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Water status and productivity of 'Hass' avocado trees in response to supplemental irrigation during winter

Tatiana Cantuarias-Avilés[1 ✉], Simone Rodrigues da Silva[1], Sérgio Figueiredo Angolini[1], Bruna do Amaral Brogio[1], Edypol Guilherme Baptista[1] and Lígia Broglio Micheletti[1]

[1] Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Departamento de Produção Vegetal, Avenida Pádua Dias, nº 11, CEP 13418-900 Piracicaba, SP, Brazil. E-mail: tatiana.cantuarias@gmail.com, srsilva@usp.br, sergio.angolini@usp.br, brunabrogio@usp.br, edypol_0@hotmail.com, ligiabmicheletti@gmail.com

✉ Corresponding author

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Abstract – The objective of this work was to evaluate the effects of supplemental irrigation, during winter dry season, on the water status and productivity of 'Hass' avocado (*Persea Americana*) trees. The experiment was carried out on a clayey Oxisol from 2014 to 2016, when extreme climatic events were recorded in the state of São Paulo, Brazil. The rainfed regime was compared with two irrigation regimes, applied during the whole and half of the irrigation run time defined by the grower, corresponding to 5,091 and 2,545 m^3 ha^{-1} water, respectively. The following variables were evaluated: soil water tension; leaf water potential, color, and chlorophyll content; leaf and fruit abscission rates; tree size; and fruit size and yield. Supplemental irrigation applied during half of the run time increased fruit yield by 18.2%. However, irrigation applied during a fixed-time period and the occurrence of unusual rainfall spells caused soil water logging, negatively affecting tree growth and water status.

Index terms: *Persea americana*, canopy volume, chlorophyll content, fixed-time irrigation, water logging, yield efficiency.

Estado hídrico e produtividade de abacateiros 'Hass' em resposta à irrigação suplementar invernal

Resumo – O objetivo deste trabalho foi avaliar os efeitos da irrigação suplementar, durante a estação seca de inverno, no status hídrico e na produtividade de abacateiros 'Hass' (*Persea Americana*). O experimento foi realizado em Latossolo argiloso de 2014 a 2016, quando eventos climáticos extremos foram registrados no Estado de São Paulo. O cultivo em sequeiro foi comparado com dois regimes de irrigação suplementar, aplicados durante o total e a metade do tempo de irrigação definido pelo produtor, o que equivaleu a 5.091 e 2.545 m^3 ha^{-1} de água, respectivamente. Foram avaliados as variáveis: tensão de água no solo; potencial hídrico, coloração e teor de clorofila foliares; taxa de abscisão de folhas e frutos; tamanho das plantas; e tamanho e produção de frutos. A irrigação suplementar aplicada em metade do tempo de irrigação aumentou em 18,2% a produção de frutos. No entanto, a aplicação de irrigação de duração fixa e a ocorrência de chuvas atípicas durante a estiagem invernal favoreceram o encharcamento prolongado do solo, com efeitos negativos sobre o crescimento e o estado hídrico das árvores.

Termos para indexação: *Persea americana*, volume de copa, conteúdo de clorofila, irrigação por tempo fixo, encharcamento, eficiência produtiva.

Introduction

Avocado (*Persea americana* Mill.) production in the Southeastern region of Brazil – which includes the states of São Paulo, Minas Gerais, Rio de Janeiro, and Espírito Santo – occurs mainly under rainfed conditions, with no supplemental irrigation during the winter dry period. This practice, however, is common in some regions of Mexico, Guatemala, Honduras, Dominican Republic, Cuba, Colombia, and Venezuela, which are characterized by very different edaphoclimatic conditions (Carr, 2013). Therefore, more information is necessary on the proper managements for rainfed avocado production, in order to validate the cultural practices applied in other countries, aiming to optimize avocado yield in Brazil.

Successful rainfed avocado production depends on the amount and distribution of annual rainfall, on the atmospheric evaporative demand, and on the water storage capacity of soil and subsoil (Whiley & Schaffer, 1994). Knowledge on the main effects of water stress on avocado tree physiology and productivity is also required in order to define adequate strategies for reducing the negative impacts of drought on tree growth and production.

In the state of São Paulo and in other avocado-growing regions in Brazil, the period of most severe water stress occurs from the beginning of autumn, in April, to the end of winter, in September, coinciding with the stage of floral bud differentiation (Oliveira et al., 2008), flowering, initial fruit set, and spring vegetative flush (Silva et al., 2017) for all the commercially exploited cultivars. During flowering, the evaporative surface of the avocado tree canopy increases by up to 90%, due to the presence of abundant small flowers with a high evaporation rate, leading to an increment of 13 to 15% in the total tree transpiration rate (Whiley et al., 1988). Therefore, the occurrence of water stress during this phenological stage may cause flower abortion, fruitlet abscission, and early leaf drop (Whiley & Schaffer, 1994; Schaffer et al., 2013), restricting photoassimilate availability to support fruit set and undermining the tree's productive potential. Restricted water supply during flowering and fruit set may also lead to smaller fruit size (Lahav et al., 2013) and deteriorated internal fruit quality, as it increases the incidence of pulp browning (Bower et al., 1989).

In the current context of global climatic changes, the variation in water availability caused by the increasing occurrence of extreme climatic events, such as droughts and floods, might negatively affect avocado production, due to the high susceptibility of this species to the lack of water and oxygen in the soil (Labanauskas et al., 1978; Gil et al., 2009). Avocado has a shallow root system that is very sensitive to water deficit and soil water logging events, which may result in wilting or abscission of leaves and fruits and might irreversibly undermine final fruit quality (Bower et al., 1989; Gil et al., 2009).

Several studies have quantified the effects of water deficit on avocado trees, both in controlled environments (Gil et al., 2009) and in the field (Neuhaus et al., 2009) by measurements of sap flow (Cantuarias-Avilés, 1995), leaf water potential (Neuhaus et al., 2009), leaf thickness (Sharon, 1999), leaf temperature (Cantuarias-Avilés, 1995), stomatal conductance (Gil et al., 2009; Neuhaus et al., 2009), and the swelling and shrinkage patterns of trunks and fruits (Silber et al., 2019). However, these researches were conducted under climatic conditions that are very distinct from those prevailing in Brazil.

The objective of this work was to evaluate the effects of supplemental irrigation, during winter dry season, on the water status and productivity of 'Hass' avocado trees.

Materials and Methods

The trial was conducted from 2014 to 2016 in a commercial 'Hass' avocado orchard, at the farm Fazenda Santa Cecília, located in the municipality of Bernardino de Campos, in the southwest region of the state of São Paulo, Brazil. The local climate is Cwa, according to Köppen's classification, i.e., subtropical, rainy in summer and dry in winter, with 1,500 mm mean annual rainfall. The soil is classified as a clayey, deep Oxisol, i.e., a Latossolo Vermelho Distrófico, according to the Brazilian soil classification (Santos et al., 2013), with low drainage, 62.2% total pore volume, 32.9% volumetric soil moisture content at field capacity of 10 kPa soil water tension, 22.2% volumetric soil moisture content at permanent wilting point of 150 kPa soil water tension, 1.08 g cm^{-3} bulk density, and 2.86 g cm^{-3} particle density. 'Hass' avocado trees, grafted onto seedling rootstocks, were planted in 2010 on 0.40-height mounds, in a 9.0x4.5-m spacing, totalizing 246 plants per hectare. From the second year

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of planting onwards, 30 L h^{-1} per plant were applied for irrigation; for this, the SuperNet pressure-regulated micro-sprinkler (Netafim Ltd., Tel Aviv, Israel), with a 3.5-m wetted diameter, was installed 1.4 m from each tree trunk. The orchard was managed following the standard cultural traits recommended for avocado trees (Silva et al., 2017).

The following treatments were evaluated: T1, no supplemental irrigation in winter, from April to September, representing the common growing condition of rainfed avocado production in Brazil; T2, supplemental irrigation applied during half of the fixed time period defined by the grower; and T3, irrigation during the total fixed time period, which varied from 2 to 6 hours per day throughout the experimental period (Figure 1), depending on rain occurrence and on field observations of plant phenological stage, fruit load, and canopy leaf color and turgidity. During 2014–2016, the T2 and T3 irrigated treatments received 2,545 and 5,091 m^3 ha^{-1} water, respectively. In that period, soil water tension was continuously monitored six times a week, with two tensiometers installed at 40 and 80-cm soil depth, positioned 2.25 m from the tree trunk. The ATMOS 41 automatized meteorological station (Decagon Devices Inc., São José dos Campos, SP, Brazil) was installed in the experimental plot to collect hourly measurements of rainfall, solar radiation, wind speed and direction, relative air humidity, and air temperature.

Plant water status was assessed during the dry period by regular measurements of leaf water potential, leaf chlorophyll content, and leaf color. Leaf and fruit abscission rates were recorded for five tagged shoots per tree. Leaf water potential was measured in ten sunlit leaves per treatment from the previous summer flush, sampled from the medium portion of fruitless shoots in the outer part of the canopy, on both sides of the tree row; this was done in the field, between midday and 2:00 p.m., the period of highest evaporative demand, using the Model 600 portable pressure chamber (PMS Instrument Company, Albany, OR, USA). Leaf chlorophyll content, expressed in ICF units, was measured in sections from the central portion of the limb of 50 mature leaves per treatment, sampled from the medium portion of fruitless shoots developed in the previous vegetative flush, using the CFL 1030 clorofiLOG digital chlorophyll-meter (Falker Automatação Agrícola Ltda., Porto Alegre, RS, Brazil). Leaf color was evaluated with the CR-300 chroma meter (Konica Minolta Sensing Americas, Ramsey, NJ, USA) in the same limb sections used for chlorophyll content determination. The $h^o/L \times C$ color index, proposed by Amarante et al. (2008) to describe leaf color of 'Royal Gala' and 'Fuji' apples, was calculated from the colorimetric variables luminosity (L), chrome (C), and hue angle (h^o).

Annually, the leaf abscission rate was estimated by the difference between leaf counts on five tagged shoots per tree, in 12 trees per treatment, in July and September. Similarly, the fruit abscission rate was calculated by the difference in fruit counts, also on five tagged shoots per tree, in October and December, after the first and second natural fruit drop period of 'Hass' avocado, respectively (Silva et al., 2017). Fruit yield was annually computed in the harvest date by counting and weighing all fruits picked from each measured tree. Individual fruit weight was measured with a digital scale in 200 fruits randomly collected from all plants of each treatment. Tree height (H) and mean width (W) were measured after harvest with a ruler and used to calculate canopy volume (V, m^3), by: $V = 4/3 \times \pi \times H/2 \times W/2$ (Mickelbart et al., 2007).

The experiment was set up on a randomized complete block design, with three treatments, four replicates, and three plants per plot, totalizing 36 measured trees. Data were subjected to analyses of variance using the SAS statistical software, version 9.0 (SAS Institute Inc., Cary, NC, USA). Treatments were compared by Tukey's test. All statistical analyses were performed at 5% probability. Data that did not meet the assumptions of the analysis of variance were either transformed by the Box-Cox method or subjected to nonparametric analyses with Kruskal-Wallis' or Friedman's tests.

Results and Discussion

In the 2014–2016 triennium, severe climatic events were recorded during the winter dry period in the experimental site. Throughout most of the rainy season in 2014, below-normal rainfall was registered in Southeastern Brazil, due to an intense, persistent, and anomalous high-pressure system that set up on the Atlantic Ocean in January 2014, blocking the moisture flow from the Amazon forest and the development and passage of the cold front systems responsible for summer rainfall in the region. This blocking system lasted for 45 days, until mid-February 2014, which is extremely rare for that period (Marengo et al., 2015). Therefore, the severe drought in 2014 depleted soil moisture in all treatments (Figure 1 A), with soil water tensions overpassing the critical threshold of 50 kPa recommended for 'Hass' avocado irrigation management in clayey soils (Richards et al., 1962). During the drought period of 2014, the irrigations

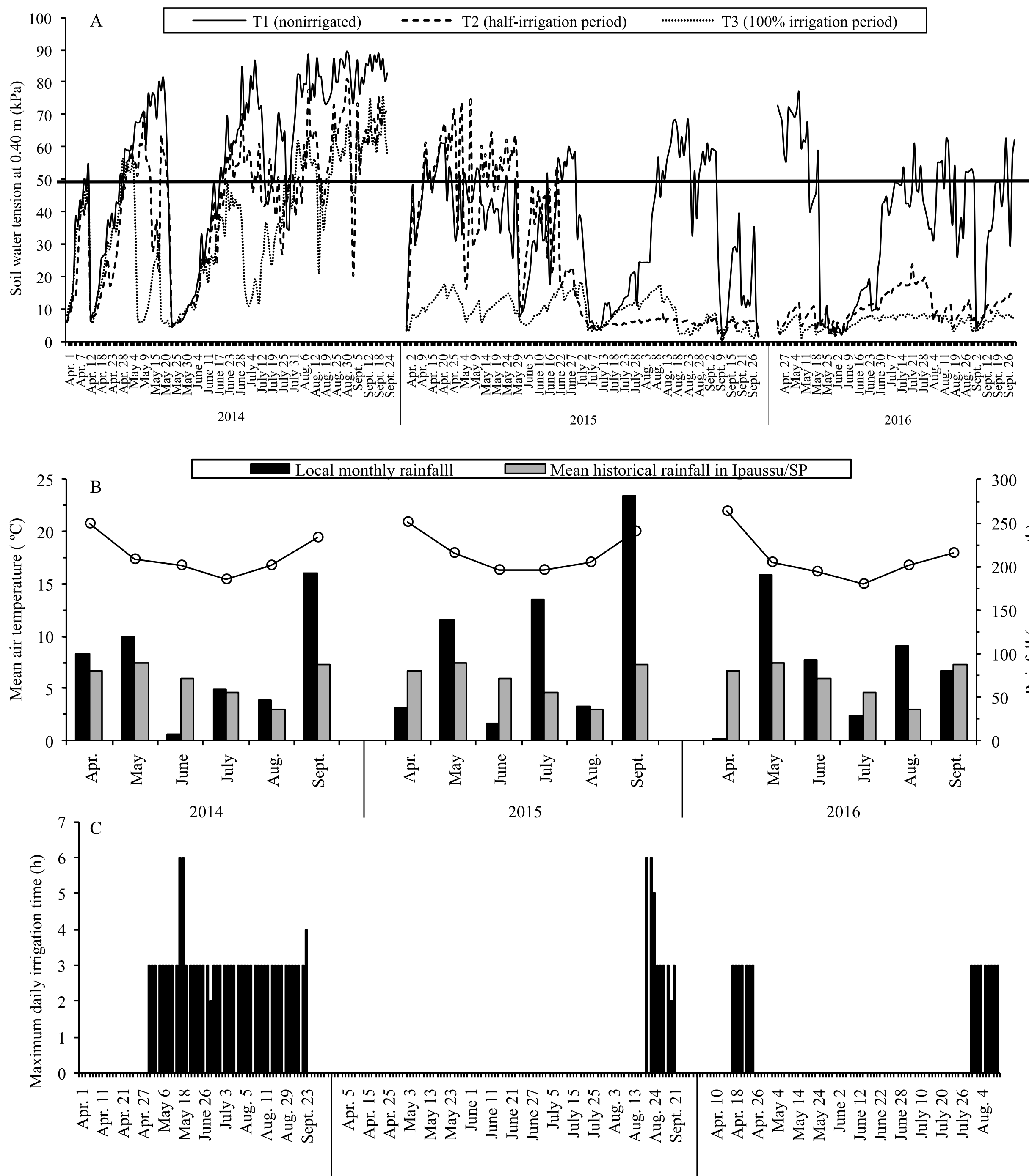

Figure 1. Variation of soil moisture at 40-cm depth in the different treatments (A); local monthly rainfall and mean air temperature, and mean historical rainfall in the municipality of Ipaussu, in the state of São Paulo, Brazil (B); and maximum daily irrigation time from April to September in the 2014–2016 triennium (C).

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applied by the grower, from May to September (Figure 1 C), were insufficient to replace soil moisture; therefore, soil water tension remained above the critical 50 kPa-threshold value in all treatments (Figure 1 A).

Paradoxically, during the 2015 winter period, intense and atypical rainfall was recorded in the experimental plot in May, July, and September (Figure 1 B), totaling 139.6, 162.8, and 281.0 mm, respectively. These amounts are substantially higher than the mean monthly historical rainfall of 90.0, 55.8, and 86.9 mm registered for these months in 1999–2017 in the municipality of Ipaussu, located 20 km from the experimental site (CIIAGRO, 2017).

In April 2015, at the beginning of the dry period, soil water tension values in the T1 and T2 treatments exceeded the critical threshold of 50 kPa (Figure 1 A), due to the effects of the previous year's severe drought and to the below-normal rainfall recorded during the summers months at the beginning of that year. Later, in July 2015, an atypical cumulative rainfall of 158 mm in the experimental plot caused soil water logging in all treatments. Between August and September, during the flowering period, T2 and T3 were irrigated with 22.7 and 45.3 $m^3\ ha^{-1}$, respectively, in order to satisfy the increased water consumption throughout this stage. In September 2015, an atypical cumulative monthly rainfall of 281 mm in the experimental site (Figure 1 B) caused prolonged soil water logging, with mean monthly water tensions of 4.9 and 1.7 kPa, at 40 cm-depth, in the T2 and T3 treatments, respectively (Figure 1 C). Such conditions promote avocado root asphyxia and tree decline (Ploetz & Schaffer, 1989).

In 2016, the occurrence of intense rainfall in May and June, totaling 284.4 mm, kept soil tension below the field capacity of 10 kPa in both irrigated treatments. From July onwards, the soil started to dry out gradually and soil water tension increased in all treatments. In that year, soil water tension in the fully irrigated T3 treatment remained below field capacity throughout the whole winter period (Figure 1 A).

Along the 2014–2016 triennium, the irrigation management was inefficient in keeping soil moisture within the recommended levels, causing soil moisture depletion in 2014 and prolonged soil saturation in the following two years due to the occurrence of atypical rainfall events. It should be noted that the irrigation management adopted by the grower during the winter dry season was based on fixed time periods, defined by the visual assessment of leaf turgidity and color, phenological stage, and fruit load in the field.

The irrigation management affected some of the variables that characterize plant water status (Table 1). In the 2014–2016 period, there was a significant reduction in the mean leaf color index (h°/LC) and mean leaf chlorophyll content in the irrigated treatments, indicating a more intense degree of canopy yellowing. In addition, leaf water potential and fruit abscission rate did not differ between treatments, whereas, in 2016, the trees of the T2 treatment had a significantly lower leaf abscission rate.

In 2014–2016, the trees receiving supplemental irrigation during the dry winter season showed a smaller

Table 1. Midday leaf water potential (LWP_{MD}), leaf color index (h°/LC), leaf chlorophyll content (LCC), and leaf (LAR) and fruit (FAR) abscission rates of 'Hass' avocado (*Persea Americana*) trees under different supplemental irrigation regimes, during the winter dry season in the state of São Paulo, Brazil(1).

Variable	T1	T2	T3	CV (%)	P-value
			Year 2014		
LWP_{MD} (MPa)	-0.28a	-0.36a	-0.32a	32.14	0.2532
h°/LC	0.51a	0.44b	0.46ab	22.69	0.0132
LCC (ICF units)	59.23a	57.87a	60.35a	6.10	0.0646
LAR (%)	9.21a	10.43a	9.88a	35.37	0.7148
FAR (%)	71.86a	77.29a	67.93a	44.60	0.6831
			Year 2015		
LWP_{MD} (MPa)	-0.34a	-0.47a	-0.45a	35.17	0.1129
h°/LC	0.48a	0.41b	0.38c	32.56	<0.0001
LCC (ICF units)	74.42a	70.85b	68.07c	6.08	<0.0001
LAR (%)	34.76a	10.37b	27.85ab	48.63	0.0105
FAR (%)	78.96a	81.76a	76.96a	33.17	0.3002
			Year 2016		
LWP_{MD} (MPa)	-0.84a	-0.81a	-0.64a	36.15	0.4148
h°/LC	0.31a	0.26b	0.24b	19.94	<0.0001
LCC (ICF units)	72.39a	61.02b	61.37b	7.38	<0.0001
LAR (%)	59.37a	82.42a	82.84a	24.75	0.1948
FAR (%)	76.39a	75.54a	82.30a	29.11	0.1120
			Triennium 2014–2016		
LWP_{MD} (MPa)	-0.49a	-0.55a	-0.47a	53.95	0.2847
h°/LC	0.43a	0.37b	0.36b	15.91	<0.0001
LCC (ICF units)	68.01a	63.24b	63.26b	9.81	<0.0001
LAR (%)	34.44a	34.41a	40.19a	31.93	0.6531
FAR (%)	75.74a	78.20a	75.73a	36.53	0.9155

(1)Means followed by equal letters do not differ by Tukey's test, at 5% probability. T1, no supplemental irrigation in winter; T2, supplemental irrigation applied during half of the fixed time period defined by the grower (2,545 $m^3\ ha^{-1}$ water); and T3, supplemental irrigation applied during the total fixed time period (5,091 $m^3\ ha^{-1}$).

variation in mean canopy volume than the nonirrigated ones (Table 2). This situation may be a consequence of the prolonged saturation of the superficial soil layers in the irrigated treatments, which may have caused root asphyxia, negatively affecting tree growth. The smaller vegetative growth of the irrigated plants in the evaluated triennium might also have been caused by their significantly larger fruit load, which exerts a stronger inhibitory effect on vegetative growth.

Compared with the nonirrigated treatment, T2 showed significantly higher cumulative fruit yields (Table 2), as well as 18.2 and 38.0% higher cumulative fruit yield and number of fruits per tree, respectively. In 2015 and 2016, the heavier fruit load of the trees with a smaller canopy volume also resulted in higher yield efficiencies in T2. However, smaller-sized fruit were produced with both irrigated treatments, probably due to the declining plant water status caused by the atypical rainfall events and the consequent high water contents in the soil.

Table 2. Canopy volume (V), fruit yield (FY), number of fruits (NF), individual fruit weight (IFW), and yield efficiency (YE) of 'Hass' avocado (*Persea Americana*) trees under different supplemental irrigation regimes, during the winter dry season in the state of São Paulo, Brazil(1).

Variable	T1	T2	T3	CV (%)	P-value
			Year 2014		
V (m^3 per tree)	38.69a	43.54a	42.43a	6.77	0.4216
FY (kg per tree)	84.63a	88.45a	88.48a	23.30	0.8668
NF (fruits per tree)	448a	500a	518a	26.38	0.3990
IFW (g)	192.49a	193.96a	174.70b	20.69	<0.0001
YE (kg per m^3)	2.24a	2.07a	2.20a	55.76	0.6786
			Year 2015		
V (m^3 per tree)	54.44a	50.36a	49.57a	17.52	0.3685
FY (kg per tree)	108.46b	137.10a	97.92b	23.52	0.0037
NF (fruits per tree)	511b	756a	562b	27.42	0.0029
IFW (g)	200.60a	184.27b	186.09b	21.69	<0.0001
YE (kg per m^3)	2.01b	2.79a	2.08b	24.23	0.0028
			Year 2016		
V (m^3 per tree)	116.63a	98.67ab	89.11b	19.02	0.0052
FY (kg per tree)	51.92a	64.08a	55.48a	34.90	0.3213
NF (fruits per tree)	259b	427a	405a	7.09	0.0071
IFW (g)	213.89a	164.94b	142.45c	23.04	<0.0001
YE (kg per m^3)	0.44b	0.69a	0.64ab	38.22	0.0308
			Triennium 2014–2016		
V (m^3 per tree)	77.94a	55.13b	46.68b	23.28	<0.0001
FY (kg per tree)	245.01b	289.63a	241.88b	17.74	0.0275
NF (fruits per tree)	1218b	1683a	1485ab	20.14	0.0023
Mean IFW (g)	202.33a	181.06b	167.75c	22.24	<0.0001
Mean YE (kg per m^3)	1.56a	1.85a	1.64a	18.72	0.3511

(1)Means followed by equal letters do not differ by Tukey's test, at 5% probability. T1, no supplemental irrigation in winter; T2, supplemental irrigation applied during half of the fixed time period defined by the grower (2,545 m^3 ha^{-1} water); and T3, supplemental irrigation applied during the total fixed time period (5,091 m^3 ha^{-1}).

Conclusions

1. Supplemental irrigation applied during the winter dry season significantly increases the cumulative fruit yield of 'Hass' avocado (*Persea Americana*).
2. Irrigation applied at fixed time periods during the winter dry season, together with the occurrence of unusual rainfall events, negatively affects 'Hass' avocado tree water status and growth.

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