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Simulation model of the growth of sweet orange (*Citrus sinensis* L. Osbeck) cv. Natal in response to climate change

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Abstract The objective of the present study was to develop a simulation model of the growth of sweet orange (*Citrus sinensis* L. Osbeck) cv. Natal in response to climate change based on system dynamics principles. The model was developed based on a system analysis of the factors that affect crop biomass formation. The main variables considered were atmospheric carbon dioxide (CO_2), air temperature, transpiration, rainfall, water deficit, irrigation depth, canopy volume, and the respective interrelationships. Simulations were performed for the period from 2010 to 2100. Overall, the model results indicate that the increase in atmospheric CO_2 concentrations predicted in the Intergovernmental Panel on Climate Change (IPCC) report, combined with air temperatures higher, lower, or equal to those generally occurring in natural environments, will result in higher water use efficiency by orange trees. When other factors, such as the soil water deficit, were included in the model, the water productivity was predicted to be lower in 2100 without irrigation than when irrigation was included. It is concluded that the model is suitable for determination of the effects of climate change on water use efficiency of sweet orange cv. Natal. Increased atmospheric CO_2 concentrations will result in higher CO_2 assimilation in orange trees and therefore in increased biomass production (g) per unit of water transpired (mm). However, this positive effect may be masked by other effects of atmospheric CO_2 increases, mainly those associated with temperature.

1 Introduction

Climatic change is mainly a result of high concentrations of greenhouse gases in the atmosphere. According to data from the Intergovernmental Panel on Climate Change (IPCC 2014), atmospheric carbon dioxide (CO_2) concentrations have increased considerably between 1750

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and 2011 by approximately 40%, with a trend toward that further increases in the future (Stich et al. 2008; IPCC 2014).

Assimilation of CO_2 by crops is affected by several factors. Water availability has been reported to be the main factor affecting CO_2 assimilation by crops (Delgado et al. 2010). However, under adequate water conditions, photosynthesis of orange trees throughout the year is mainly affected by variations in the air and soil temperature, the day length, and, obviously, the plant developmental stage (Ribeiro and Machado 2007; Ribeiro et al. 2009). Temperature is one of the variables with the greatest influence on CO_2 assimilation in orange trees. The optimum temperature for photosynthesis of citrus species is between 25 and 30 °C, and photosynthate production by orange trees considerably decreases at lower or higher temperatures (Medina et al. 2002; Ribeiro et al. 2004; Machado et al. 2005; Ribeiro and Machado 2007; Ribeiro et al. 2009; Magalhães Filho et al. 2009). Other studies have reported that maximum stomatal conductance in citrus species occurs at approximately 30 °C, and maximum photosynthesis occurs between 22 and 25 °C (Machado et al. 2002).

Crop responses to increased atmospheric CO_2 are not always positive because crops are affected by all environmental factors. The current CO_2 levels limit CO_2 assimilation in plants such as orange trees, and increasing atmospheric CO_2 from 800 to 1000 ppm stimulates photosynthesis (Amthor 2001). However, atmospheric CO_2 levels close to 1000 ppm have been reported to be excessive and cause phytotoxicity (Pinto et al. 2004).

Currently, there is considerable concern regarding the effects of climate change on crop yield, and there is a growing interest in understanding the processes, mechanisms, and factors within the soil-plant-atmosphere system that are affected by increases in atmospheric CO_2 concentrations and changes in air temperature. Well-established models for the behavior of herbaceous crops in response to climate change already exist. This is the case of the AquaCrop model, which was developed based on the reevaluation and restructuring of bulletin 33 of the Food and Agriculture Organization of the United Nations (FAO; Doorenbos and Kassan 1979), with the goal of addressing drought and further improving water use efficiency (Steduto et al. 2009; Raes et al. 2009). However, for tree crops such as citrus trees, which have long life cycles, further studies of the responses to climate change are needed, and this may be achieved through modeling.

A comprehensive method connecting climate factors with the yield pattern of tree crops over the years is therefore necessary. This type of study fits perfectly in the system dynamics methodology, which is a new type of integrated analysis of chains of natural cyclical events (Capra 1996).

The objective of the present study was to develop a simulation model for growth responses to climate changes in sweet orange (*Citrus sinensis* L. Osbeck) cv. Natal, based on the principles of system dynamics, to investigate the effects of climate change/climate variability mediated by changes in atmospheric CO_2 concentrations and variations in air temperature and to determine their implications on water use efficiency in citrus production in the region of São José do Rio Preto, São Paulo, Brazil.

2 Materials and methods

A dynamic simulation model for water use efficiency in citrus tree crops (ESM-Citrus) was developed using a system dynamics approach using the platform STELLA 10.0.5 (ISEE SYSTEMS 2001; 2009) A system analysis of citrus production and yield formation was performed, considering the existence in the literature of well-established models that simulate the production of herbaceous crops in response to climate change, such as the AquaCrop model (Steduto et al. 2009; Raes et al. 2009). Owing to the lack of simulation models for tree crops, the possibility of adapting existing models to tree crops by integrating data from previous studies has long been envisioned.

The initial steps included the identification of elements and processes involved in yield formation in citrus species in studies investigating the effects of climate changes, namely, changes in atmospheric CO_2 concentrations, the relationships of atmospheric CO_2 concentrations with air temperature, and their influence on water use efficiency in citrus production.

2.1 Structuring of the simulation model of water use efficiency in citrus species (ESM-Citrus)

The conceptual diagram presented in Fig. 1 illustrates the main variables involved in crop yield formation, based on which the present model was developed.

After identifying the main variables involved in yield formation and their inter-relations, a causal diagram, also called an influence or causal loop diagram, was built to represent the model's structure (Fig. 2).

The inter-relations among the main variables are presented in Fig. 2. The variables' water use efficiency and CO_2 affect the main accumulations in the system. The reference evapotranspiration (ETo) and transpiration (Tr) quantitatively influence the behavior of the water use

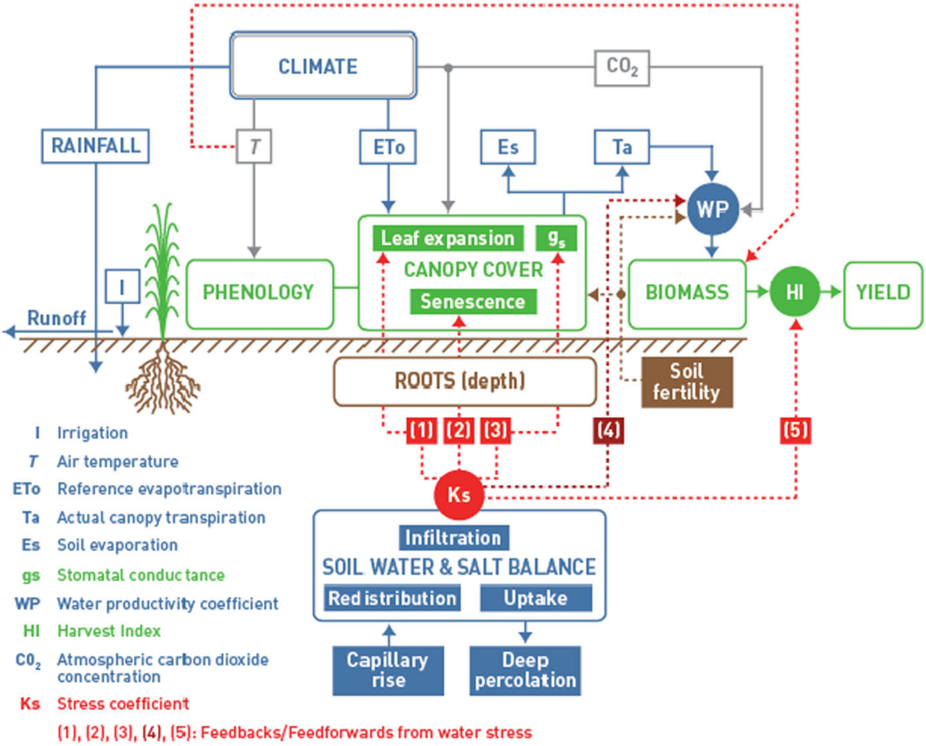

Fig. 1 Conceptual diagram of the process of yield formation (taken from FAO, Raes et al. 2012)

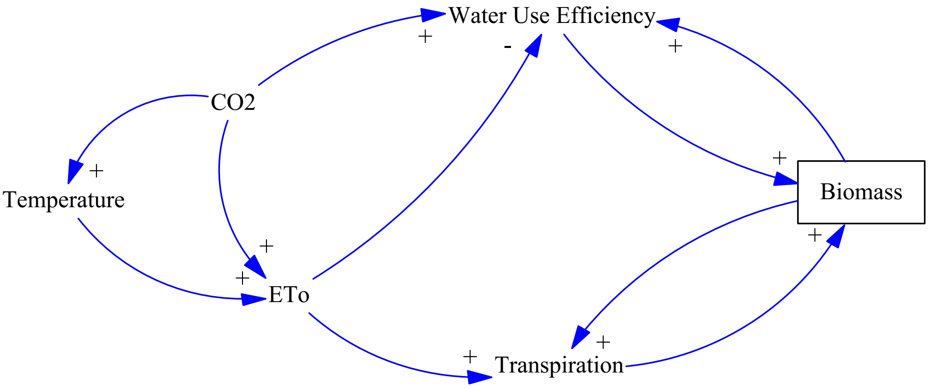

Fig. 2 Influence diagram for the developed model. Source: result of study obtained during the model's development

efficiency. Biomass is the main accumulated stock in the system. Water use efficiency and biomass receive water during yield formation. CO_2 also strongly influences biomass formation and water use efficiency, as a substrate for carboxylation. ETo and Tr fill or empty the main stocks and therefore act as flows.

The feedback loops between system components can be described as follows: increased CO_2 concentrations will result in increased water use efficiency (+). An increased transpiration rate will result in increased water use efficiency, and increased biomass will result in increased water use efficiency (+). Increased reference evapotranspiration will result in decreased water use efficiency (−). There is positive feedback between biomass and transpiration (+).

Based on the causal loop diagram (Fig. 2), a stock and flow diagram was built (Fig. 3) to describe the functioning of the system in more detail, allowing mathematical simulations of water use efficiency in sweet orange cv. Natal.

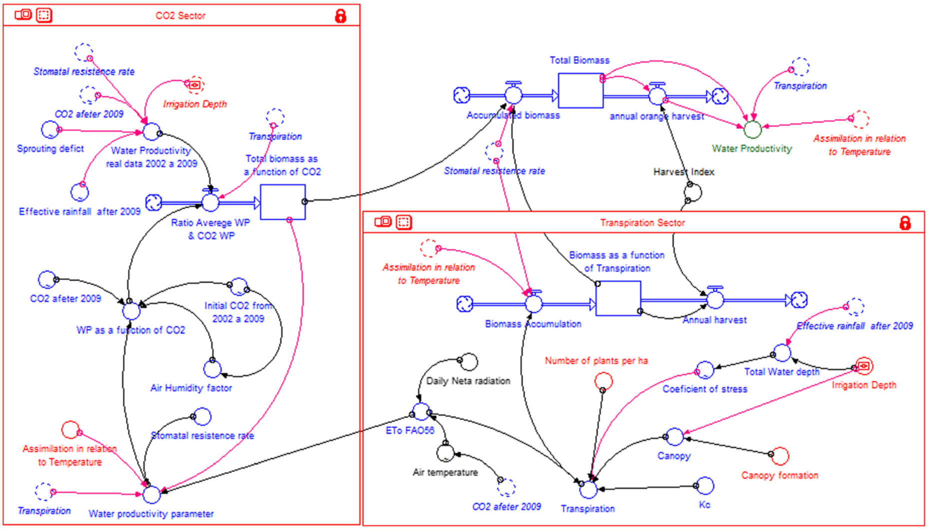

Fig. 3 Stock and flow diagram. Source: study result

2.2 Mathematical base for the development of ESM-Citrus

The water use efficiency (WP) was calculated using the method described in studies published by the FAO (Steduto et al. 2007; Raes et al. 2009; Raes et al. 2012). Equations 1, 2, and 3 were essential for the calculation of WP and normalization of CO_2 atmospheric concentrations for WP.

$$WP = \left(\frac{\mathrm{B}}{\sum \frac{Tr}{ETo}} \right) [CO_2] \qquad (1)$$

where

B	Total biomass, g m^{-2}, kilogram of biomass per square meter
WP	Water productivity (water use efficiency), g m^{-2}, kilogram of biomass per square meter and per millimeter of water transpired, or kilogram of biomass per cubic meter of water transpired
Tr	Crop transpiration (mm)
ETo	Reference evapotranspiration (mm)
CO_2	Atmospheric CO_2 concentration (ppm)

Transpiration was calculated according to Eq. 2 (Raes et al. 2009).

$$Tr = Ks{*}D{*}\%CC{*}K\mathrm{ctrx}{*}ETo \qquad (2)$$

where

Ks	Drought stress coefficient (decimal)
%CC	Canopy cover (decimal)
Kc_{Trx}	Crop coefficient (Kc) for maximum transpiration (non-dimensional)
ETo	Reference evapotranspiration (mm)

All complex CO_2 fixation metabolic processes at the biochemical level are included in the parameters of Eqs. 3 and 4 (Steduto et al. 2007).

$$WP = WP_b \frac{C_{a,o}}{C_a} {*} D \qquad (3)$$

where

WP	Water use efficiency normalized for atmospheric CO_2 concentration (g m^{-2} mm^{-1})
WP_b	Biomass water use efficiency (calculated using the yields obtained from Citrosuco company) (g m^{-2} mm^{-1})
$C_{a,\,o}$	Annual mean atmospheric CO_2 concentration measured at Mauna Loa Observatory (Hawaii) for the reference year
C_a	Annual mean atmospheric CO_2 concentration measured at Mauna Loa Observatory (Hawaii) for the year when the biomass is produced
D	Empirical factor approximating the sum of Δw, i.e., the sum of the difference in water vapor concentration between the intercellular space and the atmosphere for a given

situation (Δw) and a reference situation (Δw_o). Steduto et al. (2007) recommend calculating D using Eq. 4, where $C_{a,\ o}$ is the reference CO_2 concentration of 360 ppm

$$D = a - b \times \left(C_a - C_{a,o}\right) \tag{4}$$

where

$a = 1$ and $b = 0.000138$.

The coefficients a and b in Eq. 4 were determined by Steduto et al. (2007), who performed experiments in environment chambers under controlled conditions of CO_2 emissions, having normalized saturation water vapor pressure, air temperature, and humidity, among others. The authors suggested that with adaptations, Eq. 4 could be used for normalization for different atmospheric CO_2 concentrations.

During model structuring, coefficients that enabled simulation of carboxylation in orange trees, namely, carboxylation rate as a function of temperature (Table 1), were included in the model, and a stomatal resistance coefficient of 23% was used (Machado et al. 2005). In addition to stomatal resistance, an inflection point was considered that established a 50% decrease in carboxylation starting at 600 ppm CO_2. This inflection point was based on previous reports that atmospheric CO_2 levels close to 1000 ppm are excessive and cause phytotoxicity (Pinto et al. 2004; Streck and Alberto 2006; Streck 2005; Machado et al. 2005; Amthor 2001).

2.3 Source of information used to test ESM-Citrus

After building the model, yield data for consecutive years for sweet orange cv. Natal grown with and without irrigation were acquired and used to test whether the water use efficiency values simulated by the model were similar to those supplied by the FAO for C_3 plants (15 to 20 g m^{-2} mm^{-1}).

Data for sweet orange cv. Natal grown under two management systems, with or without irrigation, were used. Trees were planted in 1998, and yield data were collected beginning in 2002, when the orchards were 5 years old. The sweet orange cv. Natal was used in both cases, using the lemon cv. Cravo as rootstock. Cultivation was performed without irrigation in the Onda Verde municipality and with drip irrigation (flow rate 2 L h^{-1}) in the municipality of Altair. The total annual depth of irrigation water applied (Table 1) varied, depending on the number of days with application of irrigation for 6, 8, or 10 h, which in turn depended on the crop development stage and rainfall. The Citrosuco company, which supplied the yield data,

Table 1 Total irrigation water depth applied in each year

	2002	2003	2004	2005	2006	2007	2008	2009
∑ETo (mm)[a]	1566	1406	1414	1436	1403	1449	1382	1445
Irrigation (mm)[b]	793.6	769.6	795.2	809.6	798.4	644.8	788.8	710.4
Effective rainfall[c]	766.55	942.14	826.98	893.11	982.49	816.29	758.35	1064.56
Days with irrigation[b]	124	116	122	126	104	97	118	107

[a] IAC data bank

[b] Citrosuco company

[c] Effective rainfall calculated as proposed by the USDA Soil Conservation Service (USDA-SCS) using rainfall data supplied by the DAEE (Barbosa et al. 2005)

determines the days of irrigation application considering the days of rainfall and applies irrigation during 90 to 130 days per agricultural year, depending on the climate. The company never applies irrigation in January, February, June, or December.

For the irrigated area, all evapotranspiration was replaced by irrigation, and therefore, the stress coefficient (K_s) was considered to be 1. For the area without irrigation, the stress coefficient was calculated for each year using the value of rainfall, which was obtained as follows: the total irrigation water depth was considered as 100% of the evapotranspiration volume, i.e., 1. The percentage water stress for the conditions without irrigation was calculated using this value and the value of effective rainfall, which was the only water supplied to the area without irrigation.

Rainfall data for the two orchards, which were used as a basis for the model simulation, were obtained from the State of São Paulo Department of Waters and Electrical Power (Departamento de Águas e Energia Elétrica - DAEE). Potential evapotranspiration values were obtained from the management points of the Campinas Agronomic Institute (Instituto Agronômico de Campinas - IAC).

A crop coefficient (Kc) for maximum transpiration ($K\text{c}_{\text{Trx}}$) during the phenological cycle of citrus trees of 0.85 was considered, as recommended by Doorenbos and Pruitt (1984, 1997).

2.4 WP calculation

The total biomass was calculated using the yield data for sweet orange cv. Natal supplied by the Citrosuco company. The yields corresponded to the useful biomass of sweet orange cv. Natal, the fruit itself, for both cultivation conditions (with and without irrigation). These values were converted into total biomass using a conversion factor based on previous studies that determined the percentage of orange trees that corresponded to useful biomass (Mattos Junior et al. 2003).

Canopy volume (Vc) values for sweet orange cv. Natal trees for the years for which Citrosuco company supplied the yield data were calculated using values from previous reports (Quaggio et al. 2004; Graça et al. 2001; Stuchi and Donadio 2000; Ledo et al. 1999). With this information, it was established that the trees in the irrigated area had fully formed canopy volume (100% Vc). For trees in the non-irrigated area, Vc was calculated considering the percent reduction value based on Levy et al. (1978) and Romero et al. (2006). Those studies reported that canopy volume is positively correlated with water consumption, indicating a need to use a reduction factor in the calculation of Vc for orange trees grown without irrigation. The percent reduction value used was based on Romero et al. (2006), who reported a 41% reduction in canopy volume of citrus trees grown under deficit irrigation.

Transpiration per plant was calculated using the canopy volume values. Transpiration per hectare for each agricultural year, with and without irrigation, was calculated using the transpiration per plant and the number of plants per hectare.

The steps to obtain the equations fed to the STELLA software were as follows: the data supplied by Citrosuco company were analyzed, and some variables were observed to affect plant yield, namely, the water deficit occurring during the sprouting stage (WDS) of sweet orange cv. Natal that resulted from climate conditions and the stage of the crop cycle. Water deficit was determined by calculating the water balance for the period corresponding to the yield data (2002 to 2009).

The highest annual water deficit occurred between the second half of May and mid-August. During that period, in the area with irrigation, the water lost by evapotranspiration was replaced by irrigation. From an analysis of the yield data under the two cultivation conditions (with and without irrigation), a multiple linear correlation equation was built for each condition. The multiple linear correlation for the area with irrigation is expressed in Eq. 5.

$$\mathrm{WP} = -480.76 - 0.084 * \mathrm{WDS} + 1.31 * \mathrm{CO}_2 - 0.007 * I \tag{5}$$

where

WP	Water productivity ($\mathrm{g\ m^{-2}\ mm^{-1}}$);
WDS	Water deficit during sprouting (mm); application range ($70 \le \mathrm{WDS} \le 400$)
CO_2	Atmospheric CO_2 concentration (ppm); application range ($280 \le \mathrm{CO}_2 \le 1200$)
I	Water irrigation depth applied during the crop cycle (mm); application range ($600 \le I \le 900$)

The three variables included in Eq. 5 explained 77% of the WP variability of the real yield data recorded between 2002 and 2009 ($R^2 = 0.77$).

The multiple correlations for the area without irrigation is expressed in Eq. 6;

$$\mathrm{WP} = -10.24 - 0.03 * \mathrm{WDS} + 0.04 * \mathrm{ER} \tag{6}$$

where

WP	Water productivity ($\mathrm{g\ m^{-2}\ mm^{-1}}$);
WDS	Water deficit during sprouting (mm); application range ($70 \le \mathrm{WDS} \le 400$);
ER	Effective rainfall (mm); ($600 \le \mathrm{ER} \le 1000$)

The two variables included in Eq. 6 (water deficit during sprouting and effective rainfall) explained 96% of the WP variability without irrigation ($R^2 = 0.96$).

Equations 5 and 6 were fed to the STELLA software as model input variables. Simulations were run in STELLA using the real yield values obtained for the areas with and without irrigation.

Water use efficiency variations in response to changes in air temperature were simulated using CO_2 assimilation response curves obtained by Machado et al. (2005) at different air temperatures using chambers with controlled conditions of air temperature and different CO_2 concentrations (Table 2). The authors reported a stomatal control of photosynthesis coefficient of 23%.

The model included additional parameters in its structure that were also essential. The water deficit included in the model was obtained from Marengo (2006), who modeled the behavior of rainfall until 2100. This was used to estimate the future behavior of water deficit. The input data used in the model are presented in Table 3.

Table 2 Annual CO_2 assimilation rate as a function of air temperature

Temperature (°C)	25 °C	30 °C	40 °C
Assimilation percentage (%)	81.37	93.01	59.96
Annual amount of CO_2 assimilation ($\mathrm{g\ m^{-2}\ year^{-1}}$)	527.40	648.15	388.61

Source: adapted from Machado et al. (2005)

The characteristics of the nine scenarios with irrigation and the nine scenarios without irrigation used in the model simulations are presented in Table 4.

3 Results and discussion

All atmospheric CO_2 concentration projections by the IPCC used in the present study indicate increases in atmospheric CO_2 concentrations between 2010 and 2100 (sustainable–SUST 387–544 ppm; maximum–MAX 413–1142 ppm; minimum–MIN 366–794 ppm). The simulations obtained using the present model exhibited increased water productivity with the highest atmospheric CO_2 concentrations, both with and without irrigation. CO_2 is the primary substrate of photosynthesis in plants, and increased atmospheric CO_2 concentrations result in increased plant growth rates; furthermore, this beneficial effect of higher CO_2 concentrations is more pronounced in C_3 plants, such as citrus species (Taiz and Zeiger 1991) (Table 5).

The developed model revealed higher water productivity for all CO_2 concentrations projected by the IPCC and higher decreases in CO_2 assimilation rates in response to rising air temperature in the area without irrigation (scenarios A through I) compared with the irrigated area (scenarios J through R) (Table 5).

For 25 °C and 30 °C, the WP was higher for the MAX than for the SUST and MIN CO_2 concentration levels, both without (scenarios A and B, D and E, G and H) and with irrigation (scenarios J and K, M and N, P and Q). For 40 °C, the CO_2 assimilation was highest with the highest atmospheric CO_2 concentrations (scenarios C, F, I, L, O and R; Table 5).

The continuous increase in atmospheric CO_2 has been considered to have positive effects on agriculture (Streck and Alberto 2006; Streck 2005). This is because CO_2 is the primary substrate of photosynthesis, the process through which CO_2 is fixed and converted to carbohydrates via the Calvin cycle, and its increase results in increased plant growth rates (Taiz and Zeiger 2004). This is common to C_4 and C_3 plants, such as orange trees (Zhang and Dang 2005; Ainsworth and Long 2005; Streck and Alberto 2006; Streck 2005).

Table 3 Description of the variables used to build the model–input data

Variables	Characteristics
Annual CO_2 assimilation as a function of air temperature (decimal)	Three temperatures, 25 °C, 30 °C, and 40 °C corresponding to 0.2, 0.1, and 0.4, respectively
Rainfall (mm)	Overall mean (865 mm) calculated for the period from 2002 to 2009 and considering the rainfall behavior reported by Marengo (2006)
Water deficit (mm)	Overall mean (57.76 mm), which was obtained by calculating the water balance for the years for which plant yields were obtained (2002 to 2009). In simulations, an initial water deficit of 54 mm was considered for 2010, which was gradually increased up to 74 mm in 2100, based on Marengo (2006)
Stomatal resistance (decimal)	0.23 (Machado et al. 2005)
Canopy volume (decimal)	1.0 with irrigation and 0.59 without irrigation (Romero et al. 2006)
Water irrigation depth	Overall mean (775 mm) calculated from the irrigation data supplied by Citrosuco company for the period from 2002 to 2009
CO_2 (ppm)	Three atmospheric CO_2 concentrations (SUST, MIN, and MAX) projected by the IPCC
Inflection point	50% decrease in carboxylation at 600 ppm CO_2 based on Pinto et al. (2004), Streck and Alberto (2006), Streck (2005), Machado et al. (2005), and Amthor (2001)

Table 4 Scenarios proposed and evaluated in the present study

Scenarios	Description of the scenarios for the without irrigation area
A	Temperature 25 °C, CO_2 in sustainable atmosphere (387–544) ppm
B	Temperature 30 °C, CO_2 in sustainable atmosphere (387–544) ppm
C	Temperature 40 °C, CO_2 in sustainable atmosphere (387–544) ppm
D	Temperature 25 °C, CO_2 in maximum atmosphere (413–1142) ppm
E	Temperature 30 °C, CO_2 in maximum atmosphere (413–1142) ppm
F	Temperature 40 °C, CO_2 in maximum atmosphere (413–1142) ppm
G	Temperature 25 °C, CO_2 in minimum atmosphere (413–794) ppm
H	Temperature 30 °C, CO_2 in minimum atmosphere (413–794) ppm
I	Temperature 40 °C, CO_2 in minimum atmosphere (413–794) ppm
Scenarios	Description of the scenarios for the irrigated area
J	Temperature 25 °C, CO_2 in sustainable atmosphere (387–544) ppm
K	Temperature 30 °C, CO_2 in sustainable atmosphere (387–544) ppm
L	Temperature 40 °C, CO_2 in sustainable atmosphere (387–544) ppm
M	Temperature 25 °C, CO_2 in maximum atmosphere (413–1142) ppm
N	Temperature 30 °C, CO_2 in maximum atmosphere (413–1142) ppm
O	Temperature 40 °C, CO_2 in maximum atmosphere (413–1142) ppm
P	Temperature 25 °C, CO_2 in minimum atmosphere (413–794) ppm
Q	Temperature 30 °C, CO_2 in minimum atmosphere (413–794) ppm
R	Temperature 40 °C, CO_2 in minimum atmosphere (413–794) ppm

The water use efficiency was higher with irrigation than without irrigation (Table 5). Without irrigation, the highest water productivity was 27.69 g m^{-2} mm^{-1} for 2100, which was observed for scenario B. Scenario K, with irrigation, exhibited the same characteristics as scenario B and presented water productivity of 59.1 g m^{-2} mm^{-1}.

The developed model gathers the variables involved in water productivity of sweet orange cv. Natal, in an attempt to understand how environmental factors, air temperature, and CO_2

Table 5 Water productivity of sweet orange cv. Natal under different scenarios

Scenarios	CO_2	Temperature °C	2020	2030	2040	2050	2060	2070	2080	2090	2100
Water productivity of sweet orange cv. Natal without irrigation area WP g m^{-2} mm^{-1}											
A	SUST	25 °C	10.92	13.71	15.87	17.66	19.2	20.57	21.82	22.97	23.95
B		30 °C	12.7	15.91	18.4	20.46	22.23	23.8	25.23	26.56	27.69
C		40 °C	10.1	12.74	14.77	16.46	17.91	19.2	20.38	21.47	22.39
D	MAX	25 °C	10.57	13.19	15.14	8.34	8.95	9.46	9.88	10.23	10.51
E		30 °C	12.3	15.32	17.55	9.65	10.36	10.94	11.42	11.83	12.15
F		40 °C	9.77	12.25	14.08	7.76	8.34	8.81	9.21	9.54	9.8
G	MIN	25 °C	10.39	13.1	15.18	16.88	18.28	19.46	10.23	10.66	10.99
H		30 °C	13.05	16.36	18.9	20.97	22.7	24.14	12.68	13.21	13.62
I		40 °C	10.06	12.86	14.98	16.7	18.12	19.32	10.17	10.6	10.94
Water productivity of sweet orange cv. Natal with irrigation WP g m^{-2} mm^{-1}											
J	SUST	25 °C	14.56	20.31	25.98	31.57	37	42.19	47.1	51.73	55.65
K		30 °C	15.55	21.64	27.64	33.56	39.32	44.82	50.03	54.94	59.1
L		40 °C	12.38	17.37	22.29	27.15	31.86	36.36	40.62	44.63	48.04
M	MAX	25 °C	18.95	25.8	32.71	19.83	23.29	26.7	30.03	33.25	36.08
N		30 °C	20.32	27.57	34.88	21.12	24.79	28.4	31.93	35.35	38.35
O		40 °C	16.08	22.07	28.09	17.07	20.07	23.02	25.91	28.7	31.15
P	MIN	25 °C	9.58	14.83	20.65	26.75	33.03	39.41	22.91	26.09	28.88
Q		30 °C	10.19	15.75	21.93	28.4	35.06	41.83	24.32	27.69	30.65
R		40 °C	8.14	12.68	17.73	23.01	28.44	33.96	19.76	22.51	24.93

CO_2 concentrations projected by the IPCC, *SUST* sustainable (387–544 ppm), *MAX* maximum (413–1142 ppm), *MIN* minimum (413–794 ppm), *WP* water productivity parameter (g m^{-2} mm^{-1})

concentrations affect the plant biomass accumulation and thus water use efficiency, of orange trees over time. It should be noted that the highest water productivity (gram of plant biomass per millimeter water transpired) values were observed for 30 °C air temperature, both with and without irrigation, being 59.1 g m^{-2} mm^{-1} for 2100 under maximum atmospheric CO_2 concentration (scenario E in Table 5). This result is in accordance with Machado et al. (2005), who studied the sweet orange cultivars Valencia, Murcote, and Tahiti and observed higher CO_2 assimilation rates between 25 and 30 °C, decreasing at air temperatures above 30 °C. The data from that study were fundamental for the composition of the scenarios tested in the present study because negative effects on stomatal conductance under extreme temperatures (15 and 40 °C), which resulted in decreased photosynthetic rates, were reported.

Martinez et al. (2014) subjected forage plants to a temperature increase of 2 °C, which was also based on the scenarios predicted by the IPCC, and observed that the temperature increase predicted to occur until 2050 could have beneficial effects on the physiology and biochemical and biophysical processes involved in forage plant growth. Furthermore, in that study, a 32% increase in leaf area and 16% increase in shoot biomass were observed when compared to plants grown under normal conditions. The model for the growth of sweet orange cv. Natal developed in the present study that used a combination of scenarios of increased air temperature and carbon dioxide concentrations predicted increases in water use efficiency. This is mainly because the model considered increased biomass production up to 30 °C and 600 ppm CO_2. If increases in CO_2 concentration are accompanied by increased air temperature, the crop growth and yield may not increase (Taiz and Zeiger 2004; Taiz and Zeiger 1991; Streck 2005, Siqueira et al. 2001). This may be due to the negative effects of increased atmospheric CO_2 concentrations on citrus productivity (Allen and Vu 2009; Idso and Kimball 1991; Ribeiro and Machado 2007; Ribeiro et al. 2009; Magalhães Filho et al. 2009).

Other studies that used modeling to predict the impacts of climate change on agricultural yields also indicated decreased yields with high levels of atmospheric CO_2 due to the simultaneous increase in temperature. The model by Krishnan et al. (2007) predicted a decrease in rice production of approximately 56% with 700 ppm CO_2 and an air temperature increase of 4 °C. The United Nations (2013) used the conceptual base of the FAO programs CropWat and AquaCrop to generate equations to predict potato and corn yields mediated by variability and/or climate changes in Colombia and concluded that the use of modeling, in addition to being useful for yield predictions, made it possible to model the photosynthetic response of each crop to environmental conditions.

The simulations performed for 2020 through 2100 indicated a gradual increase in plant biomass produced (g) per millimeter water transpired in sweet orange cv. Natal with increased atmospheric CO_2. This was the main result of the model developed. However, previous studies have found that if increased CO_2 concentrations occur together with increased water vapor deficit, both transpiration rates and CO_2 assimilation will be negatively affected, thereby decreasing plant growth and thus water productivity (Medina et al. 1998, 1999; Machado et al. 2005).

Other studies also reported more pronounced decreases in photosynthesis rates in orange trees with decreased soil water content (Medina et al. 1998, 1999). Under drought conditions, there is stomatal closure to limit water vapor loss to the atmosphere, resulting in decreased CO_2 assimilation and plant productivity (Medina et al. 1998).

Martin et al. (1995) studied the responses of lemon plants to high CO_2 concentrations combined with high and low temperatures and observed that high CO_2 concentrations combined with high temperatures (42 °C day/32 °C night) resulted in 87% increased growth, whereas the same CO_2 concentrations combined with lower temperatures (29 °C day/21 °C night) only increased growth by 21%.

4 Conclusions

The developed model graphically and mathematically represents the responses to climate changes of the processes involved in water use efficiency in sweet orange cv. Natal. Citrus crop yields will increase up to 600 ppm atmospheric CO_2 and 30 °C air temperature, but they will decrease at higher temperatures and CO_2 concentrations.

Increased atmospheric CO_2 concentrations will have a positive effect on CO_2 assimilation in orange trees, resulting in increased biomass produced (g) per millimeter of water transpired. However, this positive effect may be masked by other effects of CO_2 increases, especially those associated with air temperature and water vapor deficit.

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