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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 CO_2 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 CO_2 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

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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 signficantly 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.

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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; McGeehin & Mirabelli 2001; Haines *et al.* 2006; O'Sullivan 2015). 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 CO_2 concentration, which in turn affect photosynthetic processes. Understanding the potential impacts of increased CO_2 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 CO_2 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 (ET_o), 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

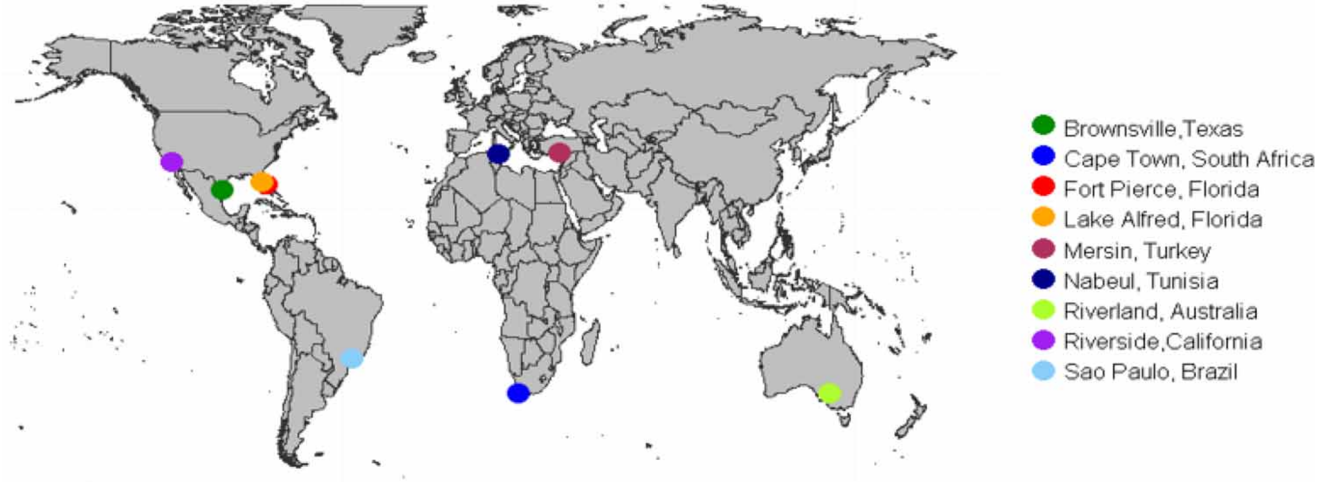


Figure 1 | Map of the locations used in this study which represent the major citrus producing areas across the world.

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 CO_2 concentration.

Available soil water content (AWC, $cm^3\ cm^{-3}$) was computed using the pedo-transfer function (Gupta & Larson 1979) based on Equation (1):

$$\theta_p = a \text{ x sand (\%)} + b \text{ x silt (\%)} + c \text{ x clay (\%)} + d \text{ x organic matter (\%)} + e \text{ x } \rho_b (\text{g/cm}^3) \quad (1)$$

where θ_p is predicted water content ($cm^3\ cm^{-3}$) at a given matric potential, ρ_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: θ_p at 33 kPa) and permanent wilting point (PWP: θ_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)):

$$\Delta S = P + G_w + IRR_{net} - (Q_d + Q_r + ET_c + I) \quad (2)$$

$$IRR = \frac{IRR_{net}}{(1 - LR) \times f_i} = \frac{ET_c + \Delta S + Q_r + Q_d + I - (P + G_w)}{(1 - LR) \times f_i} \quad (3)$$

where ΔS 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_r is surface water runoff (mm), ET_c is plant evapotranspiration (mm), I is the

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

	Parameter	
Location	**Irrigation system**	**Soil type**
Brownsville	Flood	Laredo
Lake Alfred	Micro sprinkler	Candler sand
Fort Pierce	Micro sprinkler	Mayakka
Nabeul	Drip	Calcaric Regosols
Sao Paulo	Drip	Haplic Ferralsols
Cape Town	Drip	Lithic Leptosols
Riverland	Drip	Calcic Xerosols
Riverside	Drip	Greenfield
Mersin	Drip	Chromic Luvisols

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 ET_o values. Detailed information about the modification of (γ_s/γ_a) can be found in Allen *et al.* (1998) and Fares *et al.* (2016):

$$ET_o = \frac{0.408\Delta\,(R_n - G) + \gamma(900/T + 273)u_2(e_s - e_a)}{\Delta + \gamma(1 + (\gamma_s/\gamma_a))} \quad (4)$$

where ET_o is daily reference evapotranspiration (mm d^{-1}), R_n 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), u_2 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 (γ_s/γ_a) 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.

Climate change scenarios

Potential future climate change scenarios for two future periods 2055s (2046–2065) and 2090s (2081–2100) 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).

RESULTS AND DISCUSSION

Climate characteristics

Analysis of 20 years (1986–2005) minimum and maximum temperatures, and precipitation provided useful information about climate variables in the study locations. As expected, the selected study sites have different climates (Figure 2). Annual rainfall distribution was not uniform across the months; most of the locations have a unimodal rainfall distribution (Figure 2). Sao Paulo receives the highest rainfall (2,016 mm yr^{-1}) (Table 3) and monthly rainfall was greater than corresponding evapotranspiration (Figure 2). Our

Table 2 | Projected increases in mean air temperature under different RCPs and corresponding CO_2 levels for two future periods

	Change in mean temperature (°C)			
RCP	**2055s**	**2090s**	**CO_2 equiv. (ppm)**	**Key features**
RCP 2.6	1.0	1.0	490	Peak and decline, which leads to very low greenhouse gas concentration
RCP 4.5	1.4	1.8	650	Stabilization scenario, radiative forcing is stabilized before 2100
RCP 6.0	1.3	2.2	850	Stabilization scenario, radiative forcing is stabilized after 2100

Sources: Moss *et al.* (2010) and Stocker *et al.* (2013).

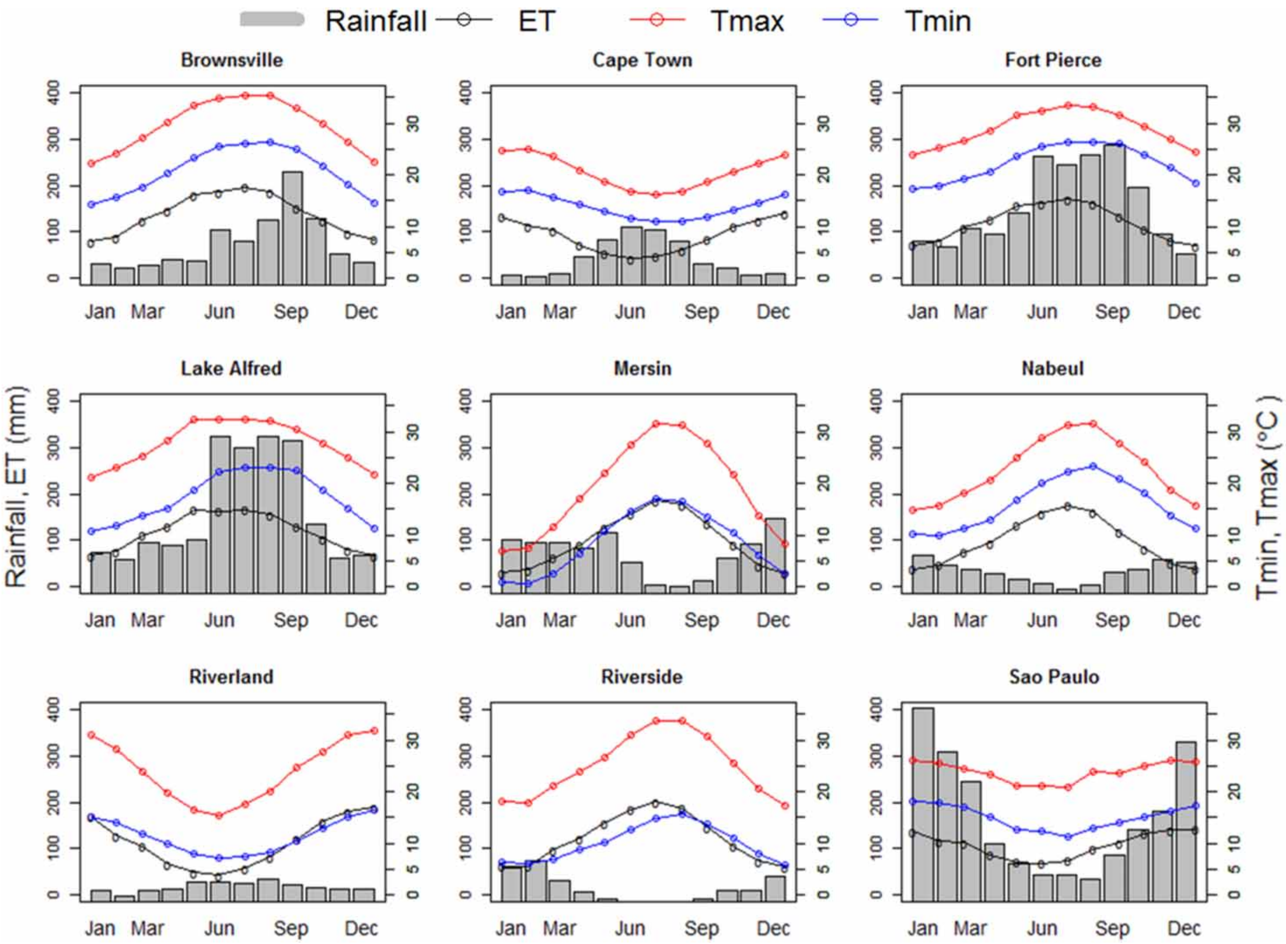


Figure 2 | Seasonal climate characteristics of study sites for the baseline period (1986–2005).

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 ET_o was significantly greater than rainfall for about ten months of the year (Figure 2). Annual ET_o 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 ET_o 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)

Location	Tmin (°C)	Tmax (°C)	P (mm)	ET_o (mm)	Deficit (P-ET_o) (mm)
Brownsville	20.7	29.5	1,023.4	1,641.1	−617.7
Cape Town	13.8	20.7	651.3	1,079.8	−428.5
Fort Pierce	22.2	29.0	1,931.9	1,423.4	508.5
Lake Alfred	17.2	27.7	1,972.3	1,412.0	560.3
Mersin	8.4	18.9	973.6	1,166.4	−192.8
Nabeul	15.9	22.7	531.4	1,165.9	−634.5
Riverland	11.4	24.0	367.3	1,344.9	−977.6
Riverside	10.0	25.1	331.7	1,452.4	−1,120.6
Sao Paulo	15.0	23.9	2,015.5	1,288.5	726.9

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 ET_o 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 ET_o and IRR with an increase in CO_2 concentrations for seed corn and coffee in Hawaii. Similarly, several studies reported a projected reduction in ET_o with increases in CO_2 concentration (Allen *et al.* 1991; Lockwood 1999). Hussain *et al.* (2013) also reported that elevated CO_2 concentration resulted in

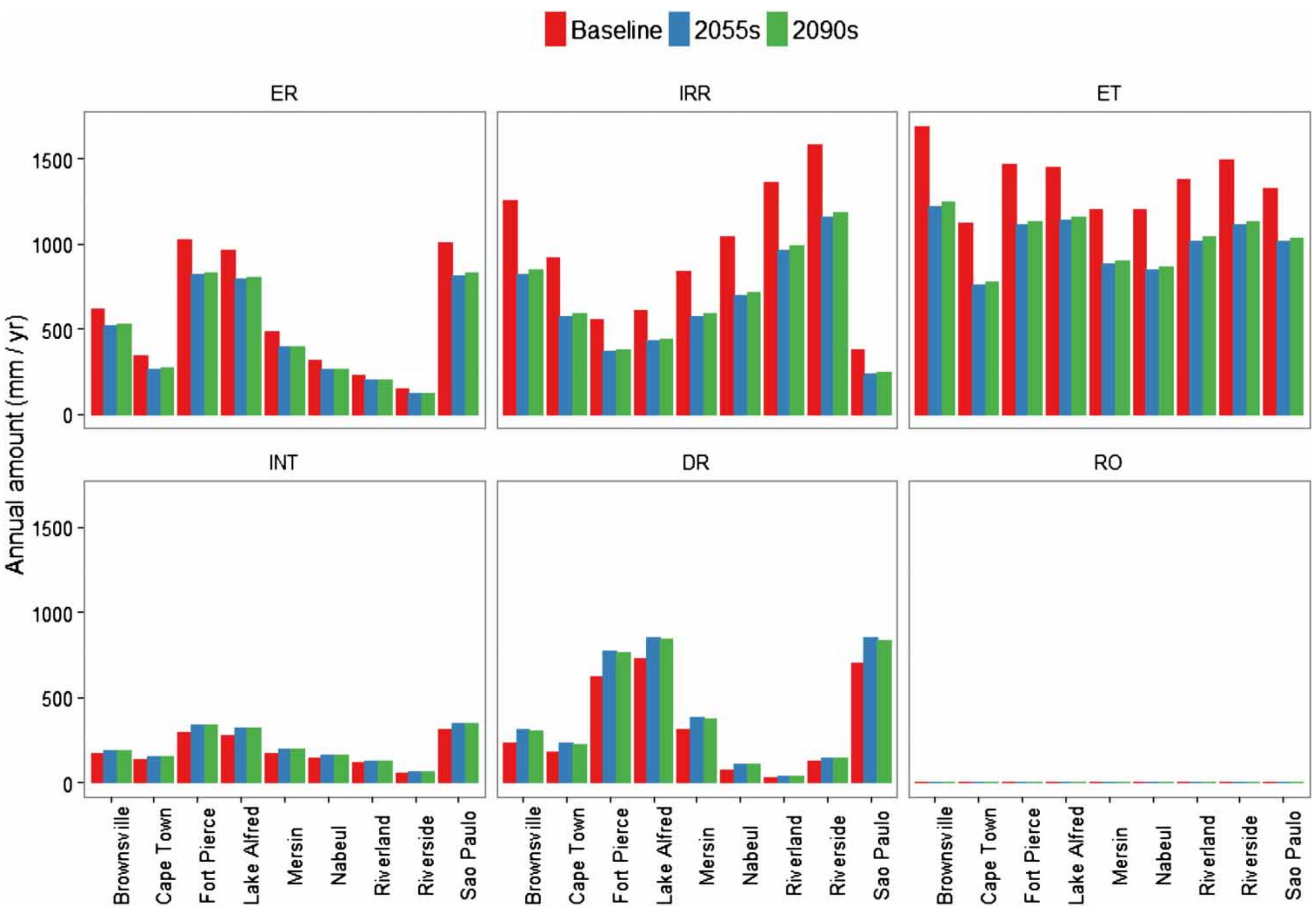


Figure 3 | Model output summary for major water budget components by study site. Results are based on combined temperature and precipitation scenarios.

a significant reduction in ET_o 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 CO_2 concentration would trigger plant stomata closure and thereby lead to a reduction in ET_o (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 CO_2 concentration. Allen *et al.* (2011) found that elevated CO_2 concentration enhanced water use efficiency of maize and sorghum plants at early crop growth season. They suggested that CO_2 concentration could potentially ameliorate drought stress on C4 crops. Similarly, Kimball (2016) reported that an incrase in CO_2 concentration from 353 to 550 ppm resulted in a 10% reduction in evapotranspiration. In contrast, however, studies in different parts of the world projected increases in ET_o and IRR in response to CO_2 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 ET_o is predicted in the 2055s than in the 2090s compared with the baseline period (Figure 4(b)). Additionally, while ET_o 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 ET_o 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 ET_o between RCPs show great seasonal variability (Figure 5(a) and 5(b)).

Significant decreases in both IRR and ET_o are predicted to occur at higher CO_2 concentrations (RCP 6.0) compared with the baseline, wherein most locations' IRR and ET_o 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 ET_o and IRR under elevated CO_2 concentrations. However, on the other hand, Wullschleger *et al.* (2002) argued that hydrological response of plants to CO_2 concentration is affected by the temporal and spatial scale of observation.

Overall, while future annual average IRR and ET_o 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 ET_o in response to elevated CO_2 concentration is clearly shown in Figure 6, where significantly smaller ET_o was predicted under the highest CO_2 concentration scenario (RCP 6.0, $CO_2 = 850$ ppm) of this study. Ramirez & Finnerty (1996) argued that elevated CO_2 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 CO_2 concentration of 360 ppm), an increase in temperature will result in an increase in ET_o 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 ET_o by controlling moisture-holding capacity of the air and soil vapor fluxes. Similarly, Allen (1999) reported

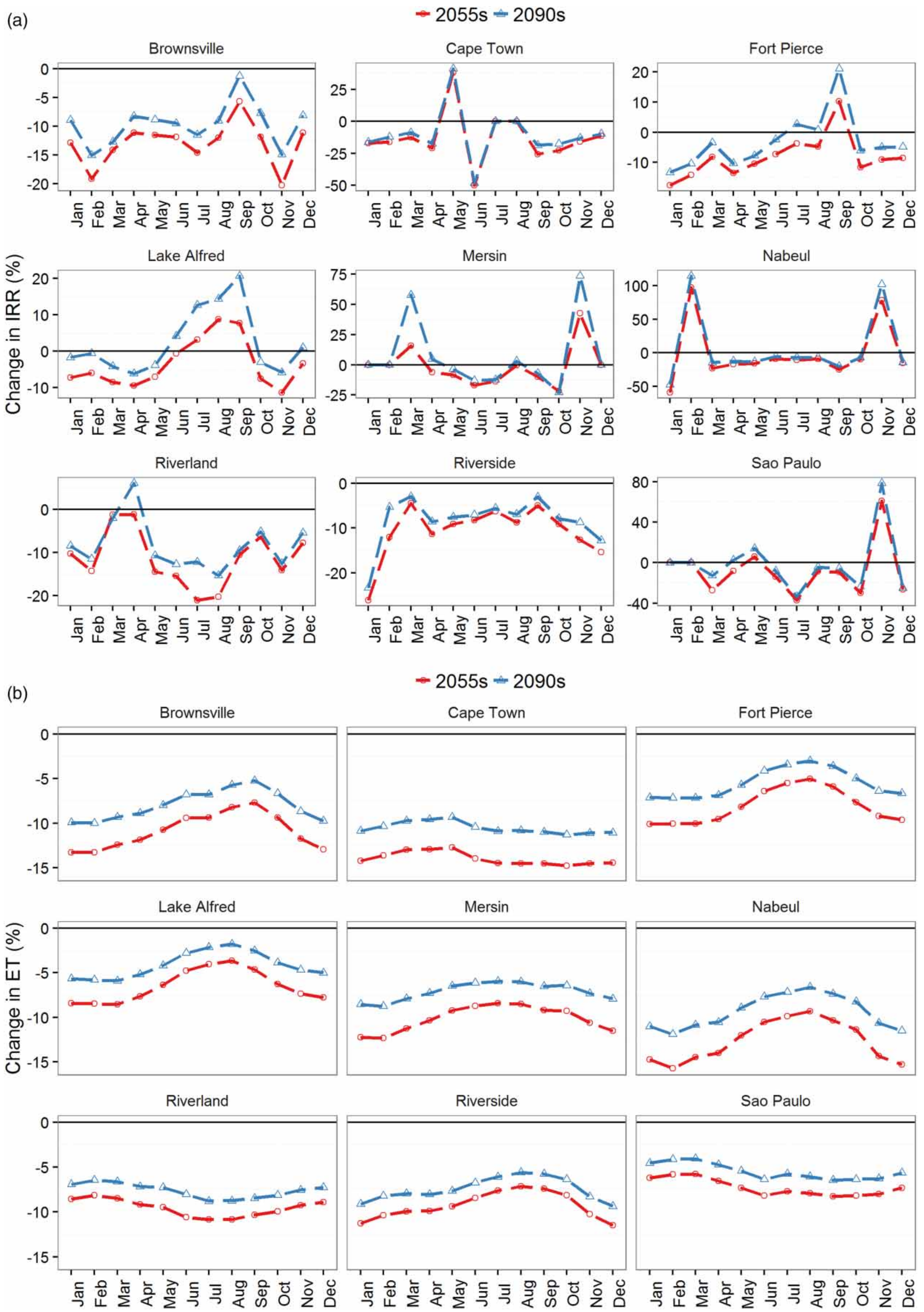


Figure 4 | Predicted changes in monthly irrigation requirement (IRR) (a) and evapotranspiration (ET_o) (b) for the two future periods (2055s and 2090s) compared with the baseline (1986–2005).

Figure 5 | Differences in monthly changes in irrigation requirement (IRR) (a) and evapotranspiration (ET_o) (b) between representative concentration pathways (RCPs).

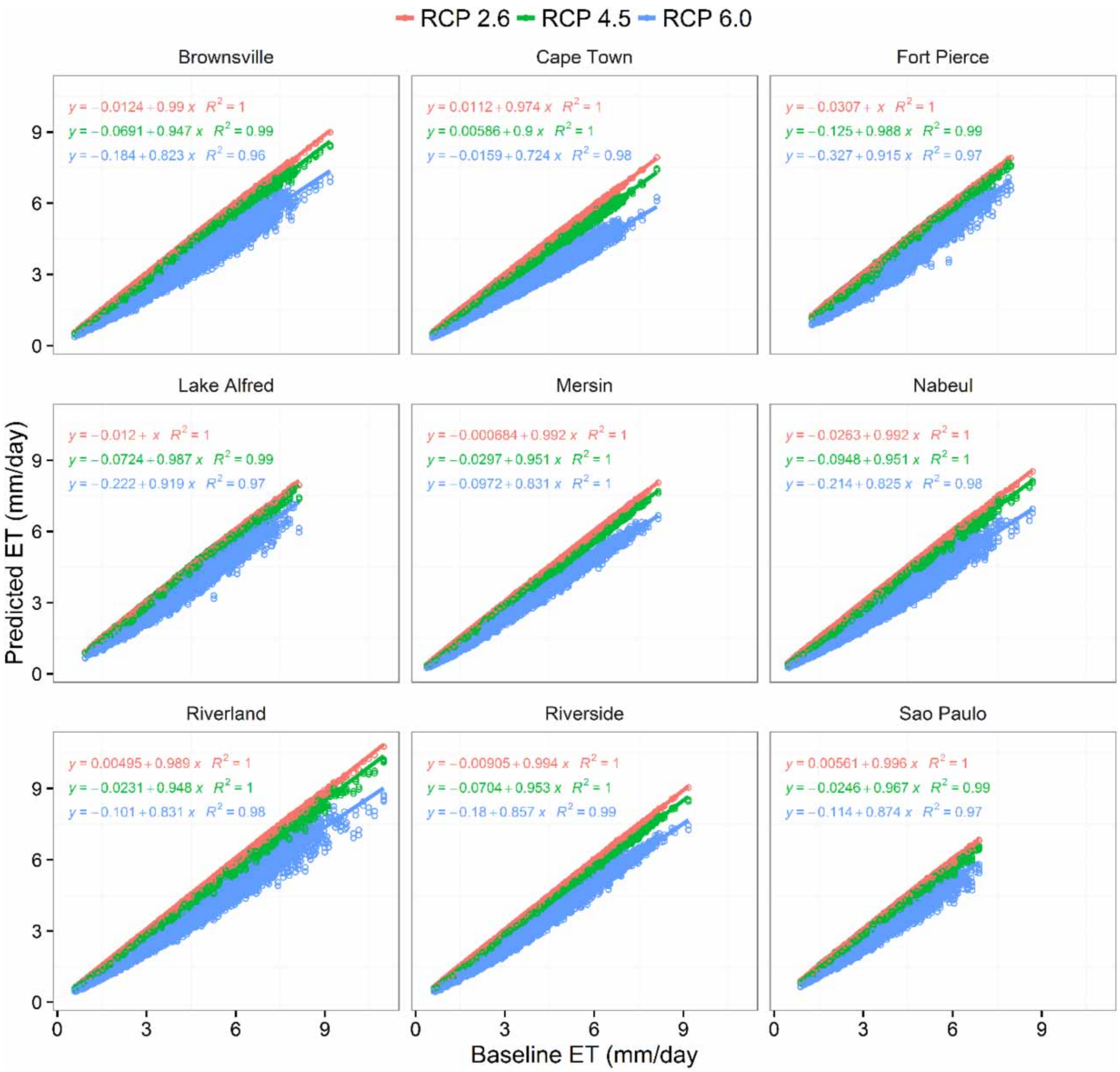


Figure 6 | Correlation between baseline evapotranspiration and predicted evapotranspiration under different representative concentration pathways (RCPs). Results are based on combined data from all precipitation scenarios.

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 CO_2 concentration increases crop yield under normal conditions, the beneficial effects of elevated CO_2 are signficantly 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 CO_2 concentration (360 ppm) will result in an increase in ET_o (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).

Table 4 | Effect of temperature on citrus irrigation requirement under current (baseline) greenhouse emission scenario (360 ppm)

Location	Baseline IRR (mm)	Change in annual IRR (%)				
		+1 °C	+1.3 °C	+1.4 °C	+1.8 °C	+2.2 °C
Brownsville	1,208	4.1	5.3	5.8	7.6	9.5
Cape Town	874	4.5	5.8	6.8	8.1	9.6
Fort Pierce	522	6.1	8.0	8.4	10.9	12.5
Lake Alfred	573	5.1	6.5	7.2	9.4	11.5
Mersin	804	3.1	5.2	6.6	8.5	9.5
Nabeul	999	3.4	5.4	6.2	7.4	8.7
Riverland	1,315	3.3	4.2	4.4	5.9	7.5
Riverside	1,535	2.9	3.7	4.2	5.3	6.5
Sao Paulo	353	9.1	10.8	10.8	13.6	13.3

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

Nevertheless, in the two future periods (2055s and 2090s), an increase in CO_2 concentration will mask the effect of temperature and will result in an overall decrease in IRR and ET_o (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 CO_2 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

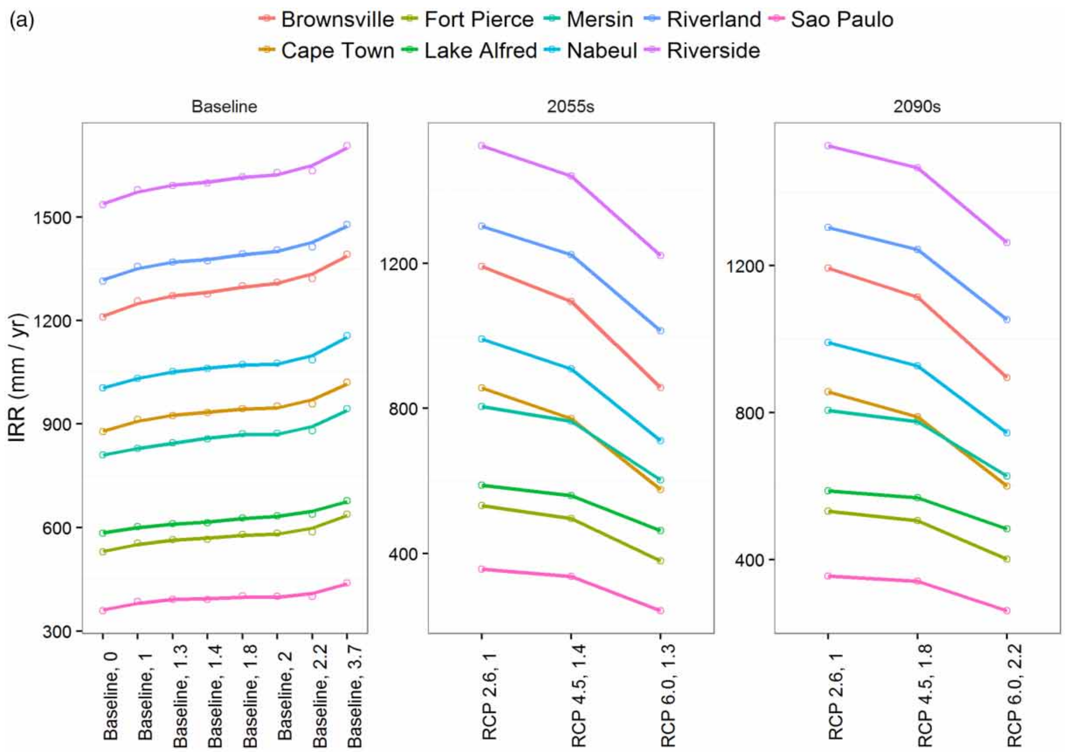
In general, as expected, reduction in rainfall will result in an increase in IRR across all study sites (Figure 8(a)). However, a change in rainfall will have a significant effect on IRR in humid regions (i.e., Fort Pierce, Lake Alfred, and Sao Paulo), where, for example, in Sao Paulo, a 20% increase 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 CO_2 concentration (RCP 6.0) scenario will still result in a decrease in IRR compared with that of the baseline. This indicates, at higher CO_2 concentrations, the effect of CO_2 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 CO_2 concentrations, and changes in ET_o were only observed between RCPs. On the other hand, an increase in rainfall and CO_2 concentration will have a positive effect on DR and INT (Figure 8(c) and 8(d)). However, the effect of CO_2 concentration on DR was not as significant as it is on IRR and ET_o. 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 CO_2 concentrations were associated with decreases in ET_o, regardless of geographic locations. Under the same CO_2 concentration, however, an increase in temperature leads to increases in both ET_o 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.



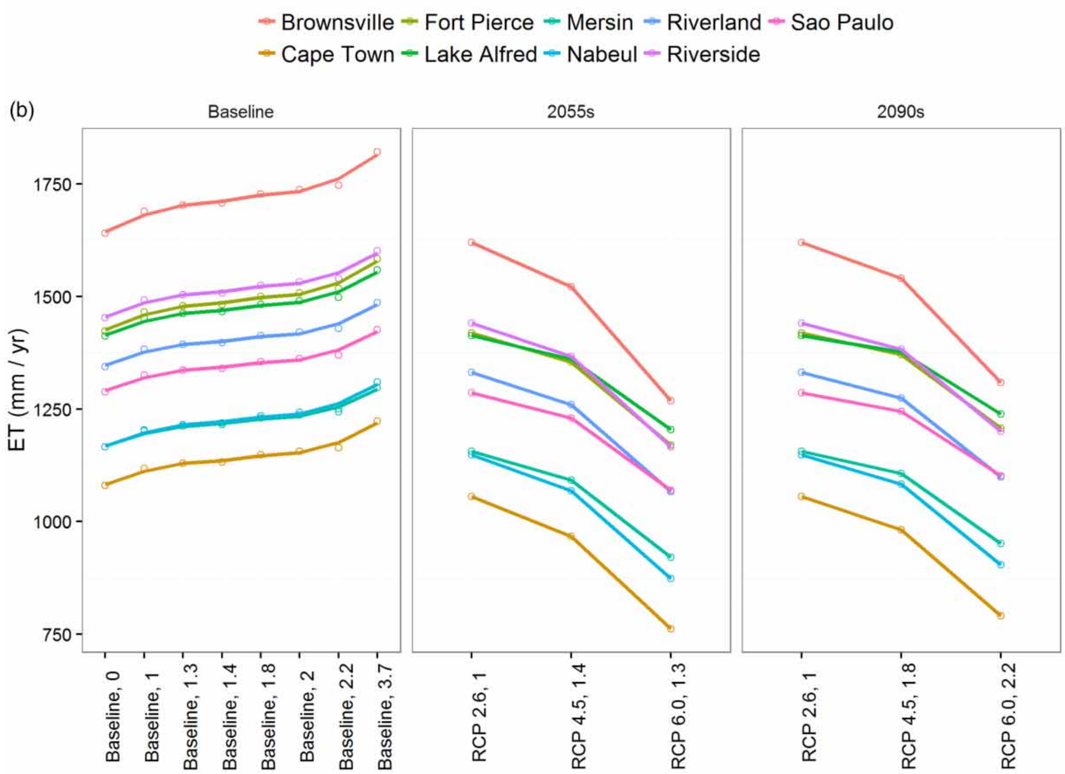


Figure 7 | Effect of temperature on projected major water budget components in the 2055s and 2090s: (a) irrigation requirement (IRR), (b) evapotranspiration (ET_O), (c) drainage (DR), and (d) canopy interception (INT). Results are based on combined data from all precipitation scenarios. *(Continued.)*

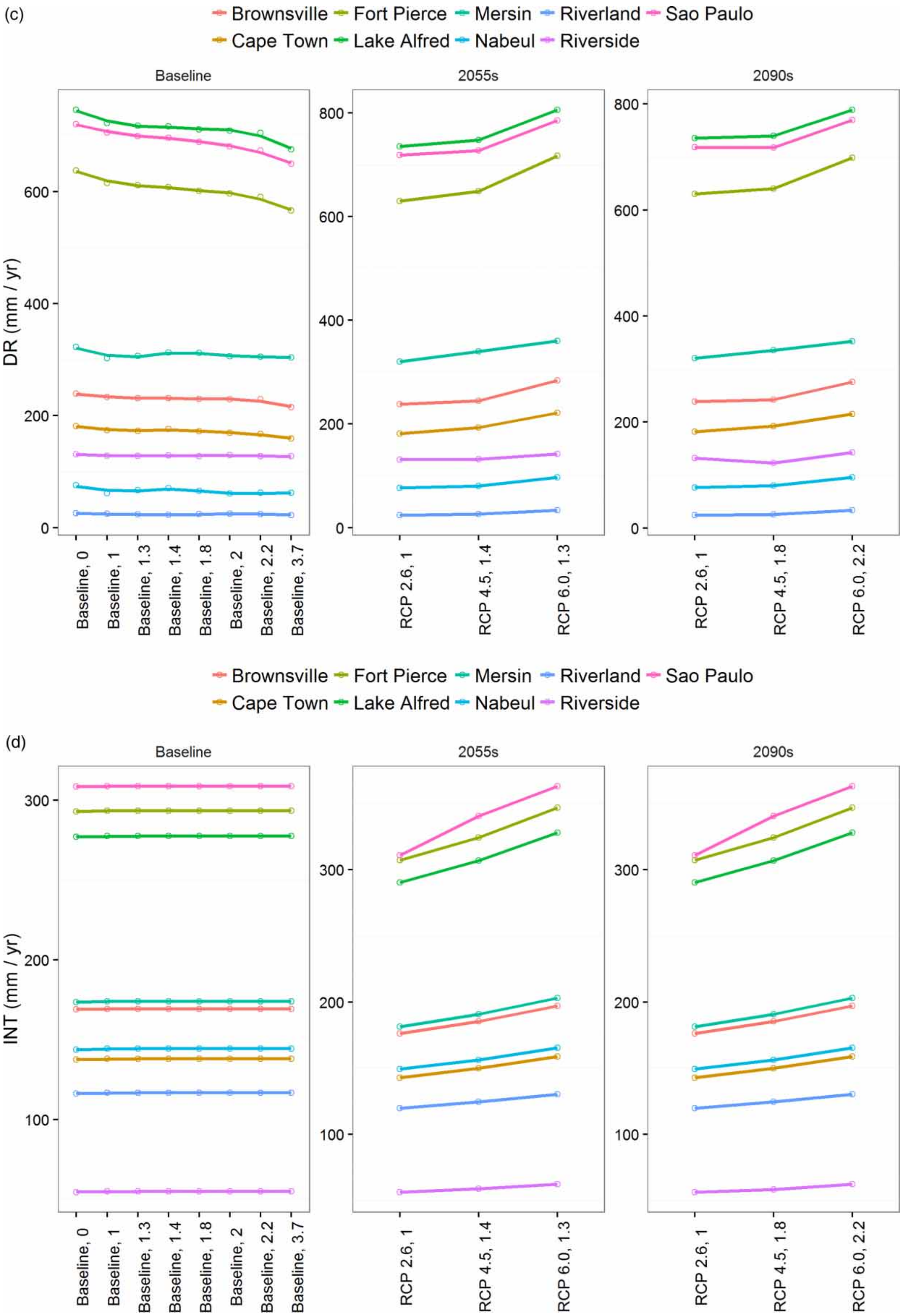


Figure 7 | Continued.

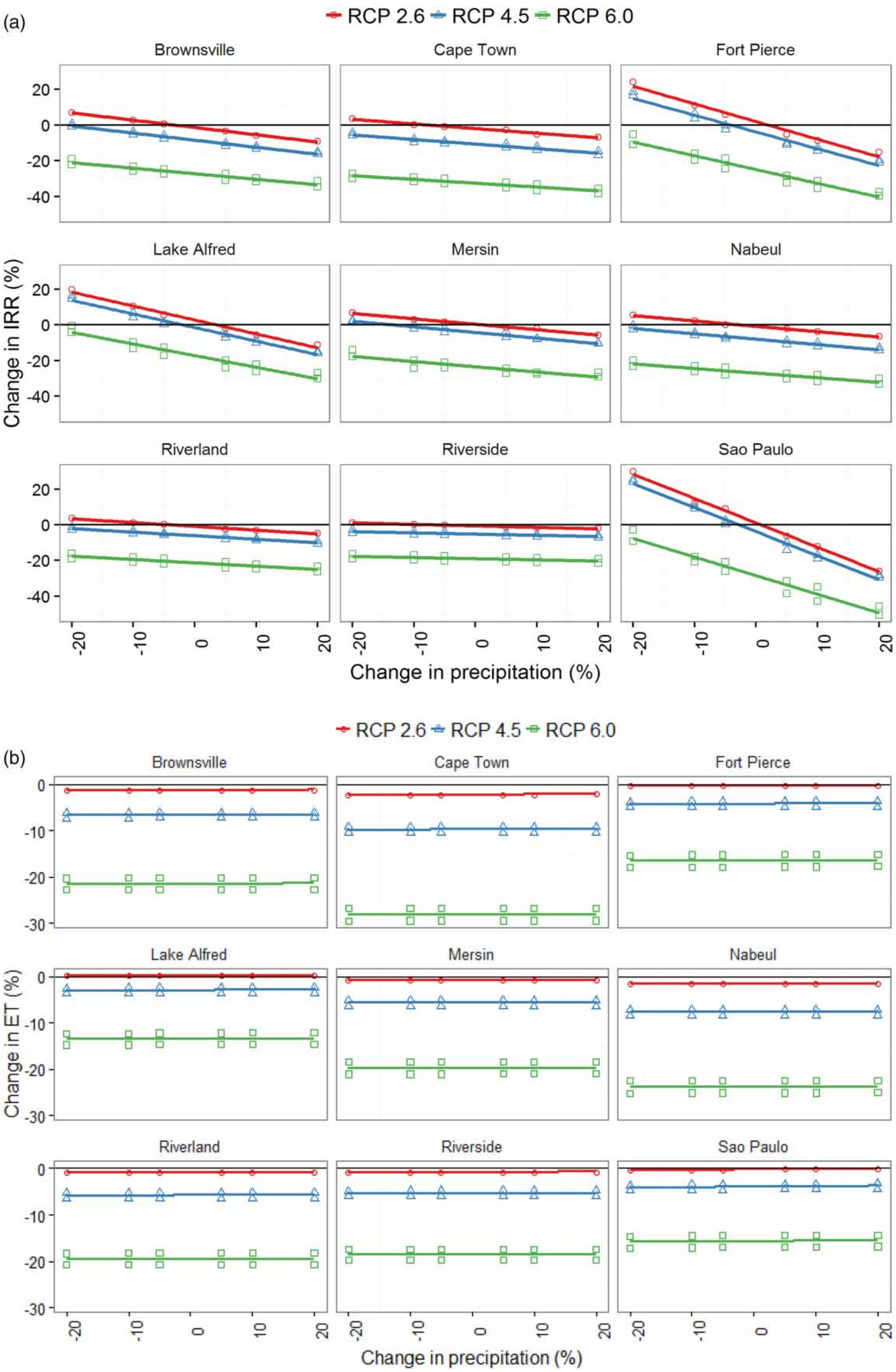
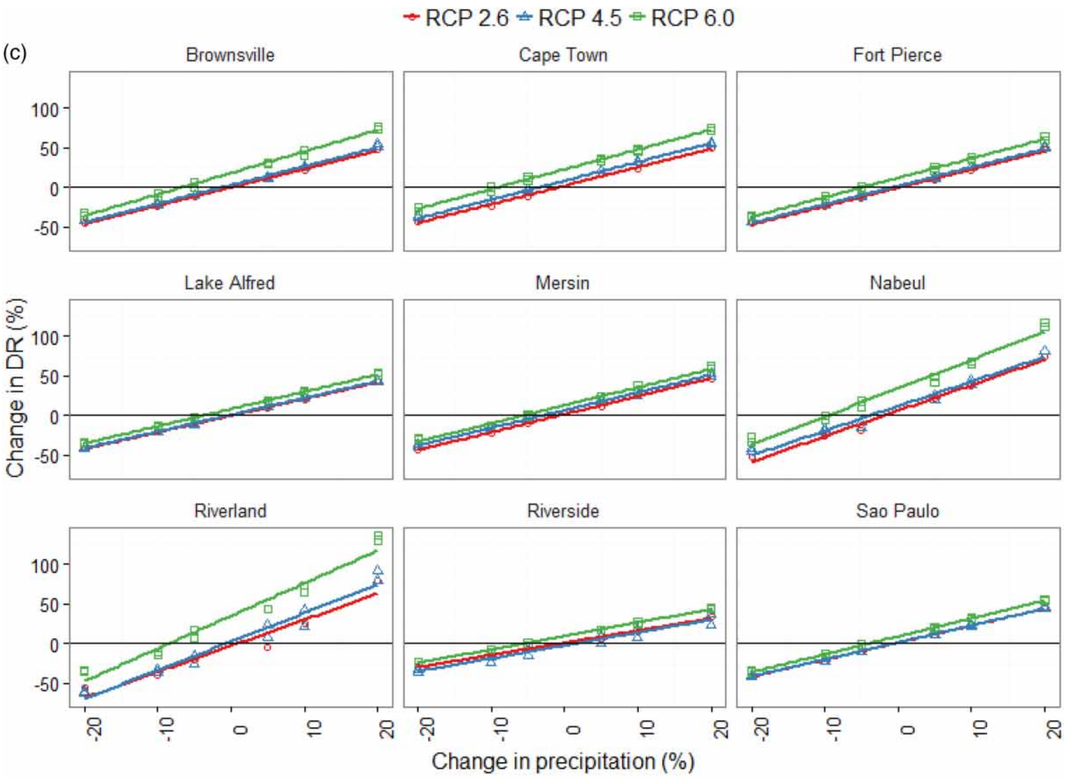


Figure 8 | Effect of change in rainfall on the major components of the water budget under different representative concentration pathways (RCPs) compared with the baseline: (a) irrigation requirement (IRR), (b) evapotranspiration (ET_O), (c) drainage (DR), and (d) canopy interception (INT). *(Continued.)*



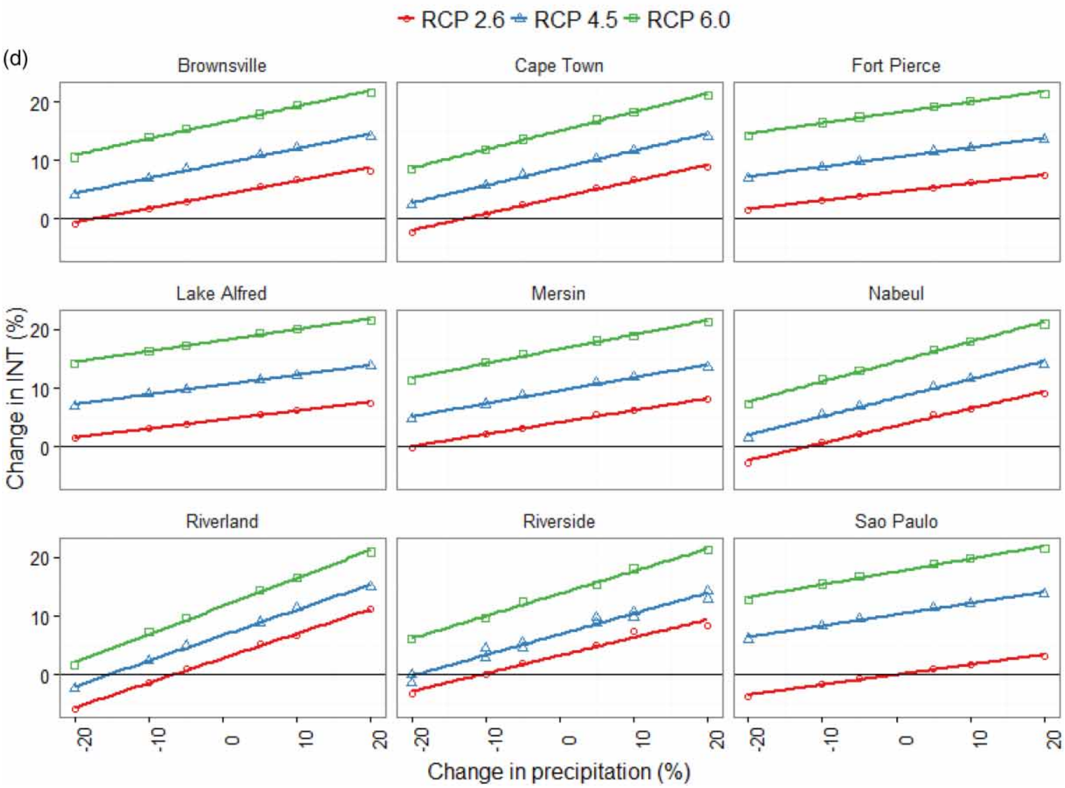


Figure 8 | Continued.

Results from this study underscore the importance of accounting the effects of CO_2 concentration in computing evapotranspiration rates. This study also provides insights into how projected increases in atmospheric CO_2 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.

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REFERENCES

Agarwal, A., Babel, M. S. & Maskey, S. 2014 Analysis of future precipitation in the Koshi river basin, Nepal. *J. Hydrol.* **513**, 422–434. doi:10.1016/j.jhydrol.2014.03.047.

Allen, L. H. 1999 Evapotranspiration responses of plants and crops to carbon dioxide and temperature. *J. Crop Prod.* **2**, 37–70. doi:10.1300/J144v02n02_02.

Allen, R. G., Gichuki, F. N. & Rosenzweig, C. 1991 CO_2-induced climatic changes and irrigation-water requirements. *J. Water Resour. Plan. Manag.* **117**, 157–178.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Allen, L. H., Kakani, V. G., Vu, J. C. V. & Boote, K. J. 2011 Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. *J. Plant Physiol.* **168**, 1909–1918. doi:10.1016/j.jplph.2011.05.005.

Arnell, N. W. 1999 Climate change and global water resources. *Glob. Environ. Change* **9**, S31–S49.

Coelho, C. A. S., Cardoso, D. H. F. & Firpo, M. A. F. 2016 Precipitation diagnostics of an exceptionally dry event in São Paulo, Brazil. *Theor. Appl. Climatol.* **125**, 769–784. doi:10.1007/s00704-015-1540-9.

Das, A. K. 2003 Citrus canker – a review. *J. Appl. Hortic.* **5**, 52–60.

Du Plessis, H. M. 1985 Evapotranspiration of citrus as affected by soil water deficit and soil salinity. *Irrig. Sci.* **6**, 51–61.

Fader, M., Shi, S., von Bloh, W., Bondeau, A. & Cramer, W. 2016 Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrol. Earth Syst. Sci.* **20**, 953–973. doi:10.5194/hess-20-953-2016.

Fares, A. & Fares, S. 2012 Irrigation Management System, IManSys, a user-friendly computer based water management software package. In: *The Irrigation Show and Education Conference*, Orlando, FL.

Fares, A., Awal, R., Fares, S., Johnson, A. B. & Valenzuela, H. 2016 Irrigation water requirements for seed corn and coffee under potential climate change scenarios. *J. Water Clim. Change* **7** (1), 39–51. doi:10.2166/wcc.2015.025.

Ficklin, D. L., Luedeling, E. & Zhang, M. 2010 Sensitivity of groundwater recharge under irrigated agriculture to changes in climate, CO_2 concentrations and canopy structure. *Agric. Water Manag.* **97**, 1039–1050. doi:10.1016/j.agwat.2010.02.009.

Gottwald, T. R., Graham, J. H. & Schubert, T. S. 2002 Citrus canker: the pathogen and its impact. *Plant Health Prog.* doi:10.1094/PHP-2002-0812-01-RV.

Gupta, S. & Larson, W. 1979 Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. *Water Resour. Res.* **15**, 1633–1635.

Haines, A., Kovats, R. S., Campbell-Lendrum, D. & Corvalan, C. 2006 Climate change and human health: impacts, vulnerability and public health. *Public Health* **120**, 585–596. doi:10.1016/j.puhe.2006.01.002.

Hassan, Z., Shamsudin, S. & Harun, S. 2014 Application of SDSM and LARS-WG for simulating and downscaling of rainfall and temperature. *Theor. Appl. Climatol.* **116**, 243–257. doi:10.1007/s00704-013-0951-8.

Hodges, A. W. & Spreen, T. H. 2006 *Economic Impacts of Citrus Greening (HLB) in Florida, 2006/7–2010/11.* Food and Resource Economics Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL.

Hodges, A., Rahmani, M., Stevens, T. & Spreen, T. 2014 *Economic Impacts of the Florida Citrus Industry in 2012–13.* University of Florida, Gainesville, FL.

Hulme, M., Mitchell, J., Ingram, W., Lowe, J., Johns, T., New, M. & Viner, D. 1999 Climate change scenarios for global impacts studies. *Glob. Environ. Change* **9**, S3–S19.

Hussain, M. Z., Van Loocke, A., Siebers, M. H., Ruiz-Vera, U. M., Cody Markelz, R. J., Leakey, A. D. B., Ort, D. R. & Bernacchi, C. J. 2013 Future carbon dioxide concentration decreases canopy evapotranspiration and soil water depletion by field-grown maize. *Glob. Change Biol.* **19**, 1572–1584. doi:10.1111/gcb.12155.

Kimball, B. A. 2016 Crop responses to elevated CO_2 and interactions with H_2O, N, and temperature. *Curr. Opin. Plant Biol.* **31**, 36–43. doi:10.1016/j.pbi.2016.03.006.

Lee, J.-L. & Huang, W.-C. 2014 Impact of climate change on the irrigation water requirement in Northern Taiwan. *Water* **6**, 3339–3361. doi:10.3390/w6113339.

Liebmann, B., Jones, C. & de Carvalho, L. M. 2001 Interannual variability of daily extreme precipitation events in the state of Sao Paulo, Brazil. *J. Clim.* **14**, 208–218.

Liu, W., Hong, Y., Khan, S. I., Huang, M., Vieux, B., Caliskan, S. & Grout, T. 2010 Actual evapotranspiration estimation for different land use and land cover in urban regions using Landsat 5 data. *J. Appl. Remote Sens.* **4**, 041873.

Liu, Y., Heying, E. & Tanumihardjo, S. A. 2012 History, global distribution, and nutritional importance of citrus fruits. *Compr. Rev. Food Sci. Food Saf.* **11**, 530–545. doi:10.1111/j.1541-4337.2012.00201.x.

Lockwood, J. G. 1999 Is potential evapotranspiration and its relationship with actual evapotranspiration sensitive to elevated atmospheric CO_2 levels? *Clim. Change* **41**, 193–212.

McGeehin, M. A. & Mirabelli, M. 2001 The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ. Health Perspect.* **109**, 185–189.

Medlyn, B. E., Barton, C. V. M., Broadmeadow, M. S. J., Ceulemans, R., De Angelis, P., Forstreuter, M., Freeman, M., Jackson, S. B., Kellomaki, S., Laitat, E., Rey, A., Roberntz, P., Sigurdsson, B. D., Strassemeyer, J., Wang, K., Curtis, P. S. & Jarvis, P. G. 2001 Stomatal conductance of forest species after long-term exposure to elevated CO_2 concentration: a synthesis. *New Phytol.* **149**, 247–264. doi:10.1046/j.1469-8137.2001.00028.x.

Morgan, K., Obreza, T. & Hanlon, E. 2007 Citrus water requirements: linking irrigation scheduling and fertilizer strategies. *Proc. Fla. State Hort. Soc.* **120**, 67–73.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. & Wilbanks, T. J. 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756. doi:10.1038/nature08823.

O'Sullivan, T. M. 2015 Environmental security is homeland security: climate disruption as the ultimate disaster risk multiplier. *Risk Hazards Crisis Public Policy* **6**, 183–222.

Ramirez, J. & Finnerty, B. 1996 CO_2 and temperature effects on evapotranspiration and irrigated agriculture. *J. Irrig. Drain. Eng.* **122**, 155–163.

Rodríguez Díaz, J. A., Weatherhead, E. K., Knox, J. W. & Camacho, E. 2007 Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. *Reg. Environ. Change* **7**, 149–159. doi:10.1007/s10113-007-0035-3.

Schubert, T. S., Rizvi, S. A., Sun, X., Gottwald, T. R., Graham, J. H. & Dixon, W. N. 2001 Meeting the challenge of eradicating citrus canker in Florida – again. *Plant Dis.* **85**, 340–356.

Shams, S., Nazemosadat, S. M., Kamgar Haghighi, A. & Parsa, S. 2012 Effect of carbon dioxide concentration and irrigation level on evapotranspiration and yield of red bean. *J. Sci. Technol. Greenh. Cult.* **2** (4).

Silva Dias, M. A. F., Dias, J., Carvalho, L. M. V., Freitas, E. D. & Silva Dias, P. L. 2013 Changes in extreme daily rainfall for São Paulo, Brazil. *Clim. Change* **116**, 705–722. doi:10.1007/s10584-012-0504-7.

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, B. & Midgley, B. M. 2013 *IPCC, 2013: Climate Change 2013: the Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

USDA 2015 *Citrus: World Markets and Trade*. United States Department of Agriculture Foreign Agricultural Services.

USDA 2016 *Citrus: World Markets and Trade*. United States Department of Agriculture Foreign Agricultural Services.

Vara Prasad, P. V., Allen, L. H. & Boote, K. J. 2005 Crop responses to elevated carbon dioxide and interaction with temperature: grain legumes. *J. Crop Improv.* **13**, 113–155. doi:10.1300/J411v13n01_07.

Villalobos, F. J., Testi, L. & Moreno-Perez, M. F. 2009 Evaporation and canopy conductance of citrus orchards. *Agric. Water Manag.* **96**, 565–573. doi:10.1016/j.agwat.2008.09.016.

Wullschleger, S., Gunderson, C. A., Hanson, P. J., Wilson, K. B. & Norby, R. J. 2002 Sensitivity of stomatal and canopy conductance to elevated CO_2 concentration – interacting variables and perspectives of scale. *New Phytol.* **153**, 485–496.

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