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ESCASSEZ HÍDRICA E IRRIGAÇÃO FUTURA NO BRASIL: UMA AVALIAÇÃO DO IMPACTO DAS MUDANÇAS CLIMÁTICAS NAS PRINCIPAIS CULTURAS IRRIGADAS DO PAÍS

DISSERTAÇÃO

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Water Scarcity And Future Irrigation In Brazil: An Assessment Of The Impact Of Climate Change On The Country's Main Irrigated Crops

Trabalho de Dissertação apresentado como requisito para obtenção do título de Mestre em Engenharia da Universidade Tecnológica Federal do Paraná (UTFPR).

Orientador(a): Cássia Maria Lie Ugaya
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Déjà vu, I've just been in this place before
Higher on the street, and I know it's my time to go
Calling you, and the search is a mystery
Standing on my feet, it's so hard when I try to be me
Yeah

(Déjà vu, Initial D)

RESUMO

O aquecimento global trará consequências nas atividades produtivas que dependem diretamente do clima, como é o caso da irrigação. No Brasil, a irrigação é parte importante e crescente na produção das culturas do país, mantendo um crescimento anual de cerca de quatro por cento e com um potencial de expansão expressivo. Sendo assim, este estudo analisa os efeitos do aquecimento global na irrigação total e seu impacto futuro na escassez hídrica do país para as culturas de cana-de-açúcar, café, arroz inundado e culturas de pivô central por meio da consideração dos cenários divergentes RCP 4.5 e 8.5. O cálculo da evapotranspiração de referência é realizado por Penman-Monteith original e com modificação considerando o efeito de fertilização do gás carbônico. Já a irrigação é calculada pelo método CROPWAT de balanço hídrico no solo. O impacto da irrigação total é feito a partir da utilização de fatores de caracterização AWARE regionalizados para sub-bacias brasileiras. Foram consideradas as previsões climáticas futuras até 2100 vindas do modelo de circulação regional ETA - HadGEM-2 para a América do Sul e previsões das áreas irrigadas no país para 2019 e 2040. Resultados de irrigação e impacto para todas as culturas foram maiores no cenário RCP 8.5, sendo mais expressivo para as regiões centrais do país devido ao aumento da temperatura e do saldo de radiação absorvida e diminuição da umidade relativa. Os resultados do efeito de fertilização do gás carbônico indicaram redução em todo o país da tendência da evapotranspiração de referência, sendo mais expressivo para regiões com ventos mais fortes. A cultura de cana-de-açúcar teve maiores resultados de volume de irrigação e impacto futuro na escassez hídrica nos dois cenários RCP pela sua extensa área irrigada no país. O impacto foi mais significativo para regiões de plantio do litoral do nordeste, mas regiões de plantio no centro do país, que utilizam majoritariamente fertirrigação, tiveram um crescimento expressivo na irrigação e aumento no impacto futuro mesmo com fatores de caracterização mais baixos. O arroz teve valores futuros expressivos de impacto na escassez hídrica de suas sub-bacias produtoras devido a valores significativos de fatores de caracterização, já o café teve resultados baixos de irrigação e impacto se comparados com arroz e cana-de-açúcar, mas sua concentração nas regiões produtoras levaram a um alto impacto nas sub-bacias do noroeste de Minas Gerais e norte do Espírito Santo. Apesar de áreas com cultivo único de cana-de-açúcar, arroz e café terem apresentado os maiores valores de volume de irrigação e impacto para suas sub-bacias, os resultados apresentaram impactos expressivos nos períodos futuros para sub-bacias com produções conjuntas entre as culturas analisadas, incluindo as de pivô central, em ambos os cenários RCP.

Palavras-chave: irrigação; aquecimento global; avaliação do ciclo de vida; LCA; LCIA.

ABSTRACT

Global warming will bring consequences to productive activities that depend directly on the climate, as is the case of irrigation. In Brazil, irrigation is an important and growing part of the country's crop production, maintaining an annual growth rate of about four percent and with a significant potential for expansion. Therefore, this study analyzes the effects of global warming on total irrigation and its future impact on the country's water scarcity for sugarcane, coffee, flooded rice and center pivot crops by considering the divergent RCP 4.5 and 8.5 scenarios. Reference evapotranspiration is calculated using the original Penman-Monteith method and a modification to consider the effect of carbon dioxide fertilization. Irrigation is calculated by the CROPWAT method with the soil water balance. The impact of total irrigation is done using regionalized AWARE characterization factors for Brazilian sub-basins. Future climate forecasts until 2100 came from the regional circulation model ETA - HadGEM-2-ES for South America and forecasts of irrigated areas in the country for 2019 and 2040 were considered. Irrigation results and impact for all crops were higher in the RCP 8.5 scenario, being more expressive for the central regions of the country due to the increase in temperature and absorbed radiation balance and decrease in relative humidity. The results of the carbon dioxide fertilization effect indicated a nationwide reduction in the trend of reference evapotranspiration, being more significant for regions with stronger winds. The sugarcane crop had the highest results for irrigation volume and future impact on water scarcity in both RCP scenarios because of its extensive irrigated area in the country. The impact was most significant for coastal northeastern planting regions, but central planting regions, which use mostly fertigation, had an expressive growth in irrigation and increase in future impact even with lower characterization factors. Rice had significant future impact values on water scarcity in its producing sub-basins due to significant values of characterization factors, while coffee had low irrigation and impact results if compared with rice and sugarcane, but its concentration in producing regions led to a high impact in the sub-basins of northwestern Minas Gerais and northern Espírito Santo. Although areas with single crops of sugarcane, rice and coffee presented the highest values of irrigation volume and impact for their sub-basins, the results showed considerable impacts in future periods for sub-basins with joint productions among the analyzed crops, including those of central pivot, in both RCP scenarios.

Keywords: irrigation; global warming; life cycle assessment; LCIA; LCA.

LIST OF FIGURES

SUMMARY

1 INTRODUCTION

The growth in the concentration of greenhouse gases, in particular carbon dioxide (CO2), and its contribution to the increase in atmospheric net radiative forcing will bring future consequences to the climate, among which are the increase in global average temperature and the increase in average precipitation (IPCC, 2014). In this context, one of the areas most affected by the changes will be agriculture due to the high dependence on climate variations and variables for crop growth (HOFFMANN *et al.*, 2011; FAO, 2017; EMBRAPA, 2018).

Agricultural activities both contribute to and suffer from the consequences of climate change. Their practice results in land use, possible deforestation and biomass burning or, in specific cases such as rice plantations, a high emission of methane gas (CH4), all of which contribute to the increase of the greenhouse effect both by emitting gases and by reducing carbon sequestration from the atmosphere. On the other hand, the plants grown in agriculture sequester CO2 to carry out photosynthesis, helping to remove this gas from the atmosphere (FAO, 2017). As for the consequences suffered, changes in evapotranspiration[1], increase in average precipitation, difference in crop suitability and planting periods, and CO2 fertilization effects are expected (FISCHER *et al.*, 2007; IPCC, 2014; FAO, 2017).

In Brazil, agriculture was considered a thematic area in the scope of the National Plan of Adaptation to Climate Change (BRAZIL, 2016) for its vulnerability to climate, which has fostered practices such as the agricultural zoning for climate risk (ZARC), which aims to reduce climate risk by the annual publication of suitable areas and species of crops in each municipality. In addition to this, a series of studies on the impacts of climate change on Brazilian agriculture (PINTO AND ASSAD, 2008; WORLD BANK AND ANA, 2013) were carried out to identify vulnerabilities and assess future agricultural zoning, culminating in the publication of the Vision 2030 - The Future of Brazilian Agriculture (EMBRAPA, 2018), which indicates, in climate change scenarios, a decrease in areas with low-risk agricultural zoning for the main crops and significant production and economic losses, with few exceptions. The Agrohydro Network complements the studies by addressing climate change in the hydrologic context (AGROHYDRO NETWORK, 2016).

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[1] Amount of water in millimeters used by the processes of plant transpiration and evaporation of water from the soil

One of the agricultural parameters most affected by climate change is the crop water requirement, a variable that defines, along with precipitation, the estimates of irrigation needed for the crop (DÖLL, 2002; HUNTINGTON, 2006; FISCHER *et al.*, 2007; HATFIELD *et al.*, 2011), which has led to the publication of studies on the impacts and variations experienced in the future irrigation requirement and its consequences for water use and water scarcity. At the global level, Döll (2002), one of the first works on the topic, evaluated for rice and non-rice crops the impact of climate change and annual climate variability on irrigation need, obtaining results indicative that two-thirds of the areas equipped for irrigation in 1995 could suffer from increased water use, also acknowledging the wide range of uncertainties attributed to the study that were not evaluated. Fischer *et al.* (2007) already addressed the issue of irrigation needs under the range of different climate change mitigation policy scenarios, adding to the work the concept of agroclimatic zones and establishing two scenarios from the modification of the A2r SRES (Special Report on Emissions Scenarios) climate scenario, with their results being positive for climate change mitigation policies for most of the world. In the same vein, Chaturvedi *et al.* (2013) analyzed the future need for irrigation from mitigation scenarios arising from two types of mitigation policies (universal carbon rate and only for fossil fuels and industry), indicating that the consideration of land use in carbon rates (universal rates) is more effective in reducing future water use for the activity. Hejazi *et al.* (2014), still considering mitigation policies, worked with the consequences on water scarcity, indicating similar results to Chaturvedi *et al.* (2013) from the consideration of six different scenarios, with water scarcity decreasing in scenarios with a universal carbon rate.

In addition to irrigation, its intensification and joint impact with land use (from agricultural expansion scenarios) has also been evaluated in global works, with Pfister *et al.* (2011) assessing water consumption and land use from the perspective of securing food for population in 2050, doing so from four joint scenarios of expansion and intensification in agriculture and obtaining indications that although increased intensification in agriculture brings higher productivity, it leads to higher water consumption and is insufficient for the predicted food demand, and a joint strategy focused primarily on reducing food waste is needed. Similarly, Huang *et al.* (2019) evaluated the effects of climate change on land use and water footprint (blue water and green water) both separately and jointly, resulting in a growth of about

70.3% of blue water in the joint scenario for the end of the century, being mainly caused by the expansion of irrigated area.

Currently, in view of the greater simulation power and the stage of development that global circularity models (GCM), global hydrological models (GHM) and global gridded crop models (GGCM) are at, studies have been carried out evaluating the need for irrigation through multi-modeling (using the output data of one model as input for another model) from the coupling of two or more types of models. Elliott *et al.* (2014) compared the results, by watershed, of permuting 5 GCM's, 10 GHM's, and 6 GGCM's to calculate water consumption for irrigation and agricultural production under RCP (Representative Concentration Pathway) 8.5 scenario, with their results being indicative that agricultural intensification by irrigation alone will not be sufficient to meet future production demand. Along these lines, Konzmann *et al.* (2013) used the LPJmL (Lund-Postdam-Jena managed Land - GHM and GGCM) integrated model fed by results from 19 GCM's to assess future global irrigation need, with results indicating reduced irrigation need due to the fertilization effect of CO2[2], higher regional precipitation and shorter crop growth periods.

Due to the variability of the results of the several global circularity models, together with the uncertainty of the models used in irrigation estimation and several uncertainties attributed throughout the analysis of climate change in agriculture, works have been done suggesting and implementing ways to reduce or account for them, as Katz (2002), who discussed several uncertainty analysis models, evaluating techniques used as model validation, sensitivity analysis, scenario analysis, Monte Carlo and downscaling, presenting alternatives to the most common uncertainty analyses, such as the probabilistic and stochastic approaches. Regarding crop model uncertainties, Asseng *et al.* (2013) compared results from 27 models for wheat productivity under climate change, indicating that there is great variability among them. Similarly, Liu *et al.* (2016) analyzed the different methods of calculating evapotranspiration, yielding better estimates for the Penman-Monteith[3] method. Boehlert, Solomon, and Strzepek (2015), in a discussion on learning from using ensembles of circulation models, concluded that using the output of several models

[2] The increase in the concentration of carbon dioxide in the air produces in plants with a C3 type of photosynthesis a decrease in their transpiration while increasing their rate of photosynthesis
[3] Evapotranspiration in the Penman-Monteith equation is derived from the energy and mass balance of the air near the surface. It is the main method of calculating the variable

(or several combinations of), rather than a single or few, decreases the chances of getting inappropriate results. Following this trend, Wang *et al.* (2017) proposes and applies for rice crops in three locations in China a Bayesian approach by adding weights to the results of several GCMs, showing better results compared to simple averaging of the same results. Gutiérrez *et al.* (2013) discusses different downscaling methods and their robustness to represent minimum and maximum temperatures of anomalous periods in Spain, with better results for weather generators and analogous methods.

Several studies have considered a detailed characterization of a crop or site to achieve more specific results, using crop-specific methods, regional data for crop parameterization and characterization, more detailed consideration of the water balance, and downscaling techniques of future climate data to better represent the local climate and crop. Currently, we highlight the study of rice, wheat, and corn crops and studies that consider several crops for specific locations or irrigation regions (a characterization of the papers regarding basic technical characteristics can be found in Table A1 in Appendix A).

The quantification of the water footprint, conceived by Chapagain and Hoekstra, (2004), is widely used in works aiming to analyze the effects of global warming on irrigation (such as CHIARELLI *et al.*, 2016; SHRESTHA, CHAPAGAIN AND BABEL, 2017 and GAROFALO *et al.*, 2019 at the regional level and SIEBERT AND DÖLL, 2010 and HUANG *et al.*, 2019 at the global level). Similarly, Life Cycle Assessment (LCA) is used in works to quantify, with impact characterization factors, how much climate change impacts water scarcity in watersheds (as in ALCAMO, FLÖRKE AND MÄRKER, 2007 and GOSLING AND ARNELL, 2016), with no specific guideline for water scarcity characterization models yet for future work. The consideration of water supply for irrigated areas under global warming is also evaluated by considering specific water balance models in dams (as in NAM, CHOI, AND HONG, 2015).

In Brazil, the consideration of future irrigation needs becomes essential due to four factors: i) the large economic impact of agriculture on the country's trade balance (about 42% of the export value in 2018 - MAPA, 2019); ii) the extensive irrigated area, with 8.2 Mha estimated by the National Water Agency (ANA, 2021), which, despite representing a small percentage of the total area, was considered by FAO as the sixth country with the largest area equipped for irrigation in the world

(FAO, 2021) and has growth prospects of about 51% by 2040 (ANA, 2021); iii) the high consumptive[4] use of irrigation in the country, representing about 50% of consumption (use without return of water to water bodies) and 66% of withdrawal (water use only) of water on average in 2018 (ANA, 2019a), with increasing percentage of participation over the year; and iv) the non-homogeneous distribution of water resources in the country, with the Amazon region (north of the country) having, through the Amazon River, 80% of the national surface water and the semi-arid area (northeast of the country) having intermittent rivers and strong periods of drought (ANA, 2019a), characterizing the area as vulnerable in the water issue.

Given the importance of irrigated agriculture in Brazil and its impact on water use, a number of works have been carried out to analyze climate impacts on agriculture, mainly for corn and sugarcane crops. In this context, Marin *et al.* (2013) evaluated water use efficiency and fresh stem mass (biomass measure) for sugarcane in São Paulo under climate scenarios (SRES A2 and B2) for 2050, reporting increases in both factors, and, complementarily, Zullo, Pereira, and Koga-Vicente (2018) obtained indications of low climate change impacts for the central sugarcane producing region in Brazil from the assessment of climate risk zones under RCP 8.5 scenario. Whereas de Oliveira, de Miranda, and Cooke (2018) reported in a study in the city of Piracicaba (São Paulo state) under A1B and A2 scenarios that sugarcane productivity will decrease about 40% and an increase of about 81% of irrigation will be required for corn. Minuzzi and Lopes (2015) evaluated the productivity and irrigation needs for first and second crop corn for central-western Brazil under the RCP 4.5 scenario for short (2025) and medium term (2055), concluding that there will be no water stress in the first crop, with a decrease in the need for irrigation in the second crop due to the reduction in the planting period. Verhage *et al.* (2017) evaluated the effect of future CO2 concentration (called CO2 fertilization effect) on Arabica coffee productivity for 2050 under RCP 4.5 scenario in 42 producing municipalities, obtaining results that indicate that there is a reduction in the impact of climate change on productivity by the fertilization effect. Minuzzi, Frederico, and Silva (2017) simulated the water efficiency, cycle length, and productivity of soybean for the main producing regions of Paraná, Santa Catarina, and Rio Grande do Sul using FAO's AquaCROP (STEDUTO *et al.*, 2009 and RAES

[4] Water use in processes characterized by partial or no return of water to the water body, such as water used in irrigation

et al., 2009) under RCP 4.5 scenario for short and medium term, indicating growth in crop productivity and water productivity even without irrigation. For the northeast region, Martins, Tomasella and Dias (2019) evaluated under RCP 4.5 and 8.5 scenarios the effect of climate change on corn productivity for short, medium and long term, indicating that productivity maintenance is possible at costs of 140% increase in water consumption for irrigation. In Paraná (southern region of Brazil), Resende *et al.* (2019) indicated an increase in the number of days with percolation and an increase in water uptake capacity by the crop, especially in RCP 8.5 scenario.

The study of impacts to watersheds is also an important theme in national studies, leading to publications such as the one made by the National Water Agency (ANA) of the impact of climate change for the semi-arid region seeking to assess the vulnerabilities of two water basins (Jaguaribe and Piranhas-Açú; WORLD BANK AND ANA, 2013). Similarly, Gondim *et al.* (2018) indicated increases in future reference evapotranspiration as well as irrigation needs for optimistic (RCP 4.5) and pessimistic (RCP 8.5) scenarios for the Jaguaribe River in the semiarid region. Contrasting results were obtained by da Silva *et al.* (2018), who evaluated the impact of climate change for four crops (beans, corn, wheat, and soybean) in the Ijuí River, showing that, for all crops, there is a reduction in the future irrigation need, indicating that climate consequences may vary depending on the region analyzed.

Although there is general consensus that irrigation will suffer consequences due to climatic change and there are several studies done in that matter for Brazil, there is still no work that comprehensively covers for all country and all relevant irrigated crops (and its perspectives of change) the effects of climate change on the future irrigation and the effects of future irrigation change on the overall water scarcity on the country. Such work enables a better and holistic understanding of the effects of climate change on irrigation and makes possible a country-wise analysis of future irrigation and water scarcity for use in decision making and as a basis for other future irrigation assessments in Brazil.

1.1 Objective

This study aims to evaluate irrigation and impact on water scarcity for the main irrigated crops in Brazil (sugarcane, coffee, soybean, corn, beans, cotton, and rice) for 3 future periods (2025, 2055, and 2085) considering two divergent future scenarios of climate change (RCP 4.5 and 8.5), thereby seeking to indicate regions of importance for future water needs and impact on water scarcity for the country and for each crop.

2 THEORETICAL BACKGROUND

This section explains the methodology used for the literature review in this study (subsection 2.1) and discusses the information and conclusions of the articles read regarding the use of global warming scenarios (subsection 2.3), climate modeling (subsection 2.4) and its bias correction (subsection 2.5), crop modeling and evapotranspiration (subsection 2.6) and additional scenarios addressed (subsection 2.7). Additionally, irrigated crops in Brazil (subsection 2.2) and the characterization of the impact of irrigation on water scarcity in the literature (subsection 2.8) are analyzed and discussed.

2.1 Literature review

The initial search for articles was done on the Scopus platform with terms (keywords) that refer to water use for irrigation, climate change, and future predictions. Table 1 shows the search done.

Table 1 - Keywords used in the main article search

Keyword for irrigation water use	(Crop OR Irrigation) W/1 Water W/1 (Requirement OR Consumption)
Keyword for climate change	AND “Climate Change”
Keyword for future forecasts	AND Future

Source: Own elaboration (2021)

The search was refined to English results for articles and reviews, totaling 161 articles of interest. A new refinement step was performed only with articles published from 2015, the period considered current, with 98 articles remaining. The snowball technique from the citations of chosen articles was used to include 11 articles about the impacts of climate change in irrigation within the specified period. The abstracts of all 109 chosen articles were read and evaluated according to the following criteria:

a) Has there been an evaluation of future climate change scenarios?
b) In the context of climate change, did the topic addressed include the water need, consumption or productivity of the agricultural crop?

The result of the reading indicated 94 relevant articles, to which the Methodi Ordinatio (PAGANI, KOVALESKI AND RESENDE, 2015) was applied, aiming at the organization and separation of the 30 articles of greatest importance. Despite the previous reading of abstracts, four articles were disregarded in further reading for not meeting the criteria used in the abstracts.

Two additional searches were conducted. The first, which considered papers conducted in Brazil, included results in Portuguese, articles prior to 2015 and added the keyword "AND 'Brazil'" to the search, totaling six more publications. The second search looked for articles published during the execution of this study (2020-2021), totaling eight more papers of interest. In the end, 40 articles were read and evaluated. Table A1 in Appendix A shows the basic technical characteristics of the articles read, such as crops studied and study locations.

2.1.1 Irrigated crops in Brazil

According to the Atlas of Irrigation (ANA, 2021), Brazil has a large number of irrigated crops, especially flooded rice (mainly states of Rio Grande do Sul, Santa Catarina and Tocantins), with 15.9% of the irrigated areas in the country, fertigated sugarcane (from the vinasse of the sugar-alcohol industry - mainly Center-South region) with 35.4% of the irrigated area, sugar cane with full or deficit irrigation (mainly producing states in the Northeast, Goiás and Minas Gerais) with 9.1%, coffee with 5.5% (mainly states of Espírito Santo, Minas Gerais, Bahia and Rondônia) and other crops irrigated by central pivots with 17.6%. Of the central pivot irrigated crops, cotton and grain production (mainly beans, soy and maize) stand out. Thus, sugarcane, coffee, cotton, beans, soy, maize and rice were considered for analysis. Other already irrigated crops were considered in the Atlas of Irrigation (such as fruit trees) and there is the possibility of other crops being irrigated in the future, but both were not considered in the scope of the study.

2.1.2 Global warming scenarios and future periods

Analysis of climate change impacts begins with the choice of future scenarios of CO2 concentration. The IPCC (Intergovernmental Panel on Climate Change), through the AR5 report (Fifth Assessment Report - IPCC, 2014), recommends as current climate change scenarios the RCP scenarios (Representative Concentration Pathways), which replaced the SRES scenarios (Special Report on Emissions Scenarios), previously recommended by AR4 (Fourth Assessment Report - IPCC, 2007). Other scenarios, such as SSP (Shared Socioeconomic Pathways) are also used for impact assessments aimed at socio-economic or political projections of greenhouse gas emissions. The IPCC models are used to parameterize the global circularity models (GCMs) to represent the climate behavior considering a given radiative forcing or CO_2 concentration. In addition, the scenarios serve to have comparability between the results obtained by different circulation models.

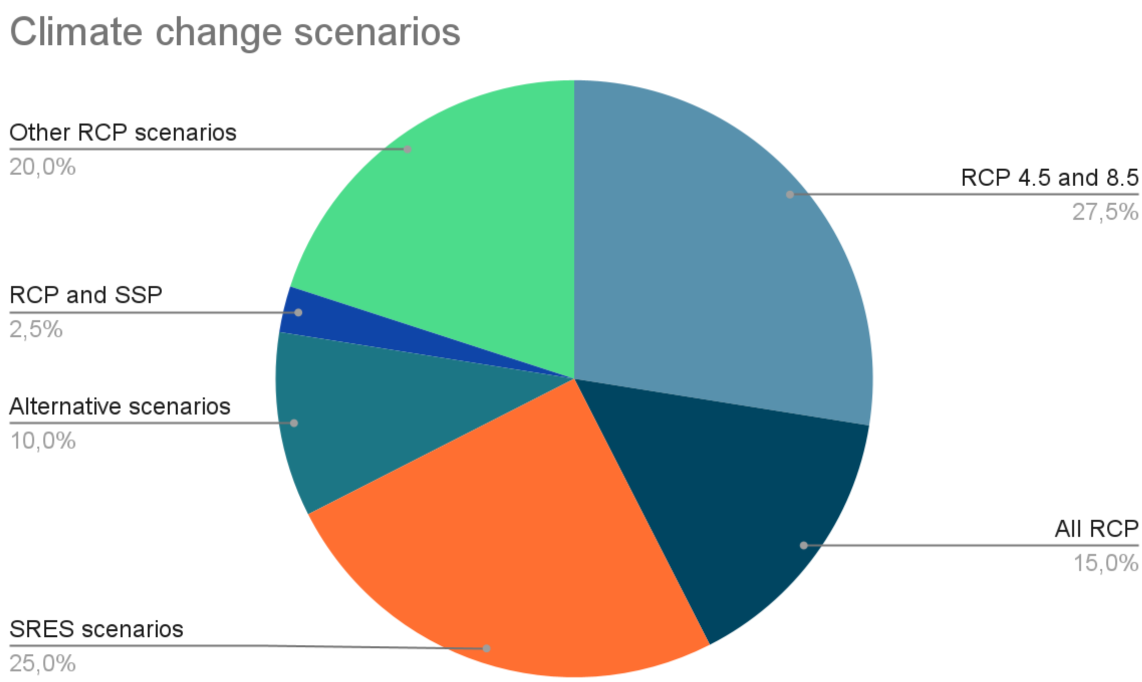
As a current approach, the RCP scenarios are 4 estimated trajectories for CO_2 concentration up to the year 2100 made by the IPCC, named from the estimated radiative forcings of each trajectory in the year 2100 and resulting from simulations of Integrated Assessment Models (IA - VAN VUUREN *et al.*, 2011). Thus, the trajectories are characterized as (adapted from VAN VUUREN *et al.*, 2011):

a) RCP 2.6 (low forcing): Peak radiative forcing at approximately 3 W/m^2 (approximately 490 ppm CO_2 equivalent) and decline to 2.6 W/m^2 by 2100. IA: IMAGE (VAN VUUREN *et al.*, 2006 and VAN VUUREN *et al.*, 2007)
b) RCP 4.5 (medium forcing): Peak-free stabilization path of the radiative forcing at approximately 4.5 W/m^2 (approximately 650 ppm CO_2 equivalent), reaching stability after 2100. IA: GCAM (CLARKE *et al.*, 2007; SMITH AND WIGLEY, 2006 and WISE *et al.*, 2009)
c) RCP 6.0 (medium forcing): Peak-free stabilization trajectory of the radiative forcing at approximately 6.0 W/m^2 (approximately 850 ppm CO_2 equivalent), reaching stability after 2100. IA: AIM (FUJINO *et al.*, 2006 and HIJIOKA *et al.*, 2008)
d) RCP 8.5 (high forcing): Radiative forcing growth path reaching approximately 8.5 W/m^2 (approximately 1370 ppm CO_2 equivalent) in 2100. IA: MESSAGE (RIAHI *et al.*, 2007)

RCP scenarios were used in 26 of the 40 studies read (65%), with the joint use of the 4.5 and 8.5 forcing scenarios standing out (50% of the papers). Consideration of all 4 scenarios was performed in only 5 papers (12.5% of the total).

The use of RCPs in the papers stems from the current publication and availability of global circulation model results for these scenarios, mainly those done under the CMIP5 (Coupled Model Intercomparison Project - TAYLOR, STOUFFER AND MEEHL, 2012). Still, papers that considered SRES scenarios accounted for 25% of the papers, mainly those published before 2017. Alternative scenarios accounted for 4 studies and one of the studies considered, in conjunction with the RCP, the SSP scenario. Figure 1 shows a graph indicative of the scenarios used.

Figure 1 - Climate change scenarios of the articles analyzed for the paper



Source: Own elaboration (2021)

With respect to the consideration of future periods, the studies divided the future years covered in their work into climate epochs (generally 20 or 30 years) that were characterized for a representative year (of half the epochs) by their average data (the average per day for the entire climate epochs). This behavior is similar to the WMO recommendation of 30 years for representing climatic periods or epochs (WMO, 1989), and aims to reduce extensive work with climatic data. Of the studies read, a temporal division was common, aiming at an analysis of climate impacts, for effects in the short term (characterized by the year 2020, 2025 or 2030), medium term (2045, 2050, 2055) and long term (2080, 2085).

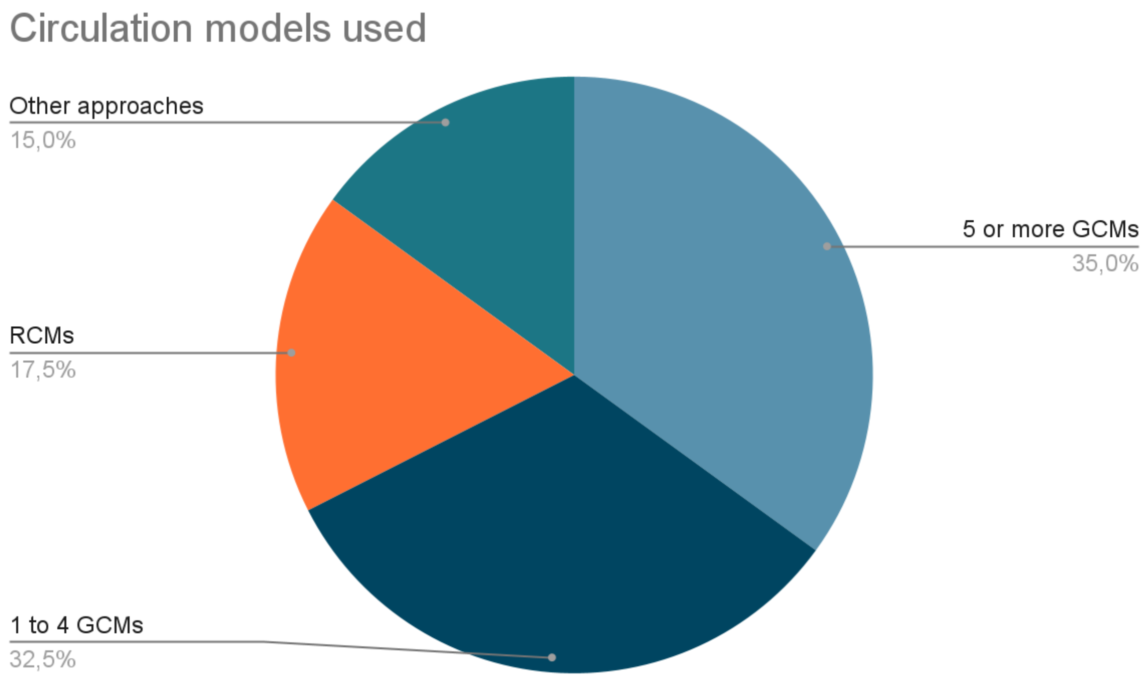
2.1.3 Circulation models

Global Circulation Models (GCM) or Regional Circulation Models (RCM) are used in simulations of climate change scenarios from the specific parameterization of each scenario (estimated CO2 concentration in RCP trajectories) and calculation of the set of equations characteristic of the modelling of atmospheric cycles. Their results are specific climate variables arranged in grids (such as surface temperature, precipitation, or wind speed and direction at 10 m above ground) that can be compared between the different models when considering a single scenario. In the case of the RCM, the model is parameterized and equated to represent the climate of a specific region of the globe.

The WGCM (Working Group on Coupled Modelling) of the WCRP (World Climate Research Programme) periodically conducts a series of simulations of GCMs and GCM ensembles aimed at increasing the knowledge and development of their climate prediction. This sequence is named CMIP (Coupled Model Intercomparison Project), which is currently in phase 5 (CMIP 5 - TAYLOR, STOUFFER, AND MEEHL, 2012) with a published summary of its sixth phase (EYRING *et al.*, 2016). The climate models participating in the simulation rounds are mostly used in climate change studies because they already have their results compared with historical data and with other models (increasing reliability) and have their data available in IPCC open databases (like <http://www.ipcc-data.org/> or <https://esgf-data.dkrz.de/projects/esgf-dkrz/>) and other sub-nodes (increasing accessibility). Similar simulations and development is carried out by the CORDEX project (Coordinated Regional Climate Downscaling Experiment), also of the WCRP, for regional and smaller scale simulations with RCP's.

Literature in the field of climate change simulations recommends using the average (arithmetic or weighted) result of GCM ensembles to decrease variability and avoid atypical or skewed results possible in single models (BOEHLERT *et al.* 2015). Of the considered papers that used data coming from GCMs, it was common to consider at least 4 different models (13 papers) or even more than 5 GCMs, (14 papers). The remaining papers considered results from ensembles of RCMs (5 papers), single model results based on good predictions of the region's climate (7 papers), few models (5 papers), or other modeling (such as climate generators - 6 papers). Figure 2 shows the distribution of the papers.

Figure 2 - Use of circulation models in the articles analyzed for the paper



Source: Own elaboration (2021)

The choice of models for a given study region was mostly made by analyzing the efficiency of the model, using methods such as Root Mean Square Error or Nash-Sutcliffe Index (NASH AND SUTCLIFFE, 1970) applied to historical results of GCM's or RCM's simulations in comparison with real results from the weather stations of the region (called model validation stage). In general, the work has relied on a number of indices for model comparison, with no specific guideline. The preferred periods for data validation were from 20 to 50 years before the study was conducted, but depended on data availability and the databases chosen.

2.1.4 Bias correction

As the results of both global (GCM) and regional (RCM) circularity models present a large area coverage and have results on spatial grids that make their use at the regional level inaccurate, it is common to apply downscaling methods, aiming at a spatial refinement of the grids to characterize the climate of smaller regions.

Downscaling methods are classified as dynamic and statistical (USAID, 2014). Dynamic methods downscale by characterizing the circularity modeling of the region, using equations and parameters specific to the region and simulating the climate by feeding the boundaries with global-level results (method used in RCMs). Statistical methods, on the other hand, apply transformations and statistical modeling based on the relationships between local and global climates to increase the number of representative grid points, thus reducing the scale.

In general, dynamic methods demand a large computational power and are not feasible for small studies, being more used when their results are already published in databases. Additionally, when the scale of the regional circularity model results (reduced by the dynamic method - RCM) is not sufficient for the region or there is the consideration of specific weather stations for validation, a further downscaling is done.

The methods used in the reviewed works varied from simple transformations (bilinear or z transform) to more robust techniques such as SDSM (Statistical Downscaling Method) or PanClim (Pattern Downscaling), and there is no guideline of methodologies to be followed. It is still recommended to estimate the limitations of the downscaling techniques and results for the region studied, since despite trying to refine the geographic information, the methods can bring a range of uncertainties in their use (USAID, 2014).

Another technique widely used in climate change work is bias correction, which addresses the systematic uncertainties of simulations by comparing their historical simulated data with actual historical data. The correction can be performed by applying simple data subtraction models, such as bias-correction (uses the difference between simulated and actual historical outcome of the climate variable) or delta method (uses the difference between future and historical simulated outcome of the climate variable) or more robust methods such as curve-fitting or quantile mapping correction, widely used for more stochastic variables such as precipitation (CCAFS, 2019).

All the studies analyzed that used GCM or RCM results as future representations of climate variables used some strategy to remove biases, and the application of models was diverse. The technique used the most among the papers was quantile mapping.

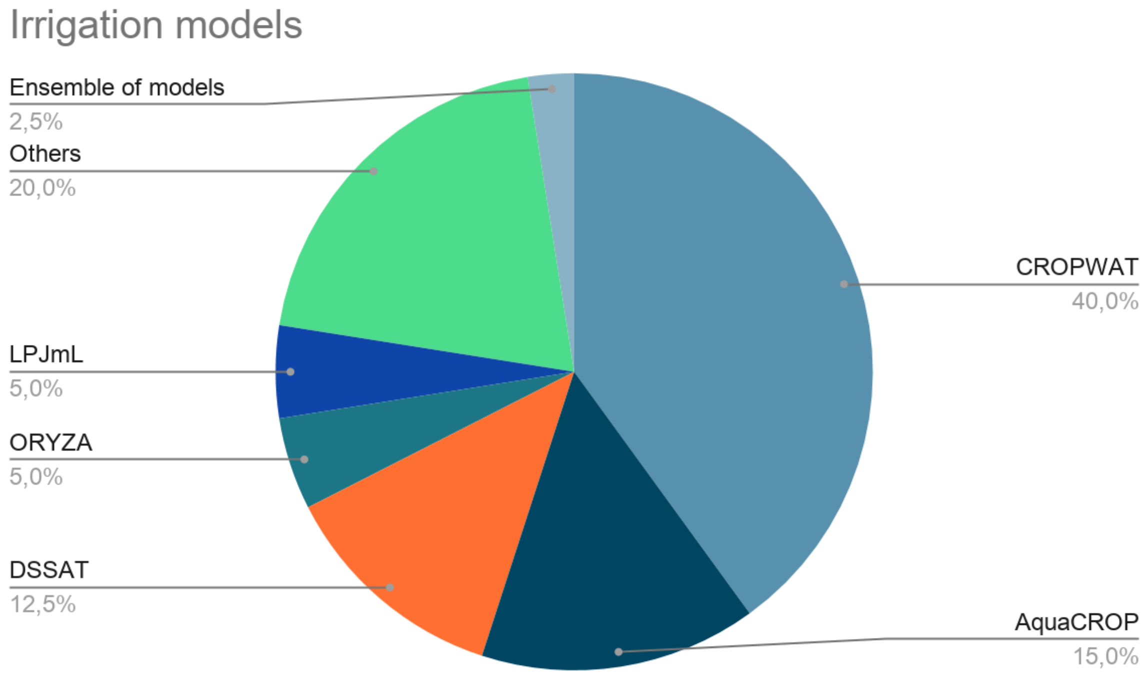
2.1.5 Crop simulation models and evapotranspiration

Using future climatic data as input, already with bias correction and adjusted scale, the analyzed studies used a specific or general method to model the future irrigation needs or water productivity of the crop. Of the methodologies chosen, the general models CROPWAT, from FAO (used in 40% of the papers - ALLEN *et al.* 1998), to calculate crop water requirement and irrigation and AquaCROP, also from FAO (used in 15% of the papers - STEDUTO *et al.* 2009 and RAES *et al.* 2009), to calculate crop water balance and yield, stand out.

General models allow the application for several crops, and are widely used on a global level or in studies that use large amounts of data both because of their ease of use and because of the reduced number of data and parameterization required. CROPWAT is used because it is a simple method of irrigation calculation that can be used for a wide range of crops, and is therefore a reliable alternative. Its calculation procedure can include anything from a simple balance of crop evapotranspiration and effective precipitation to the inclusion of water stress and soil water balance. Complementarily, the AquaCROP model uses CROPWAT modeling in conjunction with complementary equations (DOORENBOS AND KASSAM, 1979) to estimate biomass production and consequently plant yield and water productivity.

When the analyzed area was smaller or there was availability of crop data in the region, more refined models of crop development were used. The specific models seek to simulate the growth, phenology and behavior of the crop based on climatic inputs and specific parameters of the study region, and it is generally necessary to validate the model with historical data of the crop to obtain a more refined result. Of the crop-specific models, there was a large use of the DSSAT modules (Decision Support System for Agrotechnology Transfer - such as CERES-Rice, CANEGRO and CERES-Maize - 12.5% of the papers), as well as use of ORYZA for rice characterization (2 papers). Figure 3 shows the distribution of the papers as to the crop method used.

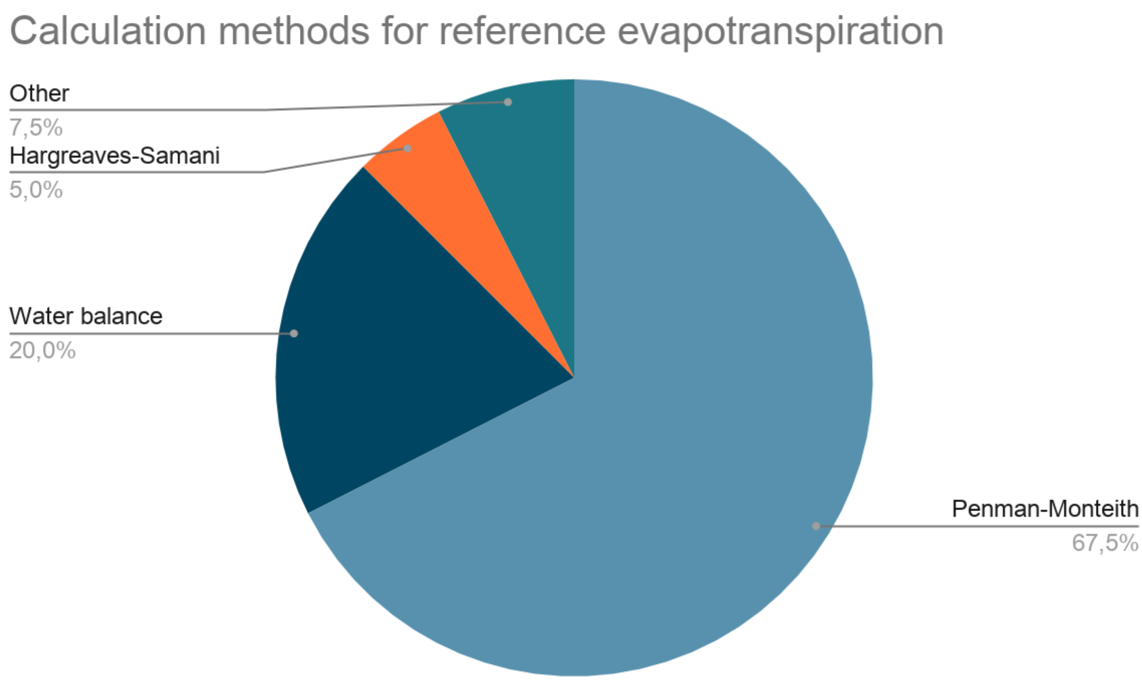
Figure 3 - Use of irrigation calculation models in the articles analyzed for the paper



Source: Own elaboration (2021)

Another point often addressed in the studies was the method for estimating reference evapotranspiration, indispensable for calculating the water balance and estimating the need for irrigation. In 67.5% of the studies, the method chosen was Penman-Monteith, recommended by FAO and which uses a series of climatic characterizations such as radiation balance results, wind speed at 2 meters and psychometric and saturation pressures to estimate reference evapotranspiration for a hypothetical crop (reference grass). The Penman-Monteith method is widely used because it is derived from a physical balance and not an approximation, which increases the reliability of its results, but it also has a large number of variables in its calculation, which makes its use difficult. As there is availability of data for Penman-Monteith calculation in this study, this method was used. The other methods used were Priestley-Taylor and Hargreaves-Samani (2 papers), Thornthwaite-Mather (1 paper) and indirect methods by water balance (8 papers). Figure 4 shows the distribution of the studies regarding the reference evapotranspiration method used.

Figure 4 - Method for calculating reference evapotranspiration in the articles reviewed for this paper



Source: Own elaboration (2021)

2.1.6 Additional scenarios

A specific evaluation of the considered works was made regarding the scenarios considered in addition to climate change. In this respect, different scenarios for irrigation (5 papers), for CO2 concentration (focused on its fertilizing effect - 14 papers) and analysis of the variation of the plant growth period or different planting dates (11 papers) were common. Additionally, the evaluation of papers by snowball indicated the use of scenarios for land use (such as agricultural expansion) and scenarios of CO2 emissions mitigation through universal or specific carbon mitigation policies.

2.1.7 Water scarcity

The Life Cycle Assessment (LCA) technique considers in its application a range of impact categories translated as characterization factors. These factors multiply the inventories of the flows causing the impacts by translating their quantity as a comparable and meaningful impact value.

The water scarcity characterization for LCA uses the water inputs and outputs as their main inventory. For irrigation in agriculture, these water flows are usually accounted as net irrigation water requirements for a given crop growth (blue water consumption) or irrigation water requirements per kilogram produced (blue water) as done by Pfister *et al.*, (2011) countrywise and Savioli (2020) for Brazilian main crops.

For the impact on water use or water scarcity, the main models used within LCA are the AWARE (Available Water Remaining - BOULAY *et al.*, 2018), which compares monthly water demand and availability for 11050 sub-basins aiming to stipulate an average value at which characterization factors are calculated, and the WSI (Water Stress Index - PFISTER, KOEHLER AND HELLWEG, 2009) which is based on a logistic approach of the Withdrawals-To-Availability ratio (WTA) to characterize the impact. The AWARE method has regionalization work and uncertainty analysis for Brazil (ANDRADE *et al.*, 2019 and ALVEs *et al.*, 2020 respectively).

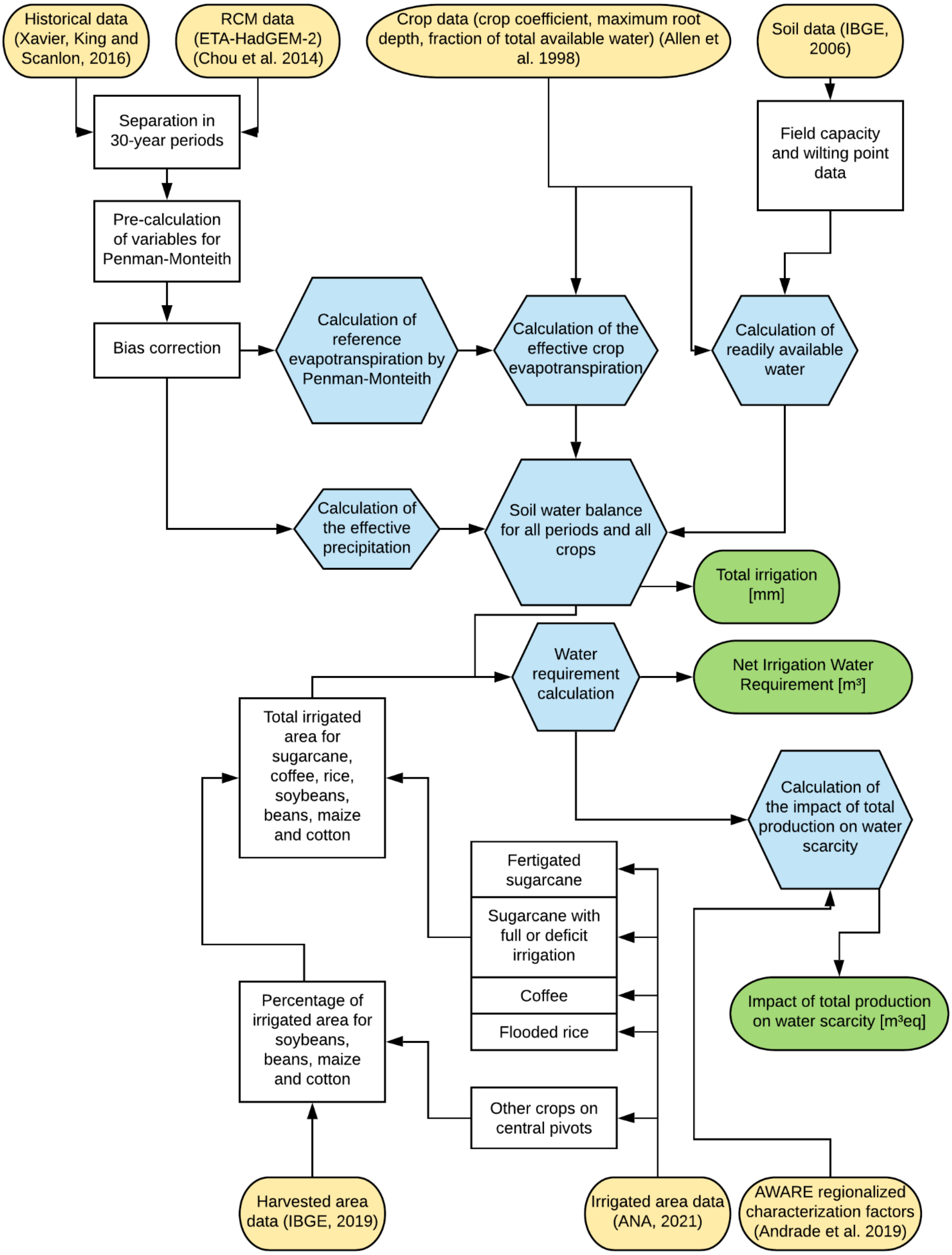
For studies that assess total production, the use of marginal characterization models is not recommended since the results don't represent a marginal change on the production of a crop but an average water use for the production. In this context Boulay, Benini and Sala (2020) worked on an AWARE average (non-marginal) characterization model with results per major watershed, but Pfister, Scherer and Buxmann (2020) pointed out that it still had issues and should be used with care. For this work, although the non-marginal AWARE model would be a choice for water scarcity characterization, the AWARE regionalized model is used for presenting a more detailed factor (Brazilian sub-basins) and thus accounting for a more refined result in the country.

3 METHODOLOGICAL PROCEDURE

3.1 Introduction

The flowchart in Figure 5 shows the step-by-step procedure performed to obtain the results (in green) of the water requirement for the study. Calculations (in blue) were performed mostly in python 3.6 using the xarray, numpy and geopandas libraries. The data sources (in yellow) are detailed in section 3.8 on “Data”.

Figure 5 - Flowchart of the methodological procedure used in the work. Boxes in yellow are the sources of data used, boxes in white are the procedures done before calculations, boxes in blue are the calculations done and boxes in green are the intended results



Source: Own elaboration (2021)

3.2 Soil water balance

The irrigation calculation procedure in this study is based on the soil water balance for a given crop from the FAO model CROPWAT (ALLEN *et al.*, 1998). This approach allows a daily iteration of climate, crop, and soil data to determine when and how much water is needed to replenish the soil to its field capacity[5] and avoid water stress of the crop at planting. Its calculation is described by Equation 1:

$$D_i = D_{i-1} - I_i - P_{eff,i} - CR_i + Et_{c,i} + DP_i \quad (1)$$

Where:

a) D_i is the water depletion on day i in [mm]
b) D_{i-1} is the water depletion on day $i - 1$ in [mm]
c) I_i is the irrigation on day i in [mm]
d) $P_{eff,i}$ is the effective precipitation on day i in [mm]
e) CR_i is the capillary rise on day i in [mm]
f) $Et_{c,i}$ is the effective evapotranspiration on day i in [mm]
g) DP_i is the deep percolation on day i in [mm]

The terms D_i e D_{i-1} indicate the water depletion of the soil on day i and the previous day ($i - 1$) respectively, i.e., the amount of water needed to replenish the soil to its field capacity. Values of D_i less than 0 indicates that the soil has exceeded its field capacity and there is water escape by runoff or deep percolation. To initialize the balance simulation, the variable D_i was set to 0 indicating soil at its field capacity and the variable D_{i-1} was set to 0 indicating no depletion from outside the simulation.

The main natural water input in the balance of Equation 1 comes from the effective precipitation ($P_{eff,i}$), which indicates how much water was effectively infiltrated into the soil and did not escape the planting area by runoff or deep

[5] Field capacity of a soil is the maximum water absorption possible for this soil before runoff happens

percolation. In this study, the term was calculated by the USDA SCS[6] equation, an empirical modeling of effective precipitation used as a standard for FAO's[7] CROPWAT 8.0 software (CLARKE *et al.*, 1998) and irrigation-related studies (CHAPAGAIN AND HOEKSTRA, 2010). Although effective precipitation already considers deep percolation, the term was kept as an escapement for the specific case where depletion is less than 0 and there is excess water in the soil. Another natural water input, capillary rise (CR_i), was considered negligent for the balance (the water table was considered far from the root zone) and was set equal to 0 in the calculations.

The main water output term of the soil balance is the effective evapotranspiration of the crop planted ($Et_{c,i}$). This term encompasses soil water evaporation and transpiration of the studied crop, indicating the surface water lost to both effects. In this work, this term was calculated from the crop coefficient of the studied plant and the reference evapotranspiration, as shown in Equation 2 (ALLEN *et al.*, 1998).

$$Et_{c,i} = Et_{0,i} * k_{c,i} \tag{2}$$

Where:

a) $Et_{0,i}$ is the reference evapotranspiration on day i in [mm]
b) $k_{c,i}$ is the crop coefficient on day i in [mm]

The coefficient of a crop is variable throughout the planting season, with an initial coefficient that increases in the development period until it reaches its peak for the mid-season period, and decreases in the final planting season. Therefore, the consideration of planting seasons and planting dates is essential to stipulate how this variable behaves throughout the annual period. In this work, the crop coefficients for the different crops studied (cotton, rice, coffee, sugarcane, beans, corn, and soybeans) were adjusted to daily values from the method described in Savioli (2018). The procedure uses data from the planting calendar for each crop and

[6] *United States Department of Agriculture, Soil Conservation Service*
[7] *Food and Agriculture Organization*

assigns, for each planting month, crop coefficient values for the entire planting period. From the monthly values, a simple average is taken to obtain an average crop coefficient for the month, and this is then corrected for the percentage of areas in the planting season in that month. The monthly values were used to characterize all the days of the respective months. Reference evapotranspiration will be discussed in more detail in section 3.4.

The irrigation term (I_i) in the soil water balance receives values only when the daily depletion (D_i) exceeds critical values for the crop studied, thus requiring human intervention in the supply of water to avoid water stress in plants. This critical value, called readily available water, is calculated from crop and soil variables, and is defined as the fraction of total soil water capacity where the plant root can effectively withdraw water, given by Equation 3 (ALLEN *et al.*, 1998).

$$RAW = p * (\theta_{fc} - \theta_{wp}) * Z_r \qquad (3)$$

Where:

a) RAW is the readily available water in [mm]
b) p is the average fraction of water available to the plant root before water stress occurs in [%]
c) θ_{fc} is the volumetric soil capacity on field capacity in [m³/m³]
d) θ_{wp} is the volumetric soil capacity on wilting point[8] in [m³/m³]
e) Z_r is the maximum root depth of the crop in [mm]

The term $(\theta_{fc} - \theta_{wp}) * Z_r$ indicates the total available water on the soil (ALLEN *et al.* 1998).

Thus, the irrigation (I_i) of Equation 1 can be described as:

[8] the wilting point of a soil is the minimum water holding capacity from which plants can no longer withdraw water

$$I_i = \begin{cases} 0 & \text{if } D_i < RAW \\ D_i & \text{if } D_i \geq RAW \end{cases} \quad (4)$$

In other words, irrigation only receives values when the depletion on the day exceeds the limit of water readily available to the crop.

To enable the irrigation calculations, a simple average for a representative year was made for the calculated data for reference evapotranspiration and effective precipitation for each chosen 30-year period.

3.3 Adapting water balance for flooded rice

The adoption of a specific soil water balance for flooded rice aims to encompass the flooding blade applied in this type of planting. To this end, Equation 1 was adapted following Jensen *et al.* (1990), resulting in Equation 5.

$$Al_i = Al_{i-1} + I_i + P_{eff,i} + CR_i - Et_{c,i} - DP_i \quad (5)$$

Where:

a) Al_i is the flooded depth for rice on the day i in [mm]

b) Al_{i-1} is the flooded depth for rice on the day $i - 1$ in [mm]

In this balance, instead of considering water depletion, irrigation is dependent on the amount of water (or depth) flooded with the soil saturated. For these conditions, irrigation is done only when the flooded depth value Al_i (or the height of the water blade) is or null, case where the soil is just on the saturation level, or is below zero, case where the soil is no longer saturated and there is depletion of water, with no irrigation for any other cases in a similar way to Equation 1. The flooded depth was considered as 50 millimeters for the whole planting because of the benefits of small flooded rice slopes (STONE, 2005).

3.4 Reference evapotranspiration

Reference evapotranspiration is defined as the surface water lost to soil evaporation together with plant transpiration for a reference crop (hypothetical grass - ALLEN *et al.*, 1998). This reference approach allows evapotranspiration to be easily adapted for other crops (from Equation 2) and for any region. In this work, this variable will be calculated from the Penman-Monteith equation (Equation 6 - ALLEN et al., 1998) which uses the energy balance and mass transfer near the surface to calculate the variable.

$$Et_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (6)$$

Where:

a) Et_0 is the reference evapotranspiration in [mm]
b) R_n is the net radiation in [MJ/m²]
c) G is the soil heat density flow in [MJ/m²]
d) γ is the psychrometric constant in [kPa/ºC]
e) T is the air temperature at 2 meters in [ºC]
f) u_2 is the wind velocity at 2 meters in [m/s]
g) e_s is the saturation vapor pressure in [kPa]
h) e_a is the real vapor pressure in [kPa]
i) Δ is the slope of the vapor pressure curve in [kPa/ºC]

The increase in future CO2 concentrations can have a significant impact on lowering evapotranspiration due to stimulation of plant photosynthesis (mainly for C3 group crops) and reduction on stomatal conductance (for C3 and C4 groups) (KIMBALL, KOBAYASHI AND BINDI, 2002, LONG *et al.*, 2004, LONG *et al.*, 2006, LEAKEY, 2009, VU AND ALLEN JR, 2009, VANUYTRECHT *et al.*, 2012). Several works had done adaptations of Penman-Monteith reference evapotranspiration to account for the changes of higher CO2, specialy for the stomatal conductance term

(1 + 0.34u2) that affects both types of photosynthesis groups (SWELAM *et al.*, 2010, ISLAM *et al.*, 2012, SANTOS *et al.*, 2020, BEN HAMOUDA *et al.*, 2021). In this work, the reference evapotranspiration is calculated using the original Penman-Monteith method and considering a modification done in Islam et al, (2012) that takes into account stomatal conductance responses from Allen, (1990), to addapt the behavior of the reference crop used in Penman-Monteith equation (reference grass crop) showed in Equation 7a.

$$Et_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + \frac{0.34u_2}{CO_2factor})} \quad (7a)$$

Where the fertilization factor takes into account the ratio between the analyzed concentration and a standard threshold of 330 ppm:

$$CO_2factor = \frac{0.0485 - 7 * 10^{-5}[CO_2] + 3.4 * 10^{-8}[CO_2]^2}{0.0485 - 7 * 10^{-5} * 330 + 3.4 * 10^{-8} * 330^2} \quad (7b)$$

Where:

a) $[CO_2]$ is the carbon dioxide concentration in [ppm]

Equation 7a addapts only the changes in stomatal conductance, but changes in CO2 concentration can have other indirect effects on the plant that raise uncertainties in the calculations. For instance, higher concentrations of CO2 can increase plant biomass and leaf area thus increasing transpiration and the increase in temperature caused by it can shift planting dates and planting areas due to climate inadequacy (KIMBALL, KOBAYASHI AND BINDI, 2002, VANUYTRECHT *et al.*, 2012). Studies in the area have been using FACE experiments (Free-air concentration enrichment) to assess such indirect effects in field experiments (LONG *et al.*, 2004, LONG *et al.*, 2006, VANUYTRECHT *et al.*, 2012).

The terms used in Penman-Monteith are all climate variables, and some are calculated from other equations because they are not data collected directly at meteorological stations. Among the variables calculated separately was the solar radiation balance (Rn), calculated by the relationship of Equation 8.

$$R_n = R_{ns} - R_{nl} \tag{8}$$

Where:

a) R_{ns} is the incident shortwave net radiation in [MJ/m²]

b) R_{nl} is the reflected longwave net radiation in [MJ/m²]

For the simulated data collected, the radiation balance (R_n) was calculated from the incident and reflected shortwave and longwave radiation and their balances. In the case of historical data the available variable was solar radiation, and it was necessary to follow equations 21-27, 37 and 39 from Allen *et al.* (1998) and use other input variables such as minimum and maximum surface temperature, elevation and latitude and longitude to calculate the reflected longwave radiation balance (R_{nl}) and equation 38, also from Allen *et al.* (1998), to calculate the incident shortwave radiation balance (R_{ns}).

Regarding the other variables, Table 2 shows the method for calculating the variables, their input data for historical and simulated data, and their equations used from Allen *et al.* (1998), marked with an asterisk.

Table 2 - Method for calculating variables for Penman-Monteith (the * indicates the equations' number used on ALLEN *et al.*, 1998)

Calculated variable	Historical data	Simulated data
G	Considered 0	Primary data
γ	Equations* 7 and 8 using elevation	Equations* 7 and 8 using elevation
u_2	Primary data	Equation* 47 using wind velocity at 10 meters
e_s	Equations* 11 and 12 using minimum and maximum surface temperatures	
e_a	Equations* 11 and 19 using minimum and maximum surface temperatures and relative air humidity	

Δ	Equation* 13 using average surface temperature

Source: Own elaboration (2021)

The reference evapotranspiration is used in Equation 2 to calculate the actual evapotranspiration for each crop.

3.5 Volume of irrigation

Although instructive, the irrigation demand in millimeters is independent of the actual irrigated area in the country, with the need to consider the irrigated volume for more conclusive water consumption results. For this, the net irrigation water requirement (NIWR - equivalent to the blue water consumption) was calculated according to Equation 9 for a daily scale.

$$NIWR_i = I_i * A_p * 10 \quad (9)$$

Where:

a) $NIWR_i$ is the net irrigation water requirement on day i in [m³]
b) I_i is the irrigation on day i in [mm]
c) A_p is the irrigated area on day i in [ha]

The net irrigation water requirement (NIWR) indicates the consumptive water use for irrigation and doesn't take into account the water losses caused by the irrigation system (because it returns to the watershed). That way the NWIR can be used for impact assessment of water scarcity.

To assess the amount of water for the crops' production, the blue water (irrigation per kilogram produced) was calculated by Equation 10. Values of production were gathered from 2018 for all periods analyzed (IBGE, 2018):

$$Blue\ Water = NIWR / production \quad (10)$$

3.6 Water stress impact assessment

The Life Cycle Assessment (LCA) technique was used in this study to assess the impact of water use for total irrigation by crop and for the whole country. The AWARE model with regionalized characterization factors (ANDRADE et al. 2019) was used due to its detailing by subwatershed in the country.

Net irrigation water requirements (NIWR - for total production) and Blue Water (for irrigation per kilogram) were considered for impact assessment, and the impact of irrigation on water scarcity was given by Equation 11 and 12 respectively.

$$Impact = NIWR * CF_{AWARE} \quad (11)$$

$$Impact = Blue\,Water * CF_{AWARE} \quad (12)$$

Where:

a) CF_{AWARE} is the AWARE characterization factor of the analyzed subwatershed in [m^3eq/m^3]

The impact results for this study take into account total crop irrigation and not its marginal irrigation (per kilogram produced) due to the fact that future crop production is not calculated considering the new irrigation demand values. Nevertheless, a marginal approximation using production results from 2019 is done within the work.

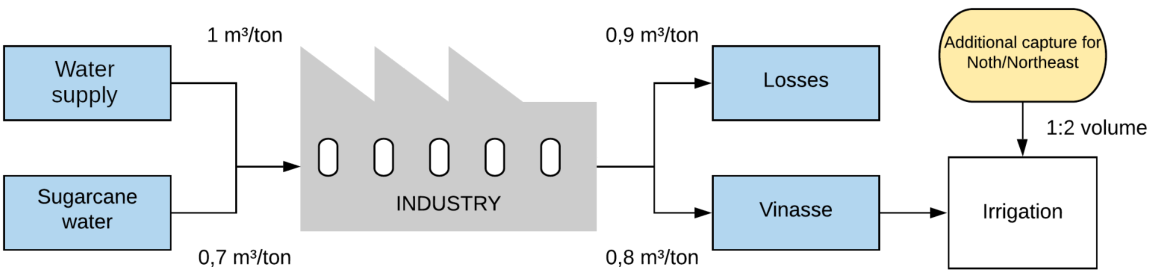
Boulay, Benini and Sala (2020) presented non-marginal AWARE characterization factors per major watershed worldwide, although Pfister, Scherer and Buxmann (2020) pointed out issues with the method and recommended its use with care. Nevertheless, the AWARE regionalization for Brazilian subwatersheds of Andrade *et al.* (2019) was chosen for both impact calculations, even with a marginal approach, due to its high detailing for Brazil and higher confiability. This choice can generate uncertainty on the impact and is addressed in the uncertainty section.

3.7 Considerations for sugarcane in irrigation volume

Sugarcane has three main types of irrigation in Brazil: fertigation, responsible for 79.5% of the irrigated area of the crop, full and deficit irrigation (together with another 20.5% - ANA, 2021). Each type has different mechanisms and characteristics regarding the volume of water used in irrigation and are treated differently in this work for the crop.

Fertigation uses the nutrients and water present in the vinasse, a residue produced by the sugar and ethanol industries and which is transported to the plantations near the industry, being reused for irrigation. Despite being reused, the vinasse water comes, in part (about 59%), directly from the water supply of the industry, which indicates indirect water use from water bodies and was consequently considered in this work as blue water input. Furthermore, fertigated areas in the North and Northeast regions have additional water withdrawal proportional to the volume of vinasse between 1:2 to 1:3 (in this work we used 1:2). The specific modeling for calculating water withdrawal for fertigation following the water cycle of a sugarcane industry (ANA, 2019b) is represented in the flowchart in Figure 6. There was no consideration of the water used for sugarcane production that serves as input for the industry as part of irrigation, which, despite virtually having water withdrawn for irrigation, would allocate all the impact of this to the last sugarcane planted, overestimating the value.

Figure 6 - Water inputs and outputs of the sugarcane industry. Adapted from ANA (2019b)



Source: Own elaboration (2021)

In this context, fertigation was modeled considering only part of the total irrigated volume coming from industry water withdrawal, which effectively withdraws water from water bodies. Other than that, fertigation often has water blades about 13 times lower than full irrigation, being this factor accounted for in the calculation. Equation 13 shows this modeling which is based on Equation 9.

$$NIWR_i = I_i * A_p * 10 \quad (9)$$

Considering the proportion of water captured by the industry (1/1.7 ≈ 59%) and that vinasse and losses get the same share of captured water (both are composed of 59% captured water).

$$NIWR_{fert} = I_{fert} * A_{fert} * 10 * 0.59 \quad (.)$$

Considering that the north and northeast production tend to have an additional capture of water for irrigation on a 1:2 proportion for volume of vinasse when fertigating (a third is additional water captured and two thirds are water from vinasse).

$$NIWR_{fert\ north\ or\ northeast} = \left(\frac{I_{fert}}{3} + \frac{2*I_{fert}*0.59}{3}\right) * A_{fert} * 10 \quad (.)$$

Lastly, considering that fertigation is done using approximately 13 times less water than the full irrigation calculated by NIWR, the formula follows as Equation 13.

$$NIWR_{fert} = 10/13 * \begin{cases} \left(\frac{I_{fert}}{3} + \frac{2I_{fert}*0.59}{3}\right) * A_{fert} & \text{if north or northeast} \\ I_{fert} * 0.59 * A_{fert} & \text{otherwise} \end{cases} \quad (13)$$

Where:

a) $NIWR_{fert}$ is the net fertigation water requirement [m³]

b) I_{fert} is the irrigation calculated on the soil water balance for fertigated areas in [mm]

c) A_{fert} is the area irrigated by fertigation in [ha]

Deficit irrigation, where only part of the full irrigation (around 1 / 2.6 of the annual water sheet - ANA, 2017) is applied in the dry period of the planting, also has adaptations to consider the smaller water volume. The adaptation was made from the multiplication of the irrigation result of the soil water balance (which represents full irrigation) by the factor of 1 / 2.6.

It is highlighted that southeast and northeast sugarcane irrigation have major differences, especially in the optimization of the irrigation system. The cultivation is more optimized in the northeast due to water being a more scarce resource and thus there is less water loss due to the irrigation system in that location. The NIWR doesn’t account for water losses due to irrigation systems and thus this effect is not represented in the results. At this work, it was chosen not to address the gross irrigation water requirements, that takes into account the effectiveness of the irrigation system, due to the focus on the consumptive water use for irrigation and their impacts on water scarcity.

3.8 Data

Considering the more refined spatial characterization, the RCM ETA, developed in Brazil by the National Institute for Space Research (INPE) with daily grid results of 0.2º x 0.2º spatial resolution for RCP 4.5 and 8.5 in South America (CHOU *et al.*, 2014) was chosen for this study. Despite the limitation in RCP scenarios, it has data on two divergent and most used scenarios in the literature. The ETA is nested by 4 different GCMs (HadGEM2-ES, MIROC5, BESM, and CanESM2), but only the nesting by HadGEM2-ES was chosen for the present study due to limitations, and the choice was based on national literature for circulation models (SILVEIRA *et al.*, 2019). ETA has data from 1961 to 2099, with its historical simulation being from 1961 to 2006. The ETA database can be accessed at <https://projeta.cptec.inpe.br>.

In this study, the divergent RCP 4.5 and 8.5 scenarios are addressed, representing optimistic (4.5) and pessimistic (8.5) results in the analyses. The choice was based on the papers read, which mostly used the two scenarios for representing distinct pathways and the limitation of the chosen regional circulation model. CO2 concentrations for the scenarios were collected from IIASA, (2021) for use in the consideration of the fertilizing effect of CO2 (Equation 7).

For Brazilian historical data, Xavier, King, and Scanlon (2016) performed a treatment of climate data from 3625 weather stations for the period from 1980 to 2013. The data were collected from the weather and climate stations of the National Institute of Meteorology (INMET), National Water Agency (ANA) and São Paulo Department of Water and Electric Energy (DAEE) and were focused on the variables of importance for the calculation of reference evapotranspiration. The treatment resulted in daily variables on a 0.25º x 0.25º grid for the entire Brazilian territory within the studied period.

The choice of climate periods was dependent on historical data and historical simulation, with the definition of the 30-year period (as stated by WMO, 1989 for definition of climate periods) from 1980 to 2010 as the historical period for data comparison. For the lacking historical period from 2006 to 2010 of the simulated data, the RCP 4.5 scenario was considered. With this, the periods 2010 to 2040 (being represented by 2025), 2040 to 2070 (being represented by 2055), and 2070 to 2100 (being represented by 2085) were considered as future periods. A validation period independent of the 30 historical years was not stipulated, and the 1980 to 2010 period itself was used for such analysis.

The variables in each climate data set went through a pre-calculation step to be able to compare and correct for bias. Table 3 shows the primary variables and those used for bias correction.

Table 3 - Primary variables and variables used for bias correction

Primary RCM variable	Primary variable of the historical data	Variable for bias correction
Incident shortwave radiation	Solar radiation	Net shortwave radiation
Reflected shortwave radiation		
Incident longwave radiation	Solar radiation	Net longwave radiation
Reflected longwave radiation		
Precipitation	Precipitation	Precipitation
Surface temperature	Surface temperature	Surface temperature
Minimum surface temperature	Minimum surface temperature	Minimum surface temperature

Maximum surface temperature	Maximum surface temperature	Maximum surface temperature
Air relative humidity	Air relative humidity	Air relative humidity
Wind velocity at 2 meters	Wind velocity at 10 meters	Wind velocity at 2 meters

Source: Own elaboration (2021)

Information on crop-specific characteristics such as crop coefficient, the fraction of total available water and maximum root depth were collected from FAO (ALLEN *et al.*, 1998) for the calculation of Equation 2 and Equation 3.

The soil map of Brazil (IBGE, 2006) was used as a source of texture data for the different soils in the country. This data was crossed with a table by Pereira *et al.* (2010) to obtain field capacity and wilting point values for the different soils, enabling their further use in the calculation of Equation 3.

The irrigated areas per municipality were collected from the Irrigation Atlas of the National Water Agency (ANA, 2021), which brings this data by typology and divided between irrigated areas of fertigated sugarcane, non-fertigated sugarcane, coffee, flooded rice, other crops irrigated by central pivot and irrigation by other methods for the year 2019 (considered for the historical periods and 2025) and 2040 (considered for the periods of 2055 and 2085).

Because of the large amount of uncertainty brought with a more detailed definition of crops and irrigation typology, the values of municipal irrigated areas for other methods were not considered in this study. The areas indicated as for other crops irrigated by central pivot were separated entirely between soybean, maize, bean, and cotton crops, which represent, together with sugarcane and coffee (whose areas have already been included in specific groups), about 89.8% of the area irrigated using this typology (ANA AND EMBRAPA, 2016). These irrigated area values for soybeans, maize, beans, and cotton were adjusted percentually from data on the harvested area of Brazilian agricultural production in 2018 (IBGE, 2018).

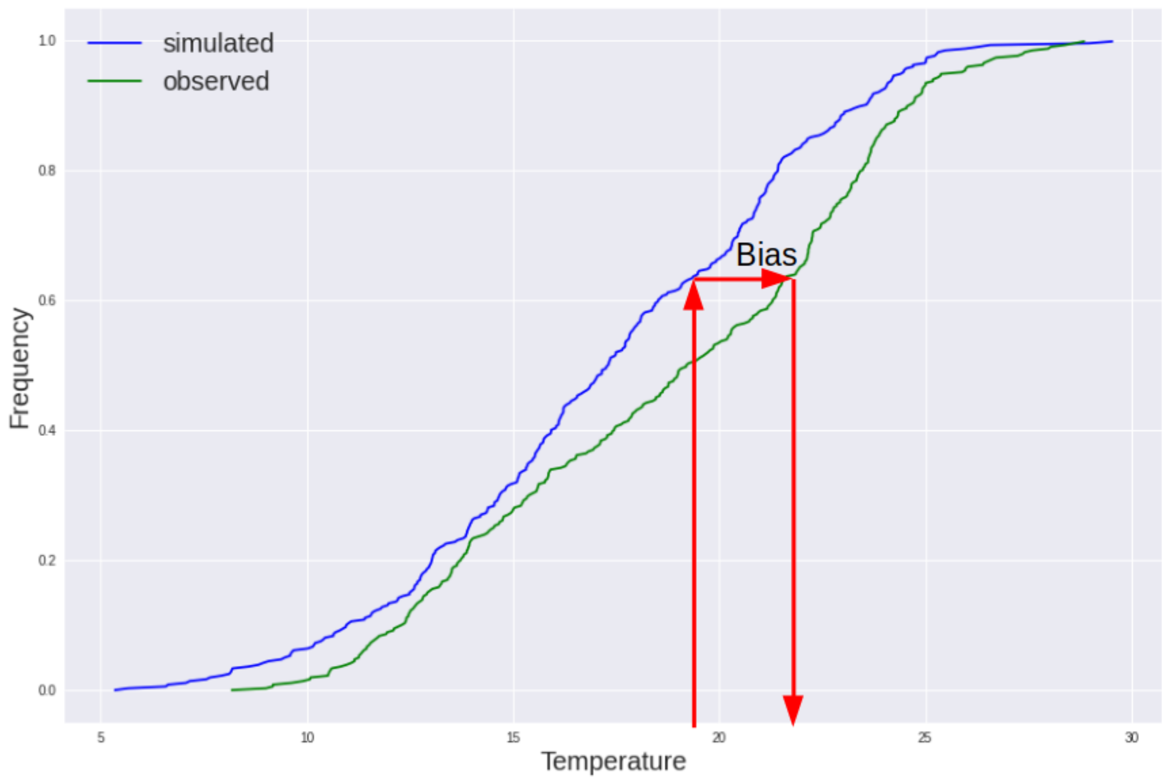
Values of full and deficit irrigated areas for sugarcane were obtained from state percentages of these typologies from ANA (2017), and these percentages were applied to the value of non-fertigated sugarcane from the Irrigation Atlas (ANA, 2021).

The efficiencies considered for each irrigation typology analyzed came from ANA (2013). Elevation data for use in the calculations prior to the Penman-Monteith equation (section 3.4) came from USGS (2020).

3.9 Bias correction

Aiming at the correction of systematic errors and consequent adjustment of the mean and variance of the simulated data, a bias correction step was performed for the net short and longwave radiation, minimum temperature, maximum temperature, precipitation, relative humidity and wind velocity at 2 meters. Initially, a grid fitting was performed using the xesmf library in python, with bilinear interpolation chosen as the method. A direct quantile mapping correction was performed. This technique uses the CDF of historical variables to map the biases between the two distributions. The correction was done at a monthly frequency (considering the data of the month for all the 30 years of the period studied) to consider seasonality. Figure 7 shows how the mapping is done.

Figure 7 - Direct quantile mapping, example for average temperature. In this case, all temperature values equal to 19ºC within the 30 years of data from this month got exchanged to 22ºC due to bias correction



Source: Own elaboration (2021)

A round of statistical tests was performed to test the results obtained in the bias correction regarding the similarity of mean (T-test[9] with initial assumption that the data had the same variance) and variance (Levene's test[10]). All tests were done for the historical period and with a significant value (p-value) of 0.05. The absolute maximum difference between the coefficients of variation of the data for the historical periods was also analyzed, especially in cases where the variance tests indicated low results, aiming to identify possible errors in the correction of biases. Table 4 shows the results obtained as a percentage of the grid that obtained positive similarity results.

Table 4 - Results of the statistical tests for the bias correction variables

Variable	T-test (average) [% of similar grid]	Levene test (variance) [% of similar grid]	Maximum absolute difference between variation coefficients (%)
Net shortwave radiation	100%	37,3%	2,26%
Net longwave radiation	100%	49,62%	8,86%
Precipitation	99,76%	99,71%	33,67%
Surface temperature	100%	74,18%	0,35%
Minimum surface temperature	100%	68,81%	0,67%
Maximum surface temperature	100%	80,91%	0,75%
Air relative humidity	100%	89,69%	0,96%
Wind velocity at 2 meters	99,5%	10,79%	11,42%

Source: Own elaboration (2021)

Due to the correction of negative values to 0, the wind speed variable at 2 meters had a low result for Levene's test. A more detailed graphical and variance evaluation of the variable showed that these corrections added to the fact that the variable is dispersed throughout the annual period (it does not follow well defined trends). The variable was submitted to a Kolmogorov-Smirnov two samples test[11] (p

[9] Null hypothesis that two independent samples have the same mean
[10] Null hypothesis that two or more samples are from populations with the same variance. It is a more robust test than the Bartlett for non-normal samples
[11] Null hypothesis that two samples are derived from the same distribution

= 0.05) to check for equal distributions and had 71.92% of positive results for the Brazilian grid. Precipitation, which underwent the same adjustment, did not have such significant differences because the value 0 is the one with the highest frequency in its distribution, but had a higher maximum difference in the coefficient of variation due to its greater dispersion during the year. As for radiation, a graphical analysis of the balance variables indicated that they have unconventional distributions (such as two peaks), which makes the variance tests difficult. Nevertheless, additional tests of Kolmogorov-Smirnov for two samples showed positive results for 100% (shortwave net radiation) and 91.05% (longwave net radiation) of the country's grid.

All variables (mainly radiation, wind, and precipitation) were graphically analyzed for distributions and their absolute differences in coefficient of variation were analyzed for errors in the result of bias correction.

The bias-corrected dataset was subsequently readjusted to the original 0.2 x 0.2 grid of the RCM and used for bias correction in the 3 future periods. With these results, the calculation of reference evapotranspiration using Penman-Monteith (Equation 6 and 7a) was done on a daily scale.

4 RESULTS

The results are divided into three parts: (i) climatic results (section 4.1), in which the historical series of reference evapotranspiration and precipitation for each region are presented and their future characteristics from the perspective of irrigation are discussed, (ii) general results for Brazil (section 4.2), in which cumulative results of all crops studied for Brazil are presented, and (iii) results for each crop (section 4.3), in which characteristics of each crop analyzed and its results regarding irrigation and impact on the country's water scarcity are shown and discussed.

4.1 Climate results

4.1.1 Evapotranspiration

The reference evapotranspiration tends to increase significantly in the central-western and southeastern regions, mainly by the climatic trend of rising temperature in the simulations of the regional circulation model ETA that assumes higher values in these regions (states of São Paulo, Goiás, Mato Grosso do Sul and Distrito Federal). The trends of increasing net radiation in conjunction with a reduction in air humidity also led to areas with increase in reference evapotranspiration (north of the state of Amazonas, the southern region of the state of Pará and the state of Mato Grosso).

Furthermore, an analysis of the evapotranspiration trend line results (of the time series from 1980 to 2100) for each region showed that there is a faster increase in evapotranspiration for the RCP 8.5 scenario compared to the 4.5 scenario, being up to twice as fast for the southeast, midwest, and part of the northern region. The increase is especially worrisome because there is a large concentration of irrigated sugarcane and center pivot crops (soybean, maize, beans and cotton) located in the mid-west and southeast of the country, which would lead to a significant increase in the irrigation required for these crops due to climatic factors, especially for the RCP 8.5 global warming scenario.

4.1.1.1 Fertilization effect of CO2

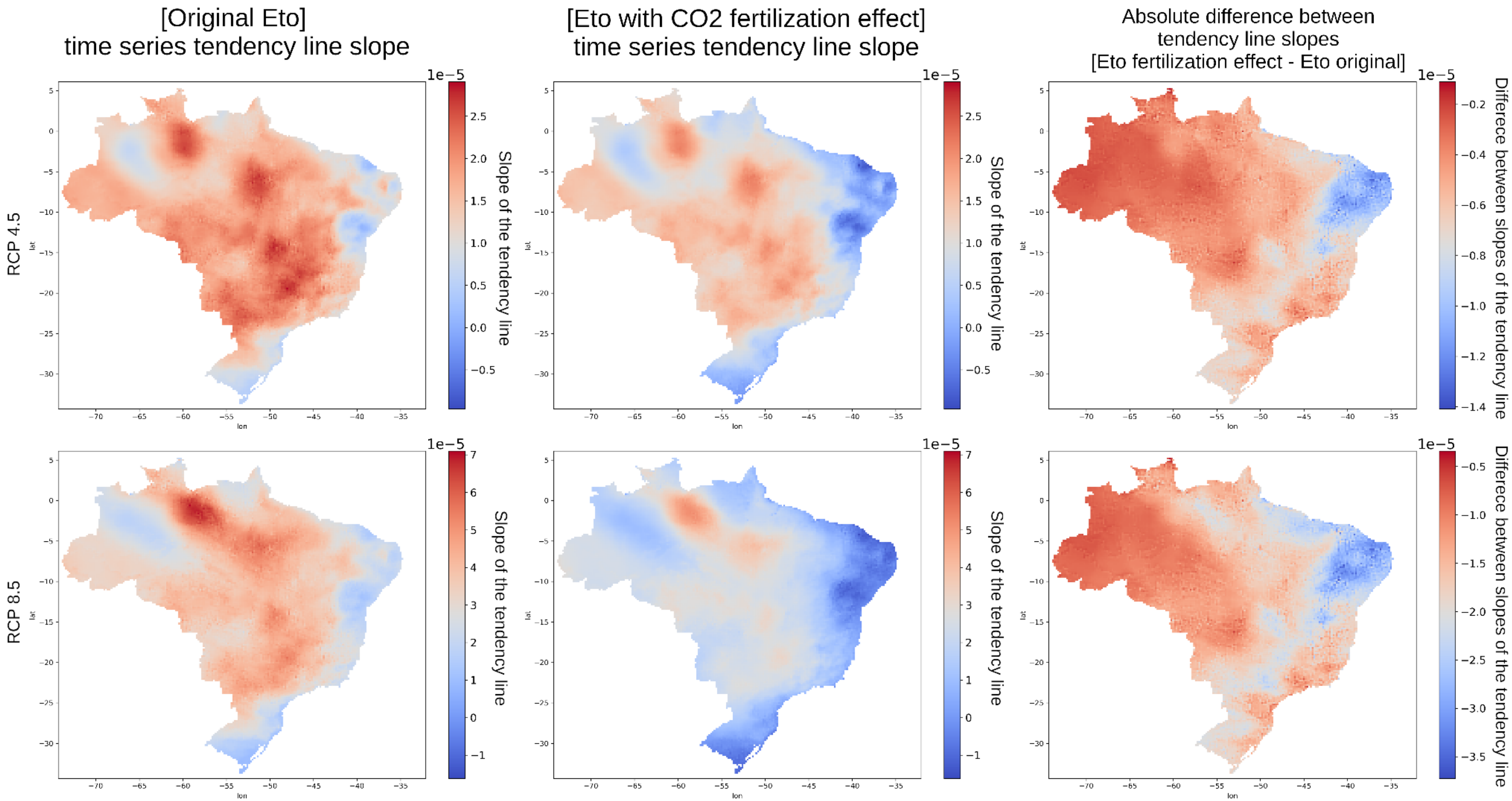
Two reference evapotranspiration scenarios, one coming from the original Penman-Monteith calculation (Equation 6) and the other with the consideration of the carbon dioxide fertilization effect (Equation 7a) were addressed in the study. The results indicated a reduction in the general trend of reference evapotranspiration throughout the country when the fertilization effect was considered, its decrease being more significant in the northeastern region as shown in Figure 8.

Across the country, the CO2 fertilization effect was shown to significantly reduce the growth of reference evapotranspiration. This reduction was milder in the north of the country and in the state of Mato Grosso do Sul (around 0.5 mm/yr to 1.5 mm/yr reduction in the growth trend) and higher in the northeast and parts of the southeast and south regions (reducing up to 3.5 mm/yr trend in the northeast region), leading some of the northeast regions to reduced future reference evapotranspiration (negative trend). The largest reductions coincide with areas of high surface wind velocity, which has a high impact on the incidence of the CO2 fertilization effect on plants, according to Equation 7a.

The results of the effect are positive for irrigated areas of various crops (central pivots, sugarcane and other crops not considered in this study) in the region of Petrolina-PE and Juazeiro-BA and in the northeastern coastal sugarcane plantations.

The overall and per crop results for irrigation and impact on water scarcity presented in the following sections used the calculated reference evapotranspiration considering the CO2 fertilization effect.

Figure 8 - Trend line slope maps for reference evapotranspiration for RCP 4.5 (first row) and RCP 8.5 (second row) calculated by original Penman-Monteith (first column) and Penman-Monteith with consideration of CO2 fertilization effect (second column). The absolute difference of the trend is presented in the third column.



Source: Own elaboration (2021)

4.1.2 Reference evapotranspiration (Et0) and precipitation (p) by region

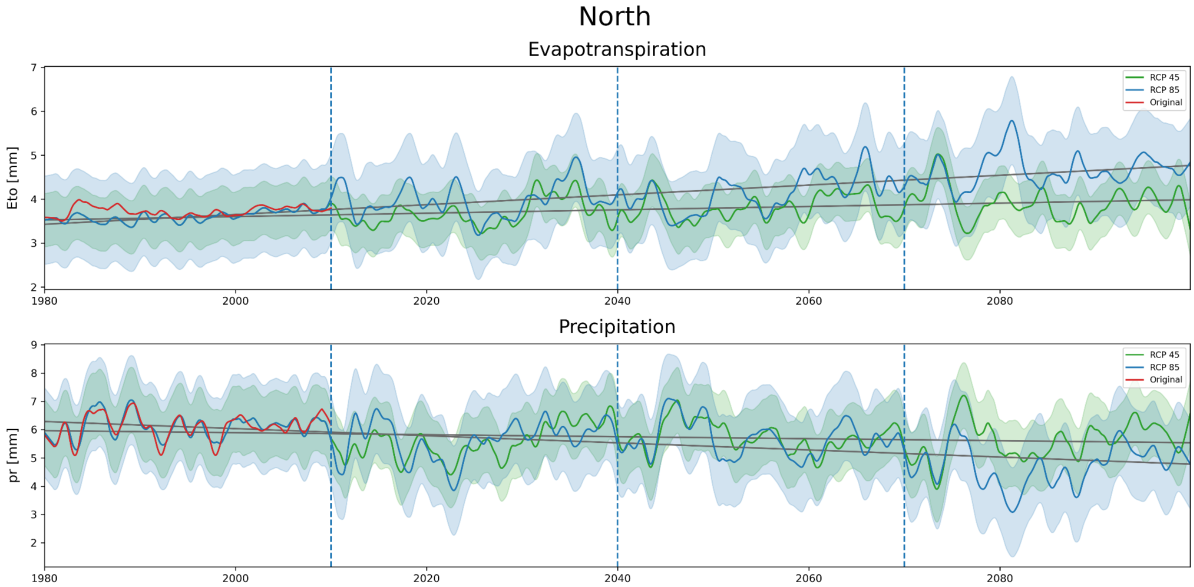
To summarize the climate results obtained, the time series of reference evapotranspiration with consideration of the CO_2 fertilization effect and precipitation were grouped by simple average for each major region of the country. For them, the future climate trends of the two variables and the behavior under the two global warming scenarios are discussed. It is pointed out that the values have high variance and are represented by their moving averages of 360 days (metric used for a year on the circulation model ETA HadGEM-2) in the period with the confidence interval of 2σ . Values of the regional averages by period (plateaus) of the climate variables used in Penman-Monteith are presented in Tables B1 to B5 in Appendix B.

It is noteworthy that evapotranspiration and precipitation can have high variability through a region and that it adds a great uncertainty for both variables on an analysis of mean values for all analyzed regions. Although an analysis per climatic region would reduce geographical variability, the results per political region were chosen for communicating better the overall climate results and trends.

4.1.2.1 North region

Figure 9 shows the average time series of reference evapotranspiration and precipitation for the northern region of the country.

Figure 9 - Time series and confidence interval of reference evapotranspiration and precipitation for the northern region under RCP 4.5 (green), RCP 8.5 (blue) and for the historical period (red) scenarios. Trends for the variables are shown in gray



Source: Own elaboration (2021)

The northern region of the country is expected to experience a considerable increase in reference evapotranspiration in both RCP scenarios mainly caused by the increase in the net radiation captured by the surface and the decrease in its relative humidity in both global warming scenarios (humidity decreased from a plateau of 82%±8.5 in the historical period to 78%±13.2 in the RCP 4.5 scenario and 69%±14.7 in the RCP 8.5 scenario in 2085).

Precipitation for the northern region tends to reduce from a level of 6.12 mm± 4.3 in the historical period to 5.59 mm±4.3 in the RCP 4.5 scenario and 4.71 mm± 4.0 in the period of 2085, with a more significant decrease already in the period of 2025. The results corroborate with the increase in evapotranspiration and consequent increase in irrigation in the region and are worrisome from the point of view of the preservation of the climate prevailing in the Amazon forest due to the dependence on green water to supply the water needs of the forest.

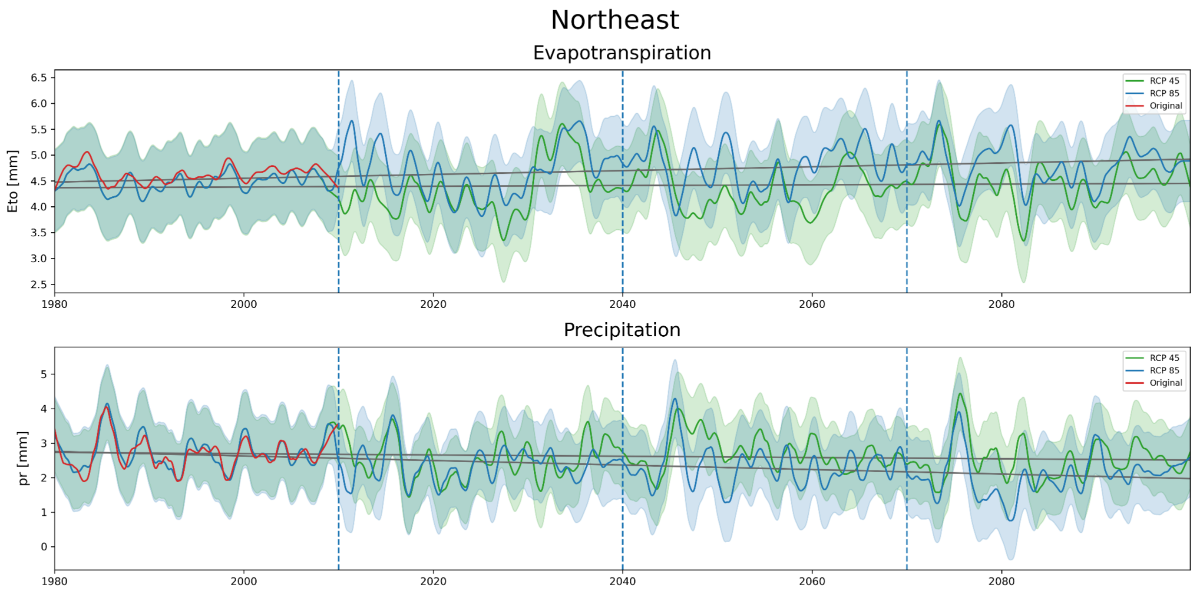
The increase in evapotranspiration is particularly significant in the irrigated planting areas in the region (states of Roraima and Tocantins with flooded rice and Rondônia with irrigated coffee), which implies an increase in water requirements for planting. Even so, the average rainfall of the region is the highest in the country, which reduces the need for blue water to supply the crops. Despite a significant percentage increase of 74% for irrigated areas in the region, the absolute total of additional irrigated hectares foreseen for 2040 is the smallest among all regions.

The differences between the scenarios were more expressive for the 2085 period, with the trends of increasing reference evapotranspiration and decreasing precipitation being maintained for both RCP scenarios.

4.1.2.2 Northeast region

The average time series of reference evapotranspiration and precipitation for the northeast is shown in Figure 10.

Figure 10 - Time series of reference evapotranspiration and precipitation for the northeast region under RCP 4.5 (green), RCP 8.5 (blue) and for the historical period (red) scenarios. Trends for the variables are shown in gray



Source: Own elaboration (2021)

Despite the presence of areas of the northeast with reduced evapotranspiration in future periods, the trend in the region is a small increase for the RCP 8.5 scenario and the maintenance of the current level in scenario 4.5 for the period of 2085. A slight decrease is predicted for the period 2025 in scenario 4.5 (from 4.48 mm±2.42 to 4.32 mm±2.49) and a slight increase in scenario 8.5 (from 4.48 mm±2.42 to 4.70 mm±2.73).

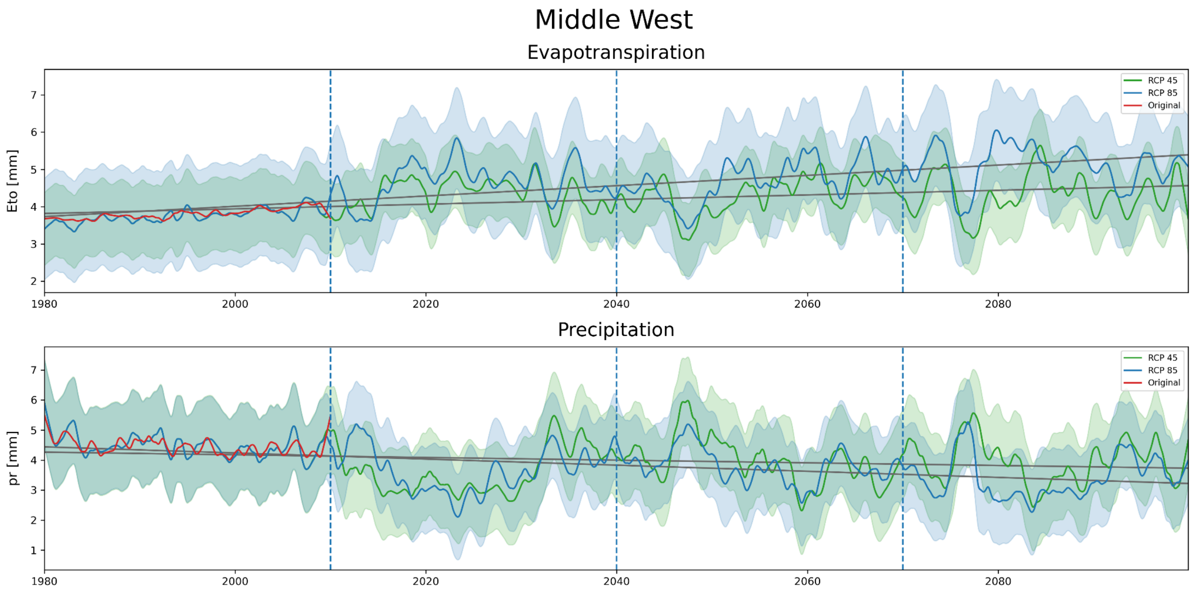
Rainfall tends to decrease slightly for the 8.5 scenario (from 2.73 mm±5.44 to 2.05 mm±5.15 in 2085) and remain constant for the 4.5 scenario. The maintenance of the precipitation and reference evapotranspiration values (specially in RCP 4.5) allows stability in the irrigation demand for crops cultivated in the northeast and avoids the growth of the impact on water scarcity since it is the region with the highest values of characterization factors for subwatersheds. Nevertheless the low values of precipitation and high values of evapotranspiration still contribute to a high irrigation necessity today and for the future.

Despite the time series trend line having low variation for both variables in RCP 4.5 and 8.5, it is pointed out that the producing region of western Bahia, which has a large irrigated area in central pivot crops and coffee, presents an increase in evapotranspiration as shown in Figure 8 for being inserted in the area affected by the increase in the absorbed net radiation and decrease in relative humidity in the center of the country.

4.1.2.3 Mid-West region

The Mid-west region has its average time series of reference evapotranspiration and precipitation shown in Figure 11.

Figure 11 - Time series of reference evapotranspiration and precipitation for the mid-western region under RCP 4.5 (green), RCP 8.5 (blue) and for the historical period (red) scenarios. Trends for the variables are shown in gray



Source: Own elaboration (2021)

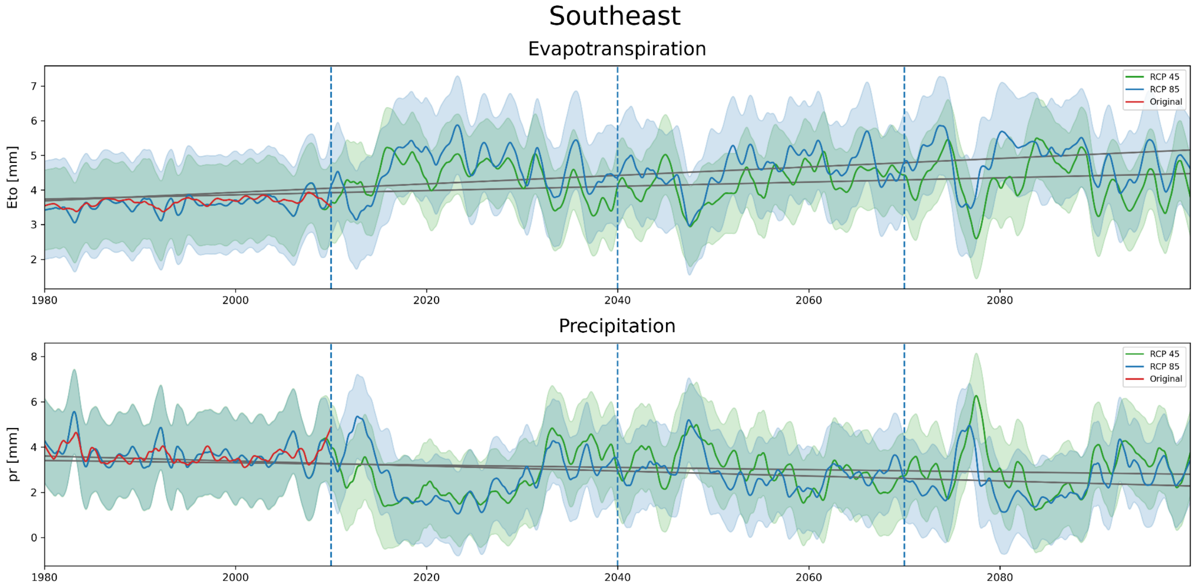
The mid-western region has a very significant plateau change in the 2025 period due to a significant decrease in humidity (73.6 %±18.2 at historical period to 64.0 %±23.3 at RCP 4.5 and 62.0 %±22.9 in RCP 8.5) and a considerable increase in the absorbed net radiation (11.0 MJ/m²±5.3 at historical period to 11.7 MJ/m²±6.7 in RCP 4.5 and 12.3 MJ/m²±7.2 in RCP 8.5) for both RCPs. This caused the trend in reference evapotranspiration to have a significant increase. Precipitation also showed a change of plateau in 2025's period, tending to decrease in future periods.

In addition to the region having high irrigation area, mainly for center pivot and sugarcane crops, the result is particularly worrisome as it also has the second highest growth forecast (in percentage and absolute) of irrigated areas for 2040 (a 66% increase from 2019 - ANA, 2021).

4.1.2.4 Southeast region

Figure 12 shows the average time series of reference evapotranspiration and precipitation for the southeast region of the country.

Figure 12 - Time series of reference evapotranspiration and precipitation for the southeast region under RCP 4.5 (green), RCP 8.5 (blue) and for the historical period (red) scenarios. Trends for the variables are shown in gray



Source: Own elaboration (2021)

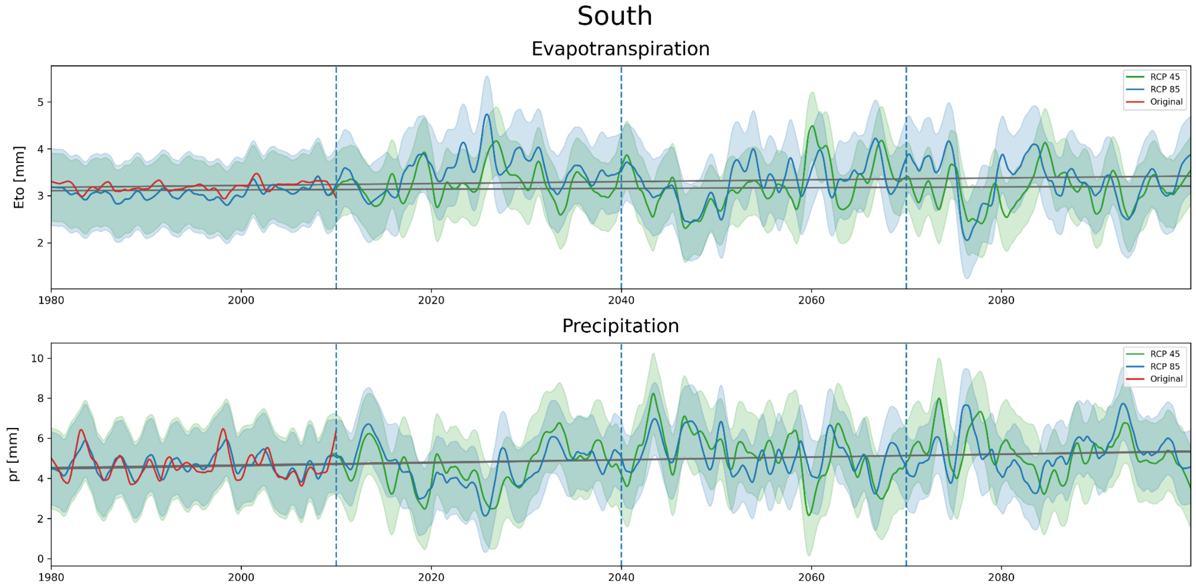
Similar to the central-western region, the southeastern region also has a high plateau of reference evapotranspiration for 2025 (3.59 mm±2.36 in the historical period to 4.34 mm±3.19 in RCP 4.5 and 4.64 mm±3.53 in RCP 8. 5) and an expressively low plateau of precipitation (3.70 mm±7.83 in the historical period to 2.63 mm±6.56 in RCP 4.5 and 2.71 mm±6.46 in RCP 8.5) for the same reasons of reduced relative humidity and increased absorbed net radiation. The results have a slight upturn in the 2055 period, but still continue with an expressive trend of increasing reference evapotranspiration and decreasing precipitation.

The situation in the region is aggravated by the fact that the expected expansion of irrigated areas for 2040 is the largest in the country in absolute numbers, with almost twice as many additional irrigated areas if compared to the mid-west region (second largest in absolute numbers - ANA, 2021), which leads the region to be a future hotspot in terms of irrigation and water scarcity.

4.1.2.5 South region

The southern region has its average time series of reference evapotranspiration and precipitation shown in Figure 13.

Figure 13 - Time series of reference evapotranspiration and precipitation for the southern region under RCP 4.5 (green), RCP 8.5 (blue) and for the historical period (red) scenarios. Trends for the variables are shown in gray



Source: Own elaboration (2021)

The climate trends in the southern region indicate a maintenance of the future reference evapotranspiration values, mainly for the rice producing regions in the south of the state of Rio Grande do Sul (Figure 13). This constancy is due to the fact that the balance of absorbed net radiation remained in a trend of slight decline, which balanced the results of significant increase in average temperature (19.6 ºC± 8.3 in the historical period to 22.4 ºC±9.5 in RCP 4.5 and 24.9 ºC±9.4 in RCP 8.5 in 2085). Precipitation values had a slight increase even as relative humidity decreased over the periods, which increased the green water available for crops in future periods. Noteworthy is the sudden drop in precipitation and rise in reference evapotranspiration values for the period 2015 to 2030, which caused an increase in irrigation demand for the region in the representative year 2025.

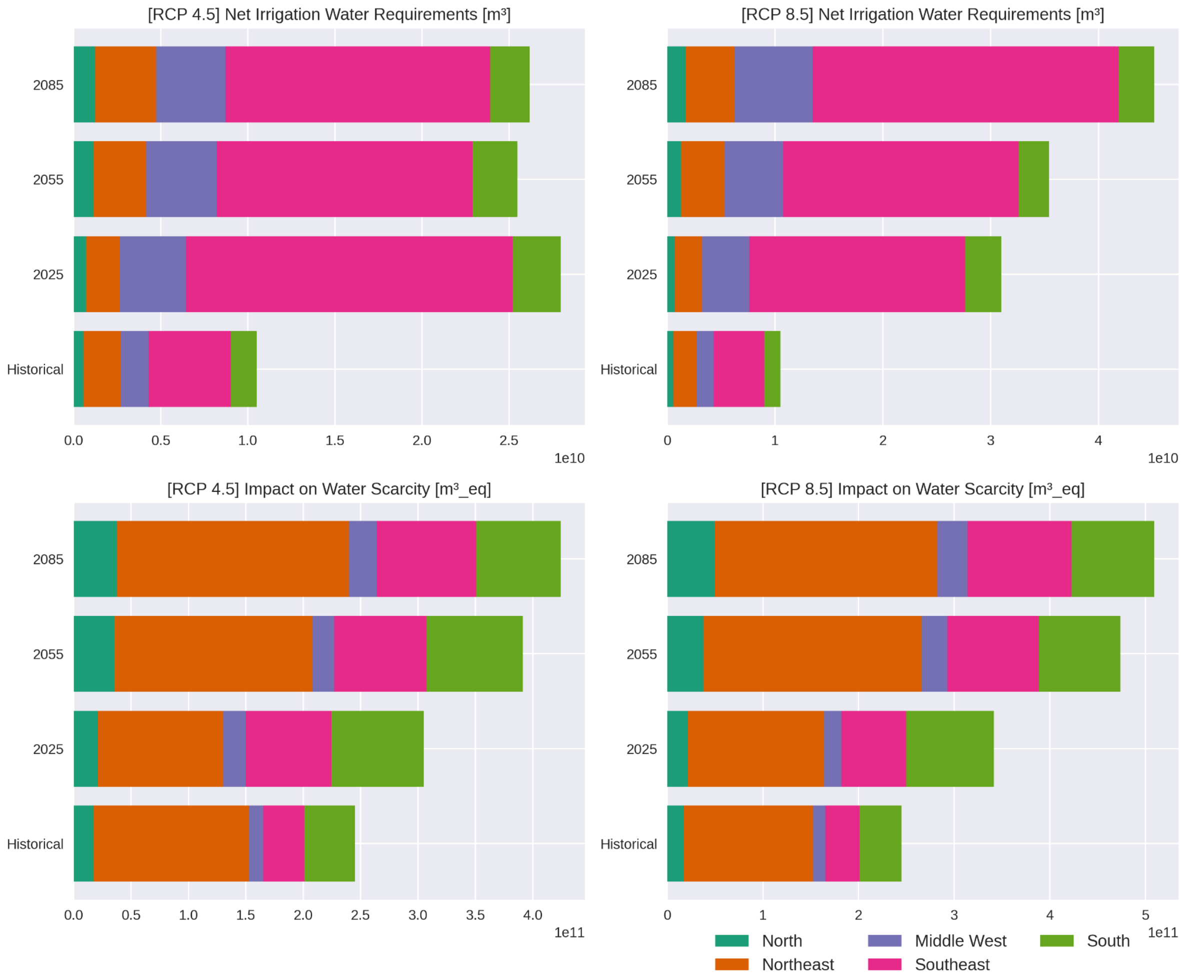
Despite currently being the second largest region in irrigated area, the growth of irrigated area is going to be average for 2040, with a total forecast of 664.781 additional hectares (a number only larger than the one for the northern region of the country).

4.2 General results for Brazil

4.2.1 Totals by region and culture

To analyze the volume of irrigation in the country, the net irrigation water requirement (NIWR - counting the efficiency of the irrigation type) and impact on water scarcity have been segmented by region in Figure 14.

Figure 14 - Net irrigation water requirement (NIWR) and total water shortage impact for Brazil cumulative by region. Results in the first column are for the RCP 4.5 scenario and in the second column for the RCP 8.5 scenario. Despite the similarities between the graphs, the values are higher for scenario 8.5



Source: Own elaboration (2021)

Total irrigation in Brazil tends to reach values of 2.7 billion cubic meters in the period 2025 for the RCP 4.5 scenario and higher than 4.5 billion cubic meters in the period 2085 for the RCP 8.5 scenario. The early plateau in the RCP 4.5 scenario is due to the joint effects of decreased precipitation and increased reference evapotranspiration in the mid-west and southeast regions, and is exacerbated by large sugarcane production, which had a large contribution to the total value of irrigation in the country. Even so, the RCP 8.5 scenario presents an increase of more than 4 times the current irrigation demand in 2085, justified by the climatic effect and growth of irrigated areas in the country, and giving even in 2025 a total irrigation demand already higher than that of the RCP 4.5 scenario. The increase becomes even more relevant when taking into account that the current atmospheric carbon concentration is following the RCP 8.5 scenario trends (IIASA, 2021).

A highlight is given to the southeast region, which has the highest amount of irrigation in all scenarios and periods. This significant participation in irrigation volume is due to the high irrigated area present in the region, mainly for the fertigated sugarcane crop (about 47% of the total irrigated area in the country). These high values are explained by a number of factors, namely the increase in reference evapotranspiration and decrease in precipitation (for the 2025 period) and increase in irrigated area forecasted for 2040 (2055’s period had the largest increase in area predicted for the country). Also noteworthy is the growth to a lesser extent of the mid-west (2.48 times the historical value in the RCP 4.5 scenario and 4.52 times in the RCP 8.5 scenario in 2085), south (1.47 times the historical value in the RCP 4.5 scenario and 2.07 times in the RCP 8.5 scenario in 2085) and northeast (1.62 times the historical value in the RCP 4.5 scenario and 2.11 times in the RCP 8.5 scenario in 2085) regions of the country.

Despite the large volume of water used for irrigation in the southeast region and the growing demand for water in the central-west region, the subwatersheds that supply the productive areas in these regions do not have a high characterization factors for water scarcity, which reduces the impact of total production compared to regions where subwatersheds have higher characterization factors. Even so, the southeast region contributed considerably to the future impact in the periods 2055 (in relation to the total impact: 25.0% for RCP 4.5 and 23.7% for RCP 8.5) and 2085 (in relation to the total impact: 23.7% for RCP 4.5 and 24.5% for RCP 8.5).

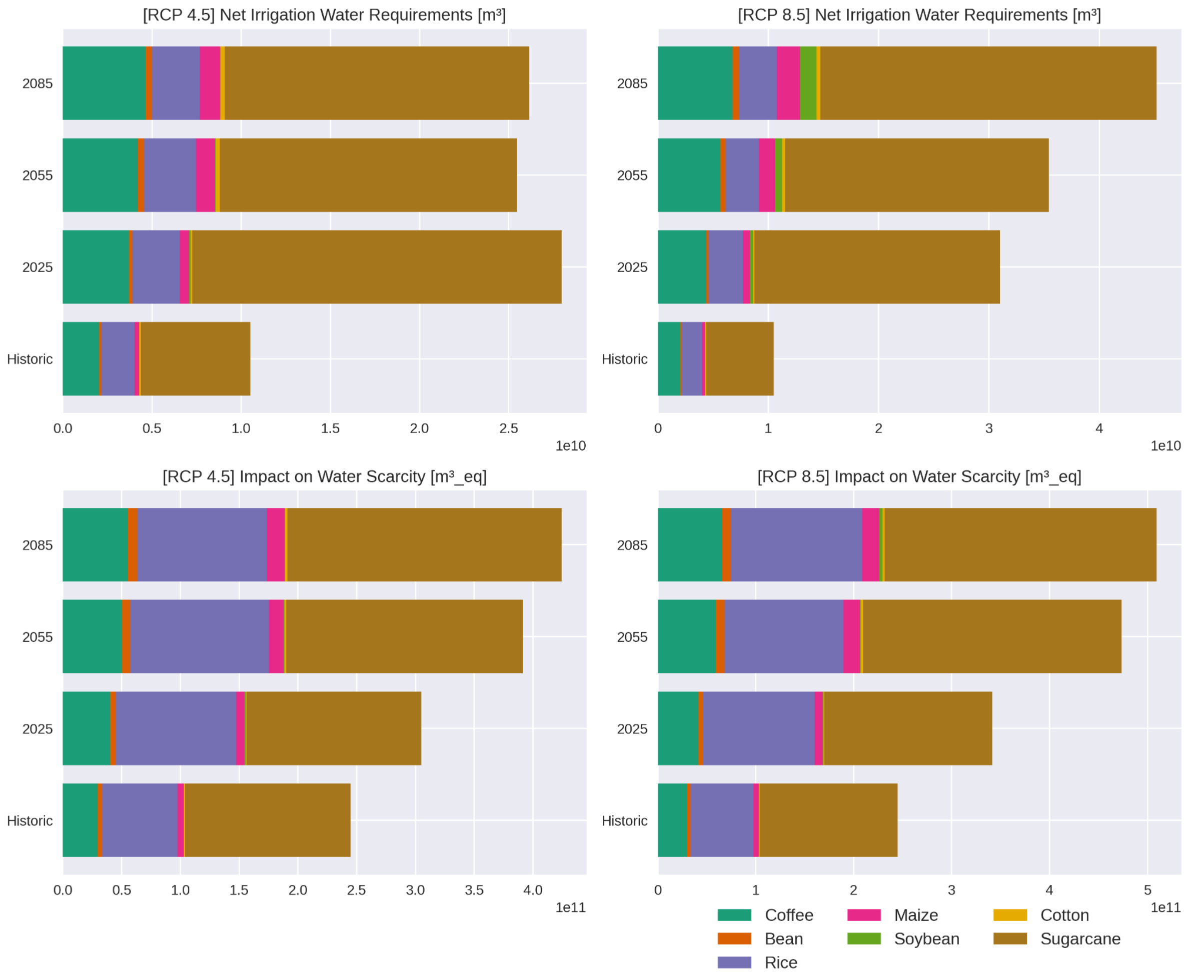
The region highlighted as a hotspot for irrigation impact on water scarcity in the country was the northeast region. The northeast has the highest characterization factors for subwatersheds in the country, which is aggravated by the fact that many of the production areas, primarily coastal sugarcane, belong to the basins with the highest factor value in the region. Thus, even with a much less expressive increase in irrigation than in other regions of the country, the northeast had a high impact on water scarcity of its total production.

The south of the country had the second highest scarcity share of the regions, mainly due to its high value of characterization factors in its flooded rice production region in the south of Rio Grande do Sul state.

Also noteworthy is the northern region of the country that, due to relatively high AWARE characterization factors for the subwatersheds of its producing regions, especially for the flooded rice producing region in the state of Tocantins, had a more significant participation in the impact on water scarcity than the central-western region of the country, despite its low total volume of irrigation.

For a better overview of irrigation and impact in the country, Figure 15 shows the total results segmented by crop.

Figure 15 - Net irrigation water requirement (NIWR) and total water shortage impact for Brazil cumulative by crop. Results in the first column are for the RCP 4.5 scenario and in the second column for the RCP 8.5 scenario. Despite the similarities between the graphs, the values are higher for scenario 8.5



Source: Own elaboration (2021)

In the context of crops, the volume of sugarcane irrigation stands out, with more than 50% of all volume of the analyzed crops. Despite the different types of irrigation for this crop (fertigation, deficit and full), the extension of its area (44.5% of the total area irrigated by crops considered in this work in 2019 and 32.8% in the 2040 forecast) still results in high values. The impact result for this crop stems mainly from this extensive water volume and high characterization factors in the coastal areas of the northeast, where it is cultivated with full and deficit irrigation.

The central pivot crops (beans, maize, soybean and cotton) did not have a significant result when compared with coffee, rice and sugarcane, even having a relevant increase in irrigated area foreseen for the 2040 scenario (from 27.0% of the area to 37.6% of the total irrigated area in the country ANA, 2021). Still is noteworthy the growth in future irrigation of maize for both RCP scenarios (total of 299.6 million cubic meters in the historical period to 1340.4 million in RCP 4.5 and 2456.2 million in RCP 8.5 for the 2085 period) and soybean for RCP 8.5 scenario (total of 299.6 million cubic meters in the historical period to 1782.0 million in the 2085 period).

Coffee and rice have not grown as much as sugarcane on irrigation, but have maintained a relevant participation in the total amount in the country. Even so, the rice culture obtained results of its total production impact on water scarcity comparable to those of sugarcane, largely due to the fact that its main producing areas (west of the state of Tocantins and south of the state of Rio Grande do Sul) are in subwatersheds with very high characterization factors. Coffee cultivation is more present in the north of the state of Espírito Santo and the west of the state of Minas Gerais, areas that in general have a low characterization factor in their subwatersheds.

4.2.2 Geographic results

The variation of the irrigation volume during the periods for the two RCP scenarios is shown in Figure 16. In this figure, the growth trend starting in 2025 for RCP 8.5 is visible by the constant increase in the quantity of municipalities in yellow color and the significant increase in the value for the most critical municipality. In the RCP 4.5 scenario, this volume tends to increase during the 2025 period and stabilize over the following periods.

The increase in irrigation for 2025 is visible in Figure 16, with the inclusion of many areas where in the historical period the need for irrigation was not present, as in the areas of central pivot planting in the west of the state of Rio Grande do Sul, coastal areas of the southern region, areas of central pivot planting in the southeast of the state of São Paulo, and central areas of the state of Mato Grosso do Sul, and a growth in the value on the color scale in producing regions.

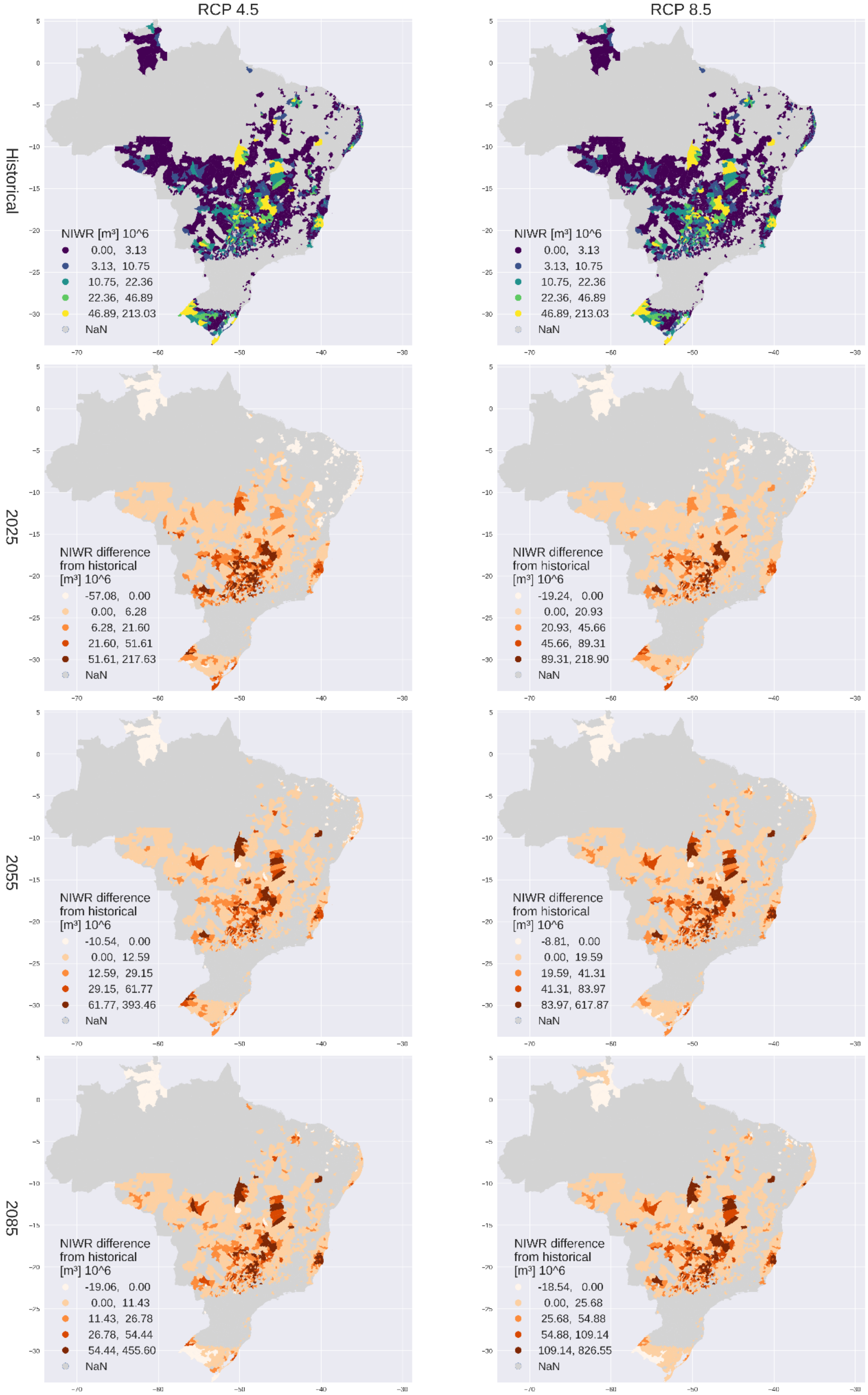
For both global warming scenarios, the increase in municipalities with high irrigation volume values in the central region of the country and in the west of Bahia stands out, mainly due to the effects of increased evapotranspiration and decreased precipitation in these locations. Areas with high volumes of irrigation already in the historical period, such as flooded rice areas in the west of the state of Tocantins and in the south of the state of Rio Grande do Sul and coffee in the state of Espírito Santo, remained with high irrigation demands.

The impact by subwatershed of the analyzed crops' total production can be seen in Figure 17. The subwatersheds of the southeastern region of the country had a constant increase in their impact values throughout the periods in the two scenarios, presenting basins with high impact as of the 2025 period. Plantation areas in western Bahia have steadily increased the impact on the subwatersheds of the region, even with low characterization factors, because the volume of irrigation had a considerable increase in the periods analyzed.

It is noteworthy that the subwatersheds of the São Francisco River have, on average, a high value of the characterization factor and consequently were more sensitive in relation to increases in irrigation in their producing regions (northern Minas Gerais and Bahia), creating an area of high impacts in the 2055 and 2085 timeframe. As pointed out in Figure 16, rice growing areas had a high volume of irrigation and had a high impact due to moderate to high characterization factors in the catchments of their growing regions.

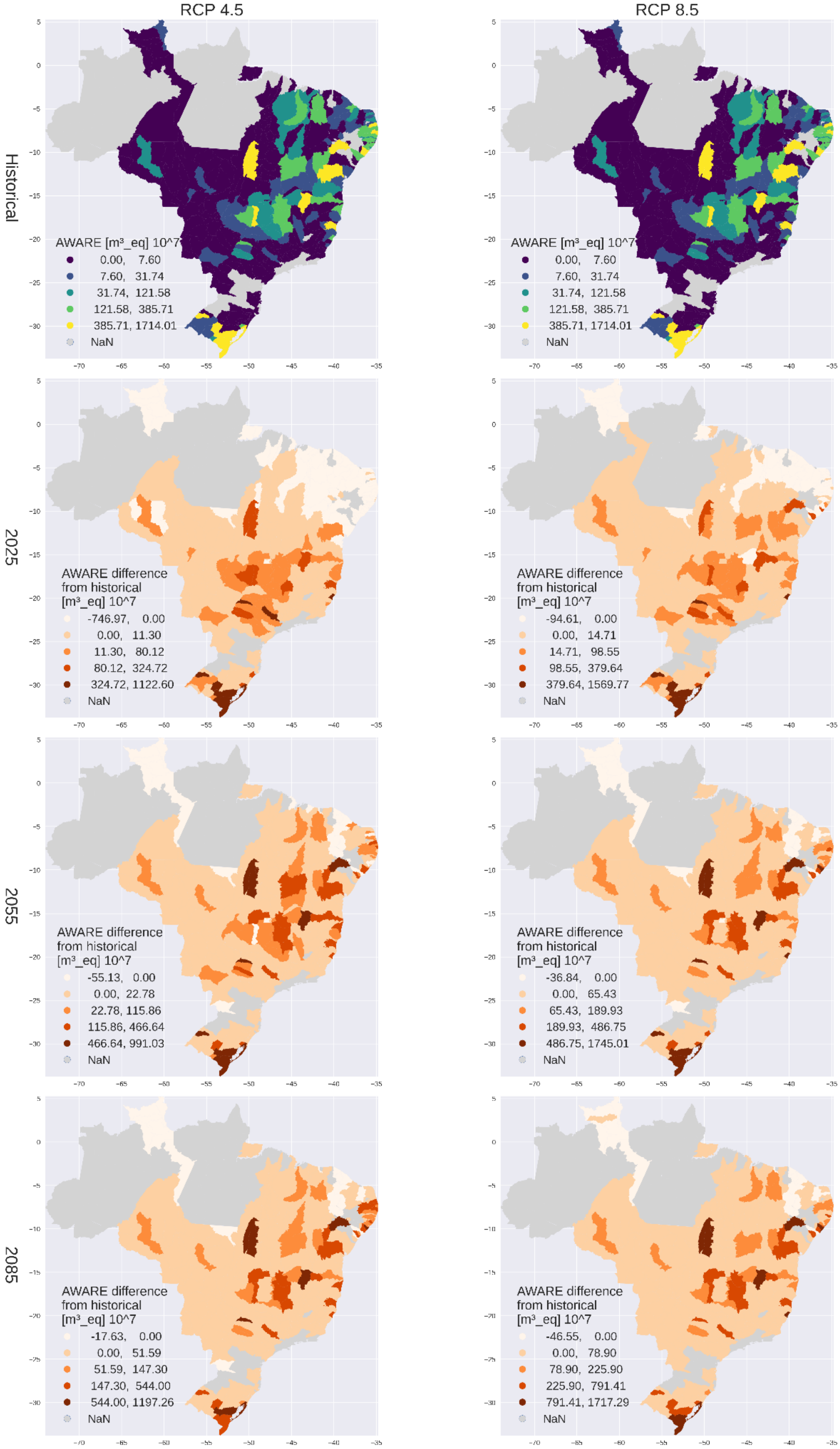
Figure 18 shows the impact and volumetric demand for irrigation for 10 basins with the highest impact during the periods analyzed. More detailed figures are shown in Table C1 in Appendix C for each of the 33 basins with higher impact during the periods analyzed (all 33 passed a threshold of 3500 million m^3eq of water chosen using the highest limit on a geographic clusterization by Jenkins method of sub-basins' impact values for all periods).

Figure 16 - Net irrigation water requirement (NIWR) in m³ of all analyzed crops for the different periods studied (rows) and different RCP scenarios (columns)



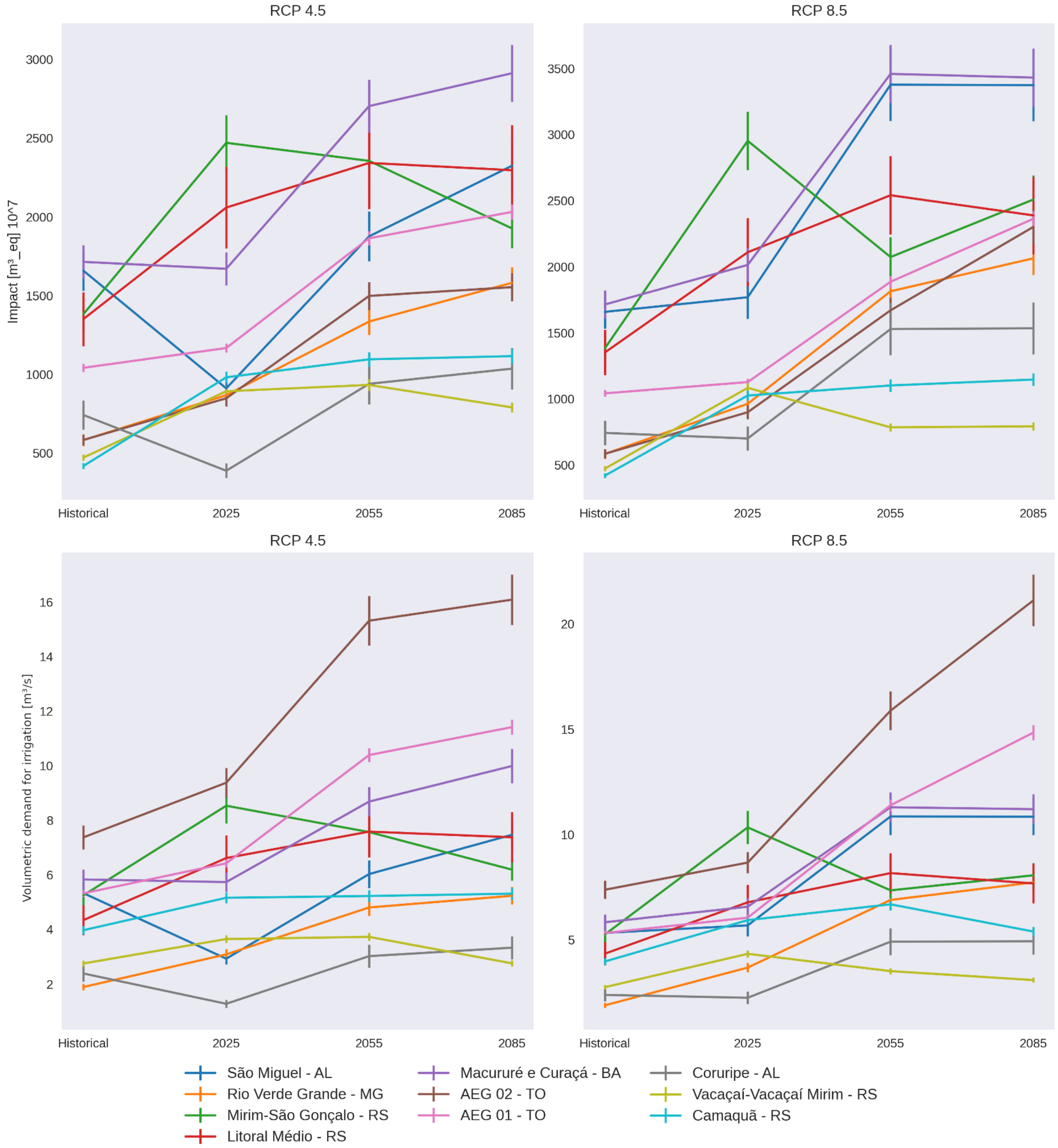
Source: Own elaboration (2021)

Figure 17 - Impact on water scarcity in m³ equivalent of all analyzed crops for the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

Figure 18 - Volumetric demand in m³/s and total impact in m³ equivalent of the 10 Brazilian sub-basins with the greatest impacts



Source: Own elaboration (2021)

From the 10 basins that had the highest impact for Brazil, 6 of them had rice cultivation as the main irrigation volume and 4 had sugarcane cultivation (all with full or deficit irrigation). The volumetric demand values tend to be higher for the basins with rice cultivation, mainly in the state of Tocantins (TO), reaching values that exceed 10 m³/s in the RCP 4.5 scenario and 14 m³/s in RCP 8.5 in the period of 2085. The same basins with rice as the main crop have a significant increase between 2025 and 2045 due to the increase in rice growing areas foreseen for 2040, reaching high levels of impact on water scarcity in their regions. As for the basins that produce sugarcane, a highlight is given to the São Miguel basin, in the state of Alagoas (AL), with volumes of 3 to 7 m^3/s in RCP 4.5 and 5 to 10 m^3/s in RCP 8.5 but with high impact values due to its high characterization factor, and Macururé and Curaçá, in the extreme north of the state of Bahia (BA), with similar impact to São Miguel and which includes the municipality of Juazeiro and large sugarcane and central pivots production, besides other irrigated areas for crops not addressed in the study. Another noteworthy crop was coffee, which, although not among the subwatersheds in Figure 18, had a majority participation in 6 watersheds with impacts considered critical, mainly in the state of Espírito Santo (ES), but also in the central portion of Bahia (Paraguaçu - BA) and northern Minas Gerais (Rio Pardo - MG).

In general, the irrigation volume results for Brazil (Figure 16), especially for the 2025 period, are in line with those presented by the National Water Agency (ANA, 2021, pg.73), including areas of high annual volume demand for irrigation, coinciding with the areas of greatest impact resulting from this work.

4.2.3 Results per kilogram produced

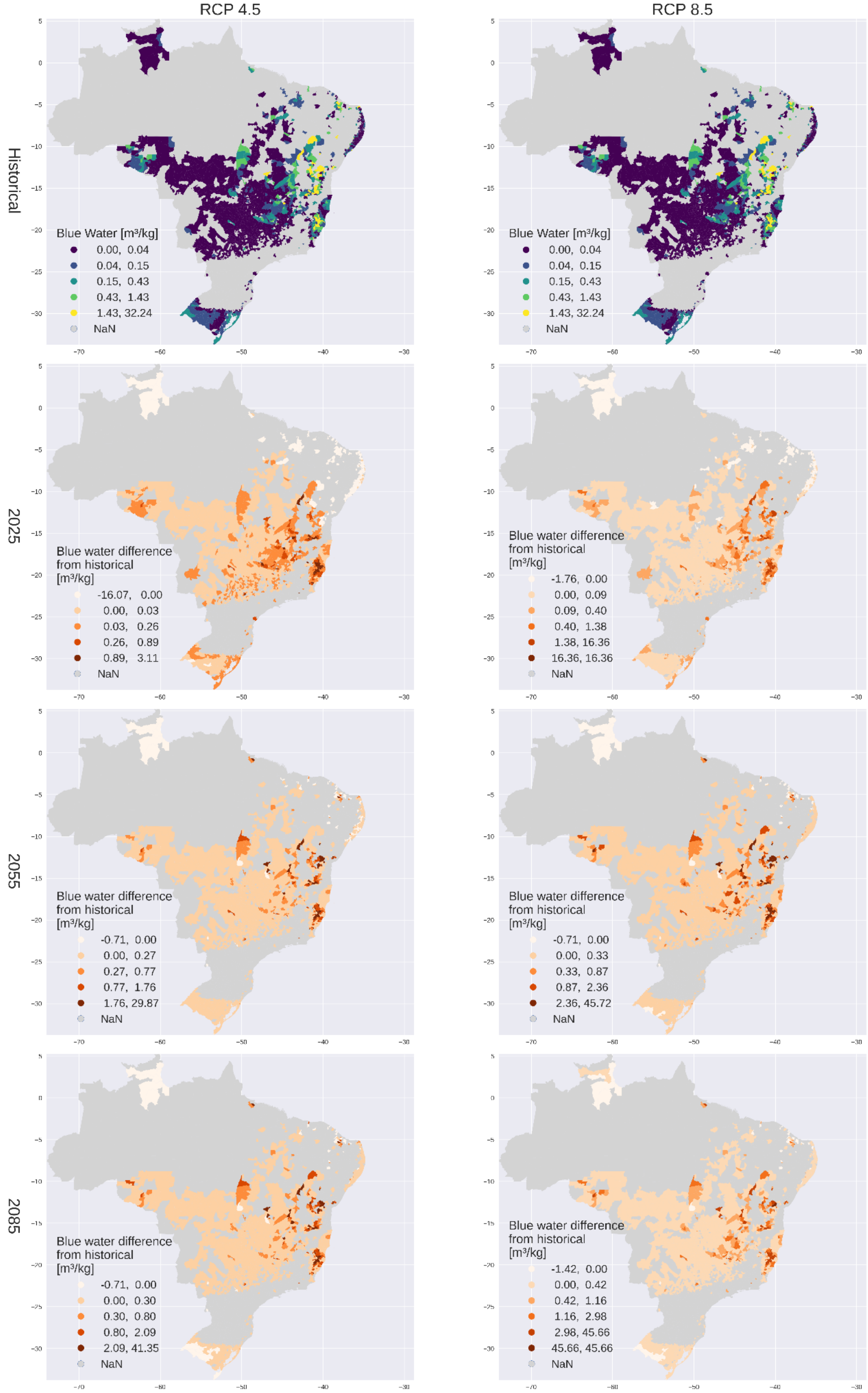
Figures 19 and 20 present the Blue Water and its impact on water scarcity respectively per municipality for all crops analyzed in this work. Results indicate that although sugarcane has a great share of the total volume of irrigation, the crop cultivated areas have a good productivity and a very low blue water overall, including in the coastal producing areas of the northeast region (which uses mainly deficit or full irrigation). In this context, a marginal increase of sugarcane production would not impact as much as other analyzed crops, nevertheless the average total production of the crop had a great share of their producing watershed impacts.

Areas that stood out with high Blue Water were mainly in the semiarid region. This area has a share of every crop analysed, especially coffee and central pivot ones, generally having a lower productivity in comparison to other planting regions of the country. Impact values for the semiarid were still higher due to the São Francisco watershed and Atlantic Northeast watershed (especially in the state of Ceará) having high values of characterization factors. The north of Espírito Santo state had higher values due to its extensive coffee production but had relatively lower impact results due to its position in a lower characterization factor sub-watershed.

Although having lower presence than the semiarid region, flooded rice regions in Tocantins had a great increase in future periods and in general were more water-demanding than the areas at Rio Grande do Sul state. This indicates that the expansion expected in these rice areas is worrisome as it would considerably increase the impact per new kilogram produced in the new areas.

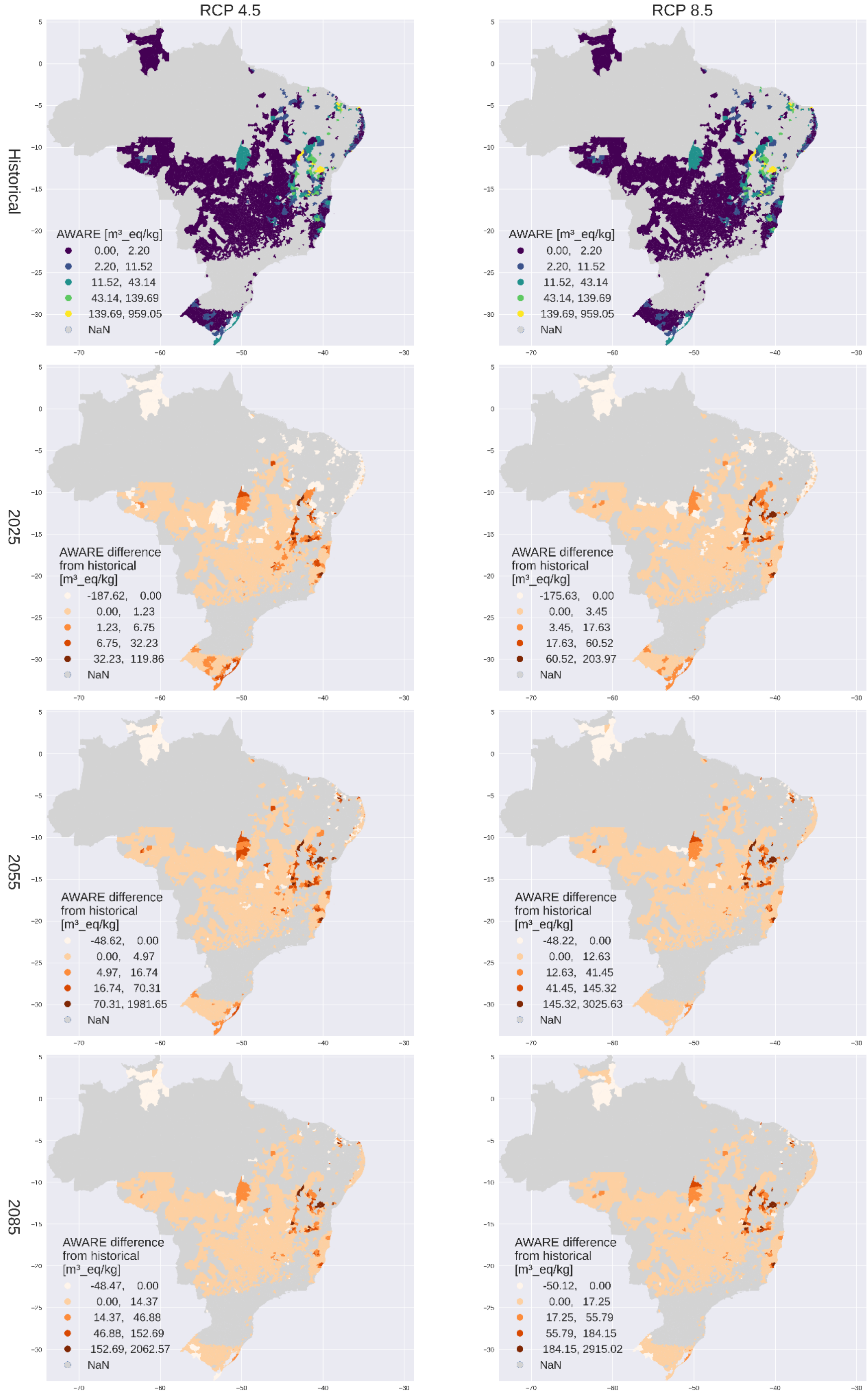
It is highlighted that the production used for this calculation is from the 2019 Brazilian production and it is not calculated for future periods. Another consideration is that all crops are analysed together, thus their specific geographical variability is not considered here.

Figure 19 - Blue Water in m³/kg of all analyzed crops for the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

Figure 20 - Impact in m³eq/kg of all analyzed crops for the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

4.3 Results by crop

The crop-specific results are shown from maps of their impact on water scarcity and maps of total irrigation volume for each period studied and for each global warming scenario.

4.3.1 Sugarcane

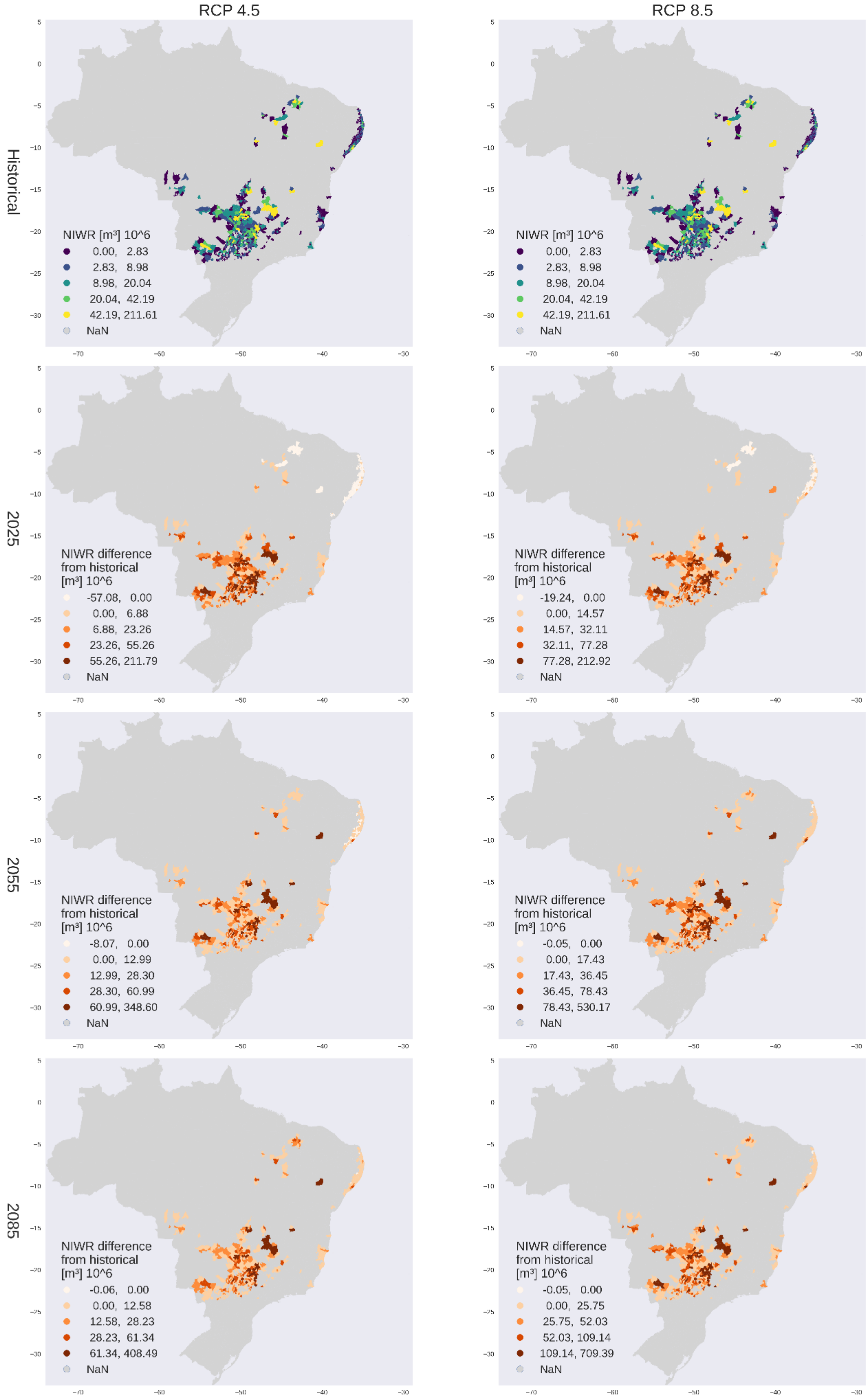
Sugarcane is one of the most important irrigated crops in the country, and its irrigation typology differs between the producing sites in the northeast of the country (northeastern coast, crops in the states of Maranhão and Piauí and the city of Juazeiro - BA), which has little fertigation and works with full or deficit irrigation, and the central portion of the country, which works almost entirely with fertigation, reducing its irrigation water consumption. Although the fertigation is lower, the northeast sugarcane production has higher optimization of the irrigation system and higher efficiency of the water use.

Despite the use of fertigation, Figure 21 shows that the southeast and mid-west regions had an increase in the number of municipalities with high irrigation volume during all periods (with more significant growth in 2025 in RCP 4.5), consequently increasing the irrigation demand from the surrounding sub-basins to meet water needs.

In the historical period few subwatersheds of the central producing region had high impacts for water scarcity compared to those of the northeast producing region (mainly for the coast and Juazeiro - BA region), however even having low characterization factors, the increase in irrigation volume in this region during the periods (especially in the RCP 8.5 scenario) brought some of its subwatersheds to a considerable impact on water scarcity, mainly in the states of Goiás and Minas Gerais, as shown in Figure 22.

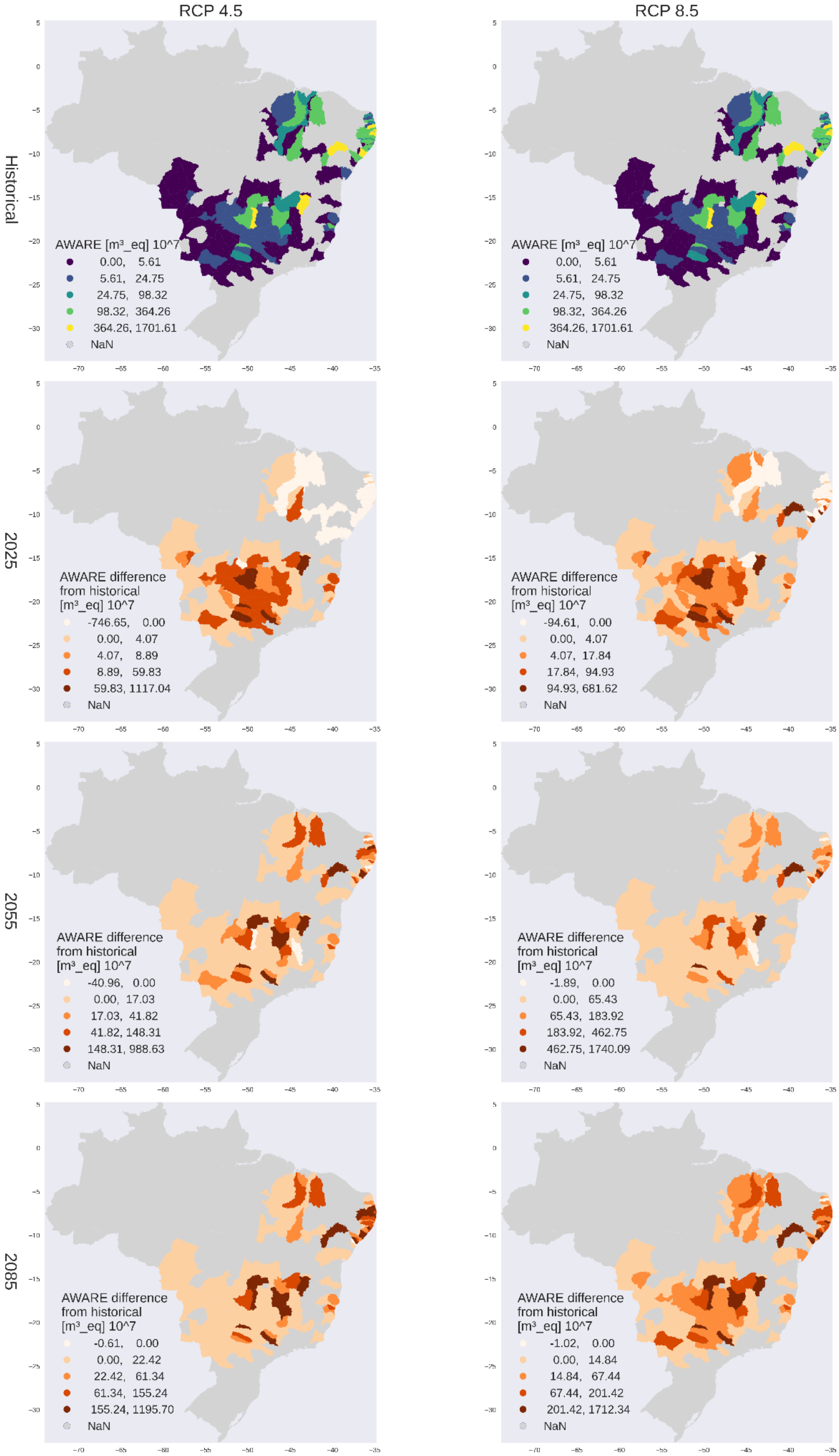
Sugarcane can be considered as the main crop impacting on water scarcity in the country if its total production is considered (Figure 15), with its majority share in the subwatersheds' impact on its producing areas.

Figure 21 - Net irrigation water requirement (NIWR) in m³ for the sugarcane crop in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

Figure 22 - Impact on water scarcity in m³ equivalent for sugarcane crop in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

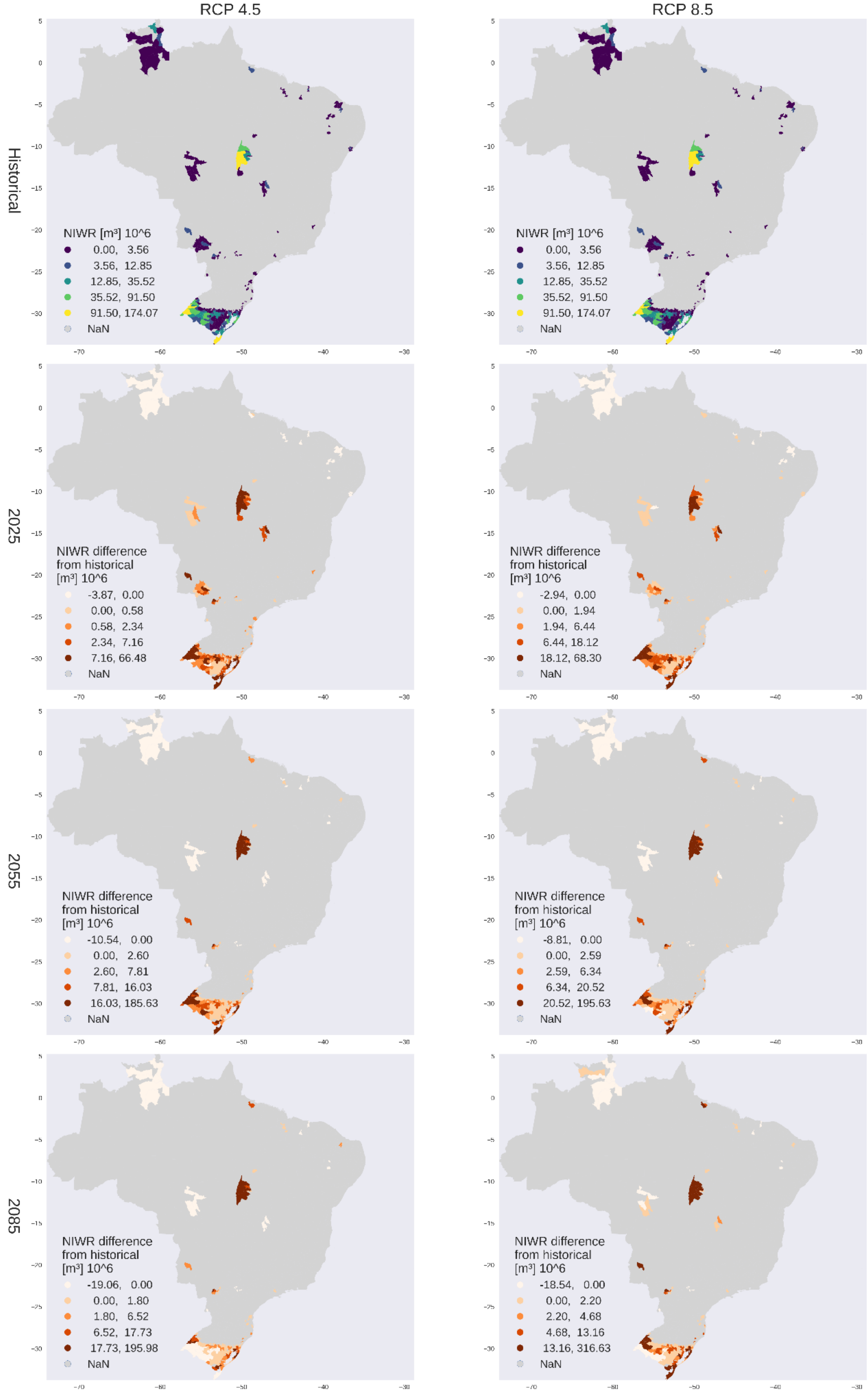
4.3.2 Flooded rice

Flooded rice is a prominent crop in two distinct areas, one of them in the extreme south of the country (in the state of Rio Grande do Sul) and the other in the western portion of the state of Tocantins, both with high volumes of crop production. This is also reflected in the total irrigated amount of the crop per municipality in Figure 23. Although a significant difference is not perceived in the areas of higher volumetric demand of water for the activity, the irrigation demand has a growth for the producing municipalities, especially in the producing areas of Tocantins, much due to the increasing trend in reference evapotranspiration and decreasing trend in precipitation in the region.

The forecast for the state of Rio Grande do Sul is a significant growth (81% of the total growth in the country) of irrigated areas for rice cultivation. Thus, even with stable climatic variables in the south of the country, the region had a slight increase in irrigated volume over the periods. For the period 2025, a conjunction of increasing evapotranspiration and decreasing precipitation raised the values of rice irrigation in the southern region, leading to a sudden growth of irrigation in the area.

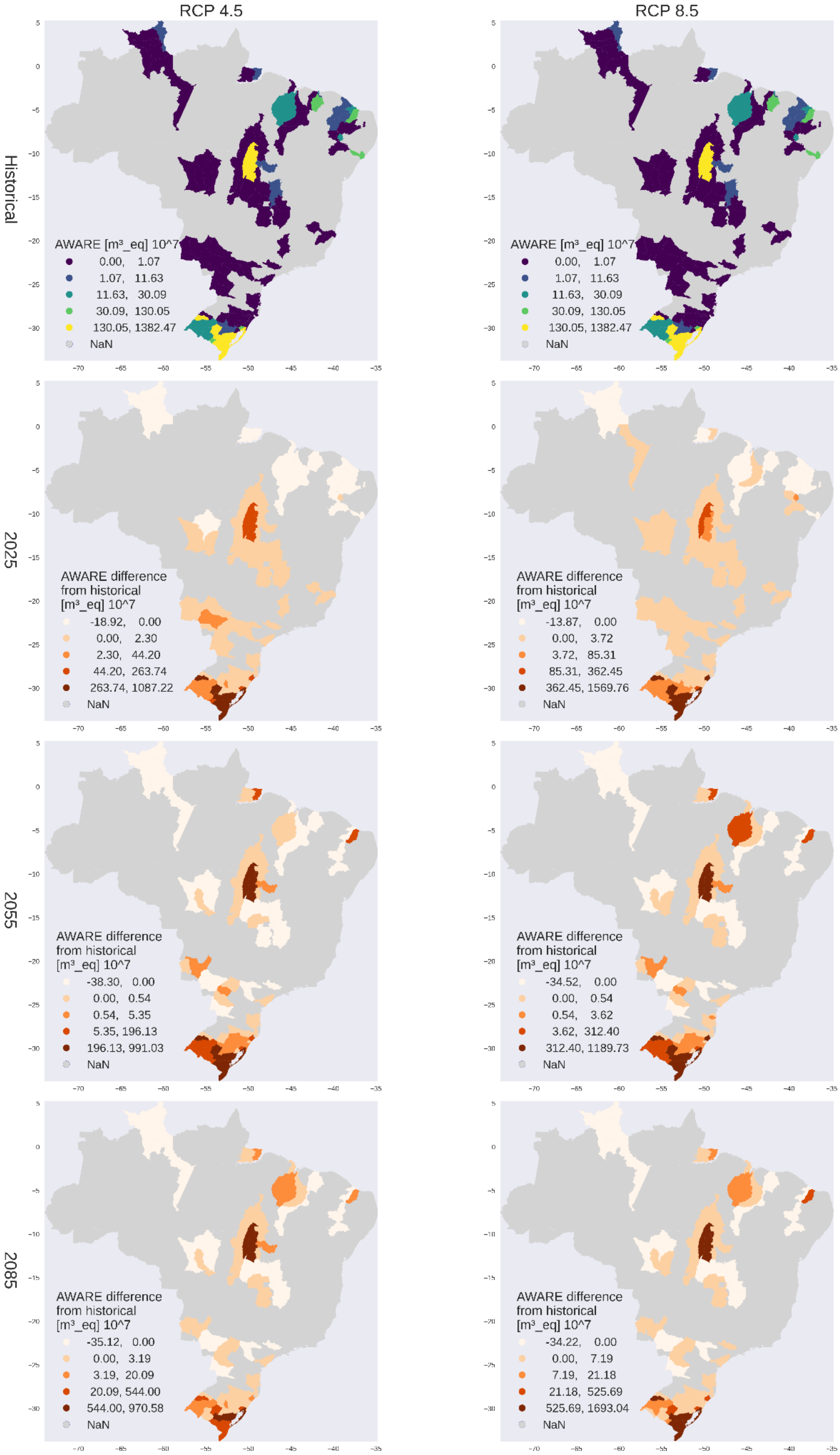
Despite the small territorial presence of rice in the country, its large water requirement for flood maintenance and relatively high values of characterization factors in the producing regions resulted in a large impact on the water scarcity of the producing subwatersheds, reaching similar impact values to those reached in the sugarcane producing subwatersheds, as shown in Figure 24.

Figure 23 - Net irrigation water requirement (NIWR) in m³ for the flooded rice crop in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

Figure 24 - Impact on water shortage in m³ equivalent for the flooded rice crop in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

The result for scarcity impacts of sugarcane and rice crops shown in Figures 22, 24 and the general result of Figure 15 indicate that the set of significant producing areas of the two crops in the same subwatersheds can lead to high results of impact on water scarcity, especially if there is a high factor of characterization in the region (examples in Appendix C). Within the scope of the periods studied, the only regions to present this characteristic are the state of Maranhão with some regions in the north of the state of Piauí and the coast of the state of Alagoas, bathed by the basins of the Parnaíba River and Eastern Northeast Atlantic, which, despite still having a very low production area already present relevant results of impact for their subwatersheds.

The configuration of rice cultivation in Brazil and its significant impacts on its producing regions lead this crop to be the second largest crop impacting on water scarcity in the country.

4.3.3 Coffee

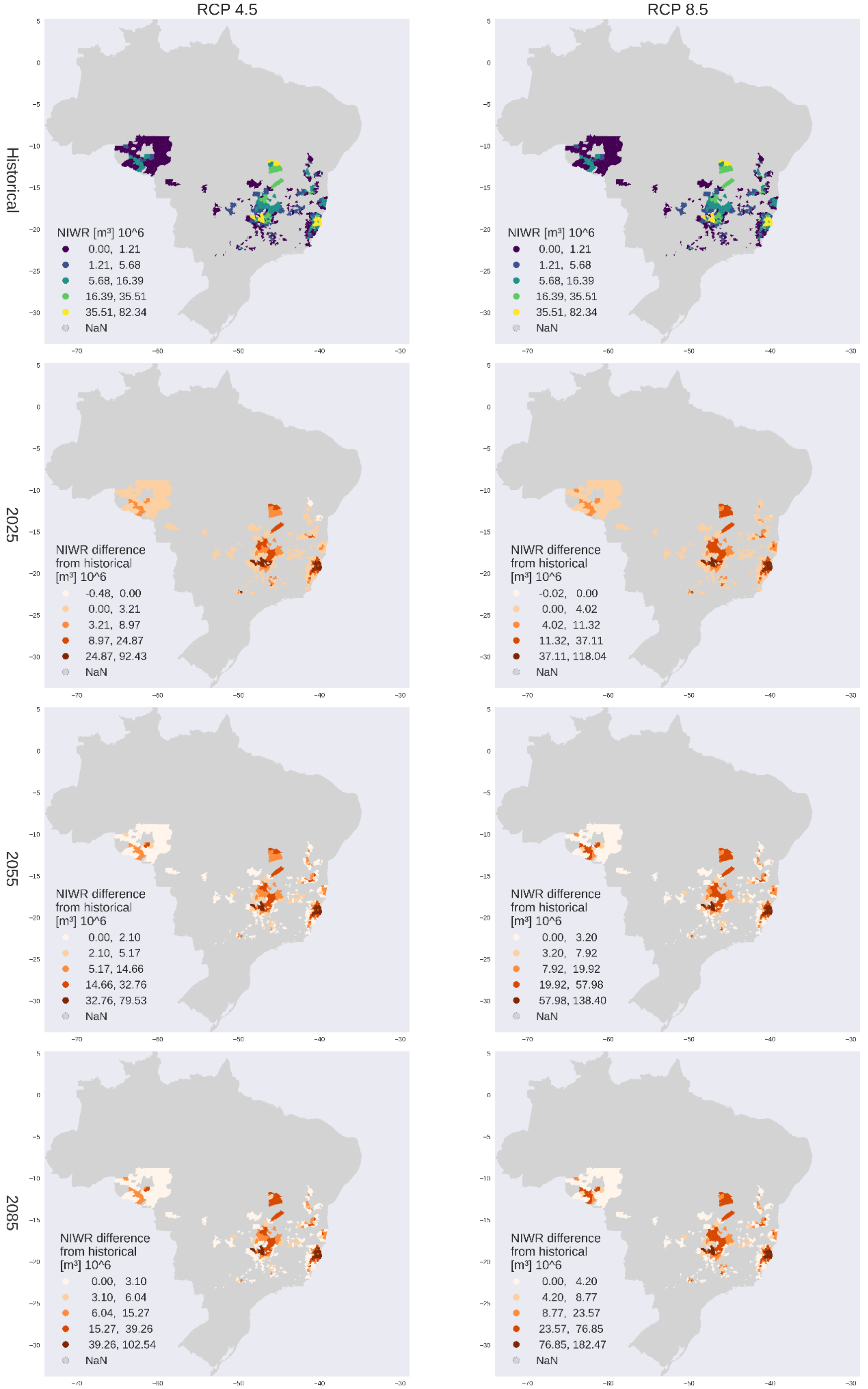
The cultivation of coffee in the country is characteristic of three main regions, one in the north of the state of Espírito Santo, another in the northwest of the state of Minas Gerais in conjunction with the west of the state of Bahia, and another in the state of Rondônia. Figure 25 of irrigation volume for the crop indicates a considerable increase in the amount of water for the activity in the two global warming scenarios for the 2025 period and a significant expansion of the areas with high values for the 2055 and 2085 periods in the RCP 8.5 scenario.

The central planting area of the country (Minas Gerais and Bahia) had high irrigation demands due to the increase in reference evapotranspiration and decrease in precipitation, much on account of the increase in average temperature, increase in absorbed net radiation and decrease in relative humidity. This led the region to have a steady growth of its irrigated volume.

The northern region of the state of Espírito Santo, had a large amount of irrigation because of the amount of areas being produced there, about 46% of the crop’s irrigated area (in both the 2019 and 2040 scenarios). The producing region in the state of Rondônia has a high share of green water in the water requirement for coffee, showing areas of heavy irrigation only for periods after 2025.

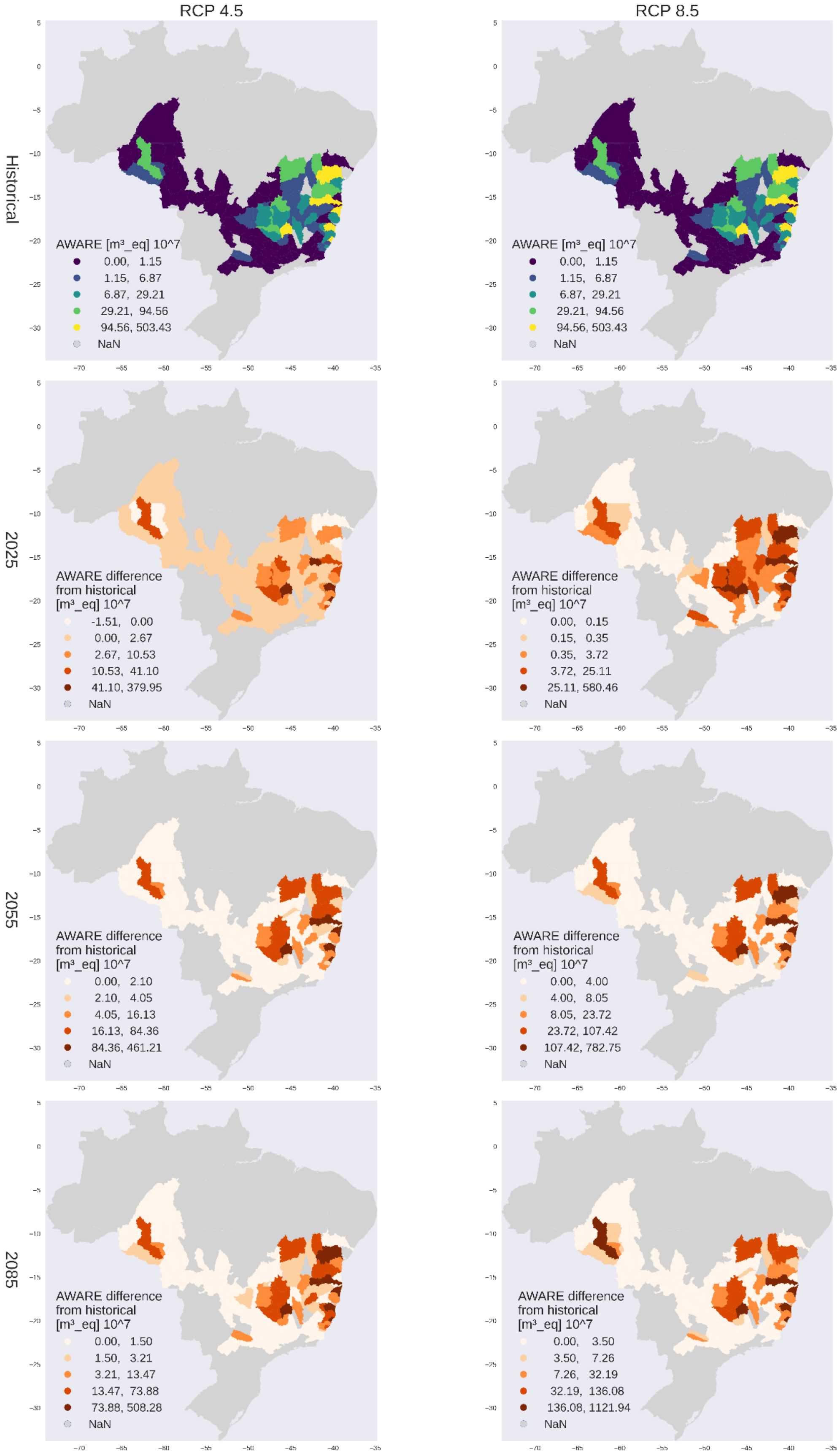
The highest impact values for this crop are significant but lower compared to rice and sugarcane crops, yet, in the same way that rice grown together with sugarcane in the same subwatershed can lead to relevant impacts, the significant production of coffee together with the expansion of the sugarcane growing region in the southeast, especially in Minas Gerais, has led to higher impacts in the upper and middle São Francisco subwatersheds, which makes the region an important hotspot for future water scarcity impact assessments, especially considering the projected expansion of both crops.

Figure 25 - Net irrigation water requirement (NIWR) in m³ for the coffee crop in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

Figure 26 - Impact on water scarcity in m³ equivalent for the coffee crop in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

The subwatersheds of the coastal regions of the eastern and southeastern Atlantic were those that presented the highest values for coffee, as shown in Figure 26, largely due to the high volume of irrigation in the north of the state of Espírito Santo and the high characterization factors of the eastern Atlantic subwatersheds. Only one subwatersheds in the state of Rondônia presented high values of impact relative to the culture starting in 2055's period.

4.3.4 Central pivot crops

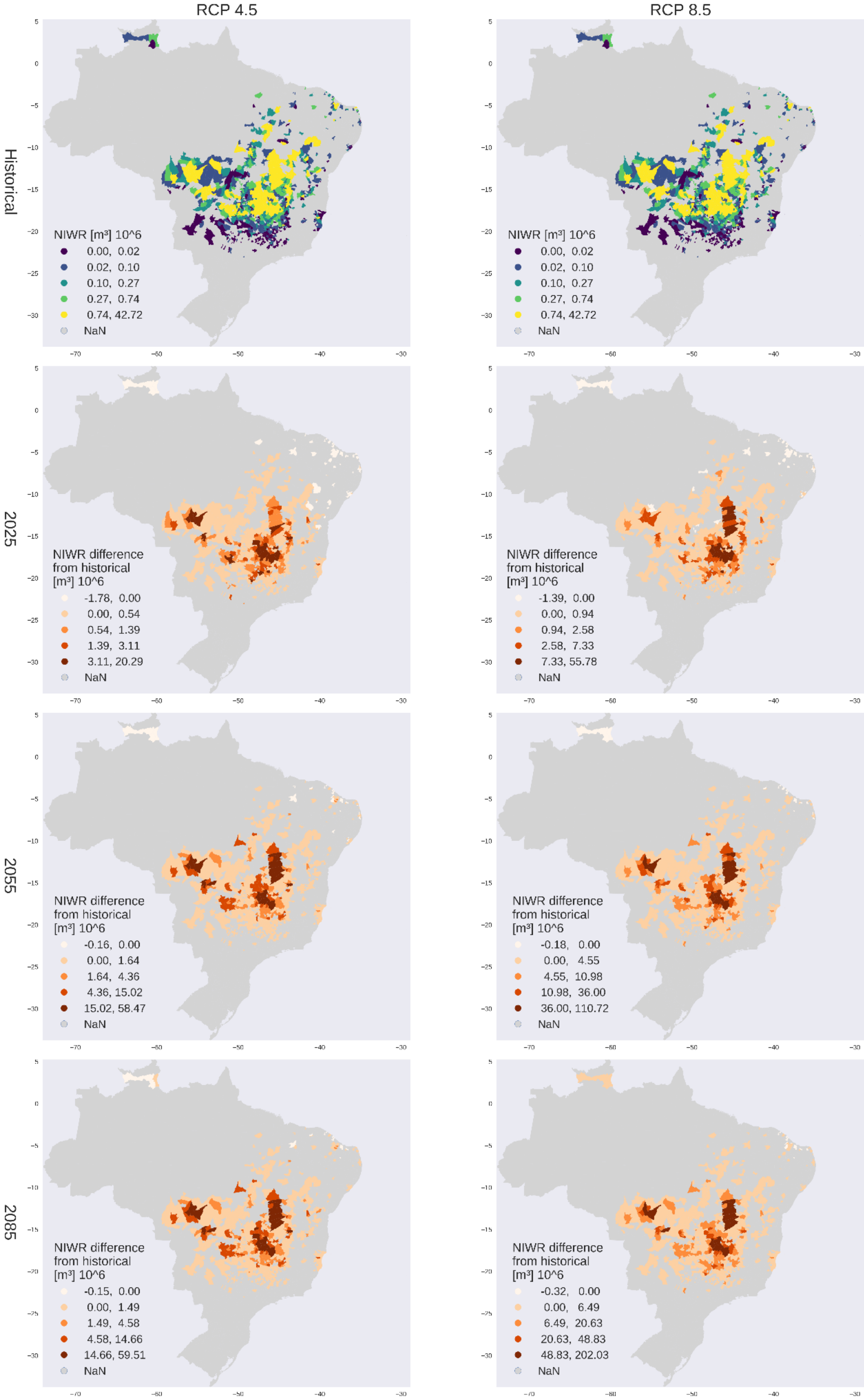
The central pivot crops considered in this work were soybean, maize, beans and cotton, and these were grouped in this result due to the low value of total volume presented in relation to the other crops in the study for all periods, despite having a large number of regions in common with the other crops. The low values are due to the fact that central pivot crops in general do not present areas planted throughout the whole year (which reduces their value in annual comparisons as in this work) and have a smaller mid-season period (mid-season crop coefficient values are the highest) if compared to the other crops studied.

Still, it is expected that crops irrigated by central pivots will have a considerable increase in their area for 2040 (about 143% increase compared to 2019), which makes for a greater number of municipalities with more expressive irrigation volume during the 2055 and 2085 periods in the two RCP scenarios, even if their irrigation in volume is not comparable to that of the other crops as indicated in Figure 27.

The impact on water scarcity is relevant in the production subwatersheds of Bahia and northern Minas Gerais, being mostly present in the São Francisco river basin in both global warming scenarios, as shown in Figure 28. Despite the low impact values, its contribution to the presence of critical basins in Brazil, with values varying from 10% to 30% in area and its joint presence in areas of great impact for other crops made the inclusion of central pivot irrigation relevant in the work.

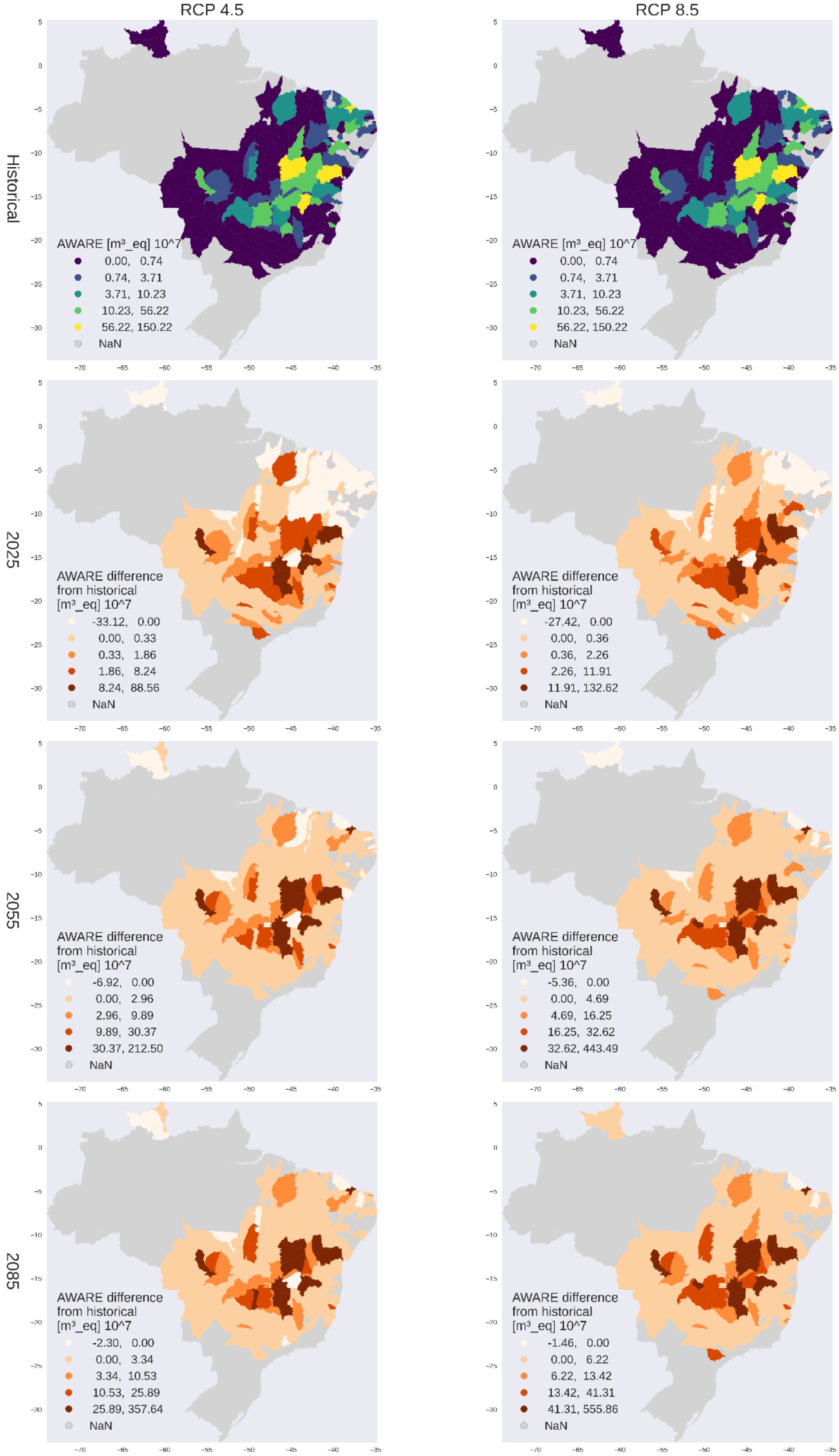
The impacts of maize and bean crops stand out as the largest contributions to high values in the subwatersheds for this set of crops.

Figure 27 - Net irrigation water requirement (NIWR) in m³ for the center pivot crops (soybean, corn, beans and cotton) in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

Figure 28 - Impact on water scarcity in m³ equivalent of central pivot crops (soybean, corn, beans and cotton) in the different periods studied (rows) and different RCP scenarios (columns)



Source: Own elaboration (2021)

4.4 Uncertainties

This study used a deterministic approach to the calculation of irrigation and water scarcity impact using scenarios to characterize possible futures of climate change, much due to the difficulty to consider overall uncertainty in the scope of the work. Nevertheless, efforts to reduce this uncertainty were done, such as bias correction of mean and variance and consideration of monthly variability for irrigation.

In this section we present a comprehensive evaluation of the possible sources of uncertainty that this study could have and discuss their possible effects on its results.

4.4.1 Input data uncertainty

This study considered a wide range of different data and generally this data was deterministic. Although that, the chosen data was considered to be the best data that could be collected for this type of broad analysis and the consideration of its uncertainty, since it is gathered from other sources, was not in the scope of this work.

In a wider view, all the input data have uncertainties that could be, by means of Monte Carlo simulation for example, propagated through for the final irrigation and impact results. For example historical climate data can have uncertainties from the measurement on the climate station, harvested and irrigated area can have uncertainties in their data collections, AWARE characterization factors can have uncertainties on their modelage (this can be a major source of uncertainty as discussed in ALVES *et al.*, 2020) and crop data and future climate data can have uncertainties on their modelling.

Soil data had an additional layer of uncertainty due to its rather general information about the soil texture, which consists of only major textures (clay, medium [assumed as loam] and sand). This lack of more specific information can generate variability in the field capacity and wilting point values. Aside from that, the literature values for field capacity and wilting point are presented as a range of values even for specific textures (in this work, the main value was considered).

4.4.2 Model uncertainty

This study relies on several models for calculations and its consideration can bring uncertainty, especially if the model is empirical. For example the model for reference evapotranspiration (Penman-Monteith), although based on a physical balance, have steps taken to calculate some of its variables (in the case they're not available) that are modeled empirically (for example the equations for calculating radiation), which can be a source of uncertainty. Another case is the effective precipitation that is modeled empirically using the precipitation values from the climate models.

Irrigation calculation was based on the CROPWAT model using the soil water balance, but there is a whole range of other methods to calculate irrigation for specific crops that can have better results but consider a wider range of crop specific variables. Thus, considering CROPWAT because it is easier to implement with the available values, even if the method is widely used, adds model uncertainty to the calculations.

The consideration of CO2 fertilization effect on the Penman-Monteith equation can bring uncertainties as the modelage of this effect is mainly empirical (and has several models) and the adaptation done considers only the hypothetical crop and not each crop individually.

This type of uncertainty could be addressed by analysing the different available models and their variability and their capacity of representing the real data, but that was outside the scope of this study.

4.4.3 Crop-specific uncertainty

Crop data was chosen from FAO and the data, in general, is not collected in Brazil but in other crop fields around the world. The assumption that this data is representative for Brazil is used in this work but even FAO recognizes that regionalized data, especially for crop coefficients, is better for works in other locations (Allen *et al.*, 1998). There is still a lack for a compilation of such data within Brazil and, given the country size and the amount of different crops planted in it, this data could have significant variability and uncertainty.

Some assumptions regarding specific crops can raise uncertainties such as the specific modelage of water balance for rice that relies on a flood depth information (considered 50mm as the ideal). Another assumption was for the sugarcane specific irrigation systems (fertigated, deficit and full) that had differences in the amount of water actually irrigated and, due to the difficulty to model specific monthly differences (such as irrigation only on the dry period as done in deficit and fertigation systems), had to be considered using general information about the water blade and not a more specific monthly approach.

4.4.4 Climate change and future assessment uncertainties

Climate change can impact several variables of agriculture. One of those variables is the expansion of irrigated areas (considered here only for 2019 and 2040 as it was the best data available), which is a dynamic and ever changing process that is hard to model. Other variables it can affect are things such as planting dates, periods and even suitability for each crop, data that was considered static in this study. It can also have side effects such as new irrigated or new relevant irrigated crops that can rise in future.

Overall, a holistic assessment that approaches these issues requires that more data is gathered and a more detailed modelage and would be suitable for a future irrigation model, but the creation of such modelage or the consideration of such point was beyond the scope of this study, and thus have to be addressed as a source of uncertainty.

4.4.5 Uncertainties due to considerations

Some considerations were done during the execution of this study and should be addressed as sources of uncertainty for its generalization purposes. One of such was the central pivot consideration as it takes into account only 4 crops for that irrigation system (maize, soybean, beans and cotton) and the irrigated area for this system is divided proportionally (by means of harvesting area) between them. Another consideration was that the irrigated areas within a municipality were divided equally for each different soil present in its area, which can potentially include areas that are not feasible for crop cultivation for example.

Other generalizations can generate spatial uncertainties such as the geographic consideration of an area of effect for climate point data in the irrigation calculation and the averaging of results for a municipality on the marginal blue water assessment.

4.4.6 Other sources of uncertainty

Even with the use of Regional Circulation Models (RCM) simulations for climate variables that have a more detailed modelling than the Global Circulation Models (GCM), the consideration of only one RCM as the correct climate modeling on that region can be misleading. Works such as Boehlert, Solomon and Strzepek (2015) indicate that it is better to consider the mean (weighted or simple) of an ensemble of climate models to get a better result overall. As such, that limitation of only one RCM can bring major uncertainties to the study and should be addressed in other studies that can overcome it.

This work used bias correction by quantile mapping to reduce the systematic error of the simulation and correct its variability using the real values of climatic variables. Although the procedure is used to reduce major uncertainties, it can lead to changes in the overall future trend of the simulated climate variable and, even with a monthly consideration for correction to avoid changes in seasonal behaviour, it can lead to changes in the seasonal behavior and variability throughout the future periods.

The monthly variability was considered in the bias correction and in the irrigation calculation, but the fact that values are averaged for a 30 years period can add another layer of variability due to the fluctuation of the values inside this period. In this context, interannual variability and seasonality of the climatic variables in that 30 years period are not considered. This can be of great importance because Brazil has regions, such as the northeast, that have high interannual variability and extended periods of climate behaviours (such as droughts that could go for years or effects of El Niño and La Niña) and these are masked by the averaging values. Considering this type of interannual variability can add great value for similar future irrigation analysis.

A higher trustability and better detailing of the Brazilian watersheds for AWARE characterization factors led to the choice of marginal regionalized characterization factors that are not recommended for non-marginal assessment (since the latter have a different modelage than the marginal). This can lead to an systematic error equal to the difference between both factors.

Marginal blue water assessment had some specific sources of uncertainty due to its lack of a future estimation of production, the spatial aggregation by average of its values to get a single municipality value and the generic result as a sum of the results for all crops.

5 CONCLUSION

This paper provides an extensive analysis of the consequences of global warming on irrigation and future agricultural production in Brazil and its impact on water scarcity in the subwatersheds for two RCP scenarios (4.5 and 8.5) for sugarcane, coffee, rice and center pivot crops.

An initial analysis of trends indicated a significant increase in reference evapotranspiration specially for the central region of the country (central-west, southeast, west of the state of Bahia and south of the state of Tocantins) due to the increase in temperature and absorbed net radiation and the decrease in relative humidity in that area. The CO2 fertilization effect has shown to lower this tendency of increase, especially in regions with high wind velocities.

Together with a decrease in precipitation, which tends to be lower in the future except for the south region, these effects would considerably increase the irrigation demand already in the 2025 period, with irrigation demands doubling in relation to the historical period. In the RCP 4.5 scenario, results show a stability period for 2055 and 2085 periods, but for RCP 8.5, which is the current pathway, there is a tendency of increase for values over four times the historical values.

The increase in evapotranspiration and decrease in precipitation can increase the irrigation for all crops, but sugarcane showed the highest increase throughout the periods analyzed, growing from a 50% share on total production irrigation in the historical period to over 66% share in 2025 for both RCP scenarios. This increase was especially worrisome for the southeast production region due to the fact that the majority of the cultivated areas of sugarcane in this region is fertigated and had a lower volume of irrigation. Southeast maintained itself as the region with the highest total irrigation volume of the country for all periods analyzed.

Although the irrigated volume results for the southeast reached high values, the watersheds in its region have high water availability and low water scarcity impact characterization. Still, the southeast doubled its impact value for the two global warming scenarios as early as 2025 and had considerable growth over the remaining future periods. The region where irrigation caused the greatest impact on water scarcity was the northeast, mainly with production regions along the semiarid and fully and deficit irrigated sugarcane regions on the east coast. The more recurrent practice of fertirrigation with the presence of sugar and alcohol industries near the coastal production region can have a great contribution in reducing the impact in the region. The semiarid region also presented the highest results of irrigation and impact per kilogram produced, showing that improving the productivity of the region can be a way to reduce its total irrigation contribution.

Flooded rice obtained low results of irrigation volume if compared with other crops, but its production in specific areas of the country (mainly Tocantins and Rio Grande do Sul) that have a high value of characterization factor produced an expressive increase of its impact on water scarcity (almost doubling) for the year 2025 maintained for further analyzed periods. The rice producing sub-basins are among those with the highest water demand for irrigation in the country and extremely high impact values on water scarcity already in the historical period and with one of the highest trends of increase in impact in the country. In the same vein, areas with significant coffee production, such as the north of Espírito Santo and central areas of Bahia, had a high impact of irrigation on water scarcity, but the crop had a low impact value relative to rice and sugarcane and little increase in its impact over the years. Center pivot crops obtained very low irrigation and impact values over all periods and scenarios.

The results shown in this paper for the impact of irrigation on water scarcity in the country show priority for reducing full and deficit irrigation of sugarcane grown in the northeast region and for increasing its productivity and show concern with the irrigation demand needed for rice production in Tocantins and Rio Grande do Sul, which has a great tendency to increase for future periods and expand its producing area. Both situations are challenging and depend on climate issues.

Climate change resulting from global warming has the potential to cause secondary effects in other impact categories that depend on climatic variables, as demonstrated in this work for water scarcity. Thus, just as actions to increase productivity and reduce irrigation by increasing efficiency or planting different crops can be a way to decrease water use in the country, its future behavior should not be addressed without taking into account climate change and the way it affects the irrigation in the country. The subsequent work on decreasing emissions and contributing to the reduction of the amount of greenhouse gases emitted into the atmosphere is also beneficial to avoid the increase in the use of water for irrigation and its resulting effect on water scarcity.

The consideration of only one regional circulation model is a limiting factor in the comprehensiveness of the results of the work, and the main point for future work is the use of a set of circulation models to obtain more expressive climatic results in the country. In the same line, the uncertainty of climatic results and its propagation to future irrigation results should be addressed. Consideration of characterization factors that takes into account non-marginality, although with caution, can be a possibility for future works that aim to use total production on its results. Other points for future work are the consideration of more specific planting area forecasts for future periods of 2055 and 2085, consideration of complete future periods (not 30 years averaged climatic variables), calculation of marginal blue water using and estimation of future production for all irrigated crops analysing the effect of climate change in the crop yield and work with other irrigated crops in the country.

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APPENDIX A - Main characteristics of articles reviewed

Table A1 - Articles for literature review and their basic characteristics

Reference	Circulation models	Crop models	Reference evapotranspiration	Climate change scenarios	Crops	Locations	Outputs	Consideration of fertilization effects of CO2
Abdoulaye et al. 2020	3 GCM	CROPWAT	Penman-Monteith	RCP 4.5 and 8.5	More than 4	Niger river, Nigeria	NIWR	No
Acharjee et al. 2017	5 GCM	CROPWAT	Penman-Monteith	RCP 4.5 and 8.5	Rice	Northeast Bangladesh	NIWR	No
Aish, Ayesh e Al-Najar, 2020	SimCLIM	CROPWAT	Penman-Monteith	-	More than 4	Gaza Strip	NIWR	No
Akoko, Kato e Tu, 2020	3 GCM	CROPWAT	Penman-Monteith	All RCP	Rice	Mwea irrigation scheme, Kenya	NIWR	No
Ashofteh, Haddad e Marino, 2015	7 GCM	CROPWAT	Penman-Monteith	SRES A2	More than 4	Aidoghmoush river, Iran	NIWR	No
Boonwichai et al. 2018	5 RCM	DSSAT	Soil water balance	RCP 4.5 and 8.5	Rice	Songkhram river, Thailand	NIWR and productivity	No
Chiarelli et al. 2016	8 GCM	AquaCROP	Soil water balance	SRES A1B	Rice, Maize and Wheat	18 African countries	Water footprint	Yes
Chowdhury, Al-Zahrani e Abbas, 2016	-	CROPWAT	Penman-Monteith	Specific	Wheat	Al-Jouf, Saudi Arabia	NIWR	No
da Silva et al. 2018	1 RCM	SWAP	Penman-Monteith	SRES A1B	Beans, Maize, Soybeans and Wheat	Ijuí river, Brazil	NIWR	No

de Oliveira, de Miranda e Cooke, 2018	-	DSSAT	Penman-Monteith	SRES A1B, A2 and B1	Sugarcane and Maize	Piracicaba, Brazil	NIWR and productivity	No
Ding et al. 2017	4 GCM	CROPWAT	Penman-Monteith	RCP 2.6, 4.5 and 8.5	Rice	Middle and lower reaches of the Yangtze River, China	NIWR	No
Ding et al. 2020	4 GCM	ORYZAv3	Soil water balance	RCP 8.5	Rice	21 locations in China	NIWR and productivity	Yes
Durodola e Mourad, 2020	1 RCM	AquaCROP	Penman-Monteith	RCP 4.5 and 8.5	Maize	Ogun-Osun river, Nigeria	NIWR and productivity	No
Fader et al. 2016	19 GCM	LPJmL	Soil water balance	Specific	More than 4	Mediterranean	NIWR and water footprint	Yes
Gao et al. 2020	3 GCM	APSIM	Hargreaves-Samani	RCP 4.5 and 8.5	Wheat	Northeast China	NIWR and productivity	No
Garofalo et al. 2019	5 GCM	CropSys; Hermes; AquaCROP and DSSAT	Priestley-Taylor e Penman-Monteith	RCP 4.5 and 8.5	Wheat	2 districts of Foggia (Italy) and 2 districts of Märkisch-Oderland (Germany)	Productivity and water footprint	Yes
Gondim et al. 2018	25 GCM	Aggregation of weights to crop coefficients	Penman-Monteith	All RCP	More than 4	Jaguaribe river, Brasil	NIWR	No
Haj-Amor et al. 2020	1 GCM	CROPWAT	Penman-Monteith	RCP 4.5, 6.0 and 8.5	Date	Metouia oasis, Tunisia	NIWR	No
Huang et al. 2019	5 GCM	GCAM	Penman-Monteith	RCP 6.0 and SSP2	More than 4	Global	Water footprint	No

Jans et al. 2021	5 GCM	LPJmL	Soil water balance	All RCP	Cotton	Cotton-producing countries	NIWR and productivity	Yes
Li et al. 2016	-	AquaCROP	Penman-Monteith	Specific	Maize and Wheat	Heihe river, China	Productivity	No
Marin et al. 2012	2 GCM	DSSAT	Penman-Monteith	SRES A2 and B2	Sugarcane	São Paulo state, Brazil	Productivity	Yes
Martins, Tomasella e Dias, 2019	3 RCM	CROPWAT	Penman-Monteith	RCP 4.5 and 8.5	Maize	Northeast Brazil	NIWR and productivity	Yes
Minuzzi e Lopes, 2015	-	AquaCROP	Penman-Monteith	RCP 4.5	Maize	Producing regions in the states of Mato Grosso, Goiás and Mato Grosso do Sul, Brazil	Productivity	Yes
Minuzzi, Frederico e da Silva, 2017	-	AquaCROP	Penman-Monteith	RCP 4.5	Soybean	Producing regions in the states of Rio Grande do Sul, Santa Catarina and Paraná, Brazil	NIWR and productivity	Yes
Nam, Choi e Hong, 2015	1 RCM	CROPWAT	Penman-Monteith	RCP 4.5 and 8.5	Rice	South Korea	NIWR and water supply potential	No
Olabanji , Ndarana e Davis, 2021	1 RCM	WEAP-MABI A	Penman-Monteith	RCP 4.5 and 8.5	Beans, Sunflower, Maize and Soybeans	Olifants dam, South Africa	NIWR and productivity	No
Saadi et al. 2015	2 GCM	CROPWAT	Penman-Monteith	SRES A1B	Tomato and	Mediterranean	NIWR and	No

					Wheat		productivity	
Shrestha e Shrestha, 2017	2 GCM	AquaCROP	Penman-Monteith	SRES A1B	Rice and Wheat	Bhaktapur district, Nepal	NIWR and productivity	Yes
Shrestha, Chapagain e Babel, 2017	3 RCM	DSSAT	Priestley-Taylor	RCP 4.5 and 8.5	Rice	Nam Oon irrigation scheme, Thailand	NIWR, productivity and water footprint	No
Sun et al. 2018	1 GCM	CROPWAT	Penman-Monteith	RCP 2.6, 4.5 and 8.5	More than 4	Loess Plateau, China	NIWR	No
Tian e Zhang, 2020	15 GCM	CROPWAT	Penman-Monteith	RCP 2.6 and 4.5	Cotton and Wheat	Central Asia	NIWR	Yes
Valverde et al. 2015	16 GCM	ISAREG	Hargreaves-Samani	SRES A1B, A2 and B1	More than 4	Guadiana river, Portugal	NIWR	No
Verhage, Anten e Sentelhas, 2017	5 GCM	Specific model for coffee	Thornthwaite-Mather	RCP 4.5	Coffee	42 municipalities of Brazil	Productivity	Yes
Wang et al. 2017	4 GCM	ORYZA2000	Soil water balance	All RCP	Rice	Kunshan, Nanjing and Kaifeng Irrigation Sites, China	NIWR and productivity	Yes
Waongo, Laux e Kunstmann, 2015	8 GCM	GLAM	Soil water balance	RCP 4.5 and 8.5	Maize	Burkina Faso	NIWR and productivity	No
Xu et al. 2019	5 GCM	DSSAT	Soil water balance	All RCP	Maize	Northeast China	NIWR	No
Ye et al. 2015	1 GCM	CROPWAT	Penman-Monteith	SRES A1B	Rice	South China	NIWR and suitability for the planting system	No

Zhang, Wang e Niu, 2019	6 GCM	CROPWAT	Penman-Monteith	All RCP	Rice, Maize, Soybeans and Wheat	China	NIWR	Yes
Zhou et al. 2017	1 GCM	CROPWAT	Penman-Monteith	SRES A2 and B2	Sunflower, Maize and Wheat	Hetao Irrigation District, China	NIWR	No

Source: Own elaboration (2021)

APPENDIX B - Tables of climatic plateaus in the periods studied by region

Table B1 - Climatic plateaus for north region

North Region				
Variable	Historical	2025	2055	2085
Reference evapotranspiration RCP 4.5 [mm]	3.61±1.27	3.68±1.59	3.81±1.64	3.92±1.76
Reference evapotranspiration RCP 8.5 [mm]	3.61±1.27	3.98±1.75	4.14±1.86	4.65±2.08
Precipitation RCP 4.5 [mm]	6.12±4.33	5.56±4.07	5.73±4.09	5.58±4.28
Precipitation RCP 8.5 [mm]	6.12±4.33	5.63±4.18	5.67±4.22	4.71±3.99
Relative humidity RCP 4.5 [%]	82.15±8.50	79.58±10.21	78.99±11.59	77.65±13.24
Relative humidity RCP 8.5 [%]	82.15±8.50	78.08±11.76	76.37±13.19	68.96±14.73
Net radiation RCP 4.5 [MJ/m²]	11.01±3.47	10.85±4.20	11.14±4.10	11.27±4.20
Net radiation RCP 8.5 [MJ/m²]	11.01±3.47	11.55±4.36	11.83±4.42	12.49±4.54
Average temperature RCP 4.5 [ºC]	27.16±1.69	28.17±2.33	29.22±2.51	30.01±2.59
Average temperature RCP 8.5 [ºC]	27.16±1.69	28.84±2.43	30.55±2.97	33.42±3.27
Surface wind velocity [2 meters] RCP 4.5 [m/s]	0.94±0.35	0.97±0.56	1.01±0.56	1.04±0.62
Surface wind velocity [2 meters] RCP 8.5 [m/s]	0.94±0.35	1.05±0.61	1.09±0.62	1.33±0.72

Source: Own elaboration (2021)

Table B2 - Climatic plateaus for northeast region

Northeast Region				
Variable	Historical	2025	2055	2085
Reference evapotranspiration RCP 4.5 [mm]	4.49±2.42	4.32±2.49	4.34±2.57	4.49±2.57
Reference evapotranspiration RCP 8.5 [mm]	4.49±2.42	4.71±2.73	4.80±2.69	4.80±2.55

Precipitation RCP 4.5 [mm]	2.73±5.44	2.41±5.02	2.73±5.44	2.51±5.15
Precipitation RCP 8.5 [mm]	2.73±5.44	2.36±4.42	2.32±4.70	2.05±4.35
Relative humidity RCP 4.5 [%]	69.07±15.94	67.91±15.17	68.27±16.72	66.93±16.41
Relative humidity RCP 8.5 [%]	69.07±15.94	66.33±15.24	65.28±15.82	63.52±15.27
Net radiation RCP 4.5 [MJ/m²]	11.98±5.92	11.22±6.21	11.32±6.18	11.52±6.10
Net radiation RCP 8.5 [MJ/m²]	11.98±5.92	12.07±6.84	12.38±6.77	12.42±6.55
Average temperature RCP 4.5 [ºC]	26.23±2.45	26.90±2.97	27.90±2.83	28.63±2.85
Average temperature RCP 8.5 [ºC]	26.23±2.45	27.59±2.54	29.14±2.58	30.97±2.82
Surface wind velocity [2 meters] RCP 4.5 [m/s]	1.82±0.77	1.86±0.98	1.84±1.01	1.88±1.01
Surface wind velocity [2 meters] RCP 8.5 [m/s]	1.82±0.77	1.97±1.00	1.99±0.99	2.08±0.95

Source: Own elaboration (2021)

Table B3 - Climatic plateaus for mid-west region

Mid-West Region				
Variable	Historical	2025	2055	2085
Reference evapotranspiration RCP 4.5 [mm]	3.75±2.03	4.34±2.72	4.32±2.85	4.34±2.93
Reference evapotranspiration RCP 8.5 [mm]	3.75±2.03	4.68±2.93	4.70±3.03	5.11±3.16
Precipitation RCP 4.5 [mm]	4.48±7.57	3.61±6.67	3.96±7.24	3.92±7.17
Precipitation RCP 8.5 [mm]	4.48±7.57	3.65±6.41	3.80±6.71	3.38±6.33
Relative humidity RCP 4.5 [%]	73.57±18.23	63.96±23.30	65.55±23.05	64.89±23.40
Relative humidity RCP 8.5 [%]	73.57±18.23	61.95±22.82	61.90±22.03	55.66±22.26
Net radiation RCP 4.5	10.96±5.28	11.65±6.71	11.61±6.95	11.53±7.01

[MJ/m²]				
Net radiation RCP 8.5 [MJ/m²]	10.96±5.28	12.33±7.18	12.34±7.34	12.82±7.51
Average temperature RCP 4.5 [ºC]	25.45±3.67	27.40±4.64	28.28±4.74	28.99±4.98
Average temperature RCP 8.5 [ºC]	25.45±3.67	28.31±4.52	29.88±4.85	32.72±5.01
Surface wind velocity [2 meters] RCP 4.5 [m/s]	1.03±0.57	1.13±0.91	1.15±0.95	1.14±0.97
Surface wind velocity [2 meters] RCP 8.5 [m/s]	1.03±0.57	1.18±0.92	1.18±0.98	1.30±1.00

Source: Own elaboration (2021)

Table B4 - Climatic plateaus for southeast region

Southeast Region				
Variable	Historical	2025	2055	2085
Reference evapotranspiration RCP 4.5 [mm]	3.59±2.36	4.34±3.19	4.22±3.22	4.26±3.37
Reference evapotranspiration RCP 8.5 [mm]	3.59±2.36	4.64±3.53	4.61±3.53	4.84±3.61
Precipitation RCP 4.5 [mm]	3.70±7.83	2.63±6.56	3.05±7.07	3.00±7.18
Precipitation RCP 8.5 [mm]	3.70±7.83	2.71±6.46	2.86±6.64	2.49±6.65
Relative humidity RCP 4.5 [%]	72.07±15.86	62.71±21.33	64.62±20.43	64.08±21.20
Relative humidity RCP 8.5 [%]	72.07±15.86	61.45±21.56	61.76±20.60	58.27±20.36
Net radiation RCP 4.5 [MJ/m²]	10.54±6.94	11.74±8.73	11.53±8.93	11.50±9.12
Net radiation RCP 8.5 [MJ/m²]	10.54±6.94	12.37±9.70	12.37±9.77	12.76±9.96
Average temperature RCP 4.5 [ºC]	22.82±4.66	24.52±5.49	25.35±5.53	26.04±5.72
Average temperature RCP 8.5 [ºC]	22.82±4.66	25.19±5.25	26.64±5.39	28.93±5.67
Surface wind velocity [2 meters] RCP 4.5 [m/s]	1.28±0.64	1.44±1.00	1.44±1.02	1.44±1.04

Surface wind velocity [2 meters] RCP 8.5 [m/s]	1.28±0.64	1.53±1.01	1.53±1.03	1.62±1.06

Source: Own elaboration (2021)

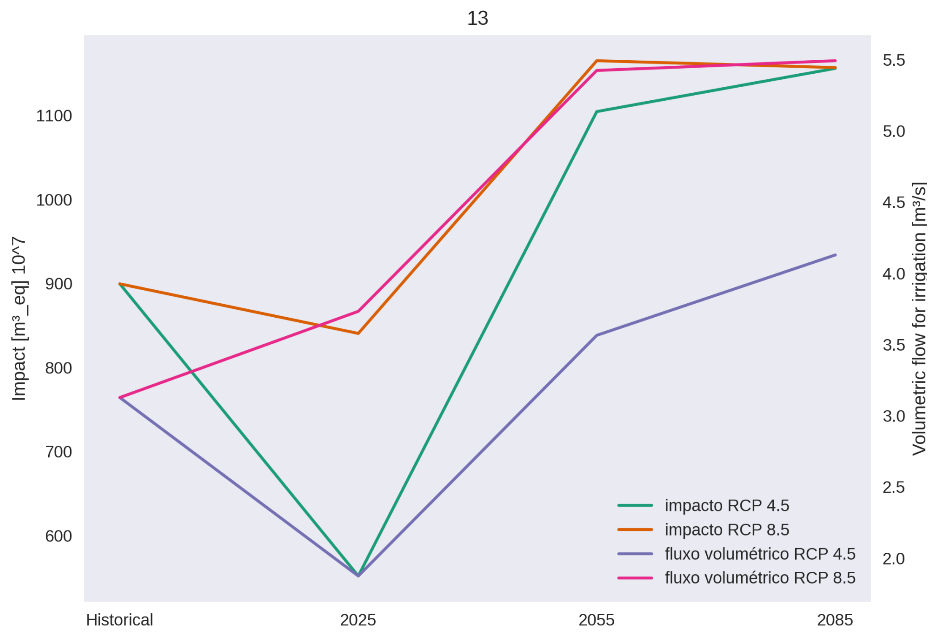
Table B5 - Climatic plateaus for south region

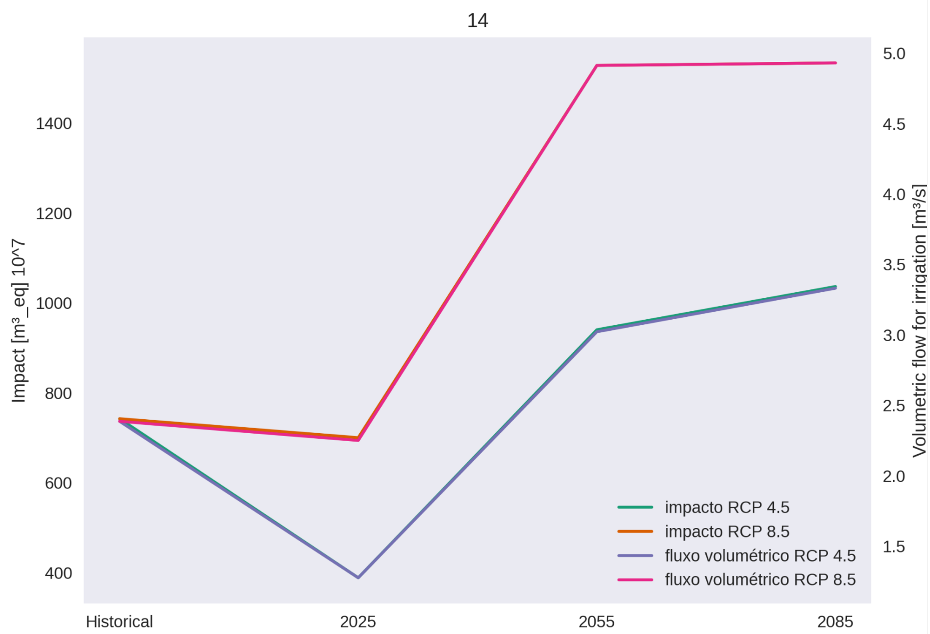
South Region				
Variable	Historical	2025	2055	2085
Reference evapotranspiration RCP 4.5 [mm]	3.05±2.99	3.26±3.51	3.21±3.59	3.11±3.52
Reference evapotranspiration RCP 8.5 [mm]	3.05±2.99	3.53±3.64	3.30±3.57	3.31±3.64
Precipitation RCP 4.5 [mm]	4.69±10.51	4.60±10.40	5.17±11.58	5.28±11.90
Precipitation RCP 8.5 [mm]	4.69±10.51	4.58±10.63	5.14±11.64	5.25±12.37
Relative humidity RCP 4.5 [%]	76.61±14.27	71.90±19.47	73.25±19.63	73.88±18.39
Relative humidity RCP 8.5 [%]	76.61±14.27	70.23±20.54	72.48±18.88	70.41±21.47
Net radiation RCP 4.5 [MJ/m²]	9.54±9.80	9.27±10.96	9.23±11.03	8.98±11.08
Net radiation RCP 8.5 [MJ/m²]	9.54±9.80	9.94±11.03	9.57±11.12	9.26±11.09
Average temperature RCP 4.5 [ºC]	19.63±8.30	21.37±9.14	22.03±8.99	22.41±9.52
Average temperature RCP 8.5 [ºC]	19.63±8.30	21.89±9.16	22.77±9.41	24.95±9.38
Surface wind velocity [2 meters] RCP 4.5 [m/s]	1.58±0.89	1.66±1.41	1.67±1.41	1.65±1.40
Surface wind velocity [2 meters] RCP 8.5 [m/s]	1.58±0.89	1.74±1.41	1.74±1.43	1.81±1.49

Source: Own elaboration (2021)

APPENDIX C - Tables of subwatersheds with critical impacts on water scarcity

Table C1 - Main crops and volumetric demand and impact on water scarcity charts for critical impact subwatersheds in Brazil

<table>
<tr><th>Subwatershed</th><th>Main irrigated crops (by irrigated volume in the historical period) and Graph of volumetric demand (m³/s) and impact (m³_eq)</th></tr>
<tr><td rowspan="2">Piauí - AL
(high impact in all scenarios and periods)</td><td>Sugarcane (80.05%) and Rice (10.79%)</td></tr>
<tr><td>

Source: Own elaboration (2021)</td></tr>
<tr><td rowspan="2">Coruripe - AL
(high impact in all scenarios and periods)</td><td>Sugarcane (99.93%)</td></tr>
<tr><td>

Source: Own elaboration (2021)</td></tr>
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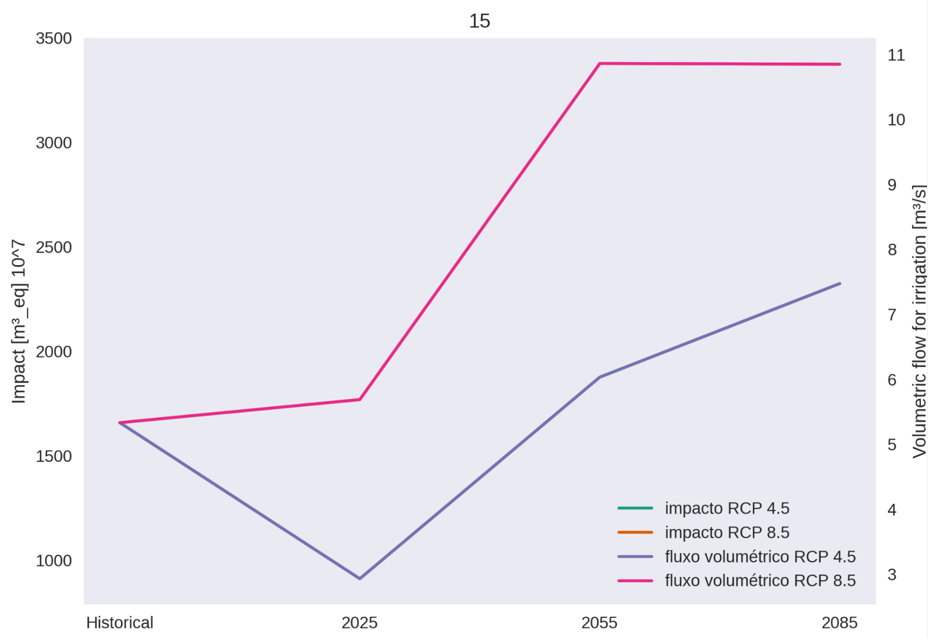
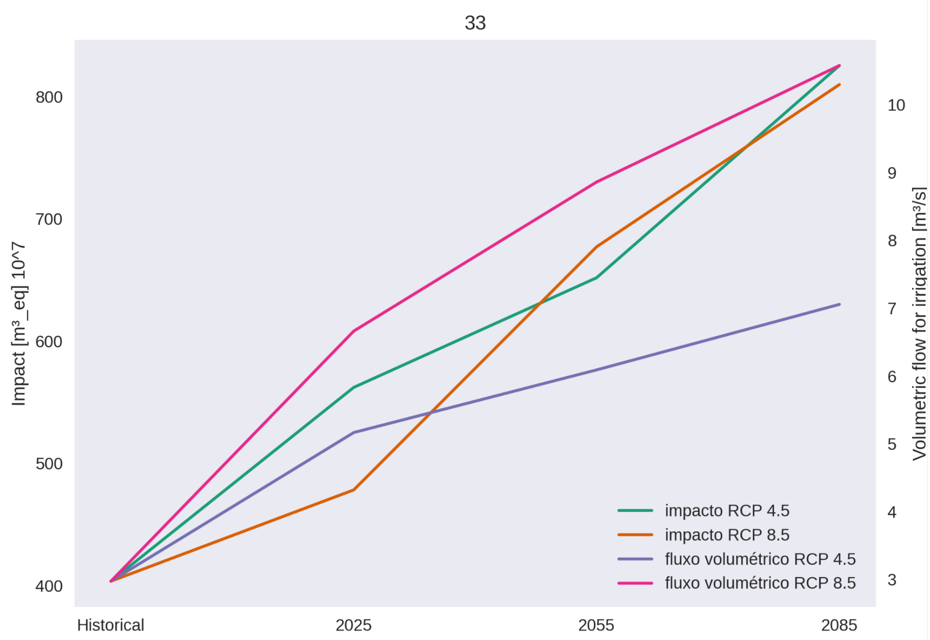
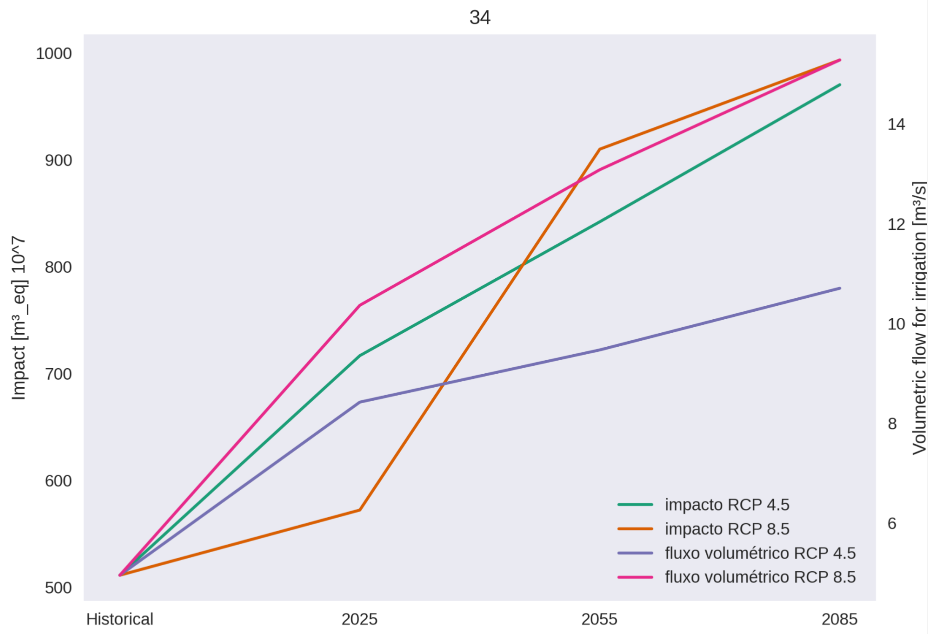
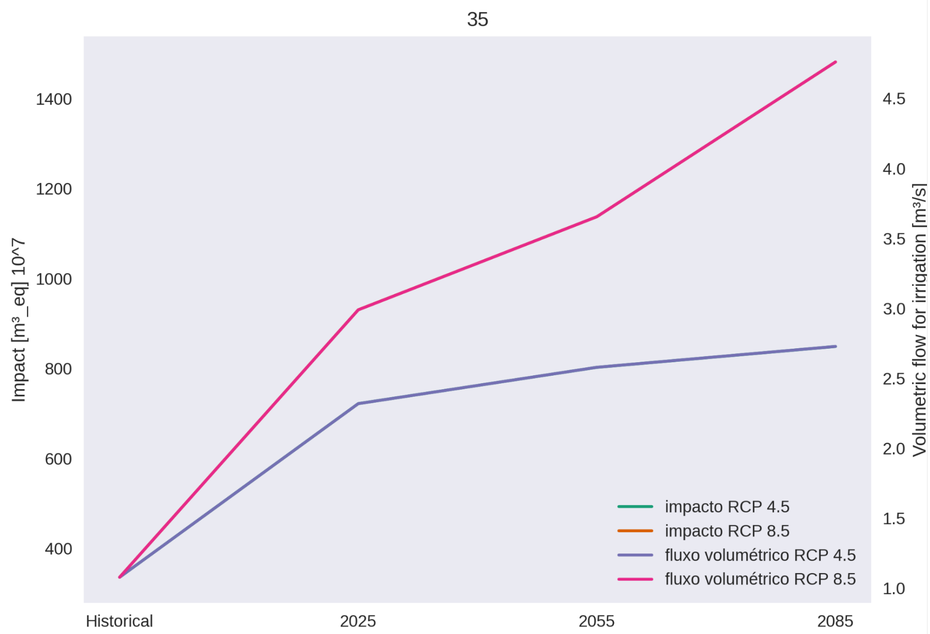
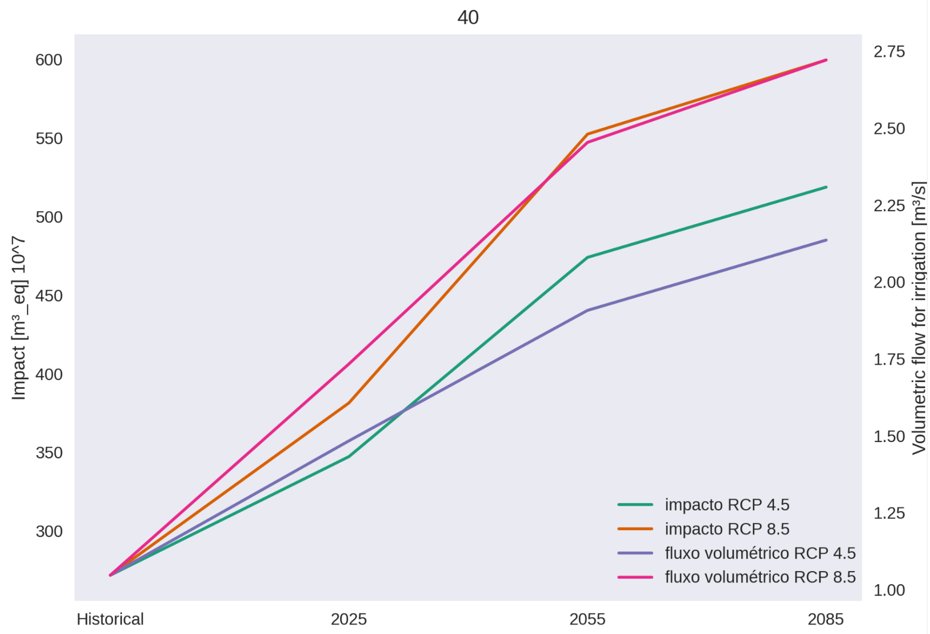
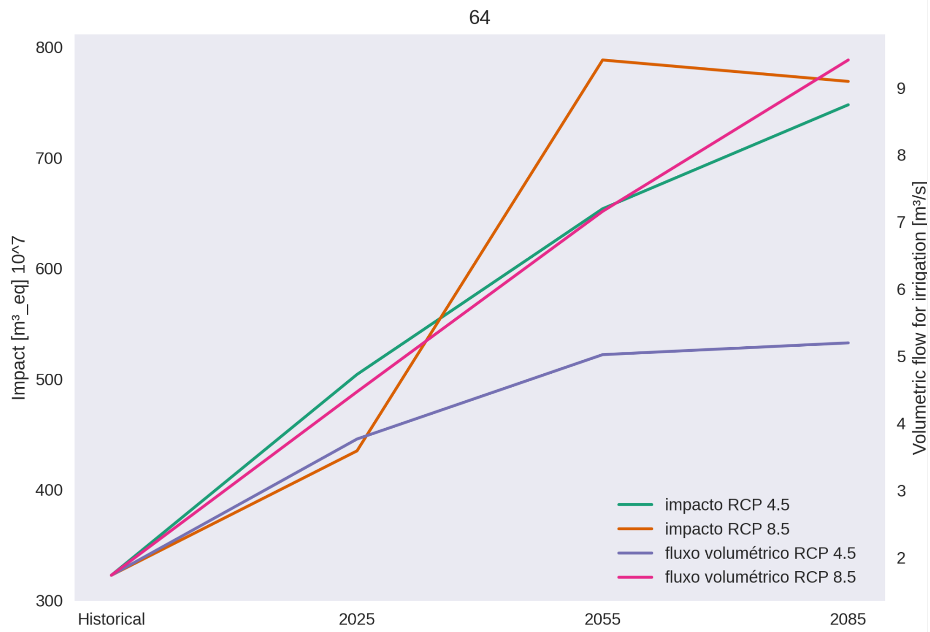
<table>
<tr><td>São Miguel - AL
(high impact in all scenarios and periods)</td><td>Sugarcane (99.94%)


Source: Own elaboration (2021)</td></tr>
<tr><td>Itaúnas - ES
(high impact in all scenarios and periods)</td><td>Coffee (73.97%) and Sugarcane (24.26%)


Source: Own elaboration (2021)</td></tr>
<tr><td>São Mateus - ES
(high impact in all scenarios and periods)</td><td>Coffee (96.76%)</td></tr>
</table>

	 **Source: Own elaboration (2021)**
Center-North Coast - ES (high impact in all scenarios and periods)	Coffee (98.29%)
	 **Source: Own elaboration (2021)**
Pardo River - MG (high impact in all scenarios and periods)	Coffee (94.36.%)

	 **Source: Own elaboration (2021)**
Surroundings of Três Marias Dam - MG (high impact in all scenarios and periods)	Coffee (68.67%) and Sugarcane (27.12.%)  **Source: Own elaboration (2021)**
Verde Grande River - MG (high impact in all scenarios and periods)	Sugarcane (80.28.%) and Central pivots (18.00%)

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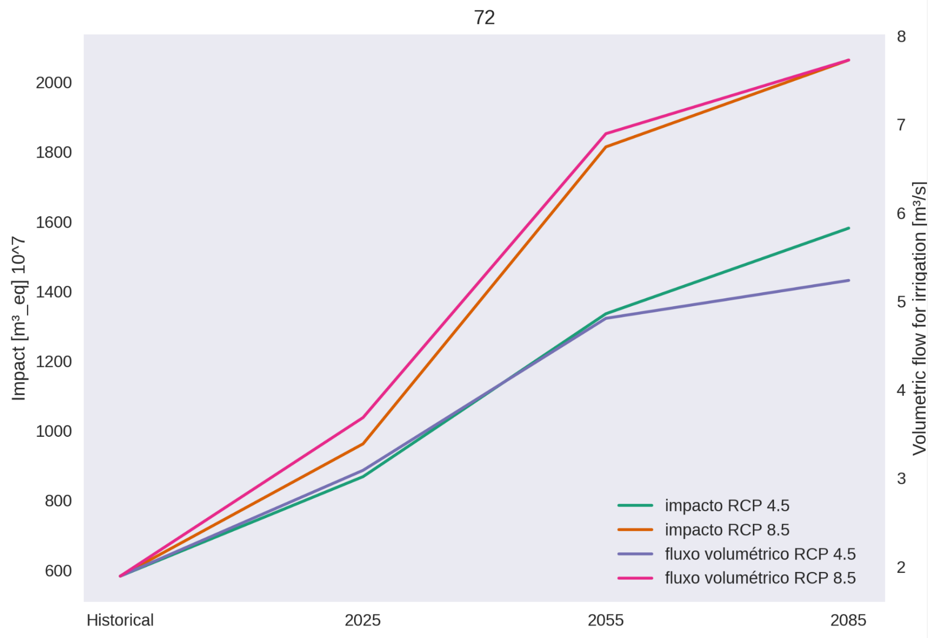
<td>

Source: Own elaboration (2021)</td>
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<tr>
<td rowspan="2">South Coast - PB
(high impact in all scenarios and periods)</td>
<td>Sugarcane (99.82%)</td>
</tr>
<tr>
<td>

Source: Own elaboration (2021)</td>
</tr>
<tr>
<td>North Coast - PB
(high impact in all scenarios and periods)</td>
<td>Sugarcane (99.62%)</td>
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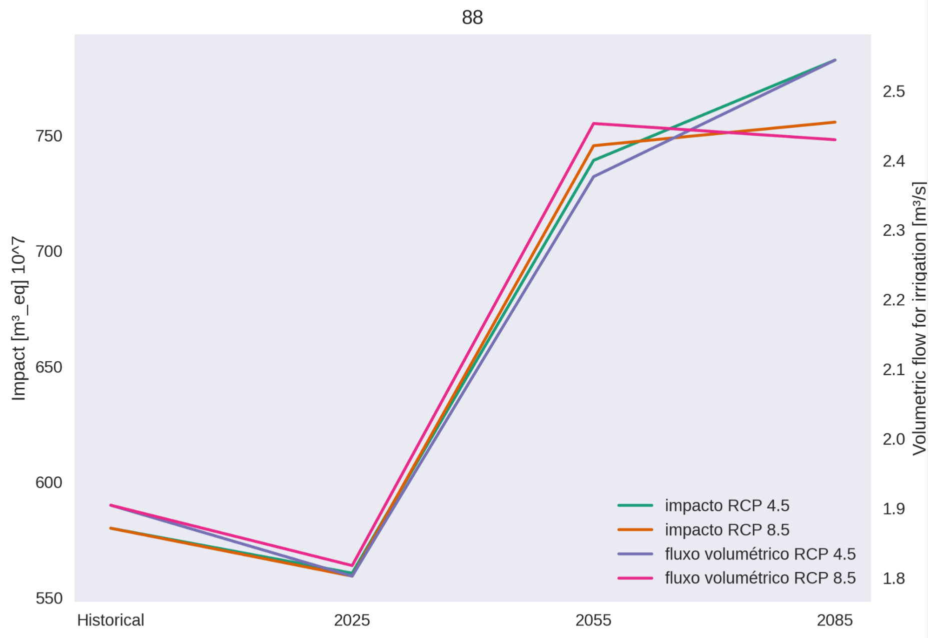
<td>

Source: Own elaboration (2021)</td>
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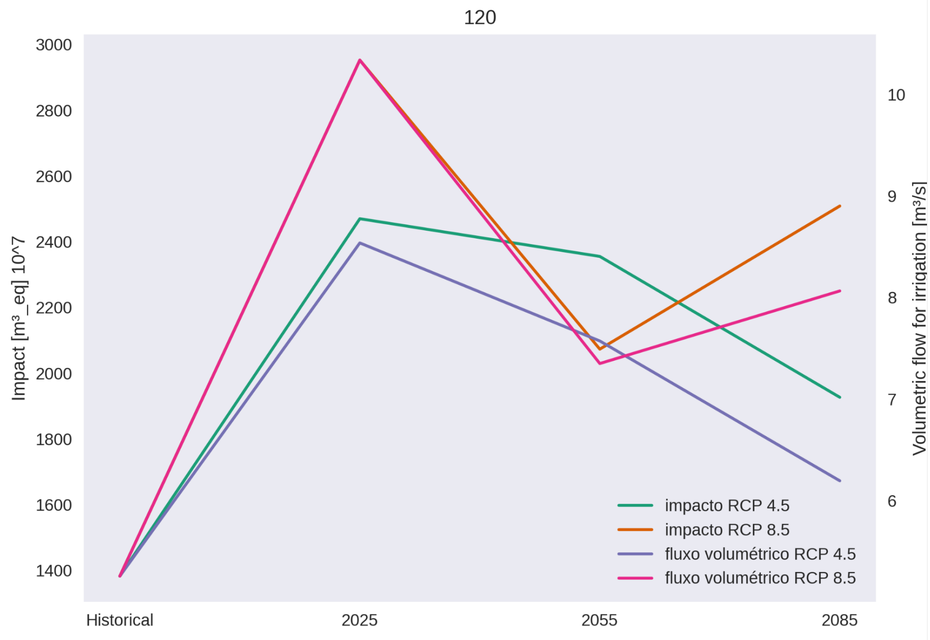
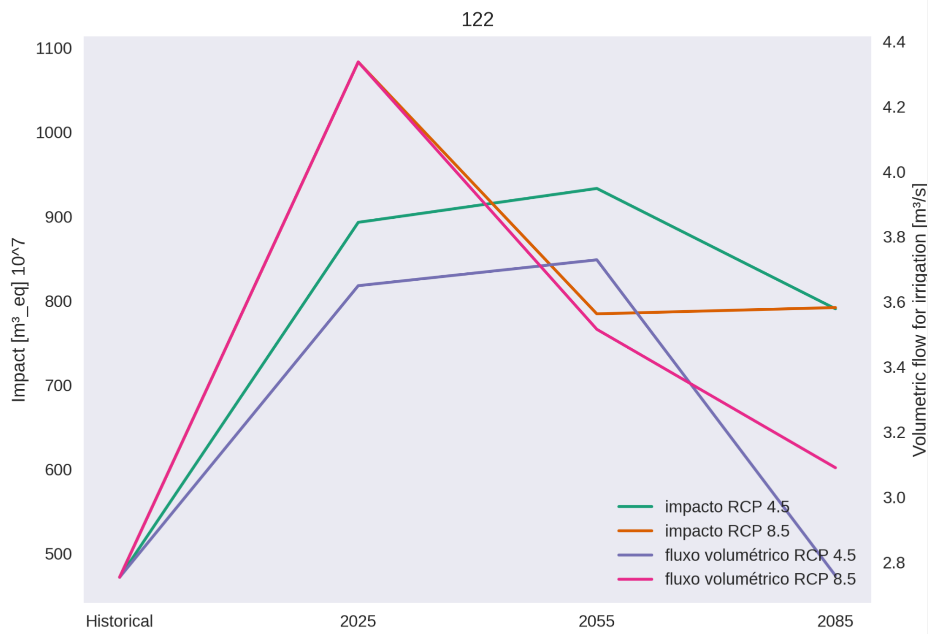
<tr>
<td>Goiana - PE (high impact in all scenarios and periods)</td>
<td>Sugarcane (100.00%)


Source: Own elaboration (2021)</td>
</tr>
<tr>
<td>Mirim - São Gonçalo - RS (high impact in all scenarios and periods)</td>
<td>Rice (100.00%)</td>
</tr>
</table>



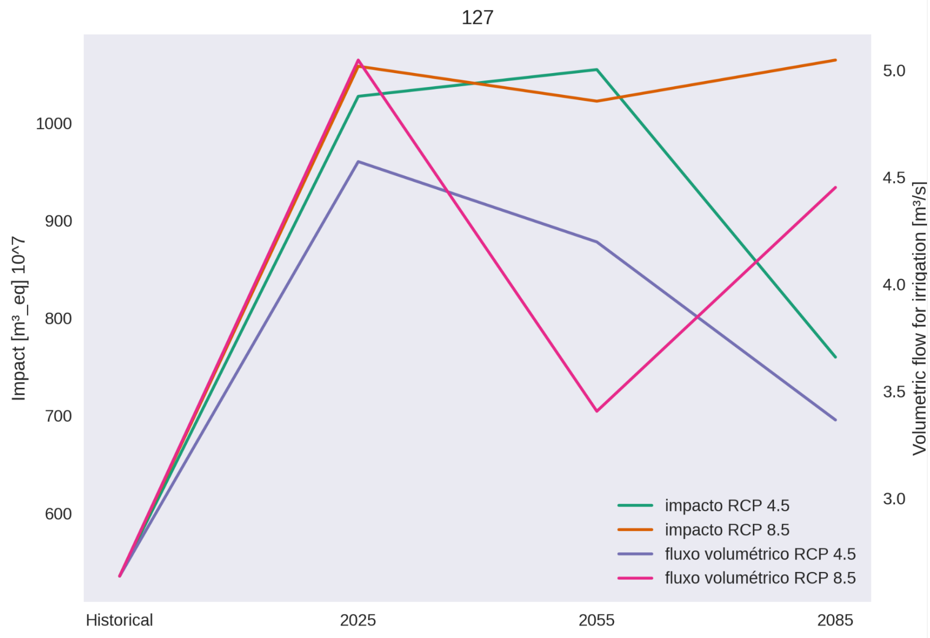
Source: Own elaboration (2021)

Vacacaí - Vacacaí Mirim - RS (high impact in all scenarios and periods)	Rice (100.00%)



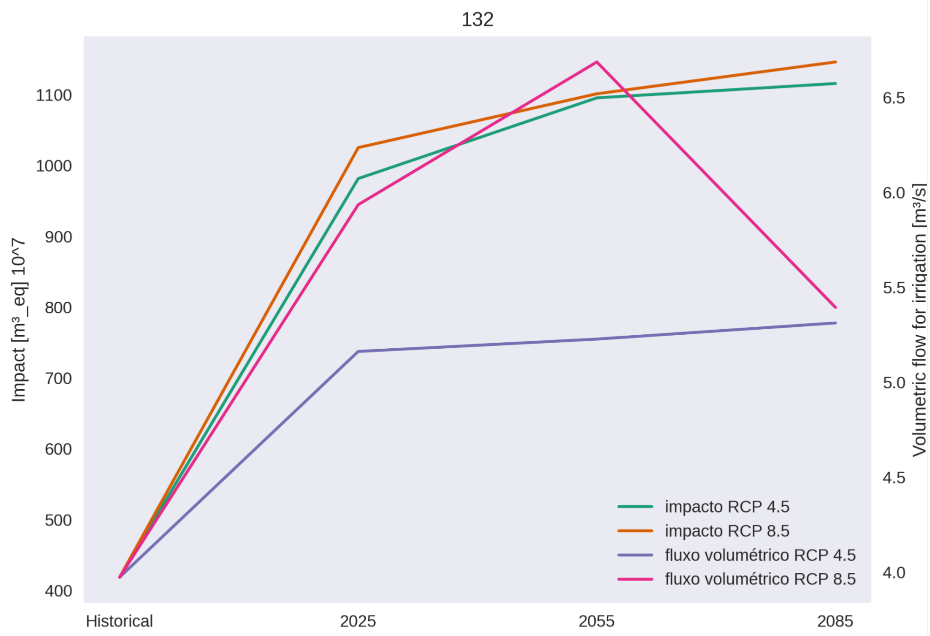
Source: Own elaboration (2021)

Butuí - Icamaquã - RS (high impact in all scenarios and periods)	Rice (100.00%)



Source: Own elaboration (2021)

Camaquã - RS (high impact in all scenarios and periods)	Rice (100.00%)



Source: Own elaboration (2021)

Central Coast - RS (high impact in all scenarios and periods)	Rice (100.00%)

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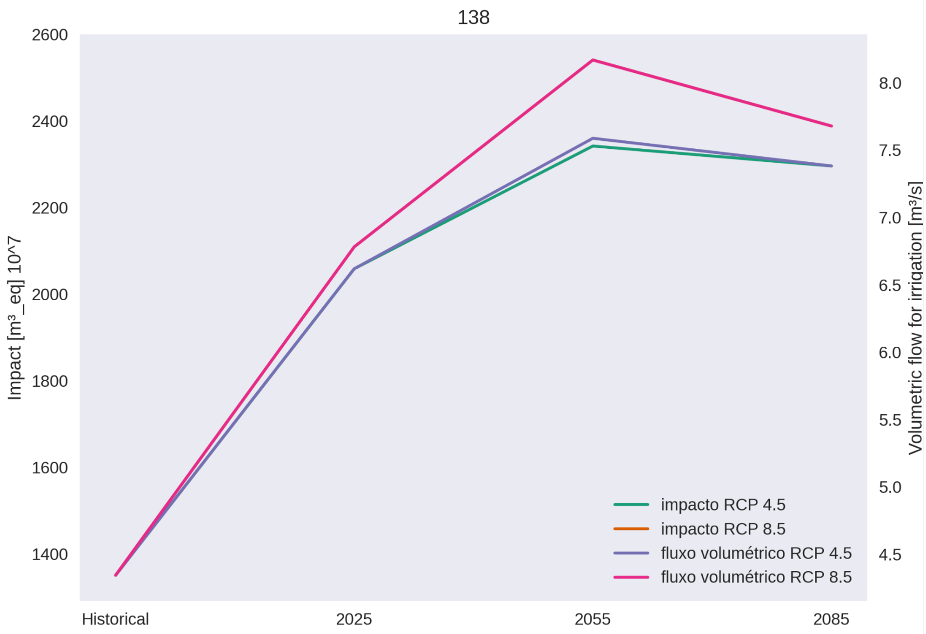

Source: Own elaboration (2021)
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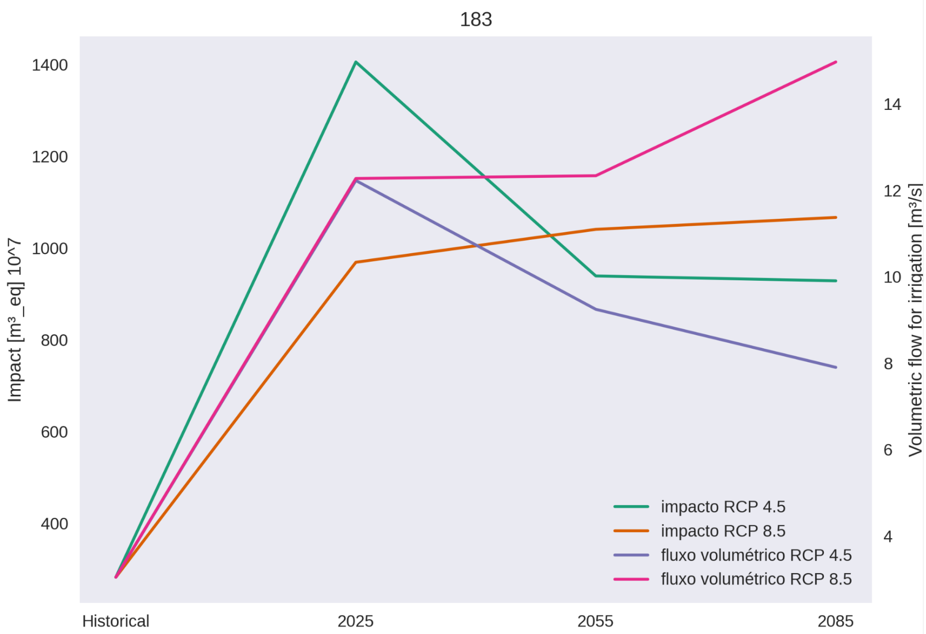
<tr>
<td>São José dos Dourados - SP (high impact in all scenarios and periods)</td>
<td>
Sugarcane (99.85%)


Source: Own elaboration (2021)
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<tr>
<td>Macururé and Curaçá - BA (high impact in all scenarios and periods)</td>
<td>Sugarcane (99.31%)</td>
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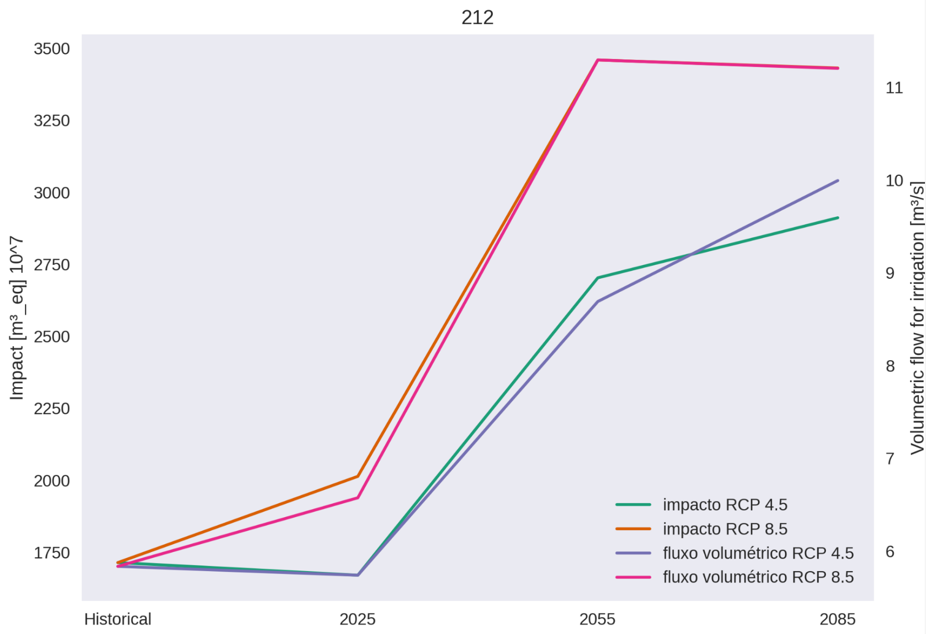

Source: Own elaboration (2021)
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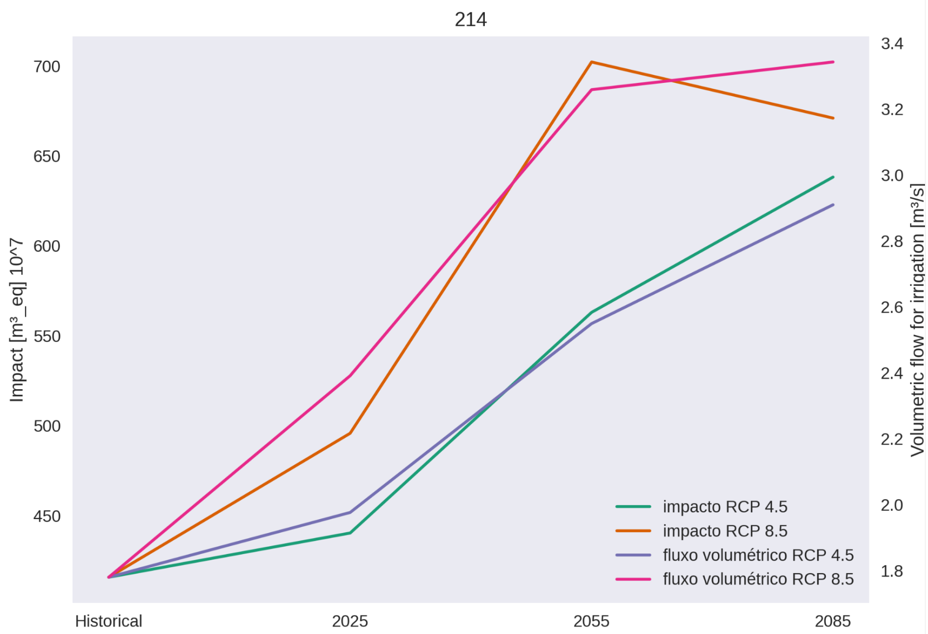
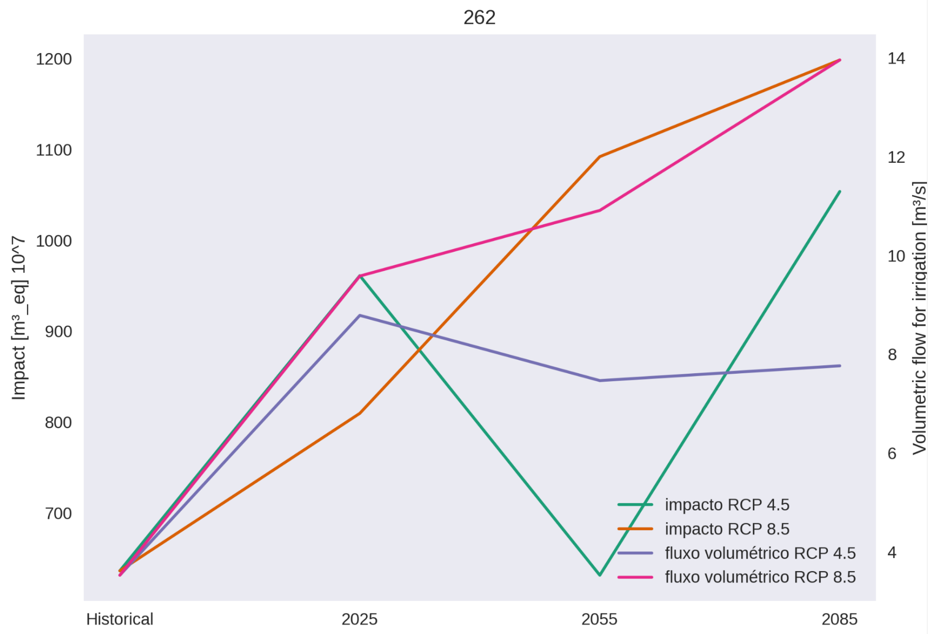
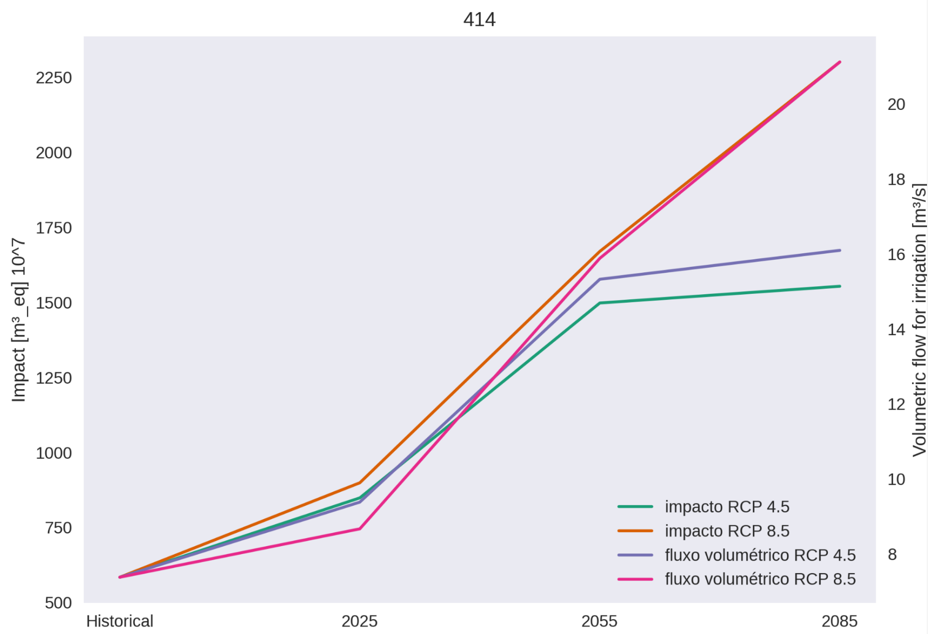
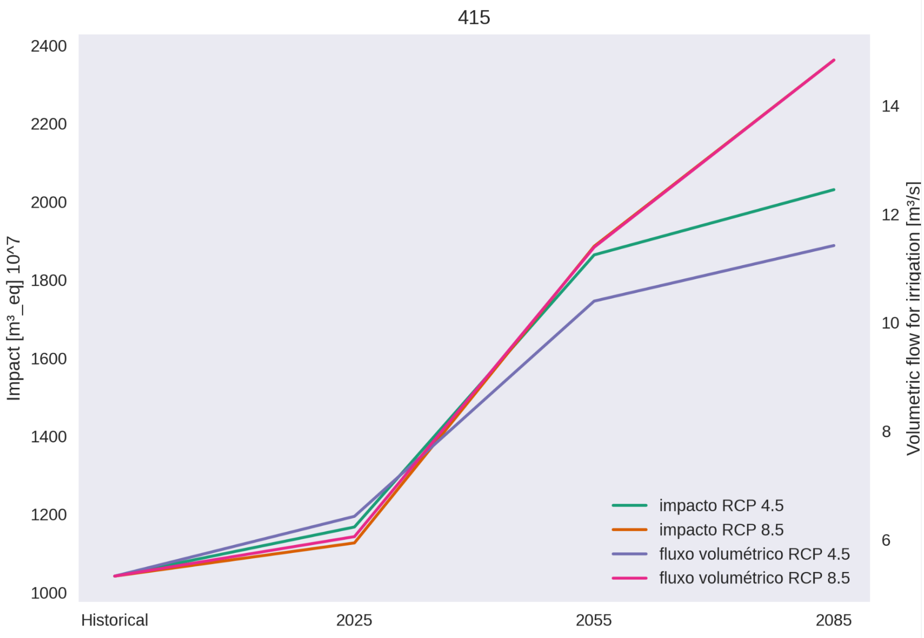
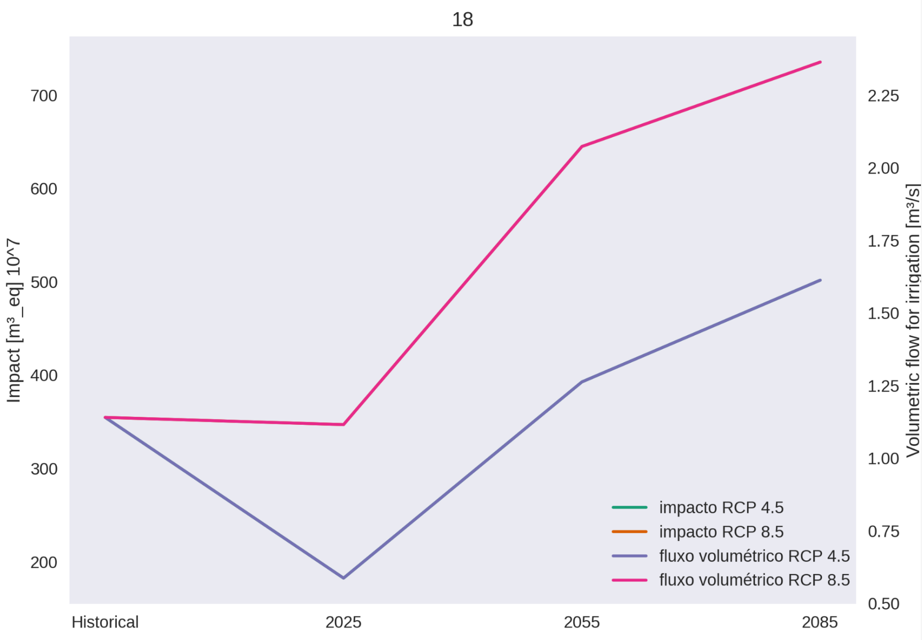
<td>Paraguaçu - BA
(high impact in all scenarios and periods)</td>
<td>
Coffee (71.73%) and Central pivot (27.06%)



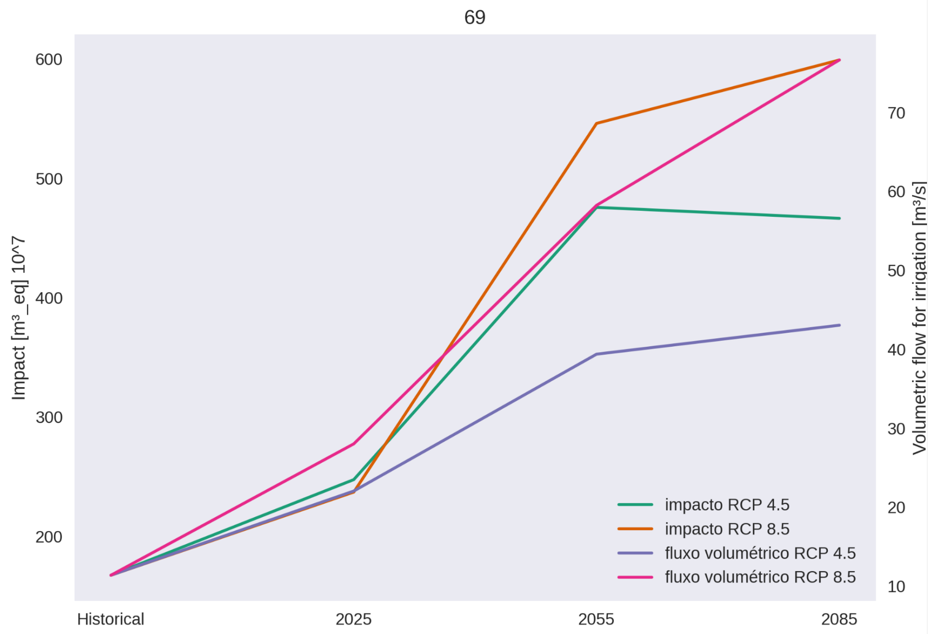
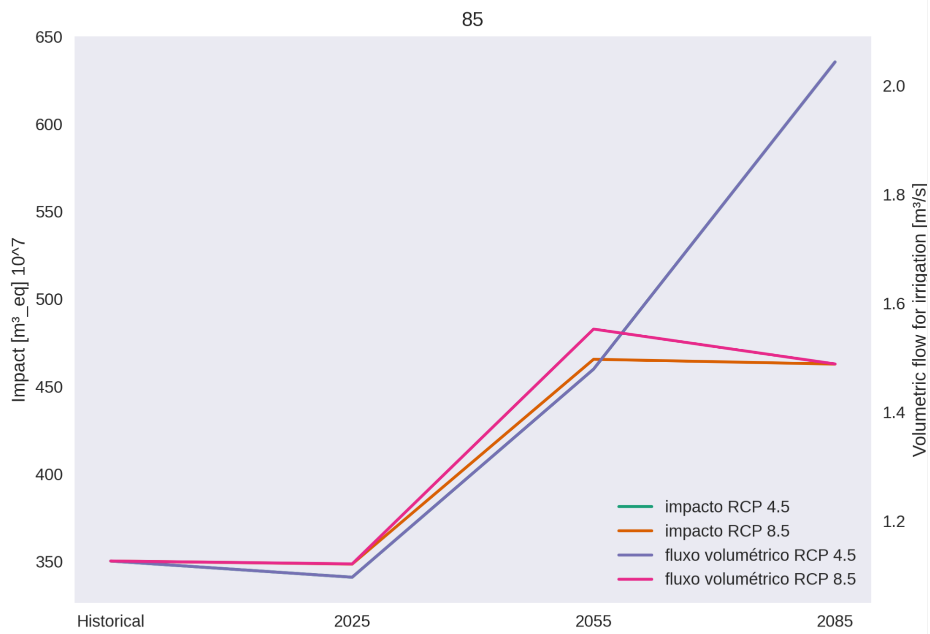
Source: Own elaboration (2021)
</td>
</tr>
<tr>
<td>Meia Ponte - GO
(high impact in all scenarios and periods)</td>
<td>Sugarcane (95.01%)</td>
</tr>
</table>

	 **Source: Own elaboration (2021)**
AEG 02 - TO (high impact in all scenarios and periods)	Rice (99.74%)
	 **Source: Own elaboration (2021)**
AEG 01 - TO (high impact in all scenarios and periods)	Rice (99.57%)

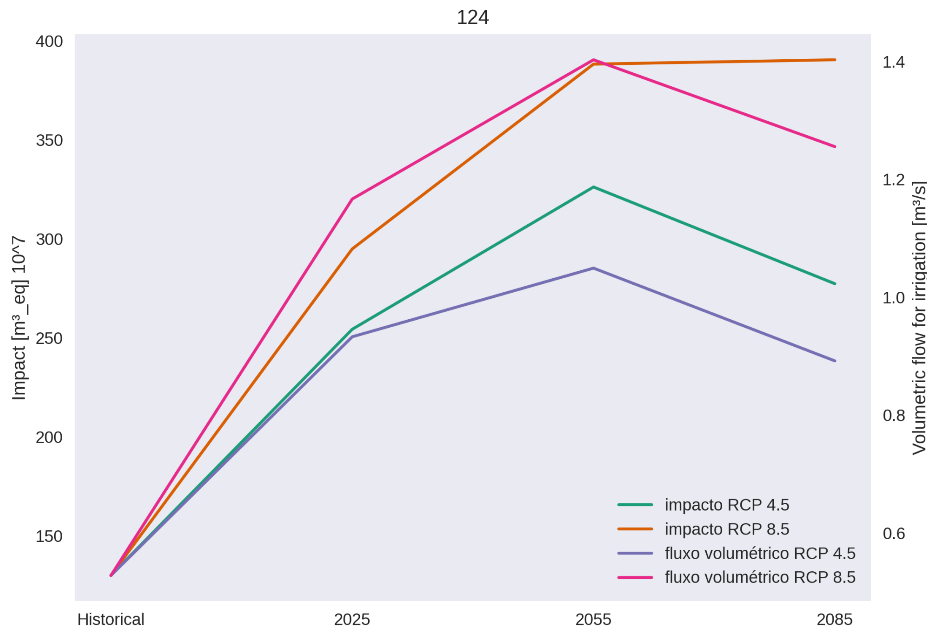
<table>
<tr><td></td><td>

Source: Own elaboration (2021)</td></tr>
<tr><td rowspan="2">CELMM - AL (periods 2055 and 2085 RCP 8.5)</td><td>Sugarcane (99.99%)</td></tr>
<tr><td>

Source: Own elaboration (2021)</td></tr>
<tr><td>Paracatu River - MG (periods 2055 and 2085 RCP 8.5)</td><td>Sugarcane (75.97%) and Coffee (17.73%)</td></tr>
</table>

	 **Source: Own elaboration (2021)**
Paraíba PB - PB (period 2085 RCP 4.5)	Sugarcane (99.25%)  **Source: Own elaboration (2021)**
GL1 - PE (periods 2055 to 2085 RCP 8.5 and 2085 RCP 4.5)	Sugarcane (100.00%)

<table>
<tr><td></td><td>


Source: Own elaboration (2021)
</td></tr>
<tr><td rowspan="2">Gravataí - RS (periods 2055 and 2085 RCP 8.5)</td><td>Rice (100.00%)</td></tr>
<tr><td>


Source: Own elaboration (2021)
</td></tr>
<tr><td>Araranguá - SC (period 2025 and 2055 RCP 8.5)</td><td>Rice (100.00%)</td></tr>
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<tr>
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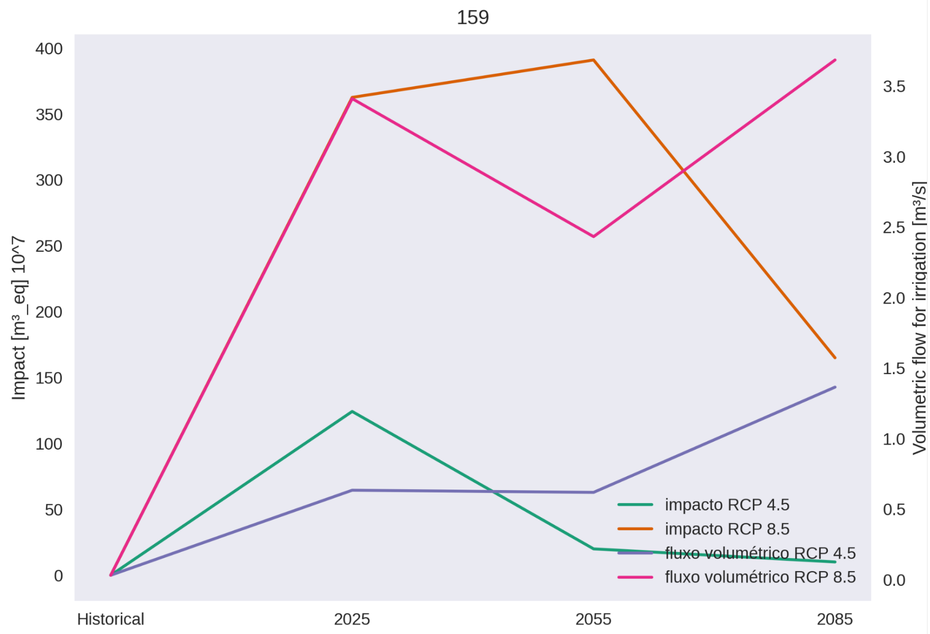
<td>

Source: Own elaboration (2021)</td>
</tr>
<tr>
<td>Mogi-Guaçú - SP
(period 2025 RCP4.5)</td>
<td>Sugarcane (100.00%)


Source: Own elaboration (2021)</td>
</tr>
<tr>
<td>Salitre - BA
(periods 2025 and 2055 RCP 8.5)</td>
<td>Sugarcane (98.89%)</td>
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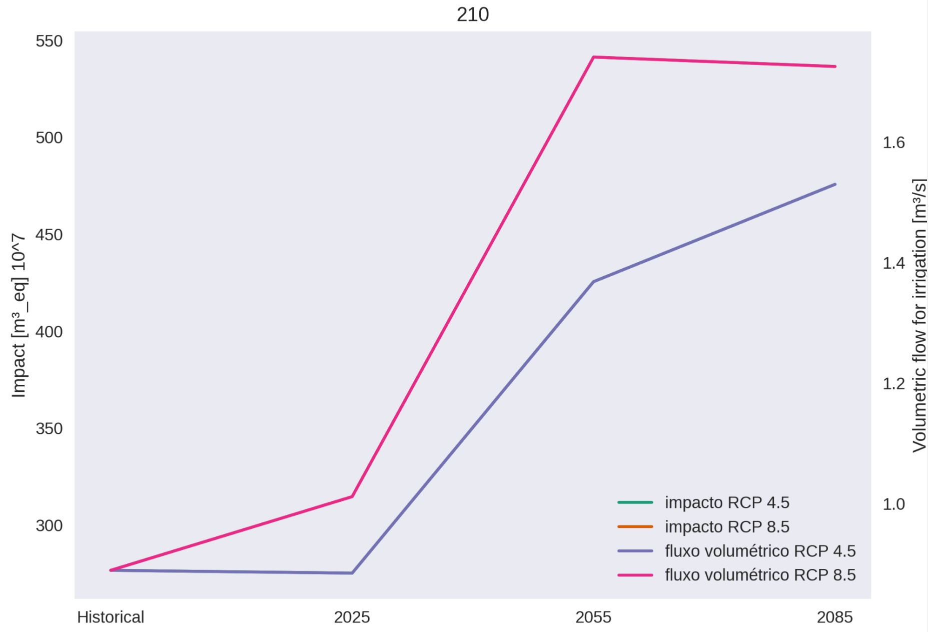
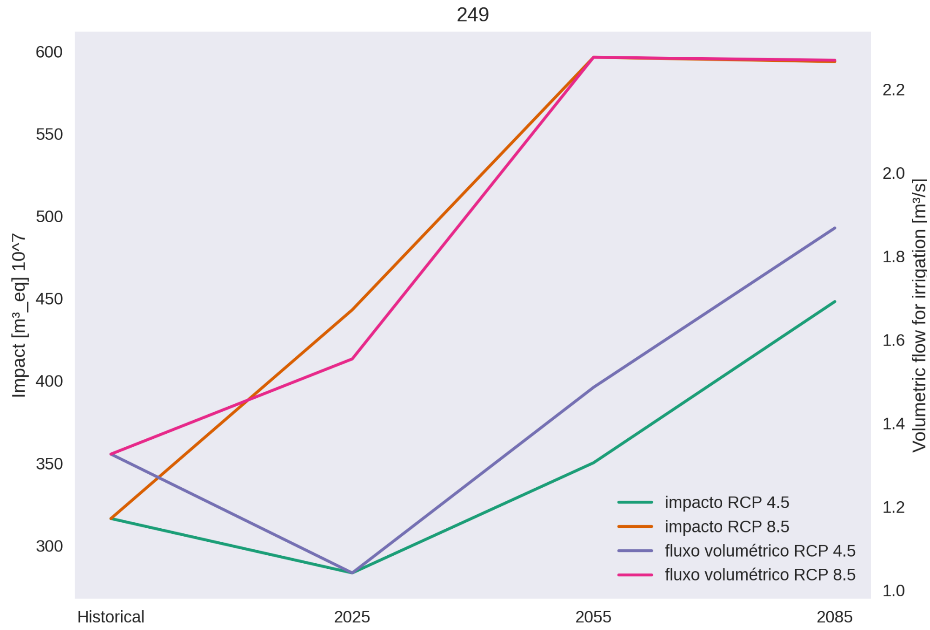
<tr><td></td><td>

Source: Own elaboration (2021)</td></tr>
<tr><td rowspan="2">Japaratuba - SE (periods 2025 and 2055 RCP 8.5)</td><td>Sugarcane (100.00%)</td></tr>
<tr><td>

Source: Own elaboration (2021)</td></tr>
<tr><td>Sergipe - SE (periods 2025 to 2085 RCP 8.5 and 2085 RCP 4.5)</td><td>Sugarcane (100.00%)</td></tr>
</table>

Source: Own elaboration (2021)

Source: Own elaboration (2021)