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NEXO ÁGUA-ENERGIA-ALIMENTO NAS BACIAS HIDROGRÁFICAS DOS RIOS PIRACICABA, CAPIVARI E JUNDIAÍ (PCJ) SOB CONDIÇÕES HISTÓRICAS E DE PROJEÇÕES DE MUDANÇAS CLIMÁTICAS

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1 RESUMO

A abordagem nexo água-energia-alimento (AEA) promove a integração entre gestão e governança em diferentes escalas e setores para o desenvolvimento socioeconômico sustentável. Este estudo objetivou modelar o nexo AEA nas Bacias dos Rios Piracicaba, Capivari e Jundiaí (PCJ) sob condições históricas e em cenários de mudanças climáticas. Modelos foram desenvolvidos nos programas WEAP e LEAP, abrangendo o período de 1995 a 2019 para a condição histórica e de 2020 a 2070 para as projeções climáticas. Utilizando o WEAP-KIB-LEAP *framework*, estabeleceu-se um modelo de interação para troca de dados entre o WEAP e o LEAP. No WEAP, as alterações na vazão das Bacias PCJ devido às mudanças climáticas foram modeladas com dados do Modelo Climático Regional Eta para os cenários RCP4.5 e RCP8.5. Os resultados indicam que, nos cenários futuros, a geração de energia hidrelétrica será comprometida, enquanto a demanda hídrica e o consumo de energia elétrica para irrigação aumentarão 35,6% e 82,7%, respectivamente, impulsionados por um crescimento na produção de alimentos projetado de 21,3%. Esses resultados evidenciam a interdependência entre os recursos água, energia e alimento nas Bacias PCJ.

Palavras-chave: WEAP, LEAP, WEAP-KIB-LEAP *framework*, irrigação, agricultura.

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2 ABSTRACT

The water-energy-food (WEF) nexus approach promotes integrated management and governance across scales and sectors to achieve sustainable socioeconomic development. This study aimed to model the WEF nexus in the Piracicaba, Capivari, and Jundiaí (PCJ) river basins under historical conditions and future climate scenarios. Models were developed using WEAP and LEAP programs, covering the period from 1995 to 2019 for historical conditions and from 2020 to 2070 for climate projections. The WEAP-KIB-LEAP framework enabled data exchange between WEAP and LEAP to model interactions effectively. In WEAP, the projected impacts of climate change on streamflow in the PCJ basins were modeled using data from the Eta Regional Climate Model under RCP4.5 and RCP8.5 scenarios. The findings indicate that, in future scenarios, hydropower generation will be compromised, while water and electricity demand for irrigation will increase by 35.6% and 82.7%, respectively, driven by a projected food production growth of 21.3%. These results highlight the interdependence between water, energy, and food resources in the PCJ basins.

Keywords: WEAP, LEAP, WEAP-KIB-LEAP framework, irrigation, agriculture.

3 INTRODUCTION

The water–energy–food (WEF) nexus approach is a field of study that allows for an in-depth understanding of the interdependencies between water resources, energy generation and consumption, and food production. Research that adopts the WEF nexus integrates management and governance at different scales and in different sectors seeks to increase efficiency in the use of resources and promote sustainable and balanced socioeconomic development (Davies; Simonovic, 2010; Koundouri; Papadaki, 2020; Wicaksono; Kang, 2019).

In studies on the EEA nexus, it is essential to consider factors that affect the interconnections between water, energy and food, such as changes in land use and land cover and climate change. In Brazil, Getirana, Libonati and Cataldi (2021) highlighted the close relationship between energy generation and food production and water availability, as the national energy matrix is largely dependent on hydroelectric power, whereas agriculture requires water for the full development of crops. Thus, drought episodes directly impact both energy production and agricultural productivity.

The "Water Resources Plan for the Piracicaba, Capivari and Jundiaí River Basins 2020 to 2035" (PCJ Committees; PCJ Basin Agency, 2020) reports that there are 13 hydroelectric plants in operation in these basins, with a total installed capacity of 59.3 MW. In the agricultural sector, the cultivation of sugarcane and fruits, especially oranges, stands out (Irrigart, 2007).

Modeling the AEA nexus, which considers both historical conditions and climate change scenarios, can contribute to the sustainable management of water resources in PCJ Basins. Such modeling can be integrated into the Water Resources Plan, one of the management instruments established by Law No. 9,433 of 1997, which instituted the National Water Resources Management System and the National Water Resources Policy (Brazil, 1997).

Therefore, this research aims to model the water–energy–food nexus in the Piracicaba, Capivari and Jundiaí River Basins under historical conditions and climate change scenarios.

4 MATERIALS AND METHODS

4.1 Location

The PCJ Basins (Figure 1), with a drainage area of approximately 15,378 km², are located between longitudes 46° and 49° W and latitudes 22° and 23.5° S, covering mostly municipalities in São Paulo (92.5%) and, to a lesser extent, Minas Gerais (7.5%). Nine main rivers make up these basins: Atibaia, Atibainha, Cachoeira, Camanducaia, Capivari, Corumbataí, Jaguari, Jundiaí and Piracicaba (PCJ Basins Agency, 2023).

Figure 1. Location of the Piracicaba, Capivari and Jundiaí River Basins and main hydrography

Source: PCJ partnership (2023)

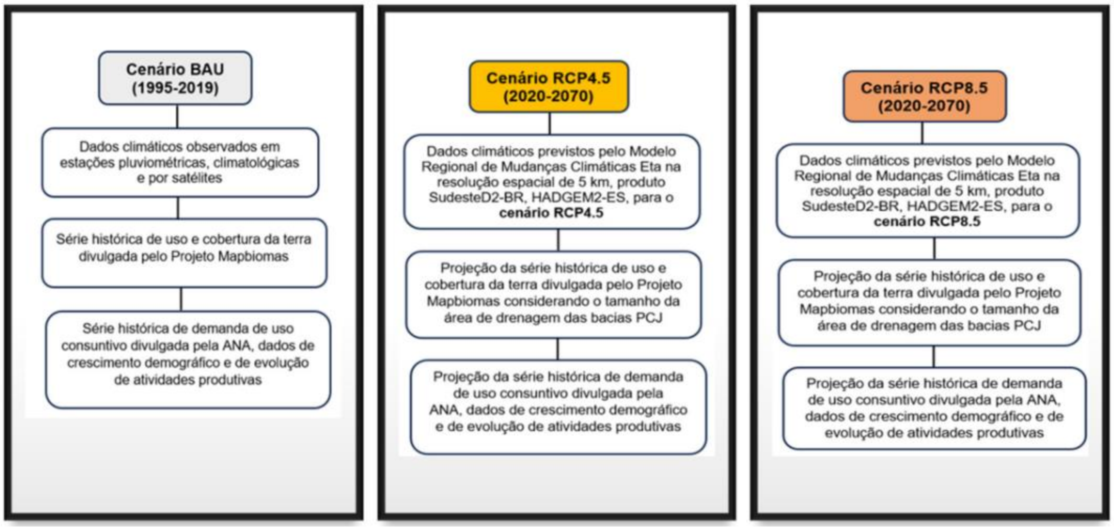
4.2 Modeling the AEA nexus

Modeling of the AEA nexus was carried out with the programs *"Water Evaluation and* Planning" *System* (WEAP) and *"Low Emissions Analysis* Platform" (LEAP), developed by the Stockholm Environmental Institute (Heaps, 2022; Sieber, 2023), to simulate integrated water and energy management in basins and their relationships with food production. WEAP allows the modeling of hydrological scenarios, whereas LEAP enables the study of energy demand and emissions. Both are interconnected by an interaction model (IM) based on the WEAP-KIB-LEAP *framework* developed by Fard and Sarjoughian (2020) and coupled via the Web API.

4.3 WEAP and LEAP models

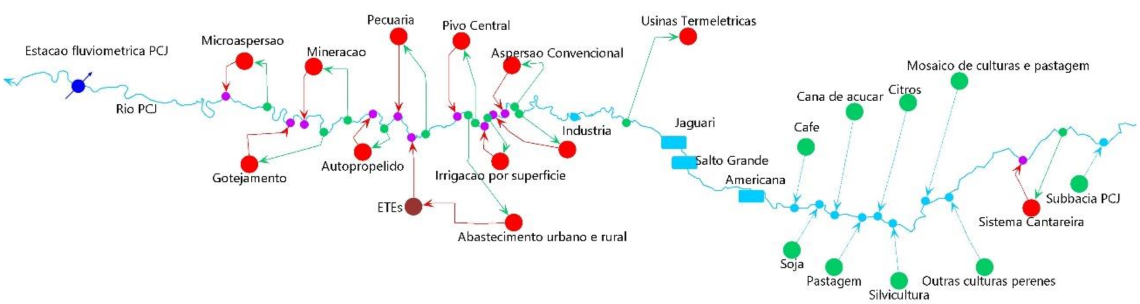
The models cover the historical period from 1995--2019, which is in line with the Census of Agriculture and climate projections from 2020--2070. In WEAP, three scenarios are defined (Figure 2): the historical scenario (BAU) and two climate change scenarios, RCP4.5 and RCP8.5, which represent different projections of greenhouse gas emissions and their climate consequences (Moss *et al.*, 2008). On the other hand, LEAP was configured for two scenarios, historical (BAU) and climate projection (RCP), in which historical data were projected into the future through linear regression.

Figure 2. Characterization of the WEAP model scenarios



The WEAP model included twelve water demands, nine subbasins, one sewage treatment plant, which represented the sum of the volume of sewage treated in the PCJ Basins, twelve transmission links, which represented the water intakes, and twelve return links, which represented the return flows, three hydroelectric plants and one fluviometric station (Figure 3).

Figure 3. Model developed in WEAP for PCJ Basins



Frame 1 presents the data sources consulted for water use, land use and cover, and climate demands. These data cover the historical period (1995--2019) used in the BAU scenario. For the RCP4.5 and RCP8.5 climate change scenarios (2020--2070), the data on water use and land use and cover demands were the same, resulting from the projection of the historical period series through linear regression. Notably, in the WEAP model, the RCP4.5 and RCP8.5 scenarios differ only in terms of climate data.

Frame 1. Data sources used for parameterization of the WEAP model

Data	**Data source**
Climate	DAEE (2023); CIIAGRO (2023); *NASA Power Project* (2023); Holbig *et al* . (2018)
Land use and land cover	Area: Mapbiomas Project (2023); Crop coefficients: Silva *et al* . (2011)
Water use demands	SNIRH (2022); CIDER (2023); SEADE (2021)

To validate the WEAP model in relation to the simulated flow, the simulated data were compared with those observed at the Artemis fluviometric station. The Nash–Sutcliffe efficiency (NSE), percentage bias (PBIAS) and ratio between the root mean square error and the standard deviation (RSR) metrics were used to evaluate the modeling performance, according to the Moriasi classification. *et al* . (2007).

The LEAP model was configured to simulate the energy demands in irrigation, considering the following methods: surface irrigation, conventional sprinkler, center pivot, self-propelled, drip and microsprinkler. The water demand data for each system were extracted from WEAP and inserted into LEAP after the MI was executed. Frame 2 presents the final energy intensity values adopted. Notably, since water demand did not vary between the RCP4.5 and RCP8.5 scenarios in WEAP, the climate change projection scenario in LEAP was called the RCP.

Frame 2. Annual energy intensity of irrigation methods/systems and their sources

Irrigation method/system	**Annual final energy intensity (electricity)**	**Annual final energy intensity (diesel)**	**Data source**
Surface irrigation	0.1561 kWh/^{m3}	0.0457 L/^{m3}	Scaloppi (1985) *apud* Medeiros and Rojas (1997)
Conventional sprinkling	0.4456 kWh/^{m3}	0.1306 L/^{m3}	Scaloppi (1985) *apud* Medeiros and Rojas (1997)
Self-propelled system	0.7581 kWh/^{m3}	0.2222 L/^{m3}	Scaloppi (1985) *apud* Medeiros and Rojas (1997)
Center pivot	0.4699 kWh/^{m3}	0.1377 L/^{m3}	Scaloppi (1985) *apud* Medeiros and Rojas (1997)
Drip	*0.2000 kWh/^{m3}	-	Marouelli and Silva (2011)
Microsprinkling	**1,600 kWh/hectare	-	Vescove and Turco (2010)

*Data calculated for the tomato vegetable, grown in an area of 80 ha, with maximum crop evapotranspiration (ETc) of 8 mm/day; **Data calculated in 2004 for the perennial orange crop, variety "Valência", irrigated with 1 microsprinkler per plant to supply 100% of the ETc.

In WEAP, the time scale used was monthly, whereas in LEAP, it was annual. One of the main advantages of the WEAP-KIB-LEAP *framework* is the possibility of integrating models with different time scales, which increases the flexibility of the analyses.

4.4 Historical climate and climate change data

The monthly precipitation data (mm) for the PCJ Basins for the BAU scenario were obtained from the website of the Department of Water and Electric Energy (DAEE) of the State of São Paulo (DAEE, 2023). The data were acquired from 20 (twenty) rainfall stations, the information for which is presented in Frame 3. The average between the 20 (twenty) stations was calculated after the missing data (gaps) were filled. The gaps present in the monthly historical series were filled via the multiple linear regression method.

Frame 3. Information from the DAEE rain gauge stations

Station	Municipality	Latitude	Longitude	Altitude
D3-027	Monte Alegre do Sul	-22.69	-46.67	750 m
D3-023	Support	-22.72	-46.84	660 m
D3-036	Pine forest	-22.79	-46.58	880 m
D3-042	Jaguariuna	-22.70	-46.98	570 m
D3-046	Morungaba	-22.87	-46.79	750 m
D3-054	Joanópolis	-22.93	-46.27	920 m
D4-012	Clear River	-22.41	-47.56	615 m
D4-035	Analandia	-22.13	-47.67	643 m
D4-036	Itirapina	-22.30	-47.74	610 m
D4-043	Corumbatai	-22.22	-47.62	592 m
D4-044	Campinas	-22.87	-47.08	710 m
D4-046	Campinas	-22.78	-47.04	600 m
D4-068	River of Stones	-22.87	-47.61	698 m
D4-069	Capybara	-23.00	-47.51	508 m
D4-099	Arthur Nogueira	-22.57	-47.15	667 m
D4-104	Piracicaba	-22.72	-47.65	491 m
E3-015	Itatiba	-22.98	-46.83	740 m
E3-099	Nazareth Paulista	-23.18	-46.40	810 m
E4-015	Indaiatuba	-23.08	-47.22	630 m
E4-124	Indaiatuba	-23.17	-47.13	700 m

Source: DAEE (2023)

The monthly temperature (°C) for the BAU scenario in the PCJ Basins was obtained from the Integrated Center for Agrometeorological Information (CIIAGRO) through the CIIAGRO ONLINE portal (CIIAGRO; IAC, 2023). Monthly data on relative humidity (%), wind speed (m/s), cloud cover fraction (%) and albedo were obtained from the NASA *Power Project Platform* (NASA Power, 2023).

Daily precipitation, temperature, wind speed and relative humidity data for the

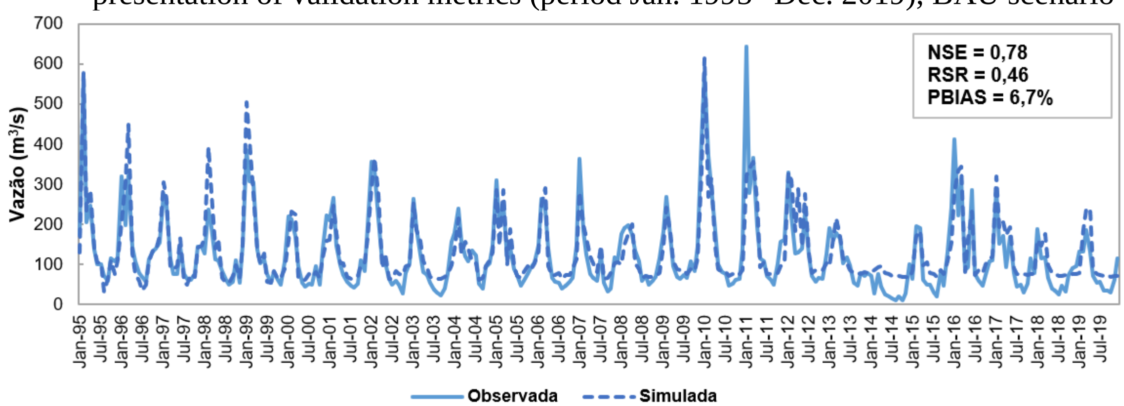
RCP4.5 and RCP8.5 climate change scenarios were obtained from the Projeta Web Platform on the basis of the "Climate Change Projections for South America Regionalized by the Eta model" (Holbig *et al., 2018) and the* Eta Regional Climate Model with 5 km resolution (SoutheastD2-BR product, HADGEM2-ES). These data underwent bias correction via the linear scaling method (Lenderink; Buishand; Van Deursen, 2007), which uses daily data from the NASA *Power Project*.

To correct for bias in the climate change data, the multiplicative correction technique was applied for precipitation, relative humidity and wind speed, whereas the addition technique was used for temperature, as recommended by Shrestha, Shrestha and Babel (2016). After correction, the data from the RCP4.5 and RCP8.5 scenarios were grouped on a monthly scale, which is the temporal scale adopted in the WEAP model.

5 RESULTS AND DISCUSSION

Figure 4 presents the validation metrics of the simulated flow by the model developed in WEAP for the BAU scenario in the PCJ Basins. The results indicate good model performance, with an NSE coefficient of 0.78, an RSR of 0.46 and a PBIAS of 6.7%, classifying the model as "very good" according to the Moriasi criteria. *et al* . (2007). The positive PBIAS, according to Gupta, Sorooshian and Yapo (1999), suggests a slight underestimation of the simulated flow in relation to that observed at the Artemis fluviometric station.

Figure 4. Comparison between the observed and simulated flow rates in WEAP with the presentation of validation metrics (period Jan. 1995--Dec. 2019), BAU scenario



NSE= Nash–Sutcliffe coefficient efficiency; RSR = ratio between the standard deviation and the root mean square error; PBIAS = percentage of bias.

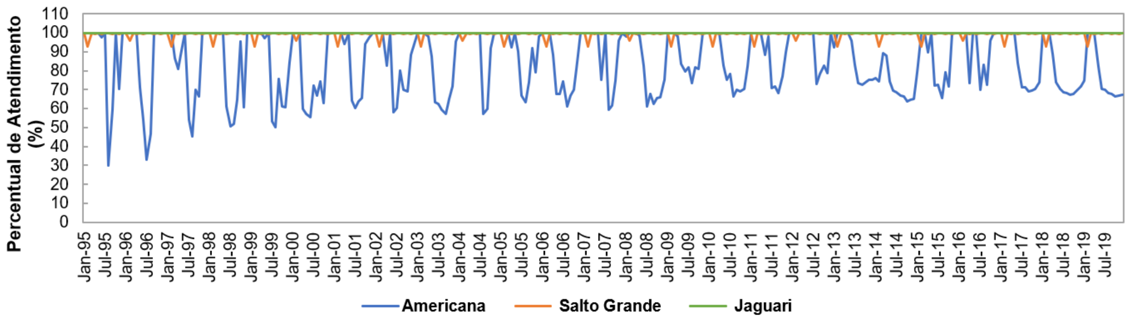
A comparison of the average annual flows of the BAU, RCP4.5 and RCP8.5 scenarios revealed reductions of 79.6% and 84.9%, respectively, in relation to those of the BAU scenario, with the average annual flow decreasing from 131. 0 m³/s (BAU) to 26.7 m³/s (RCP4.5) and 19.8 m³/s (RCP8.5), as shown in Table 1. The analysis of this variation is essential for assessing water, energy, and food, as it directly affects both the hydroelectric generation capacity in PCJ Basins and the availability of water for irrigation.

Table 1. Variation in the mean annual flow among the BAU, RCP4.5 and RCP8.5 scenarios

Scenario	Flow rate	Reduction (m ^{3} s $^{-1}$)	Reduction (%)
TRUNK	131.0	-	-
RCP4.5	26.7	104.3	79.6
RCP8.5	19.8	111.2	84.9

Figure 5 shows the percentage of power generation potential achieved by the Americana, Jaguari and Salto Grande hydroelectric plants in the BAU scenario. The American hydroelectric plant, with the largest capacity, had the highest percentage of nonfulfillment, with a minimum recorded in August 1995, when it generated only 30.9% of its potential of 30 MW, equivalent to 9.3 MW.

Figure 5. Percentage of hydroelectric power generation potential met in the PCJ basins in the BAU scenario (Jan. 1995–Dec. 2019)



For the Salto Grande and Jaguari hydroelectric plants, the service percentages varied, with Salto Grande maintaining 100% and Jaguari maintaining 93.2% and 100% (Figure 5), reflecting the differences in the turbine flows required to meet their capacities: 34.9 m³/s for Jaguari and 21.5 m³/s for Salto Grande.

In the RCP4.5 climate change scenario, hydroelectric generation is most compromised, with a minimum forecast of fulfillment in October 2031. For this period, the model projects 13.0% of the potential for the Americana hydroelectric plant (3.9 MW), 64.4% for Salto Grande (2.9 MW) and 54.1% for Jaguari (6.4 MW), which is related to a critical flow rate of 8.4 m³/s (Figure 6). In the RCP8.5 scenario, even lower fulfillment is expected in August 2026, with Americana generating 10.4% of its potential (3.1 MW), Salto Grande 51.6% (2.3 MW) and Jaguari 43.4% (5.1 MW) (Figure 7).

Figure 6. Percentage of hydroelectric power generation potential met in the PCJ basins under the RCP4.5 scenario (Jan. 2020–Dec. 2070)

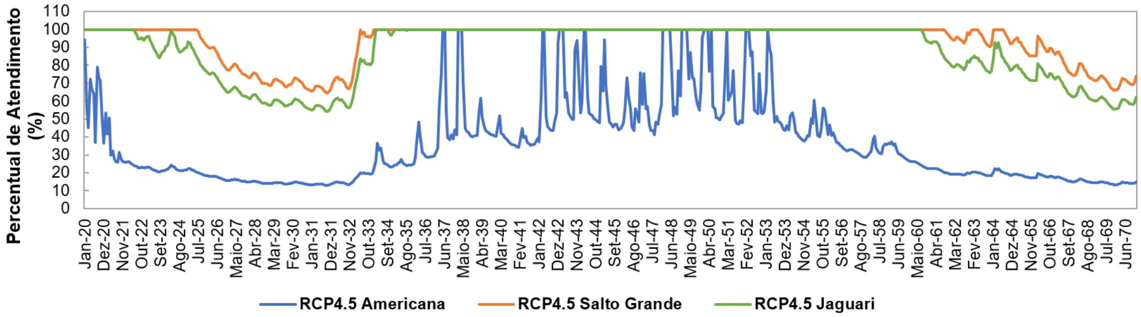
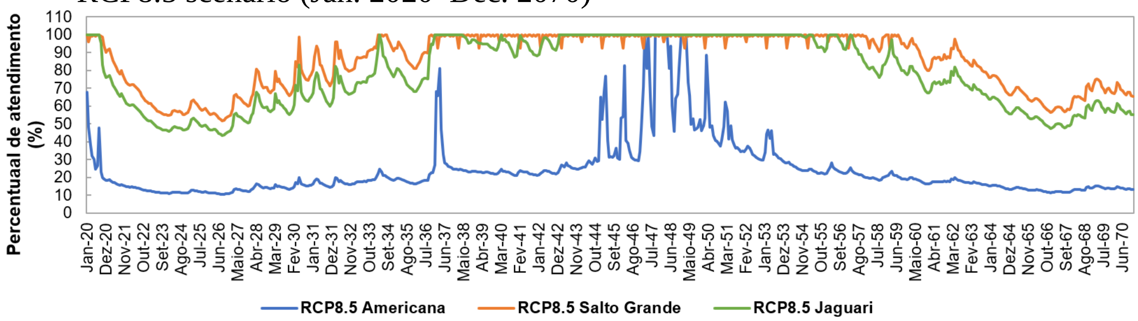


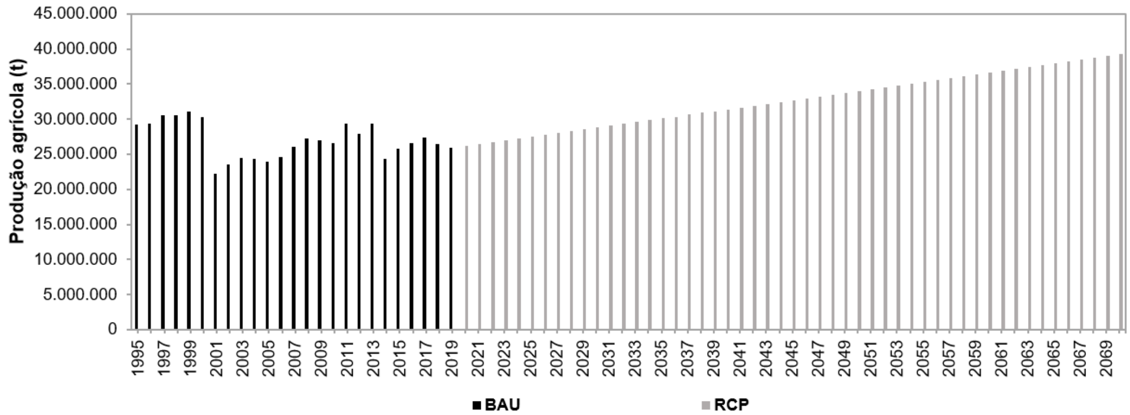
Figure 7. Percentage of hydroelectric power generation potential met in the PCJ basins in the RCP8.5 scenario (Jan. 2020–Dec. 2070)



Importantly, during periods of water scarcity, the activation of thermoelectric plants to meet the demand for electricity increases the price paid by consumers because of the high production cost of these plants. Since 2015, the National Electric Energy Agency (ANEEL) has implemented the Tariff Flag System, which informs consumers about tariff increases due to these additional costs. Tariffs vary according to the activation of the plants and are classified into Green, Yellow, Red-Level 1 and Red-Level 2 flags (ANEEL, 2023; CPFL, 2023). In this context, in times of low flow, the production cost of irrigated agriculture is relatively high.

Figure 8 illustrates agricultural production in the PCJ Basin under the BAU scenario and the projections for the RCP scenario, which encompasses the WEAP RCP4.5 and RCP8.5 scenarios. In the BAU scenario, annual agricultural production ranged between 20 and 30 million tons. In the RCP scenario projections, a gradual increase is expected, reaching approximately 39 million tons in 2070.

Figure 8. Annual agricultural production, in tons (t), in the PCJ Basin under the BAU (1995--2019) and RCP (2020--2070) scenarios



The analysis of the average annual production in the BAU scenario revealed that the main crops produced included sugarcane, citrus, corn, cassava and potatoes. In the RCP scenario, the order of the most produced crops remains the same, but with an increase in the production of grapes and soybeans and a reduction in the production of tomatoes and avocados. The total agricultural production projected for the RCP scenario is 32.72 million tons (Table 3), representing an increase of approximately 21.3% in relation to the BAU scenario (Table 2).

Table 2. Average production of the main crops cultivated in the PCJ basins in the BAU scenario

Culture	**Average production (t year $^{-1}$) in the period 1995 to 2019***
1st Sugarcane	23,248,507
2° Citrus	3,079,843
3rd Corn	202.315
4th Cassava	123,242
5th Potato	85,090
6° Tomato	74,882
7th Grape	69,215
8° Avocado	28,287
9th Coffee	23.233
10° Banana	13,402
11th Sleeve	13,299
12° Soybeans	9,687
13° Beans	5,698
14° Rice	2,798
Total	26,979,498

*Municipal agricultural production data were obtained from cider (2023); t = tons.

Table 3. Estimated average production for the main crops in the PCJ Basin in the RCP scenario

Culture	Average production (t year $^{-1}$) in the period 2020 to 2070
1st Sugarcane	31.011.065
2° Citrus	648,593
3rd Corn	377,023
4th Cassava	249,426
5th Potato	153,142
6th Grape	86,945
7° Soy	56,809
8th Banana	41,845
9° Tomato	40,660
10th Coffee	21,596
11° Avocado	18,064
12th Sleeve	12,838
13° Beans	2.120
14° Rice	74
Total	32.720.201

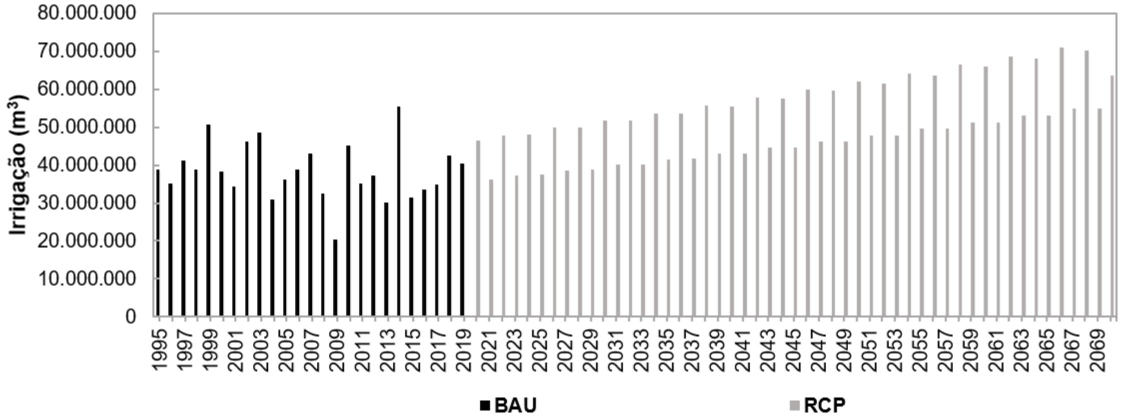
t = tons

The projected average precipitation for the RCP4.5 and RCP8.5 scenarios is 1,079.9 mm and 1,023.5 mm, respectively, representing a significant reduction compared with that of the BAU scenario, which is 1,438.7 mm (Table 4). This water deficit will require greater use of irrigation to sustain the projected increase in agricultural production, as shown in Figure 9, which presents the water demand for irrigation in the BAU and RCP scenarios. In the BAU scenario, 2014 was a year marked by an increase in the number of irrigation systems installed in the PCJ Basins in response to the severe drought that affected the region (Braga; Molian, 2018). This movement suggests that, in periods of drought, rural producers tend to adopt more irrigation systems to mitigate the risks associated with climate uncertainty, aiming to guarantee agricultural productivity.

Table 4. Variation in the average annual precipitation of the PCJ basins in the RCP4.5 and RCP8.5 scenarios in relation to the BAU scenario

Scenario	Average (mm)	Reduction (mm)	Reduction (%)
TRUNK	1,438.7	-	-
RCP4.5	1,079.9	358.8	24.9
RCP8.5	1,023.5	415.3	28.9

Figure 9. Water demand in the PCJ Basin under the BAU (1995--2019) and RCP (2020--2070) scenarios

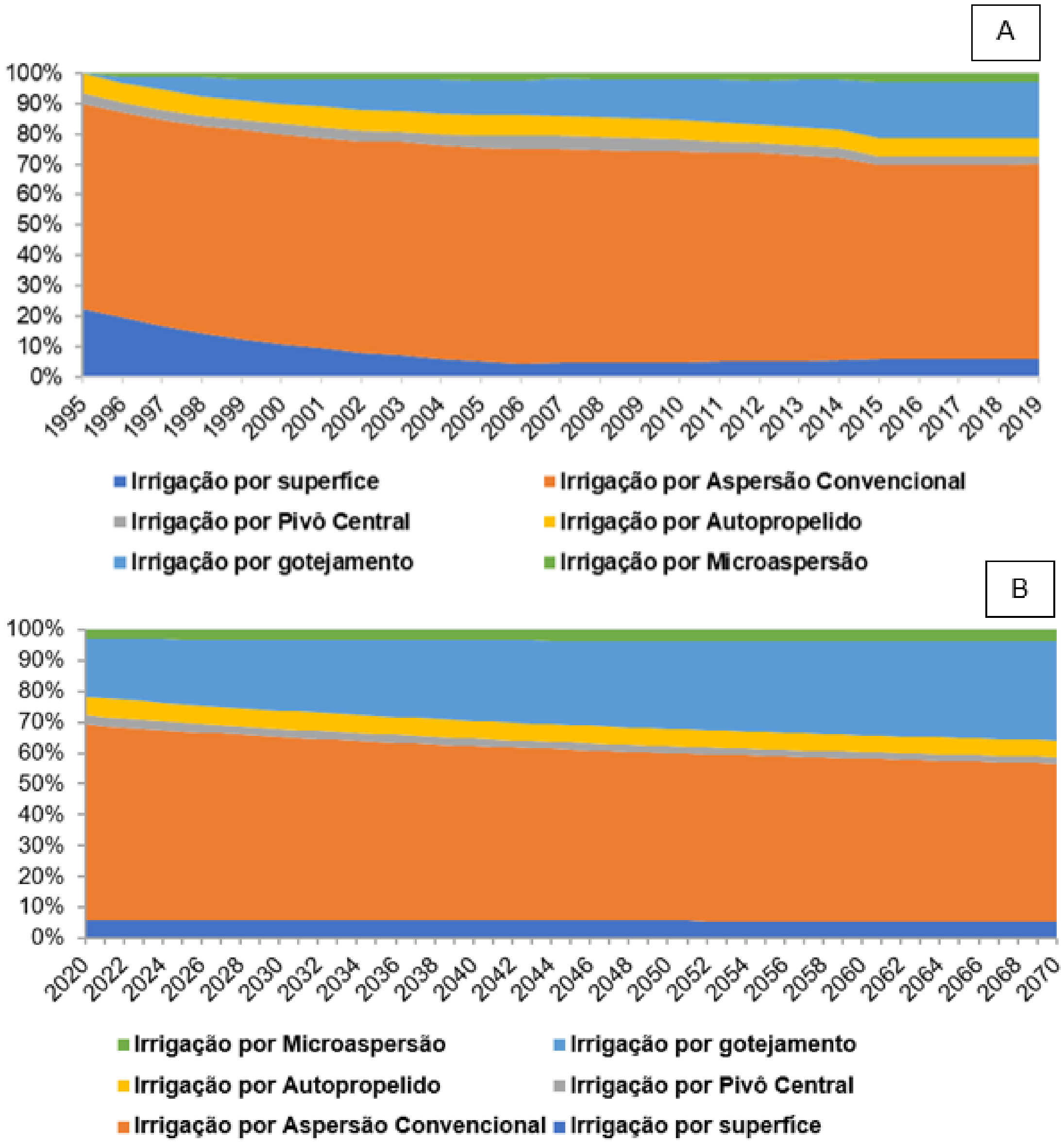


In the RCP scenario, the average water demand for irrigation increases by 35.6% compared with that in the BAU scenario (Table 5), which also implies a greater demand for energy. In both scenarios, conventional sprinkler irrigation is the most commonly used method, followed by drip irrigation, in addition to other systems, such as microsprinklers, central pivots and self-propelled systems (Figure 10).

Table 5. Variation in water demand for irrigation in the PCJ Basin under the RCP scenario (2020--2070) compared with the BAU scenario (1995--2019)

Scenario	Average water demand (m^3 $year^{-1}$)	Increase (m^3 $year^{-1}$)	Increase (%)
TRUNK	38,424,990.4	-	-
CPR	52,099,968.5	13,674,978.1	35.6%

Figure 10. Distribution of types of irrigation methods/systems used in the PCJ Basin considering A) the BAU scenario (1995--2019) and B) the RCP scenario (2020--2070)

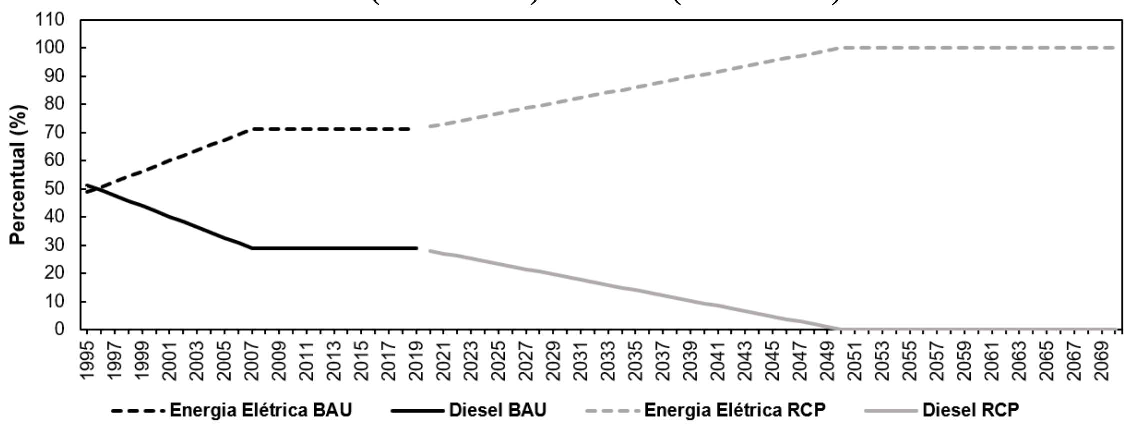


Guirao and Teixeira Filho (2010) analyzed data from the Census Survey of Agricultural Production Units in the State of São Paulo (LUPA) for the period from July 2007--September 2008 and reported that in the PCJ Basins, conventional sprinkling and dripping were, respectively, the first and second most commonly used irrigation systems, in agreement with the results of the present study.

The use of electricity and diesel to meet the energy demand for irrigation activities in the PCJ Basins varied throughout the BAU and RCP scenarios (Figure 11). Notably, the use of diesel has decreased. This reduction can be attributed to the creation of programs aimed at rural electrification.

During the BAU scenario, the following programs were implemented: "Luz no Campo", launched in 1999 by President Fernando Henrique Cardoso, and "Luz para Todos", established in 2003 by President Luiz Inácio Lula da Silva (Braga, 1999; MME, 2021). The latter program was relaunched in 2024, with an estimated budget of R$2.5 billion (Carregosa, 2023), reinforcing the trend of replacing diesel with electricity in the RCP scenario, which should reach 100% replacement in 2050.

Figure 11. Percentage variation in the use of electricity and diesel in irrigated areas of the PCJ Basin under the BAU (1995--2019) and RCP (2020--2070) scenarios



In the BAU scenario, irrigation activity in the PCJ Basin consumed an average of 43,511.2 GJs per year of electricity. In comparison, the average consumption projected for the climate change scenario (RCP) is 79,475.7 GJ per year, representing an increase of approximately 82.7% (Table 6).

Table 6. Variation in the average energy demand for electricity and diesel, in gigajoules, of irrigation activity in the PCJ Basin between the BAU (1995--2019) and RCP (2020--2070) scenarios

Scenario	Average (GJ year $^{-1}$)	Difference (GJ year $^{-1}$)	Variation (%)
	Electric Energy		
TRUNK	43,511.2	-	-
CPR	79,475.7	↑35,964.6	↑ 82.7
	Diesel		
TRUNK	63,509.8	-	-
CPR	16,446.0	↓47,063.8	↓74.1

In contrast, the average demand for diesel in the climate change scenario (RCP) was 63,509.8 GJ per year, whereas in the historical scenario (BAU), it was 16,446.0 GJ per year, representing a reduction of approximately 74.1% in diesel consumption in the irrigated areas of the PCJ Basins (Table 6).

Replacing diesel with electricity in irrigation activities in PCJ Basins can contribute to reducing greenhouse gas emissions, thus mitigating the impact of climate change. Diesel is a nonrenewable energy source that releases substantial amounts of greenhouse gases into the atmosphere (Perin *et al*., 2015). In contrast, emissions related to the use of electricity in irrigation vary according to the local energy matrix and can be zero if only renewable sources, such as wind and solar energy, are adopted.

6 CONCLUSION

In the irrigated areas of the PCJ Basins, electricity has replaced diesel as the main source of energy, owing to rural electrification programs. In years of low rainfall, rural producers turn to irrigation to ensure the future supply of water to their crops. In scenarios of water scarcity, the cost of electricity increases due to the significant participation of hydroelectric plants in the regional energy matrix, leading to an increase in the cost of production in irrigated agriculture.

In the RCP4.5 and RCP8.5 climate change scenarios, a reduction in the potential for generating electricity at the American, Salto Grande and Jaguari hydroelectric plants is expected due to the decrease in water availability in the PCJ Basin. From 2020 to 2070, agricultural production in the region is projected to grow, which will lead to increasing water demand and electricity consumption for irrigation, since rainfed agriculture will be increasingly affected by climate change.

Climate projections from the Eta Regional Climate Model, with a resolution of 5 km, indicate a reduction in annual precipitation of 24.9% in the RCP4.5 scenario and 28.9% in the RCP8.5 scenario, which significantly compromises water availability for agriculture. This interdependence between water, energy and food in the PCJ Basin represents one of the main challenges for the sustainable planning and resilience of the region in the face of climate change.

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