Potential climate change impacts on citrus water requirement across major producing areas in the world
Ali Fares, Haimanote K. Bayabil, Mongi Zekri, Dirceu Mattos-Jr and Ripendra Awal

ABSTRACT

Understanding how potential climate change will affect availability of water resources for citrus production globally is needed. The main goal of this study is to investigate impacts of potential future climate change on citrus irrigation requirements (IRR) in major global citrus producing regions, e.g., Africa, Asia, Australia, Mediterranean, Americas. The Irrigation Management System (IManSys) model was used to calculate optimum IRR for the baseline period (1986–2005) and two future periods (2055s and 2090s) subject to combination of five and seven temperature and precipitation levels, respectively. Predicted IRR show significant spatio-temporal variations across study regions. Future annual IRR are predicted to globally decrease; however, future monthly IRR showed mixed results. Future evapotranspiration and IRR are projected to decrease by up to 12 and 37%, respectively, in response to increases in CO2 concentration. Future citrus canopy interception and drainage below citrus rootzones are expected to slightly increase. Annual rainfall changes are negatively correlated with changes in IRR. These projections should help the citrus industry better understand potential climate change impacts on citrus IRR and major components of the water budget. Further studies are needed to investigate how these potential changes in CO2 concentration, temperature, evapotranspiration, rainfall, and IRR will affect citrus yield and its economic impact on the citrus industry.

Key words | citrus, climate change, IManSys, irrigation water requirement

INTRODUCTION

Citrus is one of the major fruit crops covering significant agricultural areas globally (Liu et al. 2012). While global citrus production was projected to decrease in 2016 compared with 2015 (USDA 2016), in 2015, Brazil, China, and the USA were the top citrus fruit producing countries in the world (USDA 2015). The citrus industry contributes considerably to national gross domestic products (GDPs) of several countries. For example, in the state of Florida, Hodges et al. (2014), in their economic impact analysis study, estimated that citrus fruit production contributed 3.82 billion USD from a total of 156 million boxes of citrus fruit produced during the 2012/2013 production season. While the citrus industry significantly contributes to local, national, and global economies, its production consumes considerable amounts of fresh water resources, which makes the industry compete for available fresh water resources with other major water users, e.g., production of other crops, domestic and industrial uses, and ecosystems services.
In addition, the citrus industry is also facing critical challenges, including the wide spread of diseases and pests (e.g., citrus greening, citrus canker), which results in major damage to citrus production and in economic losses (Schubert et al. 2001; Gottwald et al. 2002; Das 2003; Hodges & Spreen 2006). For example, the 2015/16 global orange production was predicted to decrease by 3.0 million metric tons, where significant yield reduction was expected in some of the major producing regions (e.g., Brazil, USA, and South Africa) (USDA 2016). Moreover, the interaction of projected increases in temperature and reduction in rainfall, in most parts of the globe, due to climate change will certainly have a significant impact on available fresh water resources. Expected increases in climate variability, severe droughts, and recurrent floods will certainly have both direct and indirect effects on the environment and natural resources (Hulme et al. 1999; McGeeth & Mirabelli 2001; Haines et al. 2006; O’Sullivan 2013). The hydrologic cycle will be likely among the key ecosystem processes that will be adversely affected by climate change (Arnell 1999; Agarwal et al. 2014; Hassan et al. 2014). This will lead to more competition for available fresh water resources between different water user groups, which could be even further aggravated by uncertainties in the extent and intensity of climate change.

Climate change and variability not only affect available water resources directly but also affect crop physiological characteristics, mainly due to increases in CO₂ concentration, which in turn affect photosynthetic processes. Understanding the potential impacts of increased CO₂ concentration in the atmosphere on plant physiology and thus agriculture has attracted attention (Allen et al. 1991; Wullschleger et al. 2002; Ficklin et al. 2010; Hussain et al. 2013), and studies have shown that an increase in atmospheric CO₂ concentration not only results in an increase in air temperature but also affects leaf stomata conductance and consequently evapotranspiration processes (Allen et al. 1998, 1991; Ficklin et al. 2010; Hussain et al. 2013; Fares et al. 2016).

In order for the citrus industry to continue to be economically viable, there is a need to better understand how potential future climate would affect availability of fresh water resources for the industry in the mid and long future periods: 2055s (2046–2065) and 2090s (2081–2100) compared with the baseline period (1986–2005) (Du Plessis 1985; Morgan et al. 2007; Villalobos et al. 2009). Such information would shed more light on the extent of potential challenges and help the citrus industry plan short-term mitigation measures and long-term adaptation strategies.

Understanding how potential climate change affects the availability of water resources and major components of the water budget is critical (Ficklin et al. 2010; Fares et al. 2016). Therefore, the objectives of this study are to (1) calculate current citrus irrigation requirements and (2) predict how potential climate change scenarios would affect citrus IRR and other field water budget components, e.g., effective rainfall (ER), evapotranspiration (ETa), canopy interception (INT), drainage (DR), and runoff (RO) across the major producing regions in the world.

**MATERIALS AND METHODS**

**Study sites**

This study was conducted in selected locations of the major citrus producing regions across the world: Africa (Cape Town, South Africa), Asia (Mersin, Turkey), Australia (Riverland, Australia), Mediterranean (Nabeul, Tunisia), North America (Riverside, California; Fort Pierce and Lake Alfred, Florida; and Brownsville, Texas), and South America (Sao Paulo, Brazil) (Figure 1). For this work, the study sites were chosen with the underlying objective to represent most of the major citrus producing regions according to the report by the United States Department of Agriculture (USDA 2016). However, it is also worth noting that this study does not include some of the leading citrus producing countries (e.g., China).

**Input data**

Daily precipitation, minimum temperature (Tmin), maximum temperature (Tmax), and wind speed data were obtained from the National Centers for Environmental Prediction – Climate Forecast System Reanalysis (NCEP-CFSR) global weather data (http://globalweather.tamu.edu/) for the baseline period (1986–2005). The baseline period was chosen based on the Intergovernmental Panel on Climate Change – Fifth Assessment Report (Stocker et al. 2013). Daily evapotranspiration data were computed.
using the modified FAO Penman–Monteith equation (Allen et al. 1998), built in the IManSys model (discussed in detail in the section below), which accounts for changes in CO₂ concentration.

Available soil water content (AWC, cm³ cm⁻³) was computed using the pedo-transfer function (Gupta & Larson 1979) based on Equation (1):

\[ \theta_p = a \times \text{sand (\%)} + b \times \text{silt (\%)} + c \times \text{clay (\%)} + d \times \text{organic matter (\%)} + e \times \rho_b (\text{g/cm}^3) \]  

(1)

where \( \theta_p \) is predicted water content (cm³ cm⁻³) at a given matric potential, \( \rho_b \) (g cm⁻³) is bulk density, and \( a, b, c, d, \) and \( e \) are regression equation fitting coefficients that were obtained from Gupta & Larson (1979) for the major soil type of the locations represented in this study.

Available water content was calculated as the difference between water content at field capacity (FC: \( \theta_p \) at 33 kPa) and permanent wilting point (PWP: \( \theta_p \) at 1,500 kPa).

Soil information used to calculate soil hydraulic properties was obtained from the FAO harmonized world soil database v 1.2 (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/).

**Irrigation Management System (IManSys) model**

The Irrigation Management System (IManSys), a numerical hydrologic simulation model (Fares & Fares 2012), was used to calculate optimum irrigation water requirements of citrus across some of the major citrus producing regions represented in this study. In addition, the model calculates the major components of the field water balance (runoff, drainage, and canopy interception). The model employs the water balance approach to simulate IRR at two layers of the soil profile. The model requires inputs related to plant water update parameters, plant root distribution, soil physical properties, irrigation system efficiency, growing season, climate and basic irrigation management practices. Additional details about the IManSys model and how it calculates the daily water balance for specific crops can be found in Fares & Fares (2012). A summary of IManSys model inputs is presented in Table 1. The major components of the soil water budget and IRR are linked through the following equations (Equations (2) and (3)):

\[ \Delta S = P + G_w + IRR_{net} - (Q_d + Q_s + ET_c + I) \]  

(2)

\[ IRR = \frac{IRR_{net}}{(1 - LR) \times f_i} = \frac{ET_c + \Delta S + Q_s + Q_d + I - (P + G_w)}{(1 - LR) \times f_i} \]  

(3)

where \( \Delta S \) is change in soil water storage (mm), \( P \) is total rainfall (mm), \( G_w \) is shallow groundwater contribution (mm), \( IRR_{net} \) is net irrigation water requirement (mm), \( Q_d \) is groundwater drainage (mm), \( Q_s \) is surface water runoff (mm), \( ET_c \) is plant evapotranspiration (mm), \( I \) is the
canopy rainfall interception (mm), $LR$ is leaching requirement to avoid salt buildup in the root zone, and $f_i$ is irrigation efficiency.

The modified FAO Penman–Monteith equation was used to account for the effect of changes in CO$_2$ concentration in future periods (Equation (4)) on future $ETo$ values. Detailed information about the modification of $(γs/γa)$ can be found in Allen et al. (1998) and Fares et al. (2016):

$$ETo = \frac{0.408Δ (Rn - G) + γ(900/T + 273)u2(e_s - e_a)}{Δ + γ(1 + (γs/γa))}$$

where $ETo$ is daily reference evapotranspiration (mm d$^{-1}$), $Rn$ is daily net radiation at the crop surface (MJ m$^{-2}$ d$^{-1}$), $G$ is soil heat flux density (MJ m$^{-2}$ d$^{-1}$), $T$ is mean daily air temperature at 2 m height (°C), $u2$ is wind speed at 2 m height (m s$^{-1}$), $e_s$ is saturation vapour pressure (kPa), $e_a$ is actual vapor pressure (kPa), $e_s - e_a$ is saturation vapour pressure deficit (kPa), $Δ$ is slope of vapour pressure curve (kPa °C$^{-1}$), $γ$ is psychrometric constant (kPa °C$^{-1}$), and $(γs/γa)$ is a function of wind speed at 2 m height (0.34 $u_2$) that accounts for CO$_2$ concentration in the FAO Penman–Monteith equation.

**Table 1** | IManSys model inputs of soil, crop, and irrigation parameters

<table>
<thead>
<tr>
<th>Location</th>
<th>Irrigation system</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownsville</td>
<td>Flood</td>
<td>Laredo</td>
</tr>
<tr>
<td>Lake Alfred</td>
<td>Micro sprinkler</td>
<td>Candler sand</td>
</tr>
<tr>
<td>Fort Pierce</td>
<td>Micro sprinkler</td>
<td>Mayakka</td>
</tr>
<tr>
<td>Nabeul</td>
<td>Drip</td>
<td>Calcaric Regosols</td>
</tr>
<tr>
<td>Sao Paulo</td>
<td>Drip</td>
<td>Haplic Ferralsols</td>
</tr>
<tr>
<td>Cape Town</td>
<td>Drip</td>
<td>Lithic Leptosols</td>
</tr>
<tr>
<td>Riverland</td>
<td>Drip</td>
<td>Calcaric Regosols</td>
</tr>
<tr>
<td>Riverside</td>
<td>Drip</td>
<td>Greenfield</td>
</tr>
<tr>
<td>Mersin</td>
<td>Drip</td>
<td>Chromic Luvisols</td>
</tr>
</tbody>
</table>

**Results and Discussion**

**Climate change scenarios**

Potential future climate change scenarios for two future periods 2055s (2046–2065) and 2090s (2081–2010) were generated based on the baseline climate records that cover the period 1986–2005. Six precipitation levels were prepared for the two future periods by adjusting daily precipitation records of the baseline period by $±5$, $±10$, and $±20\%$. Similarly, baseline minimum and maximum temperature records were adjusted by adding $±1$, $±1.4$, and $±1.3$ °C in 2055s and $±1$, $±1.8$, and $±2.2$ °C in 2090s to reflect projected changes in global mean temperature under three representative concentration pathways (RCPs): RCP 2.6, RCP 4.5, and RCP 6.0 of the Intergovernmental Panel on Climate Change – Fifth Assessment Report (IPCC–AR5), respectively. The RCPs represent changes in radiative forcing values of $±2.6$, $±4.5$, and $±6.0$ W m$^{-2}$, respectively (Table 2).

**Table 2** | Projected increases in mean air temperature under different RCPs and corresponding CO$_2$ levels for two future periods

<table>
<thead>
<tr>
<th>RCP</th>
<th>2055s</th>
<th>2090s</th>
<th>CO$_2$ equiv. (ppm)</th>
<th>Key features</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP 2.6</td>
<td>1.0</td>
<td>1.0</td>
<td>490</td>
<td>Peak and decline, which leads to very low greenhouse gas concentration</td>
</tr>
<tr>
<td>RCP 4.5</td>
<td>1.4</td>
<td>1.8</td>
<td>650</td>
<td>Stabilization scenario, radiative forcing is stabilized before 2100</td>
</tr>
<tr>
<td>RCP 6.0</td>
<td>1.3</td>
<td>2.2</td>
<td>850</td>
<td>Stabilization scenario, radiative forcing is stabilized after 2100</td>
</tr>
</tbody>
</table>

Sources: Moss et al. (2010) and Stocker et al. (2013).
results for Sao Paulo concur with the reports of other studies (e.g., Liebmann et al. 2001; Silva Dias et al. 2013; Coelho et al. 2016). Riverside receives the smallest rainfall (332 mm yr\(^{-1}\)) and \(E_{\text{T}}\) was significantly greater than rainfall for about ten months of the year (Figure 2). Annual \(E_{\text{T}}\) was greatest in Brownsville with 1,641 mm yr\(^{-1}\), while the smallest ET was in Cape Town (1,080 mm yr\(^{-1}\)). Overall, annual rainfall was smaller than annual evapotranspiration for six of the nine locations of the study, which in turn would lead to a deficit in soil moisture unless supplied with irrigation (Table 3). This is in agreement with a previous work that reported \(E_{\text{T}}\) as the major component of the hydrologic cycle (Liu et al. 2010). On the other hand, recent studies also show that irregular precipitation distribution throughout the growing season results in water deficit that could be a critical issue even in regions where rainfall is comparatively higher such as Sao Paulo (Coelho et al. 2016).

**Table 3** | Annual average summary of climate characteristics of studied locations (based on 1986–2005 data)

<table>
<thead>
<tr>
<th>Location</th>
<th>Tmin (°C)</th>
<th>Tmax (°C)</th>
<th>P (mm)</th>
<th>(E_{\text{T}}) (mm)</th>
<th>Deficit (P-(E_{\text{T}})) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownsville</td>
<td>20.7</td>
<td>29.5</td>
<td>1,023.4</td>
<td>1,641.1</td>
<td>-617.7</td>
</tr>
<tr>
<td>Cape Town</td>
<td>13.8</td>
<td>20.7</td>
<td>651.3</td>
<td>1,079.8</td>
<td>-428.5</td>
</tr>
<tr>
<td>Fort Pierce</td>
<td>22.2</td>
<td>29.0</td>
<td>1,931.9</td>
<td>1,423.4</td>
<td>508.5</td>
</tr>
<tr>
<td>Lake Alfred</td>
<td>17.2</td>
<td>27.7</td>
<td>1,972.3</td>
<td>1,412.0</td>
<td>560.3</td>
</tr>
<tr>
<td>Mersin</td>
<td>8.4</td>
<td>18.9</td>
<td>973.6</td>
<td>1,166.4</td>
<td>-192.8</td>
</tr>
<tr>
<td>Nabeul</td>
<td>15.9</td>
<td>22.7</td>
<td>531.4</td>
<td>1,165.9</td>
<td>-634.5</td>
</tr>
<tr>
<td>Riverland</td>
<td>11.4</td>
<td>24.0</td>
<td>367.3</td>
<td>1,344.9</td>
<td>-977.6</td>
</tr>
<tr>
<td>Riverside</td>
<td>10.0</td>
<td>25.1</td>
<td>331.7</td>
<td>1,452.4</td>
<td>-1,120.6</td>
</tr>
<tr>
<td>Sao Paulo</td>
<td>15.0</td>
<td>23.9</td>
<td>2,015.3</td>
<td>1,288.5</td>
<td>726.9</td>
</tr>
</tbody>
</table>
Model outputs

Evapotranspiration is the major component of the water budget in all study sites (Figure 3). Moreover, owing to variations in climatic parameters (rainfall, evapotranspiration, and temperature), effective rainfall (ER), gross irrigation requirement (IRR), and drainage (DR) showed significant differences across the studied locations. Evapotranspiration results are in agreement with findings of other studies that reported evapotranspiration as the major component of the hydrologic cycle (Liu et al. 2010). Overall, effective rainfall, gross irrigation requirement, and evapotranspiration are predicted to decrease in the 2055s and 2090s compared with the baseline period, regardless of geographic location. However, while the reduction in ER, IRR, and ET₀ were significant in 2055s and 2090s compared to baseline, the differences between the two future periods (2055s and 2090s) were relatively small (Figure 3). On the other hand, canopy interception and drainage are expected to show a slight increase during the two future periods compared with the baseline. Runoff losses were insignificant across locations. Overall, Riverside has the greatest IRR, while Sao Paulo had the smallest during the baseline period; this trend, for IRR, is projected to continue in the mid and end of the 21st century. Our results were in agreement with Fares et al. (2016), who reported a reduction in ET₀ and IRR with an increase in CO₂ concentrations for seed corn and coffee in Hawaii. Similarly, several studies reported a projected reduction in ET₀ with increases in CO₂ concentration (Allen et al. 1991; Lockwood 1999). Hussain et al. (2015) also reported that elevated CO₂ concentration resulted in
a significant reduction in ETₐ for a C4 crop (maize) compared to a C3 crop (soybean). This finding concurs with previous reports by several authors who argued that an increase in atmospheric CO₂ concentration would trigger plant stomata closure and thereby lead to a reduction in ETₐ (Medlyn et al. 2001; Wullschleger et al. 2002; Shams et al. 2012). Medlyn et al. (2001), in their meta-analysis study, showed that stomatal conductance of woody species showed up to a 21% reduction in response elevated CO₂ concentration. Allen et al. (2011) found that elevated CO₂ concentration enhanced water use efficiency of maize and sorghum plants at early crop growth season. They suggested that CO₂ concentration could potentially ameliorate drought stress on C4 crops. Similarly, Kimball (2016) suggested that CO₂ concentration increase. Fader et al. (2016) estimated that gross irrigation requirements would increase between 4 and 18% due to climate change in the Mediterranean regions by 2085s. Similarly, Lee & Huang (2014) and Rodríguez Díaz et al. (2007) reported increases in irrigation requirement, due to climate change, in northern Taiwan and Spain, respectively.

Moreover, monthly IRR reduction will not occur at a constant rate throughout the year and across the study sites (Figure 4(a)). While overall average IRR is projected to decrease in the 2055s and 2090s compared with the baseline, there will also be some increases in monthly IRR during some months of the year in most study sites (e.g., during November in Sao Paulo, and February and November in Nabeul) (Figure 4(a)). In Nabeul, Tunisia, IRR is predicted to increase by up to 100% during February and November both in 2055s and 2090s, while during January IRR is predicted to decrease by up to 50% (Figure 4(a)). Similarly, a greater decrease in ETₐ is predicted in the 2055s than in the 2090s compared with the baseline period (Figure 4(b)). Additionally, while ETₐ is projected to consistently decrease throughout the year in all study sites, the magnitude of reduction varies between months (Figure 4(b)). Overall, greater reductions in IRR and ETₐ are projected in the 2055s compared to 2090s with respect to the baseline.

Seasonal variations of irrigation requirement and evapotranspiration between representative concentration pathways

Projected changes in IRR and ETₐ between RCPs show great seasonal variability (Figure 5(a) and 5(b)).

Significant decreases in both IRR and ETₐ are predicted to occur at higher CO₂ concentrations (RCP 6.0) compared with the baseline, wherein most locations’ IRR and ETₐ are predicted to have smaller values than the baseline, except a few exceptions for IRR where slight increases in IRR were projected during some months of the year (during November in Mersin, and February and November in Nabeul) compared with the baseline. Our results are in agreement with the findings of Allen et al. (1991) and Fares et al. (2016), who observed a significant reduction in ETₐ and IRR under elevated CO₂ concentrations. However, on the other hand, Wullschleger et al. (2002) argued that hydrological response of plants to CO₂ concentration is affected by the temporal and spatial scale of observation.

Overall, while future annual average IRR and ETₐ are projected to show slight decreases under RCP 2.6, their values are within the same order of magnitude as those for the baseline, especially in the humid subtropical areas of the globe, i.e., Fort Pierce, Lake Alfred, and Sao Paulo. The significant reduction of ETₐ in response to elevated CO₂ concentration is clearly shown in Figure 6, where significantly smaller ETₐ was predicted under the highest CO₂ concentration scenario (RCP 6.0, CO₂ = 850 ppm) of this study. Ramirez & Finnerty (1996) argued that elevated CO₂ concentration will have a beneficial effect on irrigated agriculture by improving water use efficiency of crops.

Effect of temperature on major components of the water budget

Under the baseline greenhouse gas emission scenario (with an average CO₂ concentration of 360 ppm), an increase in temperature will result in an increase in ETₐ and thereby IRR, regardless of the geographic location of the study (Table 4). In agreement with this, Allen et al. (1998) reported that air temperature, among other climatic variables, regulates ETₐ by controlling moisture-holding capacity of the air and soil vapor fluxes. Similarly, Allen (1999) reported
Figure 4 | Predicted changes in monthly irrigation requirement (IRR) (a) and evapotranspiration (ETo) (b) for the two future periods (2055s and 2090s) compared with the baseline (1986–2005).
Figure 5 | Differences in monthly changes in irrigation requirement (IRR) (a) and evapotranspiration (ET\textsubscript{A}) (b) between representative concentration pathways (RCPs).
that evapotranspiration will increase about 4 to 5% per 1 °C rise in temperature under well-watered conditions. However, the effect of an increase in temperature was greater in humid areas (e.g., Sao Paulo) where an increase in average temperature by 1 °C will result on average in an 8% increase of IRR. The effect of temperature was smaller in Riverside and Riverland where an average increase of IRR by 3% is projected due to an increase in average temperature by 1 °C. A study by Vara Prasad et al. (2005) showed that while elevated CO₂ concentration increases crop yield under normal conditions, the beneficial effects of elevated CO₂ are significantly offset by negative effects of high temperature on yield and yield-components beyond optimum temperature.

It is worth mentioning that in humid areas where overall IRR is smaller (e.g., Sao Paulo), a small increase in IRR will result in greater percentage changes (Table 4 and Figure 7(a)). Similarly, an increase in temperature under the baseline CO₂ concentration (360 ppm) will result in an increase in ET₀ (Figure 7(b)), while DR and INT will slightly decrease in some places or remain constant (Figure 7(c) and 7(d)). Our findings concur with those of Fares et al. (2016), who found similar results for different crops (seed corn and coffee).
Nevertheless, in the two future periods (2055s and 2090s), an increase in CO₂ concentration will mask the effect of temperature and will result in an overall decrease in IRR and ETo (Figure 7(a) and 7(b)), while DR and INT will increase (Figure 7(c) and 7(d)). However, the magnitude of increase in DR and INT due to an increase in CO₂ concentration in the 2055s and 2090s varies significantly between study sites, where greater increases are projected in the humid areas of the study, Fort Pierce, Lake Alfred, and Sao Paulo compared with the other locations (Figure 7(c) and 7(d)). This clearly shows that the magnitude of the effect of climate change varies depending on the climate condition of the location under consideration.

**Effect of rainfall on major components of the water budget**

In general, as expected, reduction in rainfall will result in an increase in IRR across all study sites (Figure 8(a)). However, a change in rainfall will have a significant effect on IRR in humid regions (i.e., Fort Pierce, Lake Alfred, and Sao Paulo), where, for example, in Sao Paulo, a 20% reduction in rainfall would result in a 40% reduction in IRR under RCP 6.0. In contrast, however, in arid areas (e.g., Riverside), the effect of rainfall is relatively negligible compared with other locations. Surprisingly, a 20% reduction in rainfall under higher CO₂ concentration (RCP 6.0) scenario will still result in a decrease in IRR compared with that of the baseline. This indicates, at higher CO₂ concentrations, the effect of CO₂ is dominant over the change in rainfall. This is also clearly visible in Figure 8(b), where the effect of rainfall was masked by higher CO₂ concentrations, and changes in ET₀ were only observed between RCPs. On the other hand, an increase in rainfall and CO₂ concentration will have a positive effect on DR and INT (Figure 8(c) and 8(d)). However, the effect of CO₂ concentration on DR was not as significant as it is on IRR and ET₀. In most places, a unit change in rainfall will result on average in a two-fold increase or decrease in DR in the direction of change in rainfall (Figure 8(c)).

**CONCLUSIONS**

This study investigated the impacts of potential future climate change on citrus water requirements in major citrus producing regions across the world, e.g., Africa (Cape Town, South Africa), Asia (Mersin, Turkey), Australia (Riverland, Australia), Mediterranean (Nabeul, Tunisia), North America (Riverside, California; Fort Pierce and Lake Alfred, Florida; and Brownsville, Texas), and South America (Sao Paulo, Brazil).

Current IRR or water footprint of citrus shows considerable variations across the study sites. While evapotranspiration is dominant in regulating the hydrologic cycle, it is predicted to consistently decrease in all locations, on average, by up to 12 and 11% in the 2055s and 2090s, respectively. Overall, decreases in IRR at greater CO₂ concentrations were associated with decreases in ET₀, regardless of geographic locations. Under the same CO₂ concentration, however, an increase in temperature leads to increases in both ET₀ and IRR. Canopy interception and drainage will slightly increase under all RCPs at all locations, while runoff will not show a significant change.

While annual IRR is predicted to decrease consistently both during the 2055s and 2090s in all locations, monthly changes in IRR compared with the baseline showed mixed results, especially under RCPs 2.6 and 4.5, where increases in IRR were predicted during some months of the year.

<table>
<thead>
<tr>
<th>Location</th>
<th>Baseline IRR (mm)</th>
<th>Change in annual IRR (%)</th>
<th>+1°C</th>
<th>+1.3°C</th>
<th>+1.4°C</th>
<th>+1.8°C</th>
<th>+2.2°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownsville</td>
<td>1,208</td>
<td>4.1</td>
<td>5.3</td>
<td>5.8</td>
<td>7.6</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>Cape Town</td>
<td>874</td>
<td>4.5</td>
<td>5.8</td>
<td>6.8</td>
<td>8.1</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Fort Pierce</td>
<td>522</td>
<td>6.1</td>
<td>8.0</td>
<td>8.4</td>
<td>10.9</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>Lake Alfred</td>
<td>573</td>
<td>5.1</td>
<td>6.5</td>
<td>7.2</td>
<td>9.4</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Mersin</td>
<td>804</td>
<td>3.1</td>
<td>5.2</td>
<td>6.6</td>
<td>8.5</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>Nabeul</td>
<td>999</td>
<td>3.4</td>
<td>5.4</td>
<td>6.2</td>
<td>7.4</td>
<td>8.7</td>
<td></td>
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<tr>
<td>Riverland</td>
<td>1,315</td>
<td>3.3</td>
<td>4.2</td>
<td>4.4</td>
<td>5.9</td>
<td>7.5</td>
<td></td>
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<tr>
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<td>1,535</td>
<td>2.9</td>
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<td>5.3</td>
<td>6.5</td>
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<tr>
<td>Sao Paulo</td>
<td>353</td>
<td>9.1</td>
<td>10.8</td>
<td>10.8</td>
<td>13.6</td>
<td>13.3</td>
<td></td>
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</tbody>
</table>

Results are based on combined data from all precipitation change scenarios for the baseline period.

Table 4 | Effect of temperature on citrus irrigation requirement under current (baseline) greenhouse emission scenario (360 ppm)
Figure 7 | Effect of temperature on projected major water budget components in the 2055s and 2090s: (a) irrigation requirement (IRR), (b) evapotranspiration (ET), (c) drainage (DR), and (d) canopy interception (INT). Results are based on combined data from all precipitation scenarios. (Continued.)
Figure 7 | Continued.
Figure 8: Effect of change in rainfall on the major components of the water budget under different representative concentration pathways (RCPs) compared with the baseline: (a) irrigation requirement (IRR), (b) evapotranspiration (ETo), (c) drainage (DR), and (d) canopy interception (INT). (Continued.)
Figure 8 | Continued.
Results from this study underscore the importance of accounting for changes in CO₂ concentration and climate. This study also provides insights into how projected increases in atmospheric CO₂ concentration and temperature interact and affect major components of the water budget and citrus irrigation requirements. Such results are essential in the global efforts of planning climate change adaptation and mitigation strategies for the citrus industry. However, further studies are needed to investigate how citrus yield would respond under potential climate change, including an economic analysis.

ACKNOWLEDGEMENTS

This work was supported by the USDA National Institute of Food and Agriculture, Evans-Allen project 2014-35100-08916 and project Agrilife-M 1700130 funded by Texas A&M AgriLife.

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First received 26 December 2016; accepted in revised form 13 May 2017. Available online 7 August 2017