**Yield and Water Use in Almond under Deficit Irrigation**

**Gabriel Collin, Jean Caron,** Guillaume Létourneau, and Jacques Gallichand

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**ABSTRACT**

In North America, almond (*Prunus dulcis* (Mill.) D.A. Webb) trees are grown almost exclusively in the Central Valley of California. Research on deficit irrigation is needed to improve water productivity. Real-time technology assessing soil water potential to manage irrigation initiation has led to significant improvements in water productivity in other crops. The objective of this study was to examine the possibility of using real-time tensiometry for irrigation to trigger irrigation events and to generate water savings without affecting crop yield. The yield responses and water consumption of mature almond trees were quantified from 2012 to 2015 for four different irrigation strategies in a commercial orchard located in the San Joaquin Valley in California. Three of the treatments were based on soil water potential threshold (SWPT) measurements and the fourth on the grower’s current management practices, which used estimated crop evapotranspiration (ETc). The SWPT treatments were based on three different stress levels: wet (−35 kPa), medium (−45 kPa), and dry (−55 kPa). There was no significant difference in marketable yield between the grower irrigation strategy and the medium treatment, although the latter used 139 mm less water as a yearly average. In the dry treatment, there was 10% less water applied relative to the medium treatments and 30% less than the grower treatment but a 10% yield reduction compared with the medium and grower treatments. These results indicate that irrigation management for almond could be optimized by initiating irrigation at −45 kPa.

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**Core Ideas**

- **Maximum yields were obtained with wireless real-time tensiometers initiating irrigation at −45 kPa.**
- A significant 16% reduction in water use relative to the grower control was achieved by initiating irrigation at −45 kPa with no yield reduction.
- Almond crop is sensitive to water management, as being too wet (initiation at −35 kPa) or too dry (initiation at −55 kPa) reduced yield by about 11.0 and 11.3%, respectively.

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Almonds are produced on more than 345,000 ha in California, mainly in the Central Valley (USDA-NASS, 2015). This area is responsible for almost all almond production in the United States and 80% of the world’s production (Almond Board of California, 2016). Directly or indirectly, the industry provides about 104,000 jobs and yields an annual economic output of about $21.5 billion (Sumner et al., 2014). Although almonds are considered to be drought-resistant (Torrecillas et al., 1996), approximately 600 to 1500 mm of water is required annually to generate acceptable yields (Miche and Kester, 1998). In California, agriculture uses nearly 80% of the dedicated freshwater (Canessa et al., 2012). Excessive pumping leads to lower groundwater levels, saline water intrusion, and dry wells (Croye et al., 2014) and producers are under increasing social and environmental regulatory pressure to reduce water use for irrigation. The water requirements of almond trees cannot be met by current levels of precipitation (75–305 mm, depending on the area), a situation worsened by drought years, like those which prevailed in the 2004–2014 period (California Department of Water Resources, 2014). With 70% of producers now using microirrigation, water use has decreased by almost 33% over the same period (Almond Board of California, 2015) but despite this improvement, additional gains in water productivity are needed to decrease the water use associated with this major crop.

There are three main types of irrigation scheduling in use, based on climatic (Type 1), plant (Type 2), or soil water (Type 3) measurements. The climatic system, Type 1, is the most commonly used but requires an accurate estimate of local ETc, which depends on the canopy, the irrigation method, the climate, and crop development (Allen et al., 1998). Although it provides a good approximation of the quantity of water required, it does not, however, determine when it is required, as no soil or plant measurements are involved. With respect to Type 2 irrigation scheduling, researchers have developed several methods based on tree water status measurements to determine when irrigation should be activated (Fereres and Goldhamer, 2003; Fulton et al., 2001; Goldhamer et al., 2006; Shackel et al., 1997). Midday stem water potential (MSWP) has thus become the current standard irrigation management tool (Fereres and Goldhamer, 2003; Fulton et al., 2014; Shackel, 2007; Shackel

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**Abbreviations:** %ETc, percentage of cumulative crop evapotranspiration of the monitoring season; ETc, crop evapotranspiration; Kc, crop coefficient; MSWP, midday stem water potential; SWPT, soil water potential threshold; SWT, soil water potential readings obtained with tensiometers; VPD, leaf vapor pressure deficit.

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The continuous monitoring required by this technique is time-consuming (Fulton et al., 2001) and requires well-trained technicians (Williams and Araujo, 2002). Moreover, it is ill-suited to automated irrigation (Jones, 2004). Thermal sensing represents a promising alternative to detect plant stress, especially with the rapid development of unmanned aerial vehicle technology (Maes and Steppe, 2012). Dhillon et al. (2014) have also developed a set of mobile sensors that measure leaf temperature and climatic variables to predict water stress. These techniques will need to be improved before they can be fully automated (Dhillon et al., 2014; Maes and Steppe, 2012).

The Type 3 approach to irrigation scheduling uses soil water measurements. However, many researchers (Fereres, 1996; Naor, 2006) have identified difficulties with regard to these measurements, such as variability arising from soil heterogeneity, equipment cost limitations, and calibration requirements. Nonetheless, soil water measurements can be collected at multiple locations in real time, fully automated, and easily integrated into an irrigation system to provide well-timed irrigation (Hodnett et al., 1990; Moutonnet et al., 1981). Tensiometers are used to measure soil water potential and have proven to be very useful in timing irrigations (Richards and Marsh, 1961; Shock and Wang, 2011). Recent technologies based on real-time soil matric potential measurements have been successfully implemented in cranberry (Vaccinium macrocarpon Ait.) (Pelletier et al., 2013) and strawberry (Fragaria x ananassa Duchesne) (Létourneau et al., 2015; Anderson, 2015; Gendron et al., 2017) to reduce production water use and increase productivity. This technology also has shown to successfully increase celery (Apium graveolens L.) and onion (Allium cepa L.) yields, and spinach (Spinacia oleracea L.) germination (Rekika et al., 2014) and prevents tip burn in romaine lettuce (Lactuca sativa L.) grown in muck soils (Périard et al., 2015), but has never been tested for almond.

A problem that has been reported when irrigation is reduced for strawberry (Anderson, 2015, Gendron et al., 2017) and lettuce (Périard et al., 2015) production is that a small delay in initiating irrigation can be detrimental to crop growth. These studies used real-time tensiometry to manage irrigation and its potential to anticipate coming stress as well as manage deficit irrigation to limit any negative effect on crop productivity. However, this approach also has never been tested for almond production and may not necessarily be applicable, as almond is a tree crop and thus yields respond not only to yearly irrigation but, to a large extent, to fruit bearing spur numbers formed in the previous years (Lampinen et al., 2011). The crop is therefore expected to respond to both short-term and long-term water management. Therefore, additional research is needed in almond to test irrigation scheduling based on real-time soil water potential measurements. The objective of this study was to evaluate the effect of real-time soil water matric potential irrigation thresholds on almond yield and water consumption and its potential to manage deficit irrigation in a long-term trial.

**MATERIAL AND METHODS**

**Experimental Site**

The experiment was conducted from 2012 to 2015 in a mature almond tree orchard located in Shafter, CA (35.346° N, 119.2067° W), just outside Bakersfield in the San Joaquin Valley. The site is characterized by a Milham sandy loam soil (fine-loamy, mixed, superactive, thermic Typic Haplorgids) (O’Green et al., 2016). The experiment ran from 3 Apr. to 19 Aug. 2012, from 2 Apr. to 15 Aug. 2013, from 1 Apr. to 8 Aug. 2014, and from 18 May to 8 Aug. 2015. The almond (cv. Nonpareil) trees were planted on alternate rows (see further details below). The experimental plot was located on a 1.2-ha section of a 30.4-ha field, with 5.5-m (within-row) by 7.3-m (inter-row) tree spacing. Trees were irrigated with a 12-jet microsprinkler irrigation system placed midway between trees at 58 L h⁻¹ at 0.17 to 0.24 MPa, with a 2-m wetted radius (Gironet, Netafim, CA). The soil surface was kept weed-free with herbicides during the experiment according to the grower’s management practices following the state appropriate recommendation (Weed Research and Information Center; http://wric.ucdavis.edu, accessed 28 Jan. 2019).

**Experimental Design**

The trial comprised 16 rows of 22 trees each (Nonpareil variety) separated by guard rows of other varieties (‘Sonora’ and ‘Fritz’). Rows were divided into four blocks of four treatments: wet, medium, dry, and grower irrigation. Two sample trees per replicate were randomly selected to monitor tree water stress (Fig. 1). The experimental layout was arranged as a completely randomized block design, with each of the four irrigation treatments described above randomly allocated to one single row of the Nonpareil variety within each of the four blocks. All four blocks (rows) of the same treatment were irrigated at the same time, independently of the other treatments (see below), following the procedure described below.

**Climatic, Soil and Tree Water Data**

In Block 2, three tensiometers, connected to a TX3 wireless station (Hortau Inc., Saint-Nicolas, QC, Canada), were installed in each of the four treatments at three different depths: 25, 50, and 75 cm. Soil water potential data (SWT) were collected continuously at 15-min intervals and sent to a web server (Irrolis, https://irrolis.hortau.net, accessed 17 Jan. 2019). These depths were chosen after observations made on site when the cores were sampled. Roots were not present below 75 cm and root growth was sampled indicated that roots were concentrated in the 0- to 50-cm depth at the beginning of the experiments. Likewise, an oxidized layer was observed at about 75 cm, indicating that little water movement occurred below this depth. Several studies have shown that active water uptake by roots occurs mainly in the upper soil layer (0–30 cm) and decreases significantly below that depth and that the total root zone is limited to the 90- to 100-cm soil depth (Andreu et al., 1997; Koumanov et al., 1997, 2006; Vrugt et al., 2001). Tensiometers were installed at a distance of 1 m from the microsprinkler, within the 2-m wetted radius, at a 45° horizontal angle to the tree row. Because of cost limitations, only one station per treatment was used and installed within Block 2, located centrally on the site (Fig. 1). Additional handheld tensiometers were installed and used to make sure that the wireless tensiometers’ readings were representative of the overall treatment effect. Irrigation was controlled to maintain the soil water potential above the target threshold (SWPT) in each treatment: −35 kPa (wet), −45 kPa (medium), and −55 kPa (dry). The SWPT values were determined by averaging the readings of the tensiometers (the SWT data) at the 25- and 50-cm depths. These thresholds were selected according to the model of Rekika et al.
(2014), which uses site estimates of the expected ETc, the rooting depth, and the soil hydraulic properties described below to estimate the critical SWPT when the soil water supply could not meet ETc under steady-state conditions. Preliminary evaluations suggested that the driest thresholds (−55 and −45 kPa) were low enough to generate some stress to the crop relative to the wettest one (−35 kPa). When the threshold was attained, irrigation was activated for all rows of the same treatment by a control unit (CTR, Hortau Inc.), which remotely triggered solenoid valves (Irritrol, Riverside, CA; Rainbird, Azusa, CA) and an electric pump. Irrigation was stopped when the wetting front reached the tensiometer at the 75-cm depth (when the SWT at 75 cm began to increase). The grower treatment (grower) was controlled by the producer on the basis of ETc estimates and amounted to 758, 754, 685, and 450 mm yearly from 2012 to 2015. The producer aimed to replace 100% of ETc losses over 2- or 3-wk cycles.

Climatic data were measured by an automated weather station (Hortau Inc.) installed on site. Reference evapotranspiration was calculated via the Penman–Monteith equation (Allen et al., 1998) for a fully irrigated grass cover. For comparison purposes, the crop coefficient (Kc) values of Allen et al. (1998), Goldhamer and Viveros (2000), Steduto et al. (2012), and Sanden (2009) were used to estimate ETc. Water use differed from year to year as the duration of the trial varied from year to year. For that reason, the percentage of cumulative crop evapotranspiration of the monitoring season (%ETc) was used to compare water use among years and between the two treatments.

Midday stem water potential was measured weekly (12:00 PM to 16:00 PM) (Fulton et al., 2014) on the same two trees in each plot with a pump-up chamber (PMS Instrument Company, Albany, OR) and a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA). Stem water potential bags (PMS Instrument Company) were installed on shaded leaves on a lower branch near the trunk at least 10 min before measurements were taken (Fulton et al., 2001). Measurements were taken immediately after leaf excision. Before installing the stem water potential bags, leaf temperature was measured with an infrared thermometer (IR 1000, Klein Tools, IL). Shaded leaves are better suited for determining plant water status and measuring leaf temperature (Dhillon et al., 2014). Leaf temperature and relative humidity, as measured by the weather station, were used to estimate the leaf vapor pressure deficit (VPDleaf). Plant measurements were taken from the beginning of May until harvest in mid-August and were averaged per single tree per year for statistical analysis.

In 2012, soils were excavated to describe and characterize soil properties by horizon and to evaluate root growth. Profiles were made midway between trees on the same row. Thirteen undisturbed soil cores (8.2 cm diameter by 5.5 cm height) were collected at depths of 25 (×7) and 50 cm (×6) to determine bulk density, which averaged 1.67 g cm−3 at the 25-cm depth and 1.65 g cm−3 at the 15-cm depth. Data on soil saturated hydraulic conductivity and water retention curves have been reported elsewhere (Collin, 2017). Root distribution was observed in open profiles and noted. Textural classes were determined from particle size analysis of disturbed samples taken in 2011 (GeeFig. 1. Experimental design of the four treatments in a randomized complete block design in four blocks (rows). The number following the treatment represents the block number. MSWP, midday stem water potential; VPDleaf, leaf vapor pressure deficit.
Table 1. Soil chemical and physical properties

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil depth</th>
<th>2012</th>
<th>2013</th>
<th>2015</th>
<th>2012</th>
<th>2013</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grower</td>
<td>0–25</td>
<td>0.31 ± 0.01 (6)†</td>
<td>0.56 ± 0.04 (24)</td>
<td>0.58 ± 0.07 (16)</td>
<td>7.86 ± 0.18 (6)</td>
<td>6.99 ± 0.05 (24)</td>
<td>7.46 ± 0.07 (16)</td>
</tr>
<tr>
<td></td>
<td>25–50</td>
<td>0.25 ± 0.03 (3)</td>
<td>0.58 ± 0.07 (20)</td>
<td>0.54 ± 0.03 (16)</td>
<td>7.43 ± 0.04 (3)</td>
<td>7.17 ± 0.05 (20)</td>
<td>7.63 ± 0.08 (16)</td>
</tr>
<tr>
<td>Wet</td>
<td>0–25</td>
<td>0.29 ± 0.02 (9)</td>
<td>0.63 ± 0.05 (24)</td>
<td>0.34 ± 0.04 (16)</td>
<td>7.87 ± 0.02 (9)</td>
<td>6.95 ± 0.06 (24)</td>
<td>7.46 ± 0.09 (16)</td>
</tr>
<tr>
<td></td>
<td>25–50</td>
<td>0.17 ± 0.00 (3)</td>
<td>0.64 ± 0.07 (25)</td>
<td>0.47 ± 0.05 (16)</td>
<td>8.08 ± 0.02 (3)</td>
<td>6.96 ± 0.06 (25)</td>
<td>7.62 ± 0.11 (16)</td>
</tr>
<tr>
<td>Medium</td>
<td>0–25</td>
<td>0.26 ± 0.01 (9)</td>
<td>0.75 ± 0.11 (20)</td>
<td>0.42 ± 0.03 (16)</td>
<td>7.81 ± 0.07 (9)</td>
<td>6.97 ± 0.06 (20)</td>
<td>7.15 ± 0.07 (16)</td>
</tr>
<tr>
<td></td>
<td>25–50</td>
<td>0.17 ± 0.00 (3)</td>
<td>0.64 ± 0.07 (25)</td>
<td>0.47 ± 0.05 (16)</td>
<td>8.08 ± 0.02 (3)</td>
<td>6.96 ± 0.06 (25)</td>
<td>7.62 ± 0.11 (16)</td>
</tr>
<tr>
<td>Dry</td>
<td>0–25</td>
<td>0.36 ± 0.07 (9)</td>
<td>0.49 ± 0.04 (28)</td>
<td>0.50 ± 0.06 (16)</td>
<td>7.72 ± 0.17 (9)</td>
<td>7.02 ± 0.07 (28)</td>
<td>7.27 ± 0.09 (16)</td>
</tr>
<tr>
<td></td>
<td>25–50</td>
<td>0.36 ± 0.07 (9)</td>
<td>0.63 ± 0.09 (23)</td>
<td>0.56 ± 0.06 (16)</td>
<td>7.72 ± 0.17 (9)</td>
<td>7.02 ± 0.07 (28)</td>
<td>7.27 ± 0.09 (16)</td>
</tr>
</tbody>
</table>

† Mean ± SE (number of samples).

and Bauder, 1986). At the beginning and end of each season, new profiles were characterized, root distribution was recorded, and disturbed soil samples were analyzed in all plots to monitor electrical conductivity and pH at the 25- and 50-cm depths via the soil saturated extract method (Brown, 1988) to check salinity buildup under different irrigation management systems.

Yield Measurements

At harvest, two trees per replicate were mechanically shaken by commercial equipment. Immediately afterwards, almonds were collected in an average area of 5.5 by 7.3 m and weighed. Subsamples (~300 almonds) were cracked, sorted, and dried at 80°C until equilibrium weight was attained to determine marketable yield. Additional yield values were obtained from producer data for 2011 to 2014 for neighboring plots in which the same wireless tensiometer technology was used. The in-season (May to mid-August) average SWPT at 25 to 50 cm was related to these average yields to obtain more response values.

Water Use

During the monitoring period, rotary flowmeters were installed to measure the quantity of water applied, with an accuracy of ±1.5% (IP80-Series, Seametrics, WA) and ±3% (TM Series, GPI, KS). Flowmeters measured all water applied to the crop: water used for irrigation treatments and water used for fertilizer applications. Fertilizer applications were performed weekly in four shots in April, before the irrigation treatments started. Flowmeters were installed for treatments at the beginning of irrigation lines (IP80-Series flowmeters) and at the end of the first block of all irrigation treatment (TM Series flowmeters). Water use was recorded continuously by flowmeters and transmitted by a wireless station at 15-min intervals (Hortau Inc.) in the SWPT treatments and weekly for fertilization application and the grower irrigation. The SWPT treatments were connected to the grower irrigation system through manual valves to ensure that all treatments received the same fertilization. The valves were opened before and closed after the fertilizer applications by a technician. Irrigation was taken over by the producer 2 wk before harvest to allow the same preharvest management in all treatments.

Statistical Analysis

ANOVA was carried out with SAS software (SAS Institute Inc., Cary, NC) via the GLM procedure. Least significant differences were calculated to compare treatment means. Statistical comparisons were considered significant at P < 0.05. Statistical analysis and relationships were based on the mean values of seasonal MSWP, VPDleaf, SWPT, and %ETc of the whole season. The boundary approach (Webb, 1972) was used to approximate the optimum values for MDSWP, VPDleaf, SWPT, and %ETc on the basis of almond yield. The boundary data were established via the Schnug approach (Schnug et al., 1996) without excluding outliers or lifting data. Polynomial and spline functions were used on the boundary data to generate the boundary lines. The boundary line analysis was programmed using R software (R Development Core Team, Vienna, Austria). This approach is often chosen for biological databases when one has little control over the environmental conditions (Webb, 1972), like the case here, and was selected for this reason.

RESULTS AND DISCUSSION

The textural analyses showed that the soil is a fine sandy loam at both depths, consistent with O’Green et al. (2016). Soil analysis did not indicate crop limitation effects or treatment effects on pH and electrical conductivity. Soil salinity never exceeded the salt tolerance threshold of 1.5 dS m⁻¹ (Bernstein et al., 1956; Brown et al., 1953; Maas, 1990) for the 4 yr of the experiment (Table 1). Bulk density values did not indicate crop limitations and were characteristic of light-textured soils. Roots were mainly observed in the first 50 to 60 cm, as reported above, in the first two samplings and were observed to have moved deeper in the profile (70–90 cm) in 2015 and closer to the emitter.

Tree and Soil Water Status

With available water in the soil from winter rain, irrigation, additional water from fertigation, and reduced evapotranspiration demand, the trees were not subjected to hydric stress at the beginning of the season (before May). Even if irrigation treatments started in early May, stresses were mainly observed from early June to harvest, when ETc demand peaked, as confirmed by plant water status measurements.

Table 2 presents the cumulative water input, SWPTs, and the number of irrigation applications for each year of the experiment. Figure 2 presents the cumulative water components for each season: ETc, rainfall, and irrigation water for each SWPT treatment as calculated from the tensiometer readings at the 25- and 50-cm depths. During the monitoring period, the grower, wet, and medium treatments received more water than the dry
A water use trend is apparent in the three SWPT treatments over the 4-yr experimental period, the grower treatment used about 557 mm (24%) more irrigation water than the wet and medium treatments, and about 971 mm (51%) more than the dry treatment. The medium and wet treatments received similar amounts of water, probably because of the reduced growth observed in the wet treatment, which is likely to be a result of root asphyxia, leading to lower water consumption.

A water use trend is apparent in the three SWPT treatments through all 4 yr, especially so in the dry treatment. Although the target SWPT was the same every year and ETc decreased with time, water use in %ETc increased from 2012 to 2015; this increase was particularly evident at the end of 2015. In the wet and medium treatments, increased water use was observed in 2015. Water use in all treatments exceeded ETc. Qualitative in-field observations suggest that with more regular irrigation and a wetting bulb (the wetted volume by the emitter) of quite uniform size relative to uneven irrigation, almonds trees reacted by increasing root development at the periphery of the wetting bulb. In the profile dug up in 2015, roots were found deeper than in 2012 and were located in between the tensiometer and the emitter. This increased root density caused a reduction of the wetting bulb dimension, because of roots intercepting the water front moving from the emitter toward the tensiometer. As the tensiometers remained in the same location from year to year, the expected tensiometer responses were delayed because of this interception for the same irrigation duration, which led to increased water applications. This observation made in the profile is consistent with those of Coelho and Or (1999) and Vrugt et al. (2001), who showed that irrigation strategy influences root development. Consequently, in future studies for long-term use in irrigated almond orchards, tensiometers should be moved periodically to avoid such an effect.

Targeted SWPTs differed slightly from the observed values as the thresholds were difficult to achieve at the beginning of the season during fertigation and were exceeded at the end of the season during the dry period when water applications were delayed because of restricted water allocation and availability. Furthermore, since irrigation water had to be ordered in advance for a specific threshold and because SWT readings at the 50- and 75-cm depths reacted only a couple of hours after the beginning of irrigation, the start of irrigation needed to be approximated and, consequently, irrigation had sometimes to be activated earlier or was sometimes delayed relative to the target threshold because of these ordering or additional usual operational constraints (staff or equipment limitations). Despite these limitations, the thresholds for all treatments were not significantly different from the target values, except for the wet treatment in 2013. All data were kept, though, as the wet treatment still remained wetter than the medium and the dry treatments in that year.

Regarding the objective of the study, the most important difference among treatments was that the grower treatment used more water but this treatment had a more variable threshold, indicating that the grower sometimes irrigated when the soil was still wet and sometimes when it was too dry. The second important observation regarding the objective of this study was that MSWP and VPDleaf in the dry treatment (–1.346 MPa and 2.419 kPa) were different (higher for VPDleaf and lower for MSWP) from those in the other treatments (Table 3). The values were similar in the wet (–1.246 MPa and 2.371 kPa) and medium (–1.198 MPa and 2.354 kPa) treatments, except for MSWP in 2013. The grower treatment (–1.089 MPa and 2.297 kPa) showed the least stress (higher MSWP or less negative), consistent with the higher water consumption measured in this treatment. The mean seasonal MSWP in all treatments was generally maintained in the mild stress zone [–1.0 to –1.4 MPa according to Fulton et al., (2014)], except in the dry treatment in 2012–2013 (–1.643 and –1.401 MPa) and in the wet treatment in 2013 (–1.520 MPa).

### Yield Measurements

Table 4 presents the mean marketable yield for each treatment and for each year of the experiment. The mean yield from...
the experimental site was higher (3114 kg ha\(^{-1}\)) than the average yield in California (2477 kg ha\(^{-1}\)) for the same period, suggesting that the overall growing conditions were representative, if not better, than normal almond orchard operations and productivity (USDA-NASS, 2016) and that factors other than irrigation were unlikely to control plant responses.

The average yield (2012–2015) from the medium treatment (−45 kPa) exceeded that of the wet (11.0% increase) and dry (11.3% increase) treatments and these differences were significant. The results associated with the wet treatment relative to the medium treatment could be attributable to increased vegetative growth, as reported by other studies (Ebel et al., 1995; Hutmacher et al., 1994); root asphyxia causing stomatal closure and a consequent decrease in photosynthesis (Amador et al., 2012); or other constraints. Yield reductions in the dry treatment were linked to decreased fruit load and kernel size resulting from limited soil water availability and the possible years of cumulative irrigation effect on spur production (Lampinen et al., 2011).

Indeed, even if yield is possibly affected by the same year’s irrigation management, it is also affected by antecedent management (including irrigation) effects on fruit-bearing spurs produced the years before. Therefore, irrigation effects may be better evaluated by looking at long-term yield irrigation trials. When summed over 4 yr, although the grower and medium treatments produced the same average yield, the medium treatment used an yearly average of 139 mm less water (16% less). Moreover, the grower treatment produced a higher yield than the wet treatment (11.2% higher). This yield difference may be attributable to the more variable irrigation pattern in the grower treatment, as reflected by the higher SD of the SWPT of grower’s data relative to the wet treatment (Table 2). Indeed, data for the grower treatment indicated a SD of SWPT of 21.6 relative to 12.5 kPa for the wet treatment, showing that irrigation was sometimes initiated as low as −60.6 kPa (−39.0 + 1 times the SD of −21.6 kPa), in comparison with −53 kPa for the wet treatment. Dry periods in this treatment may have allowed more oxygen to enter the soil profile than the more uniform irrigation pattern in the wet treatment.

Relative to the medium treatment, the dry periods in the grower treatment may have also caused some yield decrease (the medium treatment reached a low −57.0 kPa on average for 4 yr) but also some wetter conditions in the grower treatment, with

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</thead>
<tbody>
<tr>
<td>Grower</td>
<td>3194a</td>
<td>4052a</td>
<td>3699</td>
<td>2183b</td>
<td>3280a</td>
</tr>
<tr>
<td>Wet</td>
<td>2680ab</td>
<td>3134c</td>
<td>3913</td>
<td>2085b</td>
<td>2949b</td>
</tr>
<tr>
<td>Medium</td>
<td>3067a</td>
<td>3599b</td>
<td>4110</td>
<td>2332b</td>
<td>3273a</td>
</tr>
<tr>
<td>Dry</td>
<td>2330b</td>
<td>3160c</td>
<td>3525</td>
<td>2771a</td>
<td>2942b</td>
</tr>
<tr>
<td>LSD</td>
<td>646</td>
<td>262</td>
<td>ns</td>
<td>438</td>
<td>242</td>
</tr>
<tr>
<td>P</td>
<td>0.047</td>
<td>&lt;0.0001</td>
<td>0.2429</td>
<td>0.0211</td>
<td>0.0038</td>
</tr>
<tr>
<td>P-value</td>
<td>0.0169</td>
<td>0.2299</td>
<td>0.0009</td>
<td>0.0158</td>
<td>0.2151</td>
</tr>
<tr>
<td>R(^2)</td>
<td>0.0127</td>
<td>0.0008</td>
<td>0.5568</td>
<td>0.4331</td>
<td>0.1997</td>
</tr>
<tr>
<td>VPD(_{leaf})</td>
<td>0.0171</td>
<td>0.1797</td>
<td>0.5679</td>
<td>0.3103</td>
<td>0.0386</td>
</tr>
<tr>
<td>% ET(_c)</td>
<td>0.1795</td>
<td>0.5219</td>
<td>0.0633</td>
<td>0.2154</td>
<td></td>
</tr>
</tbody>
</table>

† For each year, means followed by the same lowercase letter (a, b, c, d) within columns are not significantly different according to the least significant difference (LSD) test at P ≤ 0.05. When “ns” follows the mean, no significant differences were found between treatments.

‡ Linear contrasts were used to determine relationships between seasonal yield and the following variables: soil water potential threshold (SWPT), midday stem water potential (MSWP), leaf vapor pressure deficit (VPD\(_{leaf}\)), and percentage of cumulative crop evapotranspiration of the monitoring season (%ET\(_c\)).

§ Not applicable.

Table 3. Midday stem water potential (MSWP) and leaf vapor pressure deficit (VPD\(_{leaf}\)) for each year and irrigation treatment
irrigation initiation in the range of –27.4 kPa (–39 + 21.6 kPa), compared with –37 kPa for the medium treatment. These results indicate that all water potential irrigation treatments had a less variable SWPT than the grower treatment.

There were significant yield differences among years ($P < 0.0001$) and for the interactions among treatments and years ($P = 0.0004$) and treatments and blocks ($P < 0.0001$). Although the linear correlations were generally low ($R^2 = 0.166$ and 0.150, and 0.455 and 0.102 respectively for MSWP vs. VPD$_{leaf}$ and yield in 2012 and 2013, they were significant (data not shown).

Figure 3 shows data for all years for MSWP, VPD$_{leaf}$, and %ET$_c$ in relation to yield. Midday stem water potential was concentrated between –0.8 and –1.4 MPa in the grower treatment and between –1.0 and –1.4 MPa in the wet and the medium treatments, except in 2013, when MSWP in the wet treatment was lower than –1.4 MPa. Midday stem water potential in the dry treatment was generally lower than –1.3 MPa (indicating more stress), except in 2015, when it rose to –1.00 MPa (see Table 3). According to the boundary line, optimum yields were obtained for MSWPs between –1.1 and –1.3 MPa. This finding is consistent with that of Fulton et al. (2014), who suggested maintaining MSWP in the –1.0 to –1.4 MPa range from mid-June through to July. The VPD$_{leaf}$ data were more variable, ranging from 2 to 2.9 kPa for each treatment. Higher yields corresponded to VPD$_{leaf}$ values between 2.2 and 2.5 kPa. Although there was only one %ET$_c$ value for each treatment in each year, the boundary line
indicated the highest yields when ETc was near 100%, according to the Kc recommended by Allen et al. (1998).

In the same way, the boundary line for SWPT and yield data was used to determine the optimal value (Fig. 4). We used mean yield data from neighboring fields collected over different years and monitored with SWT stations to improve this relationship. When we used a polynomial regression on the boundary data, a SWPT of −45 kPa was found to be optimal, according to our experiment. This is wetter than the recommendations of Taylor (1965) and Micke (1996), who suggested starting irrigation between −50 and −80 kPa for deciduous fruit trees or between −50 and −70 kPa at a depth of 45 to 60 cm for almonds. On the basis of the results obtained in the experimental treatments from 2012 to 2015 (Fig. 4), however, it seems that a small deviation from the −45 kPa target value would lead to a greater decrease in marketable yield than the boundary line responses obtained for values from the neighboring fields for different years monitored with SWT stations.

Figure 5 shows simulated relationships between MSWP and %ETc and between SWPT and %ETc, with boundary lines for yield (Fig. 3 and Fig. 4), as suggested by Webb (1972). Even if the intervals between the SWPTs in this study were relatively large, the treatments were still in the mild stress range according to the MSWP values. The boundary lines for these parameters show that almond yield was affected by both insufficient and excess irrigation. Most studies focus principally on deficit irrigation, so little information is available on the effects of excess water in almond production. In a young orchard, Hutmacher et al. (1994) found no significant difference in yield between treatments receiving 150 and 175% ETc through drip irrigation. However, their experiment detected leaching even at the rate of 100% ETc and the authors questioned their irrigation frequency, application rates and wetted volume. They also showed that applying more water than required increased vegetative growth. Girona et al. (2005), on the other hand, reported no surplus vegetative growth for a 130% ETc treatment and a nonsignificant decrease in yield between 70 and 130% relative to 100% ETc in a young (<5 yr) orchard under micro-sprinkler irrigation; ours was much older (>8 yr). Nevertheless, even if this phenomenon is more frequent in flood irrigation, hypoxia has been found to cause atmospheric gas exchange problems leading to growth reductions (Drew, 1983).

For practical use and irrigation guidance, this study also indicates the importance of the choice of Kc value to calculate the 100% ETc water requirements, as the height of water to be applied through irrigation will vary according to the calculated 100% ETc and hence the chosen model. For models indicating maximum yield at 80% ETc like Sanden (2009) and those recommended by Goldhamer, as cited by Steduto et al. (2012), applying water up to 100% ETc will obviously result in 20% extra water use than other Kc values suggested by Allen et al. (1998) (Fig. 6).

According to the results of this study, increased irrigation would probably have reduced yields and led to overapplication of water. This difference emphasizes the importance of Kc in irrigation scheduling based on ETc and indicates that using the Kc suggested by Allen et al. (1998) would help producers reduce water consumption without compromising yield. The study also emphasizes the importance of having soil water potential measurements not only to detect appropriate irrigation timing but also to allow adjustment for biases with evapotranspiration models used for irrigation management.

The −45kPa threshold recommended here is for a full season, after fertilizer application and prior to harvest. This threshold reduced water use by 16% relative to the grower treatment, with the same yield. Further research is needed to determine optimum SWPTs for different stages of growth, as some additional water savings could be generated, particularly prior to harvest.
There is also a need to adjust these thresholds to account for spatiotemporal variability (Collin, 2017).

**Practical Implications**

First, the results of this study indicate that growers under the same orchard conditions can use a SWPT of −45 kPa between May and harvest to schedule irrigation with wireless

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![Graph showing boundary relationships between percentage of cumulative crop evapotranspiration of the monitoring season (%ETc) and midday stem water potential (MSWP) and between %ETc and soil water potential threshold (SWPT). Red, orange, and blue lines represent crop stress associated with different MSWP levels in almonds according to Fulton et al. (2014).](image)

![Graph showing percentage of cumulative crop evapotranspiration of the monitoring season (%ETc) related to almond yield for all experimental years, using crop coefficient values from Allen et al. (1998), Goldhamer (Steduto et al. 2012), Sanden (2009), Girona (2006), and Goldhamer and Viveros (2000).](image)
tensiometers. This threshold represents the mean value of tensiometers placed at the 25-cm depth and those at the 50-cm depth. Irrigation should be stopped when the wetting front reaches the 75-cm tensiometer. Tensiometers should be placed in the wet zone at the periphery of the wetted perimeter and moved as the perimeter evolves. Practically, they should be moved every second year as the rooting volume moves closer to the emitter with time.

If only one tensiometer station is used in a field, it should be coupled with direct observations or plant measurements of MSWP several times during the season to ensure that the system is functioning adequately. Additional soil water potential measurements at different locations should be performed to confirm that the station is located in a representative spot of the orchard. Ideally, additional stations should be added to provide a good average and to increase the net margin of almond orchards, as reported by Collin, (2017).

Second, this study shows that almond yield is adversely affected by excess water, possibly because of surplus vegetative growth or root asphyxia. Third, it was noted that using the new Kc values recommended for almond production (Steduto et al., 2012) under the conditions of this study would not only have led to increased water use but decreased marketable yield as well. Growers should therefore take care to use the Kc values best suited to their specific orchard characteristics.

**CONCLUSION**

For the 4 yr of the experiment, the medium treatment used about 20% less water than the grower treatment, with no decrease in average yield. A SWPT of −45 kPa is therefore recommended in sandy loam soils under San Joaquin Valley conditions between May and harvest to reduce irrigation water use without diminishing productivity. This study also showed that almond trees were negatively affected by both excess irrigation and deficit irrigation (−55 kPa). Finally, some attention should be paid to the Kc recommendations in almond orchards to ensure optimal yield and water use.

**CONFLICT OF INTEREST STATEMENT**

The authors declare that there is no conflict of interest.

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