Evaluation of irrigation efficiency using precision agriculture tools on a mandarin orange farm in Afourer, Paysandú, Uruguay

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Abstract.

Efficient water management in citrus farming requires monitoring systems that integrate real-time climate data and accurate soil moisture measurements to optimize irrigation decisions within a precision agriculture framework, accounting for spatial variability in soil water availability. The use of continuous monitoring technologies improves the efficiency of drip irrigation and reduces water losses associated with both water deficits and excesses in commercial production systems. Facing this need, the present study evaluated the efficiency of drip irrigation in a commercial Afourer mandarin grove of 3.25 ha in Paysandú, Uruguay, analyzing the crop water balance and its relationship with yield during the period December 2021-August 2023. To this end, a network of 20 monitoring stations equipped with HOBO® capacitive sensors was installed in a regular grid with a minimum spacing of 30 m between points, so as to capture the spatial variability of the study area, recording volumetric soil moisture (0-40 cm) continuously every 15 minutes. The data were integrated with meteorological information to estimate reference evapotranspiration using the FAO Penman–Monteith method and the Thornthwaite–Mather water balance. Physical-hydrological characterization of the soil through Richards chamber retention curves determined a notably low available water capacity of 2.05 ± 1.68 mm and a readily available water of 1.23 mm for the 0-40 cm profile, with pronounced spatial variability in the fraction of available water (FAW = 0.523-0.802), associated with differences in soil hydraulic conditions and crop response, with yields ranging from 19,312 to 92,200 kg ha^{-1}. Total precipitation was 2,461 mm and crop evapotranspiration was 1,594 mm, while effective precipitation accounted for between 6.2 and 23.4% of the total, requiring irrigation inputs of 1,012 to 1,442 mm depending on the scenario evaluated. Five irrigation schedules were analyzed: variable and fixed every 3, 5, 7, and 10 days. Despite accumulated precipitation exceeding evapotranspiration by 54%, irrigation was necessary under the evaluated scenarios due to the soil's limited water storage capacity. The 5-day irrigation cycle proved the most efficient, applying 1,236 mm across 108 events - 14% less than the variable schedule - while maintaining adequate water availability during most of the evaluated period. These results demonstrate the importance of incorporating spatial soil variability and continuous monitoring systems to improve irrigation management and advance toward more efficient precision irrigation strategies in citrus farming.

Keywords. *Precision irrigation, soil moisture sensors, water balance, available water fraction, spatial variability*

Introduction

Citrus production represents a strategic sector for the Uruguayan agro-export economy, occupying 13,477 ha and producing approximately 305 thousand tons annually. Among citrus crops, mandarins account for the largest export volume, reaching 41.5 thousand tons per year (MGAP-DIEA, 2024). Among the different mandarin cultivars, **Afourer** (*Citrus reticulata* Blanco) has gained increasing commercial importance due to its favorable fruit characteristics, including large fruit size, intense peel coloration, and easy peeling (Portalfruticola, 2022; Fontán et al., 2024). However, its productivity is strongly influenced by edaphoclimatic conditions, with water availability and efficient irrigation management being recognized as the main limiting factors (Ackermann & Díaz, 2021).

The agricultural sector accounts for approximately 87% of the total freshwater withdrawals in Uruguay (Ciganda et al., 2021; FAO-AQUASTAT, 2021), making irrigation efficiency a key component of sustainable water resource management. Increasing climate variability, including changes in rainfall patterns and prolonged drought events, has intensified pressure on national agricultural production systems, contributing to orchard abandonment and the implementation of mandatory eradication measures to reduce phytosanitary risks (MGAP, 2024).

Although irrigation adoption in Uruguayan citrus production has increased from 52.6% in 2011 to 60.6% in 2017 (MGAP-DIEA, 2018), the implementation of precision agriculture technologies for irrigation monitoring and management remains limited. Drip irrigation has become particularly important in intensive citrus production systems because of its high application efficiency (80–90%), its ability to maintain relatively stable soil moisture conditions within the root zone, and its compatibility with fertigation practices (Allen et al., 1998). Nevertheless, irrigation efficiency depends not only on the irrigation system itself but also on appropriate scheduling based on soil water storage capacity, atmospheric water demand, and crop phenological development.

Many growers still rely on subjective criteria or fixed irrigation calendars that fail to account for interannual climatic variability and seasonal environmental conditions (IICA, CEPAL, & FAO, 2020). In addition, national studies addressing the water component of citrus production through continuous monitoring technologies remain scarce.

Therefore, the objective of this study was to evaluate the efficiency of a drip irrigation system in a commercial Afourer mandarin orchard by analyzing the crop water balance and its relationship with productivity over a 21-month period using a distributed network of soil moisture sensors integrated with meteorological observations.

Materials and Methods

The study was conducted in a commercial Afourer mandarin orchard located on rural property No. 6443 in the Department of Paysandú, Uruguay (approximately 32°S, 58°W). The orchard covers 3.25 ha and consists of 4–6-year-old trees in full production equipped with a drip irrigation system. The soils correspond to CONEAT Index 9.3 and are classified as Ochric Dystric Planosols and Abruptic Ochric Dystric Argisols, with sandy loam texture, gentle slopes (1–2%), and a productivity index of 88 (Altamirano et al., 1976).

The region has a humid subtropical climate (Köppen, 1936), with a mean annual air temperature of 18.6 °C and an average annual precipitation of 1,291.7 mm (INUMET, 1991–2020).

In September 2021, a network of 20 monitoring stations was established following a regular grid with a minimum spacing of 30 m between sampling points. Each station was equipped with **HOBO®** capacitive sensors that continuously recorded volumetric soil moisture (θ_V, cm³ cm⁻³)

within the 0–40 cm soil profile, as well as air temperature and photosynthetically active radiation, at 15-min intervals. Data were collected from December 2021 to August 2023, covering a complete production cycle.

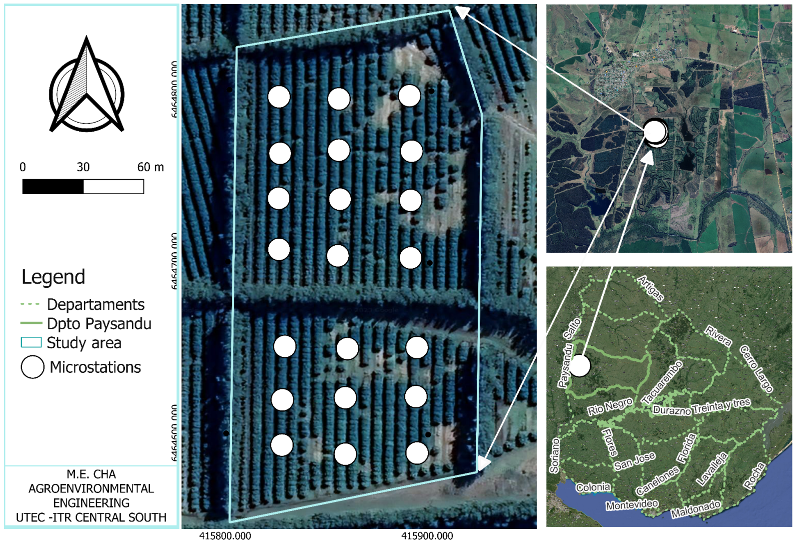

Fig. 1. Spatial distribution of the monitoring points within the commercial Afourer mandarin orchard located in Quebracho, Department of Paysandú, Uruguay. Circles indicate the location of the 20 monitoring stations equipped with capacitive soil moisture sensors.

Soil Physical and Hydraulic Characterization

Undisturbed soil samples were collected from four randomly selected locations using metal cores (~100 cm³) at four depth intervals (0–10, 10–20, 20–30, and 30–40 cm), with two replicates per depth, resulting in a total of 32 samples.

At the UTEC Soil Laboratory, the samples were conditioned, saturated, and used to determine soil water retention curves using a Richards pressure chamber (Richards, 1965). Compressed air was applied under controlled pressure to simulate different matric potentials until hydraulic equilibrium was reached, and soil water content was measured at matric potentials of 6, 10, 100, and 1500 kPa (Dane & Topp, 2020). Soil water content at field capacity (θ_{FC}) was determined at 10 kPa, whereas permanent wilting point (θ_{PWP}) was determined at 1500 kPa (Reichert et al., 2009).

Additionally, soil samples were collected at each of the 20 monitoring stations to determine particle-size distribution (sand, silt, and clay) using the pipette method (Gee & Bauder, 1986), allowing soil texture to be classified individually for each monitoring station.

The particle-size fractions obtained for each sampling point were used as input variables to estimate soil hydraulic parameters using the Van Genuchten (1980) model through the Rosetta pedotransfer function module implemented in HYDRUS software (Šimůnek et al., 2013). The resulting soil water retention curves generated for each of the 20 monitoring stations provided station-specific values of field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), allowing the fraction of available water (FAW) to be calculated on a spatially distributed basis rather than using a single reference value for the entire orchard.

Available water (AW) was calculated as:

$$AW = (\theta_{FC} - \theta_{PWP}) \times Z$$

(1)

where Z is the soil profile depth (40 cm).

Readily available water (RAW) was calculated as:

$$RAW = AW \times p \quad (2)$$

where p = 0.60 is the depletion fraction recommended for deep-rooted perennial fruit crops (Allen et al., 1998).

Meteorological Variables and Evapotranspiration

Meteorological data were obtained from an automatic weather station located approximately 700 m from the orchard, including precipitation (P, mm), air temperature (T, °C), relative humidity (RH, %), wind speed (V, $m\ s^{-1}$), solar radiation (Rs, $W\ m^{-2}$), and Class A pan evaporation (Evap., $mm\ day^{-1}$).

Reference evapotranspiration (ETo, $mm\ day^{-1}$) was calculated using the FAO-56 Penman–Monteith equation (Allen et al., 1998). Crop evapotranspiration (ETc) was estimated as:

$$ET_c = ET_o \times K_c \quad (3)$$

where Kc is the crop coefficient. A constant value of Kc = 0.80 was adopted for all phenological stages, following Allen et al. (1998) for citrus orchards with active ground cover and approximately 50% canopy cover, considering a total ground cover of 97% determined through class-count analysis.

Water Balance and Irrigation Requirement Estimation

The daily water balance was calculated using the Thornthwaite and Mather (1955) method. The fraction of available water (FAW) was calculated as:

$$FAD = (\theta_{actual} - \theta_{PWP}) / (\theta_{FC} - \theta_{PWP}) \quad (4)$$

where θ_{actual} is the volumetric soil water content measured by the sensors. FAW values were averaged across the soil profile to define irrigation thresholds.

Five irrigation scheduling scenarios were evaluated: variable scheduling (R1) and fixed irrigation intervals of 3 days (R2), 5 days (R3), 7 days (R4), and 10 days (R5). For each scenario, effective precipitation (Peff) was calculated as total precipitation minus water losses exceeding the soil water storage capacity.

The irrigation requirement was estimated using a decision rule based on two simultaneous conditions: $\theta_{actual} < RAW$ (soil moisture below the readily available water threshold) and $DEP_{fin} > 0$ (positive cumulative soil water deficit at the end of the day). Irrigation was triggered only when both conditions were satisfied simultaneously, ensuring that water was applied only when required while avoiding both insufficient and excessive irrigation.

Productivity Variables

Productivity data were collected during the 2022/2023 harvest season by selecting three trees at each monitoring station, resulting in a total of 60 sampled trees. For each tree, total fruit weight (kg) and the total number of fruits were recorded. Mean values for each monitoring station were calculated using a proximity-based approach, considering the three trees closest to each sensor, equivalent to a localized implementation of the K-Nearest Neighbors (KNN) algorithm with $K = 3$ (Sitienei et al., 2023).

The following productivity indicators were calculated: mean yield (kg ha^{-1}), mean number of fruits per tree, and mean fruit weight (g).

Data Processing and Statistical Analysis

The dataset underwent quality control through outlier detection using the interquartile range (IQR) method, applying a threshold of 1.5 × IQR. Missing observations were imputed using spatial correlation among neighboring monitoring stations. Climatic variables were aggregated to a daily time scale using temporal averages, except for precipitation, which was accumulated on a daily basis. All data processing and analyses were performed using **R** version 4.x.

Descriptive statistics included the arithmetic mean, standard deviation, coefficient of variation, minimum and maximum values, and percentiles to characterize temporal variability. Pearson's correlation coefficients were calculated to evaluate the relationship between water availability and crop productivity. Monitoring stations were classified into three categories according to their mean fraction of available water (FAW): Low (< 0.60), Medium (0.60–0.70), and High (≥ 0.70). Segmented regression analysis (Muggeo, 2003; Toms & Lesperance, 2003) was applied to identify threshold values in the relationship between FAW and productivity.

The results are presented in tables summarizing the soil physical and hydraulic properties (Table 1), cumulative water balance under each irrigation scenario (Table 2), classification of days according to FAW (Table 3), and productivity by FAW category (Table 4). Figures include the time series of the water balance for the optimal irrigation scenario (Fig. 2), the temporal evolution of the mean FAW throughout the crop phenological stages (Fig. 3), and the temporal evolution of FAW for each monitoring station according to the crop phenological stages (Fig. 4).

Result

Soil Physical and Hydraulic Characterization

Soil characterization revealed a θ_{FC} = 0,274 cm³/cm³ and θ_{PWP} = 0,264 cm³/cm³, with a bulk density of 1,507 g/cm³ and a total porosity of 0,221 cm³/cm³ (Tabla 1). Available water (AW) within the 0–40 cm soil profile was extremely low, averaging 2.05 ± 1.68 mm. The surface layer (0–20 cm) stored only 0.86 mm of available water, whereas the subsurface layer (20–40 cm) stored 3.23 mm. The calculated readily available water (RAW) of 1.23 mm represents the critical threshold for irrigation triggering.

Table 1. Soil physical and hydraulic properties by soil depth.

Variable	0-20 cm	20-40 cm	Promedio
θ_{FC} (cm³/cm³)	0,2704	0,2775	0,274 ± 0,005

θ_{PWP} (cm³/cm³)	0,2661	0,2613	0,264 ± 0,003
Bulk density (g/cm³)	1,5067	1,5074	1,508 ± 0,001
AW (mm)	0,86	3,23	2,05 ± 1,68
TP (cm³/cm³)	0,2195	0,2235	0,221 ± 0,003

Particle-size analysis of the 20 monitoring stations revealed a predominance of sandy loam soils, with mean contents of 60.8% sand, 20.6% silt, and 18.8% clay (Table 2). Six monitoring stations (Stations 4, 5, 6, 15, and, to a lesser extent, Station 17) exhibited higher clay contents (>20%) and were classified as sandy clay loam. This textural variability partially explains the spatial heterogeneity observed in soil water retention capacity and FAW values among monitoring stations.

Table 2. Particle-size distribution (sand, silt, and clay) and soil textural classification determined using the pipette method (Gee & Bauder, 1986) for the 20 monitoring stations.

Estación	Arena (%)	Limo (%)	Arcilla (%)	Clase textural
Station 1	67.1	17.8	15.1	Sandy loam
Station 2	67.0	16.7	16.3	Sandy loam
Station 3	61.7	19.1	19.3	Sandy loam
Station 4	56.8	20.6	22.7	Sandy clay loam
Station 5	58.6	18.8	22.7	Sandy clay loam
Station 6	54.9	25.0	20.1	Sandy clay loam
Station 7	59.9	20.7	19.4	Sandy loam
Station 8	60.0	21.0	19.1	Sandy loam
Station 9	62.4	22.9	14.7	Sandy loam
Station 10	61.9	20.1	18.0	Sandy loam
Station 11	62.8	21.6	15.6	Sandy loam
Station 12	62.1	20.2	17.8	Sandy loam
Station 13	62.7	19.3	17.9	Sandy loam
Station 14	59.3	21.4	19.3	Sandy loam
Station 15	53.0	21.6	25.4	Sandy clay loam

Station 16	70.4	12.9	16.7	Sandy loam
Station 17	56.1	25.3	18.6	Sandy loam
Station 18	58.3	21.4	20.3	Sandy loam
Station 19	58.3	21.4	20.3	Sandy loam
Station 20	61.9	20.1	18.0	Sandy loam
Promedio	60.8	20.6	18.8	—

Water Balance under Different Irrigation Scheduling Scenarios

During the 21-month study period, cumulative precipitation reached 2,461 mm, representing 1.90 times the historical annual average for Paysandú (1,291.7 mm). Total crop evapotranspiration (ETc) amounted to 1,593.85 mm, showing a clear seasonal pattern, with values exceeding 5 mm day^{-1} during summer and remaining below 2 mm day^{-1} during winter.

Effective precipitation accounted for only 6.2–23.4% of total rainfall, depending on the irrigation scheduling scenario (Table 3), while precipitation losses ranged from 1,884 to 2,309 mm (77–94%). Total irrigation depth decreased progressively from 1,441.97 mm under the variable irrigation schedule (435 irrigation events) to 1,011.69 mm under the 10-day irrigation interval (54 irrigation events).

Table 3. Cumulative water balance for the different irrigation scheduling scenarios.

Variable	R1	R2	R3	R4	R5
Total P (mm)	2461	2461	2461	2461	2461
Effective P (mm)	151,9	265,6	352,8	394,6	576,6
Losses (mm)	2309,1	2195,4	2108,2	2066,4	1884,4
Irrigation (mm)	1442,0	1328,2	1235,6	1197,4	1011,7
N. of irrigation events	435	176	108	76	54
Effective P/ETc (%)	9,5	16,7	22,1	24,8	36,2
Irrigation/ETc (%)	90,5	83,3	77,5	75,1	63,5
Final water deficit (DEP_{fin} ,mm)	1,8	5,5	5,5	1,8	5,5

The 5-day irrigation interval (R3) proved to be the most appropriate scheduling strategy, requiring 1,236 mm distributed over 108 irrigation events, representing a 14% reduction compared with the variable irrigation schedule while maintaining a low final water deficit (DEPfin= 5.52 mm).

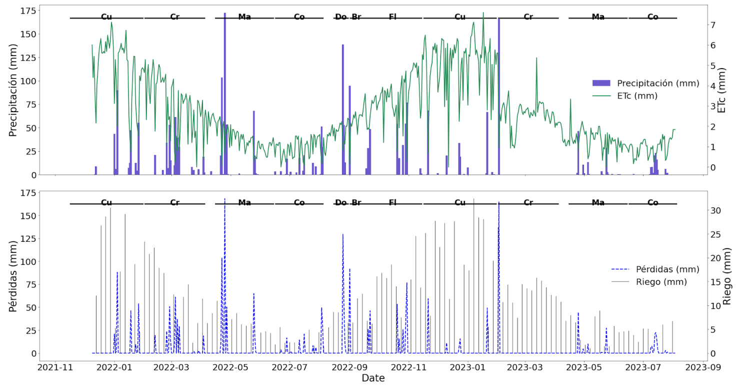

Fig. 2. Time series of precipitation, irrigation, crop evapotranspiration (ETc), and water losses under the 5-day irrigation scheduling scenario (R3) during the study period. Blue bars represent daily precipitation, green bars indicate applied irrigation, the solid red line represents ETc, and the dashed gray line shows cumulative water losses.

Temporal and Spatial Variability of the Fraction of Available Water

The fraction of available water (FAW) exhibited spatial variability among the monitoring stations, with mean values ranging from 0.523 to 0.802 and an overall average of 0.650. The classification of the monitoring stations showed a predominance of low to medium water availability conditions, with 15 stations falling within these categories and five stations exhibiting high water availability. On average, the monitoring stations recorded 38 days with excess soil water, 655 days within the optimal water availability range, and 7 days with water deficits below the permanent wilting point (Table 3).

Table 3. Number of days classified according to the fraction of available water (FAW) by monitoring station category.

FAW category	No. of stations	Mean FAW	Days with excess water	Days within the optimal range	Days with water deficit
Low (<0,60)	8	0,550 ± 0,029	22 ± 16	656 ± 57	19 ± 29
Medium (0,60–0,70)	7	0,651 ± 0,030	31 ± 27	668 ± 35	6 ± 5
High (≥0,70)	5	0,763 ± 0,033	85 ± 28	652 ± 23	6 ± 2
Overall mean	20	0,650 ± 0,093	38 ± 33	655 ± 48	7 ± 18

During the critical stages of the crop cycle (December–April), temporary declines in FAW below 0.40 were observed during several periods, particularly in January and February. These conditions reflected short-term episodes of potential water stress associated with periods of high atmospheric demand, when crop evapotranspiration (ETc) exceeded 5 mm day^{-1} and precipitation was limited.

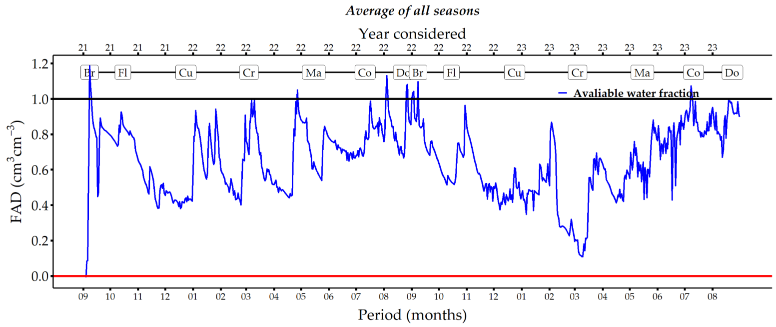

Fig. 3. Time series of the mean fraction of available water (FAW) calculated from the 20 monitoring stations distributed throughout the orchard. The dashed horizontal lines indicate the theoretical limits: FAW = 0 (permanent wilting point) and FAW = 1 (field capacity). The abbreviations at the top indicate the phenological stages of Afourer mandarin: **BR** = Budbreak; **FL** = Flowering; **FS** = Fruit set; **FR** = Fruit growth; **RI** = Fruit ripening; **HA** = Harvest; **DO** = Dormancy.

When FAW was analyzed at the individual monitoring station level, the seasonal pattern remained consistent with the orchard average; however, the magnitude and frequency of water deficit and excess events varied substantially among stations, reflecting the textural and hydraulic heterogeneity previously described (Fig. 4).

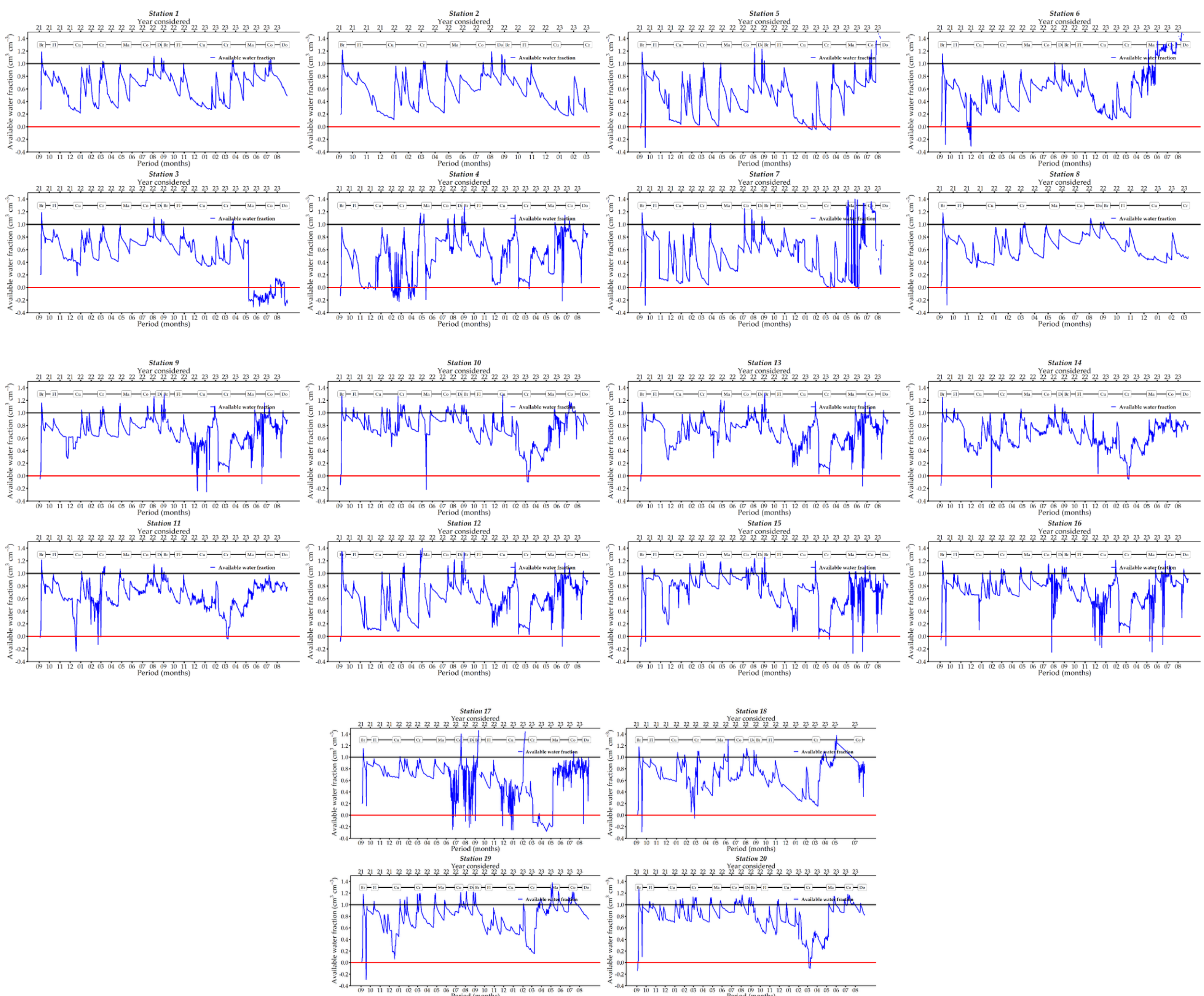

Fig. 4. Time series of the fraction of available water (FAW) for each of the 20 monitoring stations

throughout the study period. Each panel represents an individual monitoring station. The upper and lower reference lines indicate FAW = 1 (field capacity) and FAW = 0 (permanent wilting point), respectively.

Crop Productivity

Crop productivity showed marked spatial variability among the monitoring stations, ranging from 19,312 to 92,200 kg ha⁻¹, with an overall mean yield of 43,622 kg ha⁻¹. Yield variation was primarily associated with differences in fruit load, averaging 826 fruits per tree and ranging from 340 to 1,965 fruits per tree. Individual fruit weight exhibited lower relative variability, with a mean of 110.1 g and values ranging from 82.1 to 156.9 g (Table 4).

Table 4. Productivity and yield components according to FAW category.

FAW category	No. of stations	Yield (kg ha⁻¹)	Fruits per tree	Fruit weight (g)
Low (<0,60)	12	47.657 ± 21.912	873 ± 507	105,0 ± 17,9
Medium (0,60–0,70)	4	43.219 ± 18.136	743 ± 301	118,8 ± 11,5
High (≥0,70)	5	43.023 ± 16.205	868 ± 513	110,3 ± 24,7
Overall mean	21	43.622 ± 19.107	826 ± 447	110,1 ± 18,8

Water availability categories differed in productivity; however, no linear relationship was observed between greater water availability and higher yield. Monitoring stations classified as having low water availability exhibited the highest mean productivity (47,657 kg ha⁻¹), whereas the medium and high FAW categories showed similar mean yields (43,219 and 43,023 kg ha⁻¹, respectively). These findings indicate that crop productivity was not determined solely by water availability but was likely influenced by the interaction among soil properties, the spatial distribution of applied irrigation water, and other site-specific production factors.

Discussion

Soil water availability was extremely limited, with a mean available water (AW) of 2.05 mm and a readily available water (RAW) of 1.23 mm within the evaluated 0–40 cm soil profile. These values are substantially lower than those reported for productive agricultural soils, where the water storage capacity commonly exceeds 80–100 mm for similar soil depths (Reichert et al., 2009). This limited storage capacity restricts the effective utilization of rainfall and increases the dependence on irrigation as the primary source of water supply for the crop. Despite the high cumulative precipitation recorded during the study period (2,461 mm), only a small proportion was effective because of the soil's limited water retention capacity and the substantial losses associated with excess water.

The narrow difference between field capacity (θFC) and permanent wilting point (θPWP) indicates a very limited range of plant-available water storage. This condition was primarily associated with the predominance of sandy loam soils and the particle-size heterogeneity observed among monitoring stations, where some locations exhibited higher clay contents and, consequently, greater water retention capacity. Under these conditions, relatively small changes in soil moisture may result in substantial differences in the amount of water effectively available to the crop. Considering that crop evapotranspiration (ETc) exceeded 5 mm day^{-1} during periods of high atmospheric demand, the readily available water reserve can be depleted rapidly, increasing the sensitivity of the production system to irrigation interruptions or delays in water application.

The spatial variability of FAW revealed substantial differences among monitoring stations, with mean values ranging from 0.523 to 0.802 and an overall average of 0.650. Although adequate water availability prevailed during most of the study period, with 655 days within the optimal range, differences were observed in the frequency of extreme events among monitoring stations. Stations with higher FAW experienced a greater number of days with excess soil water, whereas other locations showed occasional periods of water deficit during critical crop stages. This variability reflects the combined influence of soil texture, hydraulic properties, and the spatial distribution of applied irrigation water.

During the crop's most physiologically sensitive stages, particularly flowering, fruit set, and early fruit growth, temporary declines in FAW below 0.40 may represent periods of potential water stress. Water stress during these stages may induce physiological responses associated with abscisic acid accumulation and ethylene synthesis, promoting flower and fruit abscission (Gómez-Cadenas et al., 1996). However, in the present study these events were sporadic and did not represent the prevailing condition of the production system, as adequate water availability was maintained throughout most of the crop cycle.

The 5-day irrigation interval provided the best balance between water conservation and maintenance of the crop water status, reducing the irrigation volume applied compared with the variable irrigation schedule while maintaining low levels of cumulative water deficit. Longer irrigation intervals further reduced the total irrigation volume but increased the likelihood of reaching periods of water limitation because of the soil's restricted water storage capacity. In production systems characterized by low soil water reserves, irrigation optimization should consider not only reducing the number of irrigation events but also the temporal dynamics of soil water depletion and replenishment.

The present results indicate that regulated deficit irrigation strategies, which have been extensively investigated in citrus production (González-Altozano & Castel, 2003; Ballester et al., 2014), require adjustments when implemented in soils with low water storage capacity. Although these strategies can achieve substantial water savings while maintaining satisfactory productivity (García-Tejero et al., 2010), their successful implementation depends on the soil's capacity to buffer short periods of water deficit. Under the conditions evaluated in this study, the limited water storage capacity of the soil profile restricts the possibility of extending irrigation intervals without potentially affecting the crop water status.

Crop productivity exhibited marked spatial variability, ranging from 19,312 to 92,200 kg ha^{-1}, and no linear relationship was observed between greater water availability and increased yield. Monitoring stations classified within the low FAW category even exhibited higher average productivity than those with high water availability, indicating that crop performance was determined by the interaction of multiple factors, including soil properties, the spatial distribution of irrigation water, individual tree characteristics, and water use efficiency. Individual fruit weight ranged from 82.1 to 156.9 g among monitoring stations. According to Pochintesta (2016), the optimal commercial fruit weight for **Afourer** mandarins is approximately 82.1–93 g. Consequently, part of the evaluated fruit fell within this commercial range, whereas other fruit reached larger sizes. Nevertheless, greater individual fruit weight was not necessarily associated with higher productivity, suggesting that increased water availability may promote fruit growth but does not, by itself, ensure greater yield uniformity or higher overall productivity.

Overall, these findings demonstrate that efficient irrigation management in **Afourer** mandarin orchards requires consideration of the spatial variability of soil properties in addition to the atmospheric water demand of the crop. The integration of distributed soil moisture sensors with station-specific hydraulic parameters made it possible to identify spatial differences in soil water dynamics and to establish irrigation management criteria better adapted to the actual conditions of the orchard.

Conclusion or Summary

The analysis of the water balance and the spatial variability of water availability demonstrated that the evaluated production system is characterized by a low soil water storage capacity and a high dependence on irrigation to satisfy crop water requirements. The use of a distributed soil moisture monitoring network combined with station-specific hydraulic parameters made it possible to identify spatial heterogeneity in the fraction of available water (FAW), showing that although adequate water availability predominated throughout most of the study period, localized episodes of water deficit and excess occurred as a consequence of the specific characteristics of individual monitoring stations.

Among the irrigation strategies evaluated, the 5-day irrigation interval provided the best compromise between water use efficiency and maintenance of an adequate crop water status, reducing irrigation inputs compared with the variable scheduling strategy without substantially increasing the cumulative water deficit. The absence of a direct relationship between FAW and crop productivity indicates that yield was determined by the interaction among water availability, soil properties, and other production-related factors. These findings highlight the importance of precision irrigation strategies that explicitly account for the spatial variability of soil hydraulic characteristics in order to improve irrigation efficiency and optimize water management in commercial citrus orchards.

Acknowledgments

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