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IMPACT OF CLIMATE CHANGE ON CROPS: COFFEE, WHEAT, CORN, BEAN AND SOYBEAN IN THE ALTO PARANAPANEMA BASIN

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1 ABSTRACT

The objective of this study was to adapt a simulation model of water use efficiency in citrus species, ESM-Citrus, which was previously developed and estimate the effects of climate change on yields and water use efficiency in the cultivation of coffee, wheat, corn, bean, and soybean in the Alto Paranapanema basin (BH-ALPA), São Paulo State, Brazil. A systemic analysis of crop yields was carried out, including the interactive effects of factors that interfere with the process of biomass formation: carbon dioxide (CO_2), air temperature, transpiration, irrigation depth, leaf area index and/or canopy volume, reference evapotranspiration and precipitation. Climate and yield data (under irrigated and no irrigated conditions) from farmers of the Planting in the Straw Irrigators Association of Southwestern São Paulo (ASPIPP). Part of the FAO (AquaCrop) models were used. With the systems dynamics methodology, different climatic scenarios were modeled. It was concluded that the CO_2 concentrations projected by IPCC, the scenario of sustainable CO_2 emissions, BAU (387–544 ppm), with a temperature of approximately 32°C, will provide greater water use efficiency in future decades. In contrast, the scenario of maximum CO_2 emissions, MAX (413–1142 ppm), will result in a marked reduction in water use efficiency in crops.

Keywords: System dynamics, water resources, agricultural production, climatic variability

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2 RESUMO

O objetivo deste estudo foi adaptar um modelo, de simulação de eficiência do uso da água em espécies cítricas, ESM-Citrus, previamente desenvolvido, para estimar os efeitos das mudanças climáticas sobre a produtividade e a eficiência do uso da água no cultivo de café, trigo, milho, feijão e soja na bacia do Alto Paranapanema (BH-ALPA), estado de São Paulo, Brasil. Foi realizada uma análise sistêmica da produtividade das culturas, incluindo os efeitos interativos de fatores que interferem no processo de formação de biomassa: dióxido de carbono (CO_2), temperatura do ar, transpiração, lâmina de irrigação, índice de área foliar e/ou volume do dossel, evapotranspiração de referência e precipitação. Obteve-se dados de clima e do rendimento (nas condições irrigada e não irrigada), este último junto aos produtores credenciados à Associação do Sudoeste Paulista de Irrigantes e Plantio na Palha (ASPIPP). Parte dos modelos da FAO (AquaCrop) foi utilizada. Com a metodologia de dinâmica de sistemas, diferentes cenários climáticos foram modelados. Concluiu-se que as concentrações de CO_2 projetadas pelo IPCC, o cenário de emissões sustentáveis de CO_2, BAU (387–544 ppm), com uma temperatura de aproximadamente 32 °C, proporcionarão maior eficiência no uso da água nas próximas décadas. Em contraste, o cenário de emissões máximas de CO_2, MAX (413–1142 ppm), resultará em uma redução acentuada na eficiência do uso da água nas culturas.

Palavras-chaves: Dinâmica de sistemas, recursos hídricos, produção agrícola, variabilidade climática

3 INTRODUCTION

Reports from the Intergovernmental Panel on Climate Change (IPCC) published in 2014 and 2018 indicate that the global climate changed compared with that in the preindustrial period. Some of the main changes highlighted in these reports are an increase in the atmospheric carbon dioxide (CO_2) concentration, approximately 40% between 1750 and 2011; an increase in the average global surface temperature, which reached 0.87°C in 2006–2015 compared with 1850–1900; and an increase in the frequency and magnitude of the impacts from these changes in the climate. These reports show evidence that these changes promoted impacts in organisms and ecosystems, as well as in human systems and well-being.

As agriculture is highly dependent on climate, climate change, as well as variation in the occurrence of extreme weather events, should generate significant impacts on this sector. According to statements in IPCC reports (2014, 2018) and Hatfield (2016), the impacts of climate change on agricultural production are associated with the positive effects of increasing CO_2, the negative effects of increasing temperature and, in addition, the effects of climate variables and the amount of precipitation.

Given these facts, many studies have already been conducted, and others are in progress to understand the causes and magnitude of future impacts, aiming to adapt and mitigate the effects of climate change in the agricultural sector. Most of these studies have experimentally established the dependence relationships of development and crop yields with atmospheric CO_2 concentrations associated with air temperature and water availability, among other factors (Hatfield, 2016; Hatfield *et al.*, 2011; Schlenker; Roberts, 2009; Lobell; Field, 2007; Krishnan *et al.*, 2007; Leakey *et al.*, 2006; Ainsworth *et al.*, 2005).

According to Aljazairi, Arias and Nogués (2015) and Leakey *et al.* (2006), maintaining future food security is extremely important because of the interactive effects of high CO_2 concentrations, temperature increases and water stress on the performance of crops in the environment. Additionally, to quantify the reduction in yield and even the water use efficiency of crops, all these climate changes should be considered. Many studies highlight the importance of understanding the interrelationships of all intrinsic variables related to agricultural production (Vogel *et al*., 2019; Lobell *et al.,* 2014).

Owing to the complexity of the formation process of crop yields, as it is mediated by factors and mechanisms and by an infinity of biophysical and morphological variables, the application of methodologies that carry out a systemic approach to this entire process, such as systems thinking and systems dynamics, is perfect. This methodology can also promote the integration of different perspectives with the behavior of agricultural yields and the efficiency of water use into a single model, considering the interconnections of the factors, mechanisms and variables of the complex water–soil-plant–atmosphere system. In addition to being an integrated analysis of natural cyclical event chains (Capra, 1996), system dynamics allows the prediction of results and the understanding of the impacts of climate change on crop yields.

Thus, the aim of the present study was to adapt the ESM-Citrus model to coffee, wheat, corn, soybean and bean and estimate the effects of climate change on the yields and water use efficiency of these crops in the Alto Paranapanema basin, SP, Brazil.

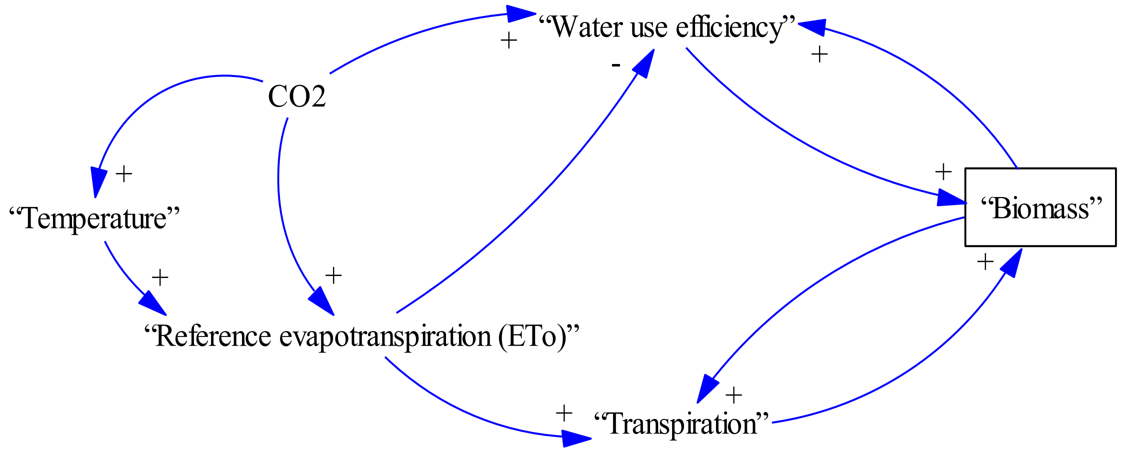
4 MATERIAL AND METHODS

In the present study, a reformulation of the model established by Pereira, Sánchez-Román and Orellana González (2017) was carried out to simulate and evaluate the behavior of the water productivity parameter in tree crops, specifically in citrus (ESM-Citrus), which is influenced by atmospheric CO_2 concentrations, as pointed out by the IPCC (2014), and by changes in air temperature, which are based on the optimum temperatures and are limited to the development of different crops. The model was based on the system dynamics methodology and was developed into the STELLA 10.0.5 platform. The STELLA software works with object-oriented programming; it is a user-friendly interface and, thus, becomes easy to experiment with, evaluate and execute scenarios via the modeled system. In the system dynamics methodology, during the development of the models, key elements that operate as support points for the evaluation and improvement of the modeled system are identified.

The elements and intrinsic processes affecting the yield of coffee, wheat, corn, soybean and bean were identified, and a detailed study of the assimilation of CO_2 and the yield of each of these crops under a variety of atmospheric CO_2 concentrations combined with different air temperatures was subsequently performed.

In the reformulation of the ESM-Citrus model, the key variables for the formation of the selected crop yields were included, after which the influence diagram for the calculation of water use efficiency was elaborated (Figure 1).

Figure 1. General influence diagram of the structure of the water productivity parameter calculation system for crop [1].



Source: Own authorship.

This diagram was arranged to represent the structure of the model, and the interrelationships established between the main variables can be identified. The variables "Water use efficiency" and "CO_2" affect the main accumulations in the system. Reference evapotranspiration (ET_o) and transpiration (Tr) quantitatively influence the course of the water productivity parameter.

Moreover, a survey was carried out with statistical and agricultural agencies and producer associations to obtain the yields of the studied crops. Data on rainfed conditions for coffee, wheat, corn, bean and soybean were collected from the Brazilian Institute of Geography and Statistics (IBGE, 2011; 2018), from the National Food Supply Company (CONAB), from the Rural Development Office (EDR) of some cities at BH-ALPA, from the Coordination of Integral Technical Assistance (CATI), and from agricultural departments of cities and farmers that are members of Southwest São Paulo Association of Irrigation and No-Till (ASPIPP). For the irrigated conditions, the studied crops were corn, soybean and bean, and data were obtained from the Olhos d'água farm in the city of Itaí, which has 510 ha of irrigated land with center pivots. The data for wheat and coffee under irrigated conditions were not consistent, making it impossible to generate agroclimatic functions and, consequently, scenarios. According to Conab (2017), wheat accounts for 90% of the cultivation area at BH-ALPA under rainfed conditions.

The crops were chosen because of their economic representativeness related to regional agricultural production in the BH-ALPA. In the reports published by the Alto Paranapanema Basin Committee (CBH-ALPA), it was evident that coffee, beans, corn, soybeans and wheat are highly important crops in the basin (Cbh-alpa, 2016). Yield and climatic data (sources of energy for yield formation) for each of these crops were obtained under irrigated and no irrigated (rainfed) conditions to understand the water productivity parameters and the influence of climate change.

Water Resources Management Unit No. 14 (UGRHI 14), corresponding to BH-ALPA, is located in the southwest region of São Paulo State. According to CBH-ALPA (2019), the climate of UGRHI 14 is tropical humid, with slight variation between most inland regions and the Paranapiacaba mountain area, with a mean annual precipitation of approximately 1,200 mm. The wettest period is from September to March, with January having the highest rainfall, followed by February and March, and August being the driest month.

The meteorological database was obtained from meteorological stations of the Integrated Agrometeorological Information Center (Ciiagro, 2019; Cetec; Ctgeo, 2015), which provides temperature (minimum, maximum and average), precipitation and ET_o data. When needed, rainfall data were acquired from the Department of Water and Electricity of São Paulo State (DAEE), with collection points obtained from all the cities of BH-ALPA. The irrigated crop areas have their own meteorological stations with ET_o calculations.

4.1 Calculation of water productivity parameters for coffee, wheat, corn, soybean and bean

To calculate water productivity parameters, also known as water use efficiency, adjacent, but fundamental, parameters were used. An in-depth study was performed on the factors, mechanisms, variables and even the interrelationships among all these variables, which are inherent to the crop biomass formation process under environmental conditions (Table 1, Table 2 and Table 3).

Table 1. Summary of the literature review on the factors, mechanisms, and intercorrelations among inherent variables and the crop yield formation process

Crop	Bean	Soybean
Leaf area, and/or leaf area index, or growth rate	- Behluli, Canko and Fetahu (2018); - Jadoski *et al*. (2003).	- Allen *et al*. (2003); - Bernacchi *et al.* (2005); - Li *et al.* (2013); - Madhu and Hatfield (2014).
Temperature correlations	- Pimentel *et al.* (2013).	- Allen *et al.* (2003); - Streck (2005).
Crop coefficient (Kc)	- Bizari *et al.* (2009); - Doorenbos and Kassan (1979); - Doorenbos and Pruitt (1984).	- Doorenbos and Kassan (1979); - Doorenbos and Pruitt (1984).
Harvest index	- Calvache *et al.* (1997).	- Ribeiro *et al.* (2017).
Stomatal conductance	- Pimentel *et al*. (2013); - Ribeiro *et al*. (2004).	- Ainsworth and Rogers (2007); - Allen *et al*. (2003); - Bernacchi *et al.* (2005); - Madhu and Hatfield (2014).
Biomass partition	- Behluli, Canko and Fetahu (2018); - Polania *et al.* (2016); - Soratto *et al*. (2013).	- Li *et al*. (2013).
Transpiration, CO_2 assimilation and its relationship with atmospheric [CO_2] elevation	- Pimentel *et al.* (2013); - Ribeiro *et al*. (2004).	- Ainsworth and Rogers (2007); - Bernacchi *et al*. (2005); - Li *et al*. (2013); - Madhu, and Hatfield (2014);
Water use efficiency	- Calvache *et al.* (1997); - Polania *et al.* (2016).	- Allen *et al.* (2003); - Calvache *et al*. (1997); - Li *et al.* (2013); - Madhu and Hatfield (2014).
Transpiration	- Ogindo and Walker (2004).	- Allen *et al.* (2003); - Li *et al.* (2013).

Source: Own authorship

Table 2. Summary of the literature review on the factors, mechanisms, and intercorrelations among inherent variables and the crop yield formation process.

Crop	Corn	Wheat
Leaf area, and/or leaf area index, or growth rate	- Allen *et al.* (2011); - Leakey *et al*. (2006); - Meng *et al*. (2014).	- Kane *et al.* (2013).
Temperature correlations	- Hamilton III *et al.* (2008); - Hatfield (2016); - Meng *et al.* (2014); - Streck (2005).	- Amthor (2001); - Farooq *et al*. (2011); - Tack, Barkley and Nalley (2015).
Crop coefficient (Kc)	- Andrade *et al.* (2006); - Doorenbos and Kassan (1979); - Doorenbos and Pruitt (1984).	- Doorenbos and Kassan (1979); - Doorenbos and Pruitt (1984).
Harvest index	- Demétrio *et al.* (2008).	- Amthor (2001); - Fujimura *et al*. (2012); - Zhong-hu and Rajaram (1994).
Stomatal conductance	- Hamilton III *et al*. (2008); - Leakey *et al*. (2006); - Meng *et al.* (2014).	- Kane *et al*. (2013); - Sikder *et al.* (2016).
Biomass partition	- Hatfield (2016); - Leakey *et al.* (2006); -Manderscheid, Martin and Weigel (2014).	- Zhong-hu and Rajaram (1994); - Santos *et al*. (2012); - Kane *et al*. (2013); - Ihsan *et al*. (2015).
Transpiration, CO_2 assimilation and its relationship with atmospheric [CO_2] elevation	- Allen *et al.* (2011); - Hamilton III *et al.* (2008); - Leakey *et al*. (2006); - Meng *et al.* (2014); - Streck (2005).	- Amthor (2001); - Kane *et al*. (2013); - Sikder *et al*. (2016); - Wu *et al.* (2004).
Water use efficiency	- Allen *et al.* (2011); - Leakey *et al.* (2006); - Manderscheid Martin and Weigel (2014); - Meng *et al.* (2014).	- Kane *et al.* (2013); - Sikder *et al*. (2016); - Wu *et al.* (2004).
Transpiration	- Lemos *et al.* (2012); - Ray *et al.* (2002); - Meng *et al.* (2014)	- Kane *et al.* (2013); - Sikder *et al.* (2016).

Source: Own authorship

Table 3. Summary of the literature review on the factors, mechanisms, and intercorrelations among inherent variables and the crop yield formation process.

Crop	Coffee
Leaf area, and/or leaf area index, or growth rate	- Carvalho *et al.* (2006) - Pereira, Camargo, and Villa Nova (2011) - Tozzi and Ghini (2016).
Temperature correlations	- DaMatta and Ramalho (2006); - Martins *et al.* (2014).
Crop coefficient (Kc)	- Doorenbos and Kassan (1979); - Doorenbos and Pruitt (1984); - Pereira, Camargo, and Villa Nova (2011).
Harvest index	- Dias *et al.* (2007).
Stomatal conductance	- DaMatta *et al.* (2016); - Dias *et al*. (2007); - Ramalho *et al*. (2013); - Sanches *et al*. (2017).
Biomass partition	- Dias *et al*. (2007).
Transpiration, CO_2 assimilation and its relationship with atmospheric [CO_2] elevation	- DaMatta and Ramalho (2006); - DaMatta *et al*. (2016); - Dias *et al.* (2007); - Ghini *et al.* (2015); - Tozzi and Ghini (2016).
Water use efficiency	- Ghini *et al.* (2015); - Ramalho *et al* (2013).
Transpiration	- Dias *et al.* (2007); - Sanches *et al.* (2017).

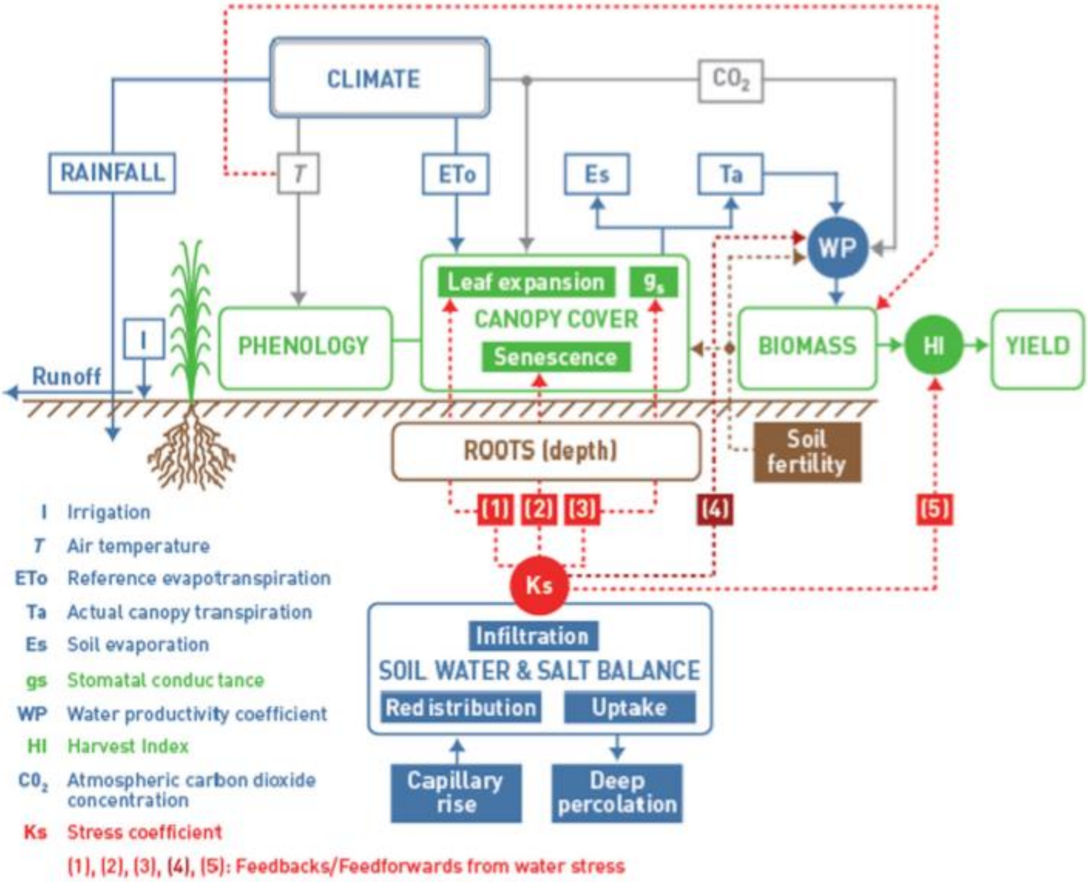
Source: Own authorship

Several of these studies were conducted in chambers with controlled conditions for air temperature, vapor pressure, photosynthetic photon flux density and differentiated CO_2 concentrations. Other studies in a FACE system ("Free Air Carbon Dioxide Enrichment"), which allows the simulation of CO_2 assimilation under field conditions, where the plants are subjected to a routine agricultural practice for commercial crop production. After this literature review (Table 1, Table 2 and Table 3), it was possible to obtain response curves for the crops.

From this literature review, the following coefficients related to carboxylation were obtained: different CO_2 concentrations; air temperature; water deficiency; growth rate of vegetation cover (CC), in some cases; canopy volume or leaf area index; biomass partition; response factor to water stress at different stages of crop development; stomatal conductance; transpiration; CO_2 assimilation; and the relationships between all these variables and water use efficiency. All this information was able to provide the requirements for agroclimatic equations for each crop.

The methodological bases of AquaCrop (versions 4.0 and 6.0) were used, as described in studies published by the Food and Agriculture Organization of the United Nations (FAO) (Raes *et al*., 2009; Raes *et al*., 2012; Steduto, Hsiao and Fereres 2007; Steduto *et al*., 2009), which simulate crop production under climate change conditions. AquaCrop is a model that performs daily water balance and evapotranspiration. In the model, evapotranspiration is separated into evaporation and transpiration, and water consumption under rainfed conditions and complete or deficient irrigation conditions is also considered, simulating the growth and yield of the main herbaceous crops under these situations (Figure 2).

Figure 2. Conceptual diagram of the yield formation process.



Source: adapted from Raes et al. (2018) and Raes et al. (2012).

In AquaCrop, transpiration is proportional to vegetative cover and allows the calculation of the water productivity parameter (WP) mediated by climatic conditions (Raes *et al*., 2009; Steduto *et al*., 2009). In these studies, the authors presented the conceptual structure of AquaCrop (Steduto *et al*., 2009), the algorithms and software solutions (RAES *et al*., 2009), and the normalization of CO_2 concentrations (Steduto; Hsiao; Fereres, 2007). A summary of the variables involved in the crop yield formation process is shown in Figure 2, which represents the conceptual diagram and presents the intrinsic variables related to crop development and yield.

Equations (1), (2) and (3) are fundamental for calculating the water productivity parameter (WP) and for normalizing the atmospheric CO_2 concentration to the water use efficiency for all the studied crops.

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

Where

B: total biomass, g m^{-2} or kg m^{-2};

WP: water productivity parameter (water use efficiency), g m^{-2} mm^{-1} or kg m^{-2} mm^{-1} or kg m^{-3} of transpired water;

Tr: Total transpiration of the crop (mm);
ET_0: Reference evapotranspiration (mm);
CO_2: Atmospheric CO_2 concentration (ppm).

Transpiration was calculated via Equation 2, which was proposed by Raes et al. (2009).

$$Tr = Ks * D * \%CC * Kc_{trx} * ETo \quad (2)$$

where
K_s: water stress coefficient (decimal);
$\%CC$: percentage of canopy cover (decimal);
Kc_{Trx}: crop coefficient (K_c) of maximum transpiration (dimensionless);
ET_0: reference evapotranspiration (mm).

All complex CO_2 fixation metabolic processes, at a biochemical level, are embedded in the parameters of Equations 3 and 4 provided by Steduto, Hsiao and Fereres (2007).

$$WP_{CO_2} = WP_b \frac{C_{a,o}}{C_a} \times D \quad (3)$$

Where
WP_{CO_2}: water use efficiency as a function of CO_2 concentration (g m^{-2} mm^{-1});
WP_b: biomass water use efficiency (g m^{-2} mm^{-1});
$C_{a,o}$: mean annual atmospheric CO_2 concentration measured by the Mauna Loa Observatory (Hawaii) for the reference year;
C_a: mean annual atmospheric CO_2 concentration measured by the Mauna Loa Observatory (Hawaii) for the year in which biomass is produced;
D: an empirical factor derived as an approximation of the sum of Δw, that is, the sum of the difference in water vapor concentration between the intercellular airspace and the atmosphere, in a given situation (Δw) and in a reference situation (Δw_0).

Steduto, Hsiao and Fereres (2007) recommend that D should be obtained via Equation (4), where $C_{a,o}$ is taken as a reference value equal to 360 ppm.

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

Where a=1 and b=0.000138.

To determine the a and b coefficients of Equation (4), Steduto, Hsiao and Fereres (2007) carried out experiments in chambers under controlled conditions for CO_2 and for all parameters related to vapor saturation pressure, air temperature and humidity, among others. Moreover, the authors suggested that Equation (4), through adjustments, could be used for the normalization of different atmospheric CO_2 concentrations.

4.2 Source of information to adapt the ESM-Citrus model for the studied crops (coffee, corn, wheat, soybean and bean)

The growing seasons at BH-ALPA are specific and different for each crop. For winter wheat, the growing season is from May until September; for corn, it is from February until June; for soybean, it is from November until March; for bean, it is from February until June; and for coffee, it is a perennial crop.

According to a survey conducted with ASPIPP members, in the documents of CONAB and Brazilian Agricultural Research Corporation (Embrapa, 2019), almost all the farmers in BH-ALPA work on the determination of evapotranspiration demand, use water evaporation measures from a Class A tank, or use equations to estimate ET_o to determine crop evapotranspiration and, thus, calculate the appropriate irrigation depth. According to information reported by interviewed members of ASPIPP, in some cases, for crop irrigation, the farmers apply all the water used in the evapotranspiration processes, according to a recommendation from EMBRAPA.

Corn, bean and soybean data were obtained from the Olhos d'água farm in Itaí, which uses the center pivot irrigation system. The farm database included the yields and irrigation depths of the studied period. Additionally, as a source of information, reports provided by ASPIPP with crop data at BH-ALPA, as well as all the techniques used during crop management, were used.

In the irrigated area, all the water taken up by evapotranspiration was provided; thus, the stress coefficient (Ks) was equivalent to 1. In the rainfed area, the stress coefficient was calculated annually according to the amount of rainfall, considering the irrigation depth as 100% of the evapotranspiration volume, which is a value equal to 1.

Using effective precipitation and the volume of water supplied to the rainfed area, it was possible to determine the percentage of water stress for this condition. For the irrigated condition, the volume of effective precipitation and irrigation depths were applied. From this and using effective precipitation, the percentage of water stress for the condition without irrigation, the only volume of water that was supplied to the nonirrigated area, was calculated. For the irrigated condition, the volume of effective precipitation and irrigation depths were taken. The total biomass was calculated from the crop yield data. The provided yield data corresponded to the “commercial biomass” under both irrigated and rainfed management conditions. A conversion factor, which is based on previous studies, was used to convert these values into total biomass.

To convert these values into total biomass, a conversion factor based on previous studies was used, which determined that the crop percentage corresponded to the net biomass. A literature review related to the conversion factor for each studied crop is shown in Tables 1, 2 and 3.

The variable canopy volume (Vc) or leaf area index was determined for each studied crop via values established in the literature. In the model, crop water use efficiency is determined, in part, by transpiration, which is related to crop characteristics and the local climate.

The transpiration per plant was obtained from the canopy volume or leaf area index. Using transpiration and the number of plants per hectare (plant density observed on farms), the amount of water transpired per hectare in each agricultural year is reached, with and without irrigation. From an analysis of yield under both irrigated and rainfed management conditions, a multiple linear correlation was created for each crop. Table 4 shows the equations for the rainfed condition.

Table 4. Agroclimatic functions of the studied crops

Crop	Function	R^2
Coffee	WP=56.6833+(-108.3005*Tmax+(-107.15026*Tmín)+204.6874* Tmed)+0.1605* ET0 +0.012415*CO_2)	0.65
Wheat	WP=72.1059422+6.54122*Tmax+7.129*Tmín+(-17.2876* Tmed)+0.178798* ET0 +(-0.000423* Pref)+(-0.13059*CO_2)	0.66
Corn	WP =-97.8192+(0.01549* ET0)+(0.005068* Pref)+0.305012* CO_2	0.81
Bean	WP=-62.1041726+0.00417856*ET0+(-0.00148152*Pref)+0.182616* CO_2	0.72
Soybean	WP=-21.22197906+0.000220966* ET0+0.003081112* Pref +0.07757043* CO_2	0.60

Source: Own authorship

Where:

WP: water productivity parameter (g m^{-2} mm^{-1});

ET_0: reference evapotranspiration (mm);

CO_2: atmospheric CO_2 concentration (ppm);

Pref: effective precipitation during the cycle (mm);

T_{max}: maximum temperature in the yield formation period (°C);

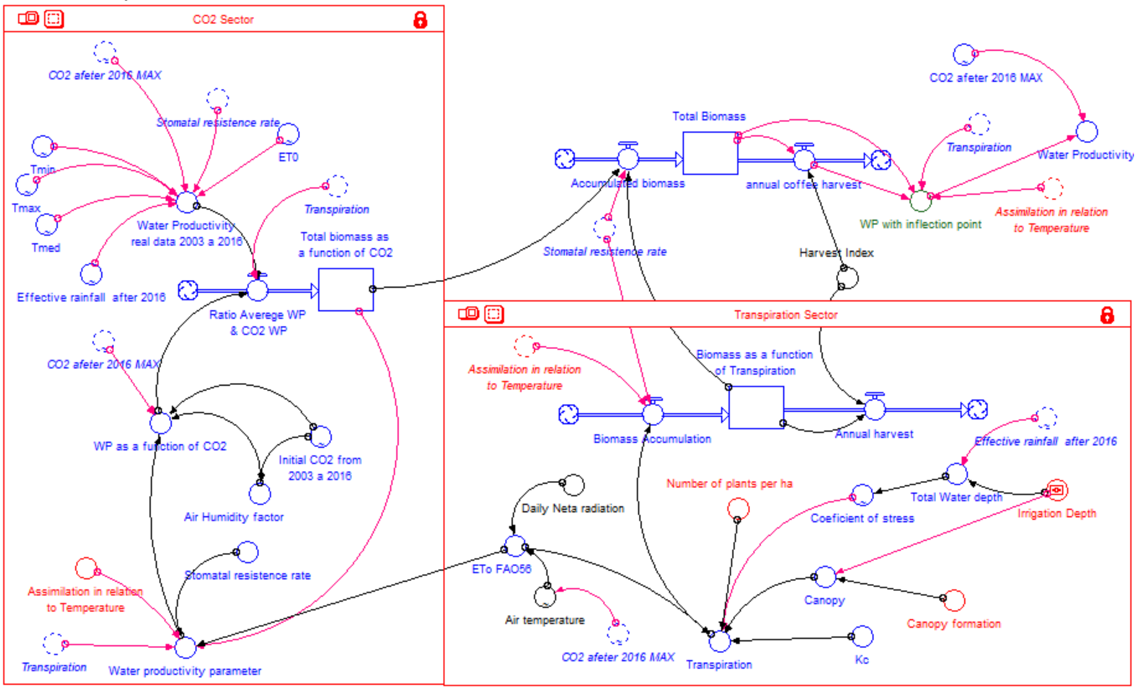
T_{min}: minimum temperature in the yield formation period (°C);

T_{med}: mean temperature in the yield formation period (°C).

The same methodology was used to obtain the correlation for the irrigated condition, adding a variable water depth.

The last step of the methodology is the model configuration, which uses system dynamics to execute and evaluate scenarios of the future impact of climate change on crops such as coffee, wheat, corn, soybeans and beans. The structured model within the STELLA environment includes interactive icons; such icons contain parameters that represent culture and environment characteristics, which account for the formation of water productivity parameters. Figure 3 shows the developed model, represented by the diagram of stocks and flows, which was built from the influences diagram.

Figure 3. Diagram of stocks and flows for coffee, which is similar for wheat, corn, beans and soybeans.



Source: Own authorship

The simulation scenarios estimate the amount (g or kg) of biomass per transpired water (mm) that will be produced in future years, which is based mainly on the atmospheric CO_2 concentration (data projected by the IPCC) and air temperature, which are important in the biomass formation of each studied crop. The scenarios were organized to make two estimations, which were based on two conditions: irrigated (when it was possible to obtain yield data in this condition—soy, corn and bean) and rainfed (all crops).

According to IPCC (2007, 2013) projections, three scenarios are characterized by marked atmospheric CO_2 concentrations: sustainable (BAU) - 387 at 544 ppm, maximum (MAX) - 413 to 1142 ppm and minimum (MIN) - 366 to 794 ppm. Furthermore, air temperature fluctuations, precipitation, reference evapotranspiration, stomatal conductance and the implications of these variables for CO_2 assimilation and water productivity parameters in the production of coffee, wheat, soybean, bean and corn were included.

5 RESULTS AND DISCUSSION

The combination of optimal temperatures for crop development (coffee ~ 25°C, corn ~ 32°C, wheat 18 - 25°C, bean ~ 20 - 25°C and soybean ~ 32°C) with high atmospheric CO_2 concentrations (sustainable - BAU 387 to 544 ppm; minimum - MIN 366 to 794 ppm; maximum - MAX 413 to 1142 ppm) resulted in relatively high values of water use efficiency. Therefore, with the structured models for each crop, which included the atmospheric CO_2 assimilation rates at different air temperatures and several coefficients related to this process as inputs, it was possible to verify the water use efficiency under different climate change scenarios.

As reported by Hatfield et al. (2011), an increase in atmospheric CO_2 generally implies greater production and crop water use efficiency. Ainsworth and Rogers (2007) reported that the leaf photosynthesis rate increases by an average of 40% at high concentrations of CO_2 (475–600 ppm). Allen et al. (2011) reported that the current atmospheric CO_2 concentration limits the growth of C3 plants, which are responsive to high CO_2 by reducing photorespiration and improving photosynthetic rates, thus increasing their growth and yield.

The extensive literature addressing the influence of climate change on agricultural production shows positive and negative photosynthetic responses in different groups of plants, mainly under variable CO_2 concentrations and temperatures (Hatfield 2016; Hatfield *et al*., 2011; Schlenker and Roberts 2009). Damatta et al. (2010) reported that this beneficial effect of high CO_2 in agricultural production can be reduced by other climate change impacts, such as different precipitation patterns and high air temperatures. The authors noted evidence that, under ideal growth conditions (i.e., good temperatures, unrestricted soil water conditions and nutrient availability), C3 plants are more likely to produce more atmospheric CO_2 than are C4 plants.

The simulations performed in the present study revealed that C3 crops (coffee, soybean and bean) more effectively influence CO_2 in CO_2 assimilation and, consequently, greater water use efficiency than C4 crops do (corn) (Figures 4, 5, 6, 7, 8, and 9). Taiz and Zeiger (1991) confirmed that an increase in the atmospheric CO_2 concentration increases the plant growth rate since CO_2 is the primary substrate for photosynthesis. These authors also reported that C3 plants benefit more from higher atmospheric CO_2 concentrations than do C4 plants. The same statement was made by Sicher and Bunce (2015), who reported that C4 plants are not as responsive to CO_2 concentration increases as are C3 plants. Under high temperatures, CO_2 assimilation is more favorable in C4 plants than in C3 plants. Some authors claim that under this condition, photorespiration is stimulated (Damatta *et al*., 2010).

The influence of environmental temperature on growth, development and crop yield formation is complex and multifaceted. The results show that this will be a key variable in yield formation and, consequently, in crop water use efficiency for both management situations (irrigated and rainfed) with high CO_2 concentrations (Figures 4, 5, 6, 7, 8, and 9).

According to Ainsworth et al. (2002), the increase in crop water use efficiency under high CO_2 concentrations is due to decreases in stomatal conductance and transpiration. In this meta-analysis, the authors evaluated soybean studies under high CO_2 (450–1250 ppm) and reported that the benefits of CO_2 in photosynthesis, under normal temperatures, can be partially canceled by the severe thermic stress that may occasionally occur.

By analyzing the generated water productivity parameters and taking the values established by the FAO for C3, coffee, wheat, soybean and bean (15–20 g m^{-2} mm^{-1}) and C4 plants, corn (30–35 g m^{-2} mm^{-1}), the yield and, therefore, the current values of the water productivity parameters until 2016 are well below those indicated by the FAO for management without irrigation. For example, from 2010–2016, corn was 14.6, 16.4, 17.1, 18.0, 17.7, 19.1, and 18.5 g m^{-2} $mm^{-1,}$ respectively, and wheat was 10.7, 11.5, 12.2, 7.6, 10.2, 17.1, and 8.4 g m^{-2} mm^{-1}, respectively. During the same period, irrigated corn grown at BH-ALPA had a water use efficiency within the range established by the FAO, with values of 32.4, 33.3, 33.4, 33.6, 33.8 and 33.7 g m^{-2} mm^{-1}.

According to Conab (2017), the yields of irrigated wheat in the Federal District and Goiás State for medium and large farmers were 6,000 kg ha^{-1} and 5,054 kg ha^{-1} in 2015, respectively. Considering the same survey by Conab (2017), in the study area, specifically in the cities of Avaré, Itapetininga and Itapeva (the most representative region for wheat grown in BH-ALPA), the yields under rainfed conditions were 1,105, 1,067 and 1,414 kg ha^{-1}, respectively, whereas under irrigated conditions, the yield was less than 6,000 kg ha^{-1}, resulting in low water use efficiency under both crop management practices.

The bean growth conditions were similar to those of wheat. In surveys published by CONAB, IBGE and ASPPIP, the current values of the water productivity parameter are below those established by the FAO (15--20 g m^{-2} mm^{-1}); in 2003 and 2004, for example, in large extension and rainfed areas, the yield was less than 900 kg ha^{-1}, implying that the water productivity parameter was approximately 5.2 g m^{-2} mm^{-1}.

The reasons for these results are the large areas at BH-ALPA with the studied crops grown under rainfed conditions; therefore, the expression of the yield potential related to water availability and distribution during the crop development cycle is highly risky. In addition, irrigation technology is not used. According to a survey conducted with the farmers CONAB, IBGE, Instituto de Economia Agrícola (IEA), Rural Development Office (RDO) and ASPIPP, many farmers in this region have not yet adhered to proper crop management practices.

The water use efficiency, influenced by atmospheric CO_2 concentrations, will be greater in areas without irrigation (Figures 4, 5 and 6, for irrigated conditions, and 7, 8 and 9, for rainfed conditions). Xu, Jiang and Zhou (2015) reported that high CO_2 generally increases net photosynthesis in almost all C3 species but not in C4 plants only under water deficit conditions.

Meng et al. (2014), in a study on the interactive effects of high CO_2 concentration and irrigation on photosynthetic parameters and corn yield, reported that, with high CO_2 and suitable irrigation, there was an increase in the net photosynthesis of corn leaves, even though greater water use efficiency occurred in the natural precipitation treatment. Leakey (2006) reported that high CO_2 can increase the photosynthetic capacity and yield of plants by adjusting their water status; therefore, high CO_2 will have a positive effect on water deficit conditions. The authors concluded that photosynthesis and corn yield are not affected by the increase in CO_2 in the absence of water deficit conditions.

Figure 4. Water productivity parameter, under irrigated condition, obtained in BAU scenario for corn, bean and soybean at specific temperatures for each crop.

BAU scenario

Corn Bean Soybean

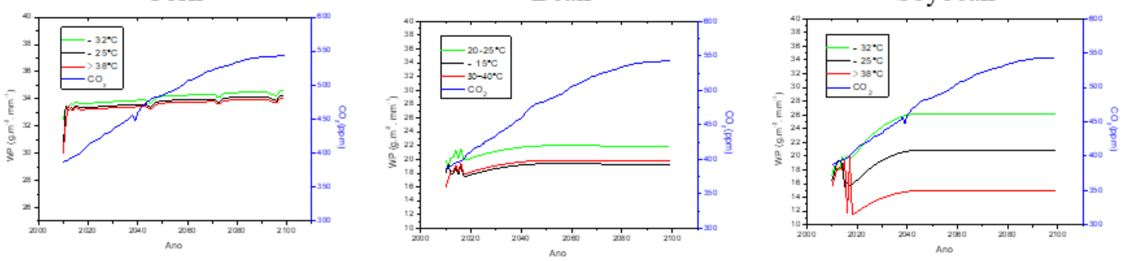


Figure 5. Water productivity parameter, under irrigated condition, obtained in MAX scenario for corn, bean and soybean at specific temperatures for each crop.

MAX scenario

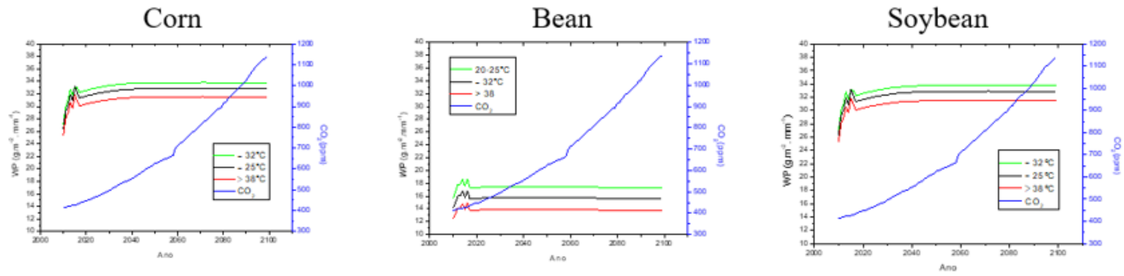
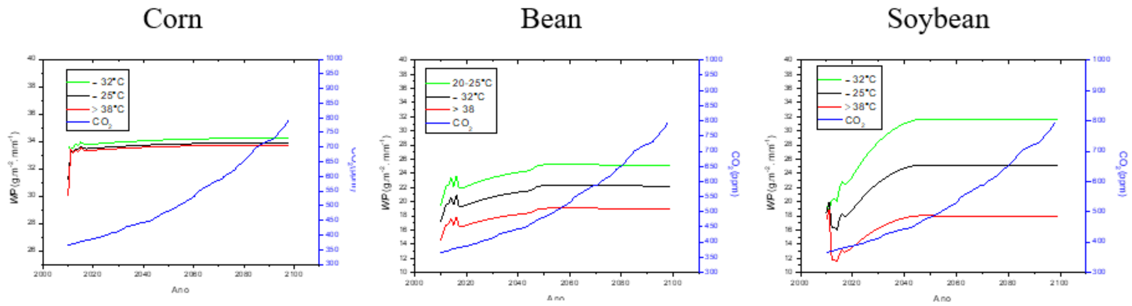


Figure 6. Water productivity parameter, under irrigated condition, obtained in MIN scenario for corn, bean and soybean at specific temperatures for each crop.

MIN scenario



Source: Own authorship

The results for the water productivity parameters of corn, bean and soybean under irrigated conditions at UGRHI 14 (Figures 4, 5 and 6) verified that the temperature effect was more notable for soybean in the BAU and MIN scenarios, where changes in climate based on temperature had a significant effect on biomass formation; in other words, a temperature increase above 38°C markedly reduced the yield of this crop.

Sicher and Bunce (2015) reported that the ideal temperature for soybean photosynthesis increases with increasing CO_2 concentration. According to the authors, this is due to photorespiration suppression and an increase in carboxylation caused by CO_2 enrichment. Another reason noted by these authors is that C4 plants are effectively saturated with environmental CO_2.

The simulation results for future years, from 2020 to 2100, show a stabilization in the amount (g) of phytomass per transpired water (mm) with the increase in atmospheric CO_2 bean for the MAX scenario and a moderate increase in water use efficiency for the BAU and MIN scenarios if the air temperature remains between 18 and 28°C, which is considered optimal for bean development.

To understand which climate change scenario would promote the best performance for the studied crops, a separate crop analysis was carried out for the established scenarios BAU, MAX and MIN.

5.1 BAU

An analysis of the water use efficiency in the BAU, MAX and MIN scenarios, shown in Figures 4, 5 and 6, reveals that the best performance scenario for the studied scenario will be the BAU scenario under irrigated conditions, with the exception of the bean crop, which will perform better under the MAX scenario.

Compared with the MAX and MIN scenarios, the BAU scenario results in reduced CO_2 emissions, which will culminate in the most favorable environment configuration for crop development in terms of temperature, evapotranspiration, relative humidity and precipitation (Ipcc, 2007, 2014).

From the results shown in Figures 4, 5 and 6, it is evident that, under irrigation, the temperature is an extremely important variable in terms of water use efficiency. The BAU and MIN scenarios clearly reveal the influence of this variable on soybean yield. The projected value of water use efficiency for the decade of 2040 under a temperature of approximately 32°C was 25.92 g m^{-2} mm^{-1}, whereas for a temperature of approximately 38°C, the water use efficiency was equivalent to 14.5 g m^{-2} mm^{-1}.

Allen Júnior et al. (2003) tested the effects of temperature combinations of 28/18, 32/26, 36/26, 40/30, 44/34°C (day/night), and CO_2 concentrations (350 and 700 ppm) on soybean evapotranspiration and water use efficiency and reported that although treatments with temperatures of 36/26°C and 40/30°C presented a relatively high canopy photosynthetic rate, they did not provide greater water use efficiency. Additionally, the authors reported that with a 700 ppm CO_2 concentration, the water use efficiency increased by approximately 60% at 28/18°C but did not increase at 40/30°C and concluded that the water use efficiency steeply decreased in treatments with relatively high temperatures, mainly because the ETo increased.

For rainfed soybean in the BAU scenario and with the optimal development temperature, in 2009 and 2016, the water productivity parameters were 13.9 g m^{-2} mm^{-1} and 19.9 g m^{-2} mm^{-1}, respectively. In future decades, the increase in atmospheric CO_2 will imply a continuous increase in the water productivity parameter, reaching 2100 with 45.6 g m^{-2} mm^{-1} at the optimal development temperature, approximately 32°C, which is more than twice the maximum value (20 g m^{-2} mm^{-1}) for C3 plants specified by the FAO (Figures 7, 8 and 9). Krishnan et al. (2007) verified, via model simulations, a 56% reduction in rice yield if the CO_2 concentration was equivalent to 700 ppm and if the air temperature increased by 4°C.

In the same way, wheat and corn accumulate in biomass. Therefore, the water use efficiency, which is strongly influenced by the atmospheric CO_2 concentration combined with the air temperature, will have, among all the studied crops, better performance in the BAU scenario.

Several studies have shown that corn, under high atmospheric CO_2 concentrations, can maintain high photosynthetic and transpiration rates in the face of limited water conditions and that this crop benefits from the increase in CO_2 in dry conditions (Allen Júnior *et al*., 2011; Leakey *et al*., 2009; Meng *et al*., 2014; Manderscheid; Erbs; Weigel, 2014). Allen Júnior et al. (2011) revealed that corn was unable to maintain high photosynthetic rates and to increase water use efficiency under water stress and CO2 concentrations, highlighting the beneficial effect of increasing CO_2 for this crop (at a favorable temperature).

In the BAU scenario simulations, an increase in the CO_2 concentration significantly increased the water use efficiency of coffee if there was no increase or sudden decrease in the air temperature. According to DaMatta et al. (2016), the ideal temperature for coffee development is between 18 and 26°C. Therefore, in this scenario and under these temperature conditions, the water use efficiency of coffee will increase, with values of 20 g m^{-2} mm^{-1} in 2020 and 48 g m^{-2} mm^{-1} in 2100. However, if the temperature increases above 35°C, an effective reduction in the carboxylation efficiency will provide a water use efficiency of approximately 6 g m^{-2} mm^{-}

^{1} in 2100, indicating crop vulnerability to future temperature fluctuations in BH-ALPA for the BAU, MAX and MIN scenarios under rainfed conditions (Figures 4, 5 and 6).

Ramalho et al. (2013) reported significant increases in water use efficiency, between 56% and 112%, which was supported by the continued trend of increased photosynthesis and decreased stomatal conductance with increased CO_2. In general, the results of DaMatta et al. (2016) and Ramalho et al. (2013) suggest that coffee can tolerate high CO_2 concentrations under optimal conditions of water, temperature and nutrient availability. The authors also mentioned that coffee notably benefited from the increase in CO_2 concentration, as did other species whose photosynthesis was largely limited by CO_2 diffusion.

Under rainfed conditions (Figures 7, 8 and 9), soybean, corn and wheat perform better in terms of water use efficiency in the BAU scenario than beans do. In these crops, the CO_2 assimilation curves always increase. A bean will have a moderate increase in water use efficiency if the air temperature does not fall outside the range of considered optimal temperatures for bean development, i.e., between 18 and 28°C.

5.2 MAX

The impact of climate change analyzed from MAX scenario simulations shows a marked reduction in the yield of coffee, wheat, corn, soybean and bean in BH-ALPA, especially when high atmospheric CO_2 concentrations are combined, an intrinsic characteristic of this scenario, with temperatures that negatively influence crop development (Figure 7). For corn, for example, the results show that the best temperature to express the potential yield is approximately 30°C. Considering this temperature, until the 2050s, the MAX scenario will provide similar values for corn to those seen in the BAU scenario.

In general, projections of increases in air temperature indicate great variation in crop yield. According to Hatfield et al. (2011), this variation occurs because the increase in temperature implies an increase in the phenological development rate, resulting in a reduction in the growth cycle and, consequently, a reduction in crop yield. Schlenker and Roberts (2009) and Hatfield et al. (2011) reported that, in a high-temperature stressful environment, the yields of soybean and corn vary by more than 50%. For wheat, as observed by Tack, Barkley and Nalley (2015), very high temperatures sharply decrease production.

Similar to what was verified for wheat, grown rainfed corn (Figures 7, 8 and 9) has reduced productivity in BH-ALPA, with a value of 13.3 g m^{-2} mm^{-1} in 2010. The results show that corn without irrigation will only reach values within the standards for C4 plants determined by the FAO, i.e., 30–35 g m^{-2} mm^{-1}, whereas in 2100 in the BAU scenario, it will reach 31.8 g m^{-2} mm^{-1}. In no other studied scenario will corn reach the FAO standard value under rainfed conditions, which highlights the importance of using irrigation to increase the resilience of agricultural crops in situations of climate change. Compared with the other studied scenarios, the MAX scenario results in the lowest water use efficiency values under irrigated conditions. However, the water use efficiency will be within the standard range established by the FAO (Figures 4, 5 and 6). For rainfed conditions, coffee and wheat in the MAX scenario will provide reduced CO_2 assimilation and, thus, will be the worst atmospheric environmental configuration for these crops (Figures 7, 8 and 9). Notably, coffee will have an approximately 88% reduction in the water productivity parameter in the 2060s if the air temperature increases to values close to or above 36°C, ranging from 43.6 to 4.9 g m^{-2} mm^{-1}.

The model developed for beans generated results that show that it will be the only crop with the best performance in the MAX scenario under rainfed conditions. In this scenario and management condition, at the end of the projection period (2090 and 2100), the water use efficiency for beans is even higher than the projected values in the BAU scenario. However, in the projections for the irrigated area among the three studied scenarios, the MAX scenario provides yield reduction and, consequently, a reduction in the water use efficiency of beans. This scenario promotes a marked reduction in the water productivity parameter for beans under irrigated conditions.

5.3 MIN

The MIN scenario is more similar, in the atmospheric configuration, to the BAU scenario, even with respect to the atmospheric CO_2 concentration. In the 2050s, in the IPCC projections, both the BAU scenario and MIN scenario presented similar CO_2 concentrations. In relation to the performance of the studied crops in this scenario and the simulations for the rainfed condition, coffee will have a CO_2 assimilation rate and, consequently, water use efficiency, similar to the BAU scenario.

The water use efficiency of corn in the MIN scenario and rainfed conditions (Figures 7, 8 and 9) was lower than the projected values for the BAU and MAX scenarios. For the irrigated condition, which also considers corn, the water productivity parameter values are essentially the same between the BAU and MIN scenarios (Figures 7 and 8).

In general, corn and bean will suffer negative impacts from the atmospheric configuration of the MIN scenario, and they will have the worst performance in this scenario under rainfed conditions (Figures 7, 8 and 10). When running the simulations for the irrigated condition in this scenario, the water productivity parameter values for soybeans and beans are even higher than the values found in the BAU scenario (Figures 4, 5 and 6).

A general observation from the results is that the benefits of high CO_2 concentrations for photosynthesis and, therefore, for better water use efficiency for the studied crops, are enhanced at environmental temperatures favorable for crop development. Therefore, a comparison of the CO_2 concentration levels (BAU, MIN and MAX) revealed that mean air temperatures of approximately 25 and 30°C benefit atmospheric CO_2 assimilation and imply higher water productivity parameter values.

Figure 7. Water productivity parameter, under rainfed condition, obtained in BAU scenario for coffee, wheat, corn, soybean and bean at the specific temperatures for each crop.

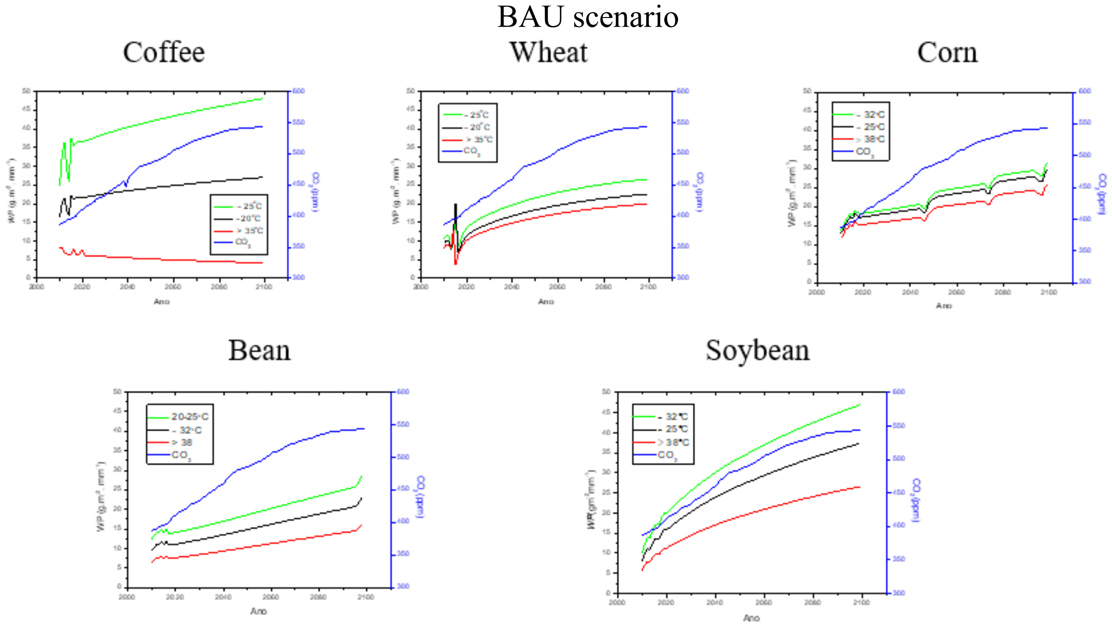


Figure 8. Water productivity parameter, under rainfed condition, obtained in MAX scenario for coffee, wheat, corn, soybean and bean at the specific temperatures for each crop.

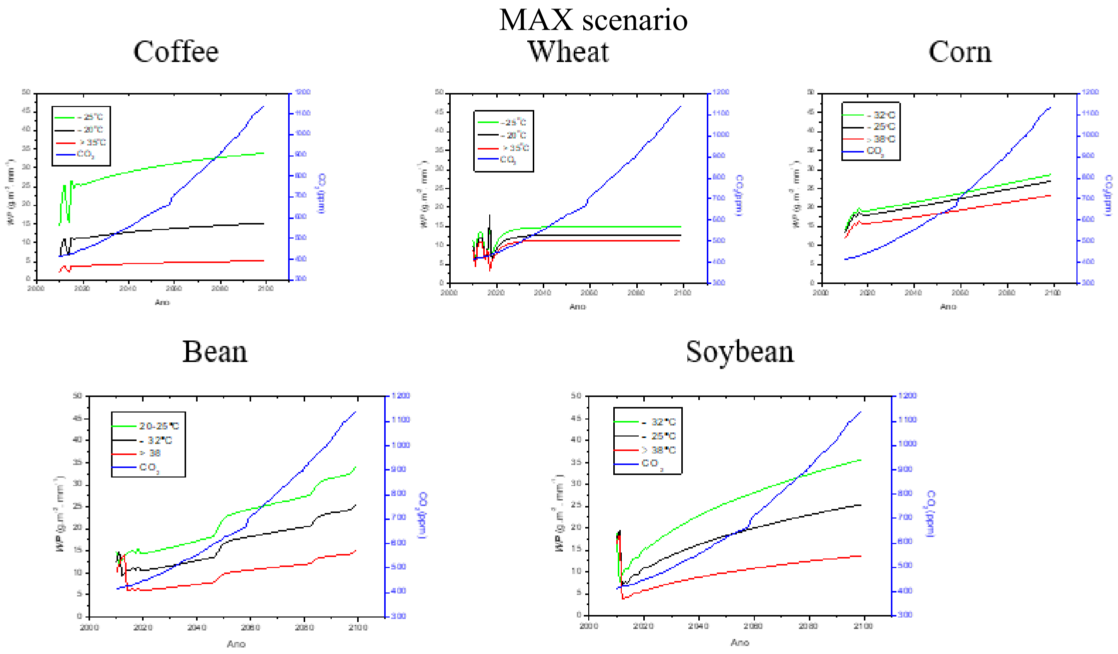
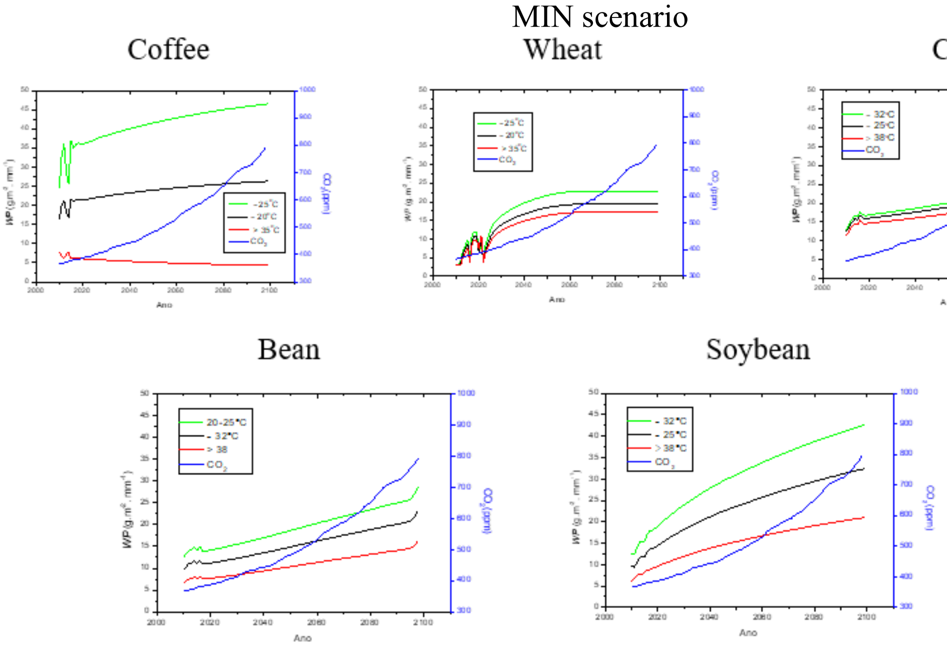


Figure 9. Water productivity parameter, under rainfed condition, obtained in MIN scenario for coffee, wheat, corn, soybean and bean at the specific temperatures for each crop.



Source: Own authorship

The results shown in Figures 7, 8 and 9 indicate that an increase in CO_2 does not result in an increase in water use efficiency for wheat, as was the case for soybean and bean. Plant growth is influenced by a combination of factors. Streck and Alberto (2006), studying the impacts of climate change on crop yield, reported that even though the modeled values for productivity are high due to high CO_2 concentrations, these beneficial effects can be inhibited by the simultaneous increase in air temperature.

A comparison of the results obtained from the two management situations, i.e., irrigated and rainfed (Figures 7, 8 and 9), revealed that the increase in atmospheric CO_2 provides greater efficiency in terms of water use for corn when this crop is cultivated under rainfed conditions because, when irrigated in 2010 and 2100, the water use efficiency was 32.4 and 34.6 g m^{-2} mm^{-1}, respectively. However, under rainfed conditions, the water use efficiency of this crop ranged from 14.6 g m^{-2} mm^{-1} in 2010 to 31.8 g m^{-2} mm^{-1} in 2100 (BAU scenario). Therefore, an increase in atmospheric CO_2 will support an increase in water use efficiency under water deficit conditions. Under conditions of high atmospheric CO_2 concentrations and limited soil water, corn can maintain high photosynthetic rates. These results confirm those reported by Leakey et al. (2009), Leakey (2006), Allen Júnior et al. (2011) and Meng et al. (2014).

6 CONCLUSION

From the structured model simulations, it is possible to infer that, in the future, plant transpiration will be altered by climatic changes. Thus, in general, crop water productivity may decrease. In the BAU, MAX and MIN scenarios, the water productivity parameter progressively decreases with increasing air temperature. High CO_2 concentrations can also increase water use efficiency, especially if the increase in this gas in the atmosphere is combined with optimum air temperatures for crop growth, which will benefit yield and water use efficiency, especially in areas without irrigation.

The BAU scenario, with a temperature of approximately 32°C, will provide the best crop performance, resulting in greater water use efficiency in future decades. In contrast, the MAX scenario will result in a marked reduction in the water productivity parameter, especially when combined with temperatures that are limiting for crop development, showing that water use efficiency will significantly decrease in a climate change environment on the basis of an increase in CO_2 and an increase in air temperature for crops.

C3 crops, mainly coffee, soybean and bean, are more responsive to high atmospheric CO_2 and have greater water use efficiency than the C4 crop corn. However, at high temperatures, the water use efficiency for CO_2 assimilation is greater in C4 plants than in C3 plants.

Bean will be the only crop to benefit from atmospheric CO_2 elevation in the MAX scenario if the air temperature does not suffer from continuous elevation.

Under irrigation conditions, the scenario that results in the greatest water use efficiency for beans and soybeans will be the MIN scenario, and those for corn will be the BAU and MIN scenarios.

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8 REFERENCES

AINSWORTH, E. A.; DAVEY, P.; BERNACCHI, C. J.; DERMODY, O.; HEATON, E. A.; MOORE, D. J.; MORGAN, P. B.; NAIDU, S. L.; YOO, H.-S.; ZHU, X.-G.; CURTIS, P. S.; LONG, S. P. A metaanalysis of elevated [CO2] effects on soybean (*Glycine max*) physiology, growth and yield. **Global Change Biology,** Chichester, v. 8, n. 8, p. 695-709, 2002.

AINSWORTH, E. A.; LONG, S. P. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. **New Phytologist,** Oxford, v. 165, n. 2, p. 351-372, 2005.

AINSWORTH, E.; ROGERS, A. The Response of Photosynthesis and Stomatal Conductance to Rising [CO2]: Mechanisms and Environmental Interactions. **Plant, Cell & Environment,** Chichester, v. 30, n. 3, 258-270, 2007.

ALJAZAIRI, S.; ARIAS, C.; NOGUÉS, S. Carbon and nitrogen allocation and partitioning in traditional and modern wheat genotypes under pre-industrial and future CO_2 conditions. **Plant Biology**, Chichester, v. 17, n. 3, p. 647-659, 2015. Available at: https://onlinelibrary.wiley.com/doi/epdf/10.1111/plb.12280. Accessed on: 4 Sept. 2019.

ALLEN JÚNIOR; L. H.; PAN, D.; BOOTE, K. J.; PICKERING, N. B.; JONES, J. W. Carbon Dioxide and Temperature Effects on Evapotranspiration and Water Use Efficiency of Soybean. **Agronomy Journal,** Madison, v. 95, n. 4, p. 1071-1081, 2003.

ALLEN JÚNIOR, L. H.; KAKANI, V. G.; VU, J. C. V., BOOTE, K. J. Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. **Journal of Plant Physiology,** Muenchen, v. 68, n. 16, p. 1909-1918, 2011.

AMTHOR, J. S. Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. **Field Crops Research**, Amsterdam, v. 73, n. 1, p. 1-34, 2001.

ANDRADE, C. L T.; ALBUQUERQU, P. E. P.; BRITO, R. A. L.; RESENDE, M. **Viabilidade e Manejo da Irrigação da Cultura do Milho.** Sete Lagoas: Embrapa Milho e Sorgo, 2006. (Circular Técnica, n. 85).

BEHLULI, A.; CANKO, A.; FETAHU, S. Leaf Area and Dry Matter Accumulation Dynamic in two Biological Types of Common Bean (Phaseolus vulgaris L.). **Albanian Journal of Agricultural Sciences,** Tirana, v. 17, n. 3, p. 143-149, 2018.

BERNACCHI, C. J.; MORGAN, P. B.; ORT, D. R.; LONG, S. P. The growth of soybean under free air [CO_2] enrichment (FACE) stimulates photosynthesis while decreasing in vivo Rubisco capacity. **Planta**, Heidelberg, v. 220, p. 434-446, 2005.

BIZARI, D. R.; MATSURA, E. E.; ROQUE, M. W.; SOUZA, A. L. Consumo de água e produção de grãos do feijoeiro irrigado em sistemas plantio direto e convencional. **Ciência Rural**, Santa Maria, v. 39, n. 7, p. 2073-2079, 2009.

CALVACHE, A. M.; REICHARDT, K.; MALAVOLTA, E.; BACCHI, O. O. S. Efeito da deficiência hídrica e da adubação nitrogenada na produtividade e na eficiência do uso de água em uma cultura do feijão. **Ciência Agrícola**, Piracicaba, v. 54, n. 3, p. 232-240, 1997.

CAPRA, F. **The web of life**. New York: Anchor, 1996.

CARVALHO, C. H. M.; COLOMBO, A.; SCALCO, M. S.; MORAIS, A. R. Evolução do crescimento do cafeeiro (Coffea arabica L.) irrigado e não irrigado em duas densidades de plantio. **Ciência e Agrotecnologia**, Lavras, v. 30, n. 2, p. 243-250, 2006.

CETEC; CTGEO. **Plano de bacia hidrográfica do alto Paranapanema 2012/2015**. Lins: Comitê da Bacia Hidrográfica do Alto Paranapanema, 2015. Available at: http://www.sigrh.sp.gov.br/public/uploads/documents/8776/planodebaciacbhalpa.pdf. Accessed on: 05 Oct. 2015.

CIIAGRO. **Ciagro Olnline:** Resenha Agrometeorológica. Campinas**:** Instituto Agronômico de Campinas, 2018. Available at: http://www.ciiagro.sp.gov.br/ciiagroonline/Listagens/Resenha/LResenhaLocal.asp. Accessed on: 30 May 2019.

CONAB. **A cultura do trigo**. Brasília, DF: Conab, 2017. Available at https://www.conab.gov.br/uploads/arquivos/17_04_25_11_40_00_a_cultura_do_trigo_versao_digital_final.pdf. Accessed on: 17 Jan. 2019.

DAMATTA, F. M.; GRANDIS, A.; ARENQUE, B. C.; BUCKERIDGE, M. S. Impacts of climate changes on cropp physiology and food quality. **Food Research International**, Oxford, v. 43, n. 7, p. 1814-1823, 2010.

DAMATTA, F. M.; RAMALHO, J. D. C. Impacts of drought and temperature stress on coffee physiology and production: A review. **Brazilian Journal Plant Physiology**, Campinas, v.18, n. 1, p. 55-81, 2006.

DAMATTA, F. M.; GODOY, A. G.; MENEZES-SILVA, P. E.; MARTINS S. C. V.; SANGLARD, L. M. V. P.; MORAIS, L. E.; TORRE-NETO, A.; GHINI. R. Sustained enhancement of photosynthesis in coffee trees grown under free-air CO_2 enrichment conditions: disentangling the contributions of stomatal, mesophyll, and biochemical limitations. **Journal of Experimental Botany**, Oxford, v. 67, n. 1, p. 341-352, 2016.

DEMÉTRIO, C. S.; FORNASIER FILHO, D.; CAZETTA, J. O.; CAZETTA, D. A. Desempenho de híbridos de milho submetidos a diferentes espaçamentos e densidades populacionais. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 43, n. 12, p. 1691-1697, 2008.

DIAS, P. C.; ARAÚJO, W. L.; MORAES, G. A.; BARROS, R. S.; DAMATTA, F. M. Morphological and physiological responses of two coffee progenies to soil water availability. **Journal Plant Physiology**, Muenchen, v. 164, n. 12, p. 1639-1647, 2007.

DOORENBOS, I.; KASSAN, A. H. **Yield response to water**. Roma: FAO, 1979. (Irrigation Drainage Paper, 33).

DOORENBOS, J.; PRUITT, W. O. **Guidelines for predicting crop water requirements**. Rome: FAO, 1984.

EMBRAPA. **Monitoramento de Irrigação no Cerrado**. Brasília, DF: Embrapa Cerrados, 2019. Available at: http://hidro.cpac.embrapa.br/index.php. Accessed on: 30 Apr. 2019.

FAROOQ, M.; BRAMLEY, H.; PALTA, J. A.; SIDDIQUE. K. H. M. Heat Stress in Wheat during Reproductive and Grain-Filling Phases. **Critical Reviews in Plant Sciences**, New York, v. 30, n. 6, p. 1-17, 2011.

FUJIMURA, S.; SHI, P.; IWAMA, K.; ZHANG, X.; GOPAL, J.; JITSUYAMA, Y. Effects of CO_2 Increase on Wheat Growth and Yield under Different Atmospheric Pressures and Their Interaction with Temperature. **Plant Production Science**, Abingdon, v. 15, n. 2, p. 118-124, 2012.

GHINI, R.; TORRE-NETO, A.; DENTZIEN, A. F. M.; GUERREIRO-FILHO, O.; IOST, R.; PATRÍCIO, F. R. A.; PRADO, J. S. M.; THOMAZIELLO, R. A.; BETTIOL, W.; DAMATTA, F. M. Coffee growth, pest and yield responses to free-air CO_2 enrichment. **Climatic Change**, Princeton, v. 132, n. 2, p. 307-320, 2015.

HAMILTON III, E. W.; HECKATHORN, S. A.; JOSHI, P.; WANG, D.; BARUA, D. Interactive Effects of Elevated CO_2 and Growth Temperature on the Tolerance of Photosynthesis to Acute Heat Stress in C_3 and C_4 Species. **Journal of Integrative Plant Biology**, Pequim, v. 50, n. 11, p. 1375-1387, 2008.

HATFIELD, J. L. Increased Temperatures Have Dramatic Effects on Growth and Grain Yield of Three Maize Hybrids. **Agricultural & Environmental Letters Research Letter**, Madison, v. 1, n. 1, p 1-5, 2016.

HATFIELD, J. L.; BOOTE, K. J.; KIMBALL, B. A.; ZISKA, L. H.; IZAURRALDE, R. C.; ORT, D.; THOMSON, A. M.; WOLFE, D. W. Climate impacts on agriculture: implications for crop production. **Agronomy Journal**, Madison, v. 103, n. 2, p. 351-370, 2011.

IBGE. **Produção Agrícola** - Lavoura Temporária. Rio de Janeiro: IBGE, 2011. Available at: https://cidades.ibge.gov.br/brasil/sp/sao-miguel-arcanjo/pesquisa/14/0?ano=2014. Accessed on: 23 Mar. 2019.

IBGE. **Produção Agrícola** - Lavoura Temporária. Rio de Janeiro: IBGE, 2018. Available at: https://cidades.ibge.gov.br/brasil/sp/sao-miguel-arcanjo/pesquisa/14/0?ano=2015. Accessed on: 23 Mar. 2019.

IPCC. **Climate change 2014**: synthesis report. Geneva: IPCC, 2014. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf. Accessed on: 4 jan. 2019.

IPCC. **Climate change 2007**: Impacts, Adaptation and Vulnerability. Cambridge: Cambridge University Press, 2007. Available at: https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf. Accessed on: 04 out. 2018.

IPCC. Summary for Policymakers. *In*: IPCC. **Global warming of 1.5 °C**. Geneva: World Meteorological Organization, 2018. p. 1-26.

JADOSKI, S. O.; CARLESSO, R.; MELO, G. L.; RODRIGUES, M.; FRIZZ, Z. Manejo da irrigação para maximização do rendimento de grãos do feijoeiro. **Irriga,** Botucatu, v. 8, n. 1, p. 1-9, 2003.

KANE, K.; DAHAL, K. P.; BADAWI, M. A.; HOUDE, M.; HÜNER, N. P.; SARHAN, F. Long-term growth under elevated CO_2 suppresses biotic stress genes in non-acclimated, but not cold-acclimated winter wheat. **Plant Cell Physiology**, Oxford, v. 54, n. 11, p. 1751-1768. 2013.

KRISHNAN, P.; SWAIN, D. K.; BHASKAR, B. C.; NAYAK, S. K.; DASH, R. N. Impact of elevated CO_2 and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 122, n. 2, p. 233-242, 2007.

LEAKEY, A. D. B.; URIBELARREA, M.; AINSWORTH, E. A.; NAIDU, S. L.; ROGERS, A.; ORT, D. R.; LONG, S. P. Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. **Plant Physiology**, Rockville, v. 140, n. 2, p. 779-790, 2006.

LEMOS, J. P.; GALVÃO, J. C. C.; SILVA, A. A.; FONTANETTI, A.; CORRÊA, M. L. P.; CECON, P. R. Morphophysiology of Corn Plants in Competition with Picao-Preto and Trapoeraba Submitted to Clearings. **Planta Daninha**, Viçosa, v. 30, n. 3, p. 487–496, 2012.

LI, D.; LIU, H.; QIAOA, Y.; WANG, Y.; CAI, Z.; DONG, B.; SHI, C.; LIU, Y.; LI, X.; LIU, M. Effects of elevated CO_2 on the growth, seed yield, and water use efficiency of soybean (*Glycine max* (L.) Merr.) under drought stress. **Agricultural Water Management**, Amsterdam, v. 129, n. C, p. 105-112, 2013.

LOBELL, D. B.; FIELD, C. B., Global scale climate-crop yield relationships and the impacts of recent warming. **Environmental Research Letters,** Bristol, v. 2, n. 1, p. 1-7, 2007.

LOBELL, D. B.; ROBERTS, M. J.; SCHLENKER, W.; BRAUN, N.; LITTLE, B. B.; REJESUS, R. M.; HAMMER, G. L. Greater sensitivity to drought accompanies maize yield increase in the US Midwest. **Science**, Washington, DC, v. 344, n. 6183, p. 516-519, 2014.

MADHU, M.; HATFIELD, J. L. Interaction of Carbon Dioxide Enrichment and Soil Moisture on Photosynthesis, Transpiration, and Water Use Efficiency of Soybean. **Agricultural Sciences**, Irvine, v. 5, n. 5, p. 410-429, 2014.

MANDERSCHEID, R.; MARTIN, E.; WEIGEL, H-J. Interactive effects of free-air CO_2 enrichment and drought stress on maize growth. **European Journal of Agronomy**, Amsterdam, v. 52, n. 2, p. 11-21, 2014.

MARTINS, L. D.; TOMAZ, M. A.; LIDON, F. C.; DAMATTA, F. M.; RAMALHO, J. C. Combined effects of elevated [CO2] and high temperature on leaf mineral balance in Coffea spp. Plants. **Climatic Change**, Princeton, v. 126, n. 3/4, p. 365-379, 2014.

MENG, F.; ZHANG, J.; YAO, F.; HAO, C. Interactive Effects of Elevated CO_2 Concentration and Irrigation on Photosynthetic Parameters and Yield of Maize in Northeast China. **PLOS ONE,** Washington, DC, v. 9, n. 8, p. 1-13, 2014.

OGINDO, H. O.; WALKER, S. The determination of transpiration efficiency coefficient for common bean. **Physics and Chemistry of the Earth,** Oxford, v. 29, n. 18-19, p. 1083-1089, 2004.

PEREIRA, F. F S.; SÁNCHEZ-ROMÁN, R. M.; ORELLANA GONZÁLEZ, A. M. G. Simulation model of the growth of sweet orange (Citrus sinensis L. Osbeck) cv. Natal in response to climate change, **Climate Change**, Princeton, v. 143, p. 101-113, 2017.

PEREIRA, R.; CAMARGO, M. B. P.; VILLA NOVA, N. A. Coffee crop coefficient for precision irrigation based on leaf area index. **Bragantia**, Campinas, v. 70, n. 4, p. 946-951, 2011.

PIMENTEL, C.; RIBEIRO, R. V.; MACHADO, E. C.; SANTOS, M. G.; OLIVEIRA, R. F. In vivo temperature limitations of photosynthesis in Phaseolus vulgaris L. **Environmental and Experimental Botany**, Amsterdam, v. 91. p. 84-89, 2013.

POLANIA, J. A.; POSCHENRIEDER, C.; BEEBE, S.; RAO, I. M. Effective Use of Water and Increased Dry Matter Partitioned to Grain Contribute to Yield of Common Bean Improved for Drought Resistance. **Frontiers in Plant Science**, Lausanne, v. 7, p. 1-10, 2016.

RAES D.; STEDUTO, P.; HSIAO, T.C.; FERERES, E. AquaCrop – The FAO crop model to simulate yield response to water. *In*: FAO. **AquaCrop**. Version 4.0. Roma: FAO, 2009. Chap. 1.

RAES, D.; STEDUTO, P.; HSIAO, T. C.; FERERES, E. Calculation procedures. *In*: FAO. **AquaCrop**. Version 4.0. Roma: FAO, 2012. Chap. 3.

RAES, D.; STEDUTO, P.; HSIAO, T.C.; FERERES, E. Crop-water productivity model to simulate yield response to water. *In*: FAO. **AquaCrop**. Version 6.0-6.1: Reference Manual. Rome: FAO, 2018. Chap 1.

RAMALHO, J. C.; RODRIGUES, A. P.; SEMEDO, J. N.; PAIS, I. P.; MARTINS, L. D.; SIMÕES-COSTA, M. C.; LEITÃO, A. E.; FORTUNATO, A. S.; BATISTA-SANTOS, P.; PALOS, I. M.; TOMAZ, M. A.; SCOTTI-CAMPOS, P.; LINDON, F. C.; DAMATTA, F. M. Sustained photosynthetic performance of Coffea spp. under long-term enhanced [CO_2]. **PLoS One**, Washington, DC, v. 8, n. 12, p. 1-19, 2013.

RAY, J. D.; GESCH, R. W.; SINCLAIR, T. R.; ALLEN, L. H. The effect of vapor pressure deficit on maize transpiration response to a drying soil. **Plant and Soil,** Netherlands, v. 239, p. 113-121, 2002.

RIBEIRO, A. B. M.; BRUZI, A. T.; ZUFFO, A. M.; ZAMBIAZZI, E. V.; SOARES, I. O.; VILELA, N. J. D.; PEREIRA, J. L. A. R.; MOREIRA, S. G. Productive performance of soybean cultivars grown in different plant densities. **Ciência Rural**, Santa Maria, v. 47, n. 7, p. 1-8, 2017.

RIBEIRO, R. V.; SANTOS, M. G.; SOUZA, G. M.; MACHADO, E. C.; OLIVEIRA, R. F.; ANGELOCCI, L. R.; PIMENTEL, C. Environmental effects on photosynthetic capacity of bean genotype. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 39, n. 7, p. 615-623, 2004.

SANCHES, R. F. E.; CATARINO, I. C. A.; BRAGA, M. R.; SILVA, E. A. Influência da alta concentração atmosférica de CO2 (↑[CO2]atm) × disponibilidade hídrica nas relações hídricas, trocas gasosas e acúmulo de carboidratos em Coffea arabica L. **Hoehnea**, São Paulo, v. 44, n. 4, p. 635-643, 2017.

SANTOS, D.; GUIMARÃES, V. F.; KLEIN, J.; FIOREZE, S. L.; MACEDO JÚNIOR, E. K. Wheat cultivars submitted to water deficit at the beginning of flowering in greenhouse. **Revista Brasileira de Engenharia Agrícola e Ambiental,** Campina Grande, v. 16, n. 8, p. 836-842, 2012.

SCHLENKER, W.; ROBERTS, M. J. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. **Proceedings of the National Academy of Sciences**, Washington, DC, v. 106, n. 37, p. 15594-15598, 2009.

SICHER, R. C.; BUNCE, J. A. The Impact of Enhanced Atmospheric CO_2 Concentrations on the Responses of Maize and Soybean to Elevated Growth Temperatures. *In*: Combined Stresses in Plants Physiological, Molecular, and Biochemical Aspects Mahalingam, 2015. R., Ed.; Springer: Nova York, NY, EUA, 2015; pp. 27–48.

SIKDER, S.; QIAO, Y.; BAODI, D.; SHI, C.; LIU, M. Effect of water stress on leaf level gas exchange capacity and water-use efficiency of wheat cultivars. **Indian Journal of Plant Physiology**, New Delhi, v. 21, n. 3, p. 300-305, 2016.

SORATTO, R. P.; FERNANDES, A. M.; PILON, C.; CRUSCIOL, C. A. C.; BORGHI, E. Timing of nitrogen application on common bean cultivated after single corn or intercropped with palisade grass. **Pesquisa agropecuária brasileira**, Brasília, DF, v. 48, n. 10, p. 1351-1359, 2013.

STEDUTO, P.; HSIAO, T. C.; FERERES, E. On the conservative behavior of biomass water productivity. **Irrigation Science**, Heidelberg, v. 25, n. 3, p. 189-207, 2007.

STEDUTO, P.; HSIAO, T. C.; RAES, D.; FERERES, E. AquaCrop - The FAO Crop Model to simulate Yield Response to Water: I. Concepts and Underlying Principles. **Agronomy Journal**, Madison, v. 101, n. 3, p. 426-437, 2009.

STRECK, N. A.; ALBERTO, C. M. Estudo numérico do impacto da mudança climática sobre o rendimento de trigo, soja e milho. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 41, n. 9, p. 1351-1359, 2006.

STRECK, N. A. Climate change and agroecosystems: the effect of elevated atmosferic CO_2 and temperature on crop growth, development, and yield. **Ciência Rural**, Santa Maria, v. 35, n. 5, p. 734-744, 2005.

TACK, J.; BARKLEY, A.; NALLEY, L. L. Effect of warming temperatures on US wheat yields**. Proceedings of the National Academy of Sciences**, Washington, DC, v. 112, n. 22, p. 1-6, 2015.

TAIZ, L.; ZEIGER, E. **Plant physiology**. Redwood City: Benjamin: Cummings Pub. Co., 1991.

TOZZI, F. R. O.; GHINI, R. Impacto do aumento da concentração atmosférica de dióxido de carbono sobre a ferrugem e o crescimento do cafeeiro. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 51, n. 8, p. 933-941, 2016.

VOGEL, E.; DONAT, M. G.; ALEXANDER, L. V.; MEINSHAUSEN, M.; RAY, D. K.; KAROLY, D.; MEINSHAUSEN, N.; FRIELER, K. **The effects of climate extremes on global agricultural yields. Environmental Research Letters**, Bristol, v. 14, n. 5, p. 1-12, 2019. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/ab154b/pdf. Accessed on: 23 Aug. 2019.

WU, D.-X.; WANG, G.-X.; BAI, Y.-F.; LIAO, J.-X. Effects of elevated CO_2 concentration on growth, water use, yield and grain quality of wheat under two soil water levels. **Agriculture, Ecosystems and Environment**, Amsterdam, v. 104, p. 493-507, 2004.

XU, Z.; JIANG, Y.; ZHOU, G. Response and adaptation of photosynthesis, respiration, and antioxidant systems to elevated CO_2 with environmental stress in plants. **Frontiers in Plant Science**, Lausanne, v. 6, article 701, p 1-17, 2015.