

SIMULATING OF FUTURE CLIMATE CONDITIONS ON THE EFFECT OF IRRIGATION ON SUGARCANE YIELD IN SOUTHERN BRAZIL

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ABSTRACT

The objective of this study was to evaluate the technical and economic feasibility of installing central pivot irrigation systems in current days (Scenario A) and in two future scenarios, one with a 10% increase in rainfall (Scenario B1) and the other with 10% reduction in rainfall (Scenario B2). For both future scenarios, an increase of 2°C in the global temperature and the concentration of atmospheric carbon dioxide (CO₂) increasing to 528 ppm (parts per million) were considered. For the study, the recommendation for an area of clayey soil and with the sugarcane cycle was evaluated on three different planting dates: May 15, August 15 and November 15. The DSSAT/CANEGRO model was used, and under the current conditions, the simulations indicated greater yield for planting in May, both for rainfed and irrigated. For scenario B1, there was an increase in yield of 22% for rainfed and 33% for irrigated. In addition, irrigation provided yield gains in the two future scenarios of 13% and 14% for B1 and B2, respectively. Based on the results obtained, central pivot irrigation proved economically viable in the simulated climatic conditions. Therefore, the increase in sugarcane production provided by irrigation in agronomic management was sufficient to make investment in the region in question feasible. It is suggested to repeat the study in other regions, since the existing synergy between the factors that define agricultural yield can change the decision making about the implantation of irrigation systems in the production environment.

Keywords: Climate change, *Saccharum* spp., irrigation, crop modeling, DSSAT

**SIMULAÇÃO DAS CONDIÇÕES CLIMÁTICAS FUTURAS SOBRE O EFEITO DA
IRRIGAÇÃO NA PRODUTIVIDADE DA CANA-DE-AÇÚCAR NO SUDESTE
BRASILEIRO**

RESUMO

O objetivo deste estudo foi avaliar a viabilidade técnico-econômica da instalação de sistemas de irrigação do tipo pivô-central em dias atuais (Cenário A) e em dois cenários futuros, um com aumento em 10% na pluviosidade (Cenário B1) e outro com redução em 10% na pluviosidade (Cenário B2). Para ambos os cenários futuros, foi considerado um aumento de 2 °C na temperatura global e a concentração de dióxido de carbono (CO₂) atmosférico aumentando para 528 ppm (partes por milhão). Para o estudo, avaliou-se a recomendação para uma área de solo argiloso e com o ciclo da cana-de-açúcar em três diferentes datas de plantio: 15 de maio, 15 de agosto e 15 de novembro. Utilizou-se o modelo DSSAT/CANEGRO e, nas condições atuais, as simulações indicaram maior produtividade para o plantio em maio, tanto para sequeiro quanto para irrigado. Para o cenário B1, observou-se aumento na produtividade de 22% para sequeiro e 33% para irrigado. Além disso, a irrigação proporcionou ganhos de produtividade nos dois cenários futuros de 13% e 14% para B1 e B2, respectivamente. Baseando-se nos resultados obtidos, a irrigação por pivô central mostrou-se viável do ponto de vista econômico nas condições climáticas simuladas. Portanto, o incremento na produção de cana-de-açúcar proporcionado pela irrigação no manejo agrônomo foi suficiente para viabilizar o investimento na região em questão. Sugere-se repetir o estudo em outras regiões, pois a sinergia existente entre os fatores que definem a produtividade agrícola pode alterar a tomada de decisão sobre implantação de sistemas de irrigação no ambiente de produção.

Palavras-chave: Mudanças climáticas, *Saccharum* spp., irrigação, modelagem, DSSAT

INTRODUCTION

Currently, there is much debate on the global climate issue and, in 2015, the 21st Conference of the Parts (COP21) took place, in which the “Paris Agreement” was approved, whose objective is to limit the Earth’s warming to 2°C (EPE, 2016). Among the various strategies discussed, the replacement of fossil fuels by biofuels appears as the second most cited strategy, mainly in middle-income countries (FGV, 2017).

Faced with this future scenario, Brazil guaranteed its engagement in the proposal by creating the National Biofuels Program (Renovabio), which encourages sustainable production and the consumption of biofuels (FGV, 2017). The Program guaranteed predictability for the entire sugar and energy chain. With this, it is expected that there will be an increase in investments involving the sector and an increase in the supply and demand for hydrated and anhydrous ethanol (ethanol mixed with gasoline). Both are the main biofuels in terms of production and national consumption, in addition to having excellent technical and economic performance. Consequently, there may be an impact on the demand for sugarcane, the main raw material used in Brazil to produce ethanol. Therefore, the sector should work to increase the sugarcane agricultural yield (MARIN, 2016).

One of the future challenges that sugarcane and other crops will have will be the effect of climate change on agricultural production. The supposed increases in temperature and in the concentration of atmospheric CO₂ may have a negative or positive impact, depending on the physiological characteristics of the crop, the production environment and the management adopted.

At the current juncture, there are several technological alternatives that allow the design of future agricultural scenarios. Among the most used are agricultural models, mathematical analogs obtained to represent real systems (AGUIRRE, 2000). Process-based models use input data with meteorological variables, soil, plant nutritional status and management adopted under present scenarios and, with data representing future scenarios, estimate what will be the production of the crops. The Intergovernmental Panel on Climate Change (IPCC) made available, in its fourth report, data on the projection made for the increase in global temperature, indicating values between 1.8-3.6°C and an increase in the concentration of CO₂ that can reach 700 ppm in 2090-2099 (TRENBERTH et al., 2007). One of the variables that can be simulated in the search for good results, given the projected scenario, is that of irrigation management.

One of the systems that uses crop simulation models is the platform DSSAT-Decision Support System for Agrotechnology Transfer (JONES et al., 2003). This platform includes the CANEGRO model (SINGELS et al., 2008), containing support tools that assist in the manipulation of climate, soil, experimental conditions and genotype information of sugarcane crop. The system also allows seasonal and sequential simulations for the application of risk and impact studies associated with climate change (HOOGENBOOM et al., 2014).

One of the main factors affecting the yield of any agricultural crop is water availability. It is no different for sugarcane, since the water deficit can compromise production considerably depending on the variety, the phenological stage in which the plant is located and the duration of the deficit period (FARIAS et al., 2008). Inman-Bamber & Smith (2005) report that the sugarcane phase most susceptible to water stress is that of stem growth, as it causes a decrease in yield by reducing sucrose accumulation and phytomass production (ROBERTSON et al., 1999; SILVA & COSTA, 2004). Thus, irrigation appears as an alternative to maintain adequate soil water conditions throughout the crop cycle.

In a study conducted by Silva et al. (2014) on the yield potential of different cultivars of sugarcane irrigated fully by drip during two cycles, the authors reported yield above the minimum required for area renewal (six cuts or up to 65 Mg ha⁻¹). This makes it possible to increase the longevity of sugarcane, depending on the increase in production provided by irrigation. Oliveira et al. (2011) conducted a study in two environments with different water regimes and observed that there was a significant difference in crop yield, with average gains of 116 Mg ha⁻¹. The authors observed that this difference can be explained by the fact that, when irrigation depths are lower than the available water storage capacity in the soil, production gains are limited. Significant increases in yield are achieved when irrigation is performed to ensure water availability throughout the growth period. This stimulates the production of cytokinin, phytonomium responsible for the vegetative growth of the plant area part (TAKEI et al., 2002). The combination of right water availability and cytokinin allows greater absorption of nutrients by the root system of the plant and, consequently, the increase in tillering and stem elongation (INMAN-BAMBER & SMITH, 2005; SINGH et al., 2007).

Another important factor to be considered in plant production is the concentration of CO₂. Knowing the prospects made for the future climate, it is extremely important to understand the effect of increasing the concentration of this gas on agricultural production. From the point of view of plant physiology, an increase in CO₂ concentration would lead, first, to the partial closure of the stomata, which would reduce the stomatal conductance (VOLPE et al., 2011; MADEGOWDA MADHU & JERRY L. HATFIELD, 2014) and respiration (KUMAR et al., 2019). Consequently, the effects of water stress would be relatively minor. Studies indicate that the increase in CO₂ concentration in a controlled environment generates increases in the photosynthetic rate of sugarcane, water use efficiency, biomass production and yield (VU & ALLEN Jr., 2009). However,

Stokes et al. (2016) did not observe an increase in biomass production of the crop. The authors explain that the observed increase in sugarcane yield may have been influenced by the absence of water deficiency in the soil. In addition, different responses may occur due to plant age and variety used (SAGE, 2002).

Therefore, it is understood that future climatic effects on sugarcane production may vary for each region, suggesting studies with a regional focus. Thus, this study aims to evaluate the technical and economic feasibility of the implementation of an irrigation system in the sugarcane crop in the county of Ribeirão Preto, State of São Paulo, Brazil, under current and future climatic conditions.

MATERIAL AND METHODS

The simulations in this study was made using the climatic conditions of the county of Ribeirão Preto, state of São Paulo, Brazil, with headquarters located at latitude of 21°10'38" S, longitude 47°48'37" O and altitude of 531 m. The climate is characterized as semi-humid tropical, with rainy season in summer and drier season in winter (type Aw in Köppen-Geiger climatic classification). The average temperatures are higher than 18°C in all months of the year, with an annual average of 21.9°C, and the rainfall index is around of 1500 mm/year, concentrated between October and April, with January being the month of greatest precipitation (274 mm). The original vegetation of the county predominates the Atlantic Forest.

Model setup and data collect

This study was conducted with the understanding of the DSSAT/CANEGRO model, using the climatic database of the Region of Ribeirão Preto (SP) (current climate) and modeling two possible futures scenarios for sugarcane crop, aiming to compare yield in rainfed and irrigated systems, as well as to estimate the feasibility of irrigation by the central pivot method in the current and future scenario. Figure 1 shows the pattern of climate variation in Ribeirão Preto (SP).

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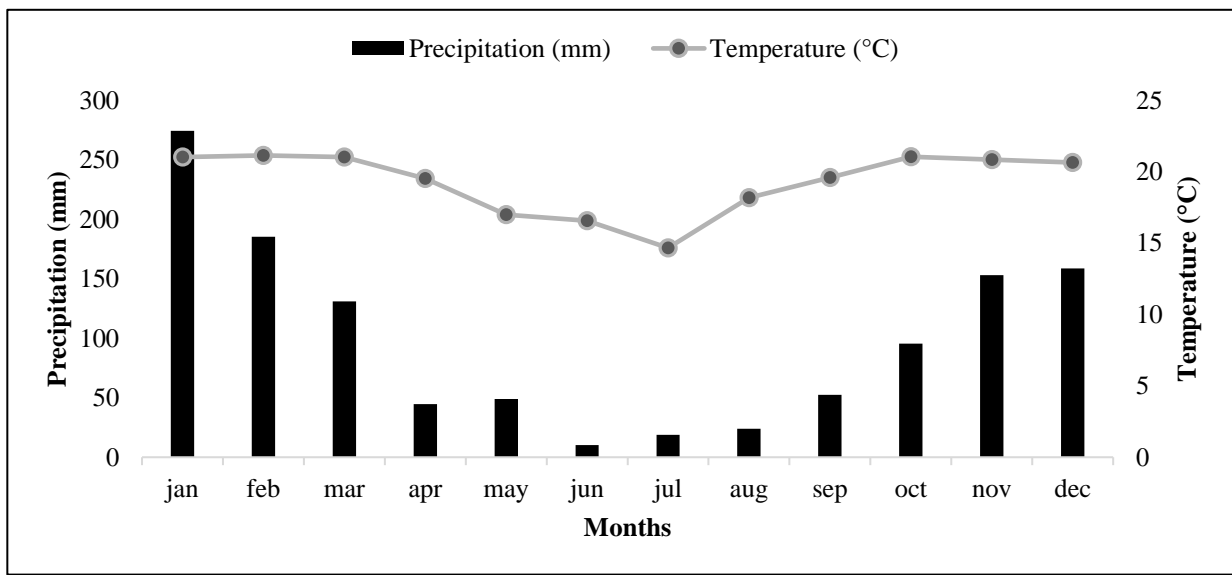


Figure 1. Monthly averages of temperature (°C) and precipitation (mm) for the period between 2001 and 2009 for Ribeirão Preto, São Paulo State, Brazil.

Soil characterization

Was searched Embrapa's soil profile database (EMBRAPA SOLOS, 2020) to represent the predominant soil in the simulation model, collecting soil profile data with the same classification as the studied region. Thus, the type of soil chosen for the simulations was the Red Nitosol, which has high iron content (above 15%), has cerosity, dark red coloration, is eutrophic and has high Cation Exchange Capacity (CTC). The soil physical-water data are defined by the DSSAT itself according to the registration in the software database. As for management, it has a frequent risk of erosion due to the bumpy relief in which it is located (SOUZA; LOBATO, 2013). It is a clay soil, with a structure that favors water retention, and maintains good drainage (IAC, 2020). Such characteristics mentioned are extremely important when it comes to water availability for plant production.

Planting conditions and cultivar

The cultivar of sugarcane used was RB-867515 using the calibration provided by Marin et al (2015). The simulations were made presenting three planting dates [May 15, August (Aug) 15 and November (Nov) 15] using the period from 2001 to 2009 as a historical series for the calculations in the future scenarios. The crop cycle was 12 months, with the harvest always one

day before planting. It was assumed that all nutritional needs of the crop were hit, so that the only variables were water availability and climate change (temperature and CO₂ concentration) all over the time. The plant population considered was 15 plants.m⁻² with spacing between lines of 150 cm and planting depth of 15 cm.

Future simulations and projections

Combinations were made regarding the studied site, soil, cultivation system (rainfed and irrigated), planting date and current and future scenarios (Table 1).

Table 1. Schematization of the data to be simulated. Ribeirão Preto, São Paulo State, Brazil.

Treatment	Local	Soil	Condition	Planting Dates	Scenario	[CO ₂] (ppm)	Historical Series
1	Ribeirao Preto	Red Nitosol	Rainfed	May 15	Current	415	2001-2009
				Aug 15	Future (B1)	528	
				Nov 15	Future (B2)	528	
2	Ribeirao Preto	Red Nitosol	Irrigated	May 15	Current	415	2001-2009
				Aug 15	Future (B1)	528	
				Nov 15	Future (B2)	528	

Subtitle: [CO₂] - CO₂ Concentration in ppm (parts per million)

The simulations with irrigation were made to add water automatically just when necessary, according to the weather in each year simulated, to supply the water demand of the crop and the deficiency of rain. The same procedure was performed for future scenarios. Two future scenarios were proposed for rainfall: an increase of 10% (B1) and a 10% reduction (B2); one future temperature scenario: increase of 2°C; and an increase in atmospheric CO₂ concentration to 528 ppm.

Simulation environment

The yield of Fresh Stalk Yield of the stem (FSY, Mg ha⁻¹), Sucrose Yield (SY, Mg ha⁻¹) and water productivity (WP, kg of dry matter mm⁻¹) were simulated, considering dry matter yield values (DMY, Mg ha⁻¹), in the regimes of rainfed (rain) and irrigated (rain and irrigation) using the

CANEGRO model (INMAN-BAMBER,1991; SINGELS et al., 2008). This model simulates the growth dynamics, which involves the production of phytomass, and the development of sugarcane, involving the accumulation of sucrose with consequent stretching of the stems. For simulation, was used meteorological data of the region, management characteristics of the production environment, characteristics of the chosen cultivar and soil properties, such as soil content, factors that can affect photosynthesis, growth, transpiration rate and carbohydrate partition (PAGANI et al., 2017).

To quantify the production of phytomass per unit of area, or yield and sucrose production, as well as its accumulation in the stems, the DSSAT/CANEGRO model uses as a calculation basis the quantification of photosynthesis through the calculation of daily biomass increment (P_G , $g\ m^{-2}\ d^{-1}$), which, at the end of the harvest period, was named Fresh stalk yield being the sum of P_G daily until harvest. The calculation is based on the efficiency of radiation use (SINGELS & BEZUIDENHOUT, 2002) and an algorithm for computing fertilization caused by atmospheric CO_2 (SINGELS et al., 2013), as follows in equation 1:

$$P_G = FI * PAR * RUE * R_{PG} \quad \text{Equation 1.}$$

Where FI is the intercept fraction of the flux density of photosynthetically active photons (PAR , $MJ\ m^{-2}$) and RUE is the efficiency of radiation use ($g\ MJ^{-1}$). The default value of $[CO_2]=330$ ppm is used by the model for calculating P_G and is then adjusted by the adjustment factor (R_{PG}) that depends on $[CO_2]$. The value of R_{PG} is calculated by combining a set of coordinated points. Each of these points is defined in the DSSAT System species file and a corn-derived function (extracted from the source code of the 2011 version of DSSAT v 4.5).

Water productivity is simulated from a derivation of the method proposed by Martiné et al. (2003), with adjustments included based on the experiments by Nassif et al. (2013). The equations below are used to calculate the rate of variation of the water mass in the stem each day, taking into an account dry matter and accumulated sucrose mass.

$$dSTKWater = (3,607 * dWS) - (3,078 * dWSuc) \quad \forall SWFP > 0,6 \quad \text{Equação 2.}$$

$$dSTKWater = (STKURed * WS) \quad \forall SWFP \leq 0,6 \quad \text{Equação 3.}$$

In which $dSTK_{Water}$ is the daily increment rate of water per mass of stem, dWS is the daily increment rate of structural dry matter of the stem; $dWSuc$ is the daily increment rate of sucrose mass in the stem; $STKURed$ is a factor in reducing the rate of water in the stem in conditions of severe drought and that varies as a function of stem mass and humidity, varying as shown in Figure 2.

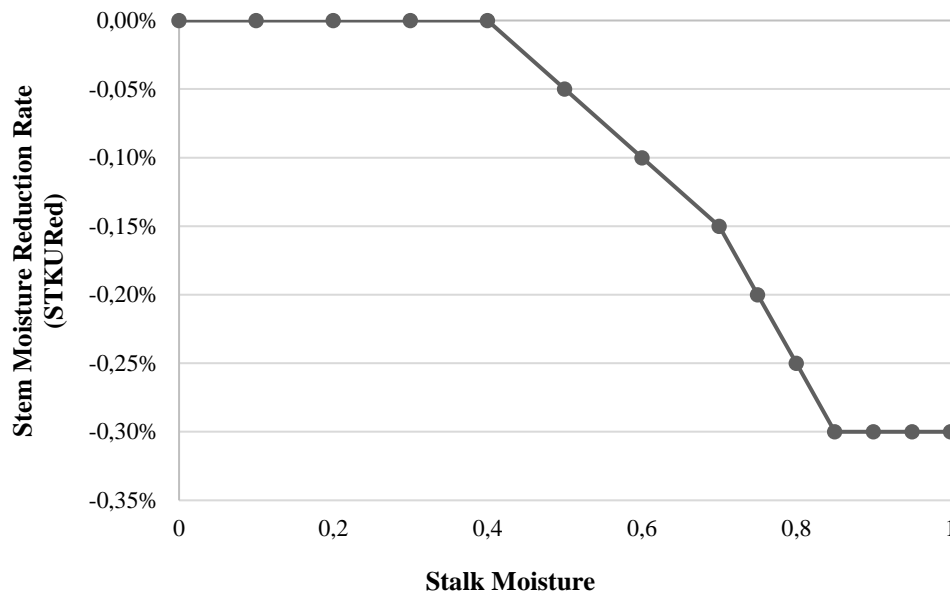


Figure 2. Variation of the rate of reduction of relative stem moisture as a function of stalk moisture and total stem mass, under severe water stress conditions. Source: MARIN (2014).

Economic feasibility analysis

For economic feasibility analysis for investments in the agro-industrial chain of sugarcane, it is necessary to understand how the sugarcane payment system called "Sucrose Sugarcane Payment" (PCTS from the Portuguese acronym) works, which follows the standards of the CONSECANA for the calculation of the industrial technological parameters of sugarcane. Some variables are obtained specifically with the aid of equipment that gives the value directly, which can be changed throughout the harvest period. Table 2 shows an example of these parameters. The rest are obtained through formulas to get in the final and most important equation as shown in Equation 4. It was provided by the CONSECANA, with the purpose of calculating the value of Total Sugar Recovered (ATR in $kg\ ha^{-1}$), a parameter priced in the market. Payment is made from the result of ATR (CONSECANA, 2006).

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Table 2. Industrial Qualitative Parameters analyzed with measurements equipment. Ribeirão Preto, São Paulo State, Brazil.

Sugarcane Industrial Parameters	
Analisy Period	August
°Brix	20
Weight of humid mass (g)	130
LAI	70
S	11

Legend: Brix - Soluble solids; LAI - Saccharimeter reading obtained with aluminum-based clarifying mixture; S - Pol of extracted broth.

$$ATR (kg ton^{-1}) = (9,6316 * POL CANE(\%) + 9,15 * ARC(\%)) * 10 \quad \text{Equation 4.}$$

Thus, for this work, estimates were made for the three cut-off dates, both for the current scenario and for the future, calculating the arithmetic mean of FSY and SY parameters and using the 9 years of simulation. Next, the arithmetic mean was calculated again for both variables analyzed, using the three planting dates. With this it was possible to calculate the amount of ATR, in kg Mg⁻¹ of sugarcane, for all scenarios considered, from the sucrose contents found.

In addition, a hypothetical area of 5,000 ha was considered, and it is worth mentioning that, in smaller and/or larger areas, the result will be the same in relation to the interpretation of the data acquired through the economic feasibility study of the proposed system, both for the current scenario and for the future. In addition, the cost of sugarcane implantation used was R\$ 6,258.41 ha⁻¹ (Table 3), the sugarcane maintenance cost was R\$ 1,193.58 ha⁻¹ (Table 4) and the implantation pivot (CAPEX) was R\$ 7,738.79 ha⁻¹ (Table 5) with the annual maintenance cost (OPEX) of the equipment of R\$ 1,335.25 ha⁻¹ (Table 5). It is worth mentioning that the cost calculation of operations as well as equipment were made considering the cost table for 2014 updated for the year 2018 using the value of General Price Index in di mode (IGP-DI) of 1.23.

Table 3. Table of costs for the implantation of the sugarcane field. Ribeirão Preto, São Paulo State, Brazil. 2018.

OPERATION	COST (R\$ ha⁻¹)
I. PREPARING THE SOIL	-
1. GRADATION (HEAVY)	R\$ 120.07
2. PALLIATION	R\$ 173.41
3. GRADATION (HEAVY)	R\$ 120.07
4. GRADATION (LIGHT)	R\$ 75.69
5. CARCARRIER MARKING	R\$ 20.51
6. TERRACE	R\$ 42.00
7. APPLICATION OF LIMESTONE	R\$ 43.39
8. CALCARIUM	R\$ 219.88
9. ADMINISTRATOR (10%)	R\$ 81.50
SUBTOTAL	R\$ 896.53
II- PLANTING	-
1. SULCATION	R\$ 182.09
2. FERTILIZER	R\$ 641.21
3. MUTE CUT (CLEAN)	R\$ 303.46
4. SEEDLING	R\$ 2,358.49
5. LOADING CHANGES	R\$ 51.59
6. SHIPPING CHANGES	R\$ 107.90
7. STEMS CUTTING	R\$ 366.74
8. FINISHING AND RECOVERY	R\$ 177.83
9. RECOVERY	R\$ 46.92
9.1. INSETICIDE	R\$ 214.97
10. HERBICIDE APPLICATION	R\$ 35.24
11. HERBICIDE	R\$ 131.93
12. ANT CONTROL	R\$ 1.41
12.1. DRILL CONTROL	R\$ 19.65
13. CARPA CONTROL	R\$ 158.87
14. LOMBO BREAK	R\$ 76.15
15. ADMINISTRATOR (10%)	R\$ 487.45
SUBTOTAL	R\$ 5,361.87
TOTAL	R\$ 6,258.41

Source: GALINDO & CARVALHO, 2016.

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Table 4. Table of costs for maintaining the cane field. Ribeirão Preto, São Paulo State, Brazil. 2018.

OPERATION	COST (R\$ ha⁻¹)
I. MANAGEMENT OF 2nd HARVEST AND BEYOND	-
1. UNRAKE	R\$ 29.60
2. CULTIVATION	R\$ 153.12
3. FERTILIZER	R\$ 436.69
4. HERBICIDE APPLICATION	R\$ 35.24
5. HERBICIDE	R\$ 74.93
6. ANT CONTROL	R\$ 1.41
6.1. DRILL CONTROL	R\$ 19.65
6.2. CIGARRINHA'S CONTROL	R\$ 108.10
7. CARPA CONTROL	R\$ 226.33
9. ADMINISTRATOR (10%)	R\$ 108.50
SUBTOTAL	R\$ 1,193.58

Source: GALINDO & CARVALHO, 2016.

Table 5. Table of investment costs for the used central pivot irrigation system (CAPEX) and equipment maintenance costs over a 15 year useful life (OPEX). Ribeirão Preto, São Paulo State, Brazil. 2018.

DESCRIPTION	PIVOT
APPLICATION EFFICIENCY RATE	85%
APPLIED DEPTH (mm)	500
INFRASTRUCTURE INVESTMENT	R\$ 1,228.38
EQUIPMENT (IRRIGATION SYSTEM/SET MOTOR PUMP/TUBES/TRACTOR)	R\$ 6,141.90
INSTALLATION	R\$ 368.51
CAPEX/HA	R\$ 7,738.79
ENERGY (R\$/HA)	R\$ 541.72
DIESEL OIL / TRACTOR (R\$/HA)	R\$ 8.60
MAINTENANCE (R\$/HA)	R\$ 232.16
ADMINISTRATIVE EXPENSES	R\$ 85.99
EMPLOYEE (R\$/HA)	R\$ 466.78
OPEX/HA	R\$ 1,335.25
R\$/MM APPLIED	R\$ 3.44
R\$/ MM EFFECTIVE*	R\$ 4.05

*Applied blade (mm) multiplied by the application efficiency rate.

The variables used to assess the economic viability of irrigation were: (i) Net Present Value (NPV), an important tool to determine the present value of future payments discounted at an appropriate interest rate, minus the cost of the initial investment, according to equation 5

(MACEDO, 2007). It is from the NPV that the options will be analyzed and that will assist in the decision-making as to the realization of the investment or not, as shown in table 6; (ii) Internal Rate of Return (IRR), considered to calculate the discount rate that must have a cash flux so that your NPV equals zero (CRUZ, 2011). It is observed that when an investment is proposed the IRR must be greater than zero and the NPV, positive, to ensure that the investment will bring profit. To complement the analysis, the return period of the investment in question ("payback period" or ROI (Return on Investment)) was identified to check, at the end of the analysis, whether the investment is economically viable, and the time required for the return on capital invested to an investor, in the form of net profit (2011).

$$NPV = \sum_{j=1}^n \frac{FC_j}{(1+i)^j} - FC_0 \quad \text{Equation 5.}$$

where NPV is the net present value (R\$);

FC_0 is the initial investment cost (R\$);

FC_j is the inputs (revenues) and outflows (costs) expected for each future period (R\$);

i is the interest rate or discount rate (%);

j is the period;

n is the project life (years).

Table 6. Decision making considering the value of the NPV.

Calculated NPV condition	Likely decision-making
$NPV > 0$	Realization of the investment
$NPV < 0$	Non-realization of the investment
$NPV = 0$	Indifferent (the investor should look at other economic indices)

RESULTS AND DISCUSSION

Fresh stalk yield and sucrose yield

Tables 7 and 8 show the values of Fresh Stalk Yield (FSY) and Sucrose Yield (SY) in Mg ha⁻¹ for sugarcane under rainfed and irrigated cultivation conditions for three distinct planting dates in the current scenario. It was noted that there was higher production of fresh stalk and sucrose in

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the planting treatment in May, for both cultivation conditions. Both yields were higher in the irrigated environment compared to the rainfed condition. In several crops, irrigation is observed to supply the water demand of plants and promotes an increase in potential yield.

Figure 3 shows the variation in the amount of fresh stalk produced by sugarcane each year, together with sucrose yield. In 2004, the highest yield values were obtained for the two cultivation conditions (rainfed and irrigated). The use of irrigation resulted in an increase of 4.02% for FSY and a drop of 2% for SY. Water availability defined the establishment of the crop during the vegetative stage (RAMESH, 2000), that is, the lack of water during this initial period can reduce biomass and sucrose production. However, if the vegetative phase of the production cycle has passed, the lack of water may compromise the production of phytomass, but not the production of sucrose that can even be increased, because vegetative growth occurs in order to compete with the sucrose accumulation process (FARIAS, 2008). That is, in moments that provide vegetative growth of the plant, sucrose accumulation will be minimal. Only when the conditions begin to limit the vegetative phase that the plant begins its process of sucrose accumulation in the stem, in the so-called maturation phase (FARIAS, 2008). Thus, there was an increase in biomass yield and a slight fall in sucrose accumulation.

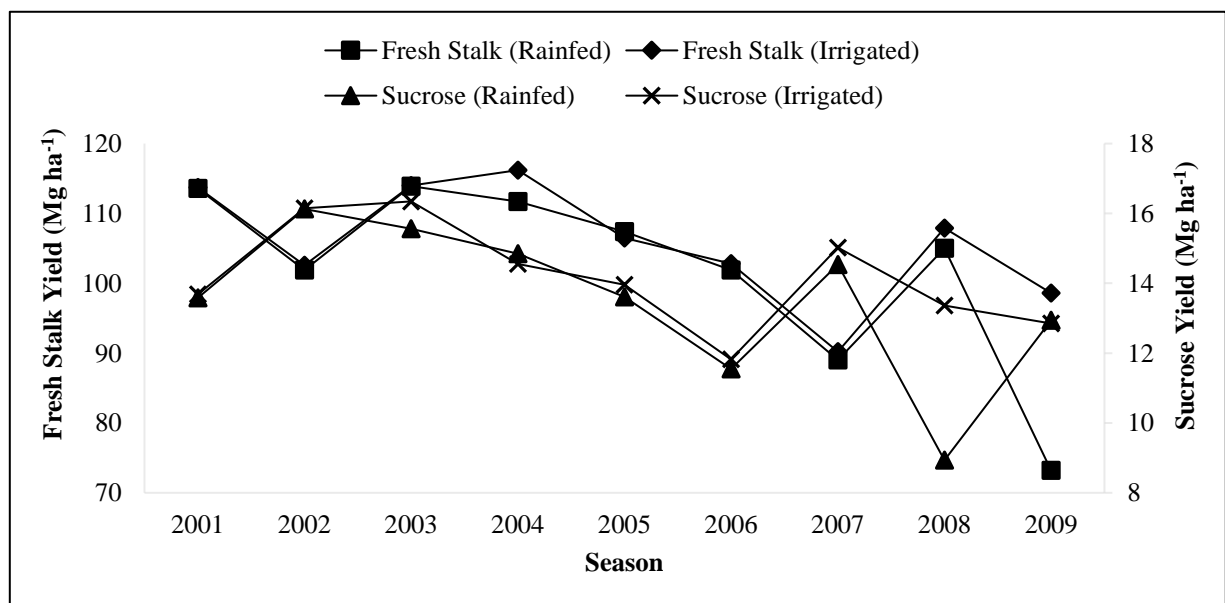


Figure 3. Fresh stalk yield (FSY) and sucrose yield (SY), under rainfed and irrigated conditions, for the best planting date (May/15), in the current scenario. Ribeirão Preto, São Paulo State, Brazil.

Table 7. Fresh stalk yield (FSY) and sucrose yield (SY) for the condition of sugarcane cultivation in rainfed environment, for three different planting dates, in the current scenario. Ribeirão Preto, São Paulo State, Brazil.

Scenario	Current Scenario – Rainfed Condition					
	FSY			SY		
	Mg ha ⁻¹			Mg ha ⁻¹		
Year	May 15	Aug 15	Nov 15	May 15	Aug 15	Nov 15
2001	120.8	113.6	71.0	16.1	13.6	5.2
2002	115.0	101.9	56.7	15.6	16.1	6.8
2003	116.4	113.9	65.9	15.2	15.6	7.7
2004	109.9	111.7	71.5	14.1	14.9	6.3
2005	108.1	107.4	68.4	14.2	13.6	7.2
2006	103.6	101.9	69.3	13.5	11.5	4.7
2007	92.9	89.0	47.8	11.2	14.5	7.9
2008	94.7	105.0	70.9	12.0	8.9	7.7
2009	115.6	73.2	75.8	16.0	12.9	4.6
Mean	108.6	102.0	66.4	14.2	13.5	6.4

Table 8. Fresh stalk yield (FSY) and sucrose yield (SY) for the condition of sugarcane cultivation in an irrigated environment, for three different planting dates, in the current scenario. Ribeirão Preto, São Paulo State, Brazil.

Scenario	Current Scenario – Irrigated Condition					
	FSY			SY		
	Mg ha ⁻¹			Mg ha ⁻¹		
Year	May 15	Aug 15	Nov 15	May 15	Aug 15	Nov 15
2001	120.6	113.7	72.8	16.7	13.7	5.5
2002	123.1	102.6	58.7	16.5	16.1	6.8
2003	117.8	114.0	65.9	16.1	16.3	7.9
2004	120.6	116.2	72.7	16.1	14.6	6.3
2005	114.3	106.5	68.4	14.8	14.0	7.7
2006	114.0	102.8	72.5	15.3	11.8	4.9
2007	109.5	90.2	52.5	14.6	15.0	7.8
2008	103.4	107.9	70.7	13.1	13.4	7.7
2009	97.9	98.6	75.8	12.6	12.8	4.9
Mean	113.5	105.8	67.8	15.1	14.2	6.6

Using the average annual yield values obtained on the three planting dates, it is possible to observe that, comparing the current scenario and the future scenario B1, there is an increase in yield of 22% for the rainfed and 33% for irrigated. The increase in yield should not be analyzed as a single variable, due to the interactions between environmental factors and plant genotype.

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Together, such interactions in the climatic scenarios simulated in this experiment resulted in an increase in the yields (FSY and SY) of the sugarcane variety studied.

It was also observed that the mean of FSY in the rainfed cultivation condition with planting in August was 119.4 Mg ha⁻¹ (Table 9), and an irrigated cultivation was 137.3 Mg ha⁻¹ (Table 10). These values were higher than those of the current scenario with planting in the same month (means of FSY of 102 and 105.8 Mg ha⁻¹, (Tables 7 and 8). In addition, in the rainfed cultivation, the highest FSY was obtained with planting in August (119.4 Mg ha⁻¹) and in irrigated cultivation, with planting in May (141.6 Mg ha⁻¹). It is noteworthy that the gains in terms of agricultural yield with the use of irrigation in management range from 1.2 to 32.8 Mg ha⁻¹. For sucrose yield, the average annual values were 14 and 15.9 Mg ha⁻¹ under the conditions of sucrose and irrigated, respectively, which were above the current average of 11.4 and 11.9 Mg ha⁻¹.

Table 9. Fresh stalk yield (FSY) and sucrose yield (SY) for the condition of sugarcane cultivation in rainfed environment, for three different planting dates, in the future scenario B1. Ribeirão Preto, São Paulo State, Brazil.

Scenario	Future Scenario B1 – Rainfed Condition					
	FSY			SY		
	t/ha			t/ha		
Year	May 15	Aug 15	Nov 15	May 15	Aug 15	Nov 15
2050	130.1	127.3	106.4	16.4	16.8	10.1
2051	132.1	120.8	87.2	15.7	13.5	12.2
2052	126.2	111.2	99.1	16.2	16.8	14.3
2053	125.3	124.4	109.5	14.3	17.7	11.3
2054	115.8	126.0	99.4	15.0	16.0	10.4
2055	118.7	119.4	93.0	14.0	13.9	9.4
2056	114.5	113.8	74.3	12.6	12.9	12.9
2057	105.2	100.7	101.3	13.0	15.7	13.0
2058	108.5	113.7	108.7	17.7	9.4	10.3
Mean	118.7	119.4	99.4	15.0	15.7	11.3

Table 10. Fresh stalk yield (FSY) and sucrose yield (SY) for the condition of sugarcane cultivation in an irrigated environment, for three different planting dates, in the future scenario B1. Ribeirão Preto, São Paulo State, Brazil.

Scenario	Future Scenario B1 – Irrigated Condition					
	FSY			SY		
	t/ha			t/ha		
Year	May 15	Aug 15	Nov 15	May 15	Aug 15	Nov 15
2001	149.2	140.3	109.2	19.7	18.1	10.9
2002	150.1	137.3	90.7	19.5	20.4	12.7
2003	146.2	143.0	102.4	19.5	21.3	14.4
2004	148.2	149.1	111.8	17.7	18.3	11.6
2005	140.4	138.7	101.7	18.1	17.4	11.2
2006	141.6	133.5	97.6	17.6	16.3	9.7
2007	134.2	121.7	77.9	16.3	18.0	13.3
2008	127.7	133.5	103.6	16.0	17.0	13.3
2009	127.6	124.9	109.9	20.1	18.2	10.7
Mean	141.6	137.3	102.4	18.1	18.1	11.6

In Figure 4, the variation in the yield of fresh stalk and sucrose over the years can be seen, for the best planting date (August). It is noted that in some years the use of irrigation has not resulted in significant gains in agricultural income. That is, even with the use of irrigation, environmental variations are a factor that interferes in sugarcane yield, and it is necessary to intervene in the genetic order, at times.

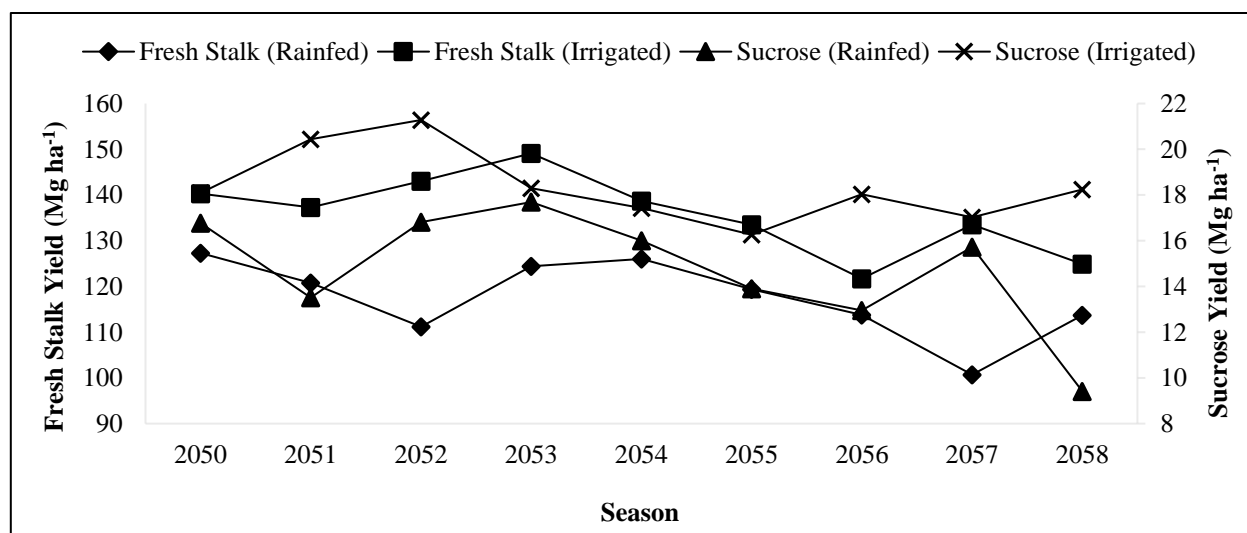


Figure 4. Stem Fresh stalk yield and sucrose yield, under rainfed and irrigated conditions, for the best planting date (Aug. 15), in future scenario B1. Ribeirão Preto, São Paulo State, Brazil.

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The values of FSY and SY in scenario B2 can be seen in Tables 11 and 12. In the same way as occurred in scenario B1, there was an increase in the average annual FSY, compared to the current scenario, 20% in rainfed cultivation (111.1 Mg ha⁻¹) and 32% in irrigated cultivation (126.5 Mg ha⁻¹). Therefore, it is understood that there will be no drop in agricultural yield of the variety studied in a future scenario whose water regime will suffer a 10% reduction, even in rainfed conditions. Sucrose yield may increase from 11.4 to 13.9 Mg ha⁻¹ (+ 21.9%) in rainfed cultivation and from 12.0 to 16.5 Mg ha⁻¹ (+ 37.5%) in irrigated cultivation. In addition, yield gains may vary from 3.5 to 39.5 Mg ha⁻¹, depending on the planting date and the year analyzed.

Table 11. Fresh stalk yield (FSY) and sucrose yield (SY) for sugarcane in rainfed cultivation, for three distinct planting dates, in future scenario B2. Ribeirão Preto, São Paulo State, Brazil.

Scenario	Future Condition B2 Rainfed					
	FSY			SY		
Year	t/ha			t/ha		
	May 15	Aug 15	Nov 15	May 15	Aug 15	Nov 15
2050	130.8	123.7	97.1	17.8	16.4	8.8
2051	138.4	129.5	78.3	17.5	19.0	11.3
2052	134.6	133.3	92.2	17.1	19.9	13.3
2053	134.5	138.8	103.2	14.7	16.9	9.6
2054	115.8	124.3	86.9	15.8	15.7	9.0
2055	117.3	122.4	81.5	13.9	14.2	8.4
2056	113.1	107.8	68.7	14.7	16.2	12.4
2057	117.4	117.2	96.2	13.0	14.1	11.7
2058	106.1	104.0	100.0	18.0	17.0	8.6
Mean	117.4	123.7	92.2	15.8	16.4	9.6

Table 12. Fresh stalk yield (FSY) and sucrose yield (SY) for sugarcane in irrigated cultivation, for three distinct planting dates, in future scenario B2. Ribeirão Preto, São Paulo State, Brazil.

Scenario	Future Condition B2 Irrigated					
	FSY t/ha			SY t/ha		
	May 15	Aug 15	Nov 15	May 15	Aug 15	Nov 15
2001	137.7	127.9	126.4	19.1	17.0	14.1
2002	146.6	133.0	113.5	18.9	19.4	16.8
2003	143.8	137.8	127.3	18.6	20.6	17.9
2004	141.1	144.2	130.7	16.8	17.8	15.3
2005	130.4	129.3	119.2	17.0	16.7	15.7
2006	127.4	128.5	121.0	16.2	15.5	12.8
2007	125.6	116.8	99.6	16.0	17.2	15.7
2008	123.8	126.7	116.6	14.8	16.1	15.5
2009	117.8	118.1	120.7	18.8	16.9	14.3
Mean	130.4	128.5	120.7	17.0	16.9	15.5

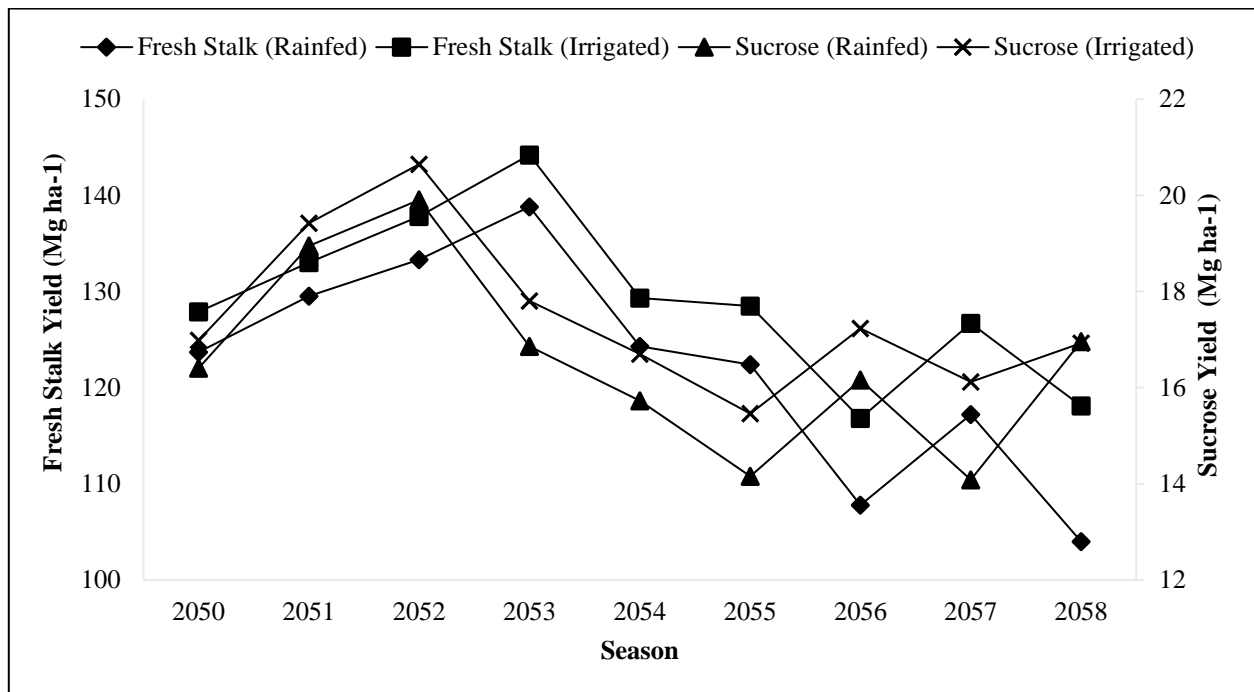


Figure 5. Stems Fresh stalk yield and sucrose yield, under rainfed and irrigated conditions, for the best planting date (Aug. 15), in future scenario B2. Ribeirão Preto, São Paulo State, Brazil.

The figures presented for future scenarios show that the adoption of an irrigation system can bring quantitative (agricultural yield) and qualitative (sucrose yield) benefits and may have a marked effect in both simulated future scenarios compared to the current scenario.

Water productivity in the rained and irrigated cultivations

Table 13 expresses water productivity in the crop, the ratio between dry matter yield and evapotranspiration, representing an indicator of water use efficiency in dry matter accumulation. It can be noted that in the simulated scenarios, sugarcane in irrigated cultivation produces more than in the cultivation of rained. This can be explained by the elimination of water deficit, enabling maximum transpiration of the crop.

Nevertheless, it is verified that the best use of water occurs in scenario B2 in the condition of rained. In it there was a decrease in the amount of rainfall and an increase of yield per unit of evapotranspiration, with 20.1 and 19.5 kg mm⁻¹ for the crops of rained and irrigated, respectively. (Figure 6). And this can be explained mainly by the increase in simulated CO₂ concentration for the coming years. De Souza et. al. (2008), observed a 30% increase in photosynthetic rate, 40% in biomass accumulation and 17% in the weight of plants grown in a protected environment with a CO₂ concentration of 720 ppm, a concentration higher than the present day of close to 400 ppm. The author explains that it is a result of an increase in CO₂ concentration, causing a reduction in stomatal conductance of 37%, reducing transpiration rates, and increasing water use efficiency by 62%.

Therefore, this increase in water use, linked to a lower stomatal opening and low transpiration rate, reflects in a better net photosynthetic performance, given by the subtraction of gross photosynthesis and transpiration plus maintenance respiration, even under a dry period, increasing the internal temperature of the plant, favoring photosynthesis and causing an increase in biomass accumulation, that is, yield (GHANNOUM et al., 2000) (remembering that in the case of C₄ plants, the dynamics of CO₂ in mesophilic cells is different from C₃ plants, and photorespiration losses can be disregarded to calculate the net photosynthetic rate (Allen et al., 1985)).

Therefore, the joint effect of the increase in temperature, the increase in CO₂ concentration and the best water use efficiency, can increase the production of sugarcane biomass, as found by Morgan et al. (2011) and Marin et al. (2012).

Table 13. Water productivity of sugarcane crop (PA, kg mm⁻¹) for current scenarios, B1 e B2. Ribeirão Preto, São Paulo State, Brazil.

Scenario	kg mm ⁻¹ [PA]	
	Rainfed	Irrigated
Current	16.1	16.8
B1	16.8	19.6
B2	20.1	19.5

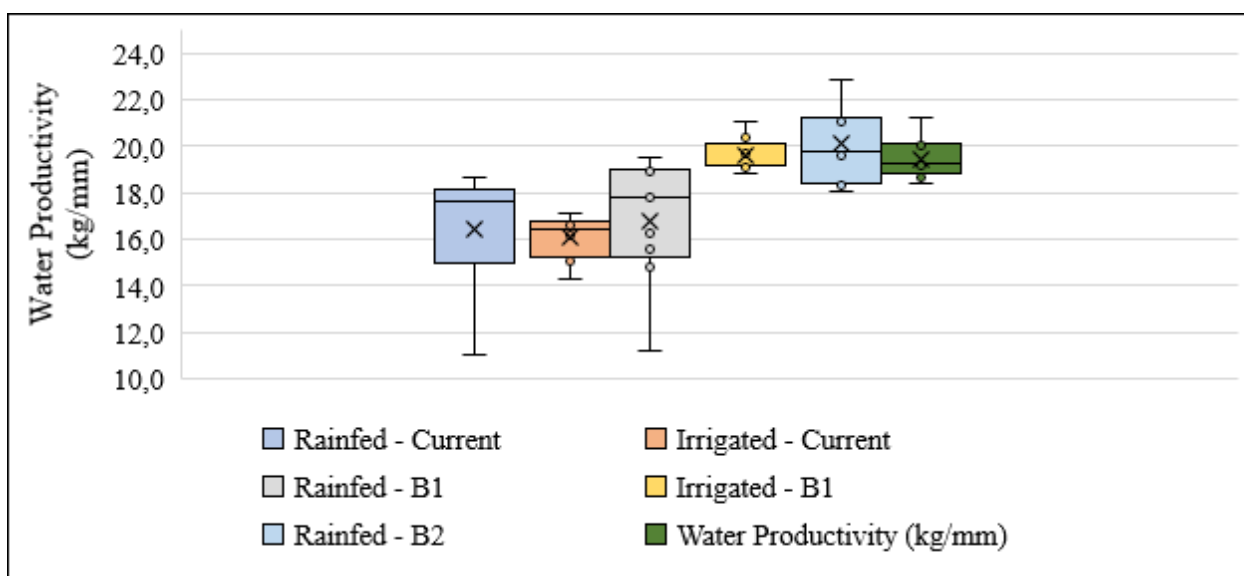


Figure 6. Water productivity (WP, kg mm⁻¹) for current scenarios, B1 e B2. Ribeirão Preto, São Paulo State, Brazil.

Economic viability of the system

Table 14 shows the results of the economic feasibility study of irrigation.

In the current scenario, IRR was 1.82%, NPV was negative and payback period was fourteen (14) years. Thus, investment in an irrigation system in the Region of Ribeirão Preto would only bring long-term economic return, without any additional investment.

In both future scenarios (B1 and B2), both NPV and IRR resulted in positive values, and payback period was three (03) years. This means that the producer would have net profit from the 4th year after investing in the irrigation system. The profit would be obtained in the short term, so the investment would be recommended for yield gains and profitability.

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Irrigated cultivation also allows to increase the shelf life of sugarcane in the field (reduction of yield losses) and generates the opportunity for the producer to invest in other sectors or processes in its production system, in order to achieve further increases in yield and profitability. In addition, the results of the economic analysis show that the cost to obtain a gain of 1 Mg ha⁻¹ of biomass is R\$ 552.77 in scenario B1 and R\$ 501.54 in scenario B2.

Table 14. Economic feasibility study for the proposed system in view of the simulated scenarios. Ribeirão Preto, São Paulo State, Brazil. 2020.

Parameters	Scenarios		
	Current (Irrigated)	Future B1 (Irrigated)	Future B2 (Irrigated)
Sugarcane yield (ton ha ⁻¹)	95.7	127.1	126.53
Sucrose yield (ton ha ⁻¹)	12	15.9	16.5
ATR (kg ha ⁻¹)	111.45	138.45	142.6
IRR (%)	1.84%	33.55%	35.82
NPV (R\$)	-R\$ 15,730,187.96	R\$ 139,295,766.10	R\$ 152,161,148.91
Payback period (year)	14	3	3
Viability	Not Viable	Viable	Viable

However, based on the assumptions assumed in this study, it was possible to identify a strong sensitivity to the ATR price. In addition, the 15 year service life was used for the irrigation system. Increasing this time to 20 years can reduce the *payback* of the current scenario. Frizzone et al. (2005), showed that the risk of the irrigation system is associated with its high service life, which makes it difficult to estimate the economic value of the project due to its variations over time.

CONCLUSIONS

If confirmed, the climate changes simulated in this study will have a positive impact on the agricultural production of sugarcane in rainfed cultivation and in both conditions simulated for rainfall (10% increase or 10% reduction).

Irrigation resulted in yield gains of 13% and 14% for scenarios B1 and B2, respectively.

Even if the edaphoclimatic conditions simulated in this study favor the cultivation of rainfed sugarcane, irrigation is a viable management option from both points of view, agricultural (increased yield) and economic (increased profitability).

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