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Harvesting Underdevelopment: Exploring the Water–Food Nexus in Brazilian Municipalities

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Abstract: Efforts to promote human development through agriculture highlight issues that require balanced approaches, considering socio-environmental factors, including equitable water allocation in regions with significant inequalities. This study aims to assess human development disparities across Brazilian regions, particularly in municipalities with high water consumption for irrigation in agriculture and livestock watering. Using public data from 2007 and 2016, a total of 300 municipalities were selected each year for analysis based on water use types. The study compared groups using the Firjan Index of Municipal Development (FIMD) as a measure of human development, employing the Kruskal–Wallis test with a 95% confidence level. We found statistically significant differences in FIMD distribution across all of the groups studied. We also verified that a set of municipalities in the Southeast did not experience significant advancements in development between 2007 and 2016, despite having high water allocations for livestock watering. Additionally, intense water use for irrigation was insufficient to elevate less advantaged regions, such as the Northeast, where half of the municipalities were classified with moderately low values in both years. The challenges in this water–food nexus study highlight the need for more integrated policies to ensure greater justice in human development and in the distribution of natural resource exploitation for agribusiness income.

Keywords: agricultural irrigation; food production; food systems; human development; regional development; water–food nexus; water management

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1. Introduction

In addition to generating energy for the power industry and enabling critical processes in the human body and natural ecosystems, water is a strategic resource that optimizes and diversifies food production through irrigation and livestock watering systems [1]. These systems can be considered important countermeasures to food insecurity, as climate change may disrupt animal heat regulation [2] and rainfall standards [3,4].

However, the literature is mixed on the benefits and harms associated with the appropriation of water for agricultural activities. While some studies report more rural development through increased productivity [3,4] and the creation of rural jobs [5,6], others raise concerns about the pressure on water bodies [7] and changes in the lifestyles of people living near irrigated areas [8,9]. As agriculture accounts for about 70% of global freshwater withdrawals, irrigation plays a central role in sustaining food production. Nevertheless, if not managed sustainably, water scarcity can become exacerbated and lead to depleted groundwater resources [10]. Balancing the benefits of agricultural water use with its potential environmental and social costs is therefore essential for long-term sustainability.

The interdependence between the water and food sectors in Brazil is shaped by neoliberal policies governing water resource regulation, which largely favor huge agribusiness companies [11]. This dynamic has led to the systematic degradation of natural ecosystems [7] and fostered unbalanced power relations, which contribute to socio-environmental conflicts [8,9,12].

The pervasive "water abundance myth" is central to this issue [13], a narrative that assumes water is perpetually available in sufficient quantities, particularly in regions supporting agricultural expansion. This belief has been politically appropriated by powerful groups, who downplay the severity of water scarcity and promote an illusion of resource abundance. By doing so, they obscure the pressing need for sustainable water management practices, ultimately aggravating both environmental degradation and social inequalities [8,9,12,13].

This can also jeopardize the well-being and prosperity of regions, communities, small food producers, and traditional peoples. Therefore, due to the potential negative social and territorial externalities caused by water allocation for these purposes, it is important to understand the repercussions of such interdependence.

In this context, the concept of the water–food nexus, along with its various linkages (e.g., water–energy–food, energy–food, water–energy), is emerging as an innovative management, governance, and policy tool [14]. The aim of this approach is not only to understand the complexity of the flows between resources but also to develop effective strategies that contribute to reducing vulnerability and promoting more coherent decision-making based on interdependencies between different sectors [15,16].

The focus to do so is on promoting more equitable and sustainable dynamics between the different sectors, territories, and actors involved, understanding who loses and who gains within a system [17]. According to Hoff [15], who presented initial evidence on how to improve water, energy, and food security through the nexus approach, exceeding critical limits at any scale could lead to (possibly irreversible) changes in systems—so-called "regime shifts"—with negative impacts on ecosystems, socio-economic development, and poverty reduction. Therefore, in order to avoid such undesirable transitions and to ensure the resilience and sustainability of the interconnected systems, a thorough understanding and careful management of the water–food nexus is essential.

Countries such as Brazil present themselves as important places to study the impact of water allocation on agricultural activities, given their historical legacy as the "breadbasket of the world" due to their high production of food and commodities that supply international markets. Such an understanding provides an opportunity to serve as a reference for other global leaders in the production and export of agricultural products that may be facing similar challenges [18–21], in addition to highlighting contradictions related to aspects of human development [8,9].

This approach enables deep analysis of the complexities and connections involved in the water–food nexus, considering not only the local dimensions but also their global implications. With its prominent position on the world's agricultural stage, Brazil therefore offers fertile ground for studying effective management strategies for these interrelated resources, recognizing the potential impacts on food security, economic development, and environmental sustainability on a global scale.

In view of the above, this study aims to test whether the country shows regional disparities in terms of human development based on water allocation for food production. The investigation was conducted by comparing the development level of a sample of

Brazilian municipalities that proportionally consume more water for irrigation and livestock watering, considering data from 2007 and 2016 and the geographical region in which each municipality is located. The study considers the regional inequalities in Brazil, which are shaped by historical disparities among the country's five regions [22]. The question to be answered is: in view of the disparities in human development between Brazilian regions, do municipalities with the highest per capita water consumption for food production achieve good levels of human development, or are inequalities merely perpetuated?

Thus, by exploring the water–food nexus from a territorial perspective, this study contributes to the literature by helping to understand dynamics beyond the urban–rural dichotomy [23], and also fills the gap from previous studies dedicated to problematizing the degree of human and municipal development in relation to the food production of municipalities located in the same administrative or geographic region [17,24–26].

The paper is organized as follows: in the next section, we provide a brief description of the agricultural production situation in Brazil during the period under study, as well as a background on the organization and human development of the Brazilian territory. The methodology is explained in Section 3. Section 4 presents the results. Then, in Section 5, we discuss the results with comments on the limitations and the significance of this study. A synthesis of the main findings and recommendations is presented in the final section.

2. Overview of Human Development Progress and Agriculture in Brazil

Over time, Brazil has undergone different regionalization processes linked to the complexity behind the economic, demographic, political, and environmental transformations of each era. The current territorial division of the country, as established by the Brazilian Institute of Geography and Statistics, is organized into macro-regions (or simply regions), states, meso-regions, micro-regions, and municipalities, as well as internal subdivisions of municipalities, such as districts and subdistricts or administrative regions.

Among these sub-national spaces, only the municipalities and states have political-administrative bodies. However, although these territories have the relative autonomy to articulate and promote their own development [27], there are profound inter- and intra-regional inequalities that reflect the uneven capacity of municipalities and states to provide goods (e.g., food) and essential public services (e.g., education, health) in adequate quantity and quality for their populations, thus depriving individuals and communities of the essential life capacities they wish to have in their living and working spaces [28–32].

The concept of territorial development goes beyond GDP growth, individual income growth, industrialization, technological progress, or modernization, whatever the scale considered. In this sense, from the perspective of Amartya Sen [33], we understand human development as a process of eliminating multiple sources of deprivation for individuals and communities throughout the territory, which can occur through optimizing spaces for political participation and access to public goods and services that are essential for well-being, such as basic sanitation, food, education, and the labor market. In view of the development trajectory of the Brazilian territory, many studies [22,28,30,32,34,35] report that inequalities between municipalities are persistent over time and are accentuated in relation to locality [36], considering the five regions of the country: North, Northeast, South, Southeast, and Midwest (Table 1).

In this context, a 2017 analysis of the 100 Brazilian municipalities with the highest GDP revealed that they contributed over half of the country's total GDP, totaling 55.3% [32]. Specifically, of these top 100, municipalities from the Southeast contributed 35% of GDP, while those from the South contributed 6.4%. Meanwhile, the top 100 municipalities from the Midwest accounted for 5.8%, from the Northeast for 5.9%, and from the North, for just 2.3%. Additionally, the indicators for the North and Northeast regions are not positive in terms of the infrastructure needed to maintain good health. Using data available for 2019, a study [34] showed that municipalities in the North and Northeast have a higher incidence of deaths and hospitalizations due to waterborne diseases. This contrasts with municipalities in the South and Southeast, which have higher basic sanitation coverage.

Table 1. Weighted average of the components of the Human Development Index (HDI) by region and Brazil, for 2000 and 2010.

Region	Municipal HDI [1]					
	Longevity		Education		Income	
	2000	2010	2000	2010	2000	2010
Midwest	0.777	0.839	0.467	0.665	0.720	0.776
North	0.717	0.796	0.333	0.557	0.613	0.670
Northeast	0.685	0.782	0.342	0.569	0.588	0.656
South	0.792	0.848	0.510	0.662	0.711	0.764
Southeast	0.778	0.845	0.541	0.688	0.735	0.773
Brazil	0.727	0.816	0.456	0.637	0.692	0.739

[1] Weighted average of the Municipal Human Development Index (IDHM) for Brazilian regions and the country, considering the respective population weights. The Municipal HDI adapts the United Nations' HDI to evaluate quality of life within municipalities, measuring education, longevity, and income specific to local contexts. These data were obtained from a publication resulting from a partnership between the United Nations Development Programme, the Institute of Applied Economic Research, and the João Pinheiro Foundation [36].

Some aspects of Brazilian human development cannot be dissociated from water allocation for food production or energy generation. This activity is intimately linked to urbanization processes, the policies and decisions of governments and other agents of economic progress, and the environmental conditions (e.g., water deficit) of the regions where municipalities are located [37,38].

For example, water use for irrigated agriculture dominates in the South and Northeast regions, while the North and Southeast regions allocate more water to thermoelectric power plants and urban supply, respectively. Irrigation has been the dominant use of water in the South since the 1930s. This is because one of its states was a pioneer in irrigated rice production [38]. However, public investment in water infrastructure and funding for fruit-growing development in the Northeast caused water use for irrigation to exceed that for municipal use in the second half of the 1980s [39]. Furthermore, despite the Midwest region of Brazil being recognized as an important livestock center for concentrating large cattle herds [40], it still records higher water consumption for irrigated agriculture than for watering livestock [38]. Among the 10 municipalities with the highest water extraction for livestock watering in 2017, 5 were from the North region and 5 were from the Midwest [38]. According to McManus et al. [40], the North region has shown accelerating trends over the years based on an analysis spanning 1977 to 2011.

In this regard, irrigation is an important and strategic technology for Brazil. The country recorded 8.2 million hectares equipped with irrigation systems for rice, coffee, sugar cane (subdivided into irrigated and fertilized), annual crops in center pivots, and other crops in 2019 [38], constituting an increase of more than 1 million hectares with respect to 2010 figures. It is estimated that the country will have 4.2 million hectares of irrigated land by 2040 [37]. These irrigated areas are expanded through projects planned by government agencies, joint private initiatives (such as cooperatives and associations), and individual private initiatives. In particular, the private sector accounts for 96.2% of the country's irrigated land [37].

In turn, this accumulation of inequalities in terms of human development (Table 1) and the development of the agricultural sector across the country, which intensified in the middle of the 20th century [41], is related to Brazil's historical–economic formation and dysfunctions between the objectives of regional policy and its instruments and institutions [31,35].

While views vary on Brazil's regional development trajectories, the literature agrees that some government policies have contributed to inequalities in human development. The industrialization process that started in the 1880s and accelerated in the 1930s resulted in significant industrial concentration, leading to industrial and financial centralization in the South and Southeast. This dominance caused these regions to become more populated, concentrating capital and services and fostering a higher level of urban development [35]. On the other hand, there is also the argument that the imbalances in development can be attributed to the insufficient national integration of an economy based on the export of primary products. This lack of integration created capitalist dynamics, which contributed to inadequate development in regions such as the North and Northeast [35].

3. Materials and Methods

We first calculated the per capita water consumption for irrigation and livestock watering for all municipalities in the country using 2007 and 2016 as reference years. Following this, we also collected and analyzed information on human development, the degree of agricultural dependence, and land concentration for a sample of these municipalities categorized into groups by type of water use, geographical region, and year. All the data utilized in this research were obtained through open access online platforms.

3.1. Studied Variables

3.1.1. Water Consumption

We collected hydrological and population data from the public domain platforms of the National Water and Basic Sanitation Agency and the Brazilian Institute of Geography and Statistics (IBGE). This indicator was obtained by dividing the total water consumption (in liters per second) for irrigation and livestock watering by the estimated population of the municipality per year.

3.1.2. Human Development

Since the census data were outdated in relation to our environmental and resource data, the most appropriate measure to quantify development was the Firjan Index of Municipal Development (FIMD). The FIMD is a numerical index that ranges from 0 to 1. The scale is the same as the HDI; the closer to 1, the more developed the municipality is. Therefore, the results of this index can be classified into four categories: high development, with results greater than 0.8; moderately high development, with results from 0.6 to 0.8; moderately low development, with results from 0.4 to 0.6; and finally, low development, with results up to 0.4.

The index includes information from official federal government statistics and was compiled by the Rio de Janeiro State Federation of Industries [42] only for Brazilian municipalities. Specifically, this index considers variables related to local employment and income generation, as well as coverage of early childhood education and primary healthcare.

3.1.3. Degree of Agricultural Dependence

The municipal gross value added (GVA) of agricultural activity was considered to reveal the degree of dependence on the agricultural sector and the respective sector's role in the economy as it quantifies the economic contribution of agriculture to the total value of production across all sectors, including industry and services. The agricultural GVA was not adjusted for inflation, and the percentage of total GDP was obtained from the Brazilian Institute of Geography and Statistics.

3.1.4. Land Concentration

Agricultural establishments encompass all units involved in the production or processing of agricultural, forestry, or aquaculture products, regardless of their size, ownership type, or location. These establishments produce either for commercial purposes, such as the sale of products, or for subsistence purposes, i.e., sustaining the producer and their family.

Consequently, a higher concentration of family farms in relation to larger corporate farms or establishments owned by other entities suggests more equitable land and wealth distribution. Based on the 2006 agricultural census, a study showed that 1% of Brazilian farms or rural establishments managed 45% of the agricultural land in the country [43]. Following the model of land concentration, the 2017 agricultural census revealed that 81.4% of Brazil's establishments had less than 50 hectares, occupying 12.8% of the establishments' total area, while those establishments with more than 2500 hectares occupied 32.8% [44].

Following this interest, the proportion of establishments that were family farms for 2007 and 2016 was estimated using data from the 2006 and 2017 IBGE agricultural censuses, respectively. This estimation was made assuming that there would be little change from one year to the next.

3.2. Database and Data Analysis

The respective FIMD values and geographical regions of the 150 municipalities with the highest per capita water consumption for irrigation and livestock watering in both years were identified. As a result, we obtained 4 groups of 150 municipalities, 1 group for each water-use type (irrigation or livestock watering) and each year.

The statistical analysis involved examining the FIMD range through quartiles (Q1 [1st quartile] and Q3 [3rd quartile]), as well as the mean, standard deviation (SD), median, minimum (min), and maximum (max) values. The values of Q1 and Q3, which can be used to describe the interquartile range, are presented separately to illustrate the distribution of data, excluding the influence of extreme values. Q1 represents the value that separates the lowest 25% of the FIMD, while Q3 marks the FIMD value that separates the highest 25%.

The Shapiro–Wilk test indicated a non-normal distribution of FIMD values. As a result, the non-parametric Kruskal–Wallis test was used to compare FIMD values across regions within each group due to the non-normal distribution found in all four analyzed groups. Significance was determined at a 95% level of confidence ($p \leq 0.05$).

Finally, the proportional (%) values for agricultural activity in total GDP and establishments owned by family farms for both years studied were described only for the municipality in each region that recorded the highest per capita flow of water consumed for irrigation and livestock watering. To support data management and analysis, we exported electronic spreadsheets with the corresponding data to the RStudio software package, version 4.3.2.

4. Results

Table 2 describes the demographic difference between the groups of municipalities studied. We found that the average population of the municipalities that used the most water for livestock watering was lower than that for irrigation. The standard deviation values were higher for the samples analyzed for irrigation activity, indicating significant variability in the number of inhabitants among these selected municipalities.

The statistical summary of FIMD values (Table 3), for the four groups of municipalities studied, reveals that the mean and other position and dispersion measures improved by 2016 compared to 2007, for both water use types. This indicates moderately high human development levels for most municipalities, as many of the IFDM values were between 0.600 and 0.800.

Table 2. Statistical summary of the population for Brazilian municipalities studied by water use type, 2007 and 2016.

Type of Water Use/Year	Min	Max	Mean	SD
Irrigation				
2007	1057	123,743	13,233.12	17,537.64
2016	1854	220,253	18,204.11	26,160.96
Livestock watering				
2007	1057	59,238	6254.64	6258.82
2016	815	33,731	6846.30	5466.04

Table 3. Statistical summary of the Firjan Index of Municipal Development (FIMD) for Brazilian municipalities under study by water use type, 2007 and 2016.

Type of Water Use/Year	Min	Max	Q1	Median	Q3	Mean
Irrigation						
2007	0.415	0.875	0.586	0.643	0.688	0.637
2016	0.482	0.826	0.652	0.698	0.733	0.687
Livestock watering						
2007	0.311	0.847	0.560	0.621	0.665	0.614
2016	0.437	0.796	0.634	0.679	0.717	0.672

In terms of region, there were differences in the distribution of high-water-consuming municipalities across Brazil's five regions in both 2007 (Table 4) and 2016 (Table 5). The South (S) and Southeast (SE) regions can be highlighted as having the highest number of municipalities with high consumption of water for irrigation, while the North (N) region had the lowest number. On the other hand, the Midwest (MW) region stood out for having the highest number of municipalities with high consumption of water for animals in both years, with this number increasing. Curiously, the Northeast (NE) was the only region that did not have any municipality recorded as being among the 150 highest for livestock watering, in both 2007 and 2016.

Table 4. Statistical summary of the Firjan Index of Municipal Development (FIMD) and Kruskal–Wallis test results by region and water use type, 2007.

Type of Water Use/Region	n	Median FIMD (Q1–Q3)	H-Statistic	df	*p*-Value
Irrigation					
MW	15	0.650 (0.628–0.720)	40.8	4	<0.0001
N	6	0.541 (0.530–0.611)			
NE	19	0.516 (0.480–0.577)			
S	63	0.630 (0.600–0.667)			
SE	47	0.688 (0.620–0.739)			
Livestock watering					
MW	89	0.618 (0.574–0.648)	23.9	3	<0.0001
N	36	0.575 (0.506–0.651)			
NE	0				
S	9	0.630 (0.618–0.664)			
SE	16	0.695 (0.656–0.740)			

The box plots in Figure 1 and the medians in Tables 4 and 5 show that the Midwest, South, and Southeast regions stand out for having moderately high FIMD values in both years and types of water use; this is despite an apparent decrease and high variance in the Southeast for municipalities dedicated to livestock watering observed in 2016. However, in 2016, the FIMD values for half of the municipalities selected from the Northeast were categorized as moderately low, while the median identified for all the other regions achieved a moderately high level, including the North region.

Table 5. Statistical summary of the Firjan Index of Municipal Development (FIMD) and Kruskal–Wallis test results by region and water use type, 2016.

Type of Water Use/Region	n	Median FIMD (Q1–Q3)	H-Statistic	df	*p*-Value
Irrigation					
MW	20	0.697 (0.662–0.730)	28.0	4	<0.0001
N	9	0.612 (0.588–0.682)			
NE	20	0.597 (0.555–0.692)			
S	56	0.715 (0.677–0.739)			
SE	45	0.702 (0.674–0.739)			
Livestock watering					
MW	105	0.686 (0.644–0.726)	19.0	3	<0.001
N	34	0.637 (0.588–0.679)			
NE	0				
S	6	0.693 (0.656–0.713)			
SE	5	0.633 (0.608–0.737)			

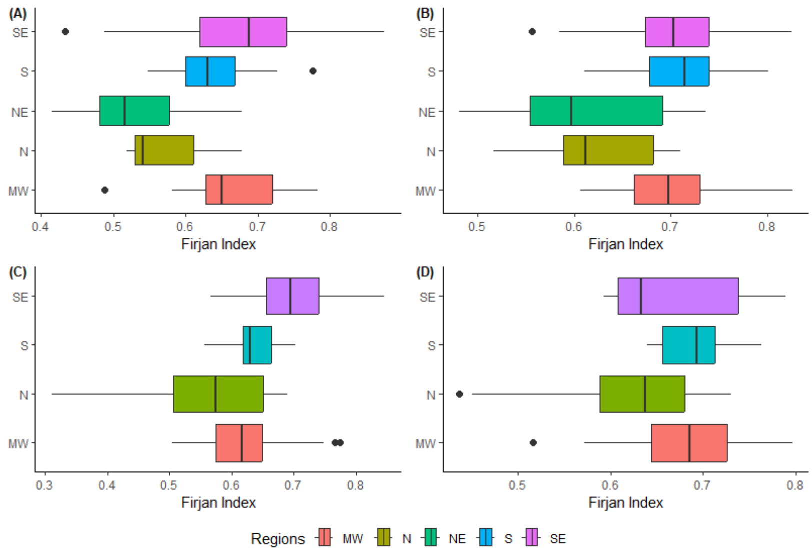

Figure 1. Box plot of the FIMD by region according to the year and water use type, 2007 and 2016. The figures labeled (**A**) and (**B**) focus on irrigation activity for 2007 and 2016, respectively, while (**C**) and (**D**) provide information on livestock watering for 2007 and 2016, respectively.

There is also a noticeable disparity in FIMD between municipalities in different regions that use high amounts of water for the same purposes. The median identified in the North region in 2016 was lower than that in the Midwest region, even though the North and Midwest regions had the highest absolute number of municipalities using water for livestock watering.

In the box plots (Figure 1), it is also possible to observe the variability in the distribution of the median, minimum, and maximum values for the FIMD, suggesting differences between municipalities within each region in terms of human development. In turn, the Kruskal–Wallis test (H-statistic) shows that the distribution of FIMD values is statistically different between regions for both years and water use types (Tables 4 and 5).

Finally, for municipalities with high irrigation, we observed that Matão, a municipality in the Southeast, had the lowest proportional agricultural GVA at 4.4% in 2007, while Vila

Propício, a municipality in the Midwest, had the highest at 64.3% in 2016. On the other hand, the highest GVA among municipalities with high water use for livestock watering was observed in a municipality in the South, Pedras Altas, which reached 64.8% in 2016. Conversely, the lowest proportion was again observed for another municipality in the Southeast, Marília, registering at 1.7% in 2007. Shifting the focus to land distribution, the northern municipalities concentrated high proportions of establishments owned by family farms in both years, with 63% in Petrolina (2007) and 77% in Jaborandi (2016). In contrast, the southern municipalities registered less than 50% of establishments owned by family farmers across both years and water use activities (Table 6).

Table 6. Agricultural gross value added (GVA) and % of establishments owned by family farms for municipalities under study by water use type, 2007 and 2016.

Type of Water Use/Region	Municipality	2007		Municipality	2016	
		Agricultural GVA	% of Family Farm Establishments [1]		Agricultural GVA	% of Family Farm Establishments [2]
Irrigation						
MW	Vila Propício	59.8	59.2	Vila Propício	66.8	44.1
N	Lagoa da Confusão	49.1	50.0	Lagoa da Confusão	49.7	21.0
NE	Petrolina	15.5	63.0	Jaborandi	64.3	77.0
S	Dom Pedrito	31.0	42.4	Barra do Quaraí	60.9	20.5
SE	Matão	4.4	38.8	Romaria	61.2	58.2
Livestock watering						
MW	Vila Rica	22.0	63.9	Araguaiana	46.1	33.1
N	Ji-Paraná	4.3	77.5	Bannach	62.8	53.6
NE [3]	-	-	-	-	-	-
S	Sant'Ana do Livramento	15.9	42.2	Pedras Altas	64.8	24.1
SE	Marília	1.7	48.0	Gurinhatã	51.4	40.1

[1] Variable with data from the 2006 Agricultural Census conducted by the Brazilian Institute of Geography. [2] Variable with data from the 2017 Agricultural Census conducted by the Brazilian Institute of Geography. [3] No northeastern municipality was identified for the specified type of water use; consequently, (-) indicates that there are no data.

5. Discussion

The results of this study suggest that human development levels among the sample of Brazilian municipalities that consume the most water for irrigation and livestock watering are related to the geographical region in which they are located, as shown by the interregional inequalities observed when comparing the FIMD values reported for 2007 and 2016 (Tables 2–5, Figure 1).

The data analysis underscores enduring regional inequalities in Brazil. We observed that while there have been some overall advancements in our set of municipalities that consume high amounts of per capita water for food production, FIMD levels continue to differ markedly among them across the five regions.

For example, municipalities in the Northeast, which have the highest water consumption for irrigation, still lag behind those in the South and Southeast for both years studied. Nevertheless, it is important to consider the complex relationships between geopolitical, social, economic, and environmental factors to understand these regional disparities, especially concerning water use in agriculture.

5.1. Effects of Capitalist Water Grabs and Environmental Factors

Although municipalities are positively affected by different water use types [1], irrigation and livestock watering systems alone may not guarantee the development of a municipality with extreme inequality [45], meaning part of the population does not have adequate access to a set of goods and services that are essential for sustaining life and well-being (e.g., land, basic sanitation) [36]. Therefore, other interventions that go beyond the efficiency of crops and livestock are needed to join forces so that the wealth generated by allocating and consuming water for food production is more equitably assimilated by the population and transformed into human development.

Based on this, it is evident that the arrival of water through irrigation projects has not ensured the promised human development for populations in all regions, including Northeast Brazil, which is home to significant irrigated fruit-growing centers [39,46]. In both years, for irrigation activities, the Northeast maintained median values for the FIMD categorized as moderately low, while the medians for all other regions were classified at a higher level in 2016—even the North, which also recorded a median value classified as moderately low in 2007 but showed better values in 2016.

In more recent years, the arrival of water for irrigation in the Northeast still seems to fall short of expectations for the region to achieve better levels of human development for all citizens, as indicated by official data from the federal government, which reveal that 1.5% of households in Northeast Brazil still lacked a bathroom in 2022 [47].

Since the Northeast is home to most of the country's irrigation projects operated by the federal government [37,48] and is a semi-arid region that is very vulnerable to droughts [49], which therefore necessitates more intensified projects like these, the political dimension of water regulation in the region cannot be dissociated from the hegemonic interests of companies over public irrigation areas. This context helps explain the moderately high and low human development values identified for the medians in the analysis of this study [12].

According to Pontes et al. [12], some dynamics and constitutional changes have favored companies in the agribusiness sector, which have occupied larger amounts of land within the Northeast region's public irrigation areas, concentrating profits and promoting negative repercussions that affect the health, work, environment, and lifestyles of women, small-scale food producers, and rural workers. These negative impacts include the sexual division of labor in fruit production for export [50], pesticide contamination of water basins [8], and increased incidence of illness (e.g., neoplasia) and mortality among rural workers and the population living in municipalities that are victims of a chemical-dependent food industry [8,9,12].

As if that were not enough, the region, which is not yet prepared in terms of infrastructure to receive larger population contingents, is witnessing an increase in the supply of formal jobs in the producing municipalities. This would be positive if employment contracts were not seasonal and precarious [8,12]. As a result of this increased employment, these municipalities have greater demands for basic services (e.g., health, education, sanitation) and host migrants who face inadequate housing and food conditions in anticipation of greater prosperity [12].

On the other hand, agricultural modernization in the Northeast also affects the social determinants of health of small-scale food producers, such as housing and access to land. When private profit is prioritized over human well-being, small producers are dispossessed of their homes, move to urban peripheries, and go from being self-employed to being employed by the same companies [9,12].

Along these lines, 'accumulation by dispossession' is a term coined by Harvey [51] to criticize processes, such as those seen in the irrigated areas of Northeast Brazil, in which practices mobilized by capitalism occur at the expense of the population. These practices occur through the poor distribution of wealth generated by appropriating strategic resources (i.e., land and water).

The effects of this rationality of power concentration, driven by large landowners and agribusiness, are evident in other parts of the country, including regions such as Matopiba—the main soybean frontier in the Brazilian Cerrado—which spans municipalities across three northeastern Brazilian states (Maranhão, Piauí, and Bahia), as well as one northern state (Tocantins) [52]. Commonly referred to as a region, the territorial area known as Matopiba is not a Brazilian macroregion (or simply a region) like the North, Northeast, South, Southeast, and Central-West regions. Institutionalized by the Brazilian government as a region focused on supporting agricultural development, Matopiba consists of 337 municipalities, spread across a total area of 73 million hectares. The effects in this region are also seen in the Midwest region [53] and other Latin American countries, such as Argentina [18,19], Chile [20], and Peru [21].

To gain an idea of Matopiba's accumulation of capital by privatizing social spaces and ecosystem services, data from the 2006 Census showed that 20% of the 250,238 productive establishments identified during that period generated 94.8% of gross income [54]. Thus, the challenge of solving poverty and optimizing the level of community development through agricultural activity appears related to the high concentration of gross income in the region.

The most recent federal initiative to create an agricultural and agro-industrial development plan for Matopiba [55], the Agropecuary and Agroindustrial Development Plan of Matopiba, has "the expansion and strengthening of family agriculture, livestock and agro-industry through implementing development and financial instruments which promote improved income, employment and professional qualification of rural producers and agro-industrial entrepreneurs" as one of its objectives. In this sense, the pursuit of above-average profits should not overlook the negative socio-environmental impacts of the 'accumulation by dispossession' process promoted by landowners and agribusiness [52,56]. Additionally, the loss of vegetation cover in the Cerrado driven by the expansion of irrigated production is also very negatively affecting rivers [56].

In addition to the overexploitation and degradation of ecosystem resources, uncertainties arising from climate change and the demands of the international commodity market (among other factors) have also become significant challenges in managing the water–food nexus within the context of these ecosystem pressures [57].

In analyzing the economic and social impacts of climate scenarios projected for 2040 on Brazilian agriculture, Santos et al. [58] identified the potential for a decline in the country's real GDP, along with more severe losses for the poorest families living in regions whose economies are heavily dependent on this activity. Since these uncertainties related to climate change can lead municipalities to experience declining levels of growth and, consequently, human development, these issues need to be addressed by all regions of the country, particularly in municipalities with a GDP that is generated largely by agricultural activities depending on water sources, as shown in Table 6. In other words, for the sustainable development of Brazilian municipalities, the interaction between the water and food sectors requires (among other things) strategies developed by stakeholders from different sectors that can consider geopolitical, social, economic, and environmental factors [59].

Brazil has attempted to address the complexities of the water–food nexus by formulating public policies. As highlighted by Benites-Lazaro et al. [60], there is a clear need for greater integration between the sectors, despite the existence of relevant legislation and policies tangentially related to these issues. For example, the National Plan for Adaptation to Climate Change [61] is one such policy. It explicitly mentions the need to promote interactions and synergies between sectors to improve the coherence of adaptation strategies in the context of climate change. The Forest Code [62] addresses reconciling productive land use with conserving natural resources such as water, soil, and vegetation. The National Irrigation Policy [63] proposes the sustainable use of land and water resources, integrated with various sectoral policies. Moreover, RenovaBio [64] highlights the contribution of biofuels to national fuel security, environmental preservation, and socio-economic development.

However, these policies indicate that the challenges of the nexus, as also evidenced by this study (Tables 3–5, Figure 1), have only been partially addressed within governance frameworks. Implementation remains a challenge. Regulatory solutions are still fragmented, and sectoral planning and governance traditions persist, often exacerbating already high compensation and liability costs [65]. The need for a more integrated and effective approach to address the interlinked challenges of water, food, and other natural resources continues to be urgent. As such, the convergence of such themes with reducing inequalities can be also considered as an integrated challenge.

5.2. (The Lack of) Fairer Territorial Dynamics

The concentration of higher-value crops, technologies, and technical assistance in the municipalities of the country located in the Midwest, Southeast, and South regions also appears to be another factor capable of explaining the regional asymmetries observed in the FIMD values. More than 80% of the gross value of agricultural production in 2006 [66] came from the production of 10 products, most of which were distributed among municipalities located in more developed regions, such as the South and Southeast.

Despite the decline in cattle numbers in the southeastern region, the Southeast and Midwest still host the primary beef-exporting facilities in Brazil, making them the country's main beef exporters [40]. According to MacManus et al. [40], environmental factors (e.g., temperature, humidity) in southeastern areas, along with cheaper land in the northern region, are influencing the dynamics of cattle production in Brazil. In this context, Lundström [67] also highlighted the replacement of pasture areas in the Southeast by sugarcane and orange crops as another contributing factor.

This concentration of power in the beef supply chain can lead to socioeconomic impacts in the regions where these facilities are located, particularly for the poorest citizens, limiting their ability to achieve improvements in employment and income, as it can create barriers to accessing opportunities for higher qualifications. Additionally, as farms become fewer and larger, often at the expense of small-scale cattle operations, the high level of competition in the sector may lead to significant disparities in the ability of municipalities and small farmers to convert wealth into human development [67].

In other words, the fragility of some livestock production systems and producers in adapting to environmental changes, along with the technical and financial capabilities needed to operate livestock production, may also be factors that reinforce intraregional disparities in productivity and, consequently, hinder progress toward better levels of municipal or human development through the competitiveness of the country's producers in the commodity market [40,67–69].

The same may occur for water-intensive irrigation activities. In Table 6, for example, it was observed that northeastern municipalities concentrate a significant number of establishments owned by family farmers, which could lead to improved human development levels if they had access to formal education, assistance, funding, fiscal incentives, and technology [70].

On the other hand, a poorly diversified production matrix, as evidenced in Table 6 for municipalities with higher water use for irrigation in the Midwest, such as Vila Propício [71], and for livestock watering in the South, such as Pedras Altas [72], may pose obstacles to achieving further improvements in their FIMDs, hindering their ability to reach high levels rather than moderate high ones. This assumes that municipalities and regions that are highly specialized and dependent on one sector carry the vulnerabilities of that same sector and that wealth can remain concentrated in the hands of a few landowners [11,73–75].

When communities rely heavily on external political centers, commodity markets, and consumer hubs, their autonomy for development is compromised [73,76]. This reliance makes it challenging to explore alternatives, as local groups often manage the municipality in a corporate manner, focusing on generating employment and income through specialized activities. Additionally, such specialization and dependence limit a municipality's ability to harness natural resources (such as water and land) to pursue new opportunities, thereby increasing environmental risks and liabilities [73,74,76] and eliminating possibilities for growth and the conversion of new activities into better human development levels [17].

Following this issue, it is clear that the agriculture–human development–resource nexus is particularly vulnerable to climate change [24] and has an impact on the natural landscape and the environment [8,9,12]. As such, a previous study highlighted that several sugar cane-dependent municipalities in the Southeast (characterized by high agricultural dependency and land concentration, as illustrated by some municipalities described in Table 6) experienced economic collapse following the financial downturn in the sugar cane industry.

However, considering the possibility of producers not being too specialized in a specific agricultural culture due to the seasonal vulnerabilities that can lead to crises, a study by Rathmann et al. [77] showed that diverse cultivation tended to improve the quality of life of producers from the South, as well as the local GDP and HDIs of the cities where these agricultural crops are inserted.

In the face of this neoliberal logic of injustice applied to municipalities and their inhabitants who are engaged in agriculture (Tables 4–6, Figure 1), we still agree that food reduced to a commodity loses its value as a human right to nutrition and adequate food because it begins to serve private interests [11,78], in turn, leaving communities and individuals behind in the search for better levels of development.

This is evidenced by the fact that family farmers/rural producers' households and residents of the northern and northeastern regions have been identified as having the worst levels of food insecurity in the country [30]. Current capitalist relations of production in rural areas do not spatially connect the final consumers of agricultural products with their suppliers, the natural resources used (i.e., water, land), and the environmental and social trade-offs that producers and territories make [17,79,80]. Flach et al. [81] and Silva et al. [82] found that soy and other commodities supplying international markets were produced in less developed municipalities with low water availability. Injustices in the production chain of bananas from Ecuador that are imported were also discussed by Roibás et al. [83], who found lower incomes for producers in comparison to intermediaries in the chain.

In light of this, when discussing the Brazilian policy responses to nexus challenges, the findings of this work relate to Mercure et al.'s [57] argument that "some of the policy responses may have been taken beyond Brazil", thereby calling on decision makers in the country and around the world to reflect on their role in addressing interdependencies between scarce resources in a context of environmental and social vulnerability of producing communities.

Faced with the current situation of the international commodity market, which demands large amounts of water and land, the Brazilian government is demonstrating that it is maintaining the dynamic of providing strategic inputs and natural resources such as water and food, without addressing the internal obstacles and inequities that arise from this interaction and jeopardize the development of communities [84].

Therefore, it is necessary for the country to optimize or create policies for more effective management of the trade-offs of irrigation and livestock watering systems [57], as well as to stimulate conditions to balance private interests with social welfare and the appropriation of strategic resources (i.e., water, land) for food production. As a result, development policies and their instruments and institutions should be expected to be less dysfunctional.

By reinforcing this status quo, the interregional disparities in urban development identified in this study, as well as the intraregional dynamics that impede economic and social progress, may be perpetuated over time by a laissez-faire attitude toward the interests of large landowners and corporations.

5.3. Limitations and Significance of the Study

Among the limitations of this study is the fact that it is not known to what extent the FIMD, and even consolidated indicators such as the Municipal HDI, are able to capture Brazil's regional inequality [36], given that this measure does not consider the biophysical components of the environment that affect the maintenance of life and well-being [85]. However, the FIMD has been valuable for supporting investigations on various research topics in Brazilian territory, such as maternal mortality [86] and socioeconomic growth [87,88].

The demographic diversity of the municipalities selected for this study also poses a challenge for comparison (Table 2), as does the fact that the municipalities were selected based on their reported high water consumption and not on the origin of the water consumed; this does not take into account the impact of irrigated agricultural activity on the economy of the corresponding municipalities and regions and basins that share similar natural, social, and economic characteristics. We also did not consider municipalities with lower water consumption levels for irrigation and livestock watering. Additionally, the mismatch between the proportion of establishments that were family farms and the year of this study presents a challenge. However, since the period is short, it still provides important insights into the level of wealth concentration among the municipalities studied, and other evidence supports our hypothesis and findings.

Nevertheless, we calculated the per capita amount of total water supplied to the selected municipalities to mitigate these limitations. In doing so, we considered municipalities from all geographical regions of the country and two different years to verify whether the potential inequities differ between the two analyzed periods, as well as the most recent year (2016) for which human development measure is available from the Firjan System. We also selected indicators that allow us to reflect on the representativeness of agricultural activity as a whole and land concentration (and consequently wealth), in order to provide insight into part of the sample of municipalities studied.

In light of this, we recommend that future research consider other analysis measures for aspects of human development and sets of municipalities capable of not only capturing the interaction of basins and the water allocation for production, but also the production of other non-irrigated commodities that are representative of the economy and serve as a focus of socio-environmental conflict between aspects of human development, food production, land distribution, and energy production. We also argue for the integration of research goals across different disciplines (e.g., hydrology and social sciences) to achieve more holistic and successful outcomes [89]. By fostering collaboration among specialists, we can better address the intricate challenges of the water–food nexus and broader societal issues, especially in underdeveloped regions. This collaborative approach not only enhances our understanding but also enables translating the findings into effective policies and improvements.

Finally, because the results of this study go beyond environmental and efficiency issues related to the use and allocation of one resource in favor of another, we also believe that we are making a significant contribution to nexus research and human development. According to Dalla-Fontana et al. [90] and Melo et al. [23], Brazilian research involving the nexus approach has concentrated more efforts on environmental and economic aspects than on critical issues such as the equity and governance of interdependent sectors from a territorial perspective, marginalizing one of the principles of the nexus concept idealized by Hoff [15], which is to integrate the least advantaged in decision-making processes.

6. Conclusions

In this study, we compared Brazilian regions in terms of the aggregated development level of municipalities that recorded high values for the flow of total water consumed by irrigation and livestock watering activities and the data reported for the years 2007 and 2016.

As a main result, we observe that human development levels among the municipalities studied vary by region in Brazil. Although the regions do not share the same initial development levels, water allocation for irrigation and livestock watering appears to offer potential improvements in health, education, and employment opportunities, among other factors that this study did not aim to explore. Nonetheless, the results indicate that while there were positive advancements in human development for all regions between 2007 and 2016, the Southeast region saw no such progress for the majority of municipalities focused on livestock watering, and the Northeast lagged behind the others.

The FIMD analysis also showed that municipalities with higher irrigation water use generally experienced better human development compared to those focused on livestock watering. Additionally, the Kruskal–Wallis test confirmed that the FIMD distributions were statistically different across regions, highlighting the regional disparities in human development. Furthermore, the data on agricultural GVA and the higher percentages of establishments owned by family farmers, particularly in the Northeast, imply that this region may face greater challenges in capitalizing on and converting water-intensive agricultural activities into human development.

This study provides valuable insights into how the management of water resources for agricultural activities can have a direct impact on the socio-economic development of Brazilian municipalities by considering the scope of the water–food nexus to address municipal development. Moreover, it shows that interregional inequalities in development suggest that the economic and social progress of a territory is not only limited by the allocation of strategic resources such as water for food production but also by unequal land distribution and subordination to the agricultural sector.

Given these findings, the need for comprehensive and integrated policies that are not only at aimed optimizing water management for agriculture but also at promoting equity and social inclusion is evident. Accordingly, policies that prioritize the fair distribution of resources considering the peculiarities of each region, as well as strategies that encourage sustainable agricultural practices, are fundamental to achieving these goals. In addition, it is imperative to establish mechanisms that strengthen the adaptive capacity of municipalities in the face of climate change, ensuring the efficient and resilient management of natural resources. These policies must be based on collaboration between the water, food, and economic development sectors, promoting an integrated approach to tackling the complex challenges presented by the water–food nexus.

In other words, since our findings show that the current focus on agribusiness alone is not adequately contributing to broader regional development, the social issues identified in this study on the water–food nexus underscore the need for more integrated, multi-sectoral policies and sustainable practices that promote equitable human development. This approach requires aligning agricultural objectives with broader sustainable development goals, addressing inequalities in resource allocation, and promoting equity in the distribution of benefits from natural resource use.

Finally, particularly in the Brazilian case, further studies are needed to more deeply explore the factors that may justify the perceived regional dysfunctions. These include past inequalities and other particularities of each territory, the capitalist appropriation of water and land, and aspects of governance that are of interest to urban and regional planners and other stakeholders in the water and food sectors.

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