Fertilization and precise irrigation scheduling for mature avocado[1,2]

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ABSTRACT

Irrigation scheduling (IS) and fertilization are among the most important practices in the production of horticultural crops because they affect fruit quality and quantity directly. Thus, a 15-year-old avocado orchard (cv. 'Simmonds') was used to determine precise IS, based on monitoring soil moisture content (SMC), remote sensing technologies [Unmanned Aerial Vehicle (UAV)] under two fertilization levels using granular formulation 15-3-19. In October 2015, all trees were pruned (topped and hedged) to 3.05 m height and 2.44 m diameter. In December 2015, soil moisture (SM) sensors were installed at five (10, 30, 50, 70 and 90 cm) soil depths in six locations. Trees received two fertilizer treatments: F1-9.06 kg and F2-12.07 kg of 15-3-19/tree/year every three months. Precipitation and SM data were recorded daily for 21 months; SM data was corrected with a quadratic equation ($y = -4.1881x^2 + 3.6886x - 0.3083$) generated specifically for the Coto soil series (Typic Hapludox). The SM values recorded were always greater than 41%, indicating that the avocado orchard was growing under water saturation conditions; thus, micro-irrigation was not needed. The UAV data at 5, 13 and 20 months after pruning (MAP) showed quick closure of the avocado canopy; acquiring a denser and more cylindrical shape (from 17.6 ± 2.65 m^2 to 52.7 ± 6.10 m^2), regardless of fertilizer level. Based on correlation of UAV and manual results, F2-treated trees indicated stronger correlation at 13 and 20 MAP (R^2 >0.75) than F1-trees. Yield production (110 avocados per tree = 13,200 per hectare) and leaf nutrient content did not differ significantly with fertilizer level. For commercial avocado farmers the use of SMC sensors and UAV technology could be an advantage, albeit an expensive one. Soil moisture content sensors have been shown to be very effective in irrigation water conservation. In terms of fertilization, the results suggest not using more than 9.06 kg of 15-3-19/tree/year as this amount seems enough to satisfy avocado requirements, under the experiment's conditions. Future evaluations will determine if it is possible to use less fertilizer and still maintain an optimal avocado production.

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Key words: avocado, UAV, multi-spectral, soil moisture, micro-irrigation, Oxisol, tree canopy

RESUMEN

Fertilización y programación del riego en aguacate

La programación del riego y la fertilización son las prácticas más importantes en los huertos de aguacate debido a su efecto directo en la calidad y cantidad de los frutos. Por esta razón, se utilizó un huerto de aguacate cv. 'Simmonds' de 15 años para determinar la programación del riego en forma precisa basada en el monitoreo del contenido de humedad de suelos (SMC) y tecnología de percepción remota (UAV), bajo dos niveles de fertilizante. En octubre del 2015, todos los árboles se podaron (altura y ancho) a 3.05 m altura y 2.44 m diámetro. Para medir la humedad del suelo, en diciembre del 2015 se instalaron sensores a cinco profundidades en el suelo (10, 30, 50, 70 y 90 cm). Los árboles recibieron dos niveles de un fertilizante 15-3-19: F1-9.06 y F2-12.07 kg por árbol por año, aplicado cada tres meses. La precipitación y la humedad del suelo se registraron por 21 meses; los datos de humedad del suelo se corrigieron con una ecuación cuadrática ($y = -4.1881x^2 + 3.6886x - 0.3083$) desarrollada específicamente para la serie Coto (Typic Hapludox). Los valores de humedad del suelo registrados siempre fueron mayores de 41%, indicando que el huerto de aguacates creció bajo condiciones de saturación de agua, resultando innecesario la aplicación de microrriego. Datos de UAV a los 5, 13 y 20 meses después de la poda (MAP) muestran un cierre claro de la copa de los árboles de aguacate; adquiriendo una forma más densa y cilíndrica (de 17.6 ± 2.65 a 52.7 ± 6.10 m^2), independientemente del nivel de fertilizante aplicado. Basado en las correlaciones de UAV y resultados manuales, los árboles bajo F2 obtuvieron correlaciones más fuertes a los 13 y 20 MDP (R^2 >0.75) que los árboles bajo F1. La producción (110 frutas por árbol = 13,200 frutas por hectárea) y el contenido nutricional en las hojas (en su mayoría) no difirieron debido al nivel de fertilizante. Para productores comerciales de aguacate con grandes extensiones de terreno podría resultar ventajoso el uso de tecnologías de SMC y UAV, pero se debe tener en cuenta de que representan una inversión de alto costo. El uso de la tecnología de sensores de SMC puede ser muy efectivo en el manejo y conservación del recurso agua. En términos de fertilización, los resultados sugieren no utilizar más de 9.06 kg de 15-3-19/árbol/año. En futuras evaluaciones se podría determinar si es posible utilizar una menor cantidad de fertilizante y mantener una óptima producción.

Palabras clave: aguacate, UAV, cámara multiespectral, humedad de suelos, microrriego, Oxisol, copa del árbol

INTRODUCTION

Avocado (*Persea americana*) is a subtropical fruit extremely vulnerable to excess or lack of water in the root zone (Whiley and Schaffer, 1994). Too much water caused by excessive irrigation and poor soil drainage can cause root hypoxia and provide favorable conditions for *Phytophthora cinnamomi* infection (Sterne et al., 1977). Low soil moisture during days of high evapotranspiration can dramatically reduce avocado fruit yield and quality (Bower and Cutting, 1988). In avocado, symptoms of overwatering and underwatering can be similar, resulting in droopy leaves making it difficult to determine the source of the problem (Escalera et al., 2015). For that reason, irrigation scheduling (IS) of an avocado orchard is considered one of the most critical practices because of the direct effect on fruit quality and quantity, eventually impacting farmer's profits (Escalera et al., 2015).

Determining the precise IS will vary depending on avocado variety, growing stage and tree age. These variables will affect the water demand of the avocado tree depending on soil type (i.e., sandy vs. clay) and environmental conditions such as precipitation, temperature and evaporation (Escalera et al., 2015). Efficient irrigation (EI) combined with fertigation can reduce the fertilizer application cost and increase fertilizer use efficiency. In addition, EI may reduce the loss of water and contamination of ground water by chemicals (i.e., fertilizers, pesticides) (Kiggundu et al., 2012).

Efficient irrigation can be achieved by traditional soil-based readings (i.e., soil moisture content sensors such as TDR, which uses time-domain reflectometry; capacitive sensors, etc.) and unmanned aerial vehicles (UAV). The UAV-based sensors can efficiently obtain temporal physical information on evapotranspiration and erosion, ranging from minutes to days or weeks (Srinivasan, 2006). Use of UAVs can support research in horticultural crops (e.g., avocado, citrus, mangos, etc.) to measure and map important biophysical conditions [i.e., tree condition and canopy extent after pruning (Lu et al., 2004; Johansen et al., 2018; Tu et al., 2019)] and functional parameters (Wu et al., 2020). In tree crops, vegetative growth, flowering and fruit development are crucial events (Kernot et al., 1999; Newett et al., 2001) that can be affected by using different amounts of fertilizer and different irrigation levels, especially after pruning (Connor et al., 2014). Pruning has produced a positive response by increasing flowering and consequently enhancing yield (Ikinci, 2014).

At the Agricultural Experiment Substation in Isabela, Puerto Rico, Coto is the predominant soil series. Coto series (Typic Hapludox) is a very deep, well drained, moderately permeable soil formed in sediments weathered from limestone. Coto series is found in the north central and northwestern coastal plains of Puerto Rico. This series has a moderate extent with approximately 5,261 hectares (13,000 acres). The majority of farmers in the area tend to irrigate based on visual observations of the soil surface and on rainfall patterns without taking into consideration soil water holding capacity at deeper depths and the symptoms of water stress or water excess of avocado trees. The objective of this research was to determine the effect of two different levels of fertilizer under precise irrigation scheduling on a mature avocado orchard based on continuous soil moisture monitoring with in situ sensors.

MATERIALS AND METHODS

Experiment area and description

In October 2001, an avocado orchard (cv. 'Simmonds' grafted in cv. 'Gripiña' rootstock) was planted at the Agricultural Experiment Substation (AES) in Isabela, which is located in northwestern Puerto Rico (18.46 degrees latitude and -67.05 degrees longitude), 120 m above sea level. The predominant soil is Coto series (Very-fine, kaolinitic, isohyperthermic Typic Hapludox) (Muñoz et al., 2018). The average annual precipitation is 1,651 mm, May being the rainiest month and February, the driest. Average temperature ranges from 31.1 to 18.9° C. The long-term (~29 years) monthly rainfall and minimum and maximum air temperatures (https://atmos.uw.edu/marka/normals/pr.normals.2010.html) at the Isabela substation are shown in Table 1.

With a planting distance of 9.1 m between trees and rows, we ended up with a total of 48 experimental trees. Avocado trees were submitted to two fertilizers levels arranged in a randomized complete block design with four replications. The experimental unit consisted of six avocado trees. Each tree had two micro-sprinklers with a discharge capacity of 60.6 L/h (Special Max 12-Fill-In, Maxijet Inc, Florida)[6]. The micro-sprinklers were installed on plastic stakes under each side of the canopy (~1.83 m away from the trunk), raised about 20 cm from the soil surface and connected to 1.9 cm polytubing submains (Román-Paoli et al., 2009).

Pruning and establishment of in situ sensors

In October 2015, all trees were pruned to 3.05 m height and 2.44 m diameter using a tree- pruning machine [Toppers Hedgers (TH)-Swan, TOL Inc.]. In December 2015, six soil pits were dug to install 10HS large volume soil moisture sensors (METER Group, Inc. USA). In each soil pit, six sensors were installed at depths of 10, 30, 50, 70 and 90 cm

[6]Company or trade names in this publication are used only to provide specific information. Mention of a company or trade name does not constitute an endorsement by the Agricultural Experiment Station of the University of Puerto Rico, nor is this mention a statement of preference over other equipment or materials.

TABLE 1.—*Precipitation (PPT) and maximum and minimum temperatures (T) at AES in Isabela, 29 years average.*

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
PPT -mm-	88.9	71.9	89.4	135.9	199.6	149.6	131.6	154.2	165.9	191.0	153.4	108.2	1,651.0
T. Max - °C-	27.8	28.3	28.3	29.4	30.0	30.6	30.6	31.1	31.1	30.6	29.4	28.3	29.4
T. Min - °C-	18.9	18.9	18.9	20.0	21.1	21.7	22.2	22.2	22.2	21.7	21.1	20.0	20.6

to monitor volumetric water content. In each pit, an Em 50 datalogger (METER Group, Inc., USA) was installed to collect data obtained from the 10HS soil moisture sensors. A HOBO U30-NRC Weather Station Starter (ONSET- Bourne, MA) was mounted near the avocado orchard to collect rainfall data needed for precise irrigation scheduling. Raw soil moisture content (SMC) data collected with the 10HS sensors was calibrated by using the following quadratic equation ($y = -4.1881x^2 + 3.6886x - 0.3083$) specifically developed for Coto soils. For study purposes, corrected soil moisture and precipitation data collected were considered on a daily basis from 15 December 2015 to 13 September 2017.

Fertilization and irrigation

During the experiment, from 15 December 2015 to 13 September 2017, trees were fertilized every three months with a 15-3-19 granular formulation. Two fertilization treatments were evaluated: F1-9.06 and F2-12.07 kg of fertilizer 15-3-19 per tree per year. The total nutrients applied by F1 were 167, 33.1 and 210 kg/ha of N-P_2O_5-K_2O, respectively; for F2, amounts were 223, 44.5 and 280 kg of N-P_2O_5-K_2O/ha. Weeds between avocado rows were mowed periodically. The trees were irrigated twice a week during the first months after pruning (October to December 2015). The IS was based on continuous soil moisture monitoring when SMC dropped below 35% (field capacity).

Soil fertility, tree growth, leaf nutrient analysis and yield

To determine soil fertility, we collected soil samples from each fertilizer treatment level from the depths of 0-20, 20-40, 40-60, 60-80 and 80-100 cm of each plot using a 7.62 cm bucket auger. Soil pH was measured in a 1:1 (v:v) soil-water mixture (Thomas, 1996). Exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}) were extracted using 1 mol/L NH_4OAc (Warncke and Brown, 1998), and available phosphorous (P), by Olsen extract. Organic matter (OM) was determined by loss on ignition. Total Sulphur (S) was determined via inductively coupled plasma spectrometry (ICP) (Teledyne Leeman Labs Prodigy Dual, Hudson, NH) after perchloric acid digestion (Jackson, 1958; Hossner, 1996). Nitrate (NO_3-N) content [1:1 soil: distilled (DI) water] was determined with a Nitrate-Nitrite Astoria Pacific 2 analyzer (Portland, OR). In addition, 30 avocado leaf samples were collected randomly covering N, W, S and E tree locations and simultaneously from each treatment and replicate, and analyzed for N, Ca, Mg, P, K, manganese (Mn), iron (Fe), copper (Cu), boron (B), aluminum (Al), Na and zinc (Zn). All elements previously mentioned were extracted using the Mehlich 3 method.

Tree variables (e.g., height, diameter and canopy) and fruit production were measured to determine avocado crop performance under the different fertilizer levels. Tree height was measured using a telescoping-measuring pole. Tree diameter was measured using a diameter at breast height (DBH) measuring tape. Tree canopy volume (CV) was calculated using the Fallahi et al. (1991) equation: 0.524 x tree height (m) x tree square diameter (m^2). Tree efficiency was calculated using the total average number of fruits divided by CV. Avocado was harvested once a week from mid-July to mid-September 2017. All fruits regardless of size were counted and weighed. In this study, fruit production (fruit number and size) was considered as the total average value. Only one complete harvest was possible due to hurricanes Irma and María hitting the island during September 2017.

Remote sensing data collection

Starting five months after pruning (MAP) until September 2017, orthophotos of the avocado orchard (cv. 'Simmonds') were generated using a UAV (Phantom 3 Professional 4 K Video/12 Megapixel Photo camera). The orthophotos were used to determine the canopy area. The Visible Atmospherically Resistant Index (VARI) was generated using QGIS v2.8.7. The VARI was used to estimate the amount of green in the aerial images. Image J (NIH Image)- an open source Java image (JPEG format) processing program was used for Color Threshold (CT) and Particle Analysis (PA). For PA we took into consideration only the data from 46 trees, not the 48 in the experiment, because one tree had died, and a second was from another variety.

Correlation of UAV vs. manual measurements

We calculated the coefficient of determination (R^2) using a linear regression between data collected from UAV and the manual telescopic pole on three different dates (5, 13 and 20 MAP) and at two fertilizer levels (F1- 9.06 kg and F2- 12.07 kg of 15-3-19/tree/yr). Also, root mean square error (RMSE) was used for error estimations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\overline{x}i - xi)^2}{n}}$$

where n is the number of tree canopies sampled (i.e., 23 trees per F level), $\overline{x}$ is the predicted value (UAV data) and x_i is the observed value (manual data).

Statistical Analysis

Analysis of variance (ANOVA) followed by mean separation using Tukey's Honest Significant Difference test at $P<0.05$ was used to determine soil and tissue fertility and tree variables. Statistical analysis was undertaken using JMP Version 15 (SAS Institute, Cary, NC, USA).

RESULTS

Soil chemical properties and leaf nutrients analyses

Soil P and Mg concentrations varied significantly by fertilizer level ($P<0.05$) but only at 20- to 40-cm soil depth. Lower P and Mg concentrations were found at the higher fertilizer level (F2). No statistically significant differences were found for the rest of the variables or soil depths (Table 2).

Leaf nutrients analysis

Macronutrient concentrations of N, P and K on leaf tissue differed significantly by fertilizer treatment ($P< 0.05$) (Table 3). Trees receiving F2 treatment had higher concentrations of N, P and K than those receiving F1; no significant differences were found for other nutrients (i.e., Ca, Mg Na or S).

Boron concentration in the tissue differed significantly by fertilizer level ($P< 0.05$) (Table 4). Tissue collected from F2 trees had 1.1 times higher B concentration than F1 trees. No significant differences ($P> 0.05$) were found in concentrations of Al, Cu, Fe, Mn and Zn.

Soil moisture content

From mid-December 2015 until mid-September 2017, SMC data from five soil depths were collected daily to determine when irrigation was needed. In Figure 1, average daily SMC data (from the six pits) is plotted against daily precipitation. During the 21-month study period, at least 864 mm of precipitation was received at the Isabela substation, and the SMC was always higher than 41%. Lower values and higher fluctuation of SMC were observed in the first two soil depths (0 to 20 cm and 20 to 40 cm). Deeper (40 to 100 cm) SMC stayed nearly equal or higher than 49%. These SMC values indicate that the avocado orchard was growing under near-saturated conditions, making drip irrigation unnecessary.

Tree response

No statistical difference ($P< 0.05$) was found for any of the tree variables and fruit production (number and weight) (Table 5). Average tree height, area and canopy volume were 5.72 m, 51.2 m^2 and 153 m^3, re-

TABLE 2.—*Average values of soil pH, organic matter, macronutrients (P, Ca, Mg, K and S), and nitrates in the mature avocado orchard (cv. 'Simmonds') receiving two levels of fertilizer in an Oxisol.*

Depth	pH		O.M.*		P		Ca		Mg		K		S		NO_3-N	
–cm–			--%--		mg/kg											
	F1[+]	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2	F1	F2
0–20	6.07	6.07	6.13	6.20	5.0	3.67	918	870	92	83	95	75	14	20	13.7	7.33
20–40	6.07	6.20	6.13	5.47	5.0 a	2.0 b[‡]	918	736	92 a	61 b	99	37	14	48	13.7	5.00
40–60	6.65	6.67	4.97	4.77	1.33	2.0	665	600	40.3	37.3	42.3	19.0	52	65	3.67	3.33
60–80	6.83	6.67	4.73	4.53	2.67	2.0	668	587	37	32	36	14	55	56	3.33	2.33
80-100	6.87	6.70	4.47	4.30	2.33	2.0	689	666	28.7	26	23.3	14	38.7	55	2.67	2.33

[+]F1- 9.06 kg fertilizer/tree/yr ~ 167 kg of N/ha/yr; F2- 12.07 kg fertilizer/tree/yr ~ 224 kg of N/ha/yr.
*O.M.= organic matter; P= phosphorous; Ca=calcium; Mg=magnesium; K=potassium; S=Sulfur; NO_3-N= nitrates.
[‡]Means followed by the same letter or no letters between fertilizer levels for each soil depth are not significantly different by Tukey's test at $P < 0.05$.

TABLE 3.—*Average values of N, P, K, Ca, Mg, Na, and S in the tissue of cv. 'Simmonds' in the mature avocado orchard receiving two levels of fertilizer in an Oxisol.*

	N*	P	K	Ca	Mg	Na	S
Fertilizer level	--%--	mg/kg					
F1[+]	2.20 b[‡]	0.138 b	0.75 b	2.05	0.395	0.028	0.195
F2	2.36 a	0.150 a	0.90 a	2.23	0.412	0.028	0.215

[+]F1- 9.06 kg fertilizer 15-3-19/tree/yr ~ 167 kg of N /ha/yr; F2- 12.07 kg fertilizer 15-3-19/tree/yr ~ 224 kg of N/ha/yr.
*N= nitrogen; P= phosphorous; Ca=calcium; Mg=magnesium; K=potassium; Na= sodium; S=sulfur.
[‡]Means followed by the same letter or no letters between fertilizer levels are not significantly different by Tukey's test at $p < 0.05$.

TABLE 4.—*Average values of Al, B, Cu, Fe, Mn, and Zn in tissue of cv. 'Simmonds' in the mature avocado orchard receiving two levels of fertilizer in an Oxisol.*

	Al*	B	Cu	Fe	Mn	Zn
Fertilizer level	mg/kg					
F1+	50.8	35.5 b‡	12.3	105	652	29
F2	44.8	39.3 a	12.0	99	550	29

+F1- 9.06 kg fertilizer 15-3-19/tree/yr ~ 167 kg of N /ha/yr; F2- 12.07 kg fertilizer 15-3-19/ tree/yr ~ 224 kg of N/ha/yr.

*Al= aluminum; B=boron; Cu=cooper; Fe= iron; Mn=manganese; Zn=zinc.

‡Means followed by the same letter or no letters between fertilizer levels are not significantly different by Tukey's test at $P < 0.05$.

spectively. Average avocado fruit number (#), fruit weight per tree and tree efficiency were 110 (#), 94 kg and 0.722 #/ m^3, respectively.

Figure 2 shows aerial photographs generated with UAVs at three different times: 5, 13 and 20 MAP. Based on data generated using CT-PA, average tree canopy area at 5 MAP was 17.6 ± 2.65 m^2; at 13 MAP area was 40.0 ± 4.5 m^2; and at 20 MAP, 52.7 ± 6.10 m^2. Over the 15-month period the average tree canopy increased 66.7%. In Figure 2 (left to right orthophotos), the tree canopy cover can be observed expanding, based on time after pruning, trees growing denser and acquiring a more cylindrical shape.

Figure 3 shows the correlation of avocado tree canopy area using UAV versus telescoping-measuring pole measurements from three different dates: 5, 13 and 20 MAP (trees were already receiving fertilizer applications). Based on the correlation graphs, better correlation can be observed when tree canopies are denser and closer together. Also, F2 treated trees indicated a stronger correlation at 13 MAP (R^2 = 0.798, RMSE= 2.69 m^2) and 20 MAP (R^2 = 0.854, RMSE= 0.221 m^2) compared with F1 (R^2 = 0.642, RMSE = 2.30 m^2 and R^2 = 0.728, RMSE = 2.69 m^2 at 13 and 20 MAP, respectively). At 5 MAP the RMSE values are bigger (greater than 2.90 m^2) due to trees having an irregular shape after being pruned (Figure 2).

DISCUSSION

Fertilizer treatments under precise IS (i.e., continuous SMC monitoring) in a mature avocado orchard were evaluated with the purpose of achieving higher yield without reducing fruit size and quantity. Avocado trees have shallow roots, and most of them are located in the first 60 cm of soil (~ 70%) (Michelakis et al., 1993). Increasing the amount of fertilizer does not necessarily achieve the objective and nutrients can move to greater depths where they cannot be absorbed by the roots and may end up contaminating the groundwater. In-situ SM sensors are a valu-

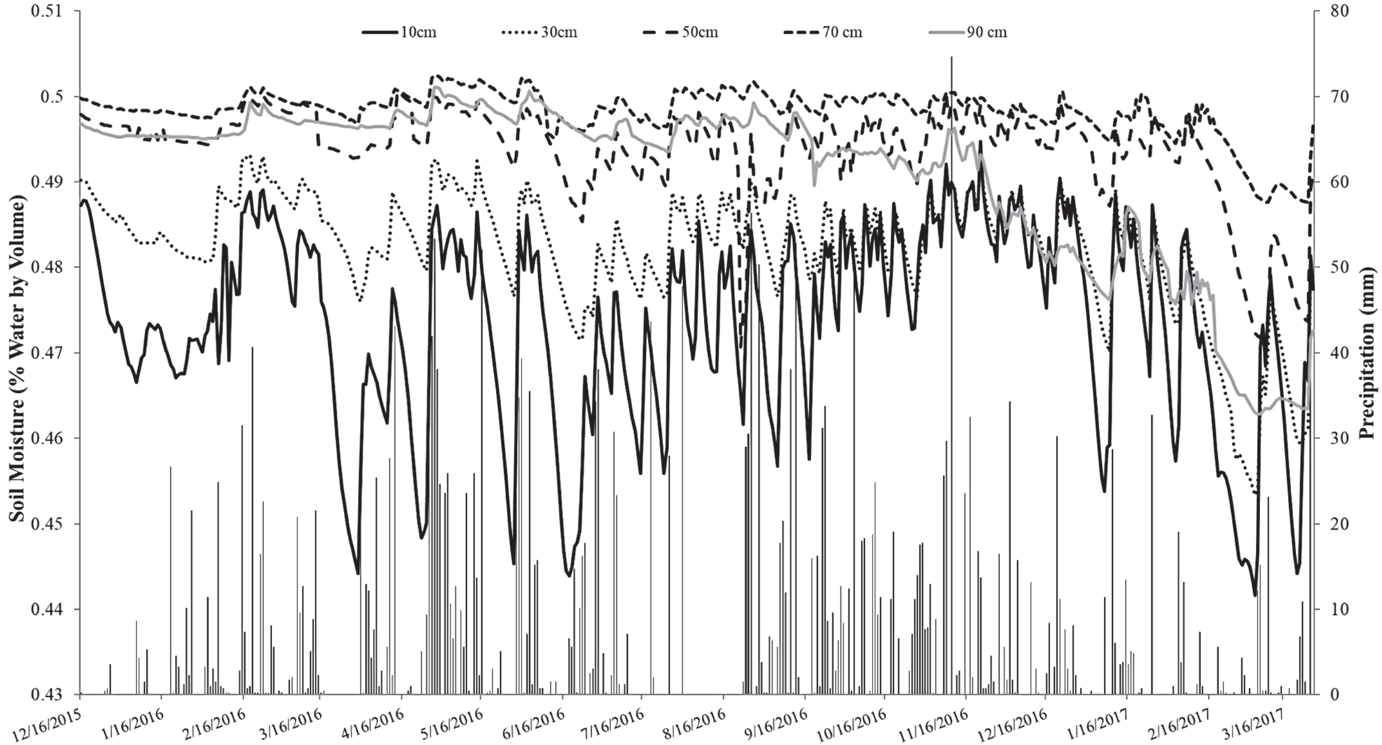

FIGURE 1. Average daily soil moisture content data of five different soil depths plotted against daily precipitation data collected from the avocado experiment site during the 21-month period (15 December 2015 to 13 September 2017) at the Agricultural Experiment Substation of Isabela, Puerto Rico.

TABLE 5.—*Tree height, area, canopy, efficiency and yield of the mature avocado orchard (cv. 'Simmonds') receiving two levels of fertilizer in an Oxisol at the Agricultural Experiment Substation of Isabela, Puerto Rico, in 2017.*

Fertilizer level	Tree height m	Tree area m^2	Tree canopy volume m^3	Tree efficiency Fruit #/m^3	Avocado Number ^ #	Avocado Weight^ kg/tree
F1⁺	5.80 a‡	51.3 a	156 a	0.716 a	112 a	92.3 a
F2	5.63 a	51.0 a	150 a	0.728 a	109 a	95.6 a

⁺F1- 9.06 kg fertilizer 15-3-19/tree/yr ~ 167 kg of N/ha/yr; F2- 12.07 kg fertilizer 15-3-19/tree/yr ~ 224 kg of N/ha/yr.
‡Means followed by the same letter between fertilizer levels are not significantly different by Tukey's test at $P < 0.05$.
^Average avocado number and weight produced under two levels of fertilizer, harvested from 15 July to 13 September 2017.

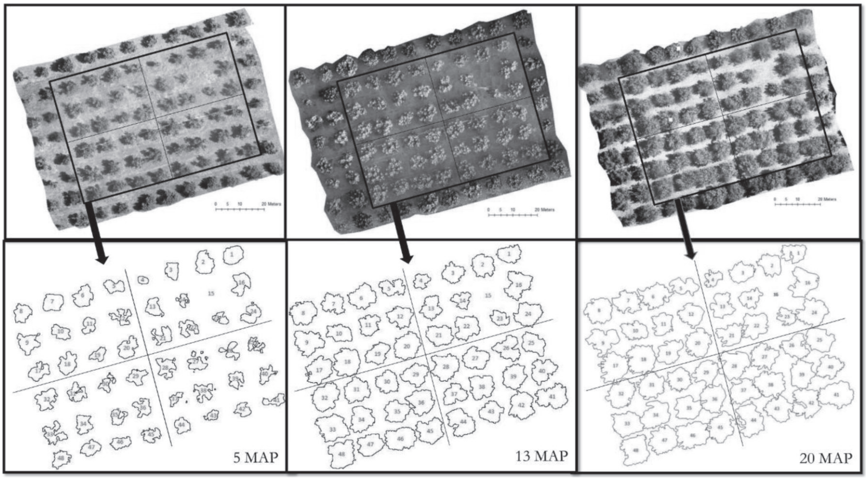

FIGURE 2. Top orthophotos represent aerial views of the whole avocado orchard (cv. 'Simmonds'), shown within the black rectangle. Outside the rectangle are trees from others avocado varieties, used as a border. Aerial top pictures were taken 5 MAP, 13 MAP and 20 MAP. The bottom images show the canopy of the 48 experimental trees at 5, 13 and 20 MAP. Tree 14 is from another cultivar and tree 15 died. For our analysis we did not take into account those two trees.

able tool for improving avocado orchard management by providing a better understanding of when and how much water is needed. In this study, SM was always higher than 41% in the soil profile (0- to 100-cm depth), which indicated no irrigation was required for the entire study period. Román-Paoli et al. (2009) reported field capacity of Coto series oscillating between 37.5 and 38.9% with a permanent wilting point of 20.7%, resulting in total available water of 18.2%. Before installing the soil moisture sensors for IS in the mature avocado orchard, the irrigation system was activated twice a week during those weeks in which none or a minimum amount of precipitation was received, and the soil surface looked dry. We saved approximately 5.84 mm of water per irrigation event of four hours. In the whole experiment of 21 months (168 events), we estimated a savings of 981 mm of water. Also, operational costs were reduced as a result of reduced or non-use of electricity, which powers the pump for the irrigation system, and maintenance costs were lower because fees for water use from a government utility canal did not have to be paid.

To determine whether mature avocado trees are receiving sufficient nutrients without contaminating the soil and water, it is necessary to perform soil and tissue analyses. In Puerto Rico it is often challenging to interpret leaf tissue analysis for avocado, as there are no local guidelines for tissue analysis for this crop. Nonetheless, when compared with California guidelines by Bender and Faber (1999), most

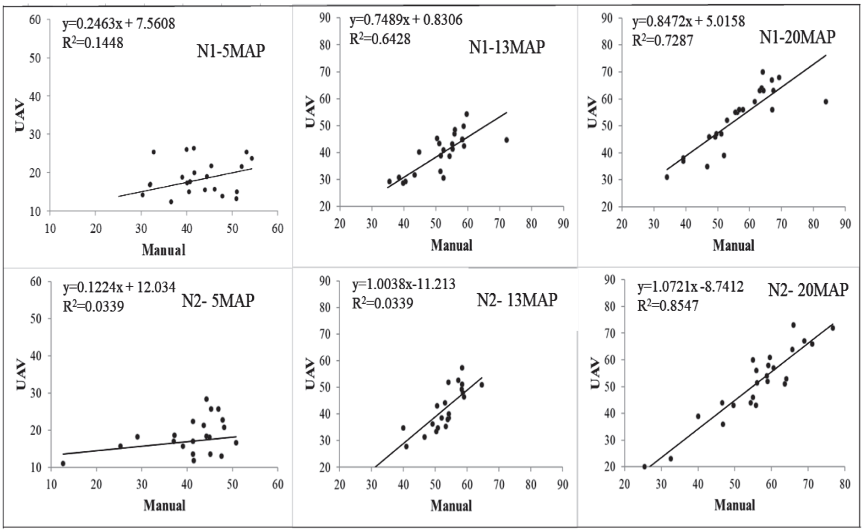

FIGURE 3. Correlation of avocado tree canopy cover (m^2) measured by UAV versus manual measurement from three different dates (5, 13 and 20 MAP) and two fertilizer levels: F1- 9.06 kg and F2- 12.07 kg of 15-3-19/tree/yr).

leaf sample values obtained in our research were in the optimum range for P (0.10 to 0.25 mg/kg), K (0.75 to 2.0 mg/kg), Ca (1.0 to 3.0 mg/kg), Mg (0.25 to 0.80 mg/kg), Na (< 0.25 mg/kg), S (0.20 to 0.60 mg/kg), B (20 to 49 mg/kg), Cu (5 to 15 mg/kg), Fe (50 to 200 mg/kg), and Zn (30 to 150 mg/kg). Also, N (> 2.2% in F2 treated trees) and Mn (> 500 mg/kg) showed high concentrations in this study, but no apparent negative responses were observed. In Puerto Rico, fertilization guidelines were published by the Agricultural Experiment Station (1998). These guidelines have been updated based on data and recommendations gathered from avocado growers. Because of differences in soil type, topography, climate and avocado cultivars planted throughout the island, soil and plant tissue analysis are widely recommended.

In terms of yield, average avocado production (110 fruits per tree = 13,200 fruits per hectare) and fruit weight (94 kg/tree = 11,280 kg / ha did not differ with respect to fertilizer level. Our results compared favorably with Román-Paoli et al. (2009) in the same orchard when the trees were 10 years younger and the yield was ~ 110 to 120 fruits per tree under adequate irrigation.

Avocado canopy areas calculated through remote sensing (UAV) technology demonstrated its benefit as a tool for orchard management. However, remote sensing results tend to be more reliable when tree canopies are denser and closer to one another after pruning compared with manual results ($R^2 > 0.8$, RMSE < 2.7 m^2).

The use of SMC and UAV technologies as part of IS for horticultural crops has shown to be convenient and effective, particularly in irrigation management. However, we should emphasize that these technologies are not indispensable to obtain optimum yields. If well maintained, the equipment is highly durable, but the initial cost can be high. The UAV can be used in different orchards or crops simultaneously. Soil moisture sensors established at deeper depths, once inserted, are difficult to remove without disturbing the soil at upper levels. The datalogger can be transferred to other sites without any problem. Data gathered on tree response under different levels of fertilizer can be used in other humid locations in Puerto Rico, but not the IS data, since each location has unique environmental and soil physical properties.

CONCLUSIONS

In this experiment, we tested the feasibility of using in-situ SMC sensors and a low-cost small UAV platform to measure SM and canopy area over a mature avocado orchard. With appropriate filtering and computation, it was possible to quantify the orchard development and health with UAV/remote sensing. The SM data helped save water and reduce operational costs. Under the conditions of this study, application of 9.06 kg of 15-3-19/tree/yr (167 kg of N/ha/yr) satisfied avocado nutrient requirements. Additional research is needed to determine if it is possible to maintain optimum avocado production with less fertilizer.

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