Miscellaneous

water and landscape
AGUA y TERRITORIO

Virtual water and water footprint: analysis for trade between Brazil and China

Agua virtual y huella hídrica: investigación para el comercio entre Brasil y China

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ABSTRACT

This study aims to quantify the volume of virtual water exported by Brazil to China between 2012 and 2022, focusing on eight key agricultural products: sugar, cotton, beef, pork, poultry, soybean oil, soybeans, and tobacco. Data were collected from Comex Stat and the Mekonnen and Hoekstra database. The study found that Brazil exported approximately 1.3 trillion m³ of virtual water, with soybeans being the most significant contributor. The research highlights the importance of efficient water use policies, as well as the potential for international trade to alleviate water scarcity issues in China. Limitations include the lack of regional data for livestock products and the focus on virtual water without considering other environmental or social factors.

KEYWORDS: Virtual water, Exports, Agricultural products, Water footprint, International trade.

RESUMEN

Este estudio tiene como objetivo cuantificar el volumen de agua virtual exportada por Brasil a China entre 2012 y 2022, centrándose en ocho productos agrícolas clave: azúcar, algodón, carne de res, cerdo, pollo, aceite de soya, soja y tabaco. Se recopilaron datos de Comex Stat y de la base de datos de Mekonnen y Hoekstra. El estudio encontró que Brasil exportó aproximadamente 1.3 billones de m³ de agua virtual, siendo la soja el mayor contribuyente. La investigación destaca la importancia de las políticas de uso eficiente del agua, así como el potencial del comercio internacional para aliviar los problemas de escasez de agua en China. Las limitaciones incluyen la falta de datos regionales para productos de origen animal y el enfoque en agua virtual sin considerar otros factores ambientales o sociales.

PALABRAS CLAVE: Agua virtual, Exportaciones, Productos agrícolas, Huella de agua, Comercio internacional.

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Água virtual e pegada hídrica: análise para o comércio entre Brasil e China

RESUMO

O presente estudo tem por objetivo quantificar o volume de água virtual exportado pelo Brasil para a China no período de 2012 a 2022, considerando oito produtos agrícolas principais: açúcar, algodão, carne bovina, carne suína, carne de frango, óleo de soja, soja e tabaco. As informações foram obtidas junto ao Comex Stat e ao banco de dados de Mekonnen e Hoekstra. Os resultados indicam que o Brasil exportou cerca de 1,3 trilhão de m³ de água virtual, sendo a soja o produto que mais contribuiu. A pesquisa evidencia a relevância de políticas voltadas ao uso eficiente da água, bem como o potencial do comércio internacional para atenuar os desafios de escassez hídrica na China. Entre as limitações, ressalta-se a ausência de dados regionais para produtos de origem animal e o enfoque exclusivo na água virtual sem abarcar outros aspectos ambientais ou sociais.

PALAVRAS-CHAVE: Água virtual, Exportações, Produtos agrícolas, Pegada hídrica, Comércio internacional.

Eau virtuelle et empreinte hydrique : analyse pour le commerce entre le Brésil et la Chine

RÉSUMÉ

Cette étude vise à quantifier le volume d'eau virtuelle exporté par le Brésil vers la Chine entre 2012 et 2022, en se concentrant sur huit produits agricoles : sucre, coton, bœuf, porc, volaille, huile de soja, soja et tabac. Les données proviennent de Comex Stat et de la base Mekonnen et Hoekstra. Les résultats montrent que le Brésil a exporté environ 1,3 billion de m³ d'eau virtuelle, la filière soja offrant la plus forte contribution. L'analyse souligne l'intérêt de politiques favorisant l'usage efficient de l'eau et le potentiel du commerce international pour atténuer les tensions liées à la pénurie hydrique en Chine. Parmi les limites, on note l'absence de données régionales pour les produits d'origine animale et le choix de ne considérer que l'eau virtuelle, sans autres dimensions environnementales ou sociales.

MOTS-CLÉS : Eau virtuelle, Exportations, Produits agricoles, Empreinte hydrique, Commerce international.

Acqua virtuale e impronta idrica : analisi per il commercio tra Brasile e Cina

SOMMARIO

Il presente studio si propone di quantificare il volume di acqua virtuale esportato dal Brasile verso la Cina nel periodo 2012-2022, focalizzandosi su otto prodotti agricoli principali: zucchero, cotone, carne bovina, carne suina, pollame, olio di soia, semi di soia e tabacco. I dati sono stati ricavati da Comex Stat e dal database di Mekonnen e Hoekstra. I risultati indicano che il Brasile ha esportato circa 1,3 bilione di m³ di acqua virtuale, con la soia come contributore più rilevante. L'analisi mette in luce l'importanza di politiche per un uso efficiente delle risorse idriche e il ruolo del commercio internazionale nel mitigare le criticità legate alla scarsità d'acqua in Cina. Tra i vincoli, si evidenzia la mancanza di dati regionali per i prodotti di origine animale e l'attenzione limitata all'acqua virtuale, senza altre prospettive ambientali o sociali.

PAROLE CHIAVE: Acqua virtuale, Esportazioni, Prodotti agricoli, Impronta idrica, Commercio internazionale.

Introduction

Brazil has become a leader in agribusiness, transitioning from a net importer of agricultural products in the 1970s to one of the world's primary food producers and suppliers. Between 1989 and 2009, agricultural exports constituted 42.53 % of total exports, while agribusiness imports were only 7.7 %[1]. The country increased its exports to China, which became its largest trading partner in 2009[2]. The Sino-Brazilian relationship intensified from 2001, when China joined the World Trade Organization (WTO). Since then, Brazilian exports to China have grown annually, encompassing a broader variety of agricultural products. In 2002, one year after China joined the WTO, Brazil's share of the Chinese agricultural market reached around 12 %, doubling from 6 % in 2000[3]. This percentage grew to 28 % in 2018. Given the central role of water in agricultural production and the growing concerns over global water scarcity, quantifying the volume of virtual water embedded in these exports can inform policies aimed at more efficient resource use. This study therefore asks: how much fresh water does Brazil effectively transfer to China through its main agricultural exports, and what does this imply for water management in both countries?

China, due to its vast territory and large population, faces challenges in food production, leading to government policies that promote internal development and the importation of agricultural products[4]. Brazil is a key trading partner, particularly in supplying agro-food products. This partnership is supported by classical Hecksher-Ohlin factor endowment theory which suggest that nations should produce and export goods that intensively use the resources they have in abundance, and the modern theory of new comparative advantages, which emphasizes specialization and innovation as drivers of international trade[5].

Countries experiencing water scarcity can adopt the strategy of importing water-intensive products and exporting goods that make more efficient use of water. This approach aims to improve global water efficiency through production and trade standards, reinforcing the validity and application of international trade theory. In the case of agricultural goods, Brazil stands out due to its abundance of arable land and water resources, enabling it to produce and offer water-intensive goods on a global scale. Moreover, the country invests in technology and efficient production methods, establishing itself as a leader in the large-scale production and export of these products[6].

Fresh water, suitable for human consumption and productive activities, represents only 2.53 % of all water on the planet. Brazil holds 13.22 % of this globally available resource, making it the country with the largest freshwater reservoir in the world[7]. Consequently, Brazil has comparative advantages in agricultural production, owing to water availability, soil quality, and specific climatic conditions[8]. However, water reserves are unevenly distributed across Brazilian territory, affecting mainly the northeast and southeast regions, which concentrate the country's largest population but still contribute to the international agricultural market[9].

China holds 6.57 % of the world's available water resources, ranking as the fifth largest holder of this resource[10]. However, its average per capita water volume (m^3) is below the world average. The low relative availability of water and its unsustainable use compromise the country's food supply, necessitating the import of water-intensive products to meet domestic demand[11].

Globally, about 70 % of water consumption is used by the agricultural sector, 20 % by the industrial sector, and 10 % for domestic consumption[12]. In Brazil, the agricultural sector is the largest consumer of water, accounting for approximately 60 % of total consumption[13]. Irrigation is the primary use of water in this sector. However, to increase the supply of agricultural products, Brazilian producers need to expand irrigated areas, thereby increasing water consumption without necessarily maximizing resource efficiency[14].

As one of the main exporters of primary products on the international market, Brazil indirectly exports the resources and inputs used in its production[15]. In 2022, about 31.92 % of Brazilian exports were destined for China, making it the largest importer of Brazilian

[1] Conceição; Conceição, 2014.
[2] Pella, 2019.
[3] Pizzol et al., 2023.
[4] Chiquesi; Nunes, 2022.
[5] Feenstra, 2015.
[6] Hoekstra; Hung, 2002.
[7] Shiklomanov; Rodda, 2003.
[8] Licks; Gelain; Almeida, 2017.
[9] Martins; Gelain; Almeida, 2020. Montoya; Finamore, 2020.
[10] Licks; Gelain; Almeida, 2017.
[11] Bispo; Martins; Cechin, 2022.
[12] Martins; Gelain; Almeida, 2020.
[13] Carmo et al., 2007.
[14] Carmo et al., 2007.
[15] Martins; Gelain; Almeida, 2020.

products[16]. The eight most exported agricultural products include sugar, cotton, beef, pork, poultry, soybean oil, soybeans, and tobacco, representing 98.24 % of the value of China's agricultural imports from Brazil between 2012 and 2022. This underscores the importance of examining the production of these goods in terms of water usage.

The concept of "virtual water" refers to the volume of fresh water used in the production process of a good or service. Building on the dataset of Mekonnen and Hoekstra (2010), the variable AVW captures the water footprint per unit of each product, while VVWE represents the total virtual water exported, calculated by multiplying export quantities by the corresponding AVW. We apply this approach to Brazil's eight most exported agricultural products: sugar, cotton, beef, pork, poultry, soybean oil, soybeans and tobacco, between 2012 and 2022, the paper quantifies the virtual water flows from Brazilian states to China. This state-level analysis highlights regional disparities in water use efficiency and supports discussions on how virtual water trade may alleviate water stress in importing countries.

Water scarcity in many parts of the world directly affects food production due to the high water consumption demanded by the agricultural industry[17]. Thus, it is relevant to analyze Brazil's indirect exports of this resource and discuss the water implications in productive and regional terms. This raises the question: do the regions that export to China have water efficiency in production compared to other regions in Brazil? Despite having the largest water reservoir in the world, some Brazilian regions suffer from shortages, which could worsen without adequate water policies, affecting food supply and long-term food security. Furthermore, the study seeks to investigate whether virtual water trade between Brazil and China can be a strategy to mitigate water pressure in the Asian country and improve the use of its water resources. This analysis contributes to a broader understanding of the dynamics of international trade, particularly in the context of efficient water resource management amid global water scarcity challenges.

In the context of climate change, variations in rainfall and temperature impact microclimates and the availability of surface water globally[18]. This impact is especially important for the agricultural sector, emphasizing the importance of water management on farms, water storage, soil conservation, and irrigation. Therefore, it is necessary to discuss the use of water in agriculture and international trade policies as a way to support adaptation measures in agricultural processes, including the development of drought-resistant crops and agricultural and landscape diversification in response to climate change[19].

Implementing policies can contribute to the sustainable management of water resources, including water monitoring and planning to deal with extreme weather events, efficient water use policies, crop diversification, and increased investments in technology and research aimed at developing more drought-resistant crops, as well as more water-efficient agricultural practices.

The text is organized into five sections, starting with this introduction. Section 2 discusses the concept of virtual water, with an emphasis on studies that apply it to analyses of international trade. Section 3 presents the methodology and data sources used. Section 4 presents the research results and discusses Sino-Brazilian water efficiency. Finally, the last section provides final remarks.

Virtual water and developments in international trade

Virtual water trade, represented by the volume of water embedded in exported products, has increased as countries become more involved in international exchanges[20]. An analysis of Brazilian soy and beef exports reveals that China was the main importer of soy from Brazil between 2011 and 2016, accounting for over 40 % of all soy exported by the country. Due to the relevant quantity and high water consumption in the production of soy, the virtual water flow associated with this trade is substantial[21].

Products from the soybean complex and beef are the Brazilian agribusiness items that require the most water for their production[22]. The export of these products implies the indirect transfer of water resources to China, which faces water scarcity. Thus, importing water-intensive products serves as a strategy to alleviate water stress in China.

[16] Agrostat, 2023.
[17] Yang et al., 2006.
[18] IPCC, 2023.
[19] IPCC, 2023.
[20] Dalin et al., 2012.
[21] Licks; Gelain; Almeida, 2017.
[22] Licks; Gelain; Almeida, 2017.

Study on Brazilian fruit exports found that the average amount of water used in producing these products in Brazil is lower than the world average[23]. They concluded that Brazilian fruit exports contribute to more rational water use in trade, as importing countries would generally use more water to produce the same quantity of goods domestically. These results support classic international trade theories, which are based on the specialization and export of goods intensive in a country's abundant resources.

Another analysis assessed virtual water exports from Brazilian states without focusing on a specific class of products[24]. This analysis determined whether the states (STs) that export the most virtual water are those with the greatest water resource availability. The results revealed that, in 2013, the largest net exporters of virtual water were Mato Grosso, Paraná, Rio Grande do Sul, São Paulo, Minas Gerais, and Goiás, which accounted for 92 % of the country's net virtual water exports. These states also have greater freshwater availability. The net importers were Ceará, Rio de Janeiro, and Pernambuco, which acquired 81% of all virtual water imported by Brazil that year. Bahia was identified as the only state facing water shortages but still exporting water-intensive products. Conversely, Amazonas and Rio de Janeiro, despite having broad access to water resources, are net importers. These findings align with the study, who observed that Mato Grosso, Paraná, and Rio Grande do Sul are the main exporters of virtual water[25].

Both studies analyzed the amount of water exported by Brazilian regions but did not address the efficiency of the states that exported the most virtual water. However, both suggest that these states have adequate water availability. The first one found that Santa Catarina is the most efficient state in fruit production in terms of water use relative to the amount exported[26]. Although it is not the largest fruit producer, the state uses less water in production. This contrasts with the concentration of fruit production and exports in the Northeast, a region relatively less abundant in water resources.

It has been shown that Brazil presents the lowest average price per cubic meter of water compared to other countries[27]. Although many products exported in 2016 were destined for regions with abundant water resources, roughly 39 percent of the total water volume traded between 2002 and 2016 was delivered to economies with more limited reservoirs. This pattern suggests that international trade enables nations endowed with plentiful water to supply water-intensive goods to markets facing scarcity. A complementary analysis indicates that over time the global food trade has contributed to more efficient allocation of water resources[28].

A decomposition-based method for assessing sectoral demand-side water stress revealed that, at the aggregate level, the Brazilian economy exhibited a moderately weak water-stress state[29]. Within this framework, the livestock and forestry sectors were characterized by strong stress levels, while sixteen other economic activities displayed moderately weak stress. A focused study of sugarcane production in Paraná from 2010 to 2020 found that the Northwest mesoregion recorded the highest average water footprint (249.3 $m^3 Mg^{-1}$) and the North Pioneer mesoregion the lowest (179.35 $m^3 Mg^{-1}$), yielding an overall mean of 206.63 $m^3 Mg^{-1}$. In addition, an examination of the linkage between economic growth and water consumption in Brazil demonstrated strong decoupling in the domestic market but expansive negative decoupling in the export sector, with exports driving GDP growth at the cost of greater water use, especially in primary-exporting agriculture and livestock activities.

Although trade may alleviate stress on water-deficient economies, exporting substantial volumes of virtual water from countries without adequate reserves can jeopardize the exporter's own water sustainability[30]. Consequently, effective policy measures are necessary to ensure virtual water sustainability, emphasizing the relevance of water footprint (WF) assessment for enhancing water resource management.

The WF is a method used to quantify the volume of water (in m^3) used in producing goods[31]. It goes beyond the direct consumption of water by consumers or producers and includes the indirect use of this resource throughout the production chain.[32] Thus, WF is a comprehensive indicator of water resource appropriation, surpassing the traditional measure of water consumption.

The WF of a product covers the use of blue, green, and gray water. Blue water refers to surface and

[23] Martins, Gelain; Almeida, 2020.
[24] Gelain, 2020.
[25] Licks; Gelain; Almeida, 2017.
[26] Martins; Gelain; Almeida, 2020.
[27] Gelain, 2020.
[28] Dalin et al., 2012.
[29] Allegretti; Montoya; Talamini, 2022.
[30] Nishad; Kumar, 2022.
[31] Hoekstra et al., 2011.
[32] Hoekstra et al., 2011

groundwater resources used in processes such as irrigation. Green water represents the volume of rainwater consumed during production, which is important for agriculture as it reduces the need for irrigation and associated costs. Gray water is related to the volume of clean water necessary to dilute the pollution generated during the production process. The calculation of green and blue water footprints of primary crops involves dividing the total volume of water used (m³/year) by the total quantity of crop produced (ton/year) over the specified period[33]. The gray water footprint is calculated as the volume of clean water required to dilute the polluted water resulting from the production process.

Determining the water footprint associated with animal products involves specific considerations different from those for primary products, since higher feed requirements increase the volume of water used for feed production, variations in moisture content across different feed types directly influence the water footprint of the final product, and regional differences in agricultural practices affect the calculation, with areas that use water less efficiently exhibiting larger water footprints for animal commodities[34].

Moreover, different animal production systems, such as industrial, pasture, and mixed systems, can influence these factors[35]. For example, the industrial production system, compared to pasture, tends to have a higher blue and gray water footprint, while the pasture system has a higher green water footprint. The WF of mixed system products generally falls between those of industrial and pasture systems.

These findings collectively support the research problem addressed in this study by providing methodological frameworks and evidence about water efficiency variations across sectors and regions, enabling the examination of whether virtual water trade can serve as a mechanism for improving global water resource allocation, particularly in addressing water scarcity challenges in importing countries like China.

Methodology

The products covered in this study were selected based on China's demand for agricultural products from Brazil. Data on Brazilian exports at the state level were collected from the COMEX STAT portal, a system for consulting and extracting data on Brazilian foreign trade. Additionally, information on the volume of virtual water (Brazilian average) in cubic meters (m³) associated with these products was obtained from the Mekonnen and Hoekstra[36] database. Table 1 provides details on the products and their NCM codes (Mercosur Common Nomenclature). To simplify and ensure objectivity in the presentation of results, the complete product descriptions have been reduced to their generic names.

To estimate the volume of virtual water exported by each Brazilian state from the mentioned products, the equation (1)[37]:

$$VVWE_{i,e,c,j} = Q_{export,i,e,c,j} \times AVW_{i,e} \quad (1)$$

Where $VVWE_{i,e,c,j}$ represents the volume of virtual water exported, m³, by Brazil, of product *i* by the state *e* to country *c* in year *j*; $Q_{export,i,e,c,j}$ corresponds to the net weight

Table 1. Description of products

CODE NCM	FULL DESCRIPTION	SHORT DESCRIPTION
020230	Beef meat, boneless, frozen	Beef
020329	Other pork meat, frozen	Pork
020714	Edible pieces and offal from cocks and poultries of the domestic species, frozen	Poultry
120190	Soya, whether crushed, other than for sowing	Soybeans
150710	Soybean oil, raw, whether degummed	Soy oil
170114	Other cane sugars	Sugar
240120	Unmanufactured smoke, fully or partially detached	Tobacco
520100	Cotton, not carded or combed	Cotton

Source: Author's elaboration.

[33] Mekonnen; Hoekstra, 2010a.
[34] Mekonnen; Hoekstra, 2010b.
[35] Mekonnen; Hoekstra, 2010b.
[36] Mekonnen; Hoekstra, 2010a; 2010b; 2010c.
[37] Licks; Gelain; Almeida, 2017.

in tons of product *i* exported by state *e* country *c* in year *j*; the variable $AVW_{i,e}$ refers to the amount of virtual water used in the production of product *i* in state *e*, in m³. The $AVW_{i,e}$ values is determined by dividing the total volume of water used in production (m³/year) by the total quantity produced (ton/year) for each crop and livestock product across different regions and production systems[38]. The rationale behind equation (1) lies in the principle that international trade in agricultural products constitutes an indirect transfer of the water resources embedded in those products, making it possible to quantify the virtual water flows between countries and assess the water implications of trade relationships. Although conceptually related to the WF, VVWE in this study refers exclusively to the volume of virtual water associated with Brazilian agricultural exports to China, expressed in m³.

The volume of virtual water exported from Brazil to China by each Brazilian state is estimated using equation (1). The total volume of virtual water exported is calculated by summing the virtual water associated with specific trade flows in each state. Some methodological procedures are justified based on relevant facts[39]:

- ✓ The data used for the virtual water volume of agricultural products is the average observed for each Brazilian state. When there is no information for a product in a given state, the national average for that product in Brazil is used.
- ✓ For livestock products, the available information on the volume of virtual water refers only to the Brazilian national average, as there is no data for individual federative units. Considering that Brazil employs both pasture and industrial production systems, the virtual water analysis is conducted for the mixed production system.
- ✓ The final year of this study is 2022 due to the availability of export data when the research commenced. To ensure a comprehensive analysis, a ten-year time frame was established, starting in 2012, following a temporal strategy similar to previous studies[40].

Results and discussions

This study aims to conduct a state-level analysis of virtual water exports from Brazil to China, examining the water efficiency implications of agricultural trade between these countries. The analysis focuses on quantifying virtual water flows embedded in eight key agricultural products exported from Brazilian states to China between 2012 and 2022, while evaluating regional variations in water use efficiency and their implications for sustainable water resource management.

The same product may require different volumes of water depending on the region where it is produced. Climatic and productivity conditions, such as soil quality and topography, directly influence water usage in production[41]. However, to simplify the analysis, following the methodologies of some authors[42], production efficiency is assessed exclusively based on water use, without considering other production conditions.

Figure 1 shows the distribution of Brazilian goods exported to China between 2012 and 2022. It is observed that shipments of soybeans dominate the bilateral trade balance, followed by sugar, poultry, beef, soybean oil, cotton, pork, and tobacco.

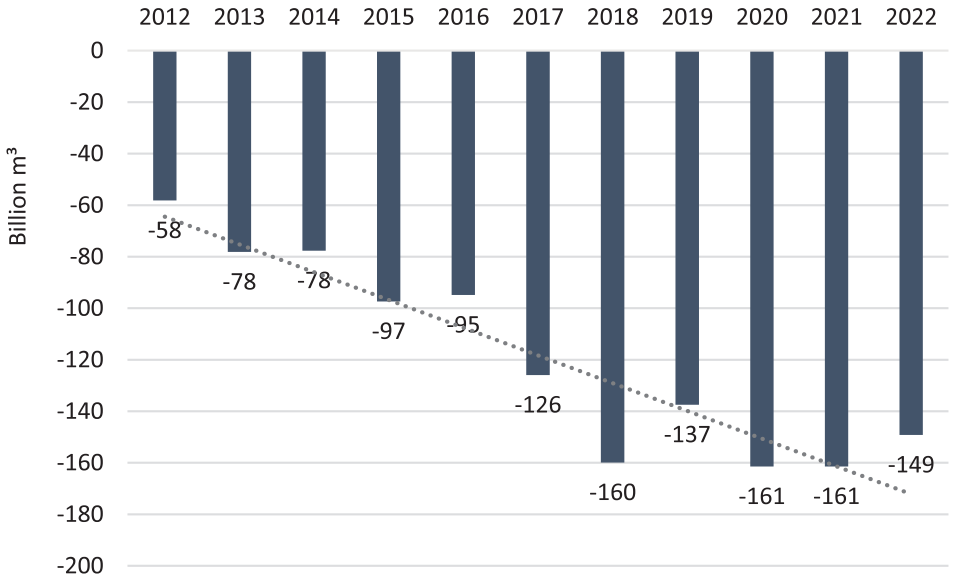
Table 2 presents the water footprint data for the eight agricultural products analyzed in this study, showing the volume of water required to produce one ton of each product. The table displays both Brazilian and global averages for green, blue, and gray water footprints, enabling comparison of Brazil's water use efficiency relative to global standards. For animal products, the data includes different production systems (industrial, grazing, and mixed) to reflect the diversity of livestock production methods. The virtual water values shown in this table serve as the basis for calculating the total volume of virtual water exported through equation (1), with the mixed production system values used for livestock products to represent Brazil's predominant production approach.

When considering the volume of virtual water for the eight products analyzed, and accounting for the mixed system for animal-origin products, it appears that sugar, cotton, poultry, and tobacco have a Brazilian average of virtual water that is lower than the global average. Conversely, beef, pork, soybean oil, and soybeans have a Brazilian average that is higher than the world average.

In animal production systems, the green footprint is smaller in the pasture-based system than in the industrial option for beef and poultry categories. In the case of pork, the industrial system requires a greater volume of water. Generally, meat production in Brazil requires

[38] Mekonnen; Hoekstra, 2010a.
[39] Licks; Gelain; Almeida, 2017.
[40] Licks; Gelain; Almeida, 2017. Martins; Gelain; Almeida, 2020.
[41] Herrera et al., 2019.
[42] Licks; Gelain; Almeida, 2017. Martins; Gelain; Almeida, 2020. Gelain, 2020.

Figure 1. Main Brazilian products exported to China in the period 2012-2022



Source: Author's elaboration based on Comexstat data.

Table 2. Quantity of water required to produce one ton of the good (in m³). Brazilian average and global average, according to Equation 1

PRODUCTS			BRAZILIAN AVERAGE								GLOBAL AVERAGE							
			Green WF		Blue WF		Gray WF		Virtual Water		Green WF		Blue WF		Gray WF		Virtual Water	
NCM (Mercosur Common Nomen-clature)	Product Description	Type of Production	Qt	%	Qt	%	Qt	%	Qt	%	Qt	%	Qt	%	Qt	%	Qt	%
020230	Beef	Industrial	8.421	96%	147	2%	244	3%	8.812	100%	8.849	85%	863	8%	712	7%	10.424	100%
		Grazing	23.729	99%	150	1%	16	0%	23.895	100%	21.121	97%	465	2%	243	1%	21.829	100%
		Mixed	20.604	99%	187	1%	61	0%	20.852	100%	14.803	94%	508	3%	401	3%	15.712	100%
020329	Pork	Industrial	8.184	92%	215	2%	525	6%	8.924	100%	4.050	78%	487	9%	687	13%	5.224	100%
		Grazing	5.482	73%	1.689	23%	318	4%	7.489	100%	7.660	88%	431	5%	632	7%	8.723	100%
		Mixed	5.109	82%	828	13%	316	5%	6.253	100%	5.210	84%	435	7%	582	9%	6.227	100%
020714	Poultry	Industrial	3.723	94%	24	1%	213	5%	3.960	100%	2.337	81%	210	7%	325	11%	2.872	100%
		Grazing	6.363	94%	35	1%	364	5%	6.762	100%	7.919	85%	734	8%	718	8%	9.371	100%
		Mixed	4.073	94%	32	1%	233	5%	4.338	100%	4.065	82%	348	7%	574	12%	4.987	100%
120190	Soybeans		2.181	99%	1	0%	15	1%	2.197	100%	2.037	95%	70	3%	37	2%	2.144	100%
150710	Soy oil		4.177	99%	2	0%	29	1%	4.208	100%	3.900	95%	135	3%	71	2%	4.106	100%
170114	Sugar		968	89%	43	4%	80	7%	1.091	100%	1.107	66%	455	27%	104	6%	1.666	100%
240120	Tobacco		2.089	94%	5	0%	124	6%	2.218	100%	2.021	69%	205	7%	700	24%	2.926	100%
520100	Cotton		4.995	78%	40	1%	1365	21%	6.400	100%	5.163	57%	2955	32%	996	11%	9.114	100%

Source: Own elaboration based on virtual water data[43].
Note: Products indicated by NCM code – Mercosur Common Nomenclature. Qt refers to the amount of water in m³/ton. WF refers to the Water Footprint of the product.

[43] Mekonnen; Hoekstra, 2010a, 2010b, 2010c.

a greater average volume of virtual water than the world average, with exceptions for beef in the industrial system, pork on pasture, and poultry in pasture and mixed systems.

For plant-origin products, the virtual water requirement for sugar, tobacco, and cotton is lower in Brazil than the world average. However, the opposite is true for soybeans and soybean oil.

To calculate virtual water, data relating to products of animal origin do not include information on the water footprint disaggregated by STs; only national and global averages are available. As a result, the water volume incorporated in animal products from the aforementioned states was prepared based on separate tables for agricultural products and products of animal origin. This distinction is necessary because, for agricultural products, there is information that allows analysis by state. The results are presented in Table 3 and Table 4.

In the analysis of water resources, it is observed that the states with the largest export flows to China are not necessarily the most efficient in terms of water use. This is because some states require less water to produce these goods compared to the main exporting states, indicating variations in water efficiency across the country. For cotton, soybeans, and soybean oil, the virtual water of the main exporting states is lower than the national average. Conversely, for sugar and tobacco, the predominant exports from Mato Grosso and Rio Grande do Sul, respectively, require a greater volume of water than the Brazilian average.

In terms of water efficiency, the states that could specialize in the production and export of sugar, cotton, soybean oil, soybeans, and tobacco are Santa Catarina, Tocantins, Maranhão (for soybeans and soybean oil), and Amazonas, respectively, as these states require the smallest volume of water to produce these goods.

Table 3. Water footprint of agricultural products exported to China (m^3) by state: maximum, minimum, and national average values, according to Equation 1

PRODUCTS			SUGAR	COTTON	SOY OIL	SOYBEANS	TOBACCO
Maximum	State		RN	RN	MS	MS	MS
	Quantity	Green Water	1.231	5.394	4.871	2.544	2.389
		Blue Water	88	29	3	2	105
		Gray Water	85	2.513	30	16	122
		Virtual Water	1.404	7.936	4.904	2.562	2.616
Minimum	State		SC	TO	MA	MA	AM
	Quantity	Green Water	745	4.275	3.117	1.628	1.700
		Blue Water	0	0	0	0	0
		Gray Water	48	1.062	27	14	115
		Virtual Water	793	5.337	3.144	1.642	1.815
Brazilian Average	Quantity	Green Water	968	4.995	4.177	2.181	2.089
		Blue Water	43	40	2	1	5
		Gray Water	80	1.365	29	15	124
		Virtual Water	1.091	6.400	4.208	2.197	2.218
State that exports the most (tons)	State			MT	PR	MT	RS
	Quantity	Green Water	910	5.029	4.534	1.924	2.126
		Blue Water	28	0	1	0	0
		Gray Water	81	1.064	30	14	117
		Virtual Water	1.019	6.093	4.565	1.938	2.243

Source: Own elaboration based on virtual water data[44] and Comexstat.
Note: RN = Rio Grande do Norte; MS = Mato Grosso do Sul; TO = Tocantins; MA = Maranhão; AM = Amazonas; MT = Mato Grosso; PR = Paraná; RS = Rio Grande do Sul; SC = Santa Catarina.

[44] Mekonnen; Hoekstra, 2010a, 2010b,2010c.

Table 4. Water footprint of livestock products exported to China (in m³/ton) by Brazilian states. Maximum, minimum and national average value, according to Equation 1

PRODUCTS	BRAZILIAN AVERAGE				GLOBAL AVERAGE		
	State that exports the most	Quantity			Quantity		
		Industrial	Grazing	Mixed	Industrial	Grazing	Mixed
Beef	SP	8.812	23.895	20.852	10.424	21.829	15.712
Poultry	PR	3.960	6.762	4.338	2.872	9.371	4.987
Pork	SC	8.924	7.489	6.253	5.224	8.723	6.227

Source: Own elaboration based on virtual water data[45] and Comexstat.

Regarding products of animal origin, this study quantifies virtual water for the mixed production system, following the same strategy adopted in literature[46]. This choice reflects the duality of production systems in Brazil, which includes both pasture and industrial systems. According to Table 3, the national average for the mixed production system for pork and beef is higher than the global average. Consequently, the country shows water efficiency only in the production of poultry. According to the Brazilian average, beef requires the greatest amount of water in the production process, followed by cotton, pork, poultry, soybean oil, tobacco, soybeans, and sugar. Notably, soybean oil demands nearly double the volume of water required to produce soybeans, attributed to the processing stage of converting grains into oil.

Figure 2 shows the volume of virtual water exported from Brazil to China for all selected products between 2012 and 2022. The negative sign denotes the indirect exit of water from the country through these exports. The water flow exhibited an oscillatory trajectory over the years investigated, but with an overall increasing trend. There was an increase in virtual water output starting in 2017, peaking in 2020 with an output flow of approximately 161.461 million m³. In 2022, there was a decrease to 149.184 million m³. The maximum value reached in 2020 represents a 178 % variation compared to 2012 (the year with the lowest result), while from 2020 to 2022, there was an 8 % negative variation in the volume of virtual water sent to China.

In 2019, despite the increase in Chinese imports of five of the eight products analyzed, there was a reduction in the volume of virtual water sent to China due to a decrease in Brazilian exports of soybeans and soybean oil to the Asian country. This drop was influenced by the end of trade tensions between the United States and China[47]. It was also affected by global outbreaks of the swine fever crisis and the economic crisis in Argentina, which impacted exports of soybeans and derivatives.

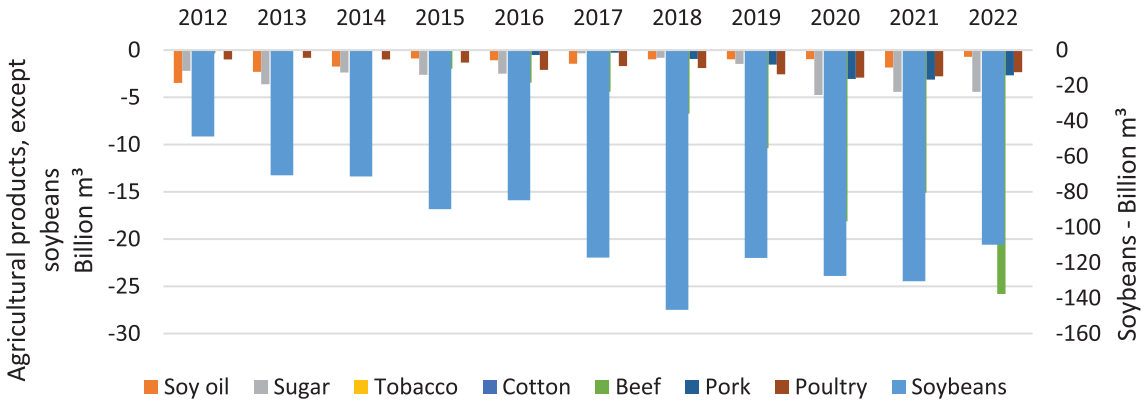
Table 5 complements Figure 2, indicating the volume exported to China during the period in millions of m³ and their respective percentages. In 2012, the amount of water sent to the Chinese market was the lowest in the period analyzed, representing approximately 4.5 % of the total sent over the eleven years. The years 2020 and 2021 had similar volumes of water sent, with a difference of 26 million m³, corresponding to a negative variation of 0.02 % in 2021 compared to 2020.

In terms of quantity exported, 2018 recorded the highest volume of products sent to China, approximately 70 million tons. However, the most exported products that year had smaller water footprints, such as soybeans, soybean oil, and tobacco, resulting in a smaller volume of virtual water exported compared to 2020 and 2021. Despite 2020 showing a greater volume of virtual water exported, the quantity sent was lower than in 2021, with a difference of 966.557 tons, indicating a variation of 1.5 %. The main reasons for this difference are the drop in the quantity exported of products with larger water footprints, such as beef, poultry, and cotton, and an increase in exports of products that require less water in production, such as soybeans, soybean oil, and tobacco.

Figure 3 illustrates the evolution of the volume of virtual water exported to China from the eight products analyzed. Soy is the most important Sino-Brazilian commercial item, representing 36.20 % of exports to the Asian country during the period investigated. For this reason, the virtual water flows for soybeans are presented on the right axis of the graph, allowing for a separate analysis relative to the other products. Furthermore, due to its water demand, soybeans were

[45] Mekonnen; Hoekstra, 2010a, 2010b, 2010c.
[46] Licks; Gelain; Almeida, 2017.
[47] Nakabashi, Teixeira; Roveri, 2020.

Figure 2. Volume of virtual water exported to China, for the products investigated, in the period 2012-2022. The dotted line represents the trend line, according to Equation 1



Source: Author's elaboration based on Comexstat data.

Table 5. Volume of virtual water exported per year for the products studied and their respective percentages from 2012 to 2022, according to Equation 1

VOLUME OF VIRTUAL WATER EXPORTED IN MILLIONS OF M³										
YEAR	SOYBEANS	SOY OIL	SUGAR	TOBACCO	COTTON	BEEF	PORK	POULTRY	TOTAL	%
2012	-48.769	-3.468	-2.197	-141	-2.255	-345	-19	-986	-58.179	4.5%
2013	-70.690	-2.307	-3.609	-126	-611	-4	-8	-825	-78.178	6.0%
2014	-71.294	-1.747	-2.378	-97	-1.145	-2	-5	-987	-77.656	6.0%
2015	-89.780	-893	-2.610	-97	-656	-1.964	-30	-1.331	-97.360	7.5%
2016	-84.789	-1.075	-2.489	-97	-359	-3.435	-521	-2.098	-94.863	7.3%
2017	-117.141	-1.449	-345	-92	-518	-4.405	-282	-1.696	-125.929	9.5%
2018	-146.580	-975	-816	-57	-1.906	-6.720	-943	-1.903	-159.898	12.3%
2019	-117.265	-969	-1.471	-149	-3.149	-10.378	-1.526	-2.559	-137.467	10.6%
2020	-127.469	-961	-4.760	-71	-4.119	-18.113	-3.056	-2.912	-161.461	12.4%
2021	-130.461	-1.849	-4.428	-81	-3.635	-15.079	-3.129	-2.773	-161.434	12.4%
2022	-109.821	-707	-4.428	-172	-3.234	-25.814	-2.667	-2.341	-149.184	11.5%
Total	-1.114.059	-16.400	-29.528	-1.179	-21.588	-86.259	-12.185	-20.410	-1.301.609	100.0%

Source: Own elaboration based on virtual water data[48] and Comexstat.

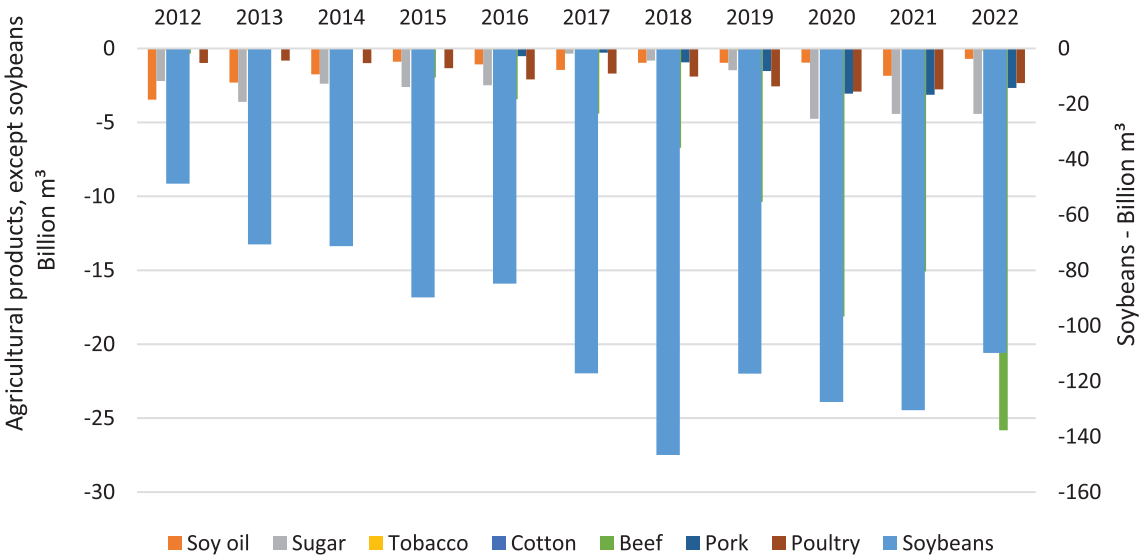
the product that most indirectly transferred water resources to China.

In 2012, beef exports to China were interrupted due to the first recorded case of Bovine Spongiform Encephalopathy (BSE), commonly known as "mad cow" disease[49]. The embargo imposed by China was lifted in 2015, resulting in an increase in Brazilian beef exports and, consequently, an increase in the volume of virtual water exported through this product (Figure 3). In 2014, 2,20 million m³ were exported, while in 2015 the volume was approximately 1.964 million m³. During this period, the quantity of beef exported increased from 16.537 tons in 2012 to 1.237.961 tons in 2022, totaling 4.136.712 tons over the years analyzed.

Table 6 presents the quantity of each product exported in thousands of tons, the value exported in millions of dollars, and the volume of virtual water exported in millions of m³, along with their respective percentages. Although the quantity of cotton exported in thousands of tons is greater than the quantity of beef, the volume of virtual water associated with exporting beef to China is more than double that associated with

[48] Mekonnen; Hoekstra, 2010a, 2010b, 2010c.
[49] Silveira, 2023.

Figure 3. Volume of virtual water exported in billions of m³ to China in the period 2012-2022, products studied individually, according to Equation 1



Source: Author's elaboration based on Comexstat data.

Table 6. Quantity exported in thousands of tons, value exported in millions of dollars, and volume of virtual water exported in millions of m³ from 2012 to 2022

PRODUCTS	QUANTITY EXPORTED (THOUSANDS OF TONS)	QUANTITY EXPORTED (%)	EXPORTED VALUE (MILLIONS OF DOLLARS)	EXPORTED VALUE (%)	VVWE (VOLUME OF VIRTUAL WATER EXPORTED) MILLION M³	VVWE (VOLUME OF VIRTUAL WATER EXPORTED) (%)
Sugar	28.282	5.0%	9.989	3.6%	−29.528	2.3%
Cotton	3.445	0.6%	6.054	2.2%	−21.588	1.7%
Beef	4.137	0.7%	22.232	7.9%	−86.259	6.6%
Poultry	4.705	0.8%	9.598	3.4%	−20.410	1.6%
Pork	1.949	0.3%	4.721	1.7%	−12.185	0.9%
Soy oil	3.753	0.7%	3.482	1.2%	−16.400	1.3%
Soy	515.258	91.7%	221.161	78.8%	−1.114.059	85.6%
Tobacco	525	0.1%	3.434	1.2%	−1.179	0.1%
Total	562.054	100.0%	280.672	100,0%	−1.301.609	100.0%

Source: Own elaboration based on virtual water data[50] and Comexstat.

cotton. This occurs because the amount of water used in the meat production process is greater.

Furthermore, it is notable that the value of beef exported by Brazil, in millions of dollars, places the product in the second most exported position, behind only soybeans, which have a notably high volume exported in tons. The increase in Chinese average income and the population's awareness of a nutritious diet have led to increased consumption of goods with higher added value, such as beef. Therefore, the value of beef is relatively high compared to other products.

Regarding the quantity exported in tons, soybeans represent 91.7 % of shipments sent relative to other products, followed by sugar with 5 %, poultry (0.8 %), beef and soybean oil (0.7 % each), cotton (0.6 %), pork (0.3 %), and tobacco (0.1 %).

The results in Table 7 indicate that from 2012 to 2022, around 1.3 trillion m³ of virtual water were exported through the analyzed products, equivalent to approximately 520,64 million full Olympic swimming pools. About 85.6 % of this total volume is represented by soybeans, which sent an average of 1,11 trillion m³ of water to China, corresponding to approximately 445,6 million full Olympic swimming pools. The table also presents

[50] Mekonnen; Hoekstra, 2010a, 2010b, 2010c.

Table 7. Main states export virtual water by agricultural products from 2012 to 2022

PRODUCT	STATE	VIRTUAL WATER	VOLUME (MILLIONS OF M³)	PERCENTAGE OF WATER VOLUME EXPORTED
Sugar	SP	1.020	−20.477	69%
	MG	1.127	−5.748	20%
	Others	BR average: 1.091Global average: 1.666	−3.304	11%
Cotton	MT	6.094	−12.900	60%
	BA	6.698	−5.201	24%
	Others	BR average: 6.400Global average: 9.114	−3.487	16%
Beef	SP	-	−28.170	33%
	MT	-	−16.591	19%
	Others	BR average: 20.852	−41.498	48%
		Global average: 15.712		
Poultry	PR	-	−9.258	45%
	SC	-	−4.547	22%
	Others	BR average: 4.338Global average: 4.987	−6.605	33%
Pork	SC	-	−7.806	64%
	RS	-	−4.159	34%
	Others	BR average: 6.253Global average: 6.227	−221	2%
Soy oil	PR	4.565	−6.549	40.0%
	RS	4.719	−4.161	25.0%
	Outros	BR average: 4.208Global average: 4.106	−5.690	35.0%
Soybeans	RS	2.462	−233.105	20.9%
	MT	1.938	−230.438	20.7%
	Others	BR average: 2.197Global average: 2.181	−650.516	58.4%
Tobacco	RS	2.244	−1.169	99.0%
	Others	BR average: 2.218Global average: 2.926	−9	1.0%

Source: Own elaboration based on virtual water data[51] and Comexstat.
Note: SP = São Paulo; MT = Mato Grosso; PR = Paraná; SC = Santa Catarina; RS = Rio Grande do Sul.

the quantity of virtual water associated with different products, highlighting the two main exporting states for each item. The state highlighted in this table leads in exporting the corresponding product.

Although São Paulo is not the one with the lowest water demand in sugar production, as indicated in Table 2, it is relatively more efficient in terms of water compared to the second-largest exporter, Minas Gerais, which requires a higher quantity of water. This analysis can be applied to other agricultural products, where the largest exporter has a lower water demand than the second-largest. In all cases, the production of the second-largest exporter does not coincide with the most water-efficient state. The same analysis could not be carried out for products of animal origin due to the lack of data by UF.

In the case of soybeans, Mato Grosso's water demand is lower than the volume required by Rio Grande do Sul, indicating greater water efficiency. According to COMEXSTAT data, Mato Grosso is the largest exporter of soybeans in Brazil and the main exporter to China. Despite the large quantity exported, Mato Grosso does not send the most water indirectly, as it requires less water in production than Rio Grande do Sul. If the objective is to adopt policies to reduce water demand in production, Mato Grosso should produce more soybeans than Rio Grande do Sul.

Study about the profitability of soybean cultivation in Rio Grande do Sul from 2004 to 2015[52], concluded that, although soybean prices and costs are strongly influenced by external prices, profitability is increasingly linked to productivity gains. During the period

[51] Mekonnen; Hoekstra, 2010a, 2010b, 2010c.

[52] Colussi et al., 2016.

evaluated, productivity in the state's crops increased by 44 %, impacting profitability. This may stimulate soybean production in Rio Grande do Sul, despite its higher water demand compared to the Brazilian and global averages.

Furthermore, it is worth noting that Mato Grosso not only has an average water consumption in soybean production lower than the national average but also below the global average. This reinforces Mato Grosso's efficiency in water terms for soybean production.

The state of Rio Grande do Sul is predominant in tobacco exports to China, accounting for 99 % of the volume of water sent. Despite this, the water used in production by this state is higher than the Brazilian average, indicating inefficiency in water terms within Brazil. However, compared to the global average, tobacco production in Rio Grande do Sul has lower average water consumption.

Table 8 presents data on the Chinese and Brazilian averages for the volume of water used in the production process of the analyzed products. The objective is to observe the difference between the amount of water China would use if it produced the products it imports from Brazil. The underlined Chinese average values indicate that they are lower than the Brazilian average values. Considering the mixed production system, two of the three animal-origin products (beef and poultry) require less water when produced in China than in Brazil. The same is true for cotton, which also requires less water in China.

Although the average amount of water used in the production process in China is lower for some of the products analyzed, the total volume of virtual water required for all production imported by China from Brazil between 2012 and 2022 would necessitate approximately 1,73 billion m³, equivalent to around 692 million full Olympic swimming pools. This value is 25 % higher than the amount spent on producing these items in Brazil, resulting in a difference of 428,8 billion m³. In other words, production in Brazil uses 428,8 billion m³ less water compared to China. This discrepancy is due to the higher water footprint of soybeans in China, which is the most prominent product in China's import balance.

China has a smaller water reservoir than Brazil, while its population is almost seven times larger than Brazil's[54]. Furthermore, China saw a reduction of

Table 8. Quantity of virtual water used for production according to the Chinese water footprint, according to Equation 1

			CHINESE AVERAGE			BRAZILIAN AVERAGE
NCM	PRODUCT DESCRIPTION	PRODUCTION SYSTEM	VIRTUAL WATER	QUANTITY (THOUSANDS OF TONS)	VVWE (MILLION M³)	VIRTUAL WATER
		Grazing	16.140			21,121
020230	Beef	Mixed	13.669	4.137	56.545	20,852
		Industrial	13.089			8,812
		Grazing	12.077			7,489
020329	Pork	Mixed	6.299	1.949	12.275	6,253
		Industrial	4.940			8,924
		Grazing	6.557			6,762
020714	Poultry	Mixed	4.207	4.705	19.794	4,338
		Industrial	2.719			3,960
120190	Soybeans			515.258	1.554.019	2.197
150710	Soy oil			3.753	21.672	4.208
170114	Sugar			28.282	46.326	1.091
240120	Tobacco			525	1.509	2.218
520100	Cotton			3.445	18.234	6.400

Source: Own elaboration based on virtual water data[53] and Comexstat.

[53] Mekonnen; Hoekstra, 2010a, 2010b, 2010c.

[54] Chiquesi; Nunes, 2022. Shiklomanov; Rodda, 2003.

around 50 % in its per capita water availability between 1964 and 2020[55]. Given this reality, international trade emerges as a strategy for China to improve the management of its water resources and address issues related to water scarcity through virtual water trading.

The results presented reveal interesting particularities about the relationship between Brazilian agricultural production, exports to China, and water use. When examining the profile of exports to China, soybeans lead the bilateral trade balance, followed by other products such as poultry, beef, and sugar. The analysis of the water footprint reveals differences between products, with beef requiring the greatest amount of water. Water efficiency varies among exporting states, indicating that the largest exporters are not always the most efficient in terms of water use.

The regional variations across Brazilian states reflect the complex interplay of climatic, technological, and agricultural management factors that influence water productivity in agricultural systems. States located in regions with favorable rainfall patterns and soil conditions, such as those in the Amazon basin, tend to rely more heavily on green water resources, resulting in lower blue water requirements for irrigation. Conversely, states in semi-arid regions may demonstrate higher water use efficiency per unit of production due to the adoption of advanced irrigation technologies and water conservation practices necessitated by water scarcity constraints. The concentration of exports in states that do not necessarily demonstrate the highest water use efficiency suggests that factors beyond water availability, such as infrastructure development, market access, and agricultural specialization, play important roles in determining export patterns. This finding has important implications for policy development, as it indicates potential opportunities for improving the overall water efficiency of Brazil's agricultural exports through strategic investments in water-efficient technologies and production practices in major exporting regions.

Finally, an analysis of the volume of virtual water exported to China highlights an increase over time, with annual fluctuations and a drop in 2022. The relationship between the volume exported and the amount of virtual water consumed per ton of product reveals interesting patterns, such as the importance of soy in this context, being the product that sent the most water indirectly to the Asian country. Comparing Brazilian and Chinese averages of water demand for these products uncovers significant disparities, reinforcing that international trade can serve as a mechanism to improve the allocation and management of water resources in importing countries experiencing scarcity.

Conclusions

Efficient management of natural resources is essential to ensure their preservation for future generations. This study focuses on analyzing the efficient use of water resources indirectly involved in the trade of agricultural products between Brazil and China. The main objective was to quantify the volume of water exported to China from 2012 to 2022, considering eight key products: beff, pork, poultry, soybeans, soy oil, sugar, tobacco and cotton. These products represent approximately 98 % of Brazilian agricultural exports to the Chinese market, with soybeans alone accounting for 91.7 % of these exports.

The findings of this study have important implications for water resource management policies in both Brazil and China, as well as for the understanding of how international trade can contribute to global water security. Based on the Brazilian average of virtual water, beef requires the greatest amount of water in its production process, followed by cotton, pork, poultry, soybean oil, tobacco, soybeans, and sugar. The total volume of virtual water exported amounted to 1,30 trillion m³, with soybeans contributing the largest portion at 85.6 %, equivalent to 1,11 trillion m³. This virtual water transfer serves as an indirect mechanism for addressing water scarcity challenges in China, where per capita water availability has declined substantially over recent decades and agricultural water demands continue to increase.

It was observed that states such as São Paulo and Mato Grosso, which lead in exports of sugar (São Paulo), cotton (Mato Grosso), and soybeans (Mato Grosso) to China, are more efficient in water use, requiring quantities lower than the Brazilian average for production. However, they are not the states with the lowest water demand in the production of these products. In terms of products of animal origin, Brazil's average water footprint for beef and pork is higher than the global average, but the country is more efficient in the production of poultry, with a national average of virtual water lower than the global average.

[55] World Bank, 2023.

The results indicate that the Brazilian average of virtual water for beef, pork, poultry, and cotton is higher than the Chinese average, although the total volume of virtual water exported by Brazil is smaller than if these products were produced in China. This suggests that international trade could help alleviate water scarcity issues in the Asian market.

From a policy perspective, the major exporting states do not always demonstrate optimal water use efficiency, suggesting opportunities for policy interventions that could enhance the sustainability of Brazil's virtual water exports. Policies promoting the adoption of water-efficient agricultural technologies, particularly in states with high export volumes but suboptimal water productivity, could reduce the water intensity of exports while maintaining or increasing export revenues. Investment in precision irrigation systems, drought-resistant crop varieties, and improved water management practices in key exporting regions could enhance Brazil's competitive advantage in global agricultural markets while promoting sustainable water use.

The study's findings also support the development of differentiated water pricing policies that reflect the true value of water resources in agricultural production. States with higher water use efficiency could be incentivized through preferential access to export markets or reduced regulatory burdens, while states with lower efficiency could be targeted for technical assistance and infrastructure development programs. Such policies would promote a more efficient allocation of water resources across Brazil's agricultural sector and enhance the country's long-term competitiveness in global markets.

For China, the results suggest that strategic diversification of agricultural import sources, with emphasis on countries and regions with high water use efficiency, could contribute to global water conservation efforts. The water savings achieved through importing agricultural products from Brazil rather than producing them domestically demonstrates the potential for trade-based approaches to water security. Chinese policies that promote imports from water-efficient producers could create market incentives for sustainable water use practices globally.

The importance of this study extends beyond the bilateral Brazil-China relationship to encompass broader questions of global water governance and sustainable development. As climate change intensifies water scarcity challenges worldwide, understanding the water implications of international trade becomes increasingly important for developing effective adaptation strategies. The methodology and findings here provide a framework for analyzing virtual water trade relationships that can be applied to other country pairs and agricultural products. As a limitation, the water footprint assessment focuses on the use of freshwater, considering the limited resources available. However, this analysis does not address other environmental issues such as climate change, mineral depletion, habitat fragmentation, land limitations, or soil degradation. Moreover, it does not encompass social and economic concerns such as poverty, employment, or well-being unless they are directly linked to the use of freshwater resources, affecting biodiversity, health, well-being, or distributive justice.

Future research should examine the dynamic aspects of virtual water trade, including how climate variability and technological change affect water use efficiency over time. Additionally, expanding the analysis to include environmental and social costs associated with water use could provide a more comprehensive assessment of the sustainability implications of virtual water trade. The integration of virtual water analysis with broader environmental impact assessments would enhance understanding of the trade-offs involved in global agricultural trade and support the development of more sustainable trade policies.

The study demonstrates that virtual water trade represents both an opportunity and a responsibility for countries with abundant water resources. Brazil's position as a major virtual water exporter carries implications for global water security that extend far beyond its borders, highlighting the need for international cooperation in developing sustainable approaches to water resource management in the context of global trade.

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Authorship

Dara Cristina Santos de Araújo: Data collection, data analysis, writing (original draft), and discussion of the results.
Michelle Márcia Viana Martins: Conceptualization, supervision, validation, funding acquisition and writing (review and editing).

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