Water-use efficiency and evapotranspiration of mango orchard grown in northeastern region of Brazil

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Abstract

Knowledge of evapotranspiration (ET) and water-use efficiency (WUE) is essential in crops management mainly in arid and semiarid regions where water resources are scarce for irrigation. Field experiments were conducted at a commercial farm to obtain the WUE and ET of mango orchard growth in a semiarid environment of northeastern region of Brazil. Measurements were performed within a randomly selected experimental plot with the spacing of 10 m × 5 m between rows and plants. Soil water balance method was used to obtain the mango orchard evapotranspiration while the Penman–Monteith method (FAO/56) was used for determination reference evapotranspiration (ET o). Soil water content was determined by six tensiometer sets installed at 0.20 m layer intervals from the soil surface down to 1.20 m soil depth. The experimental plot was irrigated with a sprinkler irrigation system based on four irrigation levels (T1 = 70%, T2 = 80%, T3 = 90% and T4 = 100% of ET o). Results showed that ET and WUE are strongly influenced by soil water availability. Mango yield varied from a minimum value of 28.06 ton/ha in treatment T4 to a maximum value of 31.06 ton/ha in treatment T3. Such difference was found to be statistically significant (P < 0.05) by Tukey’s test. Results also indicated that WUE values based on irrigation and evapotranspiration were maximum and minimum for low (treatment T1) and high (treatment T4) water levels, respectively.

1. Introduction

Irrigation has improved agricultural activities because it provides most of the world food supply and may help the economic affairs of many countries. Despite the exponentially growing population, food production is limited by available farming land and irrigation water. Irrigation plays a very important role on the economic development of many countries.

The economy of the semiarid northeastern region of Brazil is greatly affected and often determined by agricultural production of tropical fruits. The main factor contributing to low mango fruit yield is poor canopy light penetration, which affects the leaf physiology (Schaffer and Gaye, 1989). In this context, the northeastern region of Brazil displays very favorable aspects for agriculture due to high energy availability throughout the year (Silva, 2004). However, there are some water availability restrictions in the semiarid areas where the production of tropical fruits is more intense. For this reason, the water resources in such region must be appropriately used in irrigation management. Mango growing areas in the world have increased 42.5% but the mean fruit yield has increased only 1.3%, from 7.5 to 7.6 ton/ha (FAO, 2003).

The mango fruit crop is widely grown in Brazil where the producing area reaches 53% of the national fruit production area (Silva et al., 2007). When studying the water-use efficiency of a coconut orchard in the same region, Azevedo et al. (2006) observed that the application of a higher irrigation water volume did not result in higher yields of coconut fruits. Evans et al. (1993) showed that published crop coefficients for mature grapes greatly overestimate water-use early and late in the season for Washington state conditions, although peak crop coefficients were similar. Several other researchers have also determined water requirements of tree-fruit (Azevedo et al., 2003, 2008) and citrus trees (Castel, 1994), strawberry plants (Clark et al., 1996), olive trees (Michelakis et al., 1996), pineapple (Azevedo et al., 2007).

Water-use efficiency (WUE) has been defined as the ratio of crop yield to evapotranspiration (Simsek et al., 2005; Zhang et al., 2004). Aujla et al. (2005) obtained WUE as the relation between crop yield and total water applied (water productivity). Water balance method has been used for obtaining the evapotranspiration of fruit orchards (Evans et al., 1993; Clark et al., 1996; Azevedo et al., 2006). Several subtropical and tropical fruit orchards have been irrigated based on empirical coefficients. This empirical approach suggests that amount irrigation water may be excessive and thus could lead to the leaching of nutrients and pesticides into the groundwater (Schaffer, 1998). The irrigation scheduling based upon empirical values of crop coefficient may reflect on some
aspects of production costs, fruit quality and crop yield. Surplus water may produce both increasing soil salinity and groundwater table contamination. Knowledge of the changes in water levels associated with evapotranspiration and water-use efficiency in mango is essential to improve understanding of yield-limiting factors and to inform future breeding strategies. The present paper examines the water-use efficiency and evapotranspiration of an irrigated mango orchard grown in a semiarid environment based on four irrigation levels.

2. Materials and methods

2.1. Experimental site descriptions

Field experiments were conducted at the commercial mango farm located in middle reaches São Francisco River region, Petrolina, PE, Brazil (latitude: 09°09’S; longitude: 40°22’W; altitude: 365.5 m above sea level) during two fruiting cycles. Table 1 shows the mean values of several climate variables at the Bebedouro Experimental Station of the Brazilian Organization for Agriculture and Animal Research (Embrapa Semi-Arido), which is located near to the experimental plot. The site is semiarid and the soil is classified as Latosol Red–Yellow with the groundwater level ranging between 4 m and 6 m below the surface. The predominant wind direction at the experimental site is east and the rainy season is from April to August. The climate is typically tropical, with an average annual rainfall of 535.8 mm with great inter-annual variations throughout the year, a mean air temperature of 26.5 °C, relative humidity of 65.7%, and a sunshine duration of 2700 h (long-term means: 1975–2005) (Silva et al., 2006).

2.2. Measurements and studied crop

Field experiments were performed at a 12-year-old on the mango orchard (Mangifera indica L.), variety Tommy Atkins, planted with the spacing of 10 m × 5 m between rows and plants, resulting in a density of 200 trees/ha. A sprinkler irrigation system was used with one sprinkler per plant and a water discharge rate of 60 L/h. The main experimental area was surrounded by other mango fields of 200 ha. The soil matrix potential was obtained by six sets of mercury manometer tensiometers positioned under the plant canopy and spaced of 0.80 m, 1.20 m and 1.60 m from the trunk. The tensiometers porous cups were installed at 0.20 m intervals, from 0.20 m to 1.20 m soil depth. These data were collected daily at 08:00 h, 12:00 h and 16:00 h during the same periods of two fruiting cycles (from April to August in 2005 and 2006). A trench was open in the experimental site for extracting soil samples that were used to determine the water retention curves, textural class, and soil water content for each soil layer. The tensiometers were checked weekly during the experimental periods. The measurements of study variables were obtained in a selected experimental plot of 3200 m². The fruiting cycle was divided into the following phenological stages: flowering, fruit-fall, fruit-growth, and fruit-maturation. Four harvests were performed for each fruiting cycle in 2005 and 2006.

2.3. Crop irrigation management

The experimental plot was irrigated by a sprinkler irrigation system based on four water levels (T1 = 70%, T2 = 80%, T3 = 90% and T4 = 100% of reference evapotranspiration – ET0). The control treatment (T4) and crop coefficient for mango orchard (0.75) were in accordance with traditional farmer’s management practices. The reference evapotranspiration was calculated based on Penman-Monteith model using weather data from a standard meteorological station (Allen et al., 1998):

\[
ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma ([900U_2/(T + 273)](e_s - e_a) - \Delta + \gamma T + 0.34U_2)}{\Delta + \gamma (1 + 0.34U_2)}
\]  

where \(R_n\) and \(G\) are daily net radiation and soil heat flux in MJ m\(^{-2}\), respectively, \(\gamma\) is psychometric constant (kPa °C\(^{-1}\)), \(\Delta\) is the slope of the saturation vapor pressure curve (kPa °C\(^{-1}\)), \(e_s - e_a\) the vapor pressure deficit (kPa) and \(U_2\) (m s\(^{-1}\)) the mean daily wind speed at 2 m above soil surface. The following parameters: \(R_n\), \(\Delta\), \(\gamma\) and \(e_s - e_a\) were estimated by the standardized equations proposed by Allen et al. (1998). Meteorological measurements were taken at an automatic weather station close to the experimental plot for obtaining \(ET_0\), and \(G\) was presumed to be 0 in a 24 h time-period.

2.4. Soil water balance

Mango orchard evapotranspiration was calculated by soil water balance for each irrigation treatment from the mass-conservation equation:

\[
\Delta S = R + I - D/C - ET
\]  

where \(\Delta S\) is the change in water storage, \(R\) the rainfall (mm), \(I\) the irrigation amount, \(D/C\) is the drainage (D) or capillary rise (C), and \(ET\) is the evapotranspiration. All terms of Eq. (2) are expressed in mm. Surface runoff was neglected because it was practically null at the experimental site.

Soil water drainage or capillary rise (D/C) was obtained as follows:

\[
D/C = -\left( R(\theta) \frac{\partial \Phi_0}{\partial z} \right)
\]  

where \(\theta(\theta)\) is the mean soil hydraulic conductivity, \(\partial \Phi_0/\partial z\) is vertical gradient of hydraulic potential while \(\Phi_0\) and \(z\) are total soil water potential and soil depth, respectively.

Based on the van Genuchten parameters (\(\theta_s\), \(\theta_t\), \(\alpha\), \(m\) and \(n\)) and soil water potentials (\(\Phi_m\)), the soil water content (\(\theta\)), in cm\(^3\) cm\(^{-3}\),

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
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<tbody>
<tr>
<td>Weather conditions during the experimental periods compared to the long term means (1975–2005). Mean values of air temperature ((T_a)), rainfall ((R)), relative humidity ((RU)), sunshine ((S)), class A pan evaporation ((Ev)) and wind speed ((WS)).</td>
</tr>
<tr>
<td>Month</td>
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<td>March</td>
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<td>April</td>
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<td>June</td>
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<td>July</td>
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<tr>
<td>August</td>
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<tr>
<td>Average</td>
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<tr>
<td>Total</td>
</tr>
</tbody>
</table>

The values between parentheses are the long-term means (1975–2005).
for each depth were obtained as (van Genuchten (1980)):

\[
\theta = \theta_t + \frac{\theta_s - \theta_t}{\left(1 + \left|\alpha\theta\right|\right)^m} \tag{4}
\]

The hydraulic conductivity for unsaturated soil \([K(\theta)]\) is given by:

\[
K(\theta) = K_o w^m [1 - (1 - w^{1/m})^n]^{-2} \tag{5}
\]

where \(K_o\) is the saturated soil hydraulic conductivity, \(w = (\theta - \theta_t)/(\theta_s - \theta_t)\), \(\theta_t\) and \(\theta_s\) are residual and saturation soil water content, respectively. The value of \(I\) is equal to 0.5 for most soils (Mualem, 1976). The change in soil water storage (\(\Delta S\)) was determined by equation:

\[
\Delta S = S_t - S_{t-1} \tag{6}
\]

where \(S_t\) and \(S_{t-1}\) are the changes in soil water storage at times \(t\) and \(t-1\), respectively. For determining the changes in soil water storage \(S_t\) was considered the soil layers from the surface \((z = 0)\) down to the bottom of the measurements soil depth \((z = l)\), by equation:

\[
S_t = \int \theta(z)dz = \left[0.5\theta(z_0) + \sum_{i=1}^{n-1} \theta(z_i) + 0.5\theta(z_n)\right] \Delta z \tag{7}
\]

where \(\Delta z\) is the thickness of soil layer \((cm)\), \(\theta(z_0) = \theta(z_1)\) and \(\theta(z_n) = \theta(z_0)\).

2.5. Water-use efficiency

The water-use efficiency (WUE), in kg/ha/mm, of the mango orchard was obtained by two ways, according to the equations:

\[
\text{WUE}_f = \frac{Y}{T_f} \tag{8}
\]

\[
\text{WUE}_{ET} = \frac{Y}{ET} \tag{9}
\]

where \(Y\) is the mango yield, \(\text{WUE}_f\) is the water-use efficiency based on irrigation \((I)\) and \(\text{WUE}_{ET}\) the water-use efficiency based on cumulative evapotranspiration \((ET)\) for each irrigation treatment.

2.6. Experimental design and statistical analysis

The field experiments were setup employing a randomized completely block design with four replications. Each replication contains four different irrigation regimes, randomly distributed in the plots (Fig. 1). The experimental plot was divided into 16 subplots with 4 trees each, resulting in a final density of 64 trees. Analysis of variance (ANOVA) was conducted for testing the effects of soil water levels on mango yield using Turkey’s test at 5% significance level. All data were submitted to ANOVA using the ASISSTAT software (Silva, 1996).

3. Results and discussion

3.1. Soil water content

Textural class, soil water content, soil hydraulic properties and van Genuchten equation parameters for each soil layer are shown in Table 2. The soil texture of experimental area is classified as sandy with the following mean textural composition: 89.3% sand, 4.1% silt and 6.3% clay. For the soil profile from 0.20 to 1.20 m, soil water content at field capacity – \(\theta_f\) (0.33 bar) and soil water content at permanent wilting point – \(\theta_w\) (15 bar) had mean values of 0.126 cm³/cm³ and 0.044 cm³/cm³, respectively. Except for the irrigation treatment T1, the first soil layer (0–0.20 m) had soil water content \((\theta)\) values higher than \(\theta_f\). The values of \(\theta_w\) were always lower than \(\theta\) for all irrigation treatments and soil depths. The values of \(\theta_r\), \(\theta_c\) and \(\theta_w\) decreased from the upper layer (0–0.20 m) to the bottom layer (0.80–1.20 m) as a result of the soil physical characteristics of the experimental area. Also, \(\theta_w\) values are less variable than those of \(\theta_r\) for all irrigation treatments.

Fig. 2 shows the change in soil water content with soil depth for all irrigation treatments as well as the field capacity at the experimental site. Linear functions were fitted to the relationships between \(\theta\) and soil depths. There were clear differences among lines of soil water contents, mainly for the treatment T4. For all irrigation treatments, the water productivity (irrigation plus rainfall) exceeded the CET (Tables 3 and 4), implying a large amount of deep percolation. Ben-Asher and Ayars (1990), examining the deep seepage under nonuniform sprinkler irrigation, reported that water applied in excess of the daily transpiration rate is lost as deep percolation. These authors also observed that for a given amount of water, high irrigation uniformity is associated with a small amount of deep percolation, and low uniformity with a large amount of percolation. Most treatments have \(\theta_r\) near or above of \(\theta_c\). Both \(\theta_c\) and \(\theta_w\) for irrigation treatments T2, T3 and T4 showed good correlation with soil depths (statistically significant at \(p < 0.05\)). Only for irrigation treatment T1, the \(\theta\) values drop well below \(\theta_c\) in all soil depths as a consequence of the lower water level applied in this irrigation treatment. On the other hand, \(\theta\) at irrigation treatments T2 and T3 was higher than \(\theta_c\) only at the first soil layer (0–0.20 m), as a result of the sandy textural composition. Inversely, \(\theta\) at treatment T4 was lower than \(\theta_c\) only at the (0.8–1.0 m) soil layer. Values of \(\theta_w\) in the control irrigation treatment were quite high for all soil depths as a consequence of the high irrigation frequency. This result is in agreement with that reported by Zhang et al. (2004), who...
Table 2

<table>
<thead>
<tr>
<th>Soil layer (m)</th>
<th>Textural class</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
<th>cm&lt;sub&gt;3&lt;/sub&gt; cm&lt;sup&gt;-3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00–0.20</td>
<td>91.5</td>
<td>5.0</td>
<td>3.5</td>
<td>0.122</td>
<td>0.151</td>
<td>0.135</td>
<td>0.140</td>
<td>0.134</td>
<td>0.059</td>
</tr>
<tr>
<td>0.20–0.40</td>
<td>89.3</td>
<td>5.5</td>
<td>5.0</td>
<td>0.102</td>
<td>0.127</td>
<td>0.131</td>
<td>0.145</td>
<td>0.134</td>
<td>0.043</td>
</tr>
<tr>
<td>0.60–0.80</td>
<td>89.0</td>
<td>2.0</td>
<td>9.0</td>
<td>0.077</td>
<td>0.086</td>
<td>0.096</td>
<td>0.112</td>
<td>0.112</td>
<td>0.037</td>
</tr>
<tr>
<td>0.80–1.20</td>
<td>87.0</td>
<td>4.1</td>
<td>6.3</td>
<td>0.084</td>
<td>0.093</td>
<td>0.111</td>
<td>0.112</td>
<td>0.039</td>
<td>0.046</td>
</tr>
<tr>
<td>Average</td>
<td>89.3</td>
<td>5.5</td>
<td>5.0</td>
<td>0.112</td>
<td>0.140</td>
<td>0.135</td>
<td>0.140</td>
<td>0.134</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Irrigation treatments: T1 = 70%; T2 = 80%; T3 = 90%; T4 = 100% of ET<sub>o</sub> (control); sc = soil water content; F = soil water content at field capacity; wilt = soil water content at permanent wilting point; d = bulk density; K<sub>u</sub> = saturated soil hydraulic conductivity; o = saturated soil hydraulic conductivity; r = residual soil water content; α, n and the van Genuchten equation parameters.

Table 4 shows the yield (Y) and water-use efficiency (WUE) for four irrigation treatments as well as the irrigation and rainfall amounts during the experimental period. The total rainfall values were 42%, 37%, 23% and 28% of the irrigation water amounts in treatments T1, T2, T3 and T4, respectively. The values of Y, when converted into fruits weight per plant, resulted in values of 147.4 Kg, 149.8 Kg, 155.3 Kg and 140.3 Kg per plant, respectively. González et al. (2004) observed that the yield of mangoes, planted at a density of 100 trees/ha and grown in northern Australia, varied from 23.3 kg to 48.4 kg per plant. These values were much lower than those found in our study because the yield of cv. Kensington is considered to be one of the lowest in the world. Mean values Y were relatively high in all irrigation treatments. It was found a difference of 3.0 ton/ha between the treatment T3 and T4, which is statistically significant at 5% significance level according to Turkey’s test.

The mango yield in treatment T3 was 11% higher than that obtained in the control irrigation treatment (T4). By studying the impact of differences in land supplying conditions and management on the productivity of mango orchards in Thailand, de Bie (2004) reported a fruit yield of 25 ton/ha. Except for treatment T1, the WUE values based on evapotranspiration were approximately 2.2% higher than those based on irrigation. Results suggest that there was no significant effect of water level change on WUE<sub>T</sub> and WUE<sub>I</sub>. However, analysis of variance indicated significant statistical differences (p < 0.05) between the yield values for T4 and other irrigation treatments. Our results suggest that the traditional farmer’s water management practices are inappropriate for the study region.

The relationship between irrigation treatments and mango yield is best described by a quadratic function (Fig. 3). The determination coefficient (r<sup>2</sup> = 0.85) was statistically significant (p < 0.05) by t-test. Mango yield was maximum at T3 treatment.
Kang et al. (2002) found a quadratic relationship between wheat yield and biomass as well as between WUE and evapotranspiration. Al-Omran et al. (2005) showed a linear relationship between squash fruit yield and four irrigation regimes at surface and subsurface under different amendment types, with determination coefficients ranging from 0.67 to 0.97.

4. Conclusions

This paper presents results from a study the response of mangoes to different irrigation treatment. Four levels of irrigation water were applied to replicated blocks, soil water contents were monitored to deduce crop water-use, and yields were measured. From the results of this study it was possible to conclude that mango evapotranspiration and water-use efficiency are strongly influenced by the soil water level. Soil water content in the first soil layer of the control irrigation treatment was significantly higher than that of the other soil depths and water levels. The mango yield and the water-use efficiency were significantly different as irrigation treatments change from T1 (70% of ET₀) to T3 (90% of ET₀). The yield values are highest in irrigation treatment T3 and the lowest in the control irrigation treatment (100% of ET₀). Therefore, water-use efficiency in the study region can be improved by irrigation scheduling using the irrigation treatment T3 (90% of ET₀). An increase in irrigation water volume does not result in increase in mango fruits yield.

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