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Review

Evaluation of Brazilian irrigated agriculture: what to expect?

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Ensuring food security is a significant challenge facing our society today. The goal of irrigation management is to enhance food production within the existing agricultural areas while considering environmental sustainability. In Brazil, the high demand for irrigation, coupled with various technologies employed in food production, necessitates a comprehensive understanding of the historical context and technical feasibility. Irresponsible adoption of irrigation practices may escalate the risk of water scarcity and conflicts over water use. Despite substantial growth in Brazil's irrigated area over the past two decades, irrigated agriculture remains vulnerable to factors such as climate change and land cover, particularly in regions like the Cerrado and the Amazon. These vulnerabilities can directly impact rainfall patterns, consequently affecting the surface availability of water resources. It is crucial to address these challenges responsibly to ensure sustainable food production and mitigate potential environmental risks.

Key words: Irrigation, water, land use, natural resources, Brazil.

INTRODUCTION

Water, being a vital natural resource with economic value, can serve as a limiting factor in agricultural production within a region, as both excess and deficit directly impact crop development. To overcome dependence on rainfall and secure food supply, irrigation has emerged as a crucial tool in the production process, holding economic and social significance. According to EMBRAPA (2017), irrigated agriculture demonstrates 3 to 3.5 times higher productivity compared to rainfed agriculture. It not only enhances product quality, reduces unit costs, and mitigates climate impacts but also optimizes inputs and ensures regular production. This dynamic activity has witnessed steady growth, particularly intensifying between 2012 and 2019 due to increased credit and private investment in the sector. Approximately 12% of Brazil's entire cultivated area, totaling 8.2 million ha, is currently irrigated out of a potential irrigated area of around 29 million hectares (ANA, 2015). When considering additional irrigable areas, this total could reach 55.85 million hectares, with rainfed areas

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accounting for 26.69 million hectares, pasture areas for 26.73 million hectares, and agricultural areas with groundwater availability for 2.43 million hectares (ANA, 2021). The demand for water for irrigation in Brazil, excluding net evaporation in artificial reservoirs, constitutes about 52% of the total flow withdrawn, surpassing urban supply (23.8%), industrial use (9.1%), and livestock (8%) (ANA, 2019). This demand, along with other technologies in food production, contributes to the growth of Brazilian agricultural production, necessitating a comprehensive understanding, particularly with regard to the sustainability of natural resources.

Although Brazil possesses 14% of the world's drinking water, the irrigated area remains significantly lower than countries like India (76 million ha), China (70 million ha), and the United States (26.7 million hectares). The primary challenge in expanding irrigation use lies in balancing water security with food and energy security. According to ANA (2019), demand is projected to increase by over 24% by 2030, heightening conflicts over the use of this natural resource in agriculture.

In this context, water availability is significantly influenced by climatic conditions, wherein variables such as temperature rise can enhance the air's water vapor retention capacity. Consequently, this scenario leads to an increased demand for plant evapotranspiration, directly impacting water consumption for irrigation and potentially affecting future water availability for various uses within a river basin.

From an environmental standpoint, the frequency of extreme events has risen, directly reducing water availability and leading to rationing, as observed in the Cantareira region in São Paulo in 2015 (Coutinho et al., 2015), the upper Iguaçu River region in Paraná in 2020 (Diniz et al., 2021), and posing challenges to the rice harvest in the state of Rio Grande do Sul in 2020 (Fernandes et al., 2021).

Invariably, the heightened demand for water for public supply during water crises exerts pressure on government agencies to restrict water use for irrigation purposes (Neto et al., 2014). Additionally, alterations in the hydrological regime of rivers, particularly in their capacity for regulation, directly impact the granting policy established for the current climate, especially in the Brazilian semi-arid region (Valverde and Marengo, 2014). While irrigation practices contribute to food security and foreign exchange for the country, they also present conflicts with other issues, such as climate, environmental concerns, and regulatory policies. These conflicts may potentially reduce or render the adoption and expansion of irrigation unfeasible due to anticipated changes in future water availability. Therefore, this study, approached from a historical perspective, aims to comprehend how irrigated agriculture can contribute to water resource conservation and income generation amidst ongoing shifts in land use and the forecasted climate changes in Brazil.

EVOLUTION AND CURRENT IRRIGATED AREA IN BRAZIL

According to Morais (2019), the inception of irrigation projects in Brazil dates back to 1881 when the first initiatives were undertaken for rice production in Rio Grande do Sul. Subsequently, in 1903, this practice was expanded to coffee plantations in the southeast region (MIN, 2008). From the 1960s onward, despite 57.2% of the irrigated area (462,000 ha) being concentrated in the state of Rio Grande do Sul, new irrigation hubs emerged and consolidated in São Paulo, Minas Gerais, Bahia, and Santa Catarina, collectively accounting for 32% of the irrigated area (Carvalho et al., 2020).

The intensification of irrigation in Brazil gained momentum in the 1970s, driven by the correction of soil acidity in the Cerrado region, enabling its agricultural exploitation. This expansion was supported by significant government initiatives, including the establishment of the Executive Irrigation Group for Agricultural Development (GEIDA) in 1968, the Multiannual Irrigation Program in 1969, the National Integration Program in 1970, the National Program for the Rational Use of Irrigable Floodplains (PROVÁRZEAS) in 1981, the Irrigation Equipment Financing Program (PROFIR) in 1982, the National Irrigation Program (PRONI) in 1986, and the Northeast Irrigation Program (PROINE) in 1986. In the Midwest, the PRODECER program (Japanese-Brazilian Cooperation Program for the Development of the Cerrados), established through an agreement signed in 1974 and implemented from 1979 onwards, played a crucial role in facilitating the arrival of irrigation (ANA, 2017). Despite initial challenges such as limited technical, operational, industrial, and financial resources, these programs successfully contributed to the expansion of the irrigated area in the country.

However, after the launch of the National and Northeast irrigation plans in 1986, skepticism arose among the involved entities due to the associated high costs of irrigation systems at the time. This skepticism resulted in barriers that impeded the rapid development of irrigation activities (ANA, 2017).

Following the uncertainty in the previous decade, significant investments were made in research and, notably, in technical qualifications within the irrigation sector from the 1990s onward. This effort facilitated the operation of irrigation systems across diverse soil and climate conditions (Coelho Neto, 2010). Notably, many of these advancements occurred within the framework of the new national water resources policy established by the Water Law (Federal Act No. 9,433/97).

Under this law, water resources were recognized as a public asset, limited, and endowed with economic value. Subsequently, following the enactment of the Water Law, there was a considerable expansion and modernization of Brazilian agriculture. In 2013, this progression led to the introduction of Law No. 12,787 (BRASIL, 2013),

Table 1. Main historical measures of irrigation development in Brazil (adapted from ANA, 2021).

Year	Measure
1903	Operation of the Cadro reservoir for rice irrigation in Rio Grande do Sul
1909	Creation of the Drought Works Inspectorate
1934	Approval of the Water Code by Federal Decree No. 24,643/1934
1940	Creation of the Rio Grande do Sul Rice Institute
1945	Creation of the National Department for Works Against Droughts (DNOCS)
1948	Creation of the São Francisco Valley Commission (now CODEVASF)
1959	Creation of the Superintendence for the Development of the Northeast (SUDENE)
1969	Creation of the Multiannual Irrigation Program
1979	Enactment of Federal Law No. 6,662, which instituted the National Irrigation Policy
1979	Japanese-Brazilian Cooperation Program
1981	National Program for the Rational Use of Irrigable Floodplains
1982	Irrigation Equipment Financing Program
1986	National Irrigation Program and Northeast Irrigation Program
1997	Water Law (Federal Law No. 9,433/1997)
2000	Creation of the National Water Agency
2008	Permanent Forum for the Development of Irrigated Agriculture
2013	National Irrigation Policy (Federal Law No. 12,787/2013)

which established the national irrigation policy (NIP) along with the necessary mechanisms for its responsible implementation, avoiding harm to the environment and promoting the sustainable development of the agricultural sector. The primary objective of the NIP was the rational use of water and soil resources for the implementation and development of irrigated agriculture, guided by key principles, including: (i) the pre-eminence of the social function and public utility of the use of water and irrigable soils; (ii) encouragement and increased security for agricultural activities, particularly in regions prone to adverse climatic conditions; (iii) the promotion of conditions that can enhance agricultural production and productivity; and (iv) the primary or supplementary role of public authorities in the planning, funding, execution, operation, inspection, and monitoring of irrigation projects (Reis et al., 2012).

In conjunction with the national irrigation policy, water resource management bodies were established at the federal and state levels to provide guidance for the rational use of this resource, as outlined in Table 1.

While the majority of Brazil's agriculture relies on rainfed practices, the impact of measures adopted in recent decades is evident in the continual expansion of irrigated areas to fulfill the demand for both annual and perennial crops. Table 2 illustrates the progression of irrigated areas in hectares from the 1950s to 2022, emphasizing a noteworthy increase between 2020 and 2022. This period was marked by a deceleration in the national economy (ME, 2020) due to the global pandemic caused by the Coronavirus (COVID-19).

The Southeast region is the most active in terms of irrigation, followed by the South and Midwest, while the Northeast has experienced a decline in its irrigated area. Table 3 presents the irrigated areas per Brazilian region in hectares.

In 2022, of the total irrigated area, 2.9 million ha (35.5%) were irrigated with fertigation using reused water, and 5.3 million ha were irrigated with spring water (ANA, 2022). Within the 5.3 million ha irrigated with spring water, 25% were allocated for rice cultivation, 15% for sugar cane, 8% for coffee, 27% for annual crops irrigated by center pivots (such as soybeans, corn, wheat, and cotton), and 25% for other crops (including beans, sunflowers, millet, sorghum, potatoes, and grapes), as well as other irrigation systems (FAO, 2020).

Despite a significant potential for expanding irrigation areas, only 21% of the currently anthropized area with agriculture and pastures can be irrigated due to limitations in available water from local springs, primarily concentrated in the Midwest, South, and Southeast regions. This practically sets an expansion limit of 13.96 million ha (ANA, 2021). The constraint on water availability can be attributed to climate change, coupled with the occupation of recharge areas and silting processes in water bodies. Consequently, the risk of scarcity is expected to increase due to reduced precipitation and heightened evapotranspiration, particularly in semi-arid regions. This impact will affect not only public supply and electricity generation but also irrigated agriculture itself (Valverde and Marengo, 2014). Table 4 displays the additional irrigated areas by region.

Furthermore, as outlined by Sparovek et al. (2015), 2.2 million hectares (27%) are situated in areas where expansion is deemed impossible without causing environmental impacts. These areas are located in close proximity to large urban centers and cover a significant portion of the northeastern hinterland. The effective

Table 2. Irrigated area in Brazil from 1950-2022, adapted from ABIMAQ (2022), Carvalho et al. (2020) and ANA (2022).

Year	Irrigated area (ha)	Year	Irrigated area (ha)
1950	64,000	1990	2,700,000
1955	141,000	1995	3,121,644
1960	320,000	2000	3,703,981
1965	545,000	2005	4,338,991
1970	796,000	2010	4,972,091
1975	1,100,000	2015	6,039,838
1980	1,600,000	2020	6,481,812
1985	2,100,000	2022	8,195,391

Table 3. Irrigated area (ha) according to each region from 2006 to 2021. (ANA, 2022).

Region	2022		2015		2006	
	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
North	321,903	3.93	205,654	3.40	107,789	2.42
Northeast	1,181,036	14.41	1,492,901	24.72	985,348	22.12
Midwest	1,261,530	15.39	863,562	14.30	549,466	12.34
Southeast	3,862,243	47.13	2,197,829	36.39	1,586,744	35.63
South	1,568,678	19.14	1,279,892	21.19	1,224,578	27.49
Total	8,195,390	100	6,039,838	100	4,453,925	100

Table 4. Additional irrigable area for agricultural uses in Brazil (Sparovek et al., 2015).

Region	Soil and relief aptitude			Total	%
	High	Medium	Low		
North	2,059,173	3,818,623	5,148,649	11,026,445	18.0
Northeast	1,743,102	3,176,922	3,181,048	8,101,072	13.2
Midwest	8,917,466	6,555,926	3,937,393	19,410,785	31.6
Southeast	3,425,917	3,794,523	6,887,616	14,108,056	23.0
South	2,281,044	2,303,516	4,126,770	8,711,330	14.2
Total	18,426,702	19,649,510	23,281,476	61,357,688	100.0

potential, providing a more precise understanding of the short- and medium-term capabilities of the Brazilian territory, encompasses areas suitable for the intensification of rainfed agriculture with medium or high soil suitability. Notably, the current sugarcane areas with a climatic water deficit exceeding 400 mm/year are excluded from this potential (ANA, 2021).

PLUVIOMETRIC REGIME

Precipitation serves as the primary indicator of water availability in an ecosystem and is closely linked to crop productivity (Ananias et al., 2021) and the regularity of the hydrological cycle essential for maintaining watercourse flows. Conversely, precipitation is influenced by the dynamics of air masses, vertical and horizontal energy flows, and any alterations in the climate system can impact critical sectors such as water resource availability and agriculture (Santos et al., 2020).

In Brazil, the rainfall regime exhibits significant spatial variability and distinct seasonality, especially in the Northeast, Southeast, and Midwest regions, characterized by a predominant rainy season (primarily in summer) and a dry season (Correa and Galvani, 2017). The North and South regions experience a more evenly distributed rainfall throughout the year, with the North region influenced by a low atmospheric pressure system due to the intertropical convergence zone, and the South impacted by the South Atlantic convergence zone, polar

Table 5. Mean annual rainfall in Brazil by region.

Region	Sub-region	Annual average precipitation (mm)
North	West	2.450
	Northwest	3.000
	Central	2.500
	South	1.750
	North	2.000
Northwest	Northeast	1.500
	Agreste	900
	Semiarid	650
	Arid	500
	Mid-north	1.200
Midwest	Upper North	2.200
	North	2.100
	Mid-north	1.500
	East	1.600
	South	1.300
Southeast	South coast	1.500
	Norh coast	1.200
	North	800
	Central	1.400
	West	1.600
South	Western South	2.100
	South	1.800
	South coast	1.500
	Central coast	1.800
	Northeast coast	2.200

masses, convective systems, and the sea (Nery, 2005).

These seasonal and spatial variabilities underscore the necessity of irrigation, particularly in locations experiencing drier climatic conditions (Cline, 2007), where the demand for water is contingent not only on rising temperatures but also on precipitation rates (Cunha et al., 2014).

The Northeastern region of Brazil is particularly vulnerable to climate variability extremes and climate change impacts (Marengo et al., 2022; Marengo et al., 2020; Alvala et al., 2017). This vulnerability stems from the combination of high spatial and temporal rainfall variability, along with social issues such as poverty. According to Marengo et al. (2022), the average annual rainfall in the northeastern semi-arid region is below 650 mm, with the rainy season peaking between February and May, influenced by the trade winds converging from the Atlantic and the Intertropical Convergence Zone (ITCZ). Table 5 illustrates the spatial variability of average annual rainfall in different sub-regions of Brazil.

In recent decades, Brazil has faced extreme rainfall events across various time scales, including droughts in 2005, 2010, 2015, 2016, and 2020, floods in 2009, 2013, and 2014 in the Amazon, drought in the Northeast from 2012 to 2017, and a severe water crisis in the city of São Paulo between 2014 and 2015 (Alves et al., 2020).

The alteration in precipitation variability due to climate change is a critical issue with significant impacts on society and the environment. It directly affects biodiversity, agriculture, and, most importantly, water resources by reducing river flows. This has a direct repercussion on irrigation programs and overall agricultural production, given the vulnerability indicated by future projections (Alves et al., 2020).

The Intergovernmental Panel on Climate Change (IPCC, 2014) report revealed a significant increase in air temperatures near the surface in recent decades. Subsequent climate change analyses consistently indicate that agriculture is one of the most vulnerable sectors. Climate projections specific to Brazil, as estimated by Santos et al. (2020), suggest increased maximum and minimum air temperatures near the surface for all regions, especially in heat extremes, particularly in the North. Additionally, heavy rainfall is projected in the South and Southeast. Concerning the likelihood of drought and rainfall deficits, the study indicates higher susceptibility for the North and Northeast regions, necessitating irrigation to compensate for the deficit caused by evapotranspiration in the water balance, particularly in the Northeast region (Paulino et al., 2019).

According to studies by ANA (2016), Nóbrega et al. (2011), Tomasella et al. (2009), and Campos and Néris (2009), climate change impacts are projected to vary across regions, with the central Northeast experiencing intensified aridity and the southern Amazon potentially transitioning from a humid tropical climate to a sub-humid tropical climate.

In their analysis of climate change projections related to precipitation and temperature, Silva et al. (2020b) assessed nine models participating in CORDEX, all of which projected an increase in temperature across all Brazilian regions. Under the RCP8.5 scenario, the temperature anomaly indicated an increase of up to 1.58°C in the Amazon basin hydrographic region, accompanied by precipitation increases ranging between 10 and 30% in the East Atlantic, West Northeast Atlantic, East Northeast Atlantic, Paraguay, Parnaíba, Tocantins-Araguaia, and São Francisco hydrographic basins. However, other projections suggest a decrease in rainfall in the Southeast, particularly in the states of Rio de Janeiro and Espírito Santo. Simultaneously, there has been an average increase in both water volume and the average number of rainy days in the state of São Paulo (Zilli et al., 2016).

Contrarily, Bevacqua et al. (2021) and Chagas et al. (2020) observed the most frequent changes between 1980 and 2015 in the duration of rainless periods, particularly in the Southeast and the Cerrado biome region, witnessing substantial reductions in average rainfall and increases in the duration of rainless periods. From a similar standpoint, Santos et al. (2020) identified a negative trend at a rate of 5 mm/decade, notably in the states of Minas Gerais and Goiás from 1980 to 2018. Consequently, based on this observed downward trend, it becomes crucial to assess future water demand considering all users, as the increasing number of rainless days may lead to a decline in surface water availability. This situation could become even more critical when factoring in the effects of deforestation and changes in land use, contributing to heightened tensions among users and constraining the expansion of irrigated agriculture.

WATER USE CONFLICTS

Conflict over the use of water resources involves competition among agriculture, energy production, and public supply, exacerbating vulnerability resulting from water scarcity due to the lack of interconnected management in these sectors (Siqueira et al., 2021). As an illustration of these conflicts, certain Brazilian regions have witnessed reductions in water availability, leading to competition among multiple users for the resource (Gesualdo et al., 2019; Sun et al., 2016). This has resulted in diminishing flows and escalating demand, particularly for food production and urban supply in the São Francisco River basin (Lucas et al., 2021).

Another contributing factor to the escalation of conflicts over water use, especially in future scenarios, is deforestation, particularly in the Amazon region. The expansion of agricultural areas in Brazil, often associated with deforestation and land use changes, poses concerns due to its impact on the moisture cycle and energy balance, irreversibly altering the regional climate more intensely than global warming (Rattis et al., 2021; Lathuillière et al., 2016; Dobrovolski and Rattis, 2015; Leite-Filho et al., 2019). According to Sena et al. (2013), the estimated impact on the annual radiative balance due to changes in surface albedo is approximately six times greater than greenhouse gas emissions.

Agricultural expansion through deforestation and land use change is identified as the main source of greenhouse gas emissions (Edenhofer et al., 2014), and it also has significant impacts on biodiversity and ecosystem services. Therefore, any strategy aiming to intensify agriculture, reduce deforestation, and enhance productivity must consider the practice of irrigation. Figure 1 depicts the annual rate of deforestation in the Brazilian Legal Amazon, encompassing the states of Roraima, Amazonas, Acre, Rondônia, Amapá, Pará, Maranhão, Tocantins, and Mato Grosso.

The conversion of forests to pasture or agriculture results in areas with low biomass, converting the radiation balance primarily into sensible heat that heats the air (Fausto et al., 2016). This increase in sensible heat contributes to an elevated evapotranspirative demand, overburdening water systems and directly impacting irrigation programs. Deforestation in both the Amazon and the Cerrado regions extends the dry season, potentially by 5 to 6 months, disrupting the biosphere-atmosphere balance (Costa and Pires, 2010). This alteration in the dry season has direct consequences on water demand for irrigation by reducing watercourse flows. Leite-Filho et al. (2021) highlight that widespread deforestation in the Amazon region leads to reduced rainfall, resulting in both hydrological and economic deficits, with annual losses estimated at up to US$ 1 billion.

Due to its high storage of radiative energy, the Amazon region functions as a low atmospheric pressure zone and much of the available moisture is displaced along the central-southern region, influencing the rainfall regime (Pavão et al., 2017). Replacing natural vegetation cover with pastures and crops alters the aerodynamic and radiative characteristics of the surface, changing the

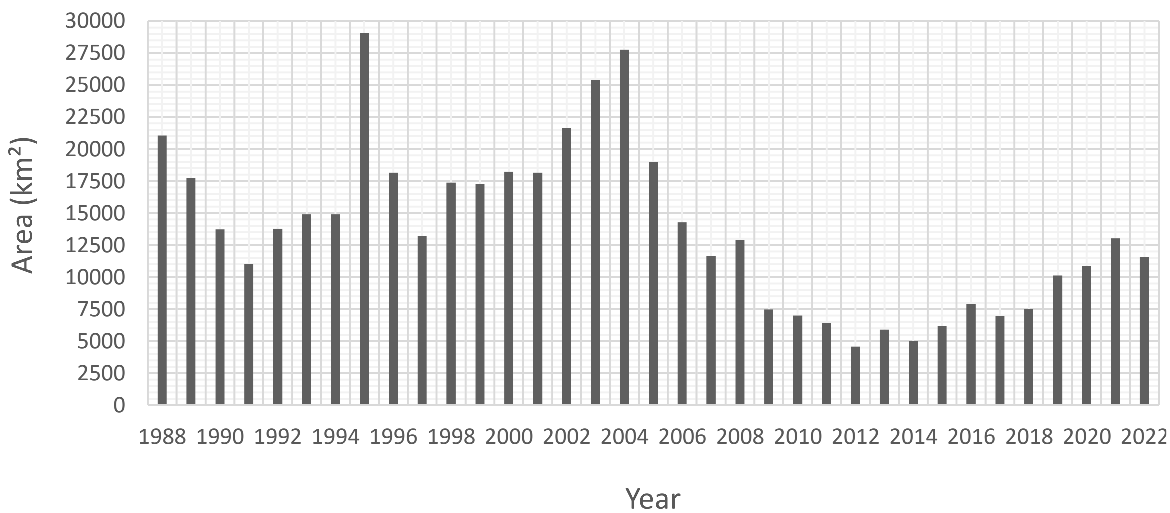

Figure 1. Annual rate of deforestation since 1988 in the Brazilian Legal Amazon.
Source: INPE (2023).

pattern of energy exchange (Biudes et al., 2015) and the thermo-hydro-regulatory effect of the surface. Consequently, there is a reduction in rainfall volume in central-southern Brazil, affecting water availability for irrigation and public and industrial supply.

Beyond concerns about potential decreases in rainfall due to deforestation, the increase in irrigated areas in these deforested regions has the effect of depleting water reserves (Carvalho et al., 2020; Velasco-Muñoz et al., 2018). This contributes to the rise in areas experiencing conflicts over water use, as large irrigation projects can lead to competition for water and energy between farmers and urban areas (Dickinson et al., 1992). Conflicts have already emerged in recently expanded irrigation areas, such as western Bahia (Cohn et al., 2016; Abrahão and Costa, 2018).

Additionally, changes in land use, coupled with the expansion of irrigated areas, can lead to significant reductions in water flow, as observed by Silva et al. (2020a). In their 39-year analysis, the authors found that the evolution of irrigation was the primary factor exerting pressure on water resources. While there was no downward trend in rainfall in the historical series analyzed, anthropogenic changes and climate variability can contribute to decreased watercourse flows (Pirnia et al., 2019).

Siqueira et al. (2021) suggest that climate change and changes in land cover and use are expected to worsen the interaction between water security and economic and social development. This is evident in the intensification of droughts in the Northeast region due to reductions in precipitation (Almagro et al., 2020), as well as reductions in additional rainfall in the Southeast and Midwest regions due to deforestation in the Amazon (Zemp et al., 2017). The mismanagement of water resources has further exacerbated the situation, creating a predicament for various water stress scenarios and fostering increased conflicts over water use (Oliveira et al., 2019).

However, despite the Brazilian government advocating a significant expansion of irrigation as a national priority, it is essential to assess the trade-offs associated with these investments (Costa et al., 2019). The growth of irrigation should not solely rely on increasing water resource usage. Rather, there should be a focus on efficiency gains in existing systems, aiming to use resources with minimal losses and minimal deterioration in water quality (Rodrigues and Domingues, 2017).

According to Bernardo (1997), there are two groups involved in the water use dispute in Brazil: one governmental, concerned with irrigation, hydroelectric power stations, and urban consumption, and the other related to the multiple uses of water by river users. In some basins, after the implementation of various irrigation projects without prior quantification of the available water volume, scarcity has been observed downstream of the catchment points. This has led to the unavailability of water for human, animal, and wildlife consumption, causing environmental impacts and social problems.

Costa et al. (2021) state that the risks of a water crisis and conflicts over water use are linked to the lack of effective governance and the high demand for the resource by different users in the same river basin. According to ANA (2019), the center-pivot irrigation method is the fastest-growing in the country and has the highest concentration of irrigated areas in the Southeast, but with a strong tendency to expand to the Midwest. Guimarães and Landau (2014) and Guimarães et al. (2018) note a concentration of center-pivot irrigated areas in Brazil, with 20% of the irrigated area concentrated in 6 municipalities and another 30% in 15 municipalities. The other half is irrigated in just 45 municipalities (Rodrigues and Domingues, 2017). Given the growing demand for water in other activities and the scarcity of water resources, there is a clear need to rationalize its use. In this case, it is important to understand the water supply, inferred from the difference between precipitation and evapotranspiration (Guimarães and Brandão, 2020), to avoid future conflicts.

Thus, there is a need for effective management of water resources through legal instruments, one of which is the granting of use licenses, reflecting the regulation between water supply and demand, allowing the granting body to restrict the amount to be abstracted (Gomes et al., 2021). On the other hand, the issuing of water use licenses in Brazil continues to be based on different criteria, which can lead to a limited expansion of irrigated agriculture in cases where the criteria are very strict or to environmental risks and water scarcity in cases where the criteria are more lenient (Guimarães and Brandão, 2020).

The most frequently used methods are based on flows Q7.10 (minimum flow with duration of 7 days in a return period of 10 years), Q90, and Q95, determined by the probabilistic distribution of flows based on the frequency with which these percentages are exceeded during the historical series. These differences in the reference flow have a significant impact on water availability. Bezerra et al. (2013) found that using the Q90 criterion would allow water to be withdrawn from the Jamari River in Rondônia seven times more than if the Q7.10 criterion were adopted. Thus, the criteria adopted for granting water use concessions need to be clear and constantly observed due to climate variability and the impact of deforestation on the rainfall regime, which can increase or decrease supply in the short term.

On the other hand, Moreira et al. (2012) showed that, although restrictive, the granting instrument alone was unable to avoid conflicts between the various uses/users in the Rio do Sono Basin in Minas Gerais, due to more grants being issued than allowed, showing a serious technical failure on the part of managers. It should be noted, therefore, that although this is a promising management tool, it is still necessary to qualify the technical staff to avoid unfavorable situations.

Considering the state of Minas Gerais, there are approximately 56 declared areas of conflict over water use, half of which are located in the Triângulo Mineiro region (IGAM, 2020). The declaration of a conflict area (DAC) occurs when a situation of surface water unavailability is confirmed, as measured by the water balance, in a given region, and as a result, the granting process becomes collective and no longer individualized (IGAM, 2010).

According to Peixoto et al. (2022), the number of conflicts over water increased between 2009 and 2019, especially regarding water quality, the expansion of agribusiness in the region known as MATOPIBA (which covers the states of Maranhão, Tocantins, southeastern Piauí, and western Bahia), and the expansion of hydroelectric activity, the latter being intensified in the northern region of the country. According to the authors, how water resources are managed in Brazil does not mitigate or resolve the conflicts arising from the relative scarcity of water since there are no technical and legal means for representative institutions, such as the Basin Committees, to act effectively in the management and handling of water resources (Thomaz Júnior, 2010).

An alternative found to reduce conflicts over the use of water in agriculture was the enactment of Law 12,787/2013, which instituted the National Irrigation Policy (NIP). The objectives of the NIP are to encourage the expansion of irrigated areas, increase productivity on a sustainable basis, and reduce climate risks by complying with environmental licensing requirements and granting water use licenses (Rodrigues and Domingues, 2017), with the main aim of conserving soil and water. Although water governance in Brazil still contributes to the increase in problems related to water scarcity (Souza Júnior et al., 2017), the tools adopted in the NIP, such as environmental licensing, are an important management tool for Public Administration (Cavalcante, 2020), allowing it to exercise the necessary control over activities that interfere with environmental conditions, ensuring the quality of production and maintenance of natural resources based on sustainable development, aiming to minimize the risks of water scarcity (Buainain and Garcia, 2015), and conflicts over water use.

Finally, irrigated agriculture can be considered an important vector of regional development and the most dynamic water-using sector in Brazil (ANA, 2021). If, on the one hand, the growth of irrigation implies greater water consumption, on the other hand, investments in this sector result in a considerable increase in productivity and the value of production. This eases the pressure to incorporate new areas for cultivation, contributing to the preservation of forest resources while guaranteeing food security for the population and production for the agro-industrial sector. In this context, it is important that expansion takes place with water security for the sector itself and for other water uses, with a reduction in conflictive situations based on the improvement of environmental agencies and investments in the preservation and recovery of natural resources.

IRRIGATION AS AN ENVIRONMENTAL STRATEGY

Although rainfed agriculture is responsible for approximately 60% of the world's food production, this system is extremely dependent on climatic conditions and vulnerable to changes in rainfall and temperature patterns (Gornall et al., 2010). The growing demand for food can be met by expanding the planted area or by increasing crop yields (Pradhan et al., 2015). The additional irrigable area represents locations with surface water availability for the adoption of irrigation, distinguishing between areas with the potential to intensify rainfed agriculture through irrigation (intensification) and areas with the potential to expand irrigated agriculture over consolidated pastures (expansion).

However, agricultural expansion through deforestation and land use change is the main source of greenhouse gas emissions (Edenhofer et al., 2014), impacting biodiversity and ecosystem services, and resulting in a decrease in water availability. Thus, the intensification of agriculture associated with the reduction of environmental impacts is an appropriate strategy for increasing food production while contributing to environmental conservation. The severe water crisis in Brazil in 2014/2015 (Marengo et al., 2015) led to serious problems for public supply and losses in agriculture and electricity generation, highlighting the great need for water resource management, especially in irrigated areas. Expanding irrigation in these areas is an effective adaptive measure in response to climate change (Rosa et al., 2018).

According to Zaveri and Lobell (2019), the use of irrigation allows for a secure supply, especially in regions that will be affected by climate change, by mitigating the thermal stress of crops. Thus, the growth of agriculture, especially irrigated agriculture, needs to consider climate risks and the availability of water resources to be sustainable and efficient, in addition to the need for massive investments in the agricultural sector to remedy some effects of these changes (Getirana, 2016).

According to Rattis et al. (2021), despite the clear climate risks for agricultural production, Brazil has adopted a policy of expansion precisely in the most vulnerable regions (Pereira et al., 2012; Marengo and Bernasconi, 2015) because it considers economic criteria that do not consider the effects of climate change and physical-environmental characteristics, providing a certain degree of direction for both the public and private sectors (ANA, 2017). In addition, according to the authors, the current agricultural growth model could lead the country to major production losses in the coming decades, making it necessary to adopt a different agricultural model that is adaptive to these climate issues.

Although there is great growth potential, there is no possibility of increasing water demand in around 27% of the current irrigated area, and a further 33% is in regions outside the priority areas for public intervention. The areas that deserve more significant public intervention and are intended for sustainable regional development represent only 13% of the irrigated area and have an additional irrigable area capacity of 27 million ha (MI, 2014). An analysis of the historical series (Table 2) shows an increase from 3.7 million hectares in 2000 to almost 8.2 million ha irrigated in 2022, corresponding to an increase rate of 121%, with growth of 26% between 2020 and 2022. Contrary to this scenario, Rodrigues and Domingues (2017) showed that, worldwide, there has been a significant reduction in the growth rate of irrigation, associated with various variables, such as long periods of stable production and lower prices, a decline in the population growth rate, as well as the demand for investment in other sectors considered strategic (Faurès et al., 2007).

In assessing the potential implications of agricultural irrigation policy on surface water scarcity in Brazil as a result of law 12.787, Multsch et al. (2020) observed that the expansion of irrigated agriculture is limited by the objectives of the national water policy to restrict water scarcity to acceptable levels. The results indicate that when seeking to intensify production practices, an attempt should be made to consider the likely regional effects on water scarcity levels to achieve sustainable production, especially in the Cerrado region, one of the main water recharge areas (Cambraia Neto and Rodrigues, 2021).

According to Guimarães and Brandão (2020), an area of 10 million ha is expected to be irrigated by 2030, 15 million ha by 2040, and 20 million by 2050, that is, a 2.44-fold increase by 2050. This highlights the need to rationalize the use of water due to the growing demand for its use in other activities, as well as the scarcity of water resources due to the increasing rates of deforestation in the Brazilian Cerrado and Amazon regions (Costa and Pires, 2010).

Among the biggest challenges facing this expansion in terms of irrigated areas are water reservoirs, electricity, water reuse, reducing the bureaucracy of environmental licensing, and licensing. Although these are important factors to be analyzed, the projected growth rate rose from 250,000 ha-year^{-1} in 2020 (ANA, 2021) to 350,000 ha-year^{-1} in 2021 (ABID, 2020), totaling an effective potential of more than 13.7 million ha by 2040. According to ANA (2021), this development mainly covers Cerrado areas, in areas that could be intensified (rainfed agriculture) or expanded (pasture areas), contributing significantly to mitigating problems related to greenhouse gas emissions, as irrigated systems alter the soil's microbial activity and substrate supply (Sapkota et al., 2020).

On the other hand, if this expansion is not properly managed and monitored, it could lead to an adverse outcome, with reduced water availability, conflicts over water use, and greater vulnerability to climate change. Campos et al. (2020) showed that organic carbon levels after 20 years under an irrigation system in sandy soils in Brazil can be re-established to levels observed in native vegetation, with an average sequestration rate of 0.82 tons C•ha^{-1}•year^{-1} more when compared to the rainfed system. Dionizio et al. (2020), when comparing both rainfed and irrigated areas, concluded that the latter have a mitigating potential in soils considered fragile and sandy, being able to sequester carbon and restore lost soil organic carbon levels at a rate of 2.6% per year, in the 0.20m layer. However, it should be emphasized that the results were achieved considering proper soil and water management.

In this way, irrigated agriculture has great potential to mitigate the impacts of climate change, as it does not require the occupation of new areas, reflecting on environmental preservation and the maintenance of biomes. Thus, when evaluating the growth projection for the year 2050, an estimated sequestration of more than 10,000,000 tons C•ha^{-1}•year^{-1} is expected. For the expansion of irrigated agriculture to be sustainable, intensive policies are needed to improve irrigation management, including studies, research, and extension actions on water management. The planning and sizing phases of a project are the most appropriate for diagnosing the possible environmental impacts resulting from irrigation, enabling necessary adjustments to minimize possible adverse effects (Bernardo, 1997).

CONCLUSION

The importance of irrigated agriculture becomes clear when considering the existence of a physical limitation to the growth of rainfed agriculture, indicating that, in the future, food production will be increasingly dependent on irrigated agriculture, which currently accounts for 12% of Brazilian agricultural areas (ANA, 2022). The expansion of irrigated agriculture in river basins with vulnerabilities between the supply and demand of water resources increases the possibility that uses will approach or exceed supply at a certain time of year (ANA, 2021), especially in situations of reduced rainfall, which can lead to water crisis scenarios and uncertainties regarding water supply, making this practice unfeasible. Irrigated agriculture, meanwhile, will have to adapt to increasingly frequent conditions of conflict over the use of water, as well as social and environmental issues, requiring greater integration between public and private institutions to reduce impacts and contribute to environmental sustainability through the development of climate-smart agriculture and strategies for adapting to changes in the climate. With considerable potential for expansion and the prospect of a significant increase in the use of water for irrigation over the next 30 years, greater planning and management efforts will be necessary and should increasingly consider the variability and prospects for change in climate and land use, where irrigated agriculture will be an important adaptive measure for coping with water scarcity and extreme events (ANA, 2021).

Regarding climate, it is important to note that climate change is already influencing several natural systems (Parmesan and Yohe, 2003). Therefore, the inclusion of a systematic analysis of adaptation to these changes should guide structured solutions that involve not only economic and hydrological models but especially those that require the use of water for irrigation. Water availability may, depending on the region, be dependent on climate change, which could impact the production system and food supply. Likewise, such events could impact producers' earnings and income and, consequently, the Brazilian trade balance. Finally, the importance of irrigated agriculture is undeniable, both for agricultural production and for promoting environmental conservation, as it does not require the opening up of new agricultural frontiers, whether in the Cerrado or in the Amazon rainforest region, guaranteeing food in quantity, quality, and at affordable costs for people. This is provided that the approach to granting water use concessions considers future climate scenarios, the recovery of deforested areas, the seasonality of the rainfall regime, and the adoption of technologies for correct irrigation management. However, for this to be effectively achieved, a new discussion about the legal framework for granting water use licenses, water resource management, and zero deforestation policies must be proposed and implemented.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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