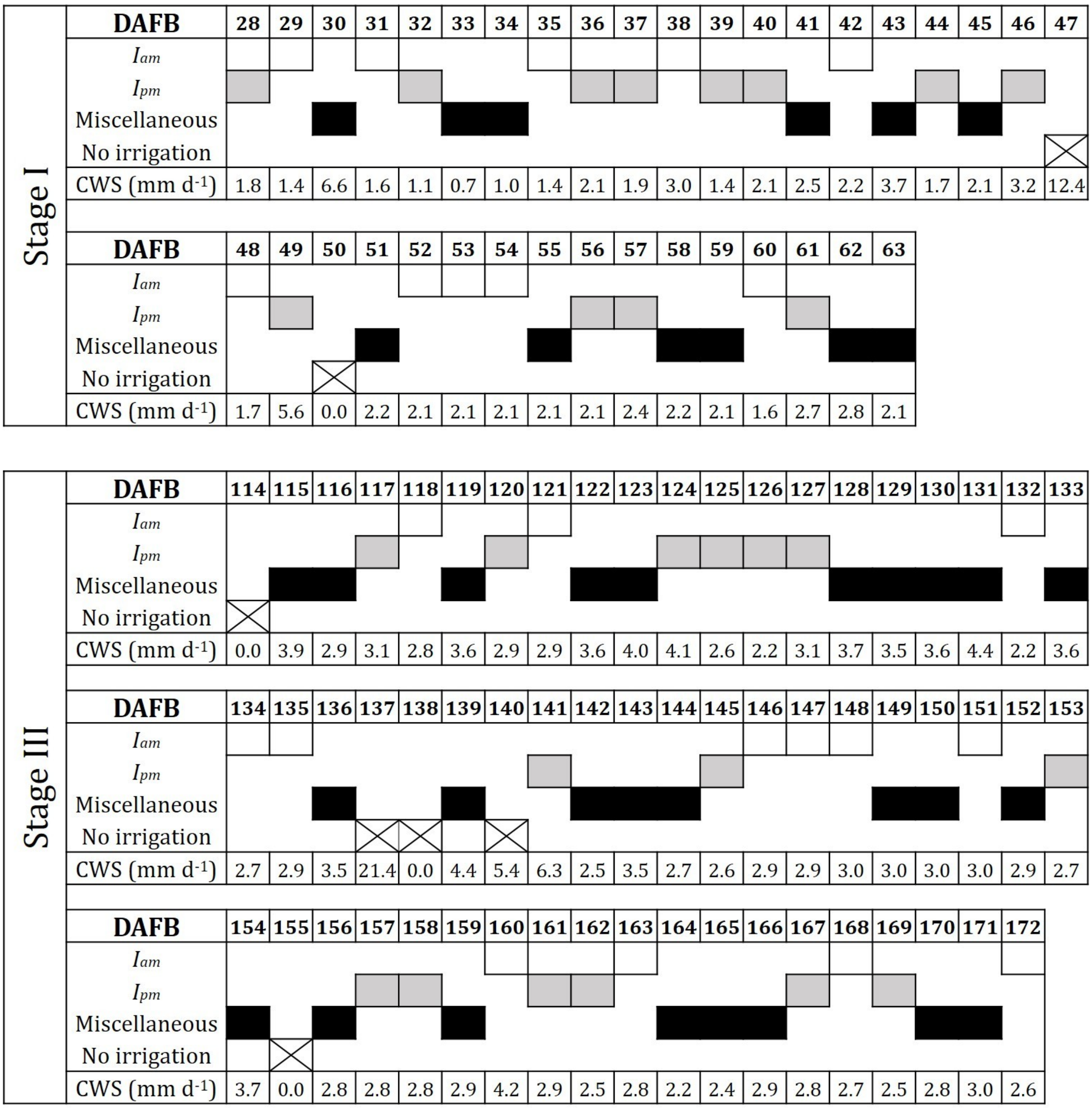
daily $ET_c$ markedly higher (5.53 ± 0.16 mm $d^{-1}$) than stage I (3.17 ± 0.20 mm $d^{-1}$). This difference was mainly caused by high temperatures, low relative humidity and almost no rainfall in the months of January and February (stage III).



Stage I

| DAFB | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Iam* |  | □ |  | □ |  |  |  | □ |  |  | □ |  |  |  | □ |  |  |  |  |  |
| *Ipm* | ▨ |  |  |  | ▨ |  |  |  | ▨ | ▨ |  | ▨ | ▨ |  |  |  | ▨ |  | ▨ |  |
| Miscellaneous |  |  | ■ |  |  | ■ | ■ |  |  |  |  |  |  | ■ |  | ■ |  | ■ |  |  |
| No irrigation |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ☒ |
| CWS (mm $d^{-1}$) | 1.8 | 1.4 | 6.6 | 1.6 | 1.1 | 0.7 | 1.0 | 1.4 | 2.1 | 1.9 | 3.0 | 1.4 | 2.1 | 2.5 | 2.2 | 3.7 | 1.7 | 2.1 | 3.2 | 12.4 |

| DAFB | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Iam* | □ |  |  |  | □ | □ | □ |  |  |  |  |  | □ |  |  |  |
| *Ipm* |  | ▨ |  |  |  |  |  |  | ▨ | ▨ |  |  |  | ▨ |  |  |
| Miscellaneous |  |  |  | ■ |  |  |  | ■ |  |  | ■ | ■ |  |  | ■ | ■ |
| No irrigation |  |  | ☒ |  |  |  |  |  |  |  |  |  |  |  |  |  |
| CWS (mm $d^{-1}$) | 1.7 | 5.6 | 0.0 | 2.2 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.4 | 2.2 | 2.1 | 1.6 | 2.7 | 2.8 | 2.1 |

Stage III

| DAFB | 114 | 115 | 116 | 117 | 118 | 119 | 120 | 121 | 122 | 123 | 124 | 125 | 126 | 127 | 128 | 129 | 130 | 131 | 132 | 133 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Iam* |  |  |  |  | □ |  |  | □ |  |  |  |  |  |  |  |  |  |  | □ |  |
| *Ipm* |  |  |  | ▨ |  |  | ▨ |  |  |  | ▨ | ▨ | ▨ | ▨ |  |  |  |  |  |  |
| Miscellaneous |  | ■ | ■ |  |  | ■ |  |  | ■ | ■ |  |  |  |  | ■ | ■ | ■ | ■ |  | ■ |
| No irrigation | ☒ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| CWS (mm $d^{-1}$) | 0.0 | 3.9 | 2.9 | 3.1 | 2.8 | 3.6 | 2.9 | 2.9 | 3.6 | 4.0 | 4.1 | 2.6 | 2.2 | 3.1 | 3.7 | 3.5 | 3.6 | 4.4 | 2.2 | 3.6 |

| DAFB | 134 | 135 | 136 | 137 | 138 | 139 | 140 | 141 | 142 | 143 | 144 | 145 | 146 | 147 | 148 | 149 | 150 | 151 | 152 | 153 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Iam* | □ | □ |  |  |  |  |  |  |  |  |  |  | □ | □ | □ |  |  | □ |  |  |
| *Ipm* |  |  |  |  |  |  |  | ▨ |  |  |  | ▨ |  |  |  |  |  |  |  | ▨ |
| Miscellaneous |  |  | ■ |  |  | ■ |  |  | ■ | ■ | ■ |  |  |  |  | ■ | ■ |  | ■ |  |
| No irrigation |  |  |  | ☒ | ☒ |  | ☒ |  |  |  |  |  |  |  |  |  |  |  |  |  |
| CWS (mm $d^{-1}$) | 2.7 | 2.9 | 3.5 | 21.4 | 0.0 | 4.4 | 5.4 | 6.3 | 2.5 | 3.5 | 2.7 | 2.6 | 2.9 | 2.9 | 3.0 | 3.0 | 3.0 | 3.0 | 2.9 | 2.7 |

| DAFB | 154 | 155 | 156 | 157 | 158 | 159 | 160 | 161 | 162 | 163 | 164 | 165 | 166 | 167 | 168 | 169 | 170 | 171 | 172 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Iam* |  |  |  |  |  |  | □ |  |  | □ |  |  |  |  | □ |  |  |  | □ |
| *Ipm* |  |  |  | ▨ | ▨ |  |  | ▨ | ▨ |  |  |  |  | ▨ |  | ▨ |  |  |  |
| Miscellaneous | ■ |  | ■ |  |  | ■ |  |  |  |  | ■ | ■ | ■ |  |  |  | ■ | ■ |  |
| No irrigation |  | ☒ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| CWS (mm $d^{-1}$) | 3.7 | 0.0 | 2.8 | 2.8 | 2.8 | 2.9 | 4.2 | 2.9 | 2.5 | 2.8 | 2.2 | 2.4 | 2.9 | 2.8 | 2.7 | 2.5 | 2.8 | 3.0 | 2.6 |

Figure 1. Irrigation timing and crop water supply (CWS = irrigation + rainfall) of 'September Bright' nectarines. Morning irrigation ($I_{am}$, from 7.00 to 12.00 h), afternoon irrigation ($I_{pm}$, from 12.30 to 17.30 h), miscellaneous irrigation (non-$I_{am}$ and non-$I_{pm}$) and no irrigation for each day after full bloom (DAFB) during fruit growth stages I and III.

## Fruit growth efficiency

The fruit thinning carried out early after fruit set led to an average crop load of 225 ± 12 fruit $tree^{-1}$ at harvest. Considering the days of $I_{am}$ and $I_{pm}$, the dynamics of FW changed

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across the 24 h period. For example, in stage I $I_{am}$ led to a steep increase of FW at and after noon, when the usual lag phase of the diel sigmoidal pattern occurred (Fig. 2A). The following day, following $I_{pm}$ FW rose quickly starting from late afternoon (Fig. 2B). In stage III (160 DAFB) $I_{am}$ did not lead to an increase in FW in the warmest part of the day (at noon and in the early afternoon) as previously shown for stage I, rather FW increased only in the late afternoon (Fig. 2B), similarly to the following day, when instead $I_{pm}$ was supplied (Fig. 2B). These different behaviours are linked to the divergent environmental conditions in the two stages. Fruit were likely to transpire a similar amount of water to the one imported by vascular activity in the warmest time of the day in stage III, when the evaporative demand is particularly high. Within each stage, $ET_c$ was similar in the two days shown in Figure 2 (2.1 and 2.7 mm at 48 and 49 DAFB, and 5.2 and 4.9 mm at 160 and 161 DAFB, respectively).

In terms of FGE, not only is VPD important, but $ET_c$ becomes prevalent, as it accounts for the soil evaporation component, which is not negligible in warm and dry conditions. Indeed, when ΔFW, RGR and FGE in stages I and III were compared, the daily $ET_c$ was highly significant ($P < 0.001$) when used as covariate in the ANCOVA analysis. Despite ΔFW being six-fold smaller in stage I than in stage III, the average RGR was significantly higher in the former (Table 1) due to rapid cell division. FGE was two-fold higher in stage I than in stage III, suggesting that in the former, less water is needed to obtain as much relative growth as for the latter.

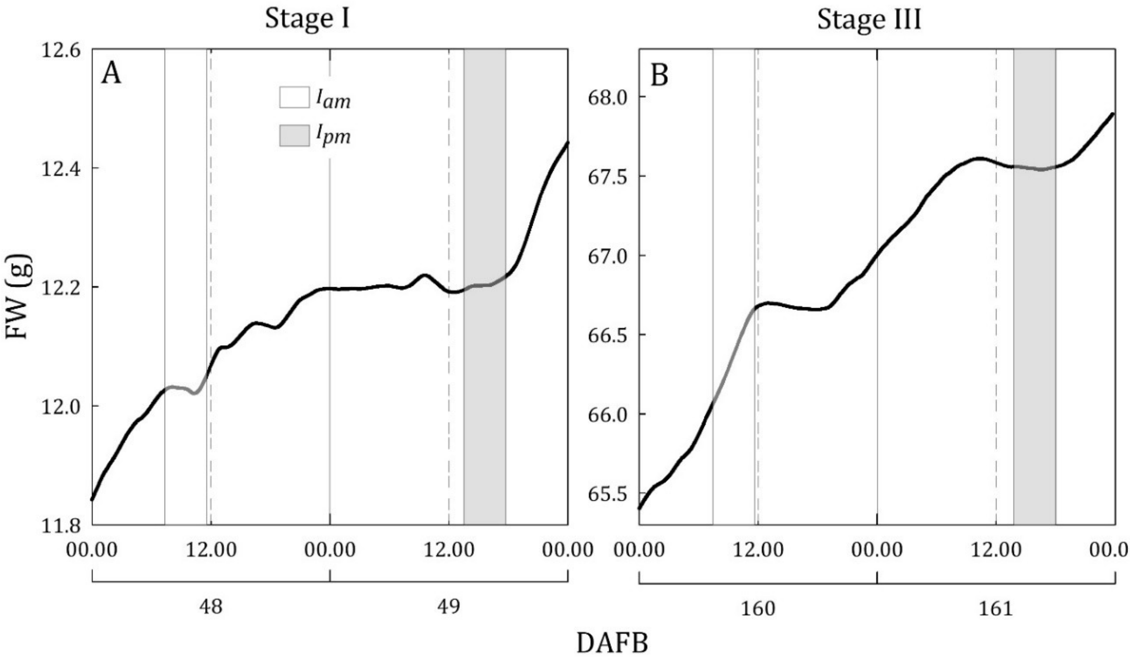

Figure 2. Average fruit weight (FW) in 'September Bright' nectarines during consecutive days of morning irrigation ($I_{am}$) followed by afternoon irrigation ($I_{pm}$) at fruit growth stages I (A) and III (B). Time expressed in days after full bloom (DAFB).

Table 1. Daily fruit weight variations (ΔFW), relative growth rate (RGR) and fruit growth efficiency (FGE) in fruit growth stages I and III of 'September Bright' nectarines. Crop evapotranspiration ($ET_c$) used as a covariate in the ANCOVA. Least square means ± standard errors are reported.

| Fruit growth stage | ΔFW (g $d^{-1}$) | RGR (mg $g^{-1}$ $d^{-1}$) | FGE (mg $g^{-1}$ $mm^{-1}$ $d^{-1}$) |
|---|---|---|---|
| I | 0.20 ± 0.09 | 29.04 ± 2.42 | 13.05 ± 1.30 |
| III | 1.19 ± 0.05 | 21.13 ± 1.55 | 6.51 ± 0.83 |
| *P* | < 0.001 | < 0.05 | < 0.001 |

Different fruit growth responses under $I_{am}$ or $I_{pm}$ highlighted minimal soil water buffering capacity (i.e. low available rootzone soil water). Opposite trends of FGE occurred in stages I and III in response to $I_{am}$ and $I_{pm}$ (Fig. 3A-B). In stage I, morning irrigation promoted a significantly higher FGE than in the afternoon (Fig. 3A). By contrast, $I_{pm}$ was significantly more beneficial for FGE than $I_{am}$ (Fig. 3B) in stage III, when days were particularly warm and dry, in accordance with Torres-Ruiz et al. (2016) who suggested that supplying water in the afternoon, when water deficit is highest, can have a positive effect on kiwifruit growth. The high $ET_c$ in stage III might have led to a considerable evaporation from the soil, that caused a lower amount of water to reach the fruit, thus reducing the FGE during this stage. In stage I, morning irrigation stimulated both diurnal and nocturnal cell expansion as suggested by Figure 2, resulting in an FGE more than two-fold higher than for afternoon irrigation. However, when the daily $ET_c$ was used as a covariate in the model no significant differences were found between $I_{am}$ and $I_{pm}$ within stage I (Fig. 3C) and III (Fig. 3D). This suggests a key role of evapotranspiration and seasonal environmental characteristics on fruit growth. In fact, when FGE response to $ET_c$ was analysed through a linear regression, each of the two stages showed opposite relationships. On the one hand, during stage I a positive response of FGE was observed along increasing $ET_c$ (Fig. 4), when FGE was the highest (Tab. 1). On the other hand, stage III highlighted a reduction of FGE at increasing $ET_c$ (Fig. 4). The reverse associations are certainly partly due to the intrinsic environmental characteristics of stages I and III (i.e. stage III being drier and warmer than stage I) but are also affected by fruit phenology (cell division vs enlargement) and vascular activity. The effect of stage-specific vascular activity in addition to the environmental control explains why, even after adjusting for $ET_c$, there is a tendency for opposite FGE responses following morning and afternoon irrigation in stages I and III (Fig. 3C-D).

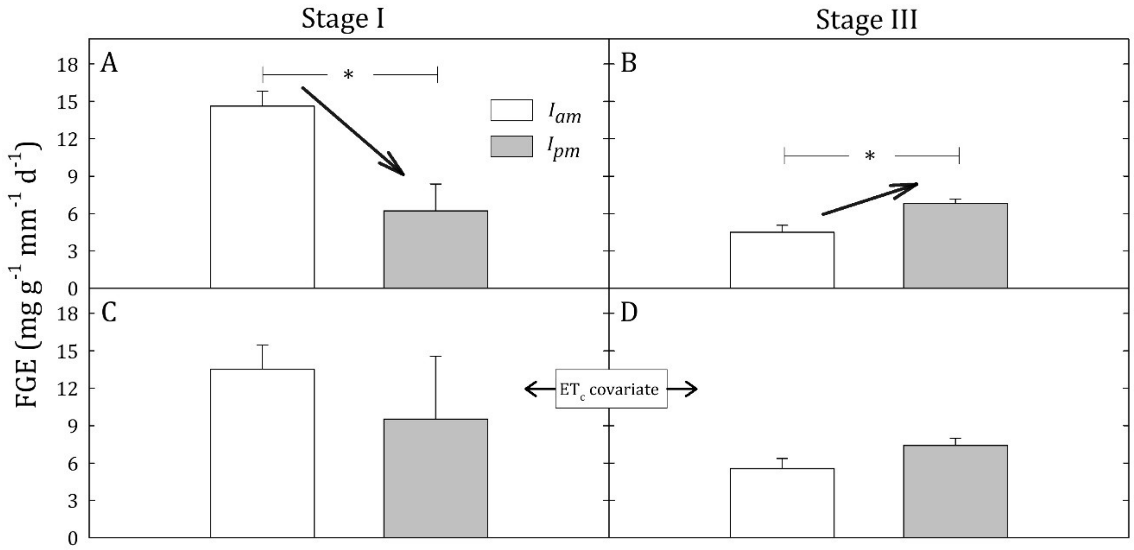

Figure 3. Fruit growth efficiency (FGE) in 'September Bright' nectarine trees under morning ($I_{am}$) and afternoon ($I_{pm}$) irrigation. T-tests for stages I (A) and III (B) and ANCOVA

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analyses performed using daily crop evapotranspiration ($ET_c$) as a covariate in stage I (C) and III (D). Asterisks represent significant differences for $P < 0.01$.

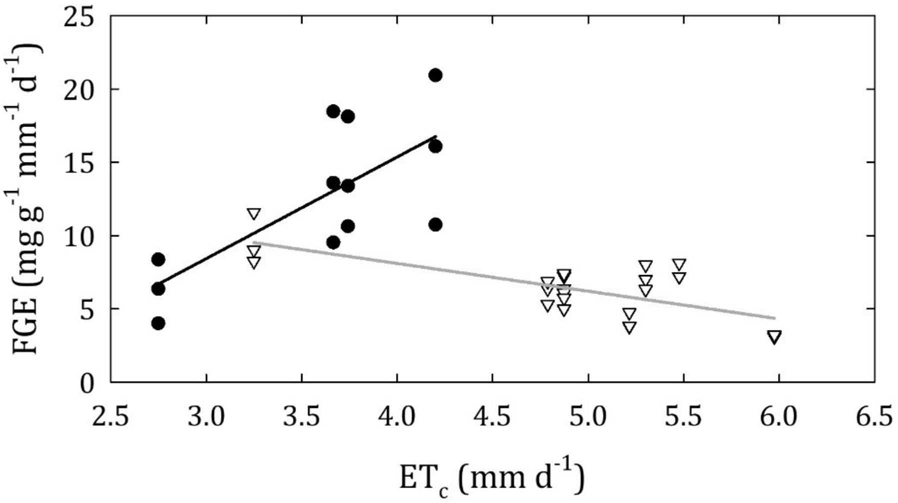

Figure 4. Linear regression analyses of fruit growth efficiency (FGE) vs crop evapotranspiration ($ET_c$) in stages I (black circles) and III (white triangles) of 'September Bright' nectarines. In stage I, FGE = −12.37 + (6.93 × $ET_c$) [$R^2 = 0.54$, $P < 0.001$]; in stage III, FGE = 15.66 + (−1.89 × $ET_c$) [$R^2 = 0.50$, $P < 0.001$].

## CONCLUSIONS

This work highlighted the effects of morning and afternoon irrigation on the fruit growth efficiency of a late-ripening nectarine cultivar in the two stages of rapid fruit growth, i.e. cell division (stage I) and cell expansion (stage III). An opposite beneficial effect of morning and afternoon irrigation was found in the two stages, with fruit growing more efficiently after morning irrigation in stage I, and when irrigated in the afternoon in stage III. These findings, although preliminary, are of pivotal importance for irrigation management as they suggest that an efficient irrigation management needs to consider at least two timescales: (i) fruit growth stage and (ii) sub-daily scale. The study of irrigation timing effects on fruit growth using fruit gauges can potentially be replicated in other fruit tree temperate crops. Future studies should consider the interaction of deficit irrigation levels and irrigation timing on fruit growth dynamics to achieve maximum water use efficiency.

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