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Virtual Water Flows of Brazil's International Trade

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Abstract

The study aims to measure virtual water flows in Brazil's international trade. The methodology is based on the input-output matrix, and the database used was the Eora Global Supply Chain Database. The results showed that Brazil exported 230.8 billion m^3 of virtual water per year, representing approximately 34.7% of the water footprint of the national production system in 2015. Virtual water imports totaled 111.6 billion m^3 with a positive balance (net exports) of 119.2 billion m^3. The country is a net exporter of this resource except for trade relations with South America and Africa, regions with negative balances of −36 billion m^3 and 3 billion m^3, respectively. The main destinations for virtual water exports from Brazil are Europe, with 41% of the total exported, followed by Asia and North America, with values close to 20%. The fact that Brazil is a net exporter of water makes sustainable use of the resource important, as the diversity of climate, soil, and water availability at a regional level is a challenge, which makes it essential to increase the efficiency of the use and management of water resources.

Keywords

Natural Resources, Water Balance, Input-Output, Environment

1. Introduction

Although the planet is mostly made up of water, more than 97% of this water is salty and, therefore, cannot be consumed. Of the freshwater, around 2% is frozen or underground, leaving 1% available for consumption. Climate change and water scarcity are two of the biggest challenges faced today, and they are intrinsically linked, as changing weather patterns cause more frequent and intense droughts in many parts of the world. Several factors exacerbate water scarcity, including drought, pollution, and poor distribution of this resource. Furthermore, the problem could be exacerbated by rising sea levels and contamination of freshwater supplies with saltwater, making it unfit for human consumption and other uses (Marengo, 2008; Tundisi, 2008; Fleury et al., 2019; Fischer et al., 2016).

Virtual water is a concept introduced by Allan (1998) and refers to the amount of water used, directly or indirectly, to produce a good. It does not mean that it has a reservoir with this water stored inside it, but that this natural resource needs to be used in its production process. The measurement of virtual water is used to develop indicators to improve the management of water resources. Therefore, it is a valuable tool for understanding water consumption in different production processes and developing strategies for more efficient use of this resource (Brum et al., 2019; Lunelli et al., 2024; Ojima et al., 2008; Nepomoceno & Dalla Valle, 2022).

International trade in virtual water is important to balance the world's water distribution and minimize the problem of water stress in some regions, as it allows a country to save its water resources by importing goods instead of producing them domestically. Data from the United Nations Educational, Scientific and Cultural Organization (UNESCO) indicate that global trade moves a volume of virtual water of 1000 to 1340 cubic kilometers. And 67% of this volume is related to the trade of agricultural products. The trade of animal products represents 23% of this total. Industrial products move 10% of the volume of virtual water (Bergmann et al., 2022). Virtual water trade creates water interdependence between countries, so a country with water scarcity can depend on imports from countries with an abundance of the resource, which can help mitigate the environmental impact by redistributing water use from areas with scarcity to others with an abundance of this resource. However, inefficient use of water in the production of goods can lead to the degradation of water resources, which can harm water net exporting countries (Lunelli et al., 2024). Therefore, information on virtual water trade can help implement public policies for the rational use of water resources.

The motivation for this study is the economic and environmental importance of water resources, and it aims to measure virtual water flows in Brazil's international trade. The results enabled improving the understanding of the water appropriation process and the characteristics of trade between Brazil and the rest of the world for the development of policies to increase the efficiency of water use.

2. Water Footprint, Virtual Water Trade and Estimates for Brazil

Allan (1998) introduces the concept of virtual water as the volume of water incorporated into products traded on the international market. It refers to the appropriation of water resources from other countries in the global trade of goods and services (Chapagain et al., 2016). The water footprint is an environmental indicator developed by Hoekstra and Hung (2002) that measures the volume of freshwater used throughout the production chain of a consumer good or service. This concept of water appropriation, created in 2002, allows us to analyze the direct and indirect use of water throughout the production chain, from raw materials to the fully finished product. Therefore, there is a complementary relationship between water footprint and virtual water (Hoekstra, 2009; Bleninger & Kotsuka 2015). The agricultural sector represents the largest part of humanity's water footprint (approximately 86% of it) and the production chain approach is necessary to understand the process of measuring the water footprint (Hoekstra & Chapagain, 2007).

According to Oel et al. (2009), the water footprint is divided into three types. The green water footprint is the water precipitated on the land that does not run off or go to aquifers, stored in the soil, and later used in the evapotranspiration of the soil and plants. Blue water refers to the consumption of surface and subsurface freshwater, which can be taken from lakes, rivers, and aquifers to be used for human consumption and the conservation of life in ecosystems. Grey water refers to the volume needed to dilute pollutants so that they become inert, and the resource can be used for consumption.

The concepts of water footprint and virtual water have currently been applied by many researchers in studies on water resources used in both agriculture and livestock farming around the world (Yu et al., 2010, Mao & Yang, 2012, Silva et al., 2013, Silva et al., 2015, Zhuo et al., 2016). The indicators mentioned are categories of analysis of sustainable development to assess the management of scarce water resources, as well as their unequal distribution in the various territorial segments of the world. Thus, by assessing countries' water footprint, the aim is to discover how the planet can provide enough fresh water to ensure people's well-being, considering that fresh water is scarce and represents, according to Gleick (2000), only 2.5% of the total water resources. The analysis of water virtually incorporated into agricultural products at different scales is essential for defining strategies that can alleviate water scarcity and promote efficiency in its use (Dabrowski et al. (2009).

Global water demand is expected to increase by 20% to 30% between 2010 and 2050 (Burek et al., 2016). Agricultural production is the main source of water consumption, and factors such as population growth, income growth, and dietary changes contribute to the increase in demand for water. The water footprint is estimated to increase by up to 22% due to climate change and land use changes by 2090. Agricultural production, given current technology, is unsustainable concerning water use, notably the blue water footprint. There is an urgent need for the development of policies and private sector actions to improve sustainability in water use and protect the ecosystems that depend on it (Mekonnen & Gerbens-Leenes, 2020).

Hoekstra and Hung (2002) mapped the global flow of virtual water by dividing the globe into net exporting and net importing countries of this resource. The water-exporting countries or regions were identified as Brazil, North America, Central America, and Southwest Asia. The European and African continents, the

Middle East, and much of Asia stand out as importers. The flows between importers and exporters occur as follows: Brazil's largest market is Europe and Asia (especially China); North America's largest markets are Europe, Asia, Africa, and a portion of Central America. Exporters with slightly smaller flows are Latin America, with its market in the central and southern regions of Asia, and southwest Asia, and as an exporter to regions of Asia itself (especially the central and southern areas).

Direct trade in water between nations is much less important than virtual water in international trade, and today, this trade identifies and divides what to produce and where, according to the amount of water available and necessary for production processes. This shows that trade provides diverse products to countries with water shortages that could not be produced, given the amount of water available, without compromising the population's supply. The principal function of this mechanism would then be to enable different locations to produce in a way that does not burden their resources and, simultaneously, allow trade between those who have an abundance or scarcity of water resources (do Carmo et al., 2007). In this context, virtual water flows have economic, social, and environmental importance, considering that they impact the diversity of products available to populations, the availability of water for human consumption, and its use by production systems, which are competitors in situations of water scarcity, which, in turn, is directly related to climate change.

The use of international trade to save water by nations involves importing products whose production is water-intensive and exporting goods with less water-intensive use (Yang et al., 2006). Water savings by countries through international trade can reduce global water stress if the flow occurs from places with high to places with low water availability. Estimates show that countries importing virtual water would need to use about 1605 Gm^3/year to produce imported goods, which are produced with 1253 Gm^3/year in exporting countries, resulting in global water resource savings of 352 Gm^3/year. This savings represents 28% of international water flows related to agricultural trade (Chapagain et al., 2016).

There are two crucial criticisms of using international trade to save global water. It is important to note that virtual water trade is predominantly green water, which has a low opportunity cost of use, as opposed to blue virtual water, which can have multiple uses and, therefore, has a higher opportunity cost (Yang et al., 2006). Approximately 52% of the global blue water footprint and 43% of international virtual blue water flows originate in regions where sustainable environmental flows are violated. Approximately 22% of the unsustainable environmental flows of the global blue water footprint occur outside the source countries, indicating that many nations have externalized their negative impacts on water resources (Mekonnen & Hoekstra, 2020). Furthermore, there are uncertainties in accounting for and estimating the scale of water resource savings through virtual water trade, as there are negative implications for water use efficiency and food security in exporting countries and for improving environmental conditions in importing countries.

Therefore, water scarcity must be solved by expanding rainfed agriculture and changes in production technology that promote efficiency gains in water use to achieve greater environmental sustainability (Yang et al., 2006).

Estimates of the Brazilian virtual water trade follows different methodologies and use data from distinct periods, and therefore, the results differ in quantitative terms. Gelain (2018) estimated that Brazil exported 2.5 trillion m^3 of virtual water in 14 years (2002 to 2016), an average of 179 billion m^3 per year for ten main products on the export list. Gelain and Istake (2016) estimated the virtual water balance for Brazil in 1997, 2003, 2008, and 2013. The result showed that the country has a deficit in net water exports, exporting more virtual water than importing. Net exports of virtual water to Brazil increased during the period analyzed: 202.9% between 1997 and 2003, 34.7% between 2003 and 2008, and 62.4% in the comparison between 2008 and 2013. Between 1997 and 2013, Brazil exported 420,697 million m^3 of water in virtual form.

In the specific case of Brazil, of each hm^3/year of water used in agriculture, 70.45% is consumed or incorporated into its production, and 29.55% returns to the environment. In agribusiness, 54.58% of the water is consumed, and the return rate is 45.42%. Therefore, Brazilian agribusiness is a major supplier of food to other countries and a major exporter of water to the global economy (Montoya and Finamore, 2020). Picoli (2016) estimated that 38% of all water used in the economy is incorporated into products destined for export, a value calculated by the author was 154.8 trillion liters or 154.8 billion m^3.

The estimates by Bergmann et al. (2019), using the methodology based on the input-output matrix, whose data are available in the World Input-Output, were that Brazilian exports of blue, gray, and green domestic virtual water in the period from 1995 to 2009 were in the approximate average proportion of 12, 7, and 129 billion m^3 per year, respectively. Brazilian imports of domestic blue, gray, and green virtual water were, on average, in the order of 4, 3, and 16 billion m^3, respectively. The analysis indicates a deficit situation in Brazil because it exports more than imports water resources embedded in production processes. The values obtained by Bergmann et al. (2019) are like Coin (2022), who estimated the annual average of 163 billion m^3 of water exported by Brazilian agribusiness in the period 2010-2020, using a methodology based on the input-output matrix and trade relations between Brazil and 42 countries.

Da Silva et al. (2016) estimated Brazil's virtual water trade based on the main agricultural commodities from 1997 to 2012. Brazil is self-sufficient in food production, with a gross virtual water export of 67.1 billion m^3/year and a net virtual water export of 54.8 billion m^3/year, mainly to Europe, which accounts for 41% of the country's total gross virtual water exports. Water resources transferred from other countries in the form of virtual water to Brazil totalize 12.3 billion m^3/year. Other South American countries export 11.2 billion m^3/year to Brazil, representing 91% of the total. The main virtual water exporting countries to Brazil are

Argentina, Uruguay, and Paraguay, with 6.4, 1.5, and 1.2 billion m^3/year, respectively, mainly through the trade of rice, beans, wheat, corn, and beef.

This study advances in relation to previous ones with a more comprehensive concept of virtual water, considering all sectors of the economy and not only agricultural commodities. Furthermore, the approach involves the three types of water (blue, green, and grey) and 189 countries and the rest of the world based on the use of the input-output matrix, enabling to estimate the multiplier effect within the country of meeting external demand (exports) and identify the destinations of Brazil's virtual water. The results will help to better understand the country's virtual water trade and develop actions and policies to increase efficiency in water use.

3. Methodology

The database used was the EORA Global Supply Chain Database (EORA, 2024) for the year 2015, which provides data on the input-output matrices of several countries and the blue, green, and gray sectoral water footprints. For details on the construction of the database, see Lenzen et al. (2012) and Lenzen et al. (2013). The data covered 26 sectors in the economy of 189 countries and the rest of the world. Monetary values in the database are in current dollars, and water footprints are measured in millions of cubic meters per year.

Considering the estimates for a given country, the impacts of exports on water generation in the national production system were estimated with the simple water multiplier (or generator) for each sector of the economy. Based on the input-output matrix, this indicator shows the amount of water needed to meet a unit of final demand. The values obtained were multiplied by the respective sectoral exports for each country. The results show the quantities of water needed in the sectors themselves (direct effect) and their production chains (indirect effect) to meet the external demands of the 189 countries. It is important to note that intermediate consumption of imported goods and services was not considered in the calculation since the objective is to estimate the amount of domestic water needed to meet export demands. The estimates are detailed below based on a specific country and were replicated for all countries in the database.

The national matrix of each country was used to estimate the simple (or generator) water multiplier based on Miller and Blair (2009). Starting the calculations to obtain the inverse Leontief matrix, one must estimate A, the so-called technical coefficient matrix, from Equation (1). The element Z_{26x26} (intermediate consumption) is the matrix of monetary flows from sector i (row) to sector j (column), X_{26} is the sectoral production vector, and its values are used to estimate $\left(\hat{X}\right)^{-1}$ (inverse diagonalized matrix) that has the inverse sectoral production values $\left(1/X_i\right)$ on the main diagonal and the rest of the zero values. A_{26x26} is a matrix of technical coefficients that can be calculated by:

$$A = Z\left(\hat{X}\right)^{-1} \quad (1)$$

The input-output system can be expressed by:

$$(I - A)X = Y \tag{2}$$

Equation (2) uses *Y*, which is the sectoral final demand, and *I*, the identity matrix that has values of one on the main diagonal and the remaining values of zero, and the other elements were defined previously. The elements of Equation (2) can be rearranged as follows:

$$X = (I - A)^{-1} Y \tag{3}$$

The inverse Leontief matrix is given by:

$$L = (I - A)^{-1} \tag{4}$$

The elements of the matrix *L* (Leontief matrix) and its elements are l_{ij}.

From the direct coefficients and the inverse Leontief matrix, it is possible to estimate for each sector of the economy how much water is generated directly and indirectly for each monetary unit produced for final demand (Miller & Blair, 2009). The calculation of the simple water multiplier for Brazil's sectors is conducted by:

$$W_{kj} = \sum_{i=1}^{n} l_{ij} v_{ki} \tag{5}$$

Direct water coefficients (blue, green, gray) are estimated by:

$$v_{ki} = W_{ki} / X_i \tag{6}$$

In Equation (6), W_{ki} is the simple water multiplier that shows the total impact, direct and indirect, on the water demand of each sector *j*; *k* is the type of water, being *a* (blue), *v* (green), and *c* (gray); l_{ij} is the *ij-th* element of the inverse Leontief matrix and v_i is the direct coefficient of blue, green, or gray water for each type of water (*k*). In Equation (6), v_{ki} is the direct water coefficient of sector *i* and water type *k*, W_{ki} is the water footprint of sector *i* and water type *k*, and X_i is the sectoral production.

Final demand has the components: Household consumption, Government, Gross fixed capital formation, Non-profit civil institutions, Stock variation, and Exports. For the present study, the component considered in the calculations was Brazil's exports to various countries. The basic Leontief model and the simple water multiplier can be used efficiently to analyze the impact of exports on the direct and indirect demand for water in the Brazilian economy. The impact on each sector is estimated by:

$$W_{cc'} = W_{kj} E_{c'} \tag{7}$$

In Equation (7), $W_{cc'}$ is the total impact on water of country *c* (blue, green, gray) of exports from country c to country c' and $E_{c'}$ is the vector of exports from country c to country c', where c and c' = 1, 2 3, …, *n* with $c \neq c'$ and *n* is the number of countries.

The W_{kj} values must be used in a diagonalized matrix $\left(\widehat{W_{kj}}\right)$ to obtain the results by sector, in which the values of the simple water multipliers will be on the main diagonal and the remaining values will be zeros. The results obtained refer to the amount of internal water (blue, green, gray) required to meet the external demand (exports) of each sector. The values have direct (sector itself) and indirect effects on the national production chain in millions of m^3 per year. Obtaining the results of Equation (6) enabled us to prepare Table 1, which shows the flows of virtual water in international trade with four countries. The rows show the exported values of virtual water, and the columns refer to the imported values of this resource. Therefore, it is possible to analyze, in detail, the virtual water flows of each country's trade. For the present study, the results for Brazil will be analyzed to identify the destinations of its virtual water, and the results of Equation (7) will show the values exported by each sector of the economy.

Table 1. Virtual water flows from international trade for four countries.

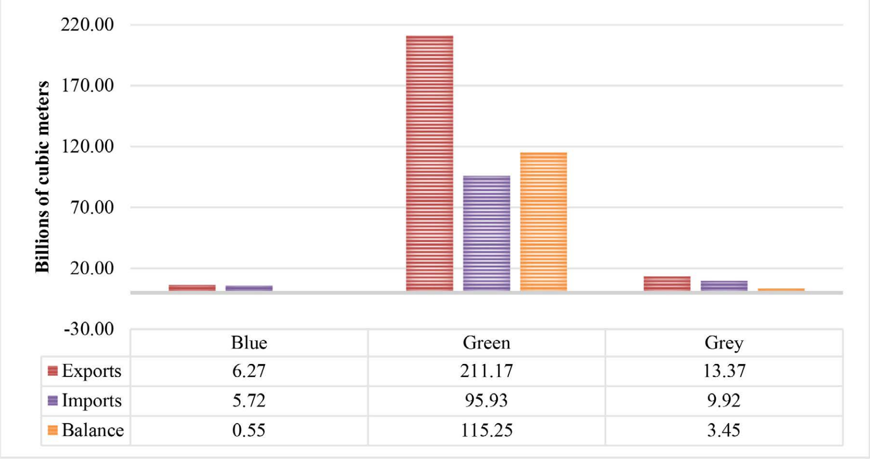
		Virtual water imports (c')			
	Country	1	2	3	4
Virtual water exports (c)	1	-	W_{12}	W_{13}	W_{14}
	2	W_{21}	-	W_{23}	W_{24}
	3	W_{31}	W_{32}	-	W_{34}
	4	W_{n1}	W_{n2}	W_{43}	-

Source: prepared by the authors.

Although the use of the input-output matrix provides advantages in environmental analysis, such as estimating the direct and indirect impacts of production chains and capturing effects in a systemic way, the assumptions of the model and available data determine its limitations. The model assumes constant returns to scale, use of inputs in fixed proportions, infinitely elastic supply, constant technology, and idle capacity. In addition, the data used is usually outdated. In the case of the present study, the data are from 2015 from a single database, which prevents intertemporal comparison of results, contrasting information between different data sources, and identification of trends, which can be partially resolved by comparing the results of the current research with previous studies on the same topic.

4. Results and Discussion

Figure 1 illustrates the virtual water flows of transactions between Brazil and the rest of the world in 2015. International trade between Brazil and its trading partners generated exports of around 230.8 billion m^3 of virtual water (blue, green, and gray) and imports of 111.6 billion m^3 with a positive balance (net exports) of 119.2 billion m^3. Green water represents most virtual water flows, with approximately 211 billion m^3 exported by Brazil and 96 billion m^3 imported from its trading partners, resulting in a balance of 115 billion m^3. Then, the movements of gray virtual water have a positive balance of 3.45 billion m^3, and blue has a positive balance of 0.55 billion m^3. The estimated values indicate that Brazil is a net exporter of virtual water, contributing to feeding the population in other countries, especially those with a shortage of the resources.



Source: Authors.

Figure 1. Exports, imports, and virtual water balance of Brazil's international trade, 2015.

Brazil's virtual water trade pattern expresses the country's list of exported and imported products, which is a major exporter of agricultural commodities and their by-products and an importer of non-food industrialized products. Therefore, the green water balance has the greatest positive value, as this type of water is widely used in agricultural production. Blue water, in a smaller amount than green water, is also important in food production, and gray water is important in industrial production, with balances in considerably lower values than green water.

Table 2 contains the results of the impacts of exports from sectors of the Brazilian economy on their respective internal production chains. The total values show that Brazil exported around 230.8 billion m^3 of virtual water in 2015, of which 6.3 was blue water, 609.1 was green water, and 13.4 was grey water. The total value exported represented approximately one-third of the water footprint of the national production sector, a share close to the estimates of Picoli (2016), who obtained 38% of the national total. Virtual water exports were one-eighth of the blue water footprint, one-third of the green water footprint, and three-quarters of the grey water footprint embodied in exports of goods and services.

The values of the Agricultural sector show that its exports caused a total impact of around 63.48 billion m^3 of water. This natural resource is exported as virtual water to other countries. Of this amount, 1.7 billion m^3 is blue, 58.7 is green, and 3.1 is gray. It is important to note that these results refer to the agricultural production chain with a direct impact on the sector and an indirect impact on its input suppliers. The impacts of exports on the overseas production chain were not accounted for; that is, the water generated by the acquisition of imported inputs was not estimated because the purpose of the study is to consider only national impacts. The Fishing sector exported around 4.4 billion m^3 of virtual water, mostly green water.

Table 2. Impacts of sectoral exports on the respective internal production chains in Brazil, 2015. Values in millions of cubic meters per year.

Export sector	Water generation in the internal production chain			Total
	Blue	Green	Gray	
1. Agriculture	1.719,7	58.708,8	3.051,0	63.480
2. Fishing	112.7	4093.9	148.1	4.355
3. Mining	112.9	2501.7	635.2	3.250
4. Food and beverages	2.567,3	92302,4	3.534,2	98.404
5. Textiles and Clothing	168.1	5415.8	412.2	5.996
6. Wood and Paper	251.3	7893.7	614.1	8.759
7. Petroleum, Chemicals, and Non-Metallic Minerals	307.0	8868.1	1.573.4	10.748
8. Metal Products	101.3	2654.8	451.0	3.207
9. Electrical and Machinery	171.8	4031.7	889.3	5.093
10. Transport Equipment	203.9	4839.9	1.157.3	6.201
11. Other Industries	90.8	3546.6	74.4	3.712
12. Recycling	178.3	6964.3	146.1	7.289
13. Electricity, Gas and Water	0.1	3.2	0.3	4
14. Construction	3.0	82.8	14.8	101
15. Maintenance and Repair of Machinery and Equipment	0.1	2.9	0.4	3
16. Wholesale Trade	1.2	36.8	4.5	43
17. Retail	2.7	81.9	10.0	95
18. Hotels and Restaurants	187.4	6638.8	288.6	7.115
19. Transportation	46.3	1268.9	235.5	1.551
20. Postal and Telecommunications	3.8	115.8	13.2	133
21. Financial Intermediation and Business Activities	20.8	658.7	57.8	737
22. Public Administration	0.9	31.5	1.9	34
23. Education, Health, and Other Services	14.7	418.7	59.8	493
24. Domestic Services	0.0	0.1	0.0	0
25. Other Services	0.0	0.8	0.0	1
26. Re-Export and Re-Import	0.3	9.0	1.0	10
Totals of Virtual Water Exports	6.266	211.171	13.374	230.812
Totals of the National Productive Sector	37.964	609.109	17.406	664.477
Share of Exports in the Total of the Productive Sector (%)	16.5%	34.7%	76.8%	34.7%

Source: Authors.

Food and beverages, Textiles and clothing, and Wood and paper are the agro-industrial sectors whose main raw materials products come from Agriculture and

Fishing. The Food and beverage sector has exported products of around 98.4 billion m^3 of virtual water, the majority (92.3 billion m^3) of which is green water, as its main suppliers of raw materials are the primary sectors of Agriculture and Fishing. The Textiles and clothing and Wood and paper sectors have the same characteristics but in smaller volumes of 6 and 8.8 billion m^3, respectively. Therefore, most of the virtual water exported by Brazil refers to the agro-industrial sectors, a value close to 50% of the total, and the other sectors that are not related to agribusiness were responsible for around 50 billion m^3 of virtual water exported, which indicates the importance of including these economic activities in the analysis of the virtual water balance in international trade. In relative terms, blue and gray water types are gaining importance in the production chains of the industrial and service sectors.

The results show that Brazil is a net exporter of virtual water, as well as an important supplier of food to the world. It is important to note that positive net exports in absolute terms refer mainly to green and gray water and, relatively speaking, to gray water. Most of the virtual water exported comes from the Food and Beverage sector, which indicates that the industrialization process of agricultural products has a high demand for water resources in its production chain. The negative balance of Brazil's virtual water trade raises concerns about the possibility of a water deficit and different regional realities, which could cause a scarcity of resources in parts of the country (Ussami & Guilhoto, 2018; Visentin & Guilhoto, 2019). It is important to mention that, unlike the traditional trade balance when it comes to virtual water, exports greater than imports are considered a negative balance, as the availability of water internally is lower.

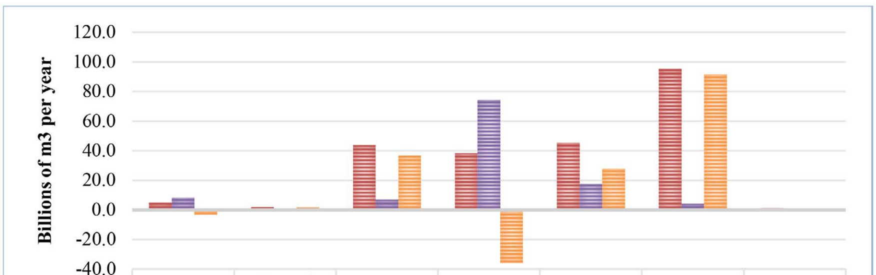
From the comparative analysis of the results with previous research, the estimated values of this study of a total of 230.8 billion m^3 of virtual water exports from Brazil, with around 180 from agribusiness, are close to the results of Gelain (2018) and Coin (2022). The first author calculated that Brazil exported an average of close to 179 billion m^3 per year for ten main export products between 2002 and 2016, and the second author estimated an average of 163 billion m^3 per year from agribusiness between 2010 and 2020. Picoli (2016) estimated a value of 154.8 billion m^3 for virtual water exported by Brazil, below the value reached in this study. The higher value for total virtual water exports in this study occurs because it considers the internal multiplier effect, that is, the sectoral interdependence present in the input-output approach, for all sectors of the economy and the period of analysis. Gelain and Istake (2016) state that Brazil has a deficit in net water exports, exporting more virtual water than imports; this corroborates the values obtained in the present study, which estimated net virtual water exports of around 119 billion m^3.

The estimates by Bergmann et al. (2019) were obtained using the input-output matrix. The averages for the period from 1995 to 2009 showed that Brazilian exports of blue, gray, and green domestic virtual water in the period were in the approximate average proportion of 12, 7, and 129 billion m^3 per year, and imports were on average in the order of 4, 3, and 16 billion m^3, respectively. The values for the present study were 6, 13, and 211 for exports and 6, 10, and 96 billion m^3 for imports. The results differ because the present research considered the data from 2015, and Bergmann et al. (2019) evaluated the data from 2009. The industrial and service sectors have higher values of gray water in their water footprints.

Da Silva et al. (2016) estimated Brazil's virtual water trade from 1997 to 2012. The authors estimated gross virtual water exports of 67.1 billion m^3/year and net virtual water exports of 54.8 billion m^3/year. The authors considered only agricultural commodities in international trade in the calculations of virtual water flows. The results obtained for Agriculture and Fisheries are approximately 68 billion m^3 in virtual water exports and are close to that estimated by Da Silva et al. (2016).

Brazil is a net exporter of virtual water. However, the balance of relations with different regions may be different according to the export and import schedules of goods and services and the different appropriations of water by the various production chains. Therefore, it becomes crucial to evaluate the virtual water flows between Brazil and its main trading partners and identify the values, types of water, and balances to better understand the impacts of international trade on the country's water resources and have information to develop policies to manage them appropriately.

Figure 2 illustrates the results of virtual water flows in trade between Brazil and different regions of the world. Europe stands out as the destination for virtual water from Brazilian exports, with around 95.5 billion m^3, followed by Asia (45.3), North America (43.6), and South America (38.3). The largest water import comes from South America, with 74.3 billion m^3, which means the balance is negative for Brazil. This is also the case for the African continent but at much lower levels.



	Africa	Central America and the Caribbean	North America	South America	Asia	Europe	Oceania
Exports	5.0	1.8	43.6	38.3	45.3	95.5	1.2
Imports	8.2	0.2	6.9	74.3	17.7	4.0	0.3
Balance	-3.2	1.7	36.7	-35.9	27.6	91.5	0.9

Source: Authors.

Figure 2. Virtual water flows from Brazil's international trade, 2015. Values in billions of m^3 per year.

Europe is the largest importer of water from Brazil, with a surplus of 95.5 billion m^3. The results indicate that the region highly depends on international trade with

Brazil, followed by North America and Asia. Da Silva et al. (2016) estimated that Europe was the destination for 41% of Brazil's virtual water exports, the same value estimated in this study. The results show that Brazil's virtual water flows in international trade involve several countries, and Brazil is a global exporter of agribusiness products.

The research results agree with Hoekstra and Hung (2002), who determined that Brazil, North America, Central America, and Southwest Asia are major water exporters, and Brazil has Europe and Asia (especially China) as its largest market. For the present study, Europe is the main destination for Brazil's virtual water, followed by Asia.

Virtual water flows are influenced by the productive structure of countries, which determines the values of the sectoral water multiplier as detailed in the Methodology and international trade agenda section. Countries that import agricultural and agro-industrial products, mainly animal protein, have goods with high water demand on their list. On the other hand, non-agricultural industrial products and services have less virtual water.

The use of international trade for the global economy can negatively influence Brazil's water availability, especially considering that there are large differences in climate and soil in the country with different levels of water supply of the regions. The Northeast Region has less availability of this resource, while the North and South Regions have greater abundance. Therefore, the country's foreign trade impacts different regions in different ways, which can increase the problem of water distribution. Possible measures to ensure the security of water resources would be the strengthening of integrated management of the National Water Resources Policy (PNRH) involving the Union, states, municipalities and civil society. Encouraging conservation and sustainable use with government programs with incentives for water-saving agricultural practices and the adoption of more efficient irrigation technologies. Protection of springs and recharge areas with the creation of permanent preservation areas and the recovery of riparian forests. Improvement of sanitation infrastructure with the expansion and improvement of basic sanitation to reduce pollution of water bodies and ensure the quality of available water. Monitoring and Inspection of the use of water resources to ensure compliance with existing laws and regulations and the deforestation of biomes, especially in the Amazon that supplies water through flying rivers to various regions of the country (Brazil, 2023; Brazil, 2024).

5. Conclusion

The methodology based on the input-output matrix proved suitable for estimating virtual water flows in Brazil's international trade. The approach involving all sectors of the economy provides a more comprehensive analysis. Virtual water flows are comparatively greater than the results of previous research, as it considers the multiplier effect in the production chains of economic activities.

The results showed that Brazil exported 230.8 billion m^3 of virtual water per year, which is approximately 34.7% of the water footprint of the national production system in 2015. Imports totaled 111.6 billion m^3 with a positive balance (net exports) of 119.2 billion m^3. Therefore, the country is a net exporter of this resource except for South America and Africa, regions with negative balances of -36 billion m^3 and 3 billion m^3. The main destinations for Brazil's virtual water exports are Europe, with 41%, followed by Asia and North America, with values close to 20%.

Considering that there is no pricing on the international market for the quantity of water appropriate for production processes, the country's situation as a net exporter makes sustainable use of the resource important, as the diversity of climate, soil, and water availability at a regional level challenge the increase of efficiency of the use and management of water resources in Brazil.

The research results can guide policies to increase water use efficiency and sustainability, with investments in research and development of products and processes that preserve this natural resource. In agriculture, drought-resistant varieties and production systems that reduce the blue water footprint and protect the soil to reduce evapotranspiration (green water) will contribute to greater sustainability. In the industrial and service sectors, the development of technologies with less use of blue water and fewer pollutants (grey water) will positively impact the water footprint and virtual water trade.

New research can be developed to estimate the impacts of international trade, considering economic and environmental variables such as greenhouse gas emissions, employment, and income. Furthermore, using the inter-regional input-output matrix to measure the impacts of international trade on environmental variables in different macro-regions can bring different points of view on policies and actions to be developed within the diverse reality of the Brazilian economy.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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