POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering
Climate Change

Master thesis

Virtual water trade at the subnational scale in South America: the role of Transnational Corporations

Supervisors

Dr. Elena De Petrillo

Prof. Francesco Laio

Prof. Luca Ridolfi

Prof. Marta Tuninetti

Candidate

Isabella Zordan

March 2024

Abstract

The production of agricultural commodities requires a massive use of freshwater resources. However, given the worldwide trade of these commodities, water resources available and used in the production sites are virtually displaced to the importing countries, by means of trading companies, addressed as Transnational Corporations (TNCs). It is therefore pivotal to uncover the role played by companies in the international redistribution of water to enhance water stewardship, a concept related to social, environmental and economic sustainability in water use. Recent research started to emphasise the importance of tracking food commodities flows at the subnational level, where the environmental and climatic heterogeneities of producing regions are directly related to variations in the unit water footprint (uWF, [m^3/ton]) of cultivated crops. This thesis aims to unveil the subnational spatial and temporal variability of unit water footprints associated with major Transnational Corporations. Specifically, the analysis is focused on traded cocoa, coffee, corn, cotton and soy, from the producing countries of Argentina, Bolivia, Brazil, Colombia, Ivory Coast and Paraguay to major importing countries, through trading companies controlling at least 80% of each analysed market. Evapotranspiration data (ET, [mm]) are estimated by means of the agro-ecological model waterCROP at the cell-grid level (5 arcmin spatial resolution) and they are coupled with sub-national trade data from the Trase database, which provides data on single trade flows ([tonnes]) from the production sites to the final importing country, through exporter and importer companies. Results on the traded virtual water volumes, and related $uWFs$, demonstrate the complexity of assessing how each company effectively relates to the water resource. Whenever neglecting the spatial heterogeneity of producing sites, upscaled average values lead to inaccurate assessments of resource use. Indeed, the subnational level of the analysis enables us to uncover how the unit water footprint of a given trader, fixed the commodity, varies according to the producing country and the final importer. For instance, in 2017 Cargill soybean export had a unitary water requirement greater in Brazil than in Paraguay ($1552\,m^3/ton$ and $1338\,m^3/ton$, respectively), conversely to what found for corn ($616\,m^3/ton$ and $831\,m^3/ton$, respectively). Always in 2017, Cargill soybean exports from Brazil to China and to Germany showed relevant differences ($1562\,m^3/ton$ and $1719\,m^3/ton$, being respectively the largest and smallest importers in terms of tonnes). The heterogeneity in volumes and their dependence on the specific geography of production at the fine-scale indicate the importance of providing traders and importing countries with detailed information about the uWF associated with trade flows. Changes in demand can influence how traders source food commodities at the local level, leading to a more conscious use of water resources.

Contents

Chapter 1 – Introduction

The agricultural sector is widely acknowledged as the largest user of freshwater resources, accounting for over 70% of global freshwater withdrawals (The World Bank, 2022) and this percentage is expected to increase due to the growing demand for food. The global population is projected to reach approximately 10 billion by 2050 (United Nations), leading to further urbanisation, land use change, and competition for natural resources. In the face of climate change challenges, it is essential to improve the efficiency and management of agricultural water use at the local scale, considering specific climatic, ecosystemic, and social features. This aligns with the concept of water stewardship, which is defined as "using water in a way that is socially equitable, environmentally sustainable, and economically beneficial" by UNIDO. To achieve this goal, stakeholders must be aware of the site-specific impacts of production and modify their actions accordingly. Additionally, agricultural practices are strongly linked to deforestation worldwide. As Pendrill et al. (2022) stated, more than 90% of tropical deforestation is driven, directly or indirectly, by agricultural expansion. This phenomenon also affects water, altering the natural hydrologic cycles and the related moisture recycling effect. This impacts the amount of rainwater available, resulting in increased irrigation requirements even in areas where they were not previously needed. Therefore, when analysing the water-to-food nexus, it is essential to consider all the existing relationships between agriculture, water, and deforestation.

Agricultural products are considered commodities – more precisely 'soft' commodities since they are not mined or extracted –, which means they are fully or substantially fungible economic goods. As a result, the market treats them as equivalent, disregarding the producer. This approach has social, economic, and environmental consequences, as it obscures the peculiar features and needs of the production areas with market-oriented thinking. In order to maintain global competitiveness, prices are often kept as low as possible. However, this can lead to worker exploitation and the use of improper agricultural practices to cut costs. This can also have a negative impact on water usage, as crops are grown in unsuitable regions to increase overall production and meet global demand. Therefore, it is important for final importers to be aware of the true pressure generated throughout the supply chain of agricultural products. Furthermore, trading companies must change their behaviour. As major actors in determining market conditions through their involvement in the international production of goods, it is pivotal that traders not only commit to zero deforestation but also adopt virtuous behaviours when reallocating global water resources.

This thesis work started from the validation and expansion of the methodology used by De Petrillo et al. (2023) in their study on the role of international corporations in virtual water trades associated with Brazilian soybeans. Specifically, the present research aimed to apply a detailed water footprint assessment to production sites at the subnational scale, in countries exposed to tropical deforestation. Spatial and temporal variations were detected for each crop under analysis, thus obtaining an overall overview of the pressure exerted on water resources by the major companies that controlled these markets. Additional analyses were performed on the predominant importing countries to uncover their dependence on specific traders and their indirect water footprint on production areas. The study was based on crops which exert a considerable ecological and ecosystemic pressure in the tropical regions, threatening biodiversity and unique ecosystems. Figure 1.1 illustrates the producing countries investigated in the present thesis.

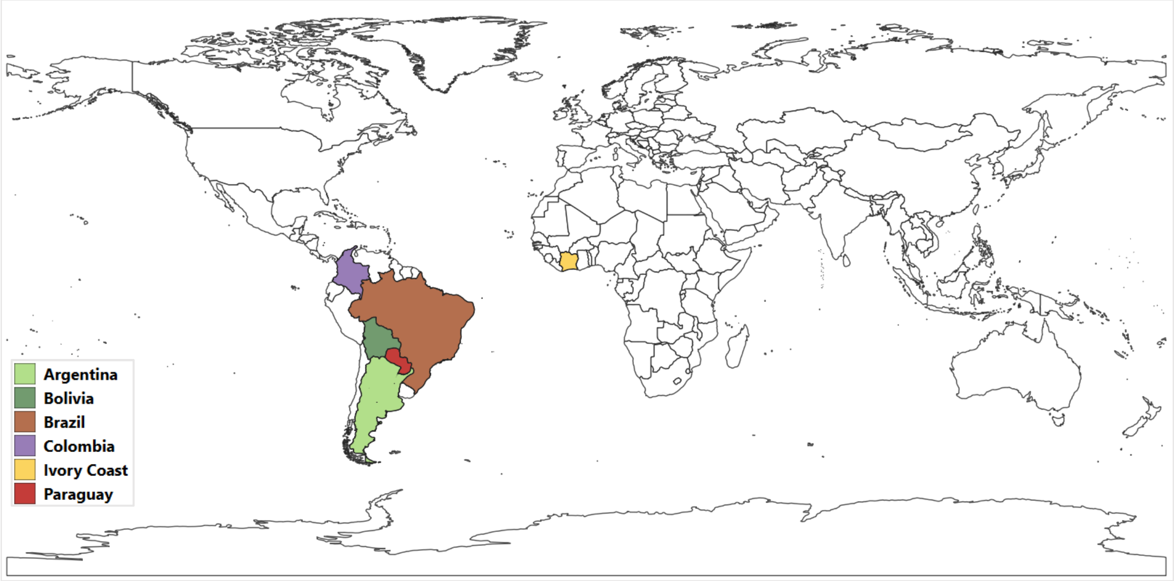


Figure 1.1: Producing countries investigated in the present thesis.

The study was focused on cocoa, coffee, corn, cotton and soybeans trade flows. Each of these crops has indeed an undeniable role in global markets. Cocoa and coffee have become part of the everyday life of people all around the world, whereas cotton has a major role in the textile industry. Corn is one of the three cereals, with rice and wheat, from which the global food system gets most of its calories (Shiferaw *et al.*, 2011). Moreover, it is not only directly consumed by humans, but it constitutes a key ingredient in animal feed, and it can be turned into biofuel. Lastly, soybean is one of the most significant crops worldwide, serving as the largest source of animal protein feed and the second largest source of vegetable oil (Our World in Data). In fact, the rapidly growing demand for soybeans is largely related to the global increase in meat consumption, known as "meatification of diets" (Weis, 2015, 2016). In South America, it results in a deforestation phenomenon driven by both soy cultivation and cattle pasture expansion (Pendrill *et al.*, 2022). Due to the vast production of these crops and the global nature of their markets, it is essential to consider the virtual water trade of exports, thus how water resources are virtually reallocated worldwide, i.e. in the importing countries. Furthermore, the intensification and extensification of production require improved water management due to the increased demand for water.

As discussed by Godar et al. (2016), there is still a lack of transparency in the supply chains of food commodities, making it complicated to individuate the exact production places and intermediate actors, i.e. traders. For this reason, the development of material-flow methods has become essential. The SEI-PCS model proposed by Godar et al. (2015) has been implemented by Trase to pursuit this goal, tracking the fine-scale trade of given agricultural products while retaining information on exporters and importers. As proposed by De Petrillo (2021), this mapping effort can be further enriched using high-resolution evapotranspiration data (Tuninetti *et al.*, 2015) to assess virtual water flows at the local scale. In this thesis, the first step was to compare Trase data used by De Petrillo (2021) with the ones currently available. The results indicate that the latest version of Trase for Brazilian soybean trades has undergone significant updates compared to the previous release (Appendix A, Figure A.1). This evidence denotes rapid improvements in supply-chain traceability, with trading companies aiming to declare in a more transparent way their supplying sites. That to avoid any wrong association with impacts generated at the local scale. The revised methodology was adapted to be applicable to any subnational analysis, according to current data availability. This study could be further improved considering evapotranspiration data provided by national organisms, as well as temporal variability in Colombian coffee yields. Moreover, the development of a methodology to allocate exports to the corresponding production site is still required for part of the crops traced by Trase. Currently, a temporal optimization approach is adopted wherever feasible, allocating trade flows based on the smallest temporal distance between ports of export and production sites.

The thesis comprises eight chapters. Chapter 2 provides an overview of the role of Transnational Corporations, from their historical origin to their current global importance in food systems. Chapter 3 presents the data used for water footprint computation. Chapter 4 outlines the methodology used to evaluate the water footprint of production, as well as the high-resolution virtual water trades. Chapter 5 presents the agricultural framework for each country examined, illustrating temporal variations in crop production as traced by Trase. Chapter 6 presents and discusses the results related to single years, while Chapter 7 is dedicated to the comparison of the results obtained by applying the methodology proposed in Chapter 4 to all available years. The objective of Chapter 7 is to identify crop-specific temporal and spatial variations in terms of unit water footprints and virtual water trades, with a particular focus on the evolving role of major Transnational Corporations. Chapter 8 presents the conclusions, limitations of this study, and potential future developments. It should be noted that more soybean-related examples have been included throughout the thesis due to its significant role in deforestation and global markets.

Appendix A includes maps that illustrate the differences between Trase versions, specifically regarding soybean exports from Brazil in 2018. Moreover, an example of inter-annual variability is shown, for the latest version, illustrating soybean exports from Brazil in 2018 and 2020. Appendix B gives some details about relevant trading companies, whereas Appendix C is a compendium of maps and plots related to Chapter 6. Appendix D and Appendix E contain maps and plots complementary to those included in Chapter 7.

Chapter 2 – The role of TNCs

In a globalized world, the main economic actors are trading companies, and more specifically Transnational Corporations (TNCs). Their activities are inextricably linked to the realisation of a single market for commodities, services, capital, labour and knowledge (Astrakhantseva, Shipshova and Antonova, 2019). As stated in the Draft United Nations Code of Conduct on TNCs of 1983 (United Nations, 1983), the following definition is given for a Transnational Corporation:

> *"An enterprise with legal entities in multiple countries, regardless of their legal form or sphere of activity. These legal entities operate under a decision-making scheme that allows for consistent policies and an overall strategy through one or more decision centres. The legal entities of this company are interconnected through ownership or other means, allowing one or several legal entities to significantly influence the activities of others. Notably, they can use the knowledge, resources, and responsibilities of others".*

TNCs are typically organised in a hierarchical structure, with the headquarters and research and development (R&D) located in the country of origin, while production centres may be located overseas. Reasons for TNCs expansion include more favourable government policies, tax avoidance, global influence, and diversification of the supply chain.

Tracing the earliest historical origins of TNCs (Greer and Singh, 2000), they might be found in the colonising and imperialist endeavours from Western Europe, which commenced in the 16th century and persisted for several centuries thereafter. However, the modern concept of TNC truly materialized in the 19th century, with industrial capitalism and market expansion to satisfy the demand for globally widespread resources. Until the late 1990s, the United States, the European Union and Japan hosted the majority of TNCs' headquarters, reason why they gained the denomination of Triad (European Commission). Nevertheless, since the turn of the millennium, the combined economic influence of the Triad has diminished due to the rapid ascent of the BRICS and Next Eleven nations (Zibaoui, 2023).

When dealing with the global trade of food commodities, four big traders need to be introduced. They are Archer Daniels Midland (ADM), Bunge, Cargill, and Louis Dreyfus, collectively known as the "ABCD companies". According to the United Nations Trade and Development Report 2023 (UNCTAD, 2023), the four agro-giants control nearly 70% of the global food market. And most importantly, they have secured a privileged position in terms of influencing prices, gaining access to funding, and directly participating in financial markets. This condition has been reached taken on financing, insurance, and investment roles traditionally associated with banking activities (UNCTAD, 2023). At page 79 of the Report, it is shown that the profits of the ABCD companies tend to rise during periods of market volatility and during social-economic crisis (e.g., Covid pandemic). It is therefore essential to be aware of the market-based speculation and lack of transparency often characterising companies' actions. Additionally to financial speculation, significant contributors to food price volatility include fluctuations in the supply and demand of crops, and adverse weather conditions, such as droughts, extreme events, and high temperatures. Overall, whenever price spikes and sudden declines are experienced, food security is put at risk, and the most dramatic effects of this instability are on developing countries. Kordos and Vojtovic (2016) explain that many TNCs exploit developing and third world countries due to their weaker and insufficient legislation, which often lacks proper environmental and social regulations. This creates the ideal conditions for resource exploitation, uncontrolled pollution, and human health issues.

Therefore, it is crucial to increase global awareness in commodity trade flows, their origins, and the actors involved in managing them. That will enable final importers to make informed decisions about the indirect pressure they may cause on production sites, changing the current situation of food abstraction and financialization. The latter has indeed caused the disconnection of agricultural products from their place of origin, strengthening the influence of financial actors, i.e. traders, in the food system (Fama and Conti, 2022). At present, agri-food chains are significantly influenced by traders rather than buyers (Gibbon, 2001), leading to the aforementioned issues.

Transnational Corporations are inevitably pivotal for the present-day globalized economy; however their attention is still too often focused on personal growth and profitability. This thesis aimed to highlight the concept of virtual water trade, which is often overlooked despite its direct relevance to food markets. It is one of the many issues that trading companies should consider in their actions, prioritising sustainability over profit in international trade and cooperating for a virtuous stewardship of water resources. Accurate and detailed virtual water volume results can assist in achieving water management objectives that companies are increasingly integrating into their business strategies.

A further critical thematic, strictly related to globalization, is the deforestation, often illegal, and destruction of peculiar and unique ecosystems all around the world. When it comes to food production, some crops emerge as highly linked to deforestation risk, such as coffee, palm oil trees and soybeans plantations. Whenever strict regulations and conservation plans are lacking, local environments and peoples are exposed to consistent land alterations. Delicate species are threatened with extinction, and social tensions arise. Transnational Corporations decisions can have the power to influence those changes, especially establishing where to source commodities based on the scientific evidence of local environmental pressures. Therefore, any footprint analysis related to trading businesses becomes an effective guidance tool.

Chapter 3 – Data

As illustrated in Chapter 1, the purpose of this study was to focus on the water footprint at subnational scale related to the production of crops exposed to deforestation risk. To do so, different data sources were considered and integrated throughout the analysis.

Trase data (details in References) were required to detect the producing local units which supplied the exporting companies, and in turn the final importers. This information was merged with evapotranspiration data (*ET*, [*mm*]) at 5 minutes arc resolution, calculated by Tuninetti et al. (2015), to compute related unit water footprints (*uWF*, [m^3/*ton*]), hence water footprints (*WF*, [m^3]), at subnational scale. CWASI database (details in References) provided unit water footprint values at the national scale, used for a first check of the results obtained. FAOSTAT data (details in References) were utilised for the preliminary exploration performed on each country under study, as reported in Chapter 5. They enabled to delineate the agricultural background, along with the most relevant country-specific cultivations in a given time horizon. Concerning spatial analysis and geographic representation, administrative shapefiles were sourced from OCHA (Humanitarian Data Exchange).

3.1 Trase database

Trase (Transparency for Sustainable Economies) is a data-driven transparency initiative which aims at mapping the international trade and financing of thirteen key commodities associated with tropical deforestation risk. As of 2021, Trase had mapped over 60% of this global trade, making it the world's most comprehensive open-access database on this trade (Gardner, 2023). It began in 2015 as a joint initiative of Global Canopy and the Stockholm Environment Institute (SEI). The initiative is currently tracking the supply chains of cocoa, coffee, corn, cotton, palm oil, palm kernel, soybean, sugarcane, wood pulp, beef, chicken, pork, and shrimp. The investigated countries are Argentina, Bolivia, Brazil, Colombia, Ecuador, Ghana, Indonesia, Ivory Coast, Paraguay, and Peru, as highlighted in Figure 3.1.

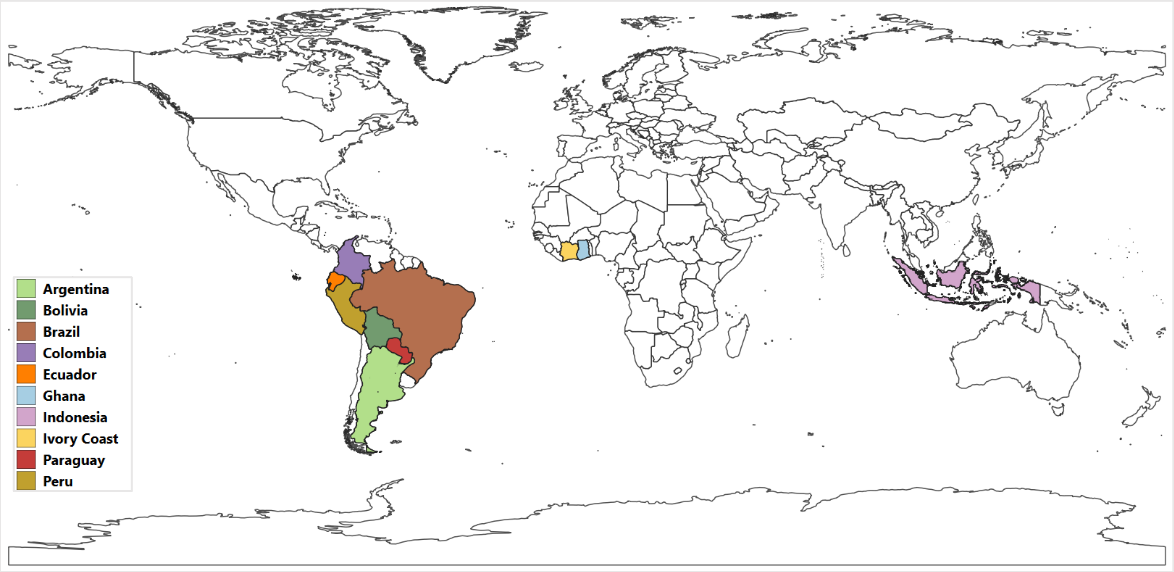


Figure 3.1: Countries exposed to deforestation risk, as mapped by Trase.

Subnational supply chains are mapped at the production scale, allowing for the identification of the original sourcing area. This is connected to the corresponding trade flow managed by trading companies, the Transnational Corporations. In this way, the local impact related to the crop under analysis is connected to the final importers. The approach used by Trase for mapping the subnational supply chains is the Spatial Explicit Information on Production to Consumption Systems (SEI-PCS), first introduced by Godar et al. (2015). This method is suitable for supply chain analysis and traceability (Godar *et al.*, 2016), and it is adapted to suit different countries and commodity contexts. Moreover, different SEI-PCS versions are used depending on data availability and methodological improvements, as reported in Table 3.1 for the entire Trase database.

Table 3.1: General overview on data available on Trase.

COUNTRY	CROP	VERSION	YEARS	RELEASE DATE
ARGENTINA	corn	0.2.3	2015-2019	-
	cotton	0.2.3	2015-2019	-
	soy	1.1.1	2015-2019	June 2022 (1.1.0)
	wood pulp	0.2.3	2015-2019	-
BOLIVIA	soy	1.0.0	2020-2021	-
BRAZIL	cocoa	2.5.0	2015-2017	-
	coffee	2.5.1	2016-2017	-
	corn	2.5.1	2015-2017	-
	cotton	2.5.1	2015-2017	-
	palm kernel	0.0.1	2015-2017	-
	palm oil	0.0.2	2015-2017	-
	soy	2.6.0	2004-2020	November 2022
	sugarcane	0.0.1	2015-2017	-
	wood pulp	0.0.1	2015-2017	-
COLOMBIA	cocoa	0.0.0	2013-2018	-
	coffee	1.0.3	2012-2021	June 2020 (1.0.2)
	palm kernel	0.0.1	2013-2018	-
	palm oil	0.0.3	2013-2018	-
	wood pulp	0.0.1	2013-2018	-
COTE D'IVOIRE	cocoa	1.0.5	2016-2019	-
ECUADOR	cocoa	0.0.0	2017-2022	-
GHANA	cocoa	0.0.2	2018-2019	-
INDONESIA	palm oil	1.2.1	2013-2020	September 2022 (1.2)
	wood pulp	3.0.3	2015-2019	February 2021 (3.0.0)
PARAGUAY	corn	1.0.0	2014-2019	-
	soy	1.2.6	2014-2019	June 2021 (1.2.2)
PERU	cocoa	0.1.0	2013-2022	-
	coffee	0.2.0	2013-2022	-

Different types of data are provided for the traced crops, depending on the ease of their traceability. Hereafter, Table 3.2 shows data availability for the main variables investigated in the present thesis.

Table 3.2: Main variables of interest for the present study, as reported by Trase. Green = information available. Red = lack of information. Yellow = information available only for certain years.

COUNTRY	CROP	PRODUCTION SITE	PORT OF EXPORT	EXPORTER GROUP	COUNTRY OF DESTINATION	TONNES	LAND USE	GEOCODE
ARGENTINA	corn	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	cotton	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	soy	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	wood pulp	🟥	🟩	🟩	🟩	🟩	🟥	🟥
BOLIVIA	soy	🟩	🟩	🟩	🟩	🟩	🟩	🟥
BRAZIL	cocoa	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	coffee	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	corn	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	cotton	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	palm kernel	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	palm oil	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	soy	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	sugarcane	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	wood pulp	🟥	🟩	🟩	🟩	🟩	🟥	🟥
COLOMBIA	cocoa	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	coffee	🟨	🟩	🟩	🟩	🟩	🟥	🟩
	palm kernel	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	palm oil	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	wood pulp	🟥	🟩	🟩	🟩	🟩	🟥	🟥
COTE D'IVOIRE	cocoa	🟩	🟥	🟩	🟩	🟩	🟩	🟩
ECUADOR	cocoa	🟥	🟩	🟩	🟩	🟩	🟥	🟥
GHANA	cocoa	🟥	🟩	🟩	🟩	🟩	🟥	🟥
INDONESIA	palm oil	🟨	🟩	🟩	🟩	🟩	🟩	🟥
	wood pulp	🟩	🟩	🟩	🟩	🟩	🟩	🟩
PARAGUAY	corn	🟩	🟩	🟩	🟩	🟩	🟩	🟥
	soy	🟩	🟩	🟩	🟩	🟩	🟩	🟩
PERU	cocoa	🟥	🟩	🟩	🟩	🟩	🟥	🟥
	coffee	🟥	🟩	🟩	🟩	🟩	🟥	🟥

As can be appreciated from Table 3.2, more than half of the traced crops have not been associated yet with the corresponding production sites, since this analysis requires capillary research and a great deal of effort. Anyway, Trase data have already given a great contribution to improve knowledge toward trade flows in countries exposed to deforestation risk. Indeed, *Deforestation exposure* (*ha*) or *Deforestation risk* (*ha*) are additional variables included for some crops, such as for soybeans in Brazil and Argentina, cocoa in Ivory Coast, and palm oil in Indonesia. Furthermore, trade flows of soybeans in Bolivia, Brazil and Paraguay, corn in Paraguay, and cocoa in Ivory Coast have been associated with *Zero deforestation*, indicating whether the trading company involved in a specific trade committed to Zero deforestation. For instance, soybeans trades from the Brazilian Amazon should always be covered by the Amazon Soy Moratorium (ASM), a sectoral agreement under which commodities traders agreed to avoid the purchase of soybeans from areas that were deforested after 2008 (Heilmayr *et al.*, 2020). Lastly, it is worth noting that the production sites for palm oil in Indonesia have been identified for the years 2018 to 2020 only, whereas for coffee in Colombia for the period 2012 to 2016. This information is marked yellow in Table 3.2.

3.2 Crop evapotranspiration data

Evapotranspiration data, sourced from Tuninetti et al. (2015), are given in the form of worldwide maps, well expressing the spatial variability for a given crop. They are estimated by means of the agro-ecological model waterCROP at the cell-grid level (5 arcmin spatial resolution). Each pixel reports an average value of actual water evapotranspired by the crop during the growing season of a year y, $ET_{a,y}$ (mm). A remarkable distinction is made between green and blue ET data. The first ones are related to the direct use of rainwater by the crop, whereas the latter give a quantification of the water used when irrigating, the non-rainwater (Velpuri and Senay, 2017). Certain cultivated areas are both rainfed and irrigated. Despite the critical importance of such information for an efficient water management, these data are not easily found. Table 3.3 reports the year corresponding to available data.

Table 3.3: Reference year of evapotranspiration data.

CROP	ET YEAR
Cocoa	2014
Coffee	2018
Corn	2014
Cotton	2018
Palm oil fruit	Not available
Soy	2018
Sugarcane	2018
Wood pulp	Not available

Due to the lack of reliable evapotranspiration data for *Palm oil fruit* and *Wood pulp*, these crops were neglected in the present thesis. Concerning the other cultivations, the years reported in Table 3.3 are the central ones of 10-year periods.

Each plant has peculiar characteristics, in terms of roots length, growing stages and sowing period, which are carefully considered in the ET computations. Paper 56 from FAO (Allen, Pereira and Raes, 1998) offers complete and detailed guidelines for computing crop water requirements. Moreover, the method for ET has been validated by De Petrillo et al. (2023) for soybeans, and it was consequently exploited in this thesis for other crops.

For regions characterised by more than one harvest per year of the same crop, evapotranspiration $ET_{a,y}$ is computed as the weighted average of the total actual evapotranspiration $ET_{a,LGP,n}$ (mm) of each growing season (Equation 3.1).

$$ET_{a,y} = \frac{\sum_n ET_{a,y,n} * A_n}{\sum_n A_n} \qquad [mm] \tag{3.1}$$

Where LGP stands for length of growing period, while A_n is the area cultivated during the growing period n.

Figure 3.2 presents, as an illustrative example, geographical distribution of ET data for coffee in Brazil, Colombia and Peru, differentiating between green (a) and blue (b) data.

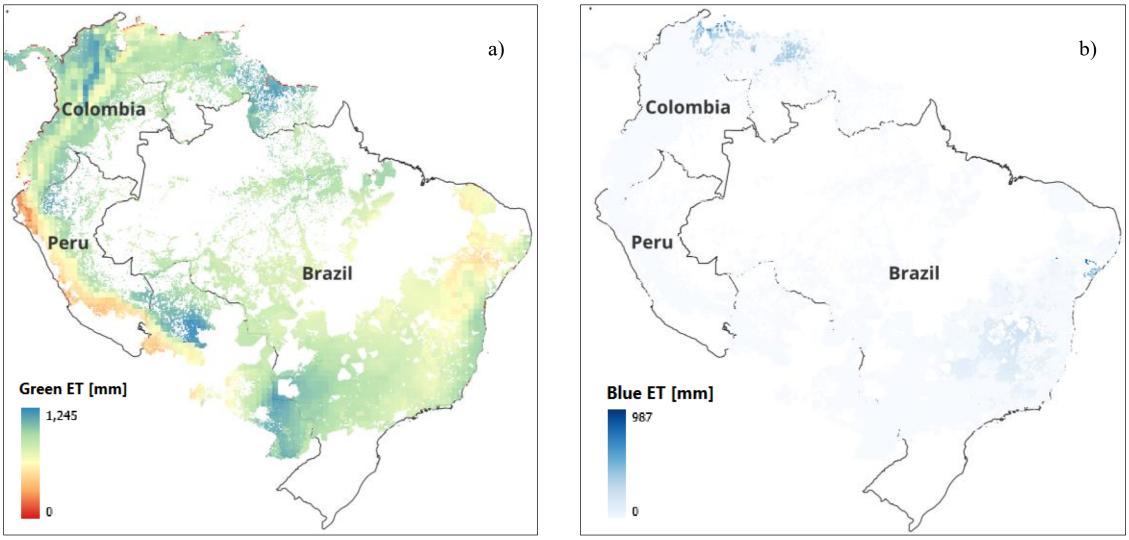


Figure 3.2: Evapotranspiration data over Brazil, Colombia and Peru. Green ET is shown on panel a, blue ET on panel b.

Evapotranspiration data were required for computing unit water footprint values (uWF, [m^3/ton]) at the local scale, as detailed in Chapter 4.1.4. The results obtained were compared with uWF of production (uWF_p) data, accessible in the CWASI database (Copying with Water Scarcity In a globalised world). CWASI provides data on Virtual Water Trade (VWT, [m^3]), Unit Water Footprint of production (uWF_p, [m^3/ton]) and supply (uWF_s, [m^3/ton]), and Water Footprint of production (WF, [m^3]) for 370 agricultural goods, at the national scale. Despite the different scale of the analysis, for a first check in terms of order of magnitude, the comparison was meaningful.

3.3 FAO statistics

FAOSTAT, the statistical database of the Food and Agriculture Organization (FAO), was exploited multiple times throughout this thesis. It provides several statistics at the national scale for more than 245 countries and territories, from 1961 to the most recent available year, i.e. 2021. Among 'Food and agriculture data', the following data were considered for the countries of interest:

- Statistics on all primary crops produced within national borders, for the variables *Area harvested* (*ha*), *Production quantity* (*tonnes*) and *Yield* (*ha/ton*). The twenty-two-year period, from 2000 to 2021, was chosen to cover fluctuations and production changes in the ongoing century, until the last year available (Chapter 5 for applications).
- Detailed trade matrices for each analysed country (*Reporter country*), to detect the major importers (*Partner countries*) of a given agricultural commodity. *Export quantity* (*tonnes*) was the evaluated variable. In this case, items needed to be manually selected, and derived products were considered as well, to be compliant with Trase datasets. Indeed, the latter expresses the equivalent traded tonnes for each traced item. The time horizon was chosen accordingly to Trase data, to cover the same time window.

3.4 Conversion factors for FAOSTAT data

FAO statistics are individually provided for primary and derived products. Therefore, to get the equivalent tonnes of a given exported crop, conversion factors were applied. The work of Mekonnen and Hoekstra (2010) was taken as reference for the entire process. Table 3.4 reports the values for *Soya beans, Cake of soya beans* and *Soya bean oil*, items evaluated within the Trase database. *Soya bean residue*, explicitly traced by Trase for Bolivia and Paraguay, is not provided by FAOSTAT. Therefore, conversion factors were applied to account for the weight changes, as given from the ratio of *Product fraction* (P_f) and *Value fraction* (V_f) of each product.

Table 3.4: Conversion factors of soybean products used to convert derived products into the equivalent primary soybean production.

Product	**V_f/P_f**
Soya beans	1.00
Cake of soya beans	0.83
Soya bean oil	1.91

Regarding cocoa trade, Trase data for Ivory Coast have been collected for *Cocoa beans, Cocoa powder, Cocoa butter, Cocoa paste* and *Cocoa waste*. In the FAOSTAT database, correspondence is found for each variable except for *Cocoa waste*. Table 3.5 illustrates the conversion factors (Mekonnen and Hoekstra, 2010) applied on FAOSTAT data, for both Ivory Coast and Brazil.

Table 3.5: Conversion factors of cocoa products used to convert derived products into the equivalent primary cocoa production.

Product	**V_f/P_f**
Cocoa beans	1.00
Cocoa butter, fat and oil	1.40
Cocoa paste not defatted	1.21
Cocoa powder and cake	0.64

Trase data for coffee in Brazil are associated with the codes 90111 (*Coffee not roasted, nor decaffeinated*), and 90121 (*Coffee roasted, not decaffeinated*). On the other hand, Colombia's records are for *Green, Processed* and *Roasted* coffee. The conversion factor reported in Table 3.6 were applied to all refined tonne types (Mekonnen and Hoekstra, 2010).

Table 3.6: Conversion factors of coffee products used to convert derived products into the equivalent primary coffee production.

Product	**V_f/P_f**
Coffee, green	1.00
Coffee, decaffeinated or roasted	1.19

For what concerns corn, Trase does not provide a description of the traded products. Therefore, only *Maize* (*corn*) was considered from the FAOSTAT database, not requiring any additional step. *Sugar cane* data do not require any transformation either. Regarding cotton, instead, data were selected for *Cotton seed, Cake of cottonseed, Cotton lint* and *linters*, and *Cottonseed oil*. Despite no additional specification is provided by Trase, the selected products were chosen for their relevance in Brazil exports. Conversion factors are reported in Table 3.7 (Mekonnen and Hoekstra, 2010).

Table 3.7: Conversion factors of cotton products used to convert derived products into the equivalent primary cotton production.

Product	V_f/P_f
Cotton seed	1.00
Cake of cottonseed	0.65
Cottonseed oil	3.00
Cotton lint, ginned	2.26
Cotton linters	2

3.5 Administrative data

National and subnational administrative boundaries were sourced from Humanitarian Data Exchange (HDX), an open platform for data sharing of United Nations Office of Humanitarian Affairs (OCHA), launched in 2014. Hereafter, administrative levels for the countries covered by Trase are detailed.

- Argentina: 0 country, 1 province, 2 department.
- Bolivia (Plurinational State of): 0 country, 1 department, 2 province, 3 municipality.
- Brazil: 0 country, 1 state, 2 municipality.
- Colombia: 0 country, 1 department, 2 municipality.
- Cote d’Ivoire: 0 country, 1 district, 2 region, 3 department.
- Ecuador: 0 country, 1 province, 2 canton, 3 parroquia.
- Ghana: 0 country, 1 region, 2 district.
- Indonesia: 0 country, 1 province, 2 district, 3 sub-district, 4 village.
- Paraguay: 0 country, 1 department, 2 district.
- Peru: 0 country, 1 region, 2 province, 3 district.

The numbers 0, 1, 2, 3 and 4 are used to identify subnational levels as part of a standardized system for organizing and categorizing geographical information. This numerical coding system helps ensure consistency and ease of data exchange across different datasets and platforms within humanitarian organisations.

Depending on the SEI-PCS version, Trase trade data are referred to different administrative levels, ranging from national to subnational data. The smaller the scale of the analysis, the more difficult the identification of supplying areas, but the more meaningful the final information

Chapter 4 – Methodology

The first objective of this thesis was to validate and generalise the methodology proposed by De Petrillo (2021) for evaluating Virtual Water flows at the subnational level. This involved establishing a link between the local environmental impacts at the production sites and the final importers of the resources. Specifically, the aim was to calculate the water footprint volumes of selected crops that are at risk of tropical deforestation and are linked to the export of related agricultural commodities. This allowed for the identification of the connection between local production and importing countries through trader companies (TNCs). The proposed methodology was based on various databases that combine environmental and trade data, as presented in Chapter 3, and aimed to provide a comprehensive analysis of water footprint flows. Moreover, this thesis aimed to analyse the spatial and temporal variability of companies' pressure at the local scale, to unveil possible changes or similar patterns, especially in relation to the same agricultural products traded from more than one country. Figure 4.1 presents the flow diagram which summarises the main steps of the developed method.

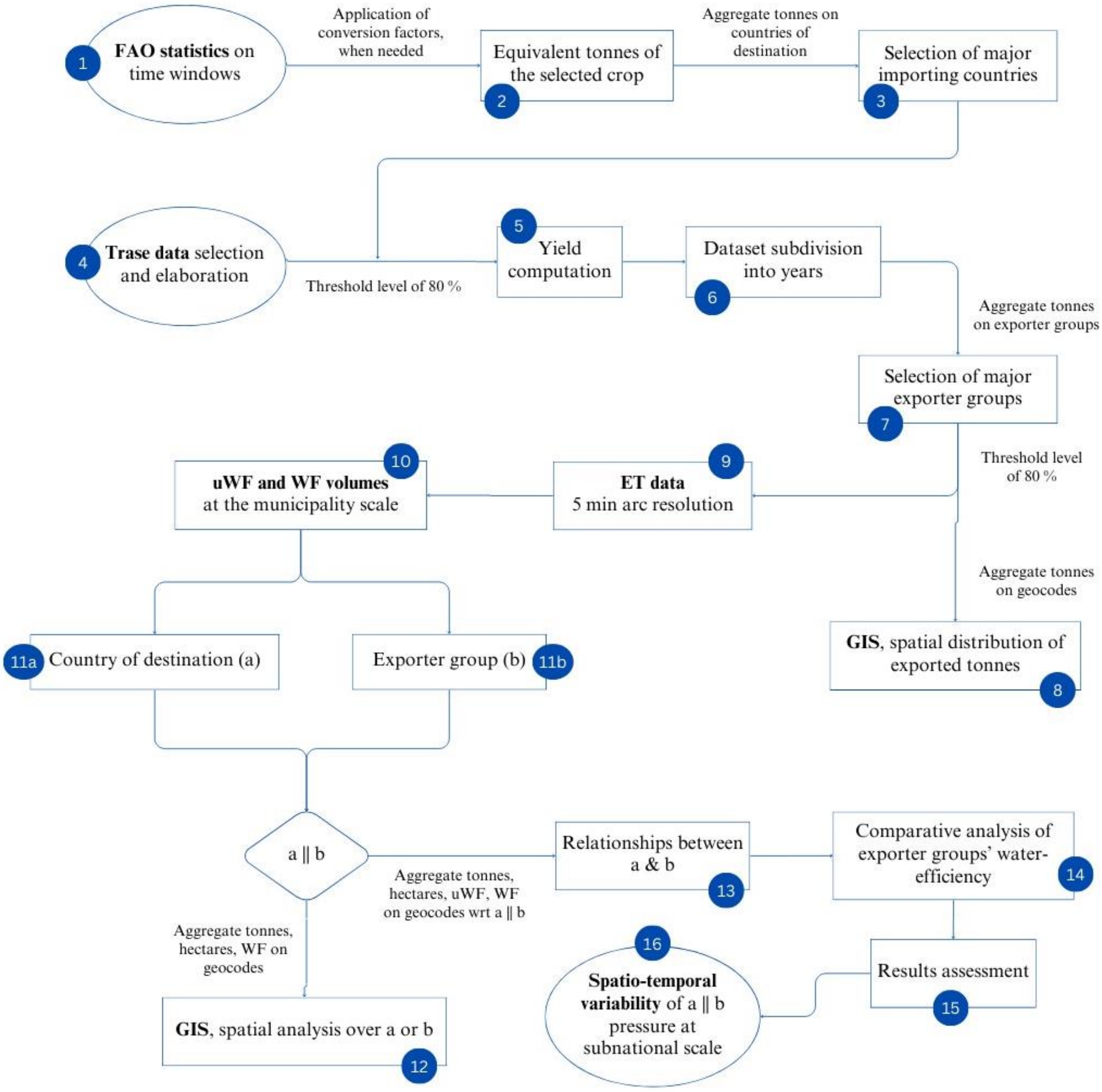


Figure 4.1: Flow diagram reporting the main logical steps of the method developed in this thesis.

A step-by-step concise explanation is provided to elucidate the content of Figure 4.1.

- Steps 1 to 3. Preliminary analysis required before delving into the elaboration of trade data.
  - Step 1 comprised the download of the detailed trade matrices provided by FAOSTAT for the crops under study.
  - In step 2, total imported equivalent tonnes were obtained by means of conversion factors.
  - In step 3, primary importing countries were identified.
- Steps 4 to 11. Development of an algorithm for the selection and elaboration of Trase data.
  - Step 4 was required for Trase data selection, based on the output of step 3.
  - In step 5, yield values were computed.
  - Step 6 subdivided the dataset according to the years covered.
  - Step 7 enabled to select the most relevant traders for each year. This required two phases: at first, a selection of the major traders for each year as a whole; secondly, a check to see whether these traders were also the predominant suppliers for each single importer country considered. As a result, each trade matrix contained data only for the top importers and the corresponding major traders, allowing to understand deeply water footprint flows and trade dependencies.
  - In step 8, the matrices values were aggregated according to the administrative unit geocodes (for the sake of simplicity, units are called generically municipality, even though each country has a different denomination for administrative levels). The results, adequate for spatial analysis in a Geographic Information System, were joined with the administrative shapefiles of the producing country. In QGIS, the production of each municipality was represented, considering the selected year.
  - In steps 9 and 10, evapotranspiration data, ET, were introduced to compute the unit water footprint, uWF, related to each trade flow, through raster calculations: cell values were averaged on the detected municipality, obtaining the ET at the local scale. These values were used to get the corresponding uWFs, which were multiplied by the aggregated trade data, resulting in the water volumes traded, VWT.
  - In step 11, municipalities' data were aggregated over the countries of destination (11a) or the exporter groups (11b), leading to two separate evaluations.
- Step 12 exploited QGIS for representing the geographical distribution of supplying sites, and the related virtual water volumes, according to the subject considered (11a or 11b).
- Step 13 highlighted the mutual relationships between importers and exporters.
- Step 14 enabled a comparative analysis on companies' water efficiency in terms of uWFs. Virtual water-weighted barycentres were computed and compared, with respect to countries' and companies' VWT.
- Step 15 assessed previous findings and evaluated the use of water resources in the production at the subnational scale, with a focus on involved biomes.
- In step 16, spatial and temporal comparisons of companies' $uWFs$ were made.

Throughout the present dissertation, the attention was maintained on trading companies, as for the reasons explained in Chapter 2.

4.1 Data processing and database organisation

Trase data were organised using a custom MATLAB R2023b algorithm to best serve the objectives of this thesis. The primary goal was to facilitate access to spatial information encompassing all municipalities involved in production for export to a chosen importing country. The data structuring was designed with a focus on spatial representation, particularly concerning the water footprint and virtual water flows. Emphasis was placed on the municipality of production and the exporter company, which were the two pivotal elements of the study. A multi-scale analysis was conducted to calculate the cumulative exports of each company from every municipality per year. Similarly, the cumulative exports from a particular municipality were calculated for the entire study year. For spatial analysis, the GIS system utilized was QGIS 3.34.0 Białowieża.

Throughout this part of methodological explanation, corn trade from Brazil is taken as illustrative example.

Table 4.1 shows the options for the download of Trase database in bulk format.

Table 4.1: Bulk data selected options for Trase database download (corn, Brazil).

Production country	Brazil
Commodities	Corn
Years	All years
Companies	All companies
Consumption countries	All countries
Indicators	All indicators

Input data were organized as outlined in Table 4.2. The table presented is a reduced version of the original one, which has dimensions of 46518x12. In the analysis conducted, the variables considered align with those displayed in Table 4.2. For reasons of space, the columns are split.

Table 4.2: Brazil, corn (2015-2017). Shortcut of Trase input data table.

YEAR	BIOME	STATE	MUNICIPALITY	LOGISTICS HUB	PORT
2015	AMAZONIA	MATO GROSSO	BOM JESUS DO ARAGUAIA	PRIMAVERA DO LESTE	SAO FRANCISCO DO SUL
2015	AMAZONIA	MATO GROSSO	BOM JESUS DO ARAGUAIA	PRIMAVERA DO LESTE	SAO FRANCISCO DO SUL
2015	AMAZONIA	MATO GROSSO	BOM JESUS DO ARAGUAIA	PRIMAVERA DO LESTE	SAO FRANCISCO DO SUL
2016	AMAZONIA	MATO GROSSO	CANARANA	CANARANA	SANTOS
2017	AMAZONIA	MATO GROSSO	CANARANA	CANARANA	SANTOS
2015	AMAZONIA	MATO GROSSO	CANARANA	CANARANA	SANTOS
2015	AMAZONIA	MATO GROSSO	CANARANA	CANARANA	SANTOS
2016	AMAZONIA	MATO GROSSO	CANARANA	CANARANA	SANTOS
2017	AMAZONIA	MATO GROSSO	DIAMANTINO	DIAMANTINO	SANTOS
2016	AMAZONIA	MATO GROSSO	GUARANTA DO NORTE	SORRISO	SANTOS

YEAR	EXPORTER GROUP	IMPORTER GROUP	COUNTRY OF DESTINATION	CORN_EQUIVALENT_TONNES	LAND_USE_HA	TRASE_GEOCODE
2015	BUNGE	BUNGE	EGYPT	2.01E+03	3.18E+02	BR5101852
2015	BUNGE	BUNGE	INDONESIA	6.76E+02	1.07E+02	BR5101852
2015	BUNGE	BUNGE	IRAN	1.38E+02	2.19E+01	BR5101852
2016	CARGILL	CARGILL	MALAYSIA	1.00E+01	7.15E+00	BR5102702
2017	CARGILL	CARGILL	MALAYSIA	1.31E+03	2.30E+02	BR5102702

YEAR	EXPORTER GROUP	IMPORTER GROUP	COUNTRY OF DESTINATION	CORN_EQUIVALENT_TONNES	LAND_USE_HA	TRASE_GEOCODE
2015	COFCO	CONCORDIA TRDG	MOROCCO	2.74E+03	4.15E+02	BR5102702
2015	COFCO	CONCORDIA TRDG	SOUTH KOREA	1.32E+03	2.00E+02	BR5102702
2016	COFCO	CONCORDIA TRDG	SOUTH KOREA	2.58E+02	1.85E+02	BR5102702
2017	ADM	AGROGRAIN	IRAN	1.03E+04	1.81E+03	BR5103502
2016	MITSUI & CO.	MITSUI & CO.	TAIWAN	4.04E+01	1.75E+01	BR5104104

4.1.1 Selection criteria for importers and traders

Given that the study’s objective was to examine major import and export players, the original tables were streamlined to retain the relevant data of interest. These players are trading companies engaged in trade flows to countries importing significant quantities of a selected commodity. The selection criterion was based on the detailed trade matrices provided by FAOSTAT for each crop analysed. Primary importing countries were identified based on the imported tonnes within the same time frame as the available Trase data (e.g., 2015-2017 for corn trade in Brazil). In making this selection, a threshold level of 80% was established. Therefore, Trase data were considered only for those importers contributing for at least 80%, and then subdivided into years.

Afterwards, another skimming was performed on data, to discover the most relevant exporting companies for each year. This time, it was required to satisfy the threshold level of 80% both ‘globally’ and ‘locally’. Firstly, traders were selected if they covered at least 80% of the trade for a given year. Secondly, they were compared with the companies specifically involved with respect to each importing country. Whenever the 80% threshold level was not satisfied at the importer scale, those traders contributing for at least 5% of its demand were added, until 80% was reached. Figure 4.2 shows the flow chart describing the criteria.

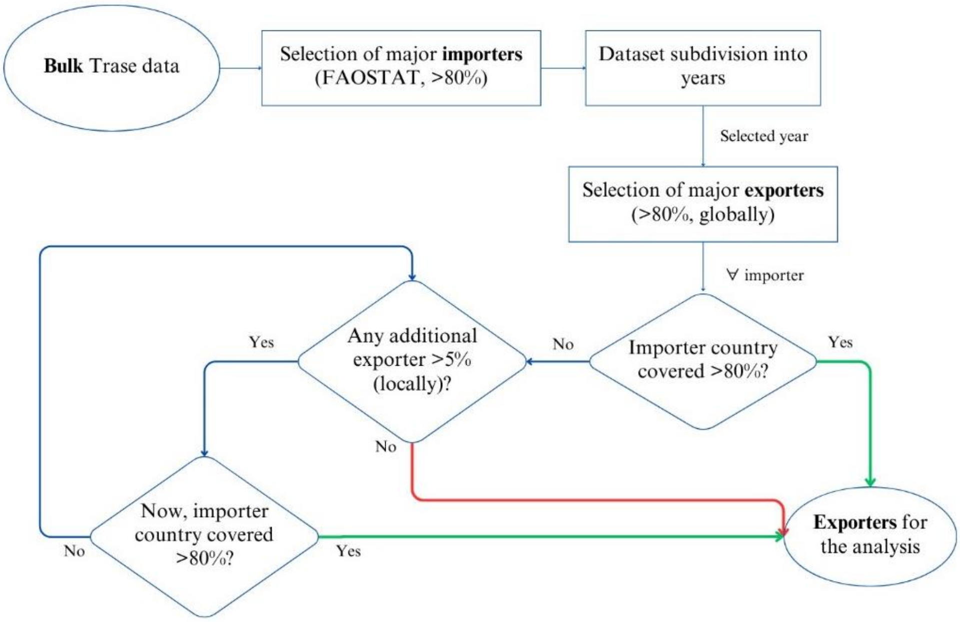


Figure 4.2: Flow chart representing the selection criteria for the exporting companies.

As a result, each trade matrix contained data only for the top importers and the respective major traders, enabling to deeply understand the virtual water flows and trade dependencies. For what concerns the analyses which results are discussed in Chapter 6, the systematic check of the imposed constraint (local coverage greater than 80%) proved to be essential. Otherwise, many importing countries would only have been described by a percentage range of 50 to 70%. Table 4.3 summarises the final number of importing countries, whose import demand was covered for more than 80% in the analyses presented in Chapter 6. Countries falling below the threshold still had a local coverage above 70%.

Table 4.3: Number of importing countries for which the 80% threshold level is satisfied, after applying the local coverage constraint.

COUNTRY	CROPS ANALYSED	N. IMPORTERS	N. IMPORTERS >80% before	N. IMPORTERS >80% after
ARGENTINA	Soy, 2019	19	15	19
BOLIVIA	Soy, 2021	3	2	3
BRAZIL	Cocoa, 2015	3	3	3
	Coffee, 2017	13	7	12
	Corn, 2017	11	10	11
	Cotton, 2017	8	5	5
	Soy, 2020	8	5	7
COLOMBIA	Coffee, 2016	7	5	5
COTE D'IVOIRE	Cocoa, 2019	9	5	9
PARAGUAY	Corn, 2019	4	2	2
	Soy, 2019	14	9	14

Coming back to the example of corn trade flows in Brazil, Trase offers insight into them spanning the years 2015 to 2017. FAOSTAT trade matrix for the same timeframe was examined. The cumulative corn equivalent tonnes related to each importing country (as reported by FAOSTAT) revealed that 11 of them collectively accounted for over 82%, as detailed in column PERC_CUM in Table 4.4.

Table 4.4: Brazil, corn (2015-2017). Importing countries accounting for over the 80% of corn traded in the selected three-year period.

IMPORTER	CORN_EQUIVALENT_TONNES	PERC [%]	PERC_CUM [%]	PERC_REL [%]
IRAN (ISLAMIC REPUBLIC OF)	1.38E+07	17.28	17.28	20.99
VIET NAM	1.04E+07	12.93	30.21	15.71
JAPAN	8.42E+06	10.51	40.72	12.77
EGYPT	6.74E+06	8.41	49.14	10.22
REPUBLIC OF KOREA	6.20E+06	7.75	56.89	9.41
CHINA, TAIWAN PROVINCE OF	5.35E+06	6.69	63.57	8.12
MALAYSIA	4.79E+06	5.98	69.55	7.26
SPAIN	4.11E+06	5.14	74.69	6.24
SAUDI ARABIA	2.09E+06	2.61	77.30	3.18
INDONESIA	2.04E+06	2.55	79.86	3.10
ALGERIA	1.96E+06	2.45	82.31	2.98

The relative percentages presented in the final column of Table 4.4 were computed in relation to the total number of tonnes exported towards the 11 countries, providing insights into their significance in corn trade. Leveraging these data, the Trase dataset was structured to generate a matrix for each year. Within these matrices, cumulative corn tonnes were computed for each trading company. Following the schema reported in Figure 4.2, prominent companies were identified. For the year 2017, for instance, it emerged that the 10 companies which satisfied the ‘global’ constraint would have represented only 60% of Iran demand (incidentally, the first importer of Table 4.4). Consequently, two additional traders were involved in the analysis (Table 4.5) to have a more exhaustive description of Iran corn imports.

Table 4.5: Brazil, corn (2017). Exporting companies accounting for over the 80% of corn traded towards the selected importing countries (Table 4.4). Dark brown highlights the traders added to satisfy the 'local' constraint for Iran.

EXPORTERGROUP	CORN_EQUIVALENT_TONNES	PERC [%]	PERC_CUM [%]	PERC_REL [%]
BUNGE	3.57E+06	16.74	16.74	19.14
CARGILL	3.32E+06	15.61	32.35	17.85
AMAGGI	2.27E+06	10.65	43.00	12.18
ADM	2.25E+06	10.55	53.56	12.07
GLENCORE	1.40E+06	6.58	60.13	7.52
LOUIS DREYFUS	1.36E+06	6.40	66.53	7.31
ENGELHART	8.81E+05	4.14	70.67	4.73
MITSUI & CO.	7.75E+05	3.64	74.31	4.16
MITSUBISHI	7.74E+05	3.63	77.94	4.15
CHS	6.93E+05	3.25	81.19	3.72
NIDERA	6.80E+05	3.19	84.39	3.65
COAMO	6.54E+05	3.07	87.45	3.51

This analysis enabled to focus on the actors who were most exposed to the risk of deforestation in the area under investigation. Furthermore, to underscore the virtual water volumes flowing from a designated municipality to an importer country via a trader company, spatial analysis was exploited. The outcomes of the custom algorithm were tailored to generate new layer features suitable for a Geographic Information System. Notably, geographical coordinates – latitude and longitude – were integrated into each municipality, allowing for the spatial representation of any computed variable's numerical value. The output became an attribute table, which could be joined with the shapefile of the producing country's municipalities, by means of the *Join* tool in QGIS. The shapefile had been previously imported in MATLAB as a string array to check the correspondence with the municipalities' identifiers provided by Trase.

4.1.2 Database preparation

In this subsection, the pre-processing steps undertaken on Trase data, before applying the algorithm outlined in Chapter 4.1.4, are detailed. Given the individual presentation of each country, specific names for administrative levels are provided in this context.

- For soybean in Argentina, the unknown departments of production were detected and erased (3924 data). Eventually, the total traded tonnes of untraced departments could be recorded and quantified, even though the geographic information lacks.
- For soybean in Bolivia, the same approach was adopted for the 2015 unknown municipalities. In the case of trade flows originating from Ascension de Guarayos department where the corresponding biome information was absent, this was obtained from El Puente department. El Puente belongs to the same province (Guarayos) and is located less than 60 km apart. Municipalities whose exported tonnes were not associated with the corresponding harvested area were neglected. Lastly, as Trase does not provide geocodes for municipalities, the names of provinces and municipalities were properly combined with the identification codes provided by the administrative shapefile sourced by OCHRA.
- For cocoa in Brazil, 174 data were neglected, due to the lack of proper information on the production sites. For coffee, 1816 data were missing; for corn 1222; for cotton 453; and for soybean 27649.

- For coffee in Colombia, data covering the years from 2017 to 2021 were removed (20581). They lacked the production site identification. Moreover, Trase geocodes pertain to production departments, which are not the smallest administrative units. The municipalities reported are those of export, which may not align with the production sites. Attempts were made to match them with shapefile codes (OCHRA); however, only a limited number corresponded. Therefore, the analysis was conducted at the department level.
- For cocoa in Ivory Coast, 2184 departments of production were missing or related to 'Indirect sourcing', therefore disregarded in the analysis. Furthermore, it was found that the identification codes assigned by Trase were incorrect. As a result, they were substituted with the codes provided by OCHRA.
- For soybean in Paraguay, it is worth noting that, despite the complete dataset, Trase geocodes pertain to production departments. Similarly to what observed for coffee in Colombia, departments are not the smallest administrative units, however the districts reported are those of export. Also in this case, attempts were made to match districts with shapefile codes (OCHRA), but only a limited number corresponded. Therefore, the analysis was conducted at the department level.

  Concerning corn, instead, departments' geocode was not provided. It was derived from the administrative shapefile sourced by OCHRA.

4.1.3 Elaboration on Evapotranspiration data

To make global evapotranspiration data applicable to the scale of analysis, given their raster format tied to pixels, the QGIS tool *Zonal statistics* was utilised. This tool provided averaged values for the variable of interest, calculated over specified polygons (i.e., the municipalities), as reported in the administrative shapefiles. Furthermore, being the analysis conducted within a georeferenced system, values perfectly aligned with precise geographical coordinates. The working Reference System was the WGS 84 – EPSG: 4326, projecting latitude and longitude coordinates onto the WGS 84 reference ellipsoid. The coordinates were determined for the centroids of the municipalities' polygons and, subsequently, linked to the attribute table containing *Zonal statistics* outputs, using the *Join* tool.

Crop evapotranspiration data do not cover the entire surface of the countries under examination, as cultivations are localised in specific areas. Furthermore, it is possible that these data are outdated (see reference years in Table 3.3) and do not include newly cultivated sites that may have been added to the Trase records. Therefore, some sites, which contributed to production and export according to the Trase database, did not have the corresponding evapotranspiration data. To address this issue, a dedicated algorithm was developed to handle with missing values. Specifically, the minimum distance approach was employed, computing the Euclidean distance among municipalities based on their coordinate values. Subsequently, the algorithm associated the missing information of a given production unit with the datum corresponding to the nearest municipality to it. It is worth specifying that this approach was exclusively applied to green evapotranspiration data. On the other hand, for blue evapotranspiration values, related to irrigation water consumption, any missing information was left. It deemed inappropriate to associate the closest value to an area where the irrigation system for the crop under analysis might be not present.

In relation to soybeans blue *ET* data in Brazil, it was found that two pixels were associated with extremely high values (in the order of 10^{10} mm). They were thus neglected as possible outliers.

4.1.4 Algorithm structure

The provided description is of general validity for each crop and each country analysed in the present thesis.

At first, the major detected importing countries were introduced as a string array, allowing the algorithm to select the cells containing these names in the column 'Country of first import'. The resulting table listed for each municipality every traded flow of the crop of interest.

Afterwards, for those countries provided with land use data, the yield $Y_i(t)$ was computed in a given year *t* at the municipality scale (Equation 4.1).

$$Y_i(t) = \frac{T_i(t)}{A_i(t)} \quad \left[\frac{\text{tons}}{\text{ha}}\right] \tag{4.1}$$

Where T is the total soybean production at the municipality scale and A is the total (rainfed plus irrigated) harvested area. Whenever Trase data did not include information on production hectares, the yield was derived through an alternative method. Utilizing TIFF files that contain global yield and harvested area values, under either rainfed or irrigated conditions (MAPSPAM; SPAM 2010), a weighted average yield was calculated. Equation 4.2 was implemented through the Raster calculator in QGIS.

$$Y_{avg} = \frac{Y_{rainfed} * A_{rainfed} + Y_{irrigated} * A_{irrigated}}{A_{rainfed} + A_{irrigated}} \quad \left[\frac{\text{tons}}{\text{ha}}\right] \tag{4.2}$$

In instances where the harvested area values fell below zero, they were adjusted to zero. Since values were at the pixel scale, the *Zonal statistics* tool on QGIS was exploited to derive average yields for the required administrative level. This path was certainly less accurate than the one described by Equation 4.1, but still provided valuable results. In this case, yield values did not vary over time, meaning that there could have been a final overestimation or underestimation of water footprint values, as for the relationship expressed in Equation 4.3. This approach was adopted for the analysis of coffee in Colombia.

Yield values were computed for each crop-producing country combination, obtaining the results described in Chapter 6. In some cases, adjustments were required. Regarding soybeans yield in Bolivia, 97 municipalities showed significantly higher values than expected, ranging from 7 to 390 tons/ha, compared to the average of 3-4 tons/ha. As a result, the corresponding trade flows were disregarded. Errors might have occurred while tracing the traded tonnes or the cultivated hectares. Similarly, the evaluation of Brazilian soybean production sites excluded one municipality, Monte Mor, located in the São Paulo state. In 2020, Monte Mor had a yield of 12 tons/ha, which was significantly higher than the values observed in the other 1600 production sites included in the analysis, where yields were lower than 5 tons/ha. Due to this discrepancy, the trade flows information from Monte Mor was considered to be incorrect. Furthermore, Monte Mor's yields remained around 2.5-4 tons/ha in previous years, making it unlikely that there was such a pronounced and sudden productivity improvement. Anyway, neglecting this municipality had minimal impact, as only two trade flows were reported based on the selected importers/exporters (Louis Dreyfus towards China).

The following step was to subdivide the database per year, to create tables containing all the trade flows for the specific year. This allowed to assess changes over time and space in the pressure that companies place on water resources in their local sourcing areas (Chapter 7.3.3). These tables were aggregated over the ‘Exporting group’, summing the crop’s equivalent tonnes, and aiming at listing the most relevant traders for the selected year, e.g. 2017. They were then introduced as a string array input, so that the algorithm could perform an additional selection over the cells of the corresponding table. From this point on, the analysis was performed on a single year at a time.

To proceed, blue and green evapotranspiration data, available at the local scale as for the procedure described in Chapter 4.1.3, were introduced in the algorithm. This enabled to compute the unit water footprint (uWF) and virtual water trade volumes (here indicated as WF, whereas in the following chapters also as VWT) associated with each municipality and trade flow, according to the Equations 4.3 and 4.4. The same evapotranspiration data were used for different years.

$$uWF_i^{g\,(b)}(\mathrm{t}) = 10 * \frac{ET_i^{g\,(b)}}{Y_i\,(t)} \qquad \left[\frac{m^3}{ton}\right] \tag{4.3}$$

$$WF_{i,T}^{g\,(b)}(\mathrm{t}) = uWF_i^{g\,(b)}(\mathrm{t}) * T_i\,(\mathrm{t}) \qquad [\mathrm{m}^3] \tag{4.4}$$

Where i indicates the administrative unit, T the traded equivalent tonnes, and *t* the reference year. The letter g stands for green, while b for blue. Furthermore, total evapotranspiration (ET_{tot}), total unit water footprint (uWT_{tot}) and total water footprint (WT_{tot}, Equation 4.5) were obtained by adding green to blue values.

$$WF_{i,T}^{tot}\,(\mathrm{t}) = WF_{i,T}^{g}\,(\mathrm{t}) + WF_{i,T}^{b}\,(\mathrm{t}) \qquad [m^3] \tag{4.5}$$

Precisely, green water footprint refers to the rainwater consumed by the crop, whereas blue water footprint to the volume of surface and groundwater consumed by means of irrigation processes (Mekonnen and Hoekstra, 2011).

The trade table of year *t* was suitable for different types of analysis. The following bullet list illustrates some of the possible derived tables and associated results.

- A table reporting unique municipalities geocodes and names. This ensured to keep track of the total number of exported tonnes and hectares required for their production in each municipality, despite the country of destination and the exporting company. Data for ET, uWF, WF and geographical coordinates were included as well. This result allowed for the identification of the most involved production sites.
- Tables reporting data for a single trader – or a single importer –, where the tonnes and hectares belonging to the same municipality were aggregated into an only row corresponding to the unique matching municipality-trading company (Table 4.6 as an example) – or municipality-importer. Statistical analysis was performed on these tables, investigating on cumulative distribution functions (CDF) and boxplot representations (Figure 4.3). Particular attention was made on the average total uWF values for the subjects analysed.

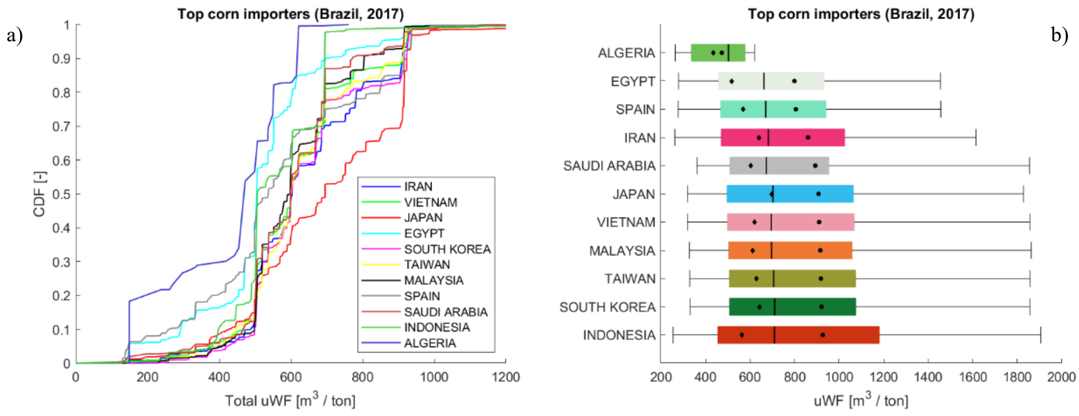


Figure 4.3: Brazil, corn (2017). Cumulative distribution functions (a) and boxplots (b) of the major importing countries.

Concerning boxplots, the box extremes represent the 25th and 75th percentiles, the line splitting the box is the median (50th percentile), the circle the average uWF, and the diamond the average uWF weighted by the exported tonnes. The bottom of the inferior whisker represents the 10th percentile, whereas the upper whisker the 90th percentile of total production. The distance between the first and third quantiles, along with the length of the whiskers, are indicators of the grade of dispersion and skewness of the percentiles distribution characterizing each company or importer.

- Tables reporting for each major trader complete information regarding the most relevant variables (tonnes, hectares, uWF, WF), linked to each country of destination supplied by the given trader. These results were crucial for making comparisons between the pressure exerted by traders on different producing countries, also varying the crop. In addition, changes over time could be delineated to see if the same importers relied on a company for multiple years. In this case, results could be ranked in descending order according to the WF variable.
- Tables which report for each major importer the same variables as in the previous point, but related to each exporting company exporting involved. Results are ordered as before.

Table 4.6 reports what was obtained for the trader Engelhart, starting from Brazil data for the year 2017. For reasons of space, the columns are split. In particular, it can be appreciated that the total uWF values are ranked in ascending order, which make it easier to identify the municipalities with the highest and lowest unit water footprints.

Table 4.6: Brazil, corn (2017). Supplying municipalities of the trader Engelhart, ranked in ascending order according to their total unit water footprint (blue column).

EXPORTERGROUP	GEOCODE	MUNICIPALITY	STATE	CORN	HA	YIELD	UWF_GREEN
ENGELHART	BR5107354	SAO JOSE DO XINGU	MATO GROSSO	6.63E+02	1.23E+02	5.40E+00	4.19E+02
ENGELHART	BR5107065	QUERENCIA	MATO GROSSO	1.25E+05	2.10E+04	5.98E+00	4.99E+02
ENGELHART	BR5107925	SORRISO	MATO GROSSO	5.79E+05	7.97E+04	7.26E+00	5.07E+02
ENGELHART	BR5218805	RIO VERDE	GOIAS	1.77E+05	2.88E+04	6.13E+00	6.96E+02

EXPORTERGROUP	WF_GREEN	UWF_BLUE	WF_BLUE	UWF_TOT	WF_TOT	LAT	LON
ENGELHART	2.78E+05	0	0	4.19E+02	2.78E+05	-10.696	-52.618
ENGELHART	6.25E+07	0	0	4.99E+02	6.25E+07	-12.158	-52.743
ENGELHART	2.93E+08	0	0	5.07E+02	2.93E+08	-12.741	-55.678
ENGELHART	1.23E+08	0	0	6.96E+02	1.23E+08	-17.739	-51.039

Table 4.7, provided as an example, details the traders who supplied Iran. Variables ranging from $CORN$ to WF_{blue} and WF_{tot} are outcomes of aggregation based on the corresponding exporter, whereas $w\_mean\_uWF_{tot}$ represents the weighted average uWF value concerning the involved municipalities. For this investigation, the focus is on the WF_{tot} values as ordering criterion. The objective is to reveal the amount of water that has been virtually displaced by considering the combined effect of uWF and traded tonnes, thus extending beyond the unitary values.

Table 4.7: Brazil, corn (2017). Trading companies of Iran, ranked in descending order according to their total water footprint (blue column).

COUNTRYOF FIRSTIMPORT	EXPORTERGROUP	CORN	HA	WF_GREEN	WF_BLUE	W_MEAN_UWF_TOT	WF_TOT
IRAN	BUNGE	1.01E+06	1.64E+05	6.28E+08	0	6.21E+02	6.28E+08
IRAN	COAMO	4.21E+05	7.74E+04	3.86E+08	0	9.16E+02	3.86E+08
IRAN	NIDERA	5.91E+05	9.06E+04	3.81E+08	0	6.45E+02	3.81E+08
IRAN	ADM	4.54E+05	7.38E+04	3.09E+08	0	6.80E+02	3.09E+08
IRAN	GLENCORE	5.37E+05	8.51E+04	3.09E+08	8.02E+04	5.75E+02	3.09E+08
IRAN	AMAGGI	3.50E+05	5.55E+04	1.82E+08	0	5.21E+02	1.82E+08
IRAN	ENGELHART	2.99E+05	4.29E+04	1.56E+08	0	5.21E+02	1.56E+08
IRAN	CHS	2.26E+05	3.91E+04	1.47E+08	0	6.50E+02	1.47E+08
IRAN	MITSUI & CO.	3.47E+04	4.82E+03	1.79E+07	0	5.18E+02	1.79E+07

The first two possible sets of tables, described in the bullet list, were well-suited for spatial analysis, thanks to the presence of geocodes and geographical coordinates. Particularly, geocodes were the pivotal point for all the following examinations, since different municipalities may hold the same name; therefore, the identification was univocal only when using georeferenced codes. For the reason explained, every comparison and spatial representation necessitated to be guided by geocodes. Furthermore, by observing the administrative shapefiles while comparing them to Trase geocodes arrays, it emerged that the fitting was exhaustive. The geographical conformity ensured that all the municipalities under analysis would be properly represented when using QGIS.

Lastly, weighted barycentres were evaluated for each company and country of import, aiming to assess the average geographical production area supplying each of them. The procedure followed was the one proposed by De Petrillo et al. (2023). Equations 4.6 and 4.7 illustrate how weighted longitude values (x, $long$) were evaluated for each exporting company, using the virtual water trade, VWT, corresponding to each production site i as weight. Same applies for latitude values (y, lat).

$$b^{x}_{comp,c}\ (t) = \frac{\sum_{i=1}^{I} long_i\ (t) * VWT_{i,comp,c}\ (t)}{\sum_{i=1}^{I} VWT_{i,comp,c}\ (t)} \tag{4.6}$$

$$b^{x}_{comp}\ (t) = \frac{\sum_{c=1}^{C}\left[b^{x}_{comp,c}\ (t) * \sum_{i=1}^{I} VWT_{i,comp,c}\ (t)\right]}{\sum_{c=1}^{C}\sum_{i=1}^{I} VWT_{i,comp,c}\ (t)} \tag{4.7}$$

Every company was identified with a number of barycentres ($b^{x}_{comp,c}$, $b^{y}_{comp,c}$) equal to the number of countries importing from it (C), where geographical coordinates were weighted by the VWT of each trade flow considered ($VWT_{i,comp,c}$). Then, a unique barycentre (b^{x}_{comp}, b^{y}_{comp}) was found for each company averaging the barycentres previously obtained by the total VWT associated with the given trader. The same procedure was applied to countries of import, which relied on K exporters. Identifying changes in production site dependence relied heavily on temporal variability.

4.2 Comparative analysis

The methodology explained in Chapter 4.1.4 was replicated over all available years once results for the last year traced by Trase had been obtained. At this point, it was worth investigating how the relative importance of each major Transnational Corporation had changed in the market for different crops. The aim was to determine whether markets had been monopolised by companies or fragmented progressively. Additionally, changes in the uWF of the selected actors could be highlighted, along with variations in corresponding VW volumes.

The index chosen for the economic analysis was the Herfindahl–Hirschman index (HHI), commonly used to measure the market concentration and consequently the market competitiveness (Brezina *et al.*, 2016). It is defined as the sum of the squares of market shares, s_i, considering all the involved actors. Equation 4.8 reports the formula.

$$HHI = \sum_{i=1}^{n} s_i^2 \tag{4.8}$$

The HHI ranges from *1*, if the market is entirely controlled by a single entity, to *1/n*, if *n* entities operate with equal market shares (Brezina *et al.*, 2016). This applies when all entities playing a role in the market are considered, so the totality of it is described. However, given the purpose of the present thesis to focus on subsets of traders, the market description was only partial. Despite the results of the HHI application gave approximative information, it was still valuable to have a first idea about the role evolution of major TNCs. It was decided not to rescale the subsets of shares as if they covered the market totality, to avoid altering their meaning and losing information. Rescaling would have resulted in the selected traders always accounting for the same percentage of the total market, with variations only in their relative values. Instead, the overall coverage associated with all of them shows fluctuations. For what concerns markets classification, several threshold levels are suggested in the literature. In this study, reference is made to the U.S. Federal Trade Commission (FTC) ('Horizontal Merger Guidelines', 2010), which proposes that the market is *unconcentrated* if the value of HHI is lower than 0.15; *moderately concentrated* if ranging from 0.15 to 0.25; *highly concentrated* if greater than 0.25. The application of these thresholds is reported in Chapter 7.3.1. It is worth specifying that the values found needed to be carefully contextualized. In fact, since several traders operated in the markets analysed, considering subsets of them inevitably led to HHI ranging in the *unconcentrated* to *moderately* concentrated thresholds. However, as discussed in Chapter 7.3.1, each market was predominantly controlled by a few TNCs, which covered even more than 50% of market shares. Nevertheless, the use of the HHI was particularly useful to highlight temporal and spatial variability in market competitiveness.

In the comparative analysis, biomes were also considered. As they are exposed to deforestation risks at varying levels, it was important to determine if sites highly threatened by land use change were also characterised by high average unit water footprints. Additionally, the analysis compared the overall water volumes displaced from a specific biome in relation to a given crop, trader, or importing country. It should be noted that all results are based on the aggregation of subnational data.

Chapter 5 – Agricultural framework

A preliminary step, before diving into the heart of the present study, was to underline the main geographical and agricultural features of the analysed countries, specifically Argentina, Bolivia, Brazil, Colombia, Ivory Coast and Paraguay. To meet this point of the analysis, as discussed in Chapter 3.3, data covering a twenty-two-year period, from 2000 to 2021, were downloaded from the Food and Agricultural Organization of United Nations database (FAOSTAT a). Specifically, in the 'FAOSTAT section, Food and Agriculture data, Production domain', detailed lists for crops and livestock products are available. The variables of interest were *Area harvested*, *Yield*, and *Production Quantity* for primary crops only, which enabled to get an overview of the evolution in time of the agricultural production in each country. In each subsection of Chapter 5, time series are presented for all the crops traced by Trase. The investigation aimed to identify fluctuations and their potential causes. Additionally, an analysis of the local climate, relevant physical-geographical elements, and changes in land use provided an explanation for crop variations over time.

5.1 Argentina

Among the South America countries, Argentina – more properly known as Argentine Republic – has the second largest extension, after Brazil. Inevitably characterised by a considerable variety of climatic regions and biomes, agricultural areas are limited to about 35 million suitable hectares over a total of 278 million (FAO, 2004; Global Yield Gap Atlas, 2023). Argentina has three major cultivated regions: arid, humid, and semi-arid regions, listed in descending order of extension (FAO, 2004). Within them, a variety of agro-ecological regions are identified, according to the concept expressing that different areas have unique combinations of natural factors, such as climate, soil type, and topography, leading to a diverse impact on agriculture. The Pampas region occupies a prominent role, and it includes the most productive provinces – Buenos Aires, Santa Fe and Córdoba –, which covered the 78% of the national soybeans production in the three-year period, 2017 to 2020 (U.S. Department of Agriculture). In addition to soybeans fields, this area is used for cultivating wheat, corn, sunflowers, cotton and other crops (U.S. Department of Agriculture). The favourable climatic conditions – temperate with a well-distinguished rainfall season –, the flat and fertile plains which are covered by grasslands, and the natural presence of many superficial water sources, such as the Paraná and Uruguay rivers, make an advantageous combination for exploiting this extremely productive agricultural area. Indeed, the Northern areas face a subtropical to temperate climate, more adequate for a variety of cultivations, whereas moving southwards the country becomes more inhospitable and arid (Peel, Finlayson and Mcmahon, 2007).

Concerning the FAOSTAT data previously presented, the first and last years of the time interval considered were individually analysed to highlight possible major changes occurred over time. In Tables 5.1, 5.2, 5.3, 5.4, the variables *Area harvested, Production Quantity*, and *Yield* are reported, for those crops covering altogether at least 80% of the total hectares or number of tonnes. If any crop analysed by Trase did not appear within this 80%, the corresponding information was added (dark brown) to understand its relevance within the national agriculture. This procedure was adopted whenever required also in the following subsections of Chapter 5.

Table 5.1: Argentina (2000). Major cultivations according to harvested area.

CROP, 2000	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	8.64	34.04	34.04	2.33
Wheat	6.22	24.52	58.56	2.49
Sunflower seed	3.47	13.70	72.27	1.75
Maize (corn)	3.09	12.17	84.44	5.43
Seed cotton, unginned	0.33	1.31	85.75	1.26

Table 5.2: Argentina (2000). Major cultivations according to produced tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	20.14	20.63	20.63	2.33
Sugar cane	18.40	18.86	39.49	65.71
Maize (corn)	16.78	17.20	56.68	5.43
Wheat	15.48	15.86	72.55	2.49
Sunflower seed	6.07	6.22	78.77	1.75
Sorghum	3.34	3.43	82.19	4.65
Seed cotton, unginned	0.42	0.43	82.62	1.26

Table 5.3: Argentina (2021). Major cultivations according to harvested area.

CROP, 2021	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	16.47	43.22	43.22	2.81
Maize (corn)	8.15	21.38	64.60	7.43
Wheat	6.39	16.78	81.38	2.76
Seed cotton, unginned	0.41	1.07	82.45	2.56

Table 5.4:Argentina (2021). Major cultivations according to produced tonnes.

CROP, 2021	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Maize (corn)	60.52	34.59	34.59	7.43
Soya beans	46.22	26.41	61.00	2.81
Sugar cane	18.63	10.64	71.64	48.60
Wheat	17.64	10.08	81.72	2.76
Seed cotton, unginned	1.04	0.59	82.32	2.56

From Tables 5.1 and 5.3, the considerable increase of hectares cultivated with soybeans can be appreciated. Specifically, from covering 34% of the harvested area in 2000, twenty-two years later they reached 43%, with a clear detachment from the second cultivation, maize. In terms of produced tonnes, instead, the reported values highlight a reverse situation: if in 2000, with 20 million tonnes, soybeans constituted the first produced crop, in 2021 it was overtaken by maize, with 60 million tonnes versus 46 million. Nevertheless, the quantitative increase was remarkable (+129% for soybeans). The justification for the observed behaviour in 2021 was found in the *Yield* values, which were 2.81 tons/ha for soybeans and 7.43 tons/ha for maize.

In a second moment, time series are represented, aiming at detecting agricultural fluctuations and their possible causes. Figure 5.1 is for maize, cotton and soybeans, whereas Table 5.5 summarises the percentage variations of the three variables considered for each crop.

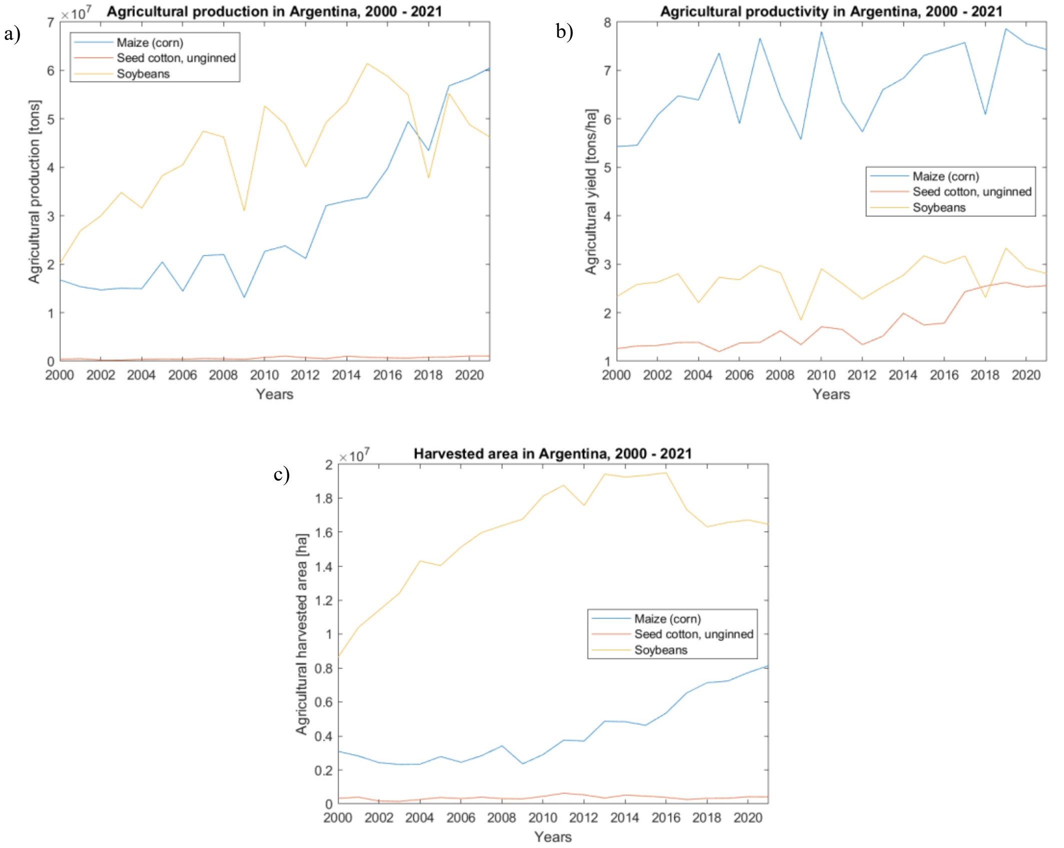


Figure 5.1: Produced tonnes (a), yields (b) and harvested area (c) of corn, cotton and soybeans cultivations, Argentina (2000-2021).

Table 5.5: Percentage increase detected for the three variables of interest (Production quantity, Yield and Area harvested) for corn, cotton and soybeans cultivations, Argentina (2000-2021).

Percentage increase [%]	*Production quantity*	*Yield*	*Area harvested*
Maize (corn)	260.68	36.75	163.75
Seed cotton, unginned	149.07	103.58	22.35
Soya beans	129.53	20.39	90.64

The numbers reported in Table 5.5 highlight a positive increment observed for each variable and each crop. Nevertheless, as appreciable in Figure 5.1b, the productivity improvement was not constant over time, due to the occurrence of climatic events. Concerning soybeans, impressive yield drops were registered for harvests in 2003-2004, 2008-2009, 2011-2012, and 2017-2018, years affected by prolonged drought periods (Sgroi *et al.*, 2021). Indeed, research on La Pampa yields confirmed the sensitivity of this crop to climatic variability (Penalba, Bettolli and Vargas, 2007). A similar behaviour is noticed for maize, whereas cotton seems to have been more resilient to the 2017-2018 drought. Its yield, indeed, slightly grew (Figure 5.1b).

5.2 Bolivia

Bolivia is a landlocked country in the very centre of South America. It is often referred to as the country of extremes, due to its remarkable diversity in terms of geography, topography, climate, and culture. Indeed, the variations in altitude are considerable, even though the country lies entirely within the Tropics, ranging from the Andes Mountains (highest peak at 6542 m) to lowland plains. That leads to a great variety of climatic conditions, soil types and vegetation, which combinations constitute different biomes. Moreover, the cultural landscape is exceptionally various, thanks to the multicultural heritage and co-existence of indigenous people, and European and African influences.

For what concerns the agricultural productivity of Bolivia, despite the challenging highlands hardly reached by water resources and proper machineries, the country hosts favourable regions, especially in its Eastern part, where the Department of Santa Cruz lies. This is of particular interest for the present study since the vast majority of soybean is produced within it. The department extends for more than 370 thousand km^2, being characterised by two main biomes, the Tropical savanna (Chaco) and the Tropical rainforests. Additionally, extensive agricultural areas are dedicated to large-scale cultivations, like soybeans, and cattle ranching, both resulting in the alarming deforestation trend faced by the country (Pacheco, Mertens and Cruz, 2004). Almost three-quarters of recent deforestation has occurred in the Santa Cruz department, mostly affecting the Chiquitano Dry Forest (Czaplicki Cabezas, 2023). The latter is a tropical dry broadleaf forest ecoregion extended between Bolivia and Brazil, and constituting a transition zone from the Tropical Amazon Forest to the Dry Chaco (Radwin M, 2023). As discussed in Chapter 7.3.2, Cargill appears to be the agro-giant mainly involved in this alarming situation (Global Witness, 2023; Radwin M, 2023).

The Santa Cruz department is acknowledged for hosting a highly significant natural region, the Pantanal, renowned for its ecological importance. This region spans across Brazil, Paraguay, and Bolivia, comprising the largest tropical wetland and flooded grasslands globally (WWF a). Facing multiple threats, such as cattle-ranching, hunting, agro-industry, and forest fires, organisations like the World Wildlife Fund have initiated protective measures for the Pantanal region since the turn of the 21st century (WWF b). Wetlands are indeed among the most productive ecosystems in the world, being the habitat for aquatic and terrestrial species. However, their complexity makes them fragile when exposed to externally induced changes.

Regarding the analysis of FAOSTAT data, Tables 5.6, 5.7, 5.8, 5.9 summarise the information related to cultivated hectares, harvested tonnes, and yield. The crops reported covered at least 80% of each variable considered in the years 2000 and 2021.

Table 5.6: Bolivia (2000). Major cultivations according to harvested area.

CROP, 2000	*AREA [kha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	617	29.44	29.44	1.94
Maize (corn)	307	14.66	44.11	2.13
Rice	156	7.46	51.57	1.91
Sunflower seed	130	6.20	57.77	0.85
Potatoes	125	5.98	63.75	5.75
Wheat	119	5.70	69.46	0.85
Barley	88	4.23	73.69	0.75
Sugar cane	84	4.00	77.69	42.96
Sorghum	43	2.04	79.73	2.21
Plantains, bananas	37	1.77	81.49	10.24

Table 5.7: Bolivia (2000). Major cultivations according to produced tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Sugar cane	3.60	40.20	40.20	42.96
Soya beans	1.19	13.36	53.56	1.94
Potatoes	0.72	8.05	61.62	5.75
Maize (corn)	0.65	7.29	68.91	2.13
Plantain, bananas	0.38	4.23	73.14	10.24
Cassava, fresh	0.34	3.82	76.96	9.90
Rice	0.29	3.34	80.30	1.91

Table 5.8: Bolivia (2021). Major cultivations according to harvested area.

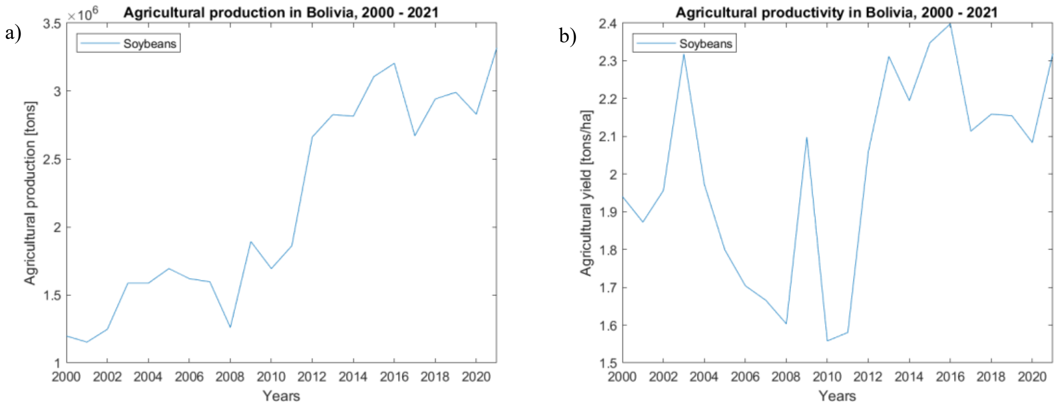
CROP, 2021	*AREA [kha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	1431	36.20	36.20	2.32
Sorghum	501	12.67	48.87	2.95
Maize (corn)	407	10.31	59.18	3.00
Wheat	201	5.08	64.26	1.67
Potatoes	191	4.84	69.10	6.65
Sugar cane	184	4.67	73.76	54.70
Rice	179	4.52	78.29	3.08
Sunflower seed	138	3.50	81.79	1.39

Table 5.9: Bolivia (2021). Major cultivations according to produced tonnes.

CROP, 2021	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Sugar cane	10.09	47.69	47.69	54.70
Soya beans	3.32	15.68	63.38	2.32
Sorghum	1.48	7.00	70.38	2.95
Potatoes	1.27	6.02	76.40	6.65
Maize (corn)	1.22	5.79	82.18	3.00

Based on Tables 5.6 and 5.8, it becomes evident that soybean was the most extensively cultivated crop, even though sugar cane overtook it when considering the produced tonnes (Tables 5.7 and 5.9). Nevertheless, the focus of Trase is maintained over the most pervasive crop to delineate its effects in terms of deforestation. Water consumption needs to be carefully considered as well.

Figure 5.2 shows soybeans time series for the three variables analysed, whereas Table 5.10 reports the percentage increase observed over the period considered.



c)

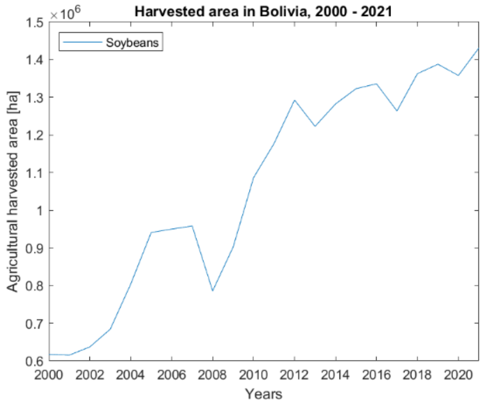


Figure 5.2: Produced tonnes (a), yields (b) and harvested area (c) of soybeans cultivations, Bolivia (2000-2021).

Table 5.10: Percentage increase detected for the three variables of interest (Production quantity, Yield and Area harvested) for soybeans cultivations, Bolivia (2000-2021).

Percentage increase [%]	*Production quantity*	*Yield*	*Area harvested*
Soya beans	177.15	19.48	131.95

Analysing the soybeans time series depicted in Figure 5.2, a notable increase is evident in both the harvested area and produced tonnes (Table 5.10). On the other hand, the yield experienced fluctuations throughout the selected period, most likely due to climatic events, despite an overall growth of 19% (Figure 5.2c).

5.3 Brazil

Certainly, Brazil takes the forefront when examining soy cultivations in South America, due to its considerable areal extension and, therefore, the quantity of soybeans exported worldwide. As discussed for Bolivia in Chapter 5.2, Brazil is also impacted by the deforestation process, even though, thanks to the Amazon Soy Moratorium (ASM)[1], observed rates have been recently declined. According to the environment minister Marina Silva (Watts J, 2023), deforestation in the Brazilian Amazon was at least 60% lower in July 2023 compared to the same month in 2022. Nevertheless, despite this encouraging accomplishment, it is crucial not to overlook the ongoing developments in the nearby Cerrado region. Cerrado is a vast tropical biome where the world's most biodiverse savanna (WWF c), grasslands, and dry or humid forests are threatened by land conversion and deforestation, mainly to create space for unsustainable monocultures and livestock farming (WWF d, 2022).

Stepping back for a moment, it is worth presenting the major natural features of Brazil, to deeply understand the diversity and richness found within this country. The impressive geographic extension, twice the size of all the European Union states (De Petrillo, 2021), enables for the co-existence of almost 20% of all natural species, evidence that gave to Brazil the label of megadiverse country (UN Environment Programme, 2019). Moreover, six terrestrial biomes cover its land,

---

[1] The Amazon Soy Moratorium, initiated in 2006, represents a sectoral agreement wherein commodities traders committed to avoid the purchase of soybeans originated from areas deforested after 2008. It aims at eradicating deforestation from Amazon soybean supply chains, concurrently playing a role in reducing the overall Amazon deforestation rates (Rausch L, 2021).

encompassing forests (Amazonia and Mata Atlantica), grasslands and savannas (Cerrado), alluvial plains (Pantanal, a biome shared with Bolivia and Uruguay), flat plains (Pampa), and dry soils (Caatinga), each one facing different climatic conditions, which vary from the more tropical north to the mostly temperate south (Peel, Finlayson and Mcmahon, 2007). Soil fertility is not homogeneous either, with variable nutrients levels (Prado *et al.*, 2012). However, the presence of irrigation systems and the use of fertilisers enable cultivations to be spread over almost the entire country, making Brazil a global agricultural supplier for crops such as soybeans, coffee, sugar, and corn.

The analysis of FAO data allowed to delineate the relative importance of the different cultivated crops (Tables 5.11, 5.12, 5.13, 5.14).

Table 5.11: Brazil (2000). Major cultivations according to harvested area.

CROP, 2000	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	13.66	26.67	26.67	2.40
Maize (corn)	11.89	23.22	49.88	2.72
Sugar cane	4.80	9.38	59.26	67.87
Beans, dry	4.33	8.46	67.72	0.70
Rice	3.66	7.16	74.88	3.04
Coffee, green	2.27	4.43	79.31	0.84
Cassava, fresh	1.71	3.34	82.64	13.48
Seed cotton, unginned	0.81	1.59	84.24	2.47
Cocoa beans	0.71	1.38	85.61	0.28
Oil palm fruit	0.08	0.16	85.77	8.29

Table 5.12: Brazil (2000). Major cultivations according to produced tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Sugar cane	326.12	66.78	66.78	67.87
Soya beans	32.82	6.72	73.50	2.40
Maize (corn)	32.32	6.62	80.12	2.72
Seed cotton, unginned	2014987	0.41	80.54	2.47
Coffee, green	1903562	0.39	80.93	0.84
Oil palm fruit	678727	0.14	81.06	8.29
Cocoa beans	196788	0.04	81.10	0.28

Table 5.13: Brazil (2021). Major cultivations according to harvested area.

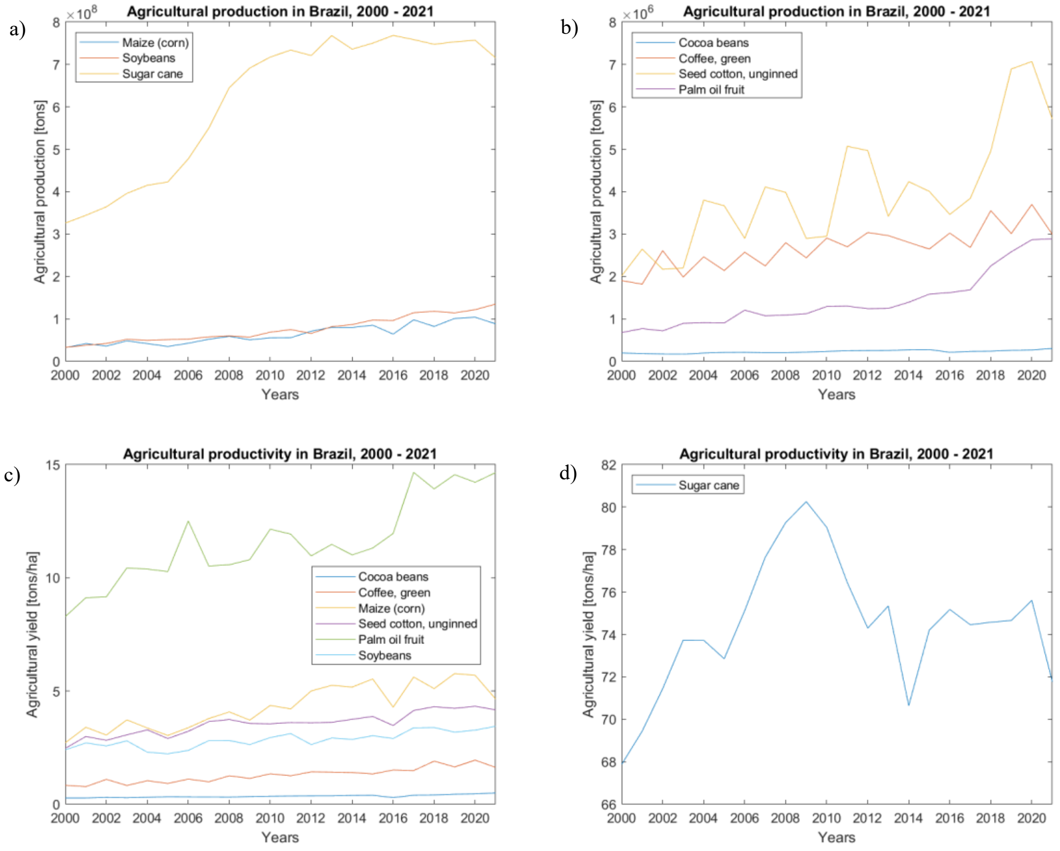
CROP, 2021	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	39.17	45.25	45.25	3.44
Maize (corn)	19.02	21.98	67.24	4.65
Sugar cane	9.97	11.52	78.76	71.77
Wheat	2.75	3.18	81.93	2.86
Coffee, green	1.84	2.12	84.06	1.63
Seed cotton, unginned	1.37	1.58	85.64	4.17
Cocoa beans	0.60	0.69	86.33	0.50
Oil palm fruit	0.19	0.23	86.56	14.65

Table 5.14: Brazil (2021). Major cultivations according to produced tonnes.

CROP, 2021	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Sugar cane	715.66	67.86	67.86	71.77
Soya beans	134.93	12.80	80.66	3.44
Maize (corn)	88461943	8.39	89.04	4.65
Seed cotton, unginned	5712308	0.54	89.59	4.17
Coffee, green	2993780	0.28	89.87	1.63
Oil palm fruit	2887696	0.27	90.14	14.65
Cocoa beans	302157	0.03	90.17	0.50

As depicted in Tables 5.11 and 5.13, soybean consistently emerges as the most cultivated crop over the selected period. However, in terms of produced tonnes, sugar cane takes absolute precedence when making comparisons (Tables 5.12 and 5.14). The explanation is found in yield values of the two crops, as reported in the last column of each table.

Figure 5.3 reports time series for the cultivations of cocoa, coffee, corn, cotton, palm oil fruit, soybeans and sugarcane. Due to the different order of magnitude of variables' numbers, crops are subdivided accordingly. Table 5.15 shows the percentage increase observed for each variable and each crop.



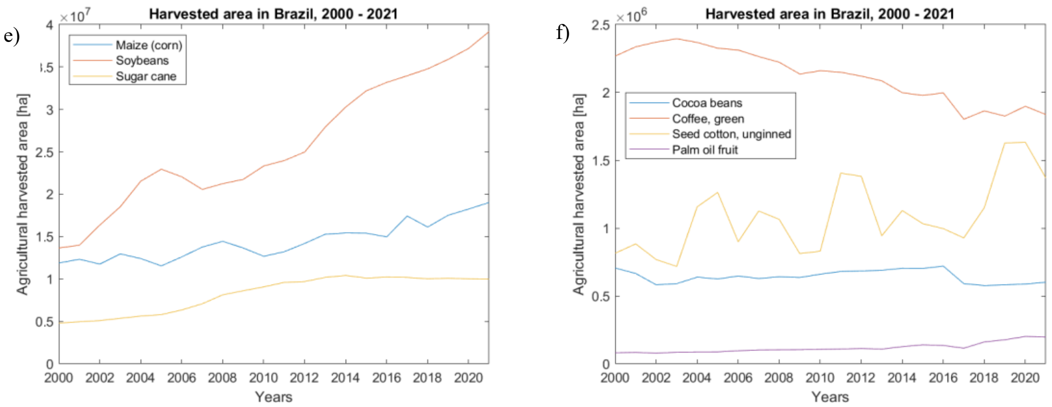


Figure 5.3: Produced tonnes (a, b), yields (c, d) and harvested area (e, f) of cocoa, coffee, corn, cotton, oil palm fruit, soybeans and sugarcane cultivations, Brazil (2000-2021).

Table 5.15: Percentage increase detected for the three variables of interest (Production quantity, Yield and Area harvested) for cocoa, coffee, corn, cotton, oil palm fruit, soybeans and sugarcane cultivations, Brazil (2000-2021).

Percentage increase [%]	*Production quantity*	*Yield*	*Area harvested*
Cocoa beans	53.54	80.38	-14.9
Coffee, green	57.27	94.19	-19.01
Maize (corn)	137.7	71.06	60
Seed cotton, unginned	183.49	68.75	68
Oil palm fruit	325.46	76.69	140.8
Soya beans	311.13	43.34	186.8
Sugar cane	119.45	5.74	107.53

Brazil stands out with a remarkable surge in soybean production (Figure 5.3b, + 311%), attributed to the synergic impact of enhanced yield (Figure 5.3c, + 43%) and an expanded cultivation area (Figure 5.3a, + 187%). Similarly to what observed for Argentina in Chapter 5.1, soybean productivity in Brazil underwent fluctuations over time, marked by significant declines in 2003-2004, 2011-2012, and 2018-2019. Major explanation is found in yield sensitivity to climatic variability. As appreciable from Table 5.15, palm oil fruit had the most impressive productive growth (+ 325%), whereas coffee and cocoa faced a noteworthy yield improvement, of 94% and 80% respectively. As a result, despite the reduction in the harvested area for cocoa and coffee, more tonnes were still produced. On the other hand, cotton was characterised by significant fluctuations in terms of cultivated hectares and produced tonnes over the whole period.

5.4 Colombia

Colombia is situated at the convergence of two large continental masses, in the northwest corner of South America. The geographic position imparts a megadiversity character to the region, with huge climatic variations and a vast range of ecosystems, from savannas to tropical Amazon rainforest, and from alpine tundra to dry tropical forest (Irwin A, 2023). Additionally, more than 60% of global paramos[2] are found on Colombian soil (Marca País Colombia), along with mangrove

---

[2] The paramo is one of the world's fastest evolving biodiversity hotspots, situated in mountainous regions between the treeline and glaciers. Its vegetation is composed mainly of giant rosette plants, shrubs and grasses. The only countries hosting this neotropical high altitude ecoregion are Colombia, Ecuador, Peru, and Venezuela. Moreover, 86% of flowering

forests[3], wetlands and coral reefs[4]. In the coastal areas and eastern lowlands, the climate is tropical, whereas it tends to be cooler in the highlands and the Andes (Peel, Finlayson and Mcmahon, 2007). Colombia faces inter-annual rainfall variability caused by the El Niño Southern Oscillation (ENSO).

Concerning agricultural activities, the country is suitable for producing coffee, corn, cocoa beans, sugarcane and palm oil, to mention a few. In 2023, it ranked as the third larger coffee producer (Arabica variety only), after Vietnam (2nd) and Brazil (1st) (Trimmer C. and Goldstein A., 2020).

Despite the multiple sustainable projects that have been recently introduced by the government, deforestation, pristine rainforest disruption and climate change remain major issues (Igini M, 2023). Additionally to coffee and palm oil/palm kernel plantations, mining activities, coca production, illegal timber traffic, infrastructure development and livestock are non-negligible deforestation causes (Davey E, 2018). According to Davey E. (2018), cocoa production has not caused significant forest losses yet. On the contrary, agroforestry-based cocoa could help in restoring degraded lands and closing pristine forests to development.

The following tables (Tables 5.16, 5.17, 5.18, 5.19) report results of FAOSTAT data analysis.

Table 5.16: Colombia (2000). Major cultivations according to harvested area.

CROP, 2000	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Coffee, green	0.67	18.07	18.07	0.94
Maize (corn)	0.57	15.30	33.38	2.11
Rice	0.47	12.65	46.03	4.73
Sugar cane	0.40	10.87	56.89	83.64
Plantains and cooking bananas	0.39	10.46	67.35	7.23
Cassava, fresh	0.18	4.80	72.15	9.99
Oil palm fruit	0.13	3.61	75.76	18.33
Beans, dry	0.11	3.10	78.86	1.08
Potatoes	0.11	2.93	81.79	12.82
Cocoa beans	0.08	2.22	84.01	0.44

Table 5.17: Colombia (2000). Major cultivations according to produced tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Sugar cane	33.96	63.16	63.16	83.64
Plantains - cooking bananas	2.82	5.25	68.41	7.23
Oil palm fruit	2.47	4.59	73.01	18.33
Rice	2.24	4.16	77.17	4.73
Cassava, fresh	1.79	3.33	80.50	9.99
Coffee, green	0.64	1.18	81.69	0.94
Cocoa beans	0.04	0.07	81.75	0.44

---

plant species are endemic to this ecosystem. The social importance of Paramo is related to its capability of acting as a sponge, soaking up water and delivering it to forests and communities at lower elevations. Despite the increased protection, it remains threatened by deforestation and overgrazing (single reference: Nature and Culture International).

[3] According to *The State of the World's Mangroves 2022*, mangrove forests are the most efficient carbon capture and storage systems on the planet. The stored carbon is currently equivalent to over 21 billion tons of CO_2. Climate mitigation and resilience against extreme weather can indeed benefit from a healthy mangrove ecosystem (Leal *et al.*, 2022).

[4] In the context of the *UN Decade of Ecosystem Restoration* (FAO and United Nations), the project "One million corals for Colombia" was launched in 2021, aiming to growing one million fragments of coral and restoring 200 hectares of reefs by March 2023 (United Nations, 2022).

Table 5.18: Colombia (2021). Major cultivations according to harvested area.

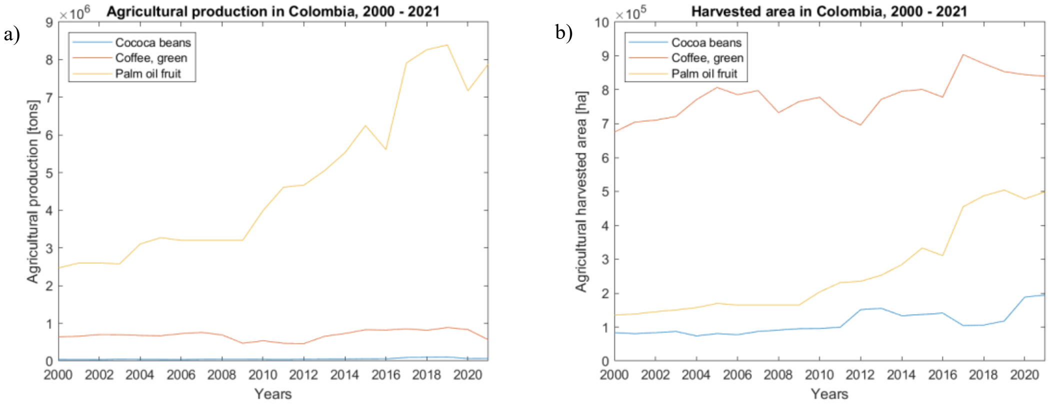
CROP, 2021	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Coffee, green	0.84	19.07	19.07	0.67
Rice	0.54	12.36	31.43	6.11
Oil palm fruit	0.49	11.34	42.77	15.79
Sugar cane	0.42	9.65	52.42	56.53
Maize (corn)	0.40	9.14	61.56	3.95
Plantains and cooking bananas	0.27	6.12	67.68	8.65
Cocoa beans	0.19	4.41	72.09	0.34
Potatoes	0.12	2.73	74.82	21.81
Bananas	0.10	2.31	77.13	23.69
Cassava, fresh	0.09	2.16	79.29	10.35
Avocados	0.09	2.14	81.43	10.41

Table 5.19: Colombia (2021). Major cultivations according to produced tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Sugar cane	24.03	43.10	43.10	56.53
Oil palm fruit	7.88	14.14	57.23	15.79
Rice	3.32	5.97	63.20	6.11
Potatoes	2.62	4.70	67.90	21.81
Bananas	2.41	4.33	72.23	23.69
Plantains - cooking bananas	2.33	4.18	76.41	8.65
Maize (corn)	1.59	2.85	79.27	3.95
Other fruits, n.e.c.	1.02	1.84	81.11	11.57
Coffee, green	0.56	1.00	82.11	0.67
Cocoa beans	0.06	0.12	82.23	0.34

As visible in Tables 5.16 and 5.18, coffee was the main cultivated crop in both the years considered. Despite that, being associated with low yields (0.94 tons/ha and 0.67 tons/ha respectively), it is not included among the products accounting for 80% of total production. Indeed, coffee only accounted for 1.18% (2000) and 1% (2021) of the produced tonnes. On the other hand, oil palm fruit is present in all tables (Tables 5.16, 5.17, 5.18, 5.19), indicating its significance for Colombian agriculture. Interestingly, cocoa bean cultivations experienced a marked growth, accounting for 4.4% of total harvested area by the end of the period (Table 5.18).

Time series for cocoa, coffee and palm oil fruit are reported in Figure 5.4. Table 5.20 shows the percentage variations of the variables analysed.



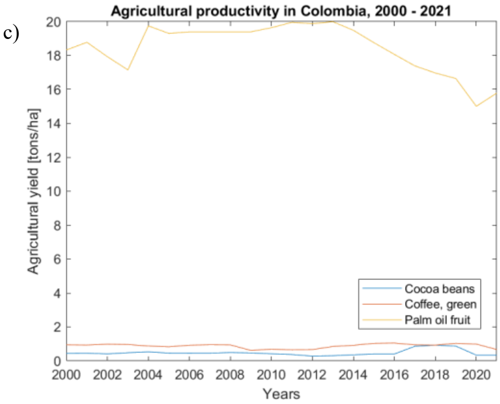


Figure 5.4: Produced tonnes (a), yields (b) and harvested area (c) of cocoa, coffee and oil palm fruit cultivations, Colombia (2000-2021).

Table 5.20: Percentage increase detected for the three variables of interest (Production quantity, Yield and Area harvested) for cocoa, coffee, oil palm fruit cultivations, Colombia (2000-2021).

Percentage increase [%]	*Production quantity*	*Yield*	*Area harvested*
Cocoa beans	77.41	-24.13	133.86
Coffee, green	-12.05	-29.29	24.39
Oil palm fruit	219.13	-13.87	270.52

Oil palm fruit saw the most impressive increase in produced tonnes and cultivated hectares (Table 5.20); however, similarly to coffee and cocoa, its yield dropped by the end of the period. Coffee harvests decreased by 12%, despite the areal expansion. In particular, in the years 2008 to 2012 the observed production decline amounted to 33% (Figure 5.4a), due to rains, clouds and hot spells caused by El Niño and La Niña (Eisa and White, 2018).

5.5 Ivory Coast

The sub-Saharan nation located in southern West Africa is the world's largest cocoa producer and, along with Ghana (the second biggest), accounts for two thirds of the global cocoa production (Kalischek *et al.*, 2023). In both nations cocoa stands out as the predominant perennial crop, contributing to the livelihoods of nearly two million farmers (Kalischek *et al.*, 2023). However, the absence of precise maps detailing cocoa cultivation areas hampers the accurate quantification of expansion into protected areas, as well as assessments of production and yields. This limitation restricts the information available for enhanced governance and sustainability measures. The results of Kalischek et al. (2023) research suggest that cocoa cultivations are an underlying driver of over 37% of forest loss in protected areas in Ivory Coast and over 13% in Ghana since the year 2000. To comprehend the reason behind the flourishing of cocoa plantations in these countries, it is necessary to analyse the local climate. Cacao trees thrive in rainforests, where they can grow under specific conditions such as almost uniform temperatures, high humidity, abundant rain, nitrogen-rich soil, and protection from wind (Scott M, 2016). Being cocoa farms particularly sensitive to climatic conditions, only a narrow band of countries between 20° north and south of the equator happen to be appropriate (Scott M, 2016). Nevertheless, temperature rise and humidity variations linked to climate change will consistently affect cocoa yields. As Figure 5.5 shows, a decade has passed since alarming projections highlighted the uncertain future of cacao tree distribution (Läderach *et al.*, 2013).

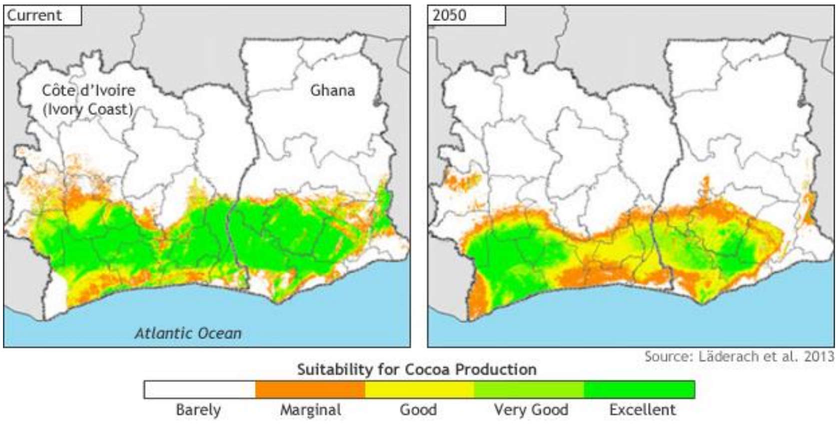


Figure 5.5: Suitability for cocoa production, Ivory Coast and Ghana. Comparison of current conditions (2013) and projections for the year 2050 (Läderach et al.*, 2013).*

The interdependency of cocoa and climate change underlines the complexity of cocoa plantations management. Specifically, a vicious cycle is triggered when cocoa farms expand into new areas. This is the final consequence of the initial deforestation process, which disrupts local weather patterns and causes carbon emissions, contributing to global climate change. As temperatures rise and droughts become more frequent, areas once cultivated become no more suitable, leading to new land clearing (Mondelez International).

Trase efforts of mapping the exports of this crop are thus extremely relevant to help tracing supply chains flows and the role of traders. This becomes especially crucial as traders should exhibit more consistent commitment to Zero deforestation in the future. Finally, cocoa related social issues, i.e. slavery and workers exploitation, must be always considered alongside the environmental problems.

Concerning the analysis of FAOSTAT data, Tables 5.21, 5.22, 5.23, 5.24 report results for the major crops in Ivory Coast.

Table 5.21: Ivory Coast (2000). Major cultivations according to harvested area.

CROP, 2000	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Cocoa beans	2	32.29	32.29	0.70
Coffee, green	0.83	13.39	45.68	0.46
Yams	0.50	8.16	53.85	8.82
Plantains and cooking bananas	0.44	7.19	61.04	3.65
Rice	0.34	5.51	66.55	1.82
Seed cotton, unginned	0.29	4.71	71.26	1.38
Maize (corn)	0.28	4.59	75.85	2.03
Cassava, fresh	0.27	4.38	80.23	7.74

Table 5.22: Ivory Coast (2000). Major cultivations according to produced tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Yams	4.45	26.92	26.92	8.82
Cassava, fresh	2.10	12.69	39.61	7.74
Sugar cane	1.67	10.10	49.71	63.24
Plantains and cooking bananas	1.62	9.82	59.54	3.65
Cocoa beans	1.40	8.46	68.00	0.70
Oil palm fruit	1.13	6.85	74.85	7.13
Rice	0.62	3.76	78.61	1.82
Maize (corn)	0.57	3.49	82.09	2.03

Table 5.23: Ivory Coast (2021). Major cultivations according to harvested area.

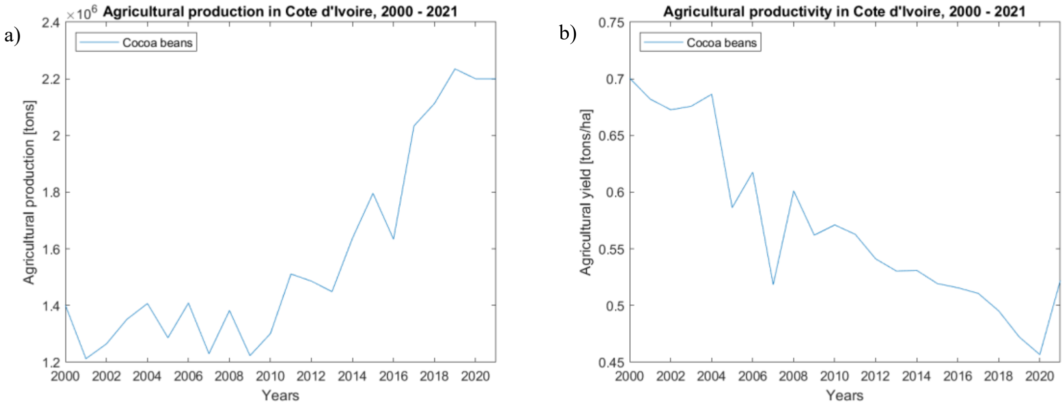
CROP, 2021	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Cocoa beans	4.21	30.00	30.00	0.52
Cashew nuts, in shell	1.98	14.16	44.16	0.42
Yams	1.44	10.24	54.39	5.46
Cassava, fresh	1.09	7.78	62.17	6.37
Coffee, green	0.99	7.12	69.29	0.13
Rice	0.58	4.14	73.43	2.85
Plantains and cooking bananas	0.55	3.95	77.38	3.83
Maize (corn)	0.52	3.69	81.07	2.20

Table 5.24: Ivory Coast (2021). Major cultivations according to produced tonnes.

CROP, 2021	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Yams	7.85	24.99	24.99	5.46
Cassava, fresh	6.96	22.15	47.14	6.37
Oil palm fruit	2.33	7.43	54.56	6.43
Cocoa beans	2.20	7.00	61.56	0.52
Plantains and cooking bananas	2.12	6.77	68.33	3.83
Sugar cane	2.10	6.69	75.02	82.86
Rice	1.66	5.28	80.30	2.85

In terms of harvested area, cocoa occupied a stable 30% of the land (Table 5.21 and 5.23). However, due to its low yield if compared to the other crops (0.52 tons/ha in 2021), cocoa production was much lower than crops such as yams and fresh cassava. Indeed, these two agricultural products occupied the first and second positions in terms of tonnes (Tables 5.22 and 5.24).

In Figure 5.6, time series for cocoa are reported, one for each variable analysed, whereas Table 5.25 shows the corresponding percentage variations.



c)

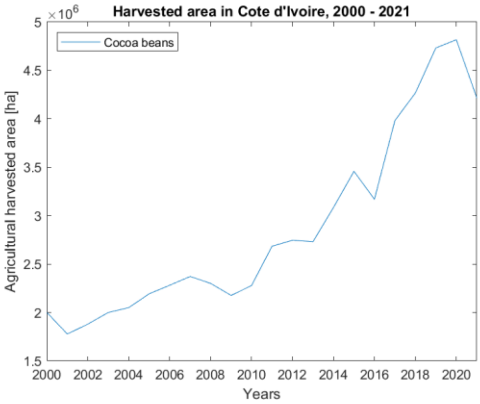


Figure 5.6: Produced tonnes (a), yields (b) and harvested area (c) of cocoa cultivations, Ivory Coast (2000-2021).

Table 5.25: Percentage increase detected for the three variables of interest (Production quantity, Yield and Area harvested) for cocoa cultivations, Ivory Coast (2000-2021).

Percentage increase [%]	*Production quantity*	*Yield*	*Area harvested*
Cocoa beans	57.02	-25.5	110.73

Cocoa plantations faced a considerable drop in productivity (– 22.5%); however, the increased cultivated surface allowed for a consequent increase in production (Table 5.25). The most relevant yield drops are observed for the years 2004-2005 and 2006-2007, whereas an almost steady decrease has been registered since 2008. In 2020-2021, a non-negligible improvement is noticed (+14%), which corresponded to an area reduction (– 12.5%).

5.6 Paraguay

Paraguay is the second and last landlocked country in South America, strategically bordered by Brazil, Bolivia, and Argentina. This agricultural country benefits from significant water sources, particularly the Paraná-Paraguay River system. The latter crosses the country, whereas the Paraná River constitutes a natural border with Uruguay. Notably, the fertile region situated between these two rivers serves as the primary hub for most of the agricultural production in the country, characterised by a climate ranging from temperate to tropical (Peel, Finlayson and Mcmahon, 2007). On the other hand, the Northwestern part of the country, with its arid climate, supports a narrower variety of cultivations, although favourable for peanut production (U.S. Department of Agriculture, b). In Figure 5.7, the two aforementioned rivers are shows, along with the Itaipú and Yacyretá dams. These dams are important for energy production. It should be noted that the Itaipú dam is the second largest hydroelectric dam in the world, in terms of gigawatts produced (Lu, 2022). They are significant for Argentina, Brazil and Paraguay; however, relevant environmental and social impacts have been caused to the region, due to the massive land changes and ecosystems alterations.

Figure 5.7: Paraguay-Paraná River basin, South America (Costa W, 2021).

As for the analysis on the considered period, summarising tables are reported (Tables 5.26, 5.27, 5.28, 5.29).

Table 5.26: Paraguay (2000). Major cultivations according to harvested area.

CROP, 2000	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	1.17	47.01	47.01	2.53
Maize (corn)	0.33	13.25	60.26	1.95
Cassava, fresh	0.20	8.06	68.33	13.47
Seed cotton, unginned	0.19	7.78	76.11	1.26
Wheat	0.13	5.10	81.21	1.81

Table 5.27: Paraguay (2000). Major cultivations according to production tonnes.

CROP, 2000	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	2.98	28.46	28.46	2.53
Cassava, fresh	2.72	25.97	54.43	13.47
Sugar cane	2.24	21.44	75.87	37.76
Maize (corn)	0.65	6.18	82.06	1.95

Table 5.28: Paraguay (2021). Major cultivations according to harvested area.

CROP, 2021	*AREA [Mha]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	3.64	60.73	60.73	2.89
Maize (corn)	0.99	16.52	77.24	4.13
Wheat	0.45	7.51	84.75	2.06

Table 5.29: Paraguay (2021). Major cultivations according to production tonnes.

CROP, 2021	*QUANTITY [Mtons]*	*PERC [%]*	*PERC_CUM [%]*	*YIELD [tons/ha]*
Soya beans	10.54	36.27	36.27	2.89
Sugar cane	7.22	24.86	61.13	68.77
Maize (corn)	4.09	14.07	75.20	4.13
Cassava, fresh	3.38	11.65	86.85	18.00

In each table, the prevalence of soybean cultivations over the other crops is appreciated, in terms of both harvested hectares and produced tonnes, at the beginning and end of the period.

Figure 5.8 represents the times series for corn and soybeans. Table 5.30 summarises the percentage variations over time.

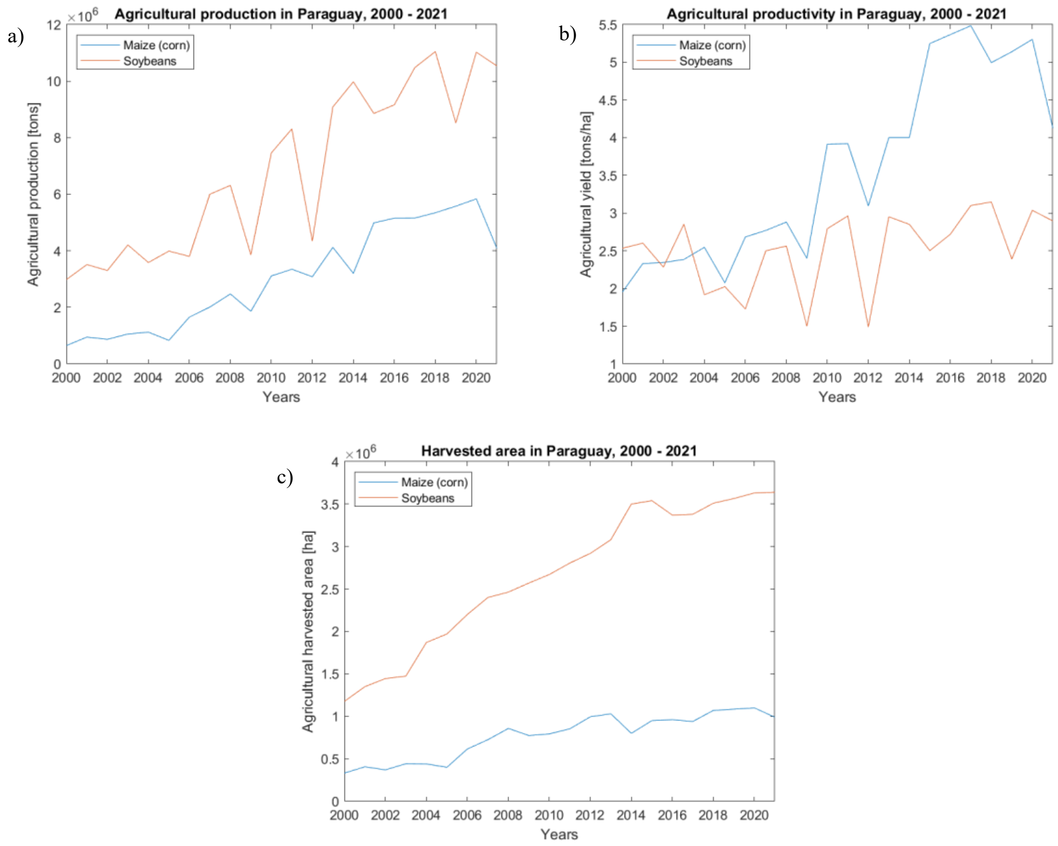


Figure 5.8: Produced tonnes (a), yields (b) and harvested area (c) of corn and soybeans cultivations, Paraguay (2000-2021).

Table 5.30: Percentage increase detected for the three variables of interest (Production quantity, Yield and Area harvested) for corn and soybeans cultivations, Paraguay (2000-2021).

Percentage increase [%]	*Production quantity*	*Yield*	*Area harvested*
Maize (corn)	531.6	111.63	198.44
Soya beans	253.58	14.28	209.4

From Figure 5.8a, the remarkable growth in soybeans harvested area is clearly observed. In 2021, more than half of the agricultural lands were cultivated with soy, with an increase of 209% over the period. However, Paraguay experienced marked oscillations in soybeans productivity, with minimum values registered for the years 2008-2009 (1.5 tons/ha) and 2011-2012 (1.48 tons/ha), as visible in Figure 5.8b. Additionally, 2003-2004 and 2017-2018 harvests were characterised by consistent drops too. Agricultural losses were caused by drought events, as discussed for Argentina in Chapter 5.1. Concerning corn, the cultivated hectares witnessed an increase; however, the substantial production growth is primarily justified by the marked yield improvement (refer to Table 5.30). Corn encountered fluctuations in yield as well: for instance, in 2020-2021, there were significant harvest losses, resulting in a 30% decline of production.

As reported by Hiba J (2022), in January 2022 northeastern Argentina, southern Brazil and Paraguay experienced a prolonged period of drought, with severe impacts on soybean and maize cultivations. This was mainly due to the La Niña climate pattern, impacting South American weather and inhibiting rainfall in the Paraná basin area. Moreover, La Niña events normally occur every five years, but, since 2019, an unusual “triple dip” of three consecutive La Niña years have occurred (Tandon A, 2023).

5.7 Comparisons on soy production

Chapter 5.7 aims to compare the four countries involved in the soybean analysis, thus Argentina, Bolivia, Brazil, and Paraguay. Firstly, the soybean values for the three variables of interest (*Area harvested*, *Production quantity*, and *Yield*) are represented throughout time series (Figure 5.9). Subsequently, normalisation is performed by considering the geographical area of each country to detect how significant the production of these crops is when compared to the overall extension of the producer (Figure 5.10).

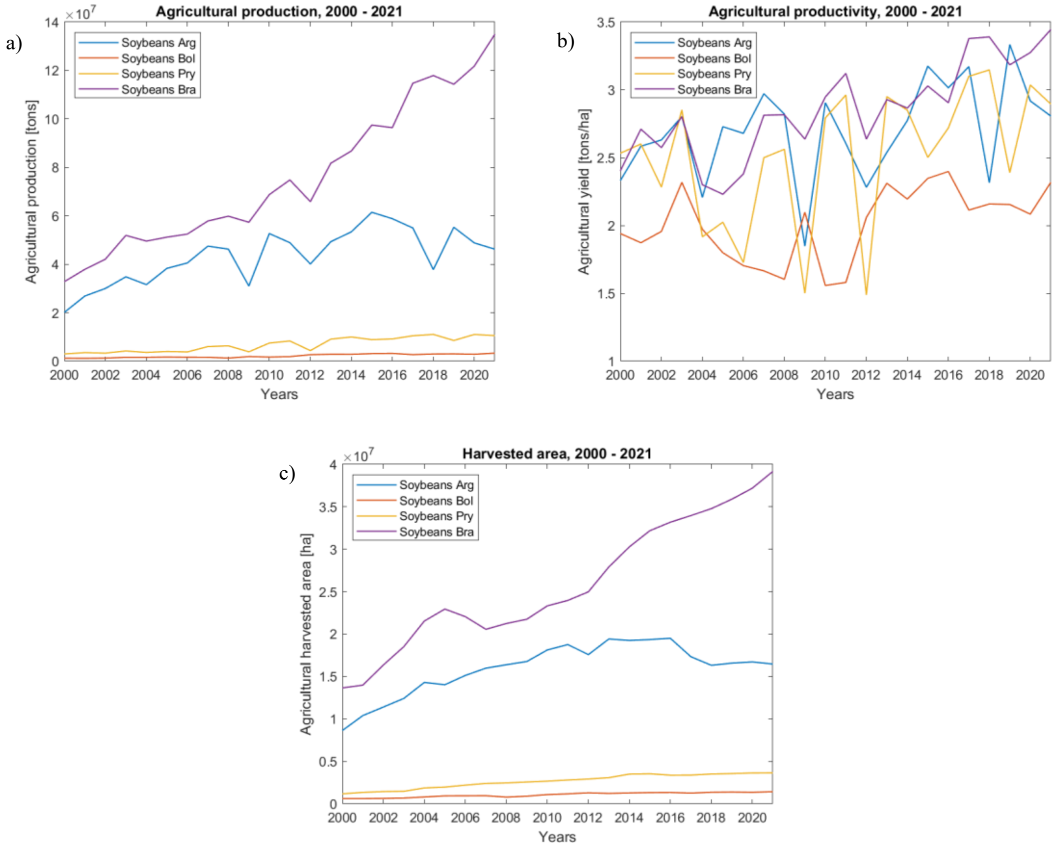


Figure 5.9: Produced tonnes (a), yields (b) and harvested area (c) of soybeans cultivations (2000-2021). Comparison among Argentina, Bolivia, Brazil and Paraguay.

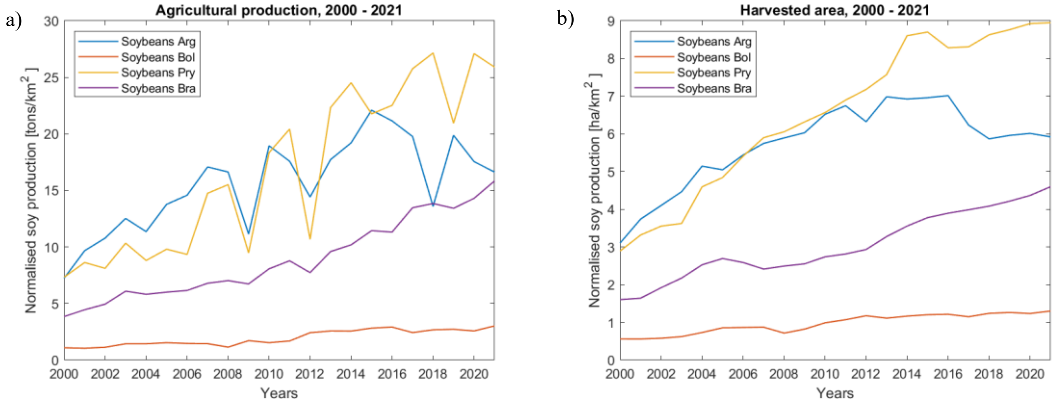


Figure 5.10: Produced tonnes (a) and harvested area (b) of soybeans cultivations (2000-2021). Comparison among Argentina, Bolivia, Brazil and Paraguay. Variables have been normalised by the area of each country.

What clearly emerges from Figure 5.10 is that Paraguay, by the end of the selected time horizon, had the highest soybean density in terms of both hectares (9 ha/km^2) and produced tonnes (25 tons/km^2). It is evident that in 2000, Paraguay's starting values were similar to those of Argentina. However, by 2021, the gap between the two countries had widened, emphasising the significance of soybean production in Paraguay. This is inevitably related to an increasing deforestation risk for some areas, especially the Dry Chaco in the North of the country (Tyldesley M, 2021). This area is currently contributing to a tiny percentage of national soy production; however, the involved area is subject to an alarming expansion. Paraguayan soybean exports are in some cases covered by Zero deforestation commitments, but this is not the case of Dry Chaco and part of the western Humid Chaco, making them exposed to illegal deforestation (Tyldesley M, 2021).

Figure 5.9c allows for a comparison of yield values among the selected countries, highlighting notable aspects:

- Bolivia tended to have a lower productivity, as well as it had the lowest soybean production, both in absolute and normalised terms.
- Bolivia's yields often exhibited an opposite trend, if compared to the values of the other countries.
- Argentina, Brazil, and Paraguay's yield drops were often in phase, like in the years 2004, 2009, and 2012. The last visible yield drop is observed in 2018 for Argentina and 2019 for Paraguay. There is evidence that each country experienced a prolonged drought period in those years, causing considerable harvest losses, with a minor magnitude in Brazil.

To deepen the analysis, unit water footprint values were studied (CWASI). The evolution in time of green *uWFs* – referred to the total amount of soybean produced in each of the four countries – is presented in Figure 5.11a. Figure 5.11b, instead, considers blue *uWF* values for Argentina and Brazil only, since there are no available data for Bolivia, whereas Paraguay's blue *uWFs* are not reported in the database for the selected period. Data are shown for the years from 2000 to 2019.

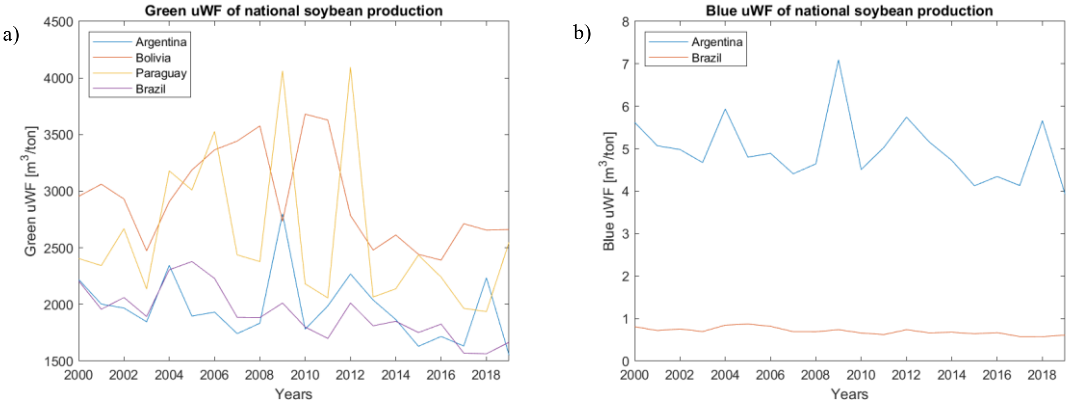


Figure 5.11: Green (Argentina, Bolivia, Brazil, Paraguay) and blue (Argentina, Brazil) unit water footprint values [m^3/ton], at the national scale (2000-2019) (CWASI).

Comparing Figures 5.9b and 5.11a, it appears that yields and green *uWFs* showed an opposite behaviour: in correspondence of years with yield drops, the *uWF* values rose, and vice versa. This leads to the conclusion that evapotranspiration values are predominant over yield ones in determining the *uWFs*. As discussed above, the recorded trend for Bolivia seems to deviate from the one of the other countries, particularly in those years characterised by positive peak values (2009, 2012). Moreover, concerning the percentage variations over the period, only Paraguay registered a growth in green *uWFs* (+ 5%), whereas Argentina, Bolivia, and Brazil faced a decrease (– 30%, – 10%, – 24% respectively).

Figure 5.12 reports the water footprint (*WF*) of soybean for the countries of interest. Data are retrieved from the CWASI database, and they cover a sixty-three-year period, from 1960 to 2016, allowing to have a first idea of the overall water consumption related to soybeans. Figure 5.12 shows the entire available time series, even if the previous analysis has been done on a shorter period, but this enables to better appreciate the changes occurred over time.

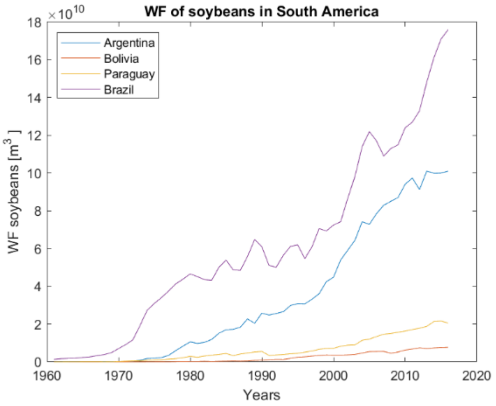


Figure 5.12: Evolution in time of water footprint values, at the national scale. Argentina, Bolivia, Brazil and Paraguay (1960-2016) (CWASI).

If considering the last seventeen years, 2000 to 2016, to be as close as possible to the studied interval of time, the percentage increase experienced by *WF* values becomes evident: 56% for Argentina, 54% for Bolivia, 59% for Brazil, and 65% for Paraguay. The higher value of the last country can be explained by the combined considerable increment in both produced tonnes (+ 253%) and *uWF* values (+ 5%), as per Equation 5.1:

$$WF\ [m^3] = uWF\ \left[\frac{m^3}{ton}\right] * produced_{soybean}\ [tons] \tag{5.1}$$

Chapter 6 – Results

Through the methodology presented in Chapter 4, the production of selected crops was assessed at the subnational scale, along with the quantification of the associated water footprint volumes, originating from local units in specific years. Additionally, the methodology allowed for the identification of virtual water volumes linked to trader companies and importing countries.

Chapter 6 presents a section for each producing country involved in the study. Moreover, subsections are included to provide descriptions for distinct crops when multiple analysis were conducted for the same producing country. Figures showing cumulative distribution functions and corresponding boxplots are reported for the major importer countries and traders, as discussed in Chapter 4.1.4. In addition, maps with weighted barycentres are utilised to enhance the virtual water flows assessment. These provide a powerful tool for the importers to understand and manage their food supply chain by means of cooperation with traders, as stated by De Petrillo et al. (2023). Results consider only the major detected actors and for soybeans in Argentina intermediate steps are discussed. For the other producing countries, maps other than the core ones are reported in Appendix C. For each producer-commodity combination presented in this chapter, the last step involved in the analysis was the investigation about the existing relationships between traders and importers. Specifically, the focus was maintained on the traded virtual water volumes. Examples are reported just once for each producing country, as Chapter 7 is dedicated to the comparative analysis of water efficiency among traders and importers' dependence on traders to determine their local pressure.

Chapter 6 shows results for the last available year (Trase) whenever possible. Cocoa trade from Brazil is an exception: in Chapter 6.3.1, the results discussed are related to trade flows in 2015. Indeed, for the years 2016 and 2017, very few data were available, making a proper investigation unfeasible.

6.1 Argentina – soy

In Argentina, the analysis was conducted on soybeans that were traded in 2019. From FAOSTAT data, it emerged that 19 countries accounted for more than 81% of the traded tonnes, in the five-year period 2015 to 2019. On the other hand, in 2019 soybeans flows towards these importers were handled for more than 81% by 8 traders (Trase data). Three additional companies were considered in the presented evaluation, to fulfil the constraint explained in Chapter 4.1.1. Tables 6.1 and 6.2 (dark brown for additional traders) allow for the identification of names and relative percentages.

Table 6.1: Argentina, soy (2015-2019). Major importing countries (FAOSTAT).

IMPORTER	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
China, mainland	3.83E+07	19.06	19.06	23.50
India	2.34E+07	11.64	30.69	14.35
Viet Nam	1.57E+07	7.83	38.52	9.65
Indonesia	1.06E+07	5.26	43.78	6.48
Egypt	9.10E+06	4.53	48.30	5.58
Algeria	6.80E+06	3.38	51.69	4.17
Spain	6.57E+06	3.27	54.96	4.03
Italy	6.33E+06	3.15	58.11	3.88

IMPORTER	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Malaysia	6.00E+06	2.99	61.10	3.68
Poland	5.92E+06	2.95	64.05	3.63
Iran (Islamic Republic of)	5.67E+06	2.82	66.87	3.48
Bangladesh	5.53E+06	2.75	69.62	3.40
United Kingdom of Great Britain and Northern Ireland	4.36E+06	2.17	71.79	2.68
Peru	3.60E+06	1.79	73.59	2.21
Türkiye	3.55E+06	1.77	75.35	2.18
Australia	3.27E+06	1.63	76.98	2.01
Philippines	2.90E+06	1.44	78.43	1.78
Venezuela (Bolivarian Republic of)	2.70E+06	1.35	79.77	1.66
Netherlands	2.66E+06	1.32	81.10	1.63

Table 6.2: Argentina, soy (2019). Major exporting companies (Trase).

EXPORTERGROUP	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
VICENTIN	3.53E+06	12.63	12.63	13.38
COFCO	3.49E+06	12.46	25.09	13.20
CARGILL	3.28E+06	11.73	36.82	12.42
ADM	3.18E+06	11.35	48.17	12.03
ACEITERA GENERAL DEHEZA SA.	2.81E+06	10.06	58.23	10.66
GLENCORE	2.76E+06	9.86	68.09	10.44
BUNGE	1.85E+06	6.63	74.72	7.02
LOUIS DREYFUS	1.77E+06	6.32	81.04	6.69
PEREZ COMPANC FAMILY GROUP	1.55E+06	5.53	86.57	5.86
ASOCIACION DE COOPERATIVAS ARGENTINAS (COOP.LTDA)	1.39E+06	4.96	91.53	5.26
CHS	8.05E+05	2.88	94.41	3.05

Before applying the algorithm described in Chapter 4.1.4, the geographical distribution of sourcing departments was analysed. This was relevant to detect the major involved areas, based on the names reported in Tables 6.1 and 6.2. Figure 6.1 reports the administrative divisions of Argentina into provinces (1st level, a) and departments (2nd level, b).

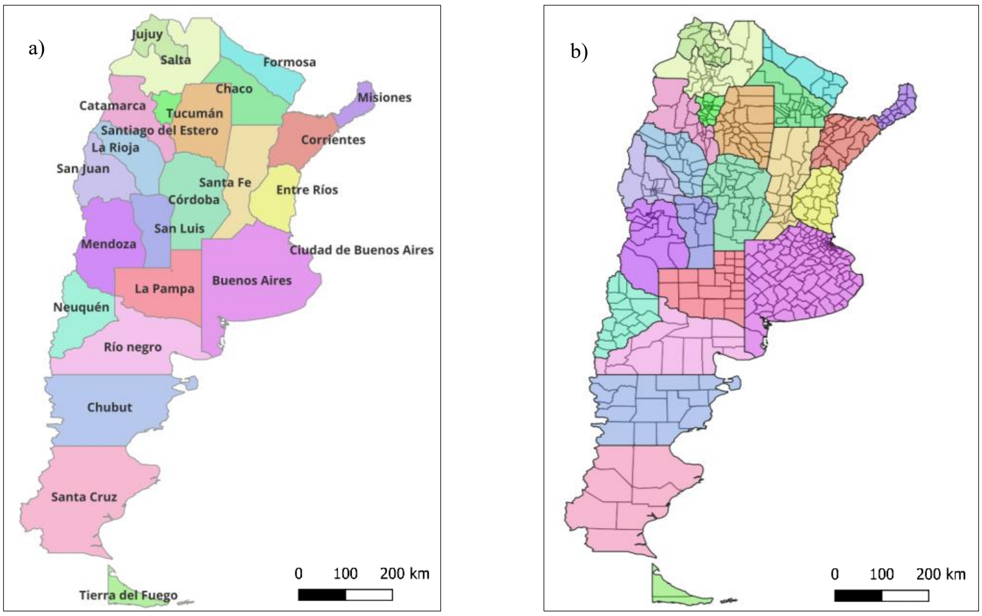


Figure 6.1: Geographic framework of Argentina. Provinces (a) and departments (b).

While skimming Trase dataset accordingly to Tables 6.1 and 6.2, it was observed that 197 departments supplied the major importers. These departments appear to be quite homogeneously distributed in the north – northeastern side of the country, as appreciable in Figure 6.2. The map in Figure 6.2a reports the produced soybean collected over 2019 in each department. According to the colour ramp, it can be observed that the most intensive production centres were in the provinces of Santa Fe, Buenos Aires and Córdoba, all falling within La Pampas region. On the other hand, Figure 6.2b shows yield values exhibited by the departments, confirming the three aforementioned provinces as the most productive ones.

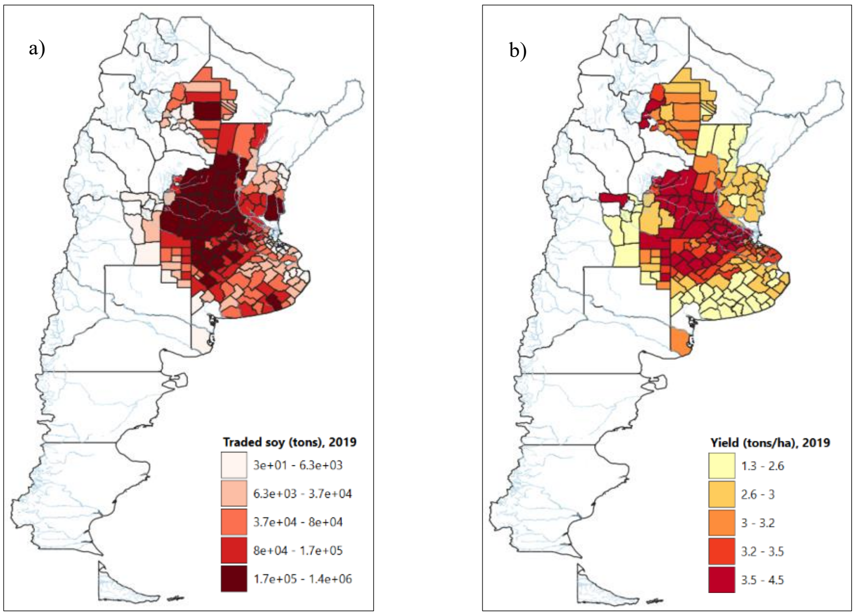


Figure 6.2: Argentina, soy (2019). Traded tonnes (a) and yield values (b) for each involved department.

Table 6.3 reports the first twenty producing departments ($1.41 * 10^7\ tons$), which covered more than 53% of the soy supplied by the 197 considered ($2.64 * 10^7\ tons$).

Table 6.3: Argentina, soy (2019). First twenty producing departments. Exported tonnes and yield values are reported.

PROVINCE	DEPARTMENTOFPRODUCTION	GEOCODE	SOY [tons]	YIELD [tons/ha]
CORDOBA	MARCOS JUAREZ	AR014063	1.40E+06	4.19
SANTA FE	GENERAL LOPEZ	AR082042	1.39E+06	3.92
CORDOBA	SAN JUSTO	AR014140	1.26E+06	3.85
CORDOBA	UNION	AR014182	1.10E+06	3.94
CORDOBA	RIO CUARTO	AR014098	1.06E+06	2.69
SANTA FE	SAN MARTIN	AR082126	7.58E+05	4.26
SANTA FE	CASTELLANOS	AR082021	7.27E+05	3.40
SANTA FE	CASEROS	AR082014	7.21E+05	4.25
SANTA FE	CONSTITUCION	AR082028	7.02E+05	4.03
SANTA FE	IRIONDO	AR082056	6.91E+05	4.35
CORDOBA	PRESIDENTE ROQUE SAENZ PENA	AR014084	5.43E+05	3.54
CORDOBA	JUAREZ CELMAN	AR014056	4.88E+05	2.93
SANTA FE	BELGRANO	AR082007	4.87E+05	4.22
SANTA FE	SAN JERONIMO	AR082105	4.78E+05	4.20
BUENOS AIRES	GENERAL VILLEGAS	AR006392	4.35E+05	3.28
CORDOBA	GENERAL SAN MARTIN	AR014042	4.27E+05	3.54
SANTA FE	SAN LORENZO	AR082119	4.02E+05	3.94
SANTA FE	SAN CRISTOBAL	AR082091	3.77E+05	3.10
SANTA FE	LAS COLONIAS	AR082070	3.54E+05	3.19
BUENOS AIRES	RIVADAVIA	AR006679	3.33E+05	4.31

Subsequently, available evapotranspiration data were elaborated accordingly to the developed algorithm. The results obtained by merging the average *ET* values (Figure 6.3), at the department scale, with the production data selected on Trase, are illustrated in Figure 6.4. This enabled to evaluate the water-efficiency of production, depending on the department's geographical and agroclimatic patterns.

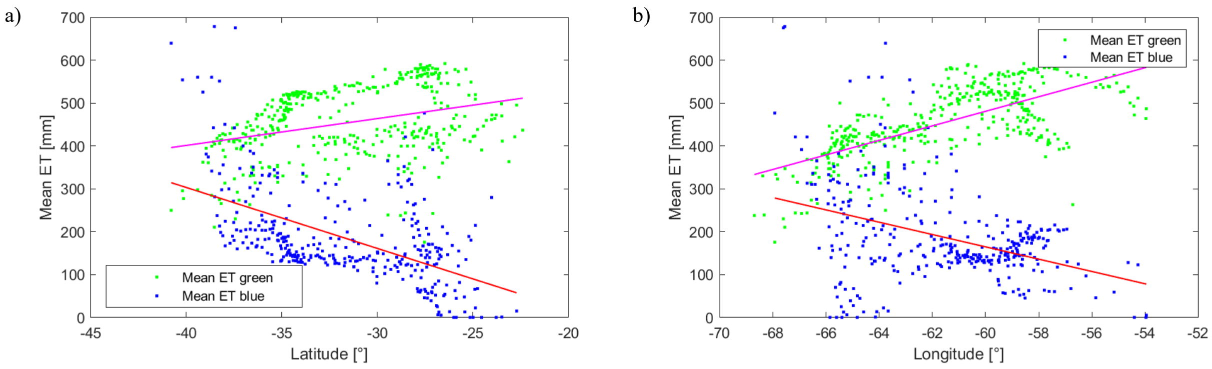


Figure 6.3: Average evapotranspiration data for each Argentinian department. Geographical distribution is shown according to the latitude (a) and the longitude (b).

The plots reported in Figure 6.3 allow to comment on the geographical heterogeneity of *ET* values. Indeed, moving northward and eastward, green *ET* tends to increase, showing an opposite trend with respect to blue *ET*. This is immediately explained by the peculiar climatic features: going from wetter regions to drier ones (more inland), the contribute coming from irrigation systems becomes relevant.

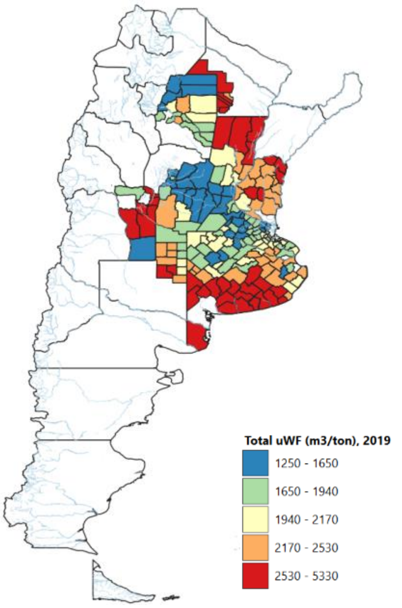


Figure 6.4: Argentina, soy (2019). Total unit water footprint values at the department scale.

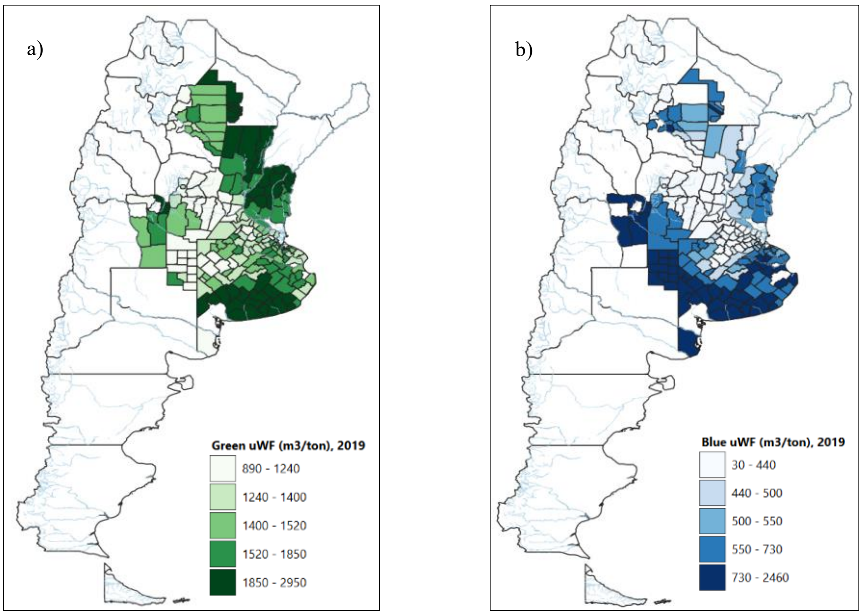


Figure 6.5: Argentina, soy (2019). Green (a) and blue (b) unit water footprint values.

From the map in Figure 6.4, it is appreciable that the highest values of uWF were found in the southern part of Buenos Aires province, in the northern departments of San Luis and Santa Fe, in part of Chaco, and in a few sites in La Pampa and Entre Ríos. Figure 6.5 provides an additional insight into green and blue unit water footprint values, to be compared with Figure 6.4. Specifically, it emerges that the south of Buenos Aires province was characterized by high values of both green and blue $uWFs$; within La Pampa and San Luis, multiple departments were found classified in the highest range of blue uWF values (Figure 6.5b). In the other areas previously mentioned, the green uWF provided the biggest contribution to the total uWF. Analysing the results, it is observed that the highest blue uWF values were found in the departments of Coronel Dorrego ($2.45 * 10^3\ m^3/ton$, Buenos Aires), Coronel Pringles ($2.12 * 10^3\ m^3/ton$, Buenos Aires), and Toay ($2.08 *$

$10^3\ m^3/ton$, La Pampa). The first two were also distinguished by the highest green $uWFs$, with $2.87 * 10^3\ m^3/ton$ and $2.95 * 10^3\ m^3/ton$ respectively.

Table 6.4: Argentina, soy (2019). Departments with the twenty highest uWF values.

PROVINCE	DEPARTMENTOFPRODUCTION	uWF_g [m^3/ton]	uWF_b [m^3/ton]	uWF_tot [m^3/ton]	SOY [tons]
BUENOS AIRES	CORONEL DORREGO	2.87E+03	2.45E+03	5.32E+03	5.52E+04
BUENOS AIRES	CORONEL PRINGLES	2.95E+03	2.12E+03	5.07E+03	1.39E+04
BUENOS AIRES	TRES ARROYOS	2.50E+03	1.74E+03	4.24E+03	1.44E+05
BUENOS AIRES	SAN CAYETANO	2.70E+03	1.53E+03	4.24E+03	6.55E+04
BUENOS AIRES	SAAVEDRA	2.38E+03	1.73E+03	4.11E+03	1.46E+04
BUENOS AIRES	ADOLFO GONZALES CHAVES	2.68E+03	1.41E+03	4.10E+03	5.40E+04
BUENOS AIRES	NECOCHEA	2.71E+03	1.36E+03	4.07E+03	9.71E+04
BUENOS AIRES	PUAN	2.05E+03	1.87E+03	3.92E+03	1.60E+03
LA PAMPA	TOAY	1.77E+03	2.08E+03	3.84E+03	2.54E+03
BUENOS AIRES	LAPRIDA	2.39E+03	1.28E+03	3.67E+03	1.09E+04
BUENOS AIRES	GENERAL LA MADRID	2.15E+03	1.27E+03	3.41E+03	3.71E+04
CHACO	CHACABUCO	2.50E+03	7.33E+02	3.23E+03	1.75E+04
BUENOS AIRES	CORONEL SUAREZ	1.94E+03	1.28E+03	3.22E+03	1.21E+05
SAN LUIS	GENERAL PEDERNERA	1.70E+03	1.51E+03	3.21E+03	1.58E+04
SAN LUIS	JUNIN	2.07E+03	1.12E+03	3.19E+03	3.26E+01
BUENOS AIRES	BENITO JUAREZ	2.20E+03	9.44E+02	3.15E+03	6.17E+04
SAN LUIS	CHACABUCO	1.92E+03	1.11E+03	3.02E+03	1.13E+03
CHACO	12 DE OCTUBRE	2.27E+03	6.69E+02	2.94E+03	4.41E+04
SAN LUIS	LA CAPITAL	1.46E+03	1.47E+03	2.93E+03	1.82E+02
SANTA FE	SAN JAVIER	2.29E+03	5.64E+02	2.86E+03	3.14E+04

In Table 6.4, the twenty highest total uWF resulted at the local scale are shown, highlighting the concentration of greater values in the Buenos Aires province. Moreover, the aforementioned Toay is the first department out of Buenos Aires figuring in the table.

The subsequent step was to compute and represent the water volumes traded at the department scale (Figure 6.6).

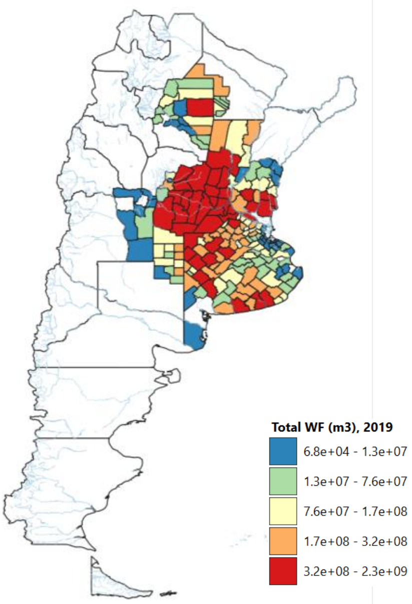


Figure 6.6: Argentina, soy (2019). Total water footprint values at the department scale.

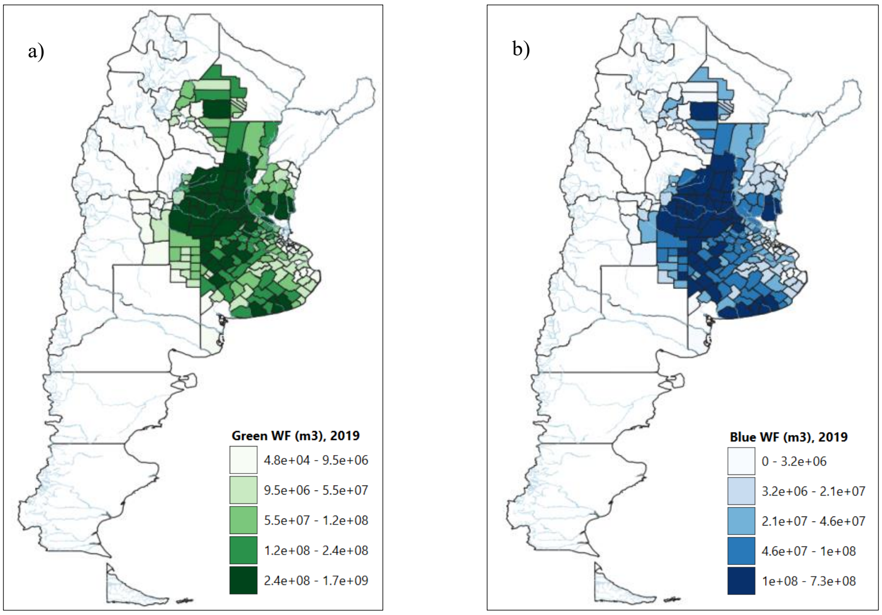


Figure 6.7: Argentina, soy (2019). Green (a) and blue (b) water footprint values.

Maps in Figures 6.6 and 6.7 highlight that, despite the unitary values of water footprint (Figures 6.4 and 6.5), the departments with the highest water requirements were mostly located in the provinces of Córdoba and Santa Fe, and partly in Buenos Aires. This confirms the relevance of annual production on final water footprint volumes, since both green and blue *WFs* (Figure 6.7) show remarkable differences when compared to *uWF* distributions (Figure 6.5).

Table 6.5: Argentina, soy (2019). Departments with the twenty highest WF values.

PROVINCE	DEPARTMENTOFPRODUCTION	WF_G [m^3]	WF_B [m^3]	WF_tot [m^3]	SOY [tons]
SANTA FE	GENERAL LOPEZ	1.75E+09	5.70E+08	2.32E+09	1.39E+06
CORDOBA	RIO CUARTO	1.57E+09	7.28E+08	2.30E+09	1.06E+06
CORDOBA	MARCOS JUAREZ	1.41E+09	4.71E+08	1.88E+09	1.40E+06
CORDOBA	SAN JUSTO	1.38E+09	3.84E+08	1.77E+09	1.26E+06
CORDOBA	UNION	1.17E+09	4.34E+08	1.61E+09	1.10E+06
SANTA FE	CASTELLANOS	1.16E+09	2.53E+08	1.41E+09	7.27E+05
SANTA FE	SAN MARTIN	9.36E+08	2.23E+08	1.16E+09	7.58E+05
SANTA FE	CONSTITUCION	8.94E+08	2.51E+08	1.14E+09	7.02E+05
SANTA FE	CASEROS	8.68E+08	2.43E+08	1.11E+09	7.21E+05
SANTA FE	IRIONDO	8.33E+08	2.03E+08	1.04E+09	6.91E+05
CORDOBA	JUAREZ CELMAN	7.01E+08	2.83E+08	9.84E+08	4.88E+05
CORDOBA	PRESIDENTE ROQUE SAENZ PENA	6.12E+08	3.15E+08	9.27E+08	5.43E+05
BUENOS AIRES	GENERAL VILLEGAS	5.92E+08	3.06E+08	8.97E+08	4.35E+05
SANTA FE	SAN CRISTOBAL	6.54E+08	1.41E+08	7.95E+08	3.77E+05
SANTA FE	LAS COLONIAS	6.00E+08	1.55E+08	7.55E+08	3.54E+05
SANTA FE	SAN JERONIMO	6.09E+08	1.44E+08	7.53E+08	4.78E+05
SANTA FE	BELGRANO	5.93E+08	1.41E+08	7.34E+08	4.87E+05
CORDOBA	GENERAL SAN MARTIN	5.06E+08	1.74E+08	6.80E+08	4.27E+05
SANTA FE	SAN LORENZO	5.32E+08	1.41E+08	6.74E+08	4.02E+05
BUENOS AIRES	TRES ARROYOS	3.61E+08	2.51E+08	6.12E+08	1.44E+05

Table 6.5 allows to notice that among the first twenty departments, only Tres Arroyos (last row) appeared also in Table 6.4. This to confirm that, in 2019, the least water efficient departments were less exploited than the others. Moreover, the names figuring in Table 6.5 correspond to the most relevant production sites (as observed in Table 6.3): this is the reason why considering uWF values is not meaningful by itself. Interestingly, none of the reported virtual water flows is solely contributed by green water, meaning that irrigation plays an important role for soybean cultivations in Argentina. The first twenty WF volumes accounted for 48% $(2.36 * 10^{10}\ m^3)$ of the total flow leaving from the 197 departments analysed $(4.88 * 10^{10}\ m^3)$.

After the comprehensive overview, water footprint assessments at the company's and importer's scales were performed. Hereafter, cumulative distribution functions (a) and boxplots (b) are reported (Figure 6.8 for major importers, Figure 6.9 for traders).

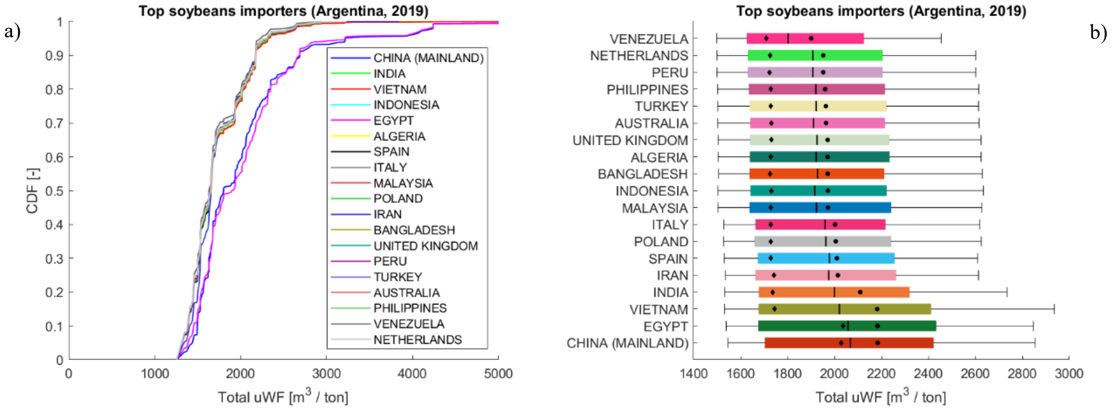


Figure 6.8: Argentina, soy (2019). Cumulative distribution functions (a) and boxplots (b) of the major importing countries.

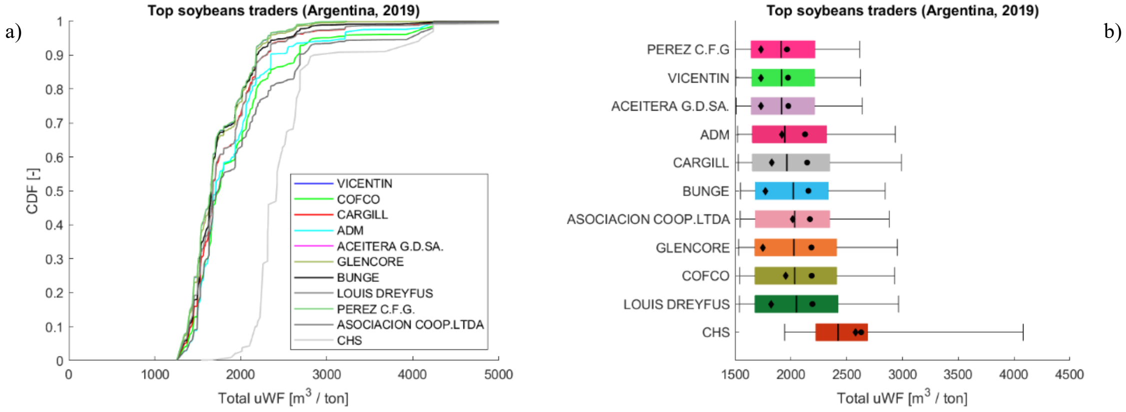


Figure 6.9: Argentina, soy (2019). Cumulative distribution functions (a) and boxplots (b) of the major exporting companies.

What emerges is the similar distribution of uWF values associated with importers and traders, whose whiskers range from around $1500\ m^3/ton$ (10th percentile) to $3000\ m^3/ton$ (90th percentile). Notably, the trader CHS constituted an exception: even though this company gave the lowest contribute in terms of traded volume (Table 6.2), the unitary pressure associated with its supplying departments resulted being the highest one (Figure 6.9). Indeed, the right whisker exceeds $4000\ m^3/ton$, and its weighted mean uWF is the only one falling above the median. Among the importing countries, China showed the highest uWF ($2.18 * 10^3\ m^3/ton$), whereas Egypt exerted the greatest pressure in terms of weighted mean uWF ($2.04 * 10^3\ m^3/ton$). On the other hand, focusing on traders, the most water-consumptive was CHS (mean uWF, $2.63 * 10^3\ m^3/ton$, and weighted mean uWF, $2.58 * 10^3\ m^3/ton$). It is worth noting that the five agrobusiness dominanting global food exports were present: ADM, Bunge, Cargill, Louis Dreyfus and COFCO. The Argentinian agro-industrial company Vicentin occupied the first position in terms of exported tonnes; at the same time, it had the second-lowest mean uWF and third-lowest weighted mean uWF, being preceded by other two Argentinian companies, Aceitera General Deheza and Perez Companc Family Group. In Figures 6.10 and 6.11, the departments supplying Vicentin (122) and CHS (50) can be identified, considering total uWF values in panel a) and water volumes in panels b). The comparison is relevant as these two companies are situated at opposite sides in terms of soybean exported tonnes and pressure on local freshwater resources.

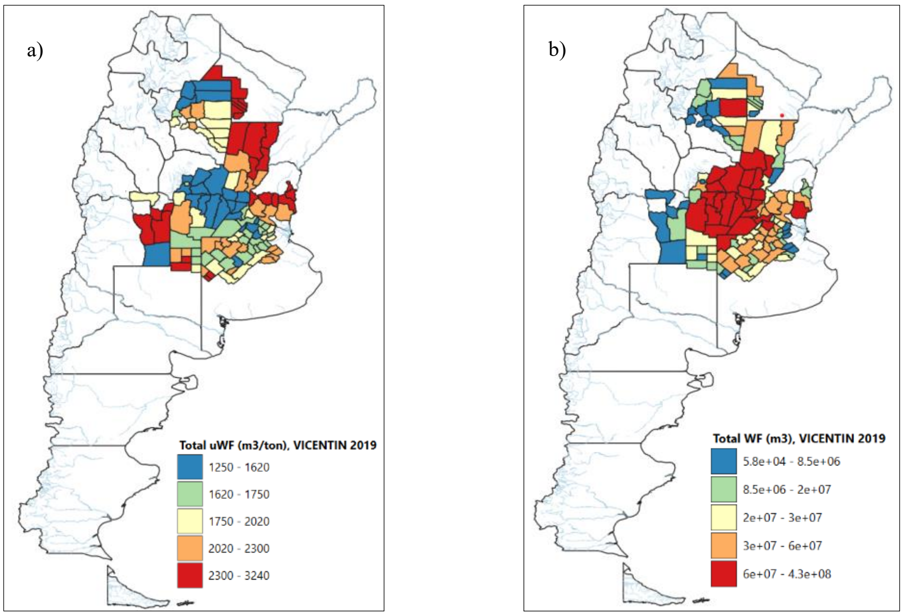


Figure 6.10: Argentina, soy (2019). Total unit water footprint (a) and total water footprint (b) values of the departments supplying Vicentin.

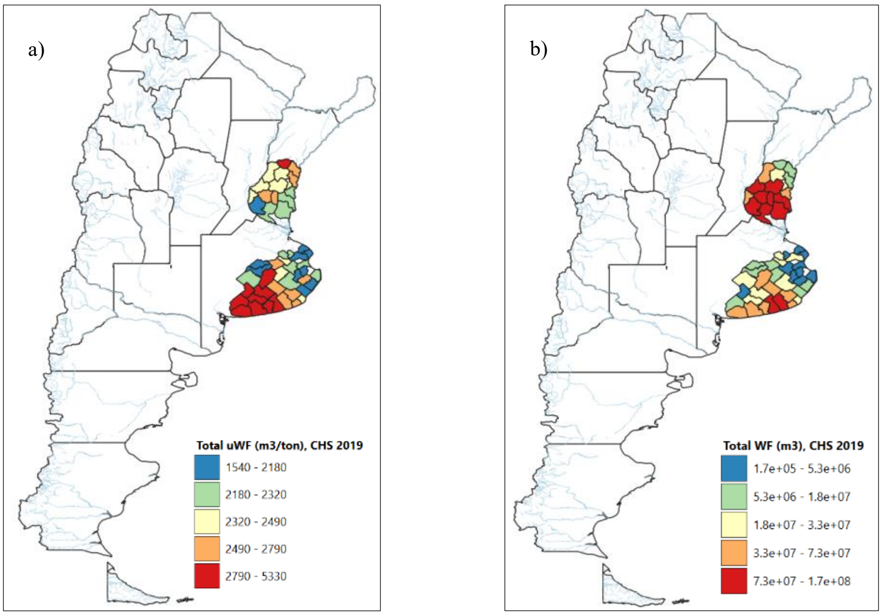


Figure 6.11: Argentina, soy (2019). Total unit water footprint (a) and total water footprint (b) values of the departments supplying CHS.

It is observed that CHS sourced from departments in the southern Buenos Aires and Entre Ríos provinces, explaining its higher total *uWF*. These production sites showed indeed high to medium-high *uWFs* (Figure 6.4). A further interesting comparison can be made by looking at the virtual water-weighted barycentres of countries' and trading companies' virtual water trade (Figure 6.12).

Figure 6.12: Argentina, soy (2019). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

What stands out is that the vast majority of countries had its weighted coordinates falling inside Córdoba province, except for Iran (in Santa Fe), and Egypt and China (in Buenos Aires). Traders, instead, were almost equally distributed in Córdoba, Santa Fe and Buenos Aires provinces. Except for CHS's barycentre, the most easterly among all, importers' and exporters' barycentres varied within very similar latitude and longitude values. The analysis enabled to delineate the different water-efficiency of soybean flows, which decreased moving towards higher water-consumptive departments.

Table 6.6: Argentina, soy (2019). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles.

COMPANY	PERC_10 [m^3/ton]	PERC_25 [m^3/ton]	PERC_50 [m^3/ton]	PERC_75 [m^3/ton]	PERC_90 [m^3/ton]
VICENTIN	1505	1649	1916	2212	2624
COFCO	1541	1676	2033	2410	2929
CARGILL	1528	1653	1963	2348	2990
ADM	1521	1653	1944	2318	2935
ACEITERA GENERAL DEHEZA SA.	1508	1643	1916	2212	2639
GLENCORE	1530	1676	2026	2409	2955
BUNGE	1546	1678	2021	2334	2844
LOUIS DREYFUS	1538	1676	2049	2421	2964
PEREZ COMPANC FAMILY GROUP	1502	1642	1911	2214	2615
ASOCIACION DE COOPERATIVAS ARGENTINAS (COOP.LTDA)	1544	1679	2033	2348	2880
CHS	1943	2223	2422	2687	4082

Table 6.7: Argentina, soy (2019). Average uWF, weighted average uWF and weighted geographical coordinates of each trader.

COMPANY	Average uWF [m^3/ton]	Weighted average uWF [m^3/ton]	Weighted LAT	Weighted LON
PEREZ COMPANC FAMILY GROUP	1964	1730	-32.7284	-62.0907
ACEITERA GENERAL DEHEZA SA.	1976	1730	-32.7307	-62.0937
VICENTIN	1973	1731	-32.725	-62.0885
GLENCORE	2183	1748	-32.8975	-62.0636
BUNGE	2155	1773	-33.461	-61.4759
LOUIS DREYFUS	2192	1824	-33.553	-62.0462
CARGILL	2145	1830	-33.5911	-62.0032
ADM	2126	1917	-34.1684	-61.7612
COFCO	2185	1953	-34.3212	-60.9874
ASOCIACION DE COOPERATIVAS ARGENTINAS (COOP.LTDA)	2170	2015	-34.4971	-60.8331
CHS	2629	2579	-34.5562	-59.263

In Table 6.6, trading companies follow the same order of the CDFs (Figure 6.9a), so they are ranked in descending order according to the exported tonnes of soybeans. On the other hand, Table 6.7 shows them ranked in ascending order with respect to the weighted average *uWF*. The comparison of traders' weighted coordinates (circles in Figure 6.12) with their weighted *uWFs* interestingly highlights the correlation between increasing southern latitude and increasing water requirements per tonne of production. This phenomenon aligns with observations made by De Petrillo (2021) on Brazilian soybean. Moreover, if looking at Figure 6.2, it is appreciable how, moving southward in the province of Buenos Aires, the yield values decreased consistently. By contrast, analysing soybean evapotranspiration data (Figure 6.13), there is no evidence of such strong change. This leads to the conclusion that the increase of *uWF* values is mainly driven by low yields, instead of high *ET* rates. Nevertheless, production at the subnational scale is also influenced by the climatic parameters embedded in the *ET* process.

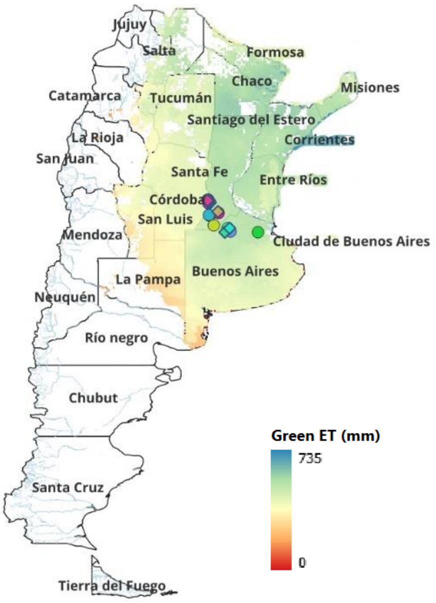


Figure 6.13: Argentina, soy (2019). Virtual water-weighted barycentres and green evapotranspiration data for soybeans.

At this point of the analysis, relationships existing between importers and exporters were investigated. For each importing country, the relative share of traders was obtained, and vice versa for traders. This enabled to underline, for instance, possible differences in the pressure exerted by the same company when supplying distinct countries. An example is given in Table 6.8, where the destinations of soybean flows handled by CHS are reported, along with the corresponding virtual water volumes and unit water footprints. Countries are ranked according to the total WF.

Table 6.8: Argentina, soy (2019). Relationships between the trader CHS and the countries relying on it.

COUNTRYOFFIRSTIMPORT	**WF_G** [m^3]	**WF_B** [m^3]	**w_mean_uWF_tot** [m^3/ton]	**WF_tot** [m^3]
CHINA (MAINLAND)	1.30E+09	4.96E+08	2.59E+03	1.80E+09
EGYPT	2.07E+08	7.24E+07	2.49E+03	2.80E+08

The relevance of such investigation is the possibility to discover in detail the indirect pressure that importing countries exerted on water resources. This knowledge could become a powerful instrument to increase the awareness of less sustainable traders, understanding in which way the national demand of a given commodity might be satisfied by different companies. For instance, China emerged as the most water-consumptive country when supplied by CHS ($2.59 * 10^3\ m^3/ton$), but its pressure was significantly lower when related to Vicentin ($1.7 * 10^3\ m^3/ton$).

6.2 Bolivia – soy

The second country analysed was Bolivia, specifically with soybeans exports in 2021. According to FAOSTAT data, three countries covered 91% of the trade in the years 2020 and 2021 (Table 6.9), and the exports were mostly managed by five companies, based on 2021 Trase data (Table 6.10). Sociedad Agroindustrial Nutrioil SA was added to satisfy the local coverage in Ecuador. Indeed, this company was responsible for more than 71% of soybeans flows towards Ecuador in 2021.

Table 6.9: Bolivia, soy (2020-2021). Major importing countries (FAOSTAT).

IMPORTER	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Colombia	1.96E+06	42.09	42.09	46.12
Peru	1.66E+06	35.57	77.66	38.97
Ecuador	6.34E+05	13.61	91.26	14.91

Table 6.10: Bolivia, soy (2021). Major exporting companies (Trase).

EXPORTERGROUP	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
INDUSTRIAS DE ACEITE S.A.	4.86E+05	34.39	34.39	38.44
HUGO SPECHAR GONZALES - GRANOS	2.26E+05	15.98	50.37	17.87
CARGILL	1.94E+05	13.69	64.06	15.30
INDUSTRIAS OLEAGINOSAS S.A.	1.77E+05	12.52	76.59	14.00
GRAVETAL BOLIVIA SA	1.01E+05	7.14	83.72	7.98
SOCIEDAD AGROINDUSTRIAL NUTRIOIL SA	8.12E+04	5.74	89.46	6.42

The administrative level considered throughout the analysis was the one of municipalities (3rd level), shown in Figure 6.14b along with Bolivian departments (1st level, Figure 6.14a). Notably, four voids are present in Oruro and Potosí, when considering the municipalities shapefile. These are the Lake Uru Uru (Oruro), Lake Poopó (Oruro), Salar de Coipasa (Oruro), and Salar de Uyuni – the world's largest salt flat (Potosí).

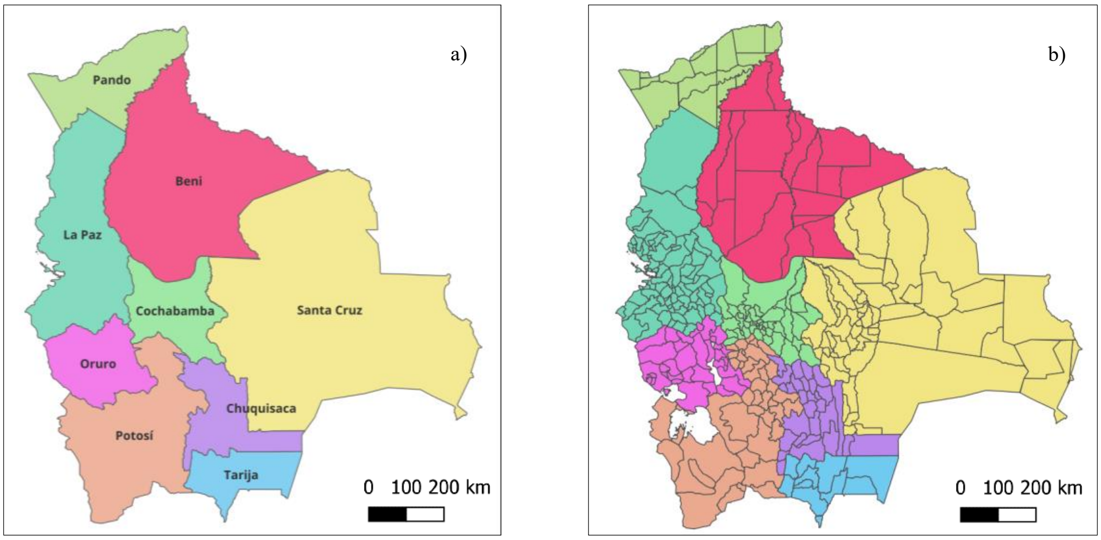


Figure 6.14: Geographic framework of Bolivia. Departments (a) and municipalities (b).

Trase dataset was skimmed, based on Tables 6.9 and 6.10, allowing the identification of the 18 sourcing municipalities (Figure 6.15). Interestingly, they all fell within Santa Cruz department, holding very similar yield values (equal until the 7th decimal point, as reported in the legend of Figure 6.15b), still producing quite different amounts of soybeans.

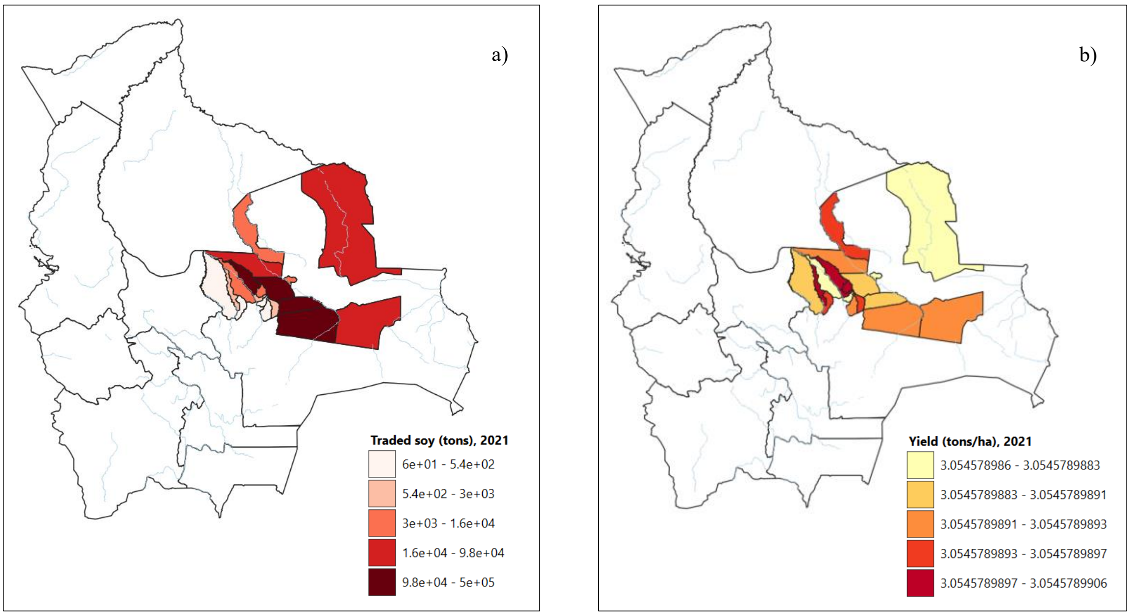


Figure 6.15: Bolivia, soy (2021). Traded tonnes (a) and yield values (b) for each involved municipality.

Table 6.11 presents the first four producing municipalities and their respective provinces, which names are not shown in Figure 6.14 for reasons of space. These accounted for 86% ($1.09 * 10^6\ tons$) of the volume traded by the 18 municipalities ($1.27 * 10^6\ tons$). In particular, San Julian covered 40% of the supplied soybeans.

Table 6.11: Bolivia, soy (2021). First four producing municipalities. Exported tonnes and yield values are reported.

PROVINCE	**MUNICIPALITYOF PRODUCTION**	**GEOCODE**	**SOY [tons]**	**YIELD [tons/ha]**
NUFLO DE CHAVEZ	SAN JULIAN	BO071103	5.08E+05	3.05
CHIQUITOS	PAILON	BO070502	2.37E+05	3.05
NUFLO DE CHAVEZ	CUATRO CANADAS	BO071106	2.17E+05	3.05
OBISPO SANTISTEBAN	SAN PEDRO	BO071005	1.27E+05	3.05

Hereafter, uWF variations are described in Figure 6.16. Only total unitary values are reported since blue evapotranspiration data were available just over the municipality of San Ignacio de Velasco, which is not included in the shortcuts reported below (Tables 6.12 and 6.13). Moreover, the colour ramp highlights that the range of variability of values is small: the lowest record is of $1.42 * 10^3\ m^3/ton$ (in San Ignacio de Velasco), while the higher of $1.61 * 10^3\ m^3/ton$ (in General Saavedra). Some municipalities shared also the same uWF. Table 6.12 reports a shortcut with the less water-efficient production sites, located in the westernmost part of Santa Cruz. Maps showing evapotranspiration variations with latitude and longitude are reported in Appendix C, Figure C.1.

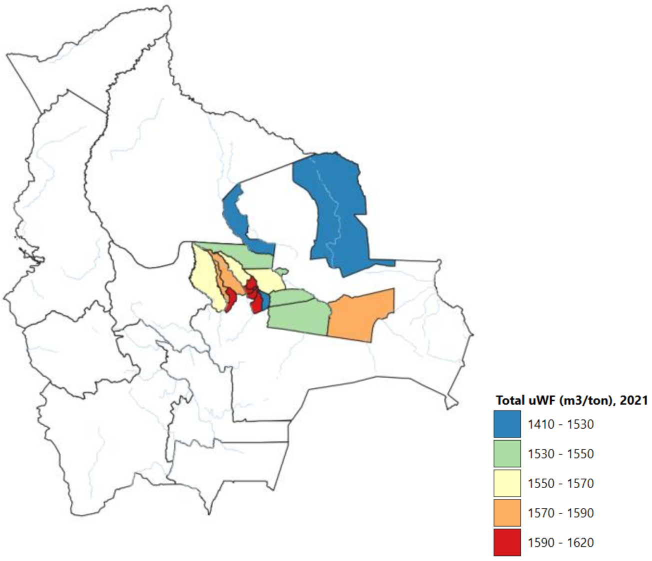


Figure 6.16: Bolivia, soy (2021). Total unit water footprint values at the municipality scale.

Table 6.12: Bolivia, soy (2021). Municipalities with the four highest uWF values.

PROVINCE	**MUNICIPALITYOFPRODUCTION**	**uWF_tot [m³/ton]**	**SOY [tons]**
OBISPO SANTISTEBAN	GENERAL SAAVEDRA	1.61E+03	2.95E+02
OBISPO SANTISTEBAN	MINEROS	1.61E+03	2.16E+03
OBISPO SANTISTEBAN	FERNANDEZ ALONSO	1.60E+03	1.43E+04
ICHILO	SAN CARLOS	1.59E+03	2.04E+02

Map in Figure 6.17 represents the virtual water volumes at the municipality scale. Looking at Table 6.13, it emerges that the areas with the highest water requirements coincided with the ones producing more. This makes sense since the unit water footprints were quite homogeneously distributed, thus produced tonnes made all the difference. The reported municipalities covered 86% of the traded water, with San Julian accounting for 40%.

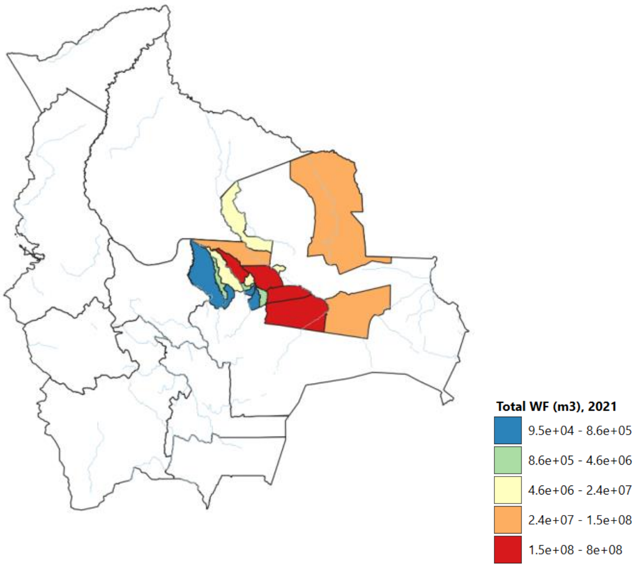
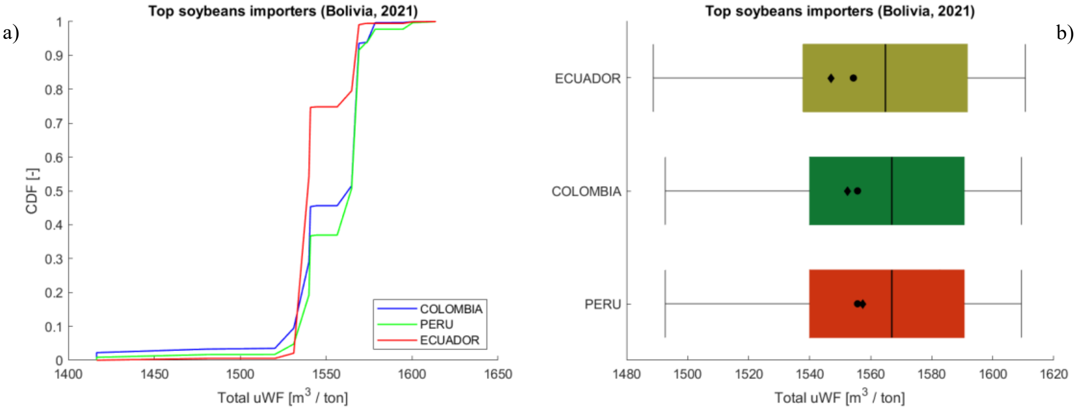


Figure 6.17: Bolivia, soy (2021). Total water footprint values at the municipality scale.

Table 6.13: Bolivia, soy (2021). Municipalities with the four highest WF values.

PROVINCE	**MUNICIPALITYOFPRODUCTION**	**WF_tot [m^3]**	**SOY [tons]**
NUFLO DE CHAVEZ	SAN JULIAN	7.97E+08	5.08E+05
CHIQUITOS	PAILON	3.65E+08	2.37E+05
NUFLO DE CHAVEZ	CUATRO CANADAS	3.35E+08	2.17E+05
OBISPO SANTISTEBAN	SAN PEDRO	1.98E+08	1.27E+05

Major importing countries and traders were analysed by means of cumulative distribution functions and boxplots (Figure 6.18).



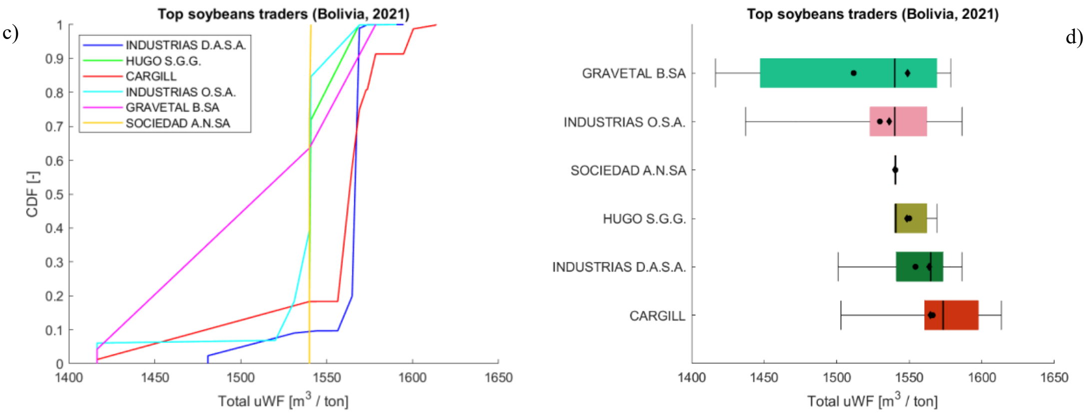


Figure 6.18: Bolivia, soy (2021). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

Traders experienced a more marked variability than countries; however, all distributions presented an asymmetric behaviour, with longer left whiskers. Regarding importers, mean uWF and weighted average uWF values were well below the median. Concerning traders, instead, the situation was different for each of them, with weighted values falling above or below the mean ones, or the medians. Notably, the only global agrobusiness figuring in the analysis was Cargill, with the highest statistics. Cargill was supplied by 12 municipalities, with San Pedro in Obispo Santisteban covering almost 40% of the traded water volume ($1.2 * 10^8\ m^3$, black oval in Figure 6.19b).

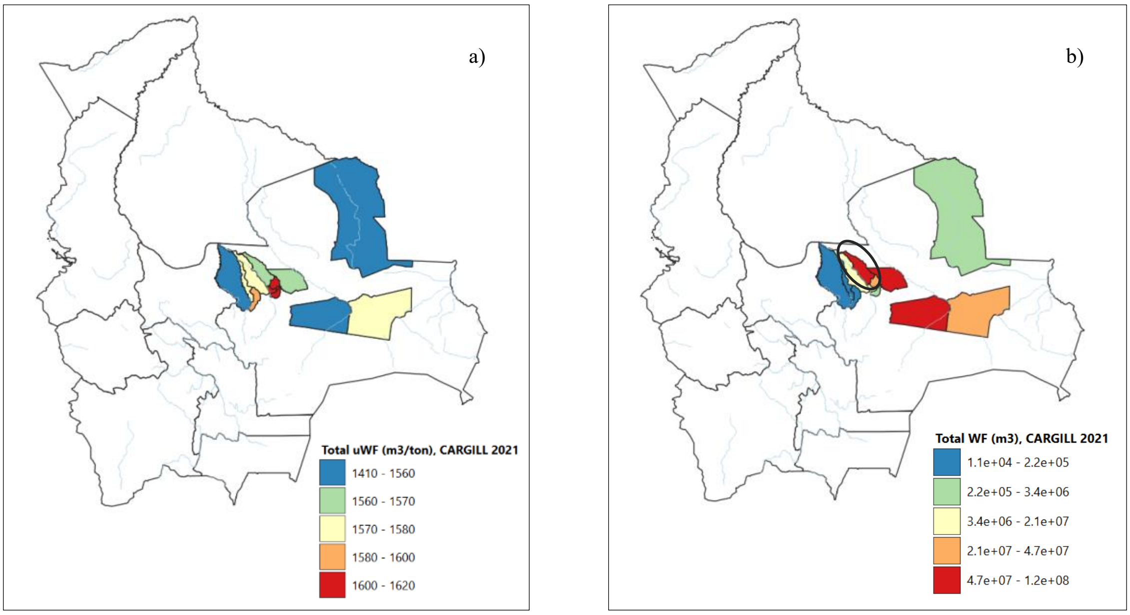


Figure 6.19: Bolivia, soy (2021). Total unit water footprint (a) and total water footprint (b) values of the municipalities supplying Cargill. Black oval (b) stands for San Pedro in Obispo Santisteban.

The following map (Figure 6.20) shows the virtual water-weighted barycentres, for countries and companies, while Tables 6.14 and 6.15 summarise the statistics used to represent the boxplots, additionally to the weighted coordinates, for each analysed company. The ordering criterion of Table 6.14 is the number of exported tonnes (same as for CDFs, Figure 6.18c), whereas Table 6.15 is ranked accordingly to the weighted mean uWF values. Figure C.2 in Appendix C shows barycentres placement along with green evapotranspiration data.

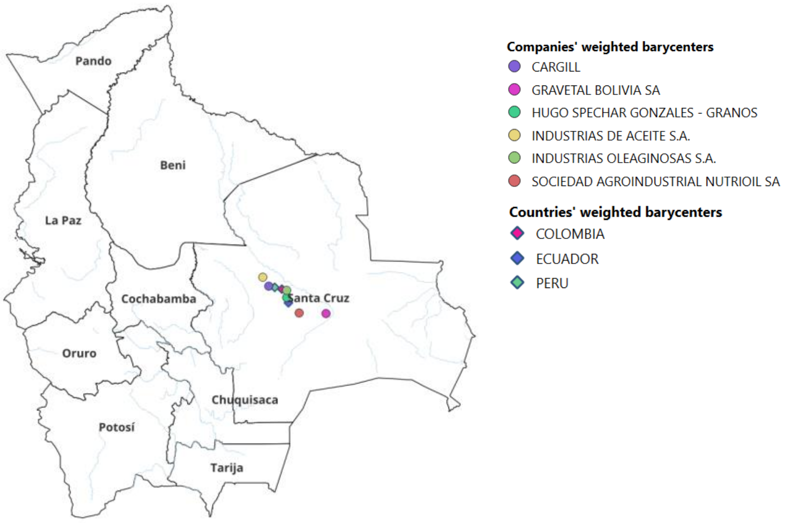


Figure 6.20: Bolivia, soy (2021). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Table 6.14: Bolivia, soy (2021). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles.

COMPANY	**PERC_10 [m³/ton]**	**PERC_25 [m³/ton]**	**PERC_50 [m³/ton]**	**PERC_75 [m³/ton]**	**PERC_90 [m³/ton]**
INDUSTRIAS DE ACEITE S.A.	1501	1541	1565	1573	1586
HUGO SPECHAR GONZALES - GRANOS	1540	1540	1541	1562	1569
CARGILL	1503	1561	1573	1598	1613
INDUSTRIAS OLEAGINOSAS S.A.	1437	1523	1540	1562	1586
GRAVETAL BOLIVIA SA	1416	1447	1540	1569	1578
SOCIEDAD AGROINDUSTRIAL NUTRIOIL SA	1540	1540	1540	1541	1541

Table 6.15: Bolivia, soy (2021). Average uWF, weighted average uWF and weighted geographical coordinates of each trader.

COMPANY	**Average uWF [m³/ton]**	**Weighted average uWF [m³/ton]**	**Weighted LAT**	**Weighted LON**
INDUSTRIAS OLEAGINOSAS S.A.	1530	1536	-17.0293	-62.3426
SOCIEDAD AGROINDUSTRIAL NUTRIOIL SA	1540	1540	-17.6137	-62.0098
HUGO SPECHAR GONZALES - GRANOS	1550	1549	-17.2196	-62.3382
GRAVETAL BOLIVIA SA	1512	1549	-17.6306	-61.3298
INDUSTRIAS DE ACEITE S.A.	1554	1564	-16.6883	-62.9622
CARGILL	1566	1565	-16.9253	-62.8044

A further investigation was done with respect to the countries supplied by each company, detailing the virtual water that was traded in each case. Reporting once more Cargill as illustrative example (Table 6.16), it emerges that 63% of its trade was directed to Peru, which showed the highest average *uWF* value (Figure 6.18b). Table 6.16 includes the separate contributes of green and blue water footprints, since Colombia was also supplied by the San Ignacio de Velasco municipality.

Table 6.16: Bolivia, soy (2021). Relationships between the trader Cargill and the countries relying on it.

COUNTRYOF FIRSTIMPORT	**SOY** [tons]	**WF_G** [m^3]	**WF_B** [m^3]	**w_mean_uWF_tot** [m^3/ton]	**WF_tot** [m^3]
PERU	1.22E+05	1.92E+08	0	1.57E+03	1.92E+08
COLOMBIA	6.80E+04	1.06E+08	2.99E+04	1.55E+03	1.06E+08
ECUADOR	3.10E+03	4.87E+06	0	1.57E+03	4.87E+06

6.3 Brazil

Brazil was investigated several times in the present thesis. Dedicated sections are presented in Chapter 6.3 for cocoa, coffee, corn, cotton and soybeans results. Before discussing individual crops, the administrative divisions of Brazil into states (a) and municipalities (b) are reported in Figure 6.21.

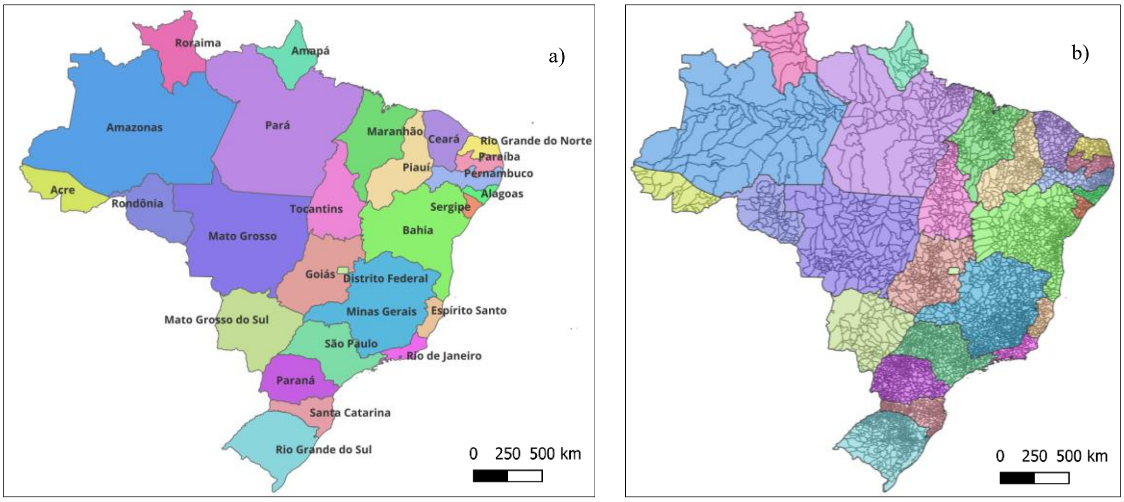


Figure 6.21: Geographic framework of Brazil. States (a) and municipalities (b).

6.3.1 Cocoa

For a meaningful analysis, cocoa trade flows were analysed for the year 2015, since 2017 Trase dataset reports only a few data. The analysis on FAO statistics outlined the major three importing countries, accounting for 82% of the total share in the three-year period 2015 to 2017 (Table 6.17). Concerning the principal traders in 2015, three of them managed almost entirely the cocoa trade flows from Brazil (Table 6.18).

Table 6.17: Brazil, cocoa (2015-2017). Major importing countries (FAOSTAT).

IMPORTER	*COCOA_EQUIVALENT _TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Argentina	7.45E+04	37.00	37.00	45.02
United States of America	7.04E+04	35.00	72.00	42.59
Chile	2.05E+04	10.18	82.17	12.39

Table 6.18: Brazil, cocoa (2015). Major exporting companies (Trase).

EXPORTERGROUP	*COCOA_EQUIVALENT _TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
CARGILL	1.08E+04	37.99	37.99	38.13
BARRY CALLEBAUT	1.05E+04	37.16	75.15	37.29
JOANES INDUSTRIAL LTDA	6.94E+03	24.50	99.65	24.58

Selecting companies and importers, 38 supplying municipalities remained. Their distribution was highly heterogeneous over Brazil, spanning the states of Rondônia, Pará, Bahia and Espírito Santo. Figure 6.22 shows the exported tonnes (a) and yield (b) values.

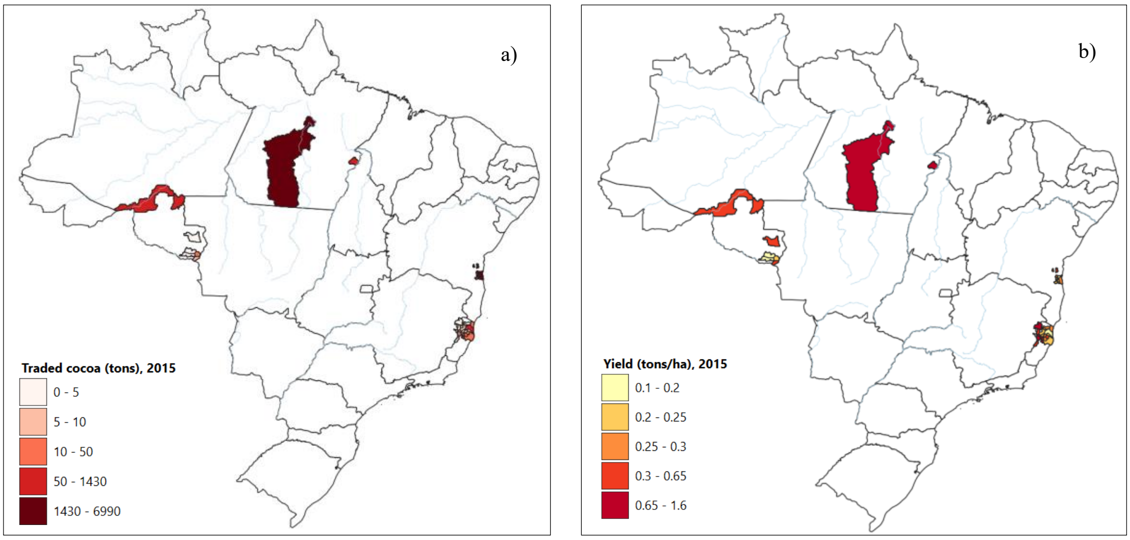


Figure 6.22: Brazil, cocoa (2015). Traded tonnes (a) and yield values (b) for each involved municipality.

The first five producing municipalities are reported in Table 6.19. They covered 69% ($1.94 * 10^4\ tons$) of cocoa traded from the 18 sourcing areas ($2.82 * \ 10^4\ tons$).

Table 6.19: Brazil, cocoa (2015). First five producing municipalities. Exported tonnes and yield values are reported.

STATE	MUNICIPALITYOFPRODUCTION	GEOCODE	COCOA [tons]	YIELD [tons/ha]
BAHIA	ILHEUS	BR2913606	6.99E+03	0.28
BAHIA	IBIRAPITANGA	BR2912707	4.49E+03	0.30
PARA	ALTAMIRA	BR1500602	3.01E+03	0.77
PARA	VITORIA DO XINGU	BR1508357	2.56E+03	0.92
BAHIA	ITAJUIPE	BR2915502	2.37E+03	0.18

Considering available ET data (Appendix C, Figure C.3), green and blue $uWFs$ were computed, thus obtaining the total unitary values (Figure 6.23). Analysing the colour ramp, it emerges that in Espírito Santo very closed municipalities had completely different uWF values. Separate green and blue maps confirm the consistent variability within this state (Appendix C, Figure C.4). Further investigation was conducted on ET data, noticing that the coastal segment of Espírito Santo and Bahia was characterised by a wide range of ET values (Appendix C, Figure C.6). Municipalities showing the five highest unit water footprints are reported in Table 6.20.

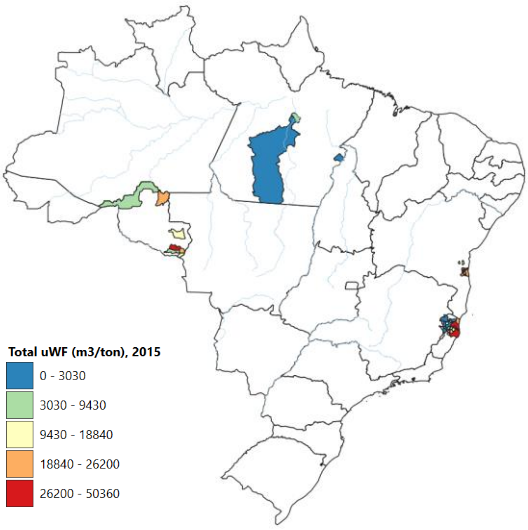


Figure 6.23: Brazil, cocoa (2015). Total unit water footprint values at the municipality scale.

Table 6.20: Brazil, cocoa (2015). Municipalities with the five highest uWF values.

STATE	MUNICIPALITYOFPRODUCTION	uWF_g [m^3/ton]	uWF_b [m^3/ton]	uWF_tot [m^3/ton]	COCOA [tons]
ESPIRITO SANTO	SAO MATEUS	4.98E+04	5.74E+02	5.04E+04	7.84E+01
BAHIA	ITAJUIPE	4.50E+04	0	4.50E+04	2.37E+03
BAHIA	BUERAREMA	3.71E+04	0	3.71E+04	1.27E+03
BAHIA	URUCUCA	3.24E+04	0	3.24E+04	2.14E+03
BAHIA	BARRO PRETO	3.04E+04	7.91E+00	3.04E+04	3.27E+02

Subsequently, virtual water volumes were obtained (Figure 6.24). Separates green and blue separate are shown in Figure C.5, Appendix C.

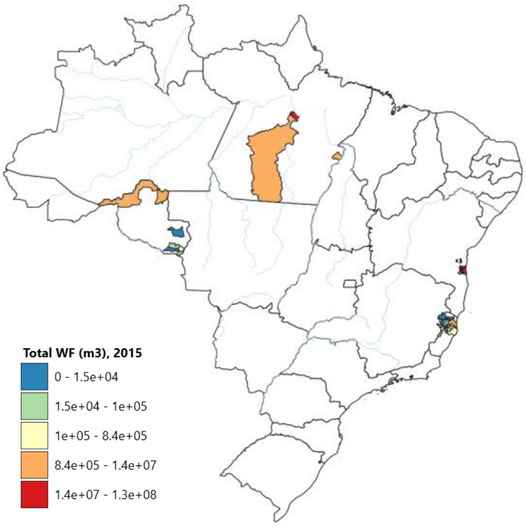


Figure 6.24: Brazil, cocoa (2015). Total water footprint values at the municipality scale.

Table 6.21: Brazil, cocoa (2015). Municipalities with the five highest WF values.

STATE	MUNICIPALITYOFPRODUCTION	WF_G [m^3]	WF_B [m^3]	WF_tot [m^3]	COCOA [tons]
BAHIA	ILHEUS	1.33E+08	8.24E+03	1.33E+08	6.99E+03
BAHIA	ITAJUIPE	1.07E+08	0	1.07E+08	2.37E+03
BAHIA	URUCUCA	6.93E+07	0	6.93E+07	2.14E+03
BAHIA	IBIRAPITANGA	6.76E+07	5.99E+02	6.76E+07	4.49E+03
BAHIA	BUERAREMA	4.72E+07	0	4.72E+07	1.27E+03

Interestingly, two of the municipalities in Table 6.20 are also among the first five most stressed one, in terms of water volumes traded (Table 6.21): Itajuipe and Buerarema, in the state of Bahia. Indeed, 93% of virtual water flows departed from the 9 municipalities considered in Bahia. Altamira and Vitoria du Xingu, even though targeted as the 3rd and 4th supplying areas (Table 6.19), had much lower water demands: $8.04 * 10^6\ m^3$ and $1.73 * 10^7\ m^3$, respectively. The latter was the first municipality out of Bahia in terms of total *WF*.

Statistics about the major importers and traders are illustrated in Figure 6.25.

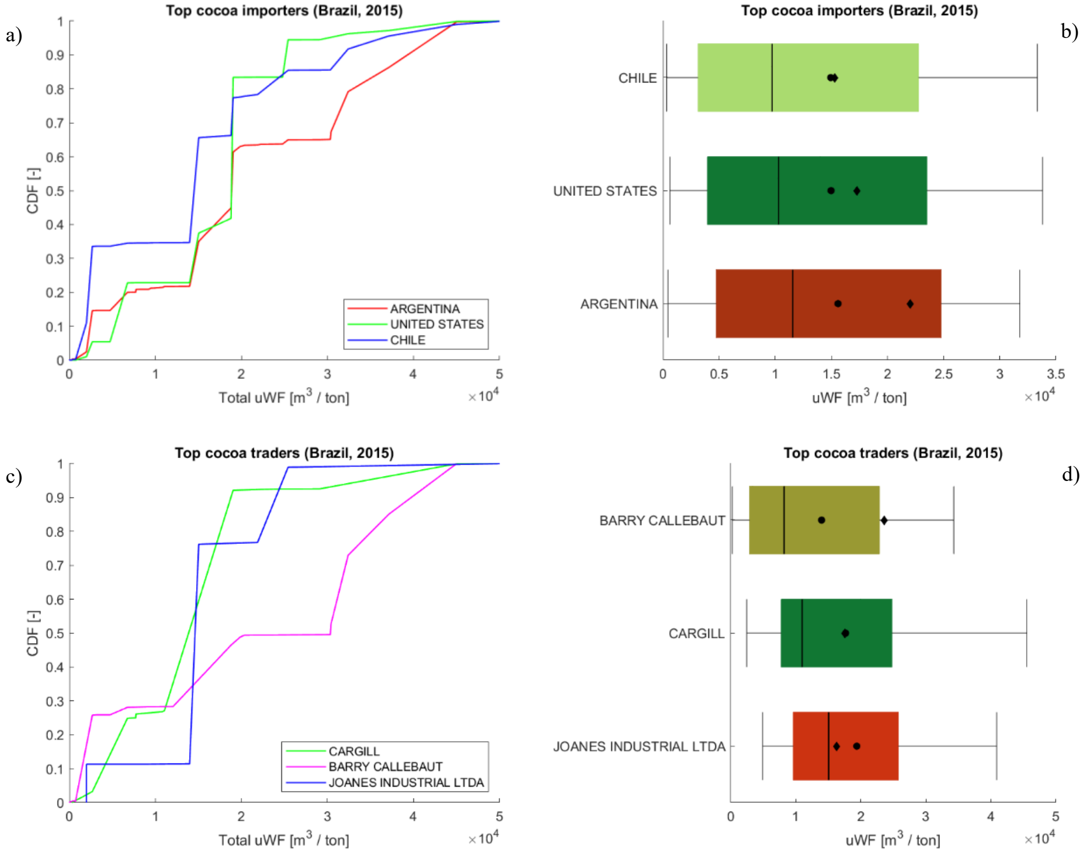


Figure 6.25: Brazil, cocoa (2015). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

Importing countries showed a similar behaviour, with mean uWF values lower than weighted mean $uWFs$, and both higher than the 50th percentile. It is noteworthy that the two types of uWF values reported were clearly separated for Argentina and the United States, while they were almost identical for Chile. On the contrary, two out of three traders had a weighted mean uWF smaller than the mean one, except for Barry Callebaut which weighted mean uWF ($2.36 * 10^4\ m^3/ton$) fell even above the 75th percentile ($2.28 * 10^4\ m^3/ton$). All boxplots are asymmetric and right skewed. Supplying municipalities of Barry Callebaut are represented in Figure 6.26.

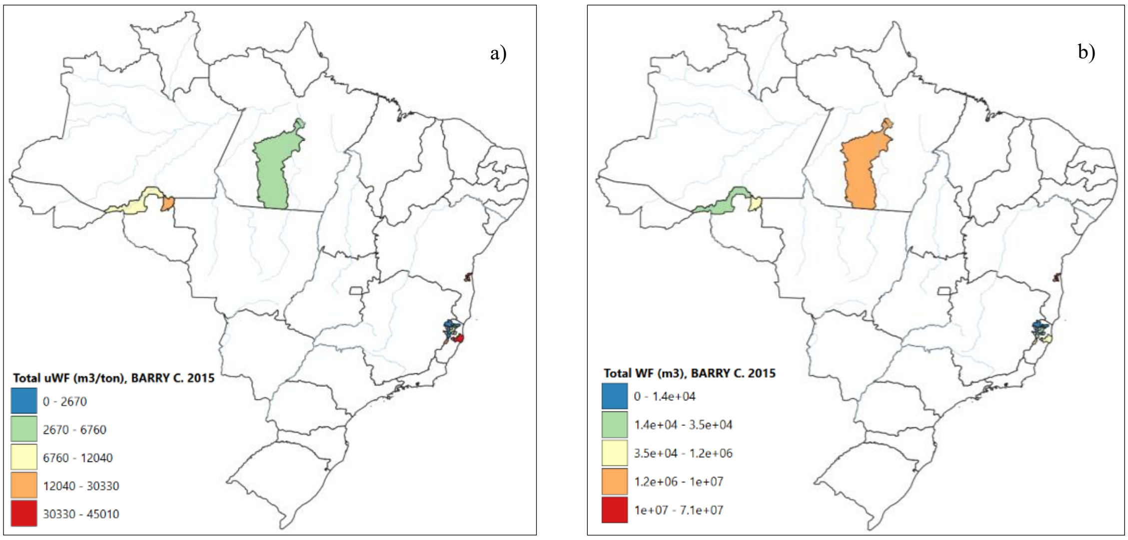


Figure 6.26: Brazil, cocoa (2015). Total unit water footprint (a) and total water footprint (b) values of the municipalities supplying Barry Callebaut.

Observing Figure 6.26, it emerges that Barry Callebaut was mostly supplied by the municipalities in the state of Bahia, those with the highest uWF values, as appreciable in Table 6.20. This explains what discussed in the previous paragraph. The distribution of virtual water-weighted barycentres (Figure 6.27) allows to observe that the closest one to Bahia's municipalities was indeed Barry Callebaut's barycentre. Moreover, all barycentres fell within Bahia.

Figure 6.27: Brazil, cocoa (2015). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

The following Tables 6.22 and 6.23 summarise percentile values, $uWFs$ and weighted coordinates for each trader. The first table presents them ordered accordingly to the exported tonnes, whereas in the second one the ordering variable is the weighted mean uWF.

Table 6.22: Brazil, cocoa (2015). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles.

COMPANY	**PERC_10 [m^3/ton]**	**PERC_25 [m^3/ton]**	**PERC_50 [m^3/ton]**	**PERC_75 [m^3/ton]**	**PERC_90 [m^3/ton]**
CARGILL	2436	7718	10952	24778	45541
BARRY CALLEBAUT	198	2867	8179	22848	34289
JOANES INDUSTRIAL LTDA	4878	9594	15038	25748	40904

Table 6.23: Brazil, cocoa (2015). Average uWF, weighted average uWF and weighted geographical coordinates of each trader.

COMPANY	**Average uWF [m^3/ton]**	**Weighted average uWF [m^3/ton]**	**Weighted LAT**	**Weighted LON**
JOANES INDUSTRIAL LTDA	19369	16263	-14.0916	-39.8674
CARGILL	17650	17572	-13.7627	-40.5146
BARRY CALLEBAUT	13954	23626	-14.4075	-39.9465

Lastly, relationships exporter-importers were analysed. Barry Callebaut was taken again as illustrative example (Table 6.24). Notably, almost 80% of its virtual water flows were directed to Argentina. Its weighted barycentre was the closest to the one of Barry Callebaut (Figure 6.27).

Table 6.24: Brazil, cocoa (2015). Relationships between the trader Barry Callebaut and the countries relying on it.

COUNTRYOFFIRSTIMPORT	**WF_G [m^3]**	**WF_B [m^3]**	**w_mean_uWF_tot [m^3/ton]**	**WF_tot [m^3]**
ARGENTINA	1.98E+08	2.24E+04	2.49E+04	1.98E+08
UNITED STATES	3.01E+07	9.65E+02	2.35E+04	3.01E+07
CHILE	2.02E+07	3.55E+03	1.57E+04	2.02E+07

6.3.2 Coffee

The analysis was conducted for the year 2017, considering 13 major importers (FAOSTAT, 2016-2017) and 26 traders (Trase, 2017). Tables 6.25 and 6.26 show the associated percentages. The last 7 exporting companies (dark brown) were added to reach, whenever possible, the 80% threshold for local coverage. Belgium was the only country remaining below 80% (around 76%).

Table 6.25: Brazil, coffee (2016-2017). Major importing countries (FAOSTAT).

IMPORTER	*COFFEE_EQ _TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Germany	7.00E+05	20.13	20.13	24.91
United States of America	6.90E+05	19.86	39.99	24.57
Italy	3.40E+05	9.79	49.78	12.11
Japan	2.42E+05	6.96	56.73	8.61
Belgium	2.27E+05	6.53	63.26	8.07
Türkiye	9.88E+04	2.84	66.10	3.52
France	8.73E+04	2.51	68.61	3.11
Canada	8.72E+04	2.51	71.12	3.11
Spain	8.00E+04	2.30	73.42	2.85
Sweden	7.64E+04	2.20	75.62	2.72
United Kingdom of Great Britain and Northern Ireland	6.18E+04	1.78	77.40	2.20
Finland	6.10E+04	1.75	79.15	2.17
Russian Federation	5.78E+04	1.66	80.82	2.06

Table 6.26: Brazil, coffee (2017). Major exporting companies (Trase).

EXPORTERGROUP	*COFFEE_EQ _TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
COOPERATIVA REGIONAL DE CAFEICULTORES EM GUAXUPE LTDA C	2.14E+05	16.93	16.93	19.71
TERRA FORTE EXPORTACAO E IMPORTACAO DE CAFE LIMITADA	1.16E+05	9.21	26.15	10.72
STOCKLER COMERCIAL E EXPORTADORA LTDA	9.74E+04	7.72	33.87	8.99
OLAM	9.60E+04	7.61	41.48	8.86
EISA - EMPRESA INTERAGRICOLA	7.32E+04	5.81	47.28	6.76
ATLANTICA EXPORTACAO E IMPORTACAO	6.65E+04	5.28	52.56	6.14
EXPORTADORA DE CAFE GUAXUPE LTDA	4.80E+04	3.81	56.37	4.43
UNICAFE COMPANHIA DE COMERCIO EXTERIOR	4.16E+04	3.30	59.67	3.84
GARDINGO TRADE IMPORTACAO E EXPORTACAO LTDA	3.87E+04	3.07	62.74	3.57
SAGRADOS CORACOES INDUSTRIA E COMERCIO DE ALIMENTOS LTDA	2.96E+04	2.35	65.08	2.73
LOUIS DREYFUS	2.81E+04	2.23	67.31	2.60
COSTA CAFE COMERCIO EXPORTACAO E IMPORTACAO LTDA	2.54E+04	2.01	69.33	2.34
CAFEBRAS COMERCIO DE CAFES DO BRASIL S/A	2.49E+04	1.97	71.30	2.29
COMEXIM LTDA	2.48E+04	1.97	73.26	2.29
VOLCAFE	2.35E+04	1.86	75.13	2.17
CAFE TRES CORACOES S. A	1.94E+04	1.54	76.67	1.79
PRATAPEREIRA COMERCIO IMPORTACAO E EXPORTACAO DE CAFE LTDA	1.65E+04	1.30	77.98	1.52
COFCO	1.61E+04	1.27	79.25	1.48
ROYAL COFFEE - COMERCIAL E EXPORTADORA DE CAFE LTDA	1.48E+04	1.17	80.42	1.37
ENGELHART	1.29E+04	1.02	81.44	1.19
TPJ COMERCIO ATACADISTA DE CAFE IMPORTACAO E EXPORTACAO LTDA	1.20E+04	0.95	82.40	1.11
EXPOCACCER- COOPERATIVA DOS CAFEICULTORES DO CERRADO LTDA.	1.20E+04	0.95	83.35	1.10
EXPERIMENTAL AGRICOLA DO BRASIL LTDA	1.10E+04	0.87	84.21	1.01
NICCHIO SOBRINHO CAFE S/A	9.60E+03	0.76	84.98	0.89
UNION TRADING COMERCIO, IMPORTACAO E EXPORTACAO LTDA	7.23E+03	0.57	85.55	0.67
KAFFEE EXPORTADORA E IMPORTADORA LTDA	4.74E+03	0.38	85.93	0.44

The selection highlighted that the supplying municipalities were 469, distributed in the south-eastern states of São Paulo, Paraná, Minas Gerais, Bahia and Espírito Santo. Anyway, most of the production was centred around São Paulo and Minas Gerais (Figure 6.28).

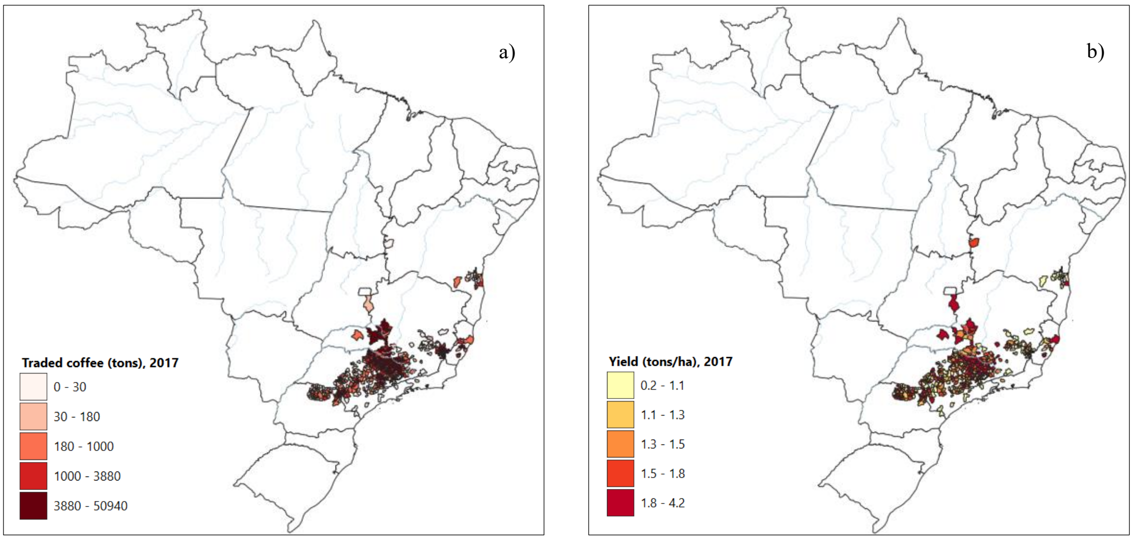


Figure 6.28: Brazil, coffee (2017). Traded tonnes (a) and yield values (b) for each involved municipality.

A shortcut of the table containing data for each municipality is reported (Table 6.27). It shows the first ten sourcing areas, which covered 20% of traded coffee ($2.21 * 10^5\ tons$, over the total $1.08 * 10^6\ tons$). By taking the first 40 municipalities, half of the total share is reached.

Table 6.27: Brazil, coffee (2017). First ten producing municipalities. Exported tonnes and yield values are reported.

STATE	MUNICIPALITYOFPRODUCTION	GEOCODE	COFFEE [tons]	YIELD [tons/ha]
MINAS GERAIS	PATROCINIO	BR3148103	5.09E+04	1.45
MINAS GERAIS	CAMPOS GERAIS	BR3111606	2.66E+04	1.81
MINAS GERAIS	NOVA RESENDE	BR3145109	2.34E+04	1.76
MINAS GERAIS	MACHADO	BR3139003	2.21E+04	1.51
MINAS GERAIS	MANHUACU	BR3139409	1.68E+04	1.43
MINAS GERAIS	CAMPESTRE	BR3111002	1.68E+04	2.11
MINAS GERAIS	SAO SEBASTIAO DO PARAISO	BR3164704	1.67E+04	1.54
MINAS GERAIS	CARMO DO RIO CLARO	BR3114402	1.64E+04	1.82
MINAS GERAIS	RIO PARANAIBA	BR3155504	1.63E+04	1.39
MINAS GERAIS	MONTE CARMELO	BR3143104	1.52E+04	1.84

Available blue and green ET data (Appendix C, Figure C.7) were merged to obtain the total unit water footprints (Figure 6.29). Municipalities in Bahia were almost entirely classified in the red range of the colour ramp, whereas the other states had a wider variability. Table 6.28 shows the first ten municipalities in terms of uWF. Comparing yield values and uWF ones, it is clear that the highest unitary pressures were recorded in the municipalities characterised by the lowest productivities. In Appendix C, separate green and blue uWF values are reported (Figure C.8).

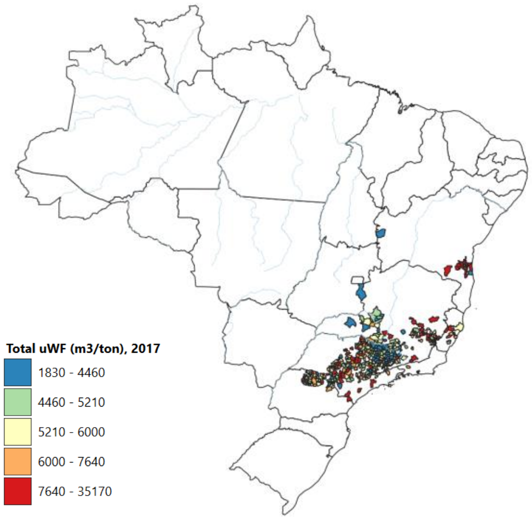


Figure 6.29: Brazil, coffee (2017). Total unit water footprint values at the municipality scale.

Table 6.28: Brazil, coffee (2017). Municipalities with the ten highest uWF values.

STATE	MUNICIPALITYOFPRODUCTION	uWF_g [m^3/ton]	uWF_b [m^3/ton]	uWF_tot [m^3/ton]	COFFEE [tons]
BAHIA	IGUAI	3.52E+04	2.69E+00	3.52E+04	25.00
BAHIA	IBICUI	2.73E+04	6.01E+01	2.74E+04	7.00
SAO PAULO	IARAS	2.54E+04	9.00E+00	2.54E+04	1.00
MINAS GERAIS	LUZ	1.84E+04	2.04E+03	2.05E+04	63.00
SAO PAULO	PIRANGI	1.75E+04	9.89E+01	1.76E+04	1.00
SAO PAULO	ARIRANHA	1.75E+04	9.06E+01	1.76E+04	2.00
SAO PAULO	PALMARES PAULISTA	1.75E+04	2.07E+01	1.75E+04	1.00
MINAS GERAIS	SAO JOSE DO GOIABAL	1.55E+04	1.56E+03	1.71E+04	2.00
MINAS GERAIS	DIONISIO	1.56E+04	1.30E+03	1.69E+04	3.00
BAHIA	DARIO MEIRA	1.66E+04	1.60E-01	1.66E+04	1.00

Water volumes are detailed in Figure 6.30 and Table 6.29. See Figure C.9 in Appendix C for separate green and blue water volumes.

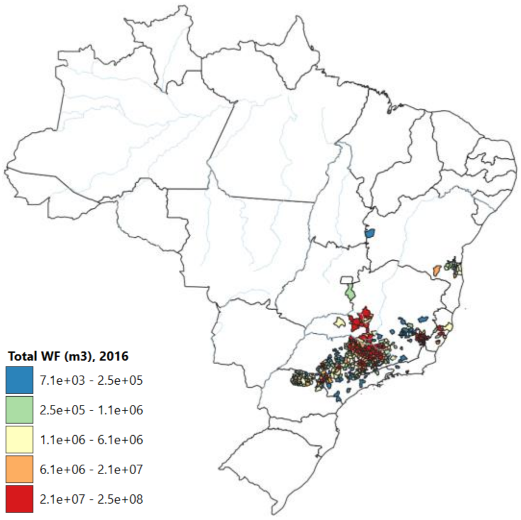


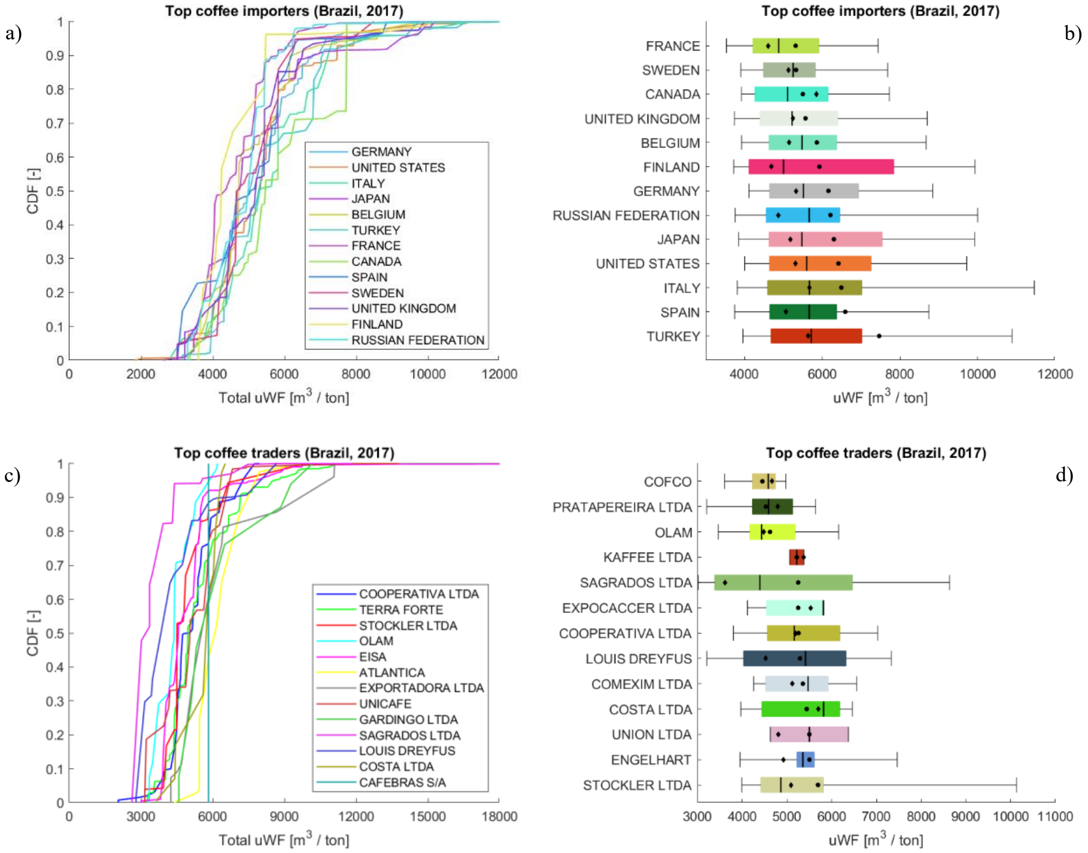
Figure 6.30: Brazil, coffee (2017). Total water footprint values at the municipality scale.

Table 6.29: Brazil, coffee (2017). Municipalities with the ten highest WF values.

STATE	MUNICIPALITYOF PRODUCTION	WF_G [m^3]	WF_B [m^3]	WF_tot [m^3]	COFFEE [tons]
MINAS GERAIS	PATROCINIO	2.93E+08	4.15E+06	2.97E+08	5.09E+04
MINAS GERAIS	CAMPOS GERAIS	1.19E+08	7.95E+05	1.20E+08	2.66E+04
MINAS GERAIS	MACHADO	1.17E+08	4.23E+05	1.17E+08	2.21E+04
MINAS GERAIS	NOVA RESENDE	1.06E+08	7.45E+05	1.06E+08	2.34E+04
MINAS GERAIS	RIO PARANAIBA	9.20E+07	4.64E+06	9.67E+07	1.63E+04
MINAS GERAIS	SERRA DO SALITRE	9.16E+07	3.88E+05	9.20E+07	1.23E+04
MINAS GERAIS	MANHUACU	9.14E+07	6.69E+04	9.14E+07	1.68E+04
MINAS GERAIS	SAO SEBASTIAO DO PARAISO	8.97E+07	7.91E+04	8.98E+07	1.67E+04
MINAS GERAIS	SIMONESIA	8.93E+07	3.47E+05	8.96E+07	1.26E+04
MINAS GERAIS	MONTE SANTO DE MINAS	7.82E+07	9.96E+04	7.83E+07	1.07E+04

Interestingly, seven out of ten municipalities in Table 6.29 appear also among the most productive ones (Table 6.27). Moreover, the fifteen sites with the highest water demand were located within Minas Gerais, accounting for 27% of the overall traded water volume ($1.54 * 10^9\ m^3$ over $5.76 * 10^9\ m^3$).

Hereafter, cumulative distribution functions and boxplots are reported (Figure 6.31). For reasons of space, traders were split into four separate plots to be better visualised.



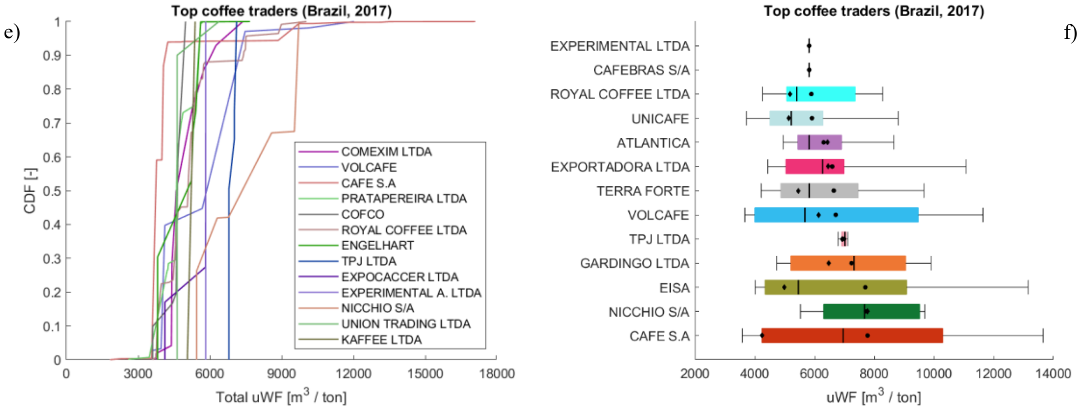


Figure 6.31: Brazil, coffee (2017). Cumulative distribution functions (a, c, e) and boxplots (b, d, f) of the major importing countries (a, b) and exporting companies (c, d, e, f).

With coffee, the variability is much more evident than cocoa results (Chapter 6.2.1). Indeed, there are both right and left skewed distributions. Additionally, the companies Cafebras S/A and Experimental Agricola Do Brazil LTDA were supplied by a single municipality (Patrocinio, in Minas Gerais). Discussing about the average uWF values, Turkey ($7.46 * 10^3\ m^3/ton$) and Café Tres Coracoes S.A ($7.78 * 10^3\ m^3/ton$) were the less water-efficient importer and trader, respectively. On the other hand, according to the weighted mean values, Canada ($5.84 * 10^3\ m^3/ton$) and Nicchio Sobrinho Café S/A ($7.77 * 10^3\ m^3/ton$) occupied the first position. Regarding importing countries, Finland had the largest gap between the 25th and 75th percentiles, while Italy between the 10th and 90th ones. Municipalities supplying Café Tres Coracoes had the highest range of uWF values and they are represented in Figure 6.32. They fell entirely within Minas Gerais.

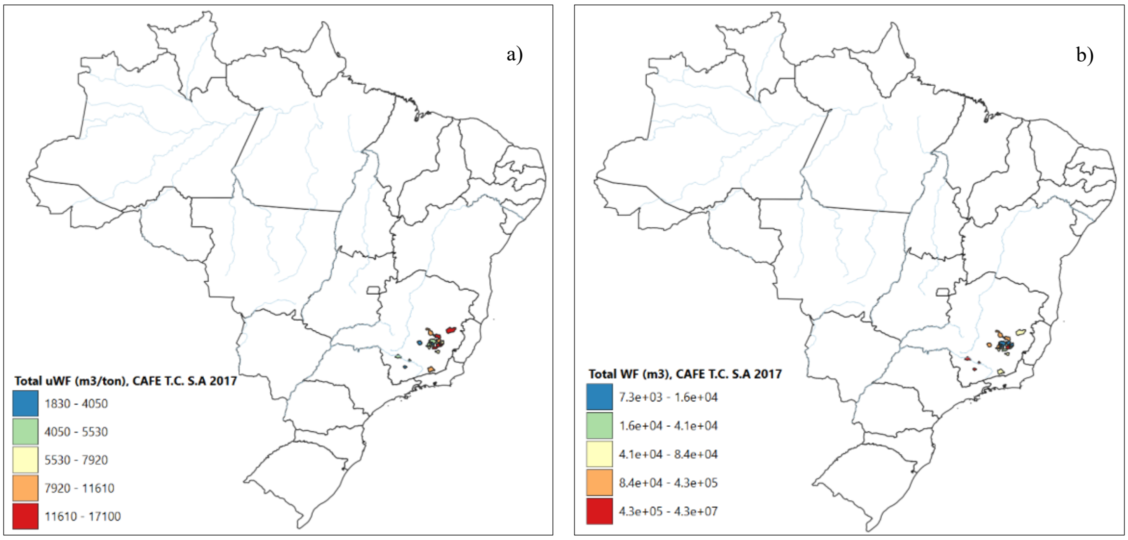


Figure 6.32: Brazil, coffee (2017). Total unit water footprint (a) and total water footprint (b) values of the municipalities supplying Café Tres Coracoes S.A.

Virtual water-weighted barycentres are displaced in Figure 6.33. Moreover, they are superimposed on green ET data in Figure C.10, Appendix C.

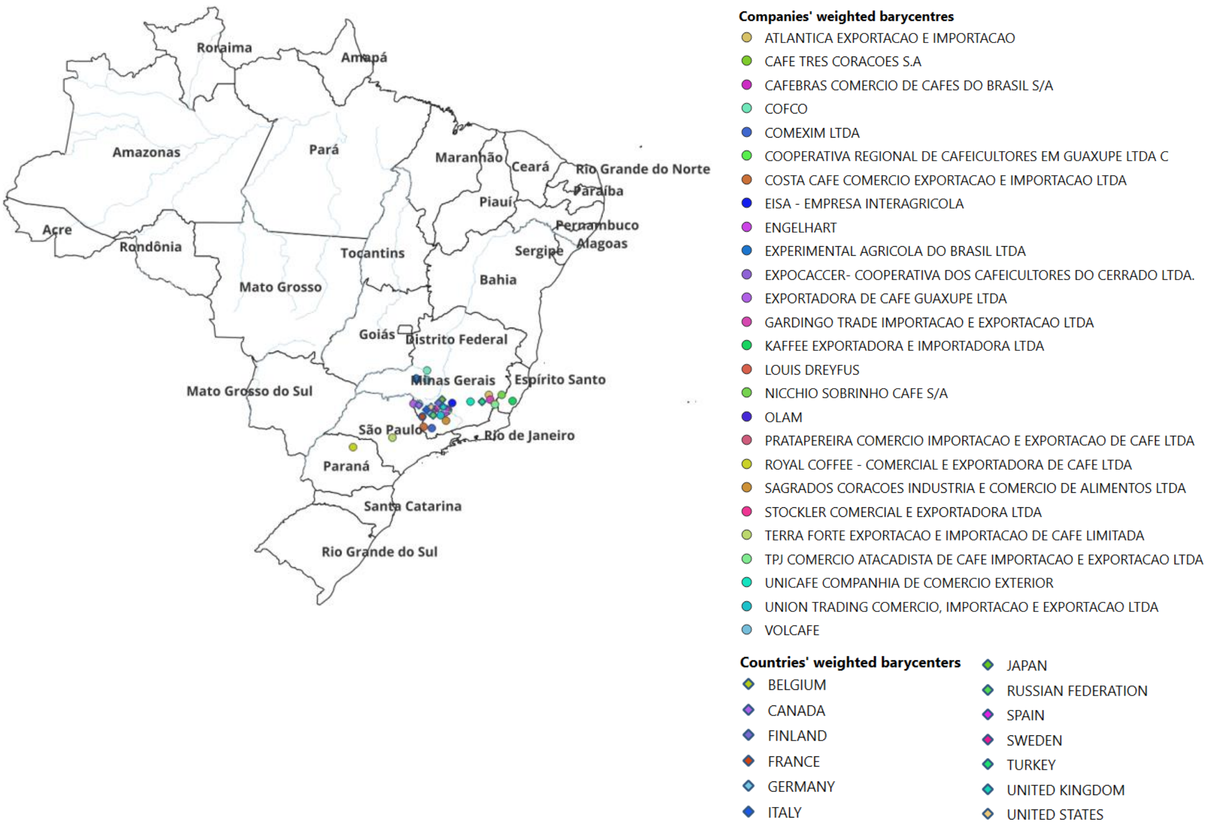


Figure 6.33: Brazil, coffee (2017). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

The vast majority of barycentres was found within Minas Gerais, except for the one of Royal Coffee (Paraná), and Terra Forte, Exportadora LTDA, Olam and France (São Paulo), and Kaffee LTDA (Espírito Santo). Table 6.30 reports statistics, while Table 6.31 *uWFs* and weighted coordinates for five illustrative companies. The second table shows the traders with highest weighted average *uWFs*.

Table 6.30: Brazil, coffee (2017). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Five examples.

COMPANY	PERC_10 [m^3/ton]	PERC_25 [m^3/ton]	PERC_50 [m^3/ton]	PERC_75 [m^3/ton]	PERC_90 [m^3/ton]
COOPERATIVA REGIONAL DE CAFEICULTORES EM GUAXUPE LTDA C	3804	4565	5165	6185	7030
TERRA FORTE EXPORTACAO E IMPORTACAO DE CAFE LIMITADA	4216	4873	5829	7465	9667
STOCKLER COMERCIAL E EXPORTADORA LTDA	3993	4417	4865	5816	10132
OLAM	3467	4173	4434	5189	6157
EISA - EMPRESA INTERAGRICOLA	4017	4342	5459	9091	13157

Table 6.31: Brazil, coffee (2017). Average uWF, weighted average uWF and weighted geographical coordinates of five traders.

COMPANY	**Average uWF [m³/ton]**	**Weighted average uWF [m³/ton]**	**Weighted LAT**	**Weighted LON**
NICCHIO SOBRINHO CAFE S/A	7726	7770	-20.0573	-41.4886
TPJ COMERCIO ATACADISTA DE CAFE IMPORTACAO E EXPORTACAO LTDA	6987	6930	-20.6423	-41.9526
GARDINGO TRADE IMPORTACAO E EXPORTACAO LTDA	7242	6468	-20.3376	-42.2416
EXPORTADORA DE CAFE GUAXUPE LTDA	6597	6455	-20.6199	-47.2333
ATLANTICA EXPORTACAO E IMPORTACAO	6307	6433	-20.0314	-42.334

6.3.3 Corn

The Trase dataset for corn trades was examined according to the 11 major importing countries (FAOSTAT, 2015-2017) and the 12 traders which satisfied both global and local constraints (Trase, 2017). Specifically, Coamo and Nidera were added to reach 80% of coverage in Iran. Tables 6.32 and 6.33 show related percentages.

Table 6.32: Brazil, corn (2015-2017). Major importing countries (FAOSTAT).

IMPORTER	*CORN_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Iran (Islamic Republic of)	1.38E+07	17.28	17.28	20.99
Viet Nam	1.04E+07	12.93	30.21	15.71
Japan	8.42E+06	10.51	40.72	12.77
Egypt	6.74E+06	8.41	49.14	10.22
Republic of Korea	6.20E+06	7.75	56.89	9.41
China, Taiwan Province of	5.35E+06	6.69	63.57	8.12
Malaysia	4.79E+06	5.98	69.55	7.26
Spain	4.11E+06	5.14	74.69	6.24
Saudi Arabia	2.09E+06	2.61	77.30	3.18
Indonesia	2.04E+06	2.55	79.86	3.10
Algeria	1.96E+06	2.45	82.31	2.98

Table 6.33: Brazil, corn (2017). Major exporting companies (Trase).

EXPORTERGROUP	*CORN_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
BUNGE	3.57E+06	16.74	16.74	19.14
CARGILL	3.32E+06	15.61	32.35	17.85
AMAGGI	2.27E+06	10.65	43.00	12.18
ADM	2.25E+06	10.55	53.56	12.07
GLENCORE	1.40E+06	6.58	60.13	7.52
LOUIS DREYFUS	1.36E+06	6.40	66.53	7.31
ENGELHART	8.81E+05	4.14	70.67	4.73
MITSUI & CO.	7.75E+05	3.64	74.31	4.16
MITSUBISHI	7.74E+05	3.63	77.94	4.15
CHS	6.93E+05	3.25	81.19	3.72
NIDERA	6.80E+05	3.19	84.39	3.65
COAMO	6.54E+05	3.07	87.45	3.51

The involved municipalities for the present analysis were 554. They appeared to be quite widespread over the entire Brazil, with a special concentration in the states of Mato Grosso, São Paulo, Minas Gerais and Espírito Santo (Figure 6.34).

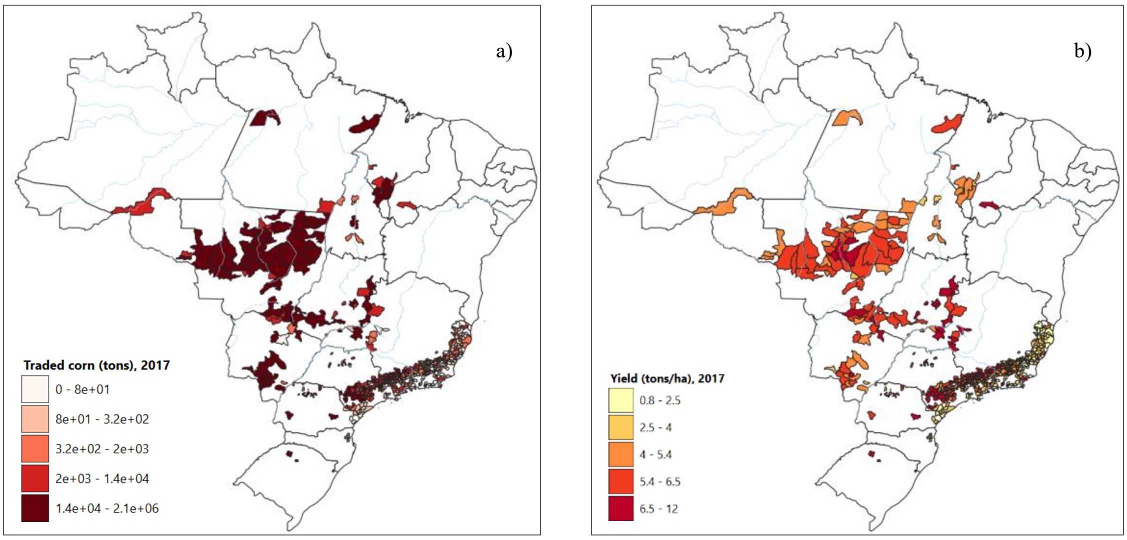


Figure 6.34: Brazil, corn (2017). Traded tonnes (a) and yield values (b) for each involved municipality.

As an example, the ten municipalities which produced more corn are reported in Table 6.34. They accounted for 43% ($7.99 * 10^6\ tons$) of the overall production ($1.86 * 10^7\ tons$), with Sorriso contributing for 11% by itself. Moreover, of this 43%, 80% was covered by municipalities situated in Mato Grosso ($6.42 * 10^6\ tons$).

Table 6.34: Brazil, corn (2017). First ten producing municipalities. Exported tonnes and yield values are reported.

STATE	MUNICIPALITYOFPRODUCTION	GEOCODE	CORN [tons]	YIELD [tons/ha]
MATO GROSSO	SORRISO	BR5107925	2.08E+06	7.26
MATO GROSSO	NOVA MUTUM	BR5106224	8.81E+05	6.42
MATO GROSSO DO SUL	MARACAJU	BR5005400	8.02E+05	5.40
GOIAS	RIO VERDE	BR5218805	7.65E+05	6.13
MATO GROSSO	QUERENCIA	BR5107065	7.07E+05	5.98
MATO GROSSO	CAMPO NOVO DO PARECIS	BR5102637	6.07E+05	6.31
MATO GROSSO	PRIMAVERA DO LESTE	BR5107040	5.71E+05	6.39
MATO GROSSO	SANTA RITA DO TRIVELATO	BR5107768	5.54E+05	6.30
MATO GROSSO	LUCAS DO RIO VERDE	BR5105259	5.41E+05	6.89
MATO GROSSO	DIAMANTINO	BR5103502	4.75E+05	5.71

For what concerns unit water footprint values, the map in Figure 6.35 enables to observe that the state with the highest concentration of 'red' municipalities was Espírito Santo. This is appreciable also in Table 6.35, where the ten less water-efficient municipalities are reported: seven of them belong to Espírito Santo. Moreover, in this state and in Minas Gerais the highest contributes of blue water were found (Appendix C, Figure C.12). Notably, seven municipalities were not recorded with evapotranspiration data, resulting in $uWFs$ equal to zero. Therefore, related exports did not figure in the virtual water volume traded by companies relying on them, which were Cargill, Glencore, ADM and Louis Dreyfus in ascending order. This inevitably resulted in an underestimation of the water displaced by them.

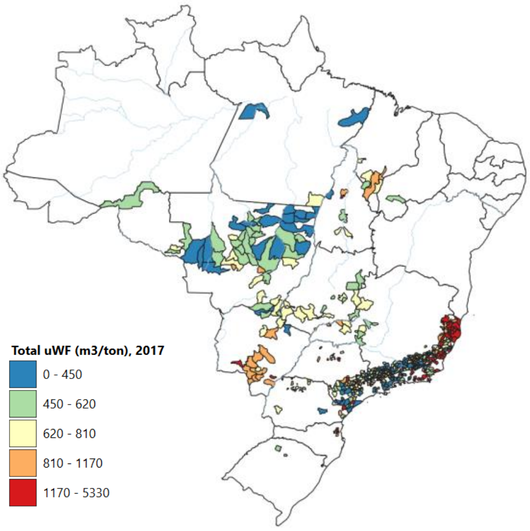


Figure 6.35: Brazil, corn (2017). Total unit water footprint values at the municipality scale.

Table 6.35: Brazil, corn (2017). Municipalities with the ten highest uWF values.

STATE	MUNICIPALITY OFPRODUCTION	uWF_g [m³/ton]	uWF_b [m³/ton]	uWF_tot [m³/ton]	CORN [tons]
RIO DE JANEIRO	CARDOSO MOREIRA	5.31E+03	2.20E+01	5.33E+03	7.31E+00
RIO DE JANEIRO	SAO PEDRO DA ALDEIA	4.84E+03	6.67E-01	4.84E+03	4.57E+00
ESPIRITO SANTO	SAO MATEUS	4.83E+03	8.81E+00	4.84E+03	2.00E+01
ESPIRITO SANTO	LARANJA DA TERRA	4.56E+03	8.38E+01	4.64E+03	6.50E+01
ESPIRITO SANTO	VILA VELHA	3.96E+03	2.32E+01	3.99E+03	1.00E+01
SAO PAULO	BARRA DO TURVO	3.94E+03	0	3.94E+03	2.12E+02
ESPIRITO SANTO	ATILIO VIVACQUA	3.89E+03	1.06E+01	3.90E+03	4.57E+00
ESPIRITO SANTO	CONCEICAO DO CASTELO	3.36E+03	1.46E+01	3.38E+03	7.20E+01
ESPIRITO SANTO	CARIACICA	3.30E+03	1.31E+01	3.32E+03	1.00E+01
ESPIRITO SANTO	CACHOEIRO DE ITAPEMIRIM	3.25E+03	3.94E+01	3.29E+03	1.13E+02

Traded virtual water volumes were then represented, as visible in Figure 6.36. Mato Grosso was confirmed as the state with the highest water requirements, being production levels very substantial within it. Figure C.13 in Appendix C for separate green and blue water volumes.

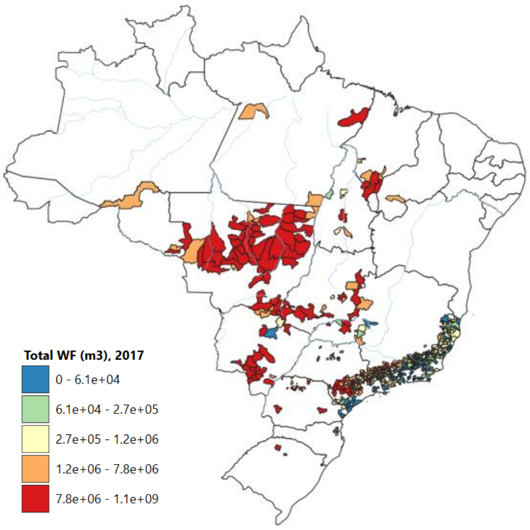


Figure 6.36: Brazil, corn (2017). Total water footprint values at the municipality scale.

Table 6.36: Brazil, corn (2017). Municipalities with the ten highest WF values.

STATE	**MUNICIPALITY OFPRODUCTION**	**WF_G [m^3]**	**WF_B [m^3]**	**WF_tot [m^3]**	**CORN [tons]**
MATO GROSSO	SORRISO	1.06E+09	0	1.06E+09	2.08E+06
MATO GROSSO DO SUL	MARACAJU	7.36E+08	0	7.36E+08	8.02E+05
GOIAS	RIO VERDE	5.32E+08	0	5.32E+08	7.65E+05
MATO GROSSO	NOVA MUTUM	5.28E+08	0	5.28E+08	8.81E+05
MATO GROSSO DO SUL	PONTA PORA	3.57E+08	0	3.57E+08	3.92E+05
MATO GROSSO	QUERENCIA	3.53E+08	0	3.53E+08	7.07E+05
MATO GROSSO	SANTA RITA DO TRIVELATO	3.35E+08	0	3.35E+08	5.54E+05
MATO GROSSO	DIAMANTINO	3.26E+08	0	3.26E+08	4.75E+05
MATO GROSSO DO SUL	ARAL MOREIRA	3.21E+08	0	3.21E+08	3.45E+05
MATO GROSSO	PRIMAVERA DO LESTE	2.97E+08	0	2.97E+08	5.71E+05

Notably, the water demand in the municipalities shown in Table 6.36 was only contributed by green water. Indeed, data on water provided by irrigation systems are available only for the states of Minas Gerais, Espírito Santo and Rio de Janeiro, situated along the east coast of Brazil. Virtual water flows from the municipalities listed in Table 6.36 accounted for 43% ($4.84 * 10^9\ m^3$) of the total traded virtual water ($1.14 * 10^{10}\ m^3$).

Statistics of importers and traders follow (Figure 6.37).

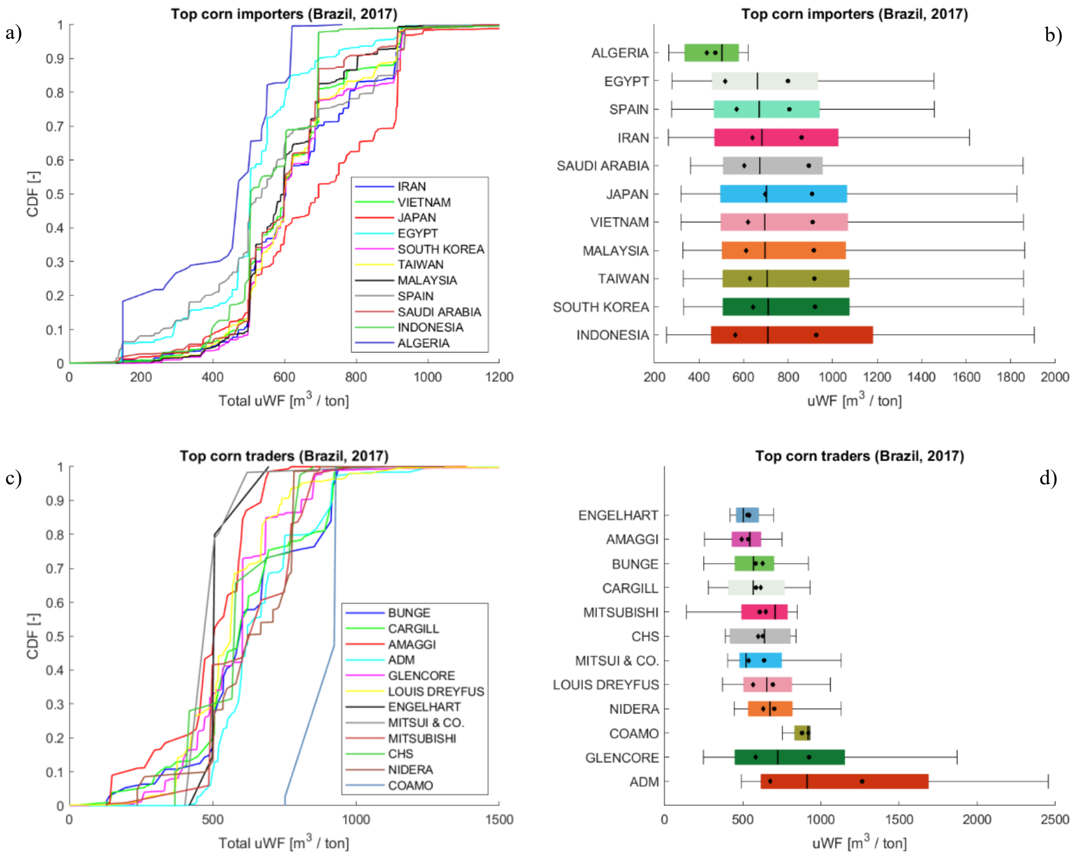


Figure 6.37: Brazil, corn (2017). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

It immediately stands out the difference between importers' and traders' distributions. The first were characterised by right skewed boxplots, with average $uWFs$ above the median and weighted average $uWFs$ below it, and almost the same dispersion of values (the only exception was Algeria: left skewed with a weighted average uWF below the median). Traders' distributions, instead, were right skewed, left skewed, or even symmetric (CHS and Bunge), with $uWFs$ falling above or below the 50th percentile, and variable whiskers lengths. Moreover, among traders, average uWF values showed great dissimilarities, ranging from 530 m^3/ton (Engelhart) to 1260 m^3/ton (ADM). As representative example, the 103 sourcing municipalities for ADM are illustrated in Figure 6.38, as this company was recorded with the highest average uWF (1260 m^3/ton) and second highest weighted one (677 m^3/ton), after Coamo.

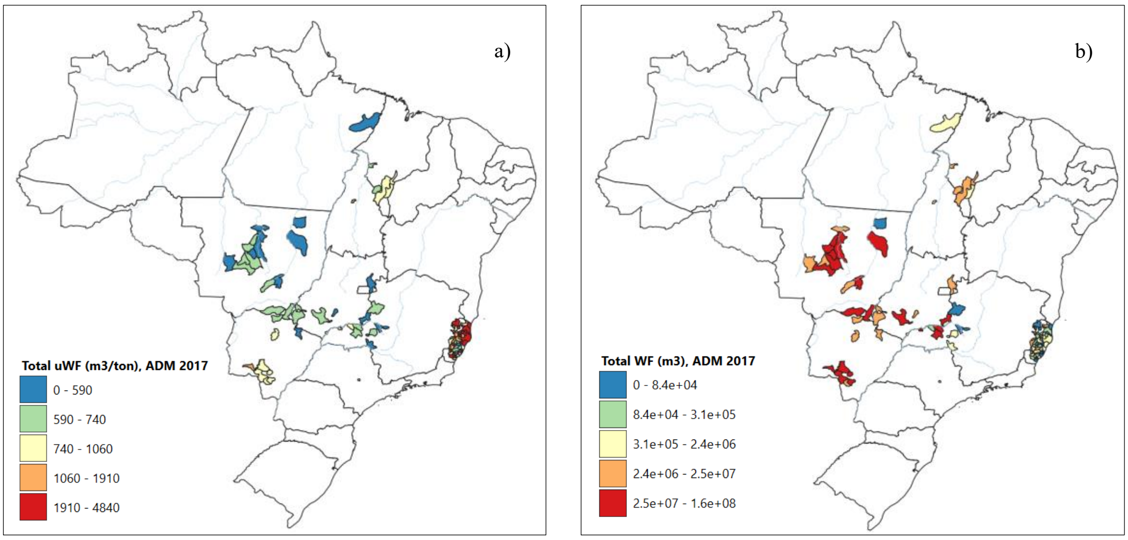


Figure 6.38: Brazil, corn (2017). Total unit water footprint (a) and total water footprint (b) values of the municipalities supplying ADM.

ADM supplied from municipalities displaced over the entire Brazil, with 51 of them in Espírito Santo, reason why its *uWF* resulted to be the highest one. Nevertheless, in terms of traded water volume, ADM mainly exerted a pressure on Mato Grosso and Mato Grosso do Sul municipalities. In Figure 6.39, virtual water-weighted barycentres are displaced, for importers and companies. They were distributed within Mato Grosso, Mato Grosso do Sul and Goiás, except for Louis Dreyfus in São Paulo. Barycentres and green *ET* values are visible in Figure C.14, Appendix C.

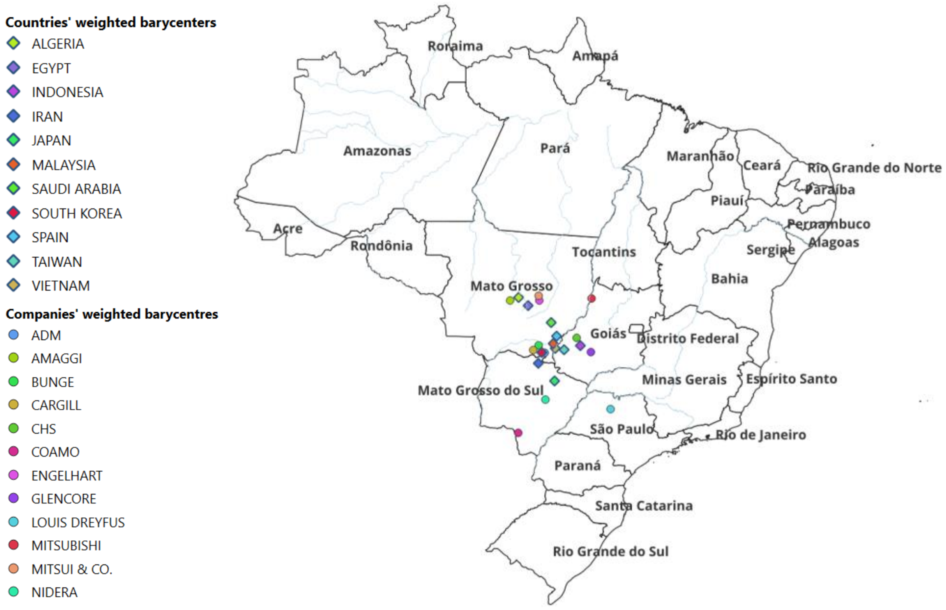


Figure 6.39: Brazil, corn (2017). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Tables 6.37 and 6.38 illustrate details for five illustrative companies each. In Table 6.37 the ordering criterion are the exported tonnes (descending order), whereas in Table 6.38 companies are shown according to the highest weighted mean *uWFs*.

Table 6.37: Brazil, corn (2017). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Five examples.

COMPANY	PERC_10 [m³/ton]	PERC_25 [m³/ton]	PERC_50 [m³/ton]	PERC_75 [m³/ton]	PERC_90 [m³/ton]
BUNGE	249	451	568	699	919
CARGILL	279	408	567	767	931
AMAGGI	255	431	545	616	751
ADM	491	617	912	1687	2455
GLENCORE	248	451	724	1151	1872

Table 6.38: Brazil, corn (2017). Average uWF, weighted average uWF and weighted geographical coordinates of five traders.

COMPANY	Average uWF [m³/ton]	Weighted average uWF [m³/ton]	Weighted LAT	Weighted LON
COAMO	879	917	-22.5739	-55.4731
ADM	1264	677	-17.3608	-53.739
MITSUBISHI	609	648	-13.8041	-50.6916
NIDERA	701	633	-20.4012	-53.7256
BUNGE	582	629	-16.8772	-54.1744

6.3.4 Cotton

Cotton trade flows were analysed for the year 2017, considering the 8 major importing countries (FAOSTAT, 2015-2017) and the corresponding 12 top companies (Trase, 2017). In this case, imports from Bangladesh, China and Vietnam were covered to about 75%. No additional traders were considered, as none of them exceeded the 5% threshold. Tables 6.39 and 6.40 for percentage details.

Table 6.39: Brazil, cotton (2015-2017). Major importing countries (FAOSTAT).

IMPORTER	*COTTON_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Indonesia	1.02E+06	16.94	16.94	19.71
Viet Nam	9.23E+05	15.40	32.34	17.92
Republic of Korea	7.08E+05	11.82	44.16	13.75
Türkiye	6.90E+05	11.52	55.68	13.40
China, mainland	5.84E+05	9.75	65.43	11.34
Malaysia	4.77E+05	7.96	73.39	9.26
Pakistan	3.91E+05	6.53	79.92	7.60
Bangladesh	3.61E+05	6.02	85.94	7.01

Table 6.40: Brazil, cotton (2017). Major exporting companies (Trase).

EXPORTERGROUP	*COTTON_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
SLC AGRICOLA PEJUCARA LTDA	1.23E+05	15.64	15.64	19.12
AMAGGI	8.99E+04	11.43	27.07	13.98
BOM FUTURO AGRICOLA LTDA	8.59E+04	10.92	37.99	13.35
CARGILL	7.28E+04	9.26	47.25	11.32
LOUIS DREYFUS	5.99E+04	7.62	54.87	9.32
EISA - EMPRESA INTERAGRICOLA	4.34E+04	5.52	60.39	6.75
BOM JESUS AGROPECUARIA	3.55E+04	4.52	64.91	5.52
ADM	3.53E+04	4.50	69.41	5.50
MITSUI & CO.	2.68E+04	3.41	72.82	4.17
TERRA SANTA AGRO	2.52E+04	3.20	76.01	3.91

EXPORTERGROUP	*COTTON_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
BOA ESPERANCA AGROPECUARIA LTDA	2.45E+04	3.11	79.13	3.80
WALTER YUKIO HORITA	2.10E+04	2.67	81.80	3.27

Skimming the Trase dataset according to Tables 6.39 and 6.40, 38 sourcing municipalities remained, mainly located within the states of Mato Grosso and Bahia (Figure 6.40).

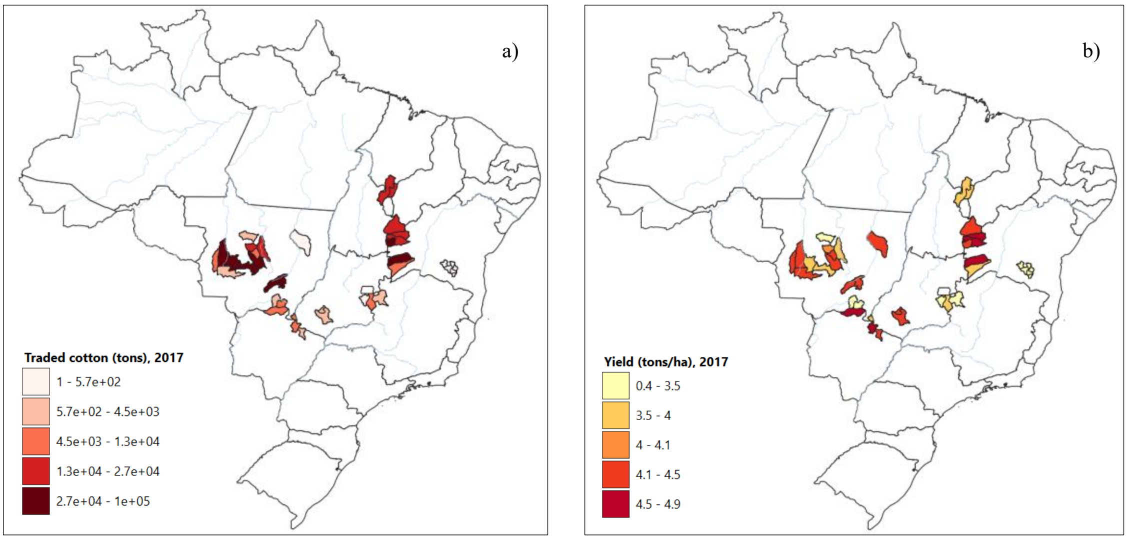


Figure 6.40: Brazil, cotton (2017). Traded tonnes (a) and yield values (b) for each involved municipality.

In particular, the five municipalities in Table 6.41 contributed for over 52% ($3.35 * 10^5\ tons$) of total cotton trade, in 2017 ($6.43 * 10^5\ tons$), with Sapezal in Mato Grosso accounting for 16% by itself ($1.02 * 10^5\ tons$).

Table 6.41: Brazil, cotton (2017). First five producing municipalities. Exported tonnes and yield values are reported.

STATE	**MUNICIPALITYOFPRODUCTION**	**GEOCODE**	**COTTON [tons]**	**YIELD [tons/ha]**
MATO GROSSO	SAPEZAL	BR5107875	1.02E+05	4.50
MATO GROSSO	CAMPO VERDE	BR5102678	8.62E+04	4.25
MATO GROSSO	PRIMAVERA DO LESTE	BR5107040	6.51E+04	4.21
BAHIA	CORRENTINA	BR2909307	4.13E+04	4.52
MATO GROSSO	DIAMANTINO	BR5103502	4.05E+04	3.99

By means of ET (Appendix C, Figure C.15) and yield data, unit water footprints were computed (Figure 6.41). It emerged that the five less water-efficient production sites were situated in Bahia (Table 6.42). The explanation can be found in blue ET data, available only over Bahia and Maranhão, whereas in Mato Grosso, Mato Grosso do Sul, Goiás and Minas Gerais only green water contributed to uWF values (Appendix C, Figure C.16). Notably, cotton crops in Formosa do Rio Preto (Bahia) were characterised by a blue ET even higher than the green one (241 mm/y versus 229 mm/y, respectively).

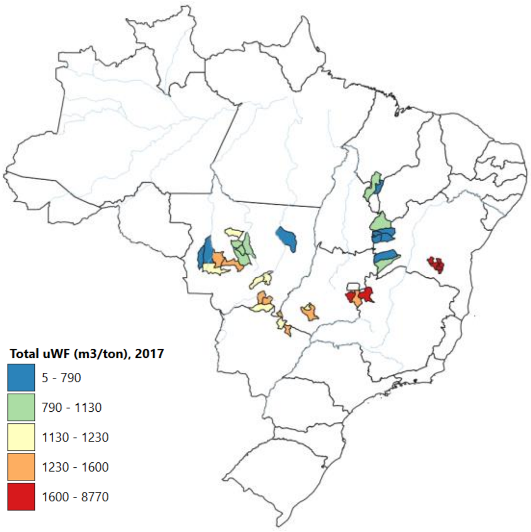


Figure 6.41: Brazil, cotton (2017). Total unit water footprint values at the municipality scale.

Table 6.42: Brazil, cotton (2017). Municipalities with the five highest uWF values.

STATE	MUNICIPALITYOFPRODUCTION	uWF_g [m^3/ton]	uWF_b [m^3/ton]	uWF_tot [m^3/ton]	COTTON [ton]
BAHIA	ITUACU	6.22E+03	2.54E+03	8.76E+03	4.20E+01
BAHIA	BRUMADO	5.85E+03	1.62E+03	7.46E+03	2.56E+02
BAHIA	TANHACU	5.14E+03	5.86E+02	5.73E+03	1.10E+02
BAHIA	CARAIBAS	5.39E+03	1.83E+02	5.57E+03	1.00E+00
BAHIA	LIVRAMENTO DE NOSSA SENHORA	2.40E+03	9.78E+02	3.38E+03	3.59E+02

Traded water volumes are reported in Figure 6.42, whereas in Figure C.17 (Appendix C) separate green and blue water volumes are reported.

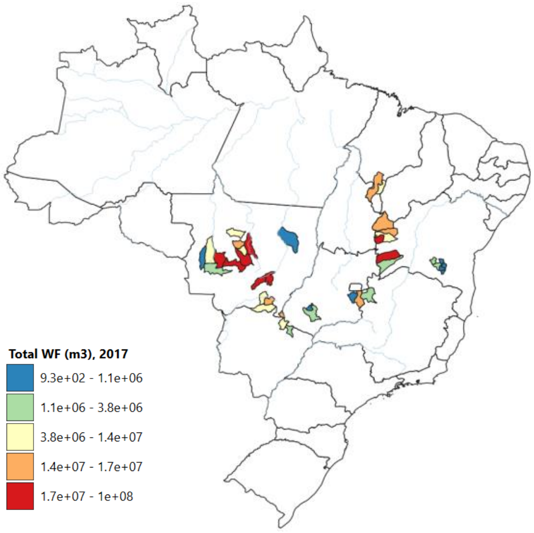


Figure 6.42: Brazil, cotton (2017). Total water footprint values at the municipality scale.

Table 6.43: Brazil, cotton (2017). Municipalities with the five highest WF values.

STATE	MUNICIPALITYOFPRODUCTION	WF_G [m^3]	WF_B [m^3]	WF_tot [m^3]	COTTON [tons]
MATO GROSSO	CAMPO VERDE	1.05E+08	0	1.05E+08	8.62E+04
MATO GROSSO	PRIMAVERA DO LESTE	7.76E+07	0	7.76E+07	6.51E+04
MATO GROSSO	DIAMANTINO	5.01E+07	0	5.01E+07	4.05E+04
MATO GROSSO	CAMPO NOVO DO PARECIS	4.35E+07	0	4.35E+07	3.53E+04
MATO GROSSO	NOVA MUTUM	3.54E+07	0	3.54E+07	3.18E+04

Table 6.43 highlights that the sites with highest water demand were found within Mato Grosso due to their high production. The reported municipalities accounted for 53% ($3.12 * 10^8\ m^3$) of virtual water trades ($5.87 * 10^8\ m^3$). The most productive site, Sapezal, occupied the 21st position thanks to its low (third to last) uWF, which compensated for the elevate number of produced tonnes. Nevertheless, ET values appeared very heterogeneous, and side-by-side pixels were associated with highly different values (Appendix C).

Hereafter, cumulative distribution functions and boxplot are shown for importers and exporters (Figure 6.43).

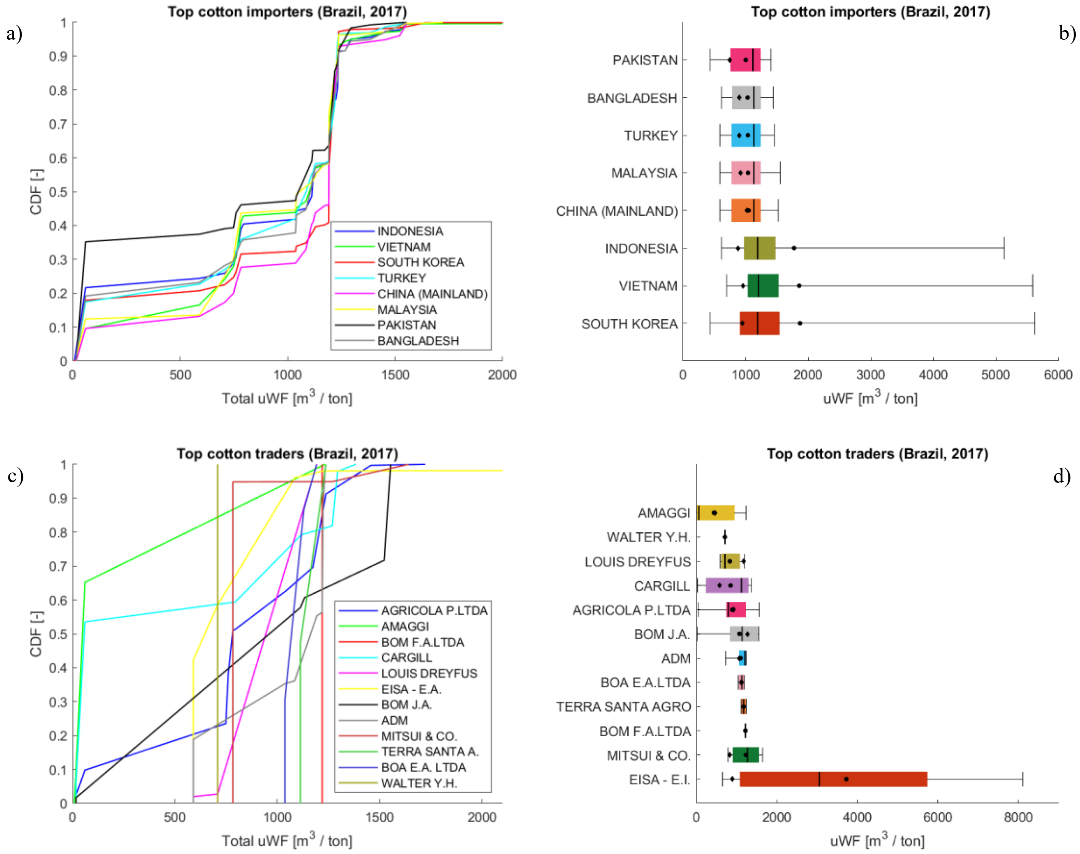


Figure 6.43: Brazil, cotton (2017). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

In this analysis, strong differences between importing countries and traders are visible. The first, despite variable whiskers lengths, were described by similar CDFs and weighted average $uWFs$, while the mean $uWFs$ differed a bit more. Conversely, companies' statistics were peculiar for each of them. Specifically, EISA – Empresa Interagricola showed the larges dispersion (distance between the 10th and 90th percentiles, $7.46 * 10^3\ m^3/ton$), along with the highest average uWF ($3.72 * 10^3\ m^3/ton$). On the other hand, Bom Jesus Agropecuaria had the highest weighted mean uWF ($1.26 * 10^3\ m^3/ton$). As an example, EISA supplying sites are reported (Figure 6.44).

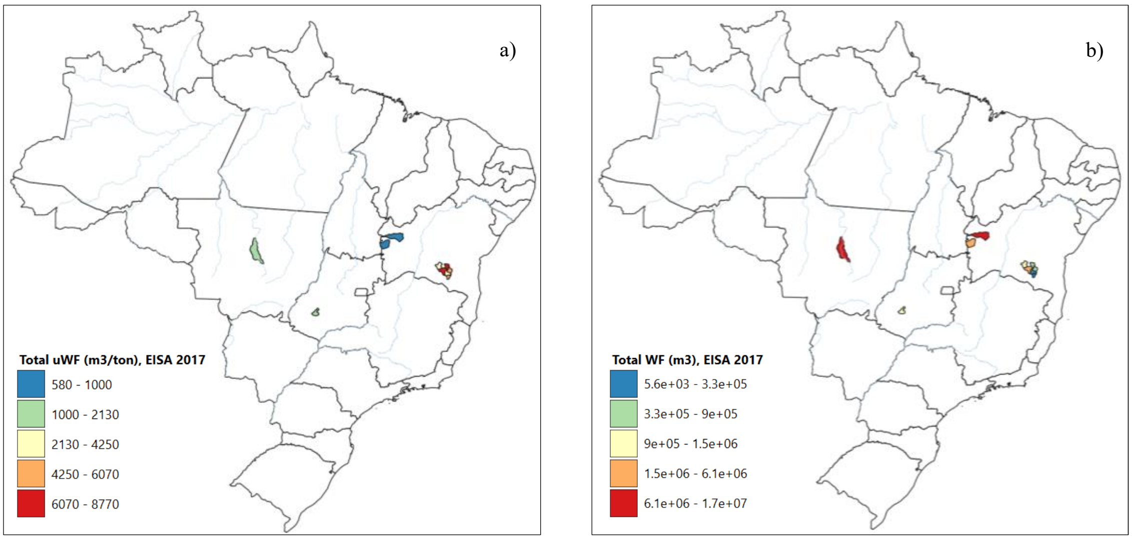


Figure 6.44: Brazil, cotton (2017). Total unit water footprint (a) and total water footprint (b) values of the municipalities supplying EISA – Empresa Interagricola.

Municipalities in Bahia, with the most considerable unit water footprints, supplied EISA, resulting in its higher average uWF. Map in Figure 6.45 represents the virtual water-weighted barycentres of importers and traders. These are combined with green ET data in Figure C.18, Appendix C.

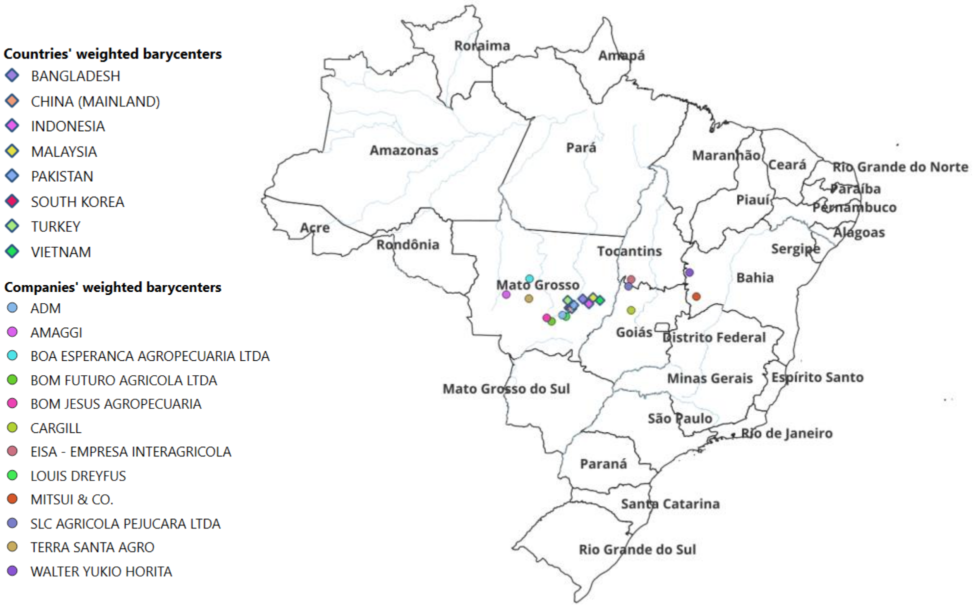


Figure 6.45: Brazil, cotton (2017). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Notably, the barycentres of the eight importing countries fell within Mato Grosso with small distances among them, whereas traders' coordinates were sparser, westwards and eastwards (Tocantins, Bahia, Goiás). The following Tables 6.44 and 6.45 show details for five illustrative companies each.

Table 6.44: Brazil, cotton (2017). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Five examples.

COMPANY	PERC_10 [m³/ton]	PERC_25 [m³/ton]	PERC_50 [m³/ton]	PERC_75 [m³/ton]	PERC_90 [m³/ton]
SLC AGRICOLA PEJUCARA LTDA	43	752	795	1221	1563
AMAGGI	9	22	61	939	1232
BOM FUTURO AGRICOLA LTDA	1219	1219	1219	1219	1219
CARGILL	26	244	1118	1288	1365
LOUIS DREYFUS	590	620	708	1072	1193

Table 6.45: Brazil, cotton (2017). Average uWF, weighted average uWF and weighted geographical coordinates of five traders.

COMPANY	Average uWF [m³/ton]	Weighted average uWF [m³/ton]	Weighted LAT	Weighted LON
BOM JESUS AGROPECUARIA	1068	1265	-15.1414	-55.3283
BOM FUTURO AGRICOLA LTDA	1219	1219	-15.4	-55.019
TERRA SANTA AGRO	1175	1178	-13.8864	-56.4901
LOUIS DREYFUS	830	1177	-15.049	-54.0925
BOA ESPERANCA AGROPECUARIA LTDA	1119	1109	-12.5825	-56.4586

6.3.5 Soy

The last crop analysed in Brazil was soybean. In this case, the investigation was focused on the 8 major importing countries (FAOSTAT, 2004-2020; Table 6.46) and their 17 top traders (Trase, 2020; Table 6.47), for the year 2020. To provide a better description, it was necessary to include the last 5 companies listed in Table 6.47. This allowed the Netherlands and France to exceed the 80% threshold, while South Korea fell just short at around 70%.

Table 6.46: Brazil, soy (2004-2020). Major importing countries (FAOSTAT).

IMPORTER	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
China, mainland	5.23E+08	52.62	52.62	65.43
Netherlands	8.51E+07	8.57	61.18	10.65
Spain	4.34E+07	4.37	65.55	5.43
Thailand	3.96E+07	3.99	69.54	4.96
France	3.50E+07	3.53	73.07	4.39
Germany	2.76E+07	2.78	75.85	3.46
Iran (Islamic Republic of)	2.30E+07	2.32	78.17	2.88
Republic of Korea	2.23E+07	2.25	80.42	2.79

Table 6.47: Brazil, soy (2020). Major exporting companies (Trase).

EXPORTERGROUP	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
ADM	8.89E+06	14.25	14.25	17.33
CARGILL	8.57E+06	13.73	27.99	16.70
BUNGE	8.15E+06	13.06	41.05	15.88
LOUIS DREYFUS	4.88E+06	7.82	48.87	9.51
COFCO	3.38E+06	5.41	54.29	6.58
COAMO	3.37E+06	5.40	59.69	6.56
AMAGGI	3.10E+06	4.96	64.65	6.03
GAVILON	2.47E+06	3.95	68.60	4.80

EXPORTERGROUP	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
ENGELHART	2.11E+06	3.39	71.99	4.12
CHS	1.88E+06	3.02	75.01	3.67
GLENCORE	1.64E+06	2.62	77.63	3.19
OLAM	1.56E+06	2.50	80.14	3.04
BIANCHINI	6.27E+05	1.00	81.14	1.22
COOPERATIVA AGRARIA AGROINDUSTRIAL	2.56E+05	0.41	81.55	0.50
CERVEJARIA PETROPOLIS	2.41E+05	0.39	81.94	0.47
COCAMAR COOPERATIVA AGROINDUSTRIAL	1.17E+05	0.19	82.13	0.23
BIANCHINI SA INDUSTRIA	8.31E+04	0.13	82.26	0.16

According to the selected actors, 1629 municipalities were left for 2020. These were quite homogeneously distributed in the central and southern states of Brazil (Figure 6.46). Paraná was the state with the highest concentration of high yield values (red, dark red of colour ramp, within the black oval in Figure 6.46b).

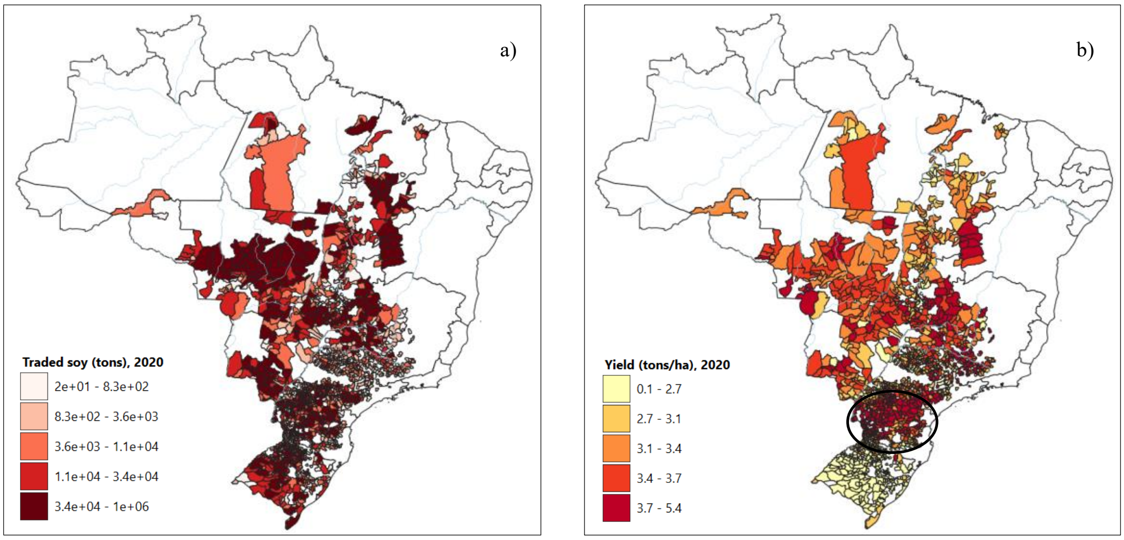


Figure 6.46: Brazil, soy (2020). Traded tonnes (a) and yield values (b) for each involved municipality.

As an example, Table 6.48 reports the first ten producing municipalities, which accounted for 15% $(7.91 * 10^6\ tons)$ of the traded soybeans $(5.13 * 10^7\ tons)$.

Table 6.48: Brazil, soy (2020). First ten producing municipalities. Exported tonnes and yield values are reported.

STATE	**MUNICIPALITY OFPRODUCTION**	**GEOCODE**	**SOY** [tons]	**YIELD** [tons/ha]
MATO GROSSO	SORRISO	BR5107925	1.01E+06	3.87
BAHIA	FORMOSA DO RIO PRETO	BR2911105	9.50E+05	3.79
MATO GROSSO	NOVA UBIRATA	BR5106240	8.57E+05	3.66
MATO GROSSO DO SUL	MARACAJU	BR5005400	8.45E+05	3.96
GOIAS	RIO VERDE	BR5218805	7.59E+05	3.60
MATO GROSSO	DIAMANTINO	BR5103502	7.54E+05	3.42
MATO GROSSO DO SUL	PONTA PORA	BR5006606	7.51E+05	3.60
BAHIA	SAO DESIDERIO	BR2928901	7.31E+05	3.80
MATO GROSSO	QUERENCIA	BR5107065	6.69E+05	3.25
MATO GROSSO	PRIMAVERA DO LESTE	BR5107040	5.80E+05	3.48

Based on *ET* data (Appendix C, Figure C.19) and yields, unit water footprint values were obtained. Observing Figure 6.47, it is immediately evident the impressive concentration of water-inefficient sites in Rio Grande do Sul. Indeed, the first municipality out of this state was found after 92 positions. The vast majority of municipalities in Rio Grande do Sul was associated with the highest range of both green and blue *uWFs* (Appendix C, Figure C.20). Their inefficiency might be caused by the low yields found in the area, additionally to the highest green *ET* values of the country (in the order of 600 mm/year). Table 6.49 shows the five less water efficient production sites, found within Rio Grande do Sul.

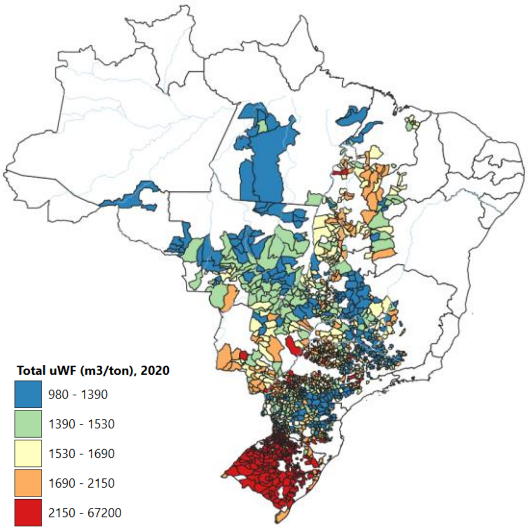


Figure 6.47: Brazil, soy (2020). Total unit water footprint values at the municipality scale.

Table 6.49: Brazil, soy (2020). Municipalities with the five highest uWF values.

STATE	**MUNICIPALITY OFPRODUCTION**	**uWF_g [m^3/ton]**	**uWF_b [m^3/ton]**	**uWF_tot [m^3/ton]**	**SOY [tons]**
RIO GRANDE DO SUL	CANDIOTA	5.68E+04	1.03E+04	6.72E+04	9.90E+02
RIO GRANDE DO SUL	MORMACO	1.34E+04	0	1.34E+04	3.28E+03
RIO GRANDE DO SUL	SANTANA DA BOA VISTA	1.17E+04	8.61E+02	1.26E+04	1.89E+04
RIO GRANDE DO SUL	MORRO REDONDO	1.01E+04	1.13E+03	1.12E+04	5.16E+02
RIO GRANDE DO SUL	ENCRUZILHADA DO SUL	1.04E+04	6.53E+02	1.10E+04	1.75E+04

On the other hand, critical virtual water volumes were concentrated not only in Rio Grande do Sul, but also in the states of Mato Grosso, Mato Grosso do Sul, Paraná, Bahia, Maranhão, Minas Gerais and Goiás. The remaining not-mentioned states had ‘red’ municipalities as well, but in a lower concentration. Figure 6.48 shows what discussed. In Appendix C, Figure C.21 shows separate green and blue water volumes.

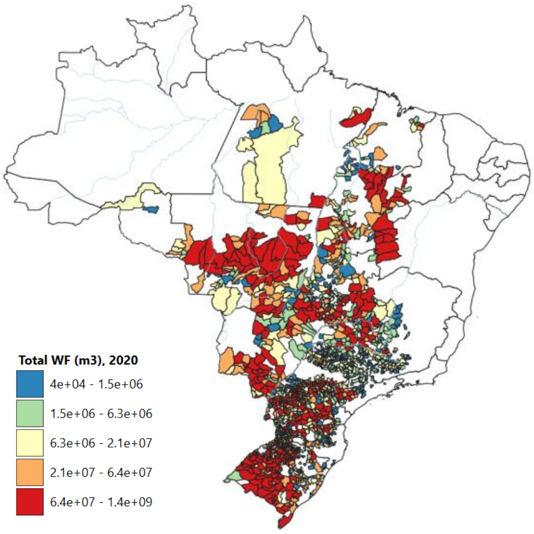


Figure 6.48: Brazil, soy (2020). Total water footprint values at the municipality scale.

Table 6.50: Brazil, soy (2020). Municipalities with the ten highest WF values.

STATE	MUNICIPALITY OFPRODUCTION	WF_G [m^3]	WF_B [m^3]	WF_tot [m^3]	SOY [tons]
BAHIA	FORMOSA DO RIO PRETO	1.21E+09	2.22E+08	1.43E+09	9.50E+05
MATO GROSSO DO SUL	MARACAJU	1.20E+09	0	1.20E+09	8.45E+05
MATO GROSSO	SORRISO	1.19E+09	0	1.19E+09	1.01E+06
MATO GROSSO DO SUL	PONTA PORA	1.19E+09	0	1.19E+09	7.51E+05
BAHIA	SAO DESIDERIO	9.37E+08	1.79E+08	1.12E+09	7.31E+05
MATO GROSSO	NOVA UBIRATA	1.08E+09	0	1.08E+09	8.57E+05
MATO GROSSO	DIAMANTINO	1.07E+09	0	1.07E+09	7.54E+05
GOIAS	RIO VERDE	1.05E+09	0	1.05E+09	7.59E+05
MATO GROSSO	QUERENCIA	9.33E+08	0	9.33E+08	6.69E+05
RIO GRANDE DO SUL	SAO GABRIEL	7.49E+08	6.35E+07	8.12E+08	1.36E+05

The ten production sites reported in Table 6.50 are meaningful to appreciate how different uWF values were if compared to water volumes. Indeed, states other than Rio Grande do Sul had municipalities with even higher recorded WFs, despite their lower uWF values. Interestingly, blue water did not contribute to the overall water demand in Mato Grosso and Mato Grosso do Sul (as appreciable from Table 6.50), Distrito Federal, and Pará. The reported ten municipalities accounted for more than 12% ($1.11 * 10^{10}\ m^3$) of the traded virtual water volume ($8.86 * 10^{10}\ m^3$).

Figure 6.49 shows importers' and traders' cumulative distribution functions and boxplots.

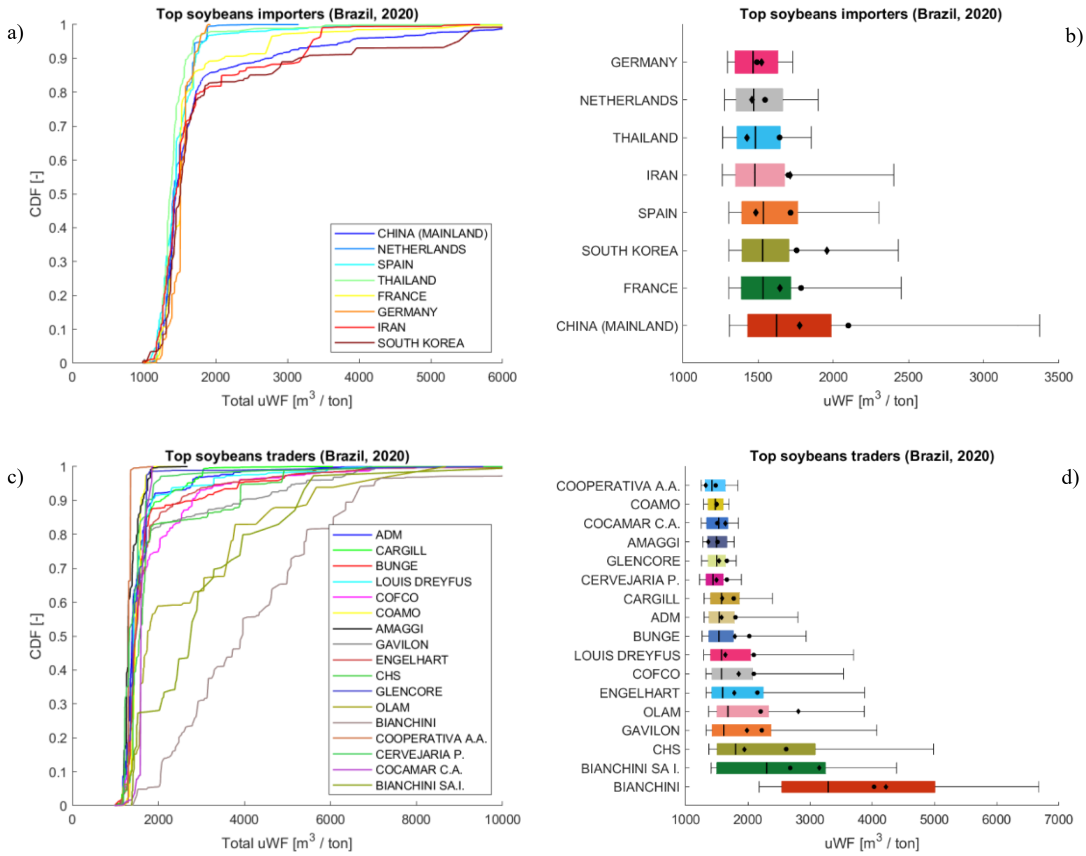


Figure 6.49: Brazil, soy (2020). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

From Figure 6.49, it is noticed that all distributions are rights skewed, with a correlation between increasing mean uWF values and increasing length of right whiskers (boxplots are indeed ranked from lowest to highest mean $uWFs$, top to bottom). Moreover, the variability between the 25th and 75th percentiles is more marked among traders than importers. From Figure 6.49c, Olam's, Bianchini SA Industria's and Bianchini's CDFs appear to be clearly separate from the others: about 40%, 70% and 95%, respectively, of the companies' supplying sites had a uWF greater than 2000 m^3/ton, whereas for the other traders this percentage ranged from 0 to 30%. Concerning importing countries, China had the highest mean uWF ($2.09 * 10^3\ m^3/ton$), in addition to the greatest dispersion. South Korea, instead, showed the greatest weighted average uWF ($1.95 * 10^3\ m^3/ton$). Regarding traders, Bianchini had the highest mean uWF ($4.03 * 10^3\ m^3/ton$) and weighted mean uWF ($4.22 * 10^3\ m^3/ton$). Its supplying sites are represented in Figure 6.50.

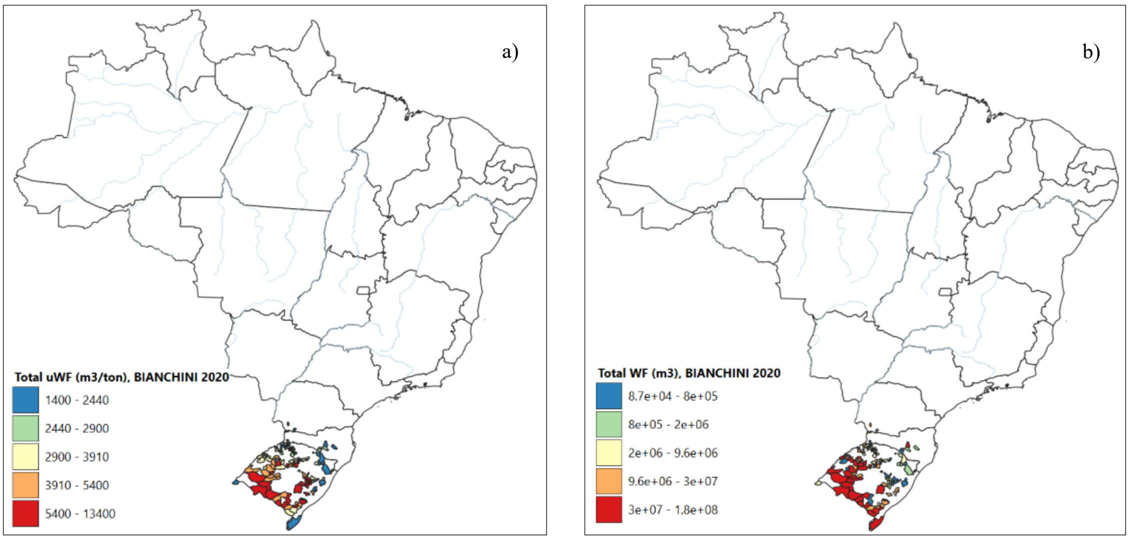


Figure 6.50: Brazil, soy (2020). Total unit water footprint (a) and total water footprint (b) values of the municipalities supplying Bianchini.

Bianchini relied on 134 production sites almost entirely located within Rio Grande do Sul. This explains its consistent *uWFs*. Figure 6.51 shows the virtual water-weighted barycentres of importers and traders. It emerges that the latter spanned over a wider range of latitude values, with Bianchini's barycentre located further south than all the others (within Rio Grande do Sul, confirming its highest weighted mean *uWF*). Barycentres and green *ET* data are shown also in Figure C.22, Appendix C.

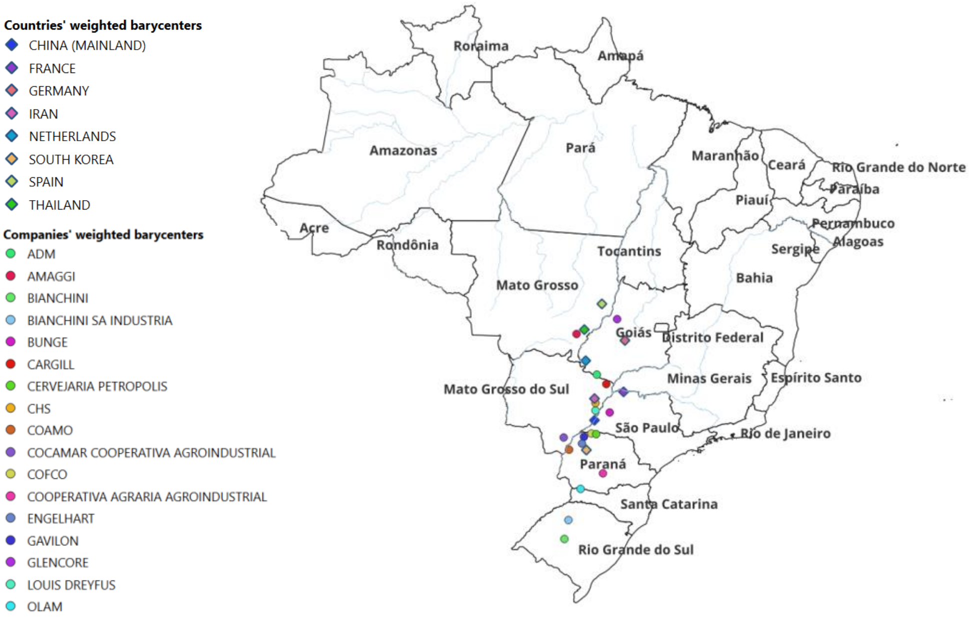


Figure 6.51: Brazil, soy (2020). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Tables 6.51 and 6.52 report percentiles, *uWFs* and weighted coordinates for five illustrative companies.

Table 6.51: Brazil, soy (2020). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Five examples.

COMPANY	PERC_10 [m^3/ton]	PERC_25 [m^3/ton]	PERC_50 [m^3/ton]	PERC_75 [m^3/ton]	PERC_90 [m^3/ton]
ADM	1295	1375	1538	1779	2804
CARGILL	1295	1400	1577	1860	2395
BUNGE	1264	1372	1534	1768	2936
LOUIS DREYFUS	1289	1400	1577	2043	3698
COFCO	1326	1420	1577	2077	3536

Table 6.52: Brazil, soy (2020). Average uWF, weighted average uWF and weighted geographical coordinates of five traders.

COMPANY	Average uWF [m^3/ton]	Weighted average uWF [m^3/ton]	Weighted LAT	Weighted LON
BIANCHINI	4028	4224	-29.5905	-54.1303
BIANCHINI SA INDUSTRIA	2680	3148	-28.3584	-53.8983
OLAM	2205	2808	-26.313	-53.081
GAVILON	2223	1989	-22.8851	-52.8678
CHS	2615	1945	-20.6818	-52.1246

6.4 Colombia – coffee

Moving to Colombia, coffee trade flows were analysed for the year 2016, as per the reason explained in Chapter 4.1.2. Specifically, the 7 major importers were considered (FAOSTAT, 2012-2016), along with the corresponding 11 top traders (Trase, 2016), as visible in Tables 6.53 and 6.54. United States and South Korea were the only two countries remaining below the 80% threshold.

Table 6.53: Colombia, coffee (2012-2016). Major importing countries (FAOSTAT).

IMPORTER	*COFFEE_EQUIVALENT _TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
United States of America	1.28E+06	42.15	42.15	51.94
Japan	3.14E+05	10.36	52.51	12.76
Germany	2.42E+05	7.98	60.48	9.83
Belgium	2.18E+05	7.20	67.68	8.88
Canada	2.15E+05	7.09	74.77	8.74
United Kingdom of Great Britain and Northern Ireland	9.92E+04	3.27	78.04	4.03
Republic of Korea	9.41E+04	3.10	81.14	3.82

Table 6.54: Colombia, coffee (2016). Major exporting companies (Trase).

EXPORTERGROUP	*COFFEE_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
FEDERACION NACIONALDE CAFETEROS DE COLOMBIA	1.48E+05	24.24	24.24	29.74
CARCAFE LTD	5.53E+04	9.06	33.31	11.12
RACAFE Y CIA S C A	4.81E+04	7.88	41.19	9.67
LOUIS DREYFUS	4.54E+04	7.44	48.63	9.12
SOCIEDAD EXPORTADORA DE CAFE DE LAS COOPERATIVAS D	4.35E+04	7.13	55.75	8.74
CIA CAFETERA LA MESETA S A	3.73E+04	6.10	61.86	7.49
CIA COL AGROINDL S A S	2.83E+04	4.64	66.49	5.69
OLAM	2.46E+04	4.03	70.52	4.94
ENGELHART CTP COLOMBIA S A S	2.42E+04	3.96	74.48	4.85
SKN CARIBECAFE LTD	2.18E+04	3.57	78.05	4.38
COFCO	2.11E+04	3.46	81.51	4.25

The analysis was performed at the department scale (1st administrative level, a), as information on production sites is based on it. Figure 6.52b also shows provinces (2nd level, b) since Trase gives export details based on them.

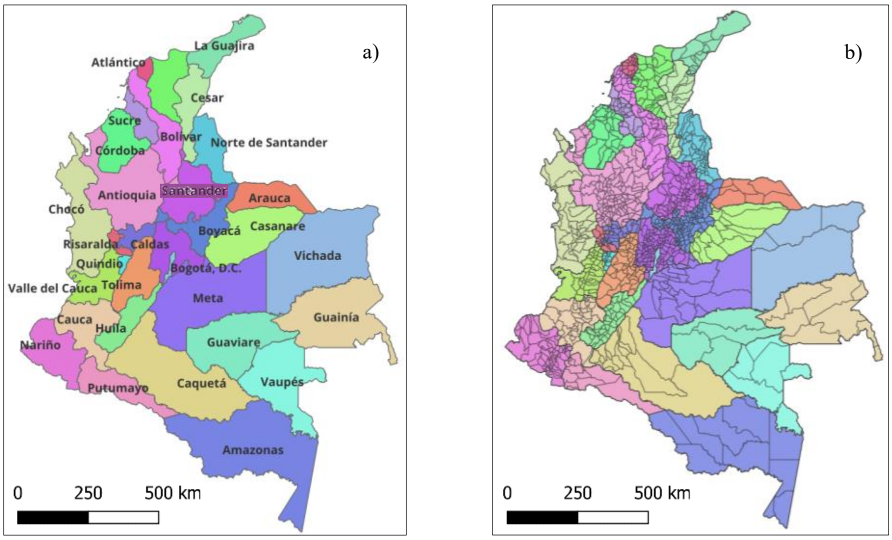


Figure 6.52: Geographic framework of Colombia. Departments (a) and provinces (b).

According to Tables 6.53 and 6.54, Trase dataset was skimmed, resulting in 18 sourcing departments (Figure 6.53). Interestingly, the higher production levels were not necessarily recorded in the most productive departments (see Caquetá and Meta, for instance). A possible explanation could be related to the scale of the analysis: the aforementioned departments, while extending inland, face different climatic conditions, ranging from Oceanic to Monsoon or Rainforest (Appendix C, Figure C.27) (Beck *et al.*, 2020). Therefore, it is not surprising that regions with high yields were not actually associated with high production values: within some of them, coffee-growing areas were very limited.

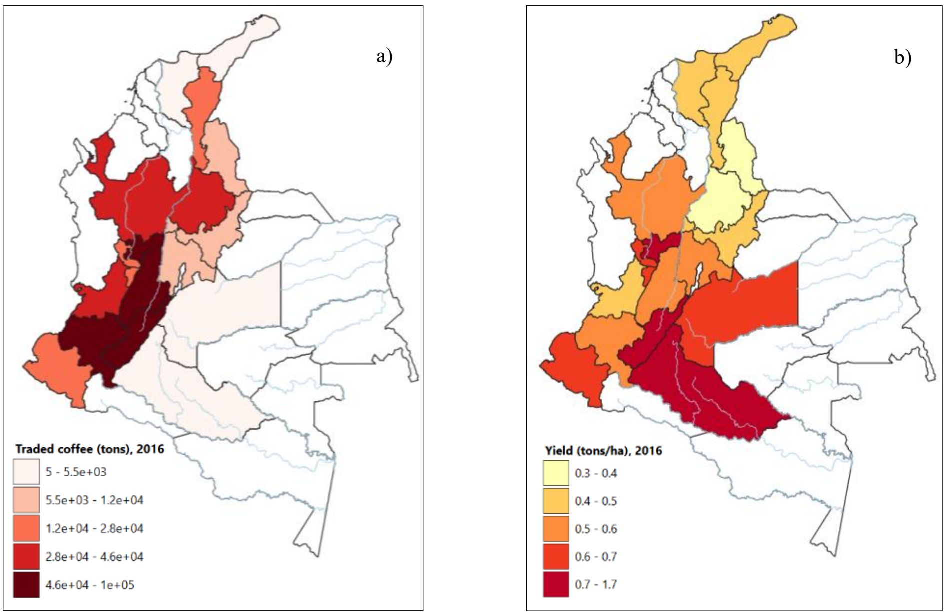


Figure 6.53: Colombia, coffee (2016). Traded tonnes (a) and yield values (b) for each involved department.

The following Table 6.55 shows the first four producing departments, accounting for 56% $(2.78 * 10^5\ tons)$ of traded coffee $(4.97 * 10^5\ tons)$. In particular, coffee supplied by Huila covered 21% of demand. This department had one of the highest yields in 2016 $(0.76\ tons/ha)$, second only to Caquetá $(1.63\ tons/ha)$. However, when considering the produced tonnes, Caquetá appeared second to last, as for the reason explained above (climatic conditions).

Table 6.55: Colombia, coffee (2016). First four producing departments. Exported tonnes and yield values are reported.

DEPARTMENT	**GEOCODE**	**COFFEE [tons]**	**YIELD [tons/ha]**
HUILA	CO41	1.06E+05	0.76
TOLIMA	CO73	7.72E+04	0.55
CALDAS	CO17	4.77E+04	0.75
CAUCA	CO19	4.70E+04	0.51

Concerning unit water footprint values (Figure 6.54), it emerges that moving northward, departments tended to be less water efficient. The regions coloured in red were indeed characterised by the highest range of green uWF values $(21 - 26 * 10^3\ m^3/ton)$. In addition, blue ET data (Appendix C, Figure C.24) were recorded for Cesar and La Guajira (north of Colombia). Table 6.56 shows data for the red-coloured departments.

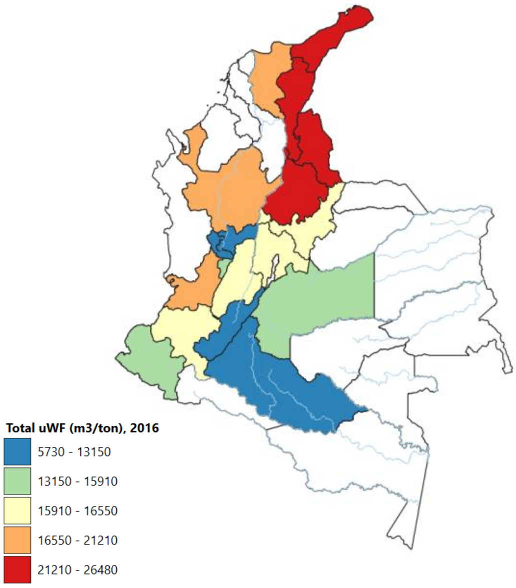


Figure 6.54: Colombia, coffee (2016). Total unit water footprint values at the department scale.

Table 6.56: Colombia, coffee (2016). Departments with the four highest uWF values.

DEPARTMENT	uWF_g [m^3/ton]	uWF_b [m^3/ton]	uWF_tot [m^3/ton]	COFFEE [tons]
NORTE DE SANTANDER	2.65E+04	0	2.65E+04	6.93E+03
SANTANDER	2.62E+04	0	2.62E+04	2.82E+04
CESAR	2.37E+04	7.54E+00	2.37E+04	1.79E+04
LA GUAJIRA	2.11E+04	1.74E+02	2.12E+04	2.57E+03

Virtual water volumes were evaluated, as reported in Figure 6.55. Once more, the importance of considering the produced tonnes of the selected commodity is clear: the highest water requirements do not necessarily coincide with the worst unitary values. For instance, according to the colour ramps of Figure 6.54 and Figure 6.55, Huila was classified in the lowest range for its total *uWF* while accounting for the second-largest virtual water volume (Table 6.57, 15% of total share). It is also evident that blue water did not contribute to the overall traded water volume in most of the considered departments (Appendix C, Figure C.25).

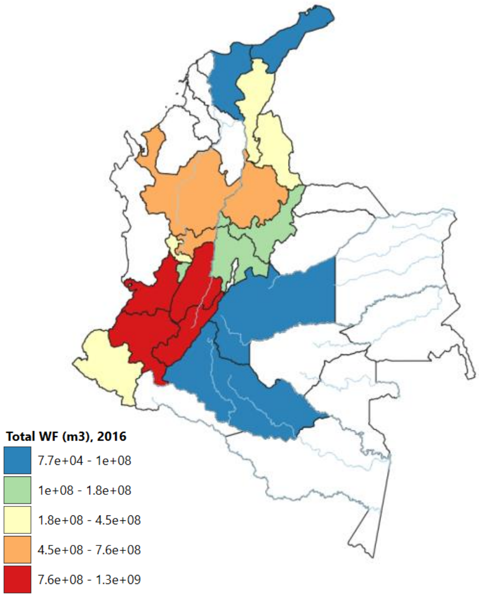
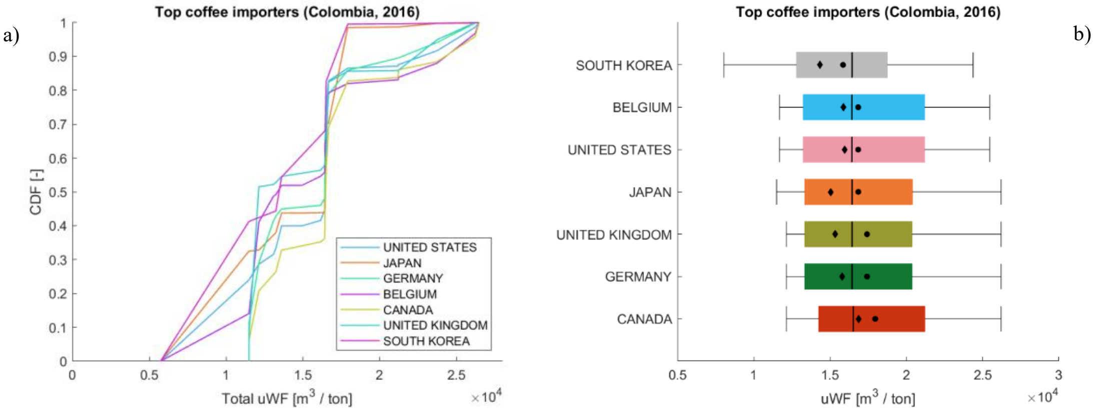


Figure 6.55: Colombia, coffee (2016). Total water footprint values at the department scale.

Table 6.57: Colombia, coffee (2016). Departments with the four highest WF values.

DEPARTMENT	**WF_G [m^3]**	**WF_B [m^3]**	**WF_tot [m^3]**	**COFFEE [tons]**
TOLIMA	1.27E+09	0	1.27E+09	7.72E+04
HUILA	1.22E+09	0	1.22E+09	1.06E+05
VALLE DEL CAUCA	7.95E+08	0	7.95E+08	4.43E+04
CAUCA	7.77E+08	0	7.77E+08	4.70E+04

The following step was to investigate on importers and traders statistics (Figure 6.56).



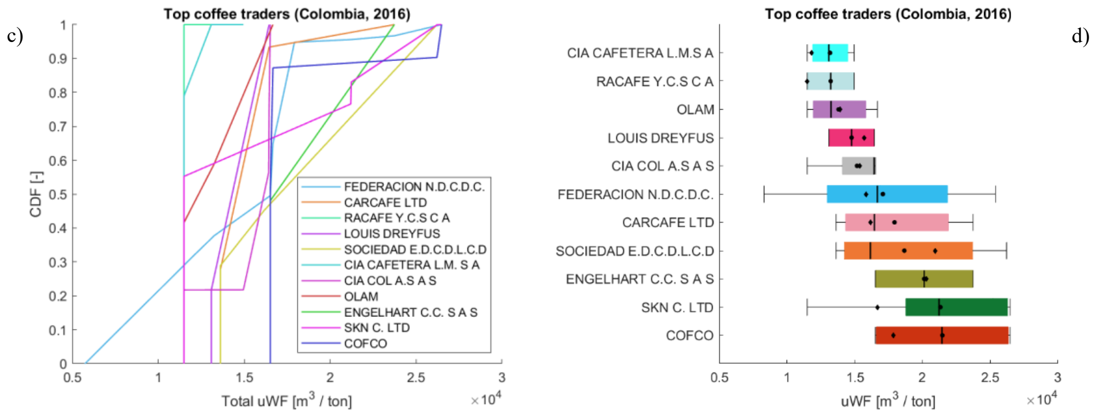


Figure 6.56: Colombia, coffee (2016). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

Observing the plots in Figure 6.56, it is noticed that importing countries had a similar range of variability in the associated $uWFs$, with mean values ranging from $1.58 * 10^4\ m^3/ton$ (South Korea) to $1.79 * 10^4\ m^3/ton$ (Canada), whereas weighted mean values from $1.43 * 10^4\ m^3/ton$ (South Korea) to $1.68 * 10^4\ m^3/ton$ (Canada). All distributions are right skewed. On the other hand, trading companies report visible differences (observe their boxplot's whiskers). Considering $uWFs$, mean values ranged from $1.32 * 10^4\ m^3/ton$ (Cia Cafereta La Meseta S A) to $2.15 * 10^4\ m^3/ton$ (Cofco), and weighted mean ones from $1.15 * 10^4\ m^3/ton$ (Racafe Y Cia S C A) to $2.1 * 10^4\ m^3/ton$ (Sociedad Exportadora de Café de las Cooperativas D). COFCO supplying departments are reported in Figure 6.57.

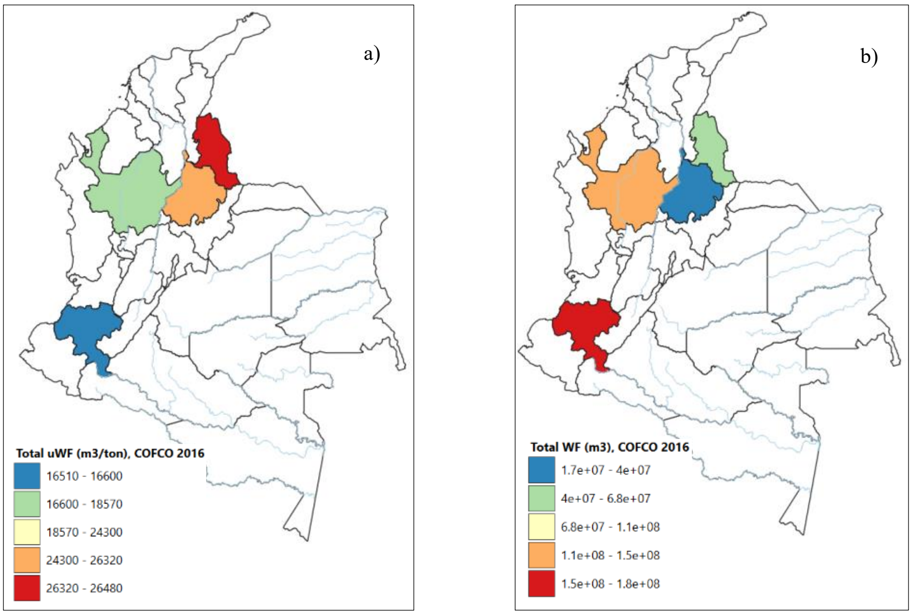


Figure 6.57: Colombia, coffee (2016). Total unit water footprint (a) and total water footprint (b) values of the departments supplying COFCO.

Even though three out of four COFCO supplying departments were among the most water consumptive ones (Figure 6.54), leading to its highest mean uWF, considering water volumes COFCO's pressure decreased (3rd position). This is explained by the company's major dependence on Cauca. In Figure 6.58, virtual water-weighted barycentres of companies and importing countries are shown. The range of variability of latitude values was slightly wider for traders than for importers. See Figure C.26 in Appendix C for their placement with respect to green *ET* data.

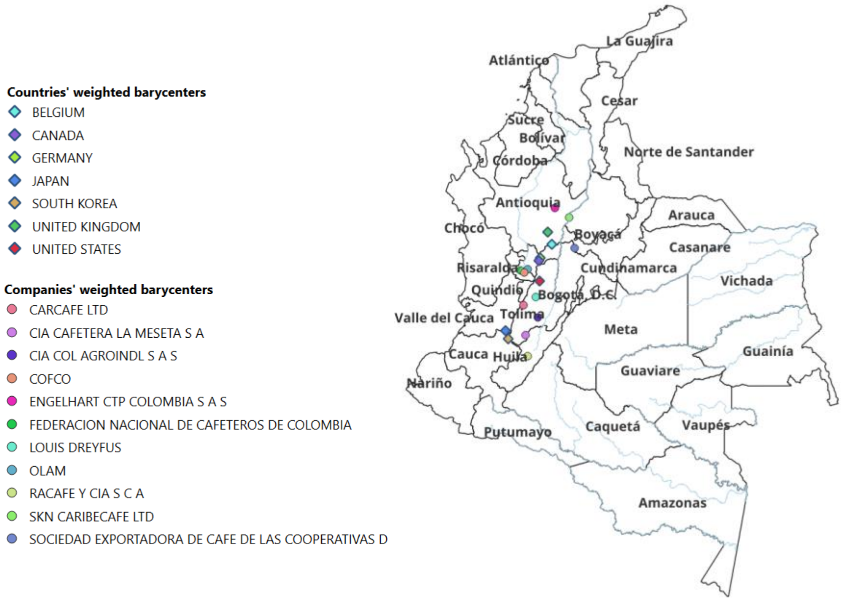


Figure 6.58: Colombia, coffee (2016). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Statistics and weighted coordinates are summarised in Tables 6.58 and 6.59 for four representative companies.

Table 6.58: Colombia, coffee (2016). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Four examples.

COMPANY	PERC_10 [m^3/ton]	PERC_25 [m^3/ton]	PERC_50 [m^3/ton]	PERC_75 [m^3/ton]	PERC_90 [m^3/ton]
FEDERACION NACIONAL DE CAFETEROS DE COLOMBIA	8299	12970	16670	21854	25382
CARCAFE LTD	13616	14324	16449	21916	23738
RACAFE Y CIA S C A	11496	11496	13224	14953	14953
LOUIS DREYFUS	13086	13086	14767	16449	16449

Table 6.59: Colombia, coffee (2016). Average uWF, weighted average uWF and weighted geographical coordinates of four traders.

COMPANY	Average uWF [m^3/ton]	Weighted average uWF [m^3/ton]	Weighted LAT	Weighted LON
SOCIEDAD EXPORTADORA DE CAFE DE LAS COOPERATIVAS D	18662	20934	5.615306	-74.2624
ENGELHART CTP COLOMBIA S A S	20129	20268	6.739525	-74.8133
COFCO	21470	17836	4.920074	-75.6864
SKN CARIBECAFE LTD	21322	16691	6.484089	-74.4071

Lastly, the virtual water volumes traded by each company were analysed. As an example, Table 6.60 reports the countries relying on COFCO. Green and blue water volumes are not included, as blue water did not contribute to any of the two importing countries. Notably, 67% of COFCO's virtual water trade was directed to the United States.

Table 6.60: Colombia, coffee (2016). Relationships between the trader COFCO and the countries relying on it.

COUNTRYOFFIRSTIMPORT	**w_mean_uWF_tot [m³/ton]**	**WF_tot [m³]**
UNITED STATES	1.81E+04	2.55E+08
CANADA	1.75E+04	5.74E+07
JAPAN	1.68E+04	3.79E+07
SOUTH KOREA	1.65E+04	1.24E+07
GERMANY	1.84E+04	9.24E+06
BELGIUM	1.88E+04	5.46E+06

6.5 Ivory Coast – cocoa

In Ivory Coast, cocoa trade flows were analysed. The actors considered were the 9 major importing countries (FAOSTAT, 2016-2019) and the corresponding 11 top traders (Trase, 2019) for the year 2019. Percentages are reported in Tables 6.61 and 6.62. The three companies written in dark brown (Table 6.62) were added to cover at least 80% of the trade towards Germany, France, Malaysia and Turkey.

Table 6.61: Ivory Coast, cocoa (2016-2019). Major importing countries (FAOSTAT).

IMPORTER	*COCOA_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Netherlands	1.89E+06	26.14	26.14	31.41
United States of America	1.11E+06	15.37	41.51	18.47
Belgium	6.83E+05	9.46	50.97	11.37
Germany	6.13E+05	8.50	59.47	10.21
France	4.58E+05	6.35	65.82	7.63
Malaysia	4.29E+05	5.94	71.76	7.14
United Kingdom of Great Britain and Northern Ireland	3.35E+05	4.64	76.39	5.57
Türkiye	2.56E+05	3.54	79.94	4.26
Estonia	2.37E+05	3.28	83.22	3.94

Table 6.62: Ivory Coast, cocoa (2019). Major exporting companies (Trase).

EXPORTERGROUP	*COCOA_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
OLAM	1.42E+05	19.99	19.99	22.85
BARRY CALLEBAUT	1.38E+05	19.40	39.39	22.17
CARGILL	1.37E+05	19.29	58.69	22.05
ECOM	4.20E+04	5.89	64.58	6.73
TOUTON	3.40E+04	4.78	69.36	5.46
ECOOKIM	3.31E+04	4.64	74.00	5.30
CNEK	3.24E+04	4.56	78.56	5.21
SACC	2.78E+04	3.90	82.46	4.46
CEMOI	1.69E+04	2.38	84.84	2.72
ECPAD	1.23E+04	1.73	86.57	1.98
SCOOPS SOCODD	6.70E+03	0.94	87.51	1.07

The analysis was performed at the department scale (3rd administrative level, b). Thus, Figure 6.59 reports Ivory Coast departments, along with districts' names (1st level, a).

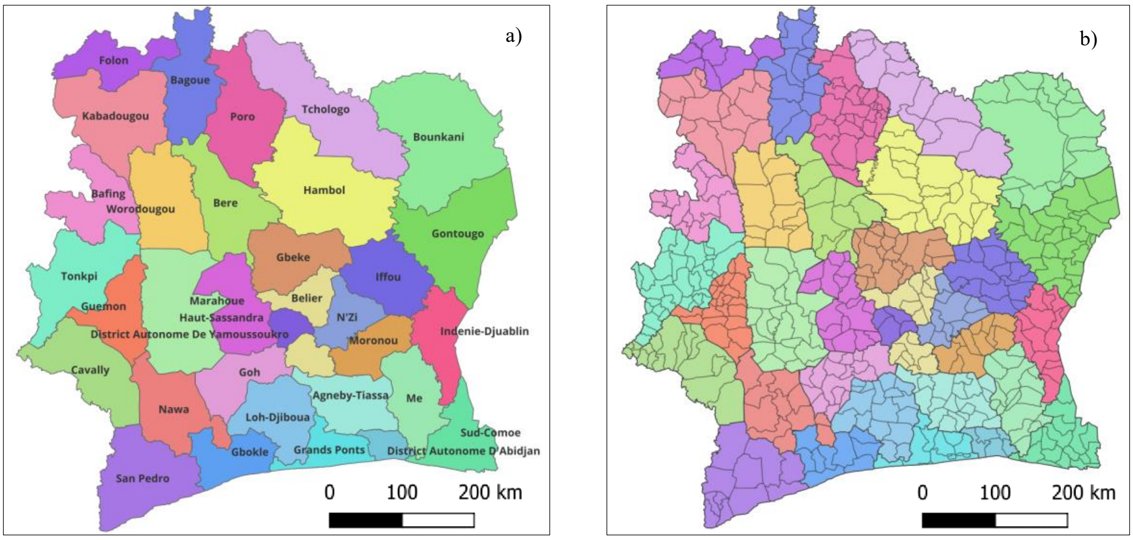


Figure 6.59: Geographic framework of Ivory Coast. Districts (a) and departments (b).

According to the names in Tables 6.61 and 6.62, 55 sourcing departments were left (Figure 6.60). They were quite homogenously widespread in the southern half of the country. Higher yield values were more concentrated in the southeastern corner of Ivory Coast; however, highly productive departments were heterogeneously displaced.

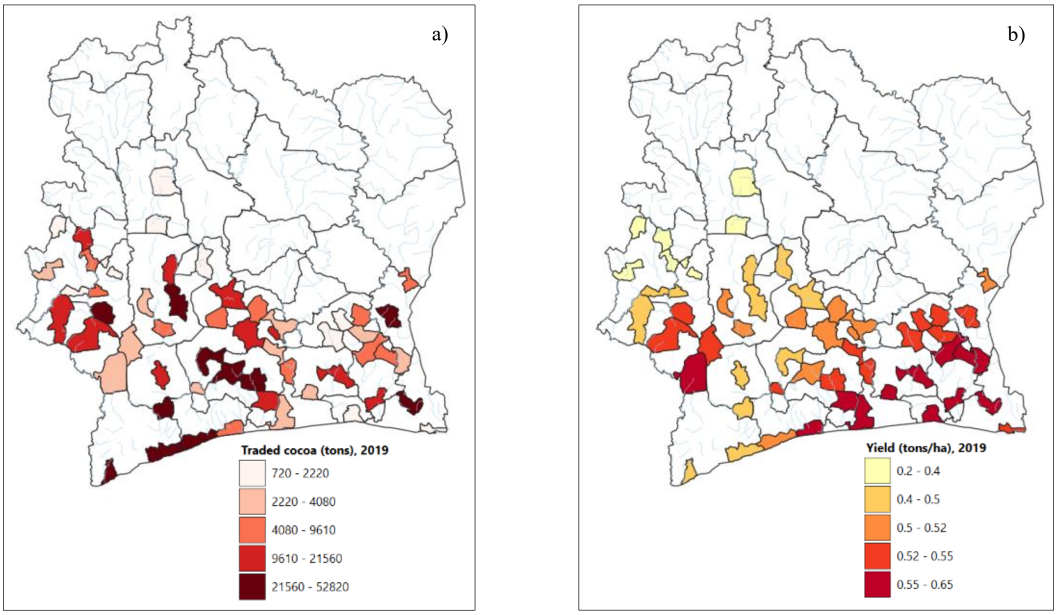


Figure 6.60: Ivory Coast, 2019. Traded tonnes (a) and yield values (b) for each involved department.

As an example, Table 6.63 illustrates the first five producing departments: they supplied 32% $(2 * 10^5\ tons)$ of traded cocoa $(6.23 * 10^5\ tons)$.

Table 6.63: Ivory Coast, 2019. First five producing departments. Exported tonnes and yield values are reported.

DISTRICT	DEPARTMENTOFPRODUCTION	GEOCODE	COCOA [tons]	YIELD [tons/ha]
SAN PEDRO	SAN-PEDRO	CI290101	5.28E+04	0.49
SUD-COMOE	ABOISSO	CI300101	4.15E+04	0.59
HAUT-SASSANDRA	DALOA	CI180102	4.12E+04	0.50
GOH	GAGNOA	CI130106	3.31E+04	0.46
GUEMON	DUEKOUE	CI160202	3.13E+04	0.53

Evapotranspiration data (Appendix C, Figure C.28) were utilised to compute the unit water footprint of each department. Notably, blue *ET* was not provided for any production site. Therefore, water demand was related to green water only. From Figure 6.61, it emerges that the less water efficient sites were located far from the coast, except for Tabou (southwestern corner, San Pedro district). Table 6.64 reports the five departments with highest *uWFs*.

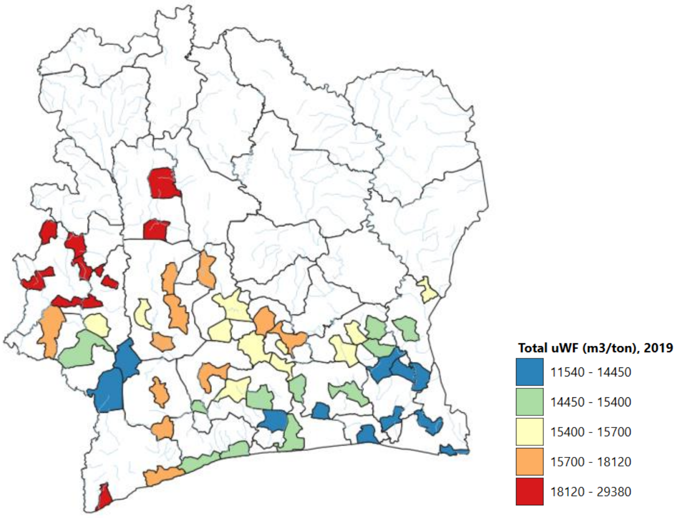


Figure 6.61: Ivory Coast, cocoa (2019). Total unit water footprint values at the department scale.

Table 6.64: Ivory Coast, cocoa (2019). Departments with the five highest uWF values.

DISTRICT	DEPARTMENTOFPRODUCTION	uWF_tot [m^3/ton]	COCOA [tons]
TONKPI	SIPILOU	2.94E+04	1.62E+03
TONKPI	BIANKOUMA	2.73E+04	1.17E+04
TONKPI	MAN	2.29E+04	9.15E+03
GUEMON	FACOBLY	2.23E+04	1.24E+03
GUEMON	KOUIBLY	2.17E+04	1.62E+03

Considering virtual water volumes, red-coloured production sites distribution changed (Figure 6.62). Specifically, Table 6.65 allows to notice that the five highest water requirements were recorded in the same departments presented in Table 6.63. San-Pedro holds the first position in both circumstances, accounting for 8.5% of traded water volume.

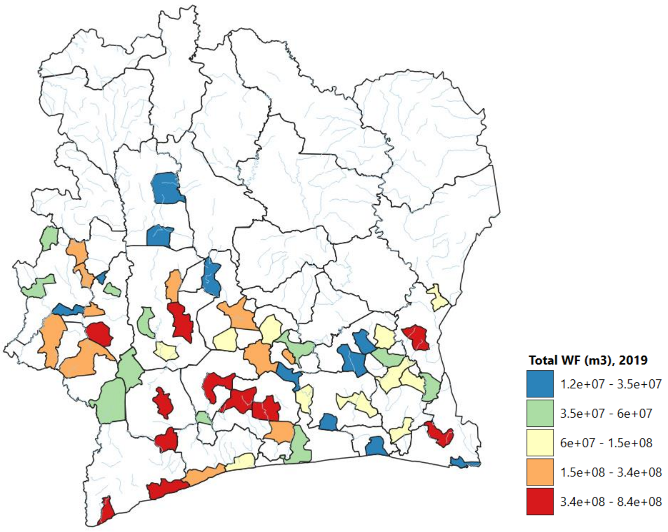
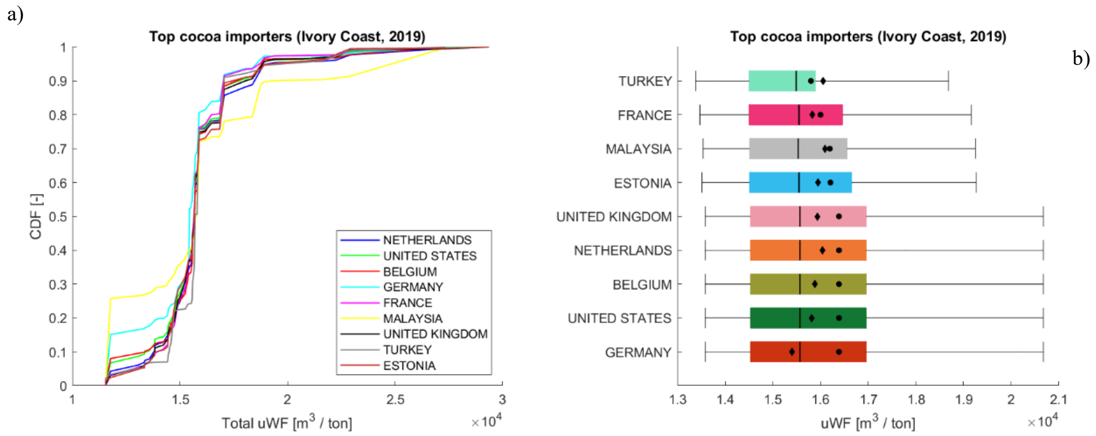


Figure 6.62: Ivory Coast, cocoa (2019). Total water footprint values at the department scale.

Table 6.65: Ivory Coast, cocoa (2019). Departments with the five highest WF values.

DISTRICT	DEPARTMENTOFPRODUCTION	WF_tot [m^3]	COCOA [tons]
SAN PEDRO	SAN-PEDRO	8.39E+08	5.28E+04
HAUT-SASSANDRA	DALOA	6.52E+08	4.12E+04
GOH	GAGNOA	5.63E+08	3.31E+04
SUD-COMOE	ABOISSO	4.89E+08	4.15E+04
GUEMON	DUEKOUE	4.88E+08	3.13E+04

Importers’ and traders’ statistics are represented in Figure 6.63.



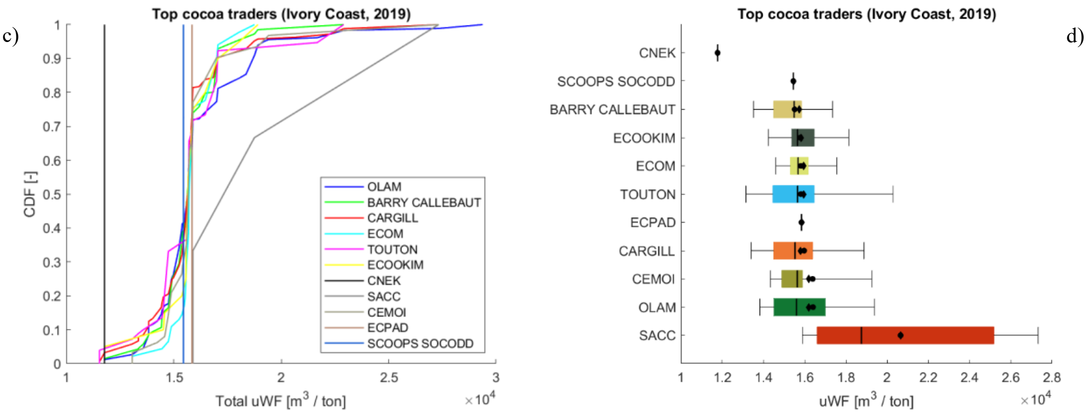


Figure 6.63: Ivory Coast, cocoa (2019). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

Similarly to the cases presented previously, cocoa importing countries from Ivory Coast were supplied by municipalities with similar uWF values. The percentiles shown in the boxplots representation are indeed very close to each other, especially for what concerns the 10th, 25th and 50th. Distributions are right skewed. Major differences are found in average and weighted average $uWFs$. Interestingly, Germany had the highest mean value $(1.64 * 10^4\ m^3/ton)$, but lowest weighted one $(1.54 * 10^4\ m^3/ton)$. Conversely, Turkey showed the lowest mean uWF $(1.58 * 10^4\ m^3/ton)$, along with the second highest weighted mean value $(1.6 * 10^4\ m^3/ton)$. On the other hand, traders distributions are considerably diversified. Even though they are all right skewed, whiskers lengths, asymmetry magnitude, mean and weighted mean $uWFs$ varied a lot. From Figure 6.63d, it is visible that Cnek, Scoops Socodd and Ecpad sourced from a single department each (Aboisso, Djekanou, and Daloa respectively), whereas Sacc's $uWFs$ were coincident and the highest among all traders $(2.06 * 10^4\ m^3/ton)$. Cargill, Olam and Barry Callebaut were supplied by more than 40 departments each, showing $uWFs$ much lower than Sacc's ones, which relied on three production sites only. Figure 6.64 details Olam's 46 supplying departments.

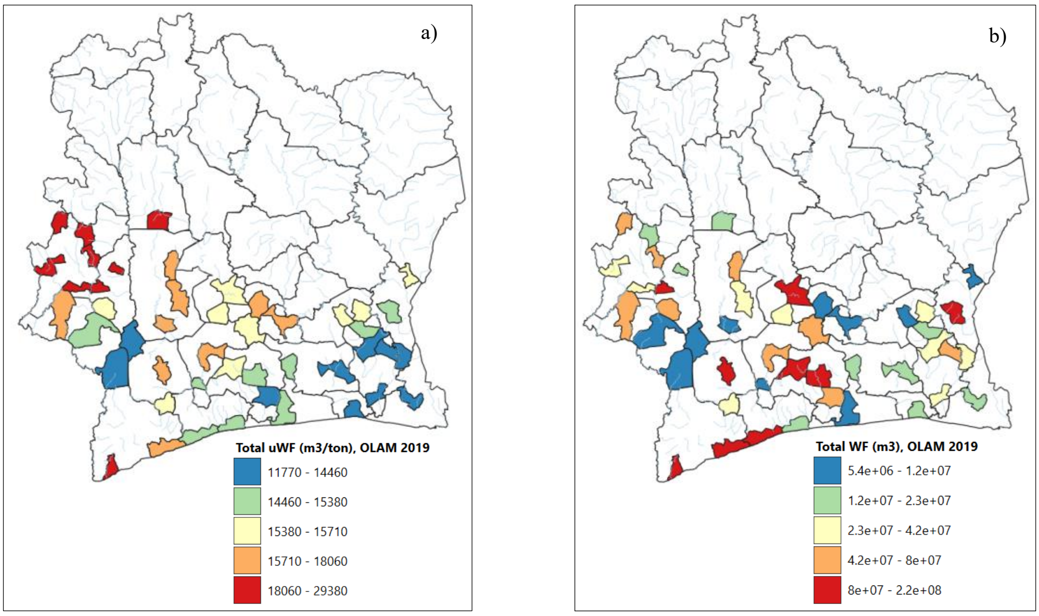


Figure 6.64: Ivory Coast, cocoa (2019). Total unit water footprint (a) and total water footprint (b) values of the departments supplying Olam.

Virtual water-weighted barycentres were represented for companies and importing countries, as shown in Figure 6.65. Almost all of them fell within Goh district. The clearest exceptions were Sacc, in Cavally, and Cnek, Scoops Socodd and Ecpad found in the district of their only supplying department. Figure C.29 in Appendix C shows barycentres and green *ET* data.

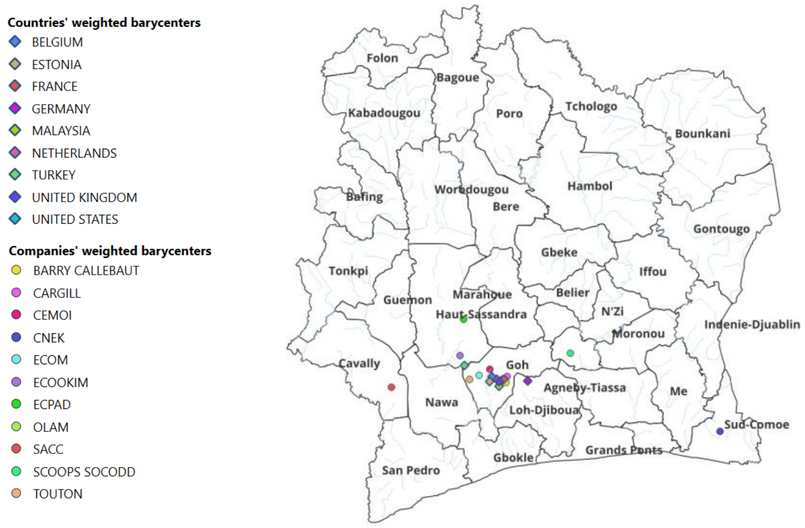


Figure 6.65: Ivory Coast, cocoa (2019). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Percentiles, unit water footprints and weighted coordinates are shown in Tables 6.66 and 6.67 for four representative companies.

Table 6.66: Ivory Coast, cocoa (2019). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Four examples.

COMPANY	PERC_10 [m^3/ton]	PERC_25 [m^3/ton]	PERC_50 [m^3/ton]	PERC_75 [m^3/ton]	PERC_90 [m^3/ton]
OLAM	13831	14518	15607	16997	19389
BARRY CALLEBAUT	13515	14500	15492	15849	17356
CARGILL	13403	14505	15532	16392	18884
ECOM	14604	15312	15681	16178	17557

Table 6.67: Ivory Coast, cocoa (2019). Average uWF, weighted average uWF and weighted geographical coordinates of four traders.

COMPANY	Average uWF [m^3/ton]	Weighted average uWF [m^3/ton]	Weighted LAT	Weighted LON
SACC	20658	20658	6.02676	-7.28778
OLAM	16406	16196	6.069088	-5.96087
CEMOI	16390	16196	6.253971	-6.07318
ECOM	15814	15949	6.177688	-6.20755

To conclude, dependencies established between traders and importing countries were examined. Table 6.68 describes what was found for Olam.

Table 6.68: Ivory Coast, cocoa (2019). Relationships between the trader Olam and the countries relying on it.

COUNTRYOFFIRSTIMPORT	w_mean_uWF_tot [m^3/ton]	WF_tot [m^3]
NETHERLANDS	1.62E+04	1.27E+09
UNITED STATES	1.62E+04	4.24E+08
UNITED KINGDOM	1.62E+04	3.02E+08
MALAYSIA	1.62E+04	1.34E+08
ESTONIA	1.62E+04	9.79E+07
BELGIUM	1.62E+04	7.69E+07
GERMANY	1.62E+04	5.90E+06

6.6 Paraguay

Paraguay was analysed twice, considering corn and soybean cultivations. Results are discussed in dedicated sections. The administrative divisions of Paraguay are reported only once, in Figure 6.66. The investigation was performed at the department level (1st administrative level, Figure 6.66a), but as Trase gives the names of the districts (2nd level) of export, these are also reported (Figure 6.66b).

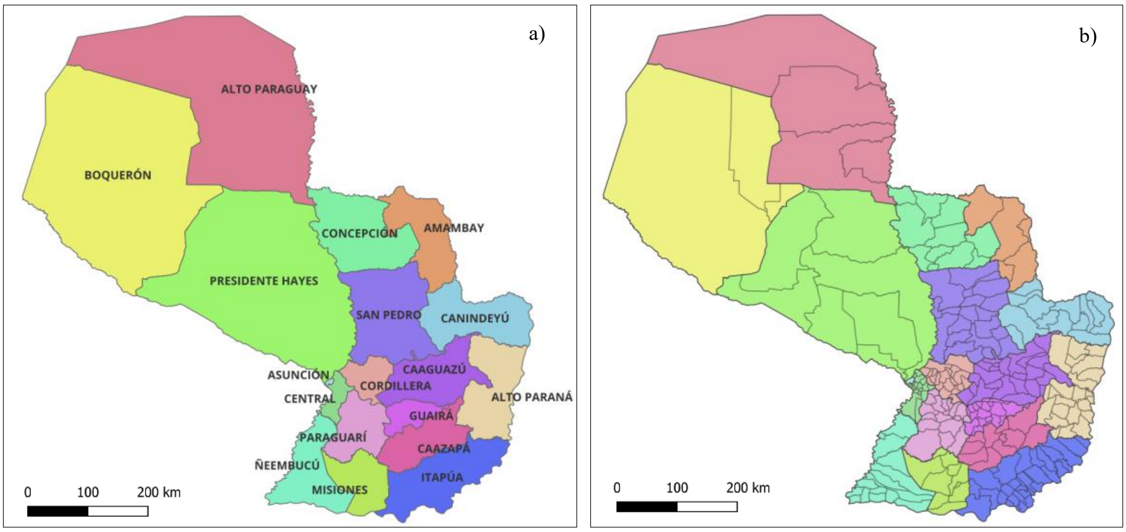


Figure 6.66: Geographic framework of Paraguay. Departments (a) and districts (b).

6.6.1 Corn

Corn trade flows were examined for the year 2019. Data accounted for four of the five major importing countries (FAOSTAT, 2014-2019) since Morocco did not rely on Paraguay corn in the selected year. Furthermore, the corresponding top traders were 18 (Trase, 2019). Tables 6.69 and 6.70 show percentages. The last two companies (Table 6.70) were added to enhance Uruguay coverage. However, trades involving Uruguay and Brazil were only described up to 75%.

Table 6.69: Paraguay, corn (2014-2019). Major importing countries.

IMPORTER	*CORN_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Brazil	5.66E+06	39.93	39.93	49.89
Chile	2.69E+06	18.98	58.91	23.71
Uruguay	1.30E+06	9.18	68.09	11.48
Republic of Korea	1.28E+06	8.99	77.09	11.24
Morocco	4.19E+05	2.95	80.04	3.69

Table 6.70: Paraguay, corn (2019). Major exporting companies.

EXPORTERGROUP	*CORN_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
AGROFERTIL SA	4.45E+05	16.17	16.17	19.55
CARGILL	3.75E+05	13.63	29.81	16.48
ADM	3.09E+05	11.22	41.03	13.56
LAR	2.71E+05	9.84	50.86	11.89
AMAGGI	1.05E+05	3.81	54.67	4.61
LOUIS DREYFUS	1.05E+05	3.80	58.48	4.60
INPASA DEL PARAGUAY	9.77E+04	3.55	62.02	4.29
INVERSIONES AGRICOLA	9.03E+04	3.28	65.30	3.96
COFCO	7.42E+04	2.69	68.00	3.26
CHS	6.97E+04	2.53	70.53	3.06
UNEXPA	6.93E+04	2.52	73.05	3.04
COOPERATIVA SANTA MARIA (COOPASAM)	5.75E+04	2.09	75.14	2.52
OVETRIL	5.20E+04	1.89	77.03	2.28
SOMAX AGRO	3.67E+04	1.33	78.36	1.61
ASEPSA TRADING	3.52E+04	1.28	79.64	1.55
KIMEX	3.30E+04	1.20	80.84	1.45
SURAGRO	3.30E+04	1.20	82.04	1.45
OLEAGINOSA RAATZ	1.88E+04	0.68	82.72	0.82

Accordingly to major importers and traders, Trase dataset was skimmed. It emerged that 11 out of 17 departments supplied corn in 2019. Notably, corn production involved only the south-southeastern side of the country, due to the favourable climatic and hydrologic conditions (Figure 6.67). Indeed, the most productive area of Paraguay falls within the Paraná-Paraguay River basin, as explained in Chapter 5.6.

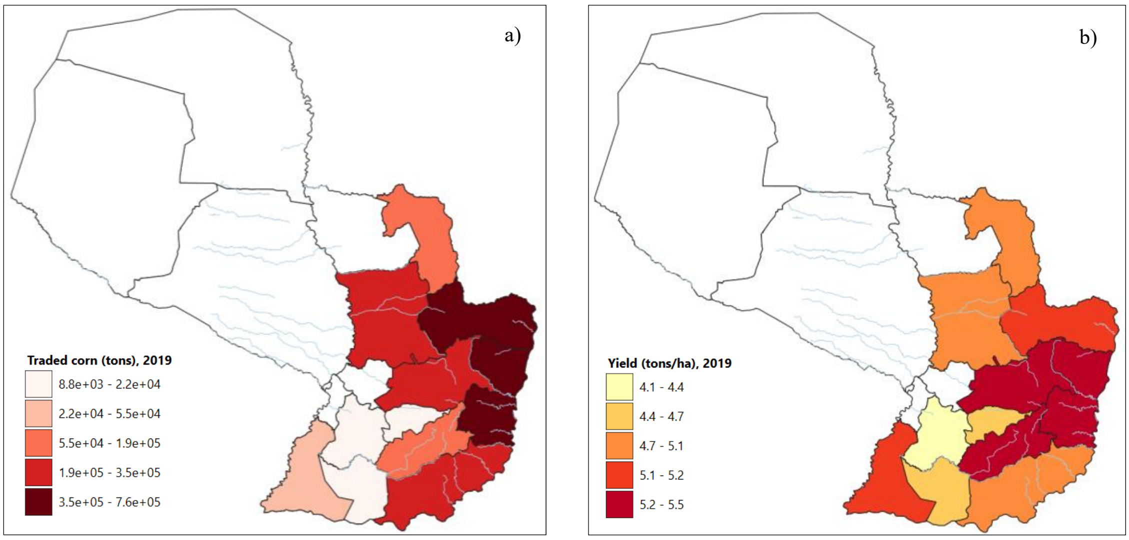


Figure 6.67: Paraguay, corn (2019). Traded tonnes (a) and yield values (b) for each involved department.

The three major producing areas are reported in Table 6.71. They covered 70% ($1.61 * 10^6\ tons$) of traded corn ($2.28 * 10^6\ tons$).

Table 6.71: Paraguay, corn (2019). First three producing departments. Exported tonnes and yield values are reported.

DEPARTMENTOFPRODUCTION	**GEOCODE**	**CORN [tons]**	**YIELD [tons/ha]**
ALTO PARANA	PY10	7.60E+05	5.44
CANINDEYU	PY14	4.93E+05	5.10
CAAGUAZU	PY05	3.54E+05	5.30

For what concerns available *ET* data (Appendix C, Figure C.30), only green water contributed to unit water footprints, which are illustrated in Figure 6.68. The three highest *uWF* values are reported in Table 6.72.

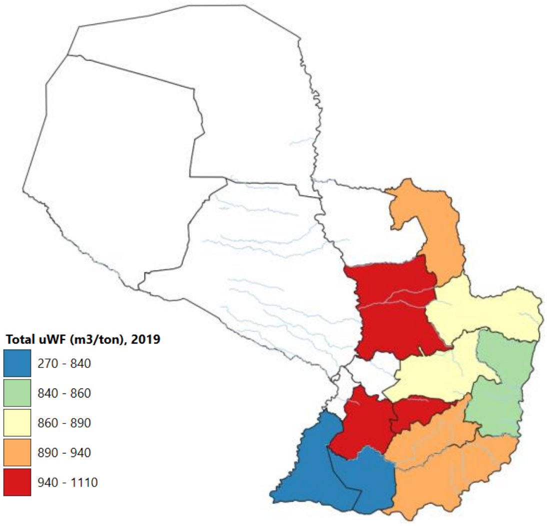


Figure 6.68: Paraguay, corn (2019). Total unit water footprint values at the department scale.

Table 6.72: Paraguay, corn (2019). Departments with the three highest uWF values.

DEPARTMENTOFPRODUCTION	uWF_tot [m^3/ton]	CORN [tons]
GUAIRA	1.10E+03	2.25E+04
PARAGUARI	9.60E+02	8.88E+03
SAN PEDRO	9.44E+02	2.65E+05

Virtual water volumes were computed and they are illustrated in Figure 6.69. As expected, the highest water requirements were found where production was higher, as confirmed by Table 6.73. The three reported departments accounted for 69% ($1.37 * 10^9\ m^3$) of the traded virtual water volume ($1.97 * 10^9\ m^3$).

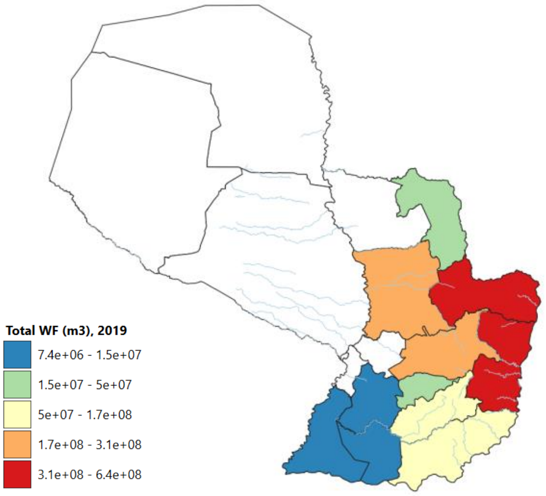
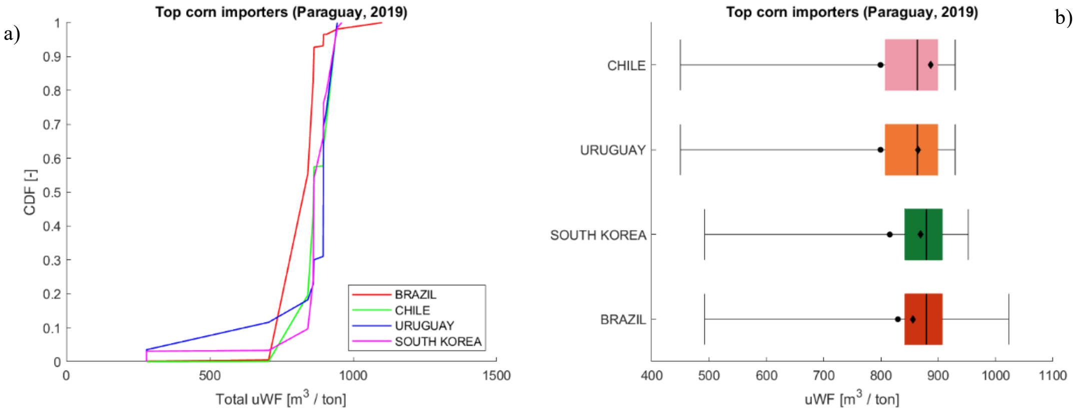


Figure 6.69: Paraguay, corn (2019). Total water footprint values at the department scale.

Table 6.73: Paraguay, corn (2019). Departments with the three highest WF values.

DEPARTMENTOFPRODUCTION	WF_tot [m^3]	CORN [tons]
ALTO PARANA	6.39E+08	7.60E+05
CANINDEYU	4.24E+08	4.93E+05
CAAGUAZU	3.06E+08	3.54E+05

Cumulative distribution functions and boxplots are shown in Figure 6.70.



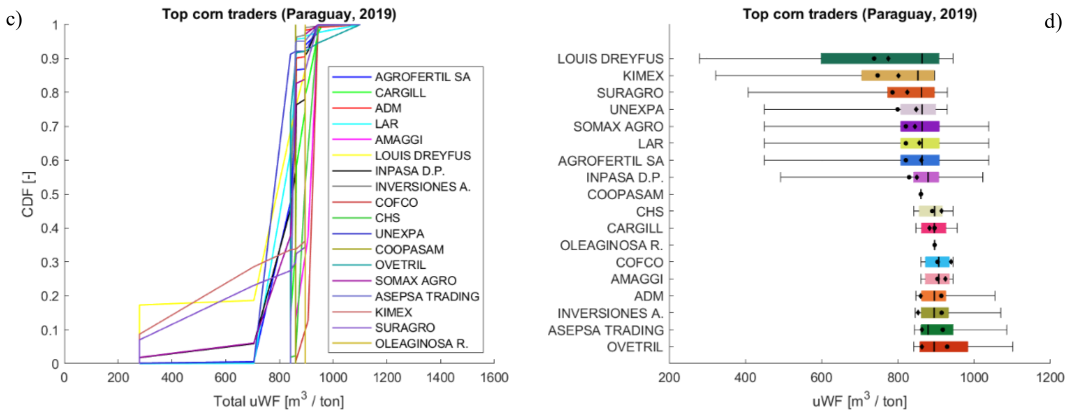


Figure 6.70: Paraguay, corn (2019). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

Notably, all importers' and eight traders' distributions are left skewed, differently from the cases analysed so far, in which right skewed distributions prevailed. Furthermore, observing traders' boxplots, the asymmetry changes while increasing mean uWF values, with Coopasam (who sourced corn from a single department) marking the turning point. Interestingly, among importing countries, Brazil had the highest average uWF ($829\,m^3/ton$) but lowest weighted one ($856\,m^3/ton$), in contrast to Chile, accounting for the lowest mean value ($799\,m^3/ton$) but highest weighted one ($887\,m^3/ton$). On the other hand, Louis Dreyfus hold the last place for both average uWF ($737\,m^3/ton$) and weighted uWF ($775\,m^3/ton$), whereas the most water demanding companies were Ovetril (average uWF of $929\,m^3/ton$) and COFCO (weighted uWF of $939\,m^3/ton$). Figure 6.71 reports, as illustrative example, the supplying departments of Louis Dreyfus.

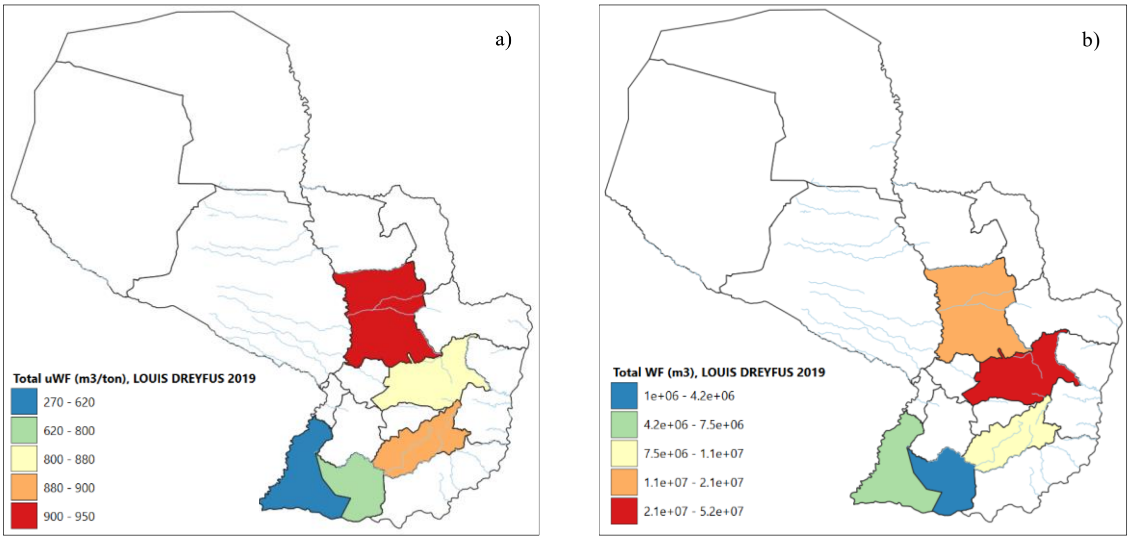


Figure 6.71: Paraguay, corn (2019). Total unit water footprint (a) and total water footprint (b) values of the departments supplying Louis Dreyfus.

Map in Figure 6.72 shows the virtual water-weighted barycentres of companies and importing countries. It emerges that the barycentres mostly fell within Caaguazú, partly in San Pedro, Canindeyú, Alto Paranà, Itapúa, and once in Caazapá (Suragro). Moreover, companies' barycentres covered a wider range of latitude values. In Appendix C, Figure C.31 shows them with green *ET*.

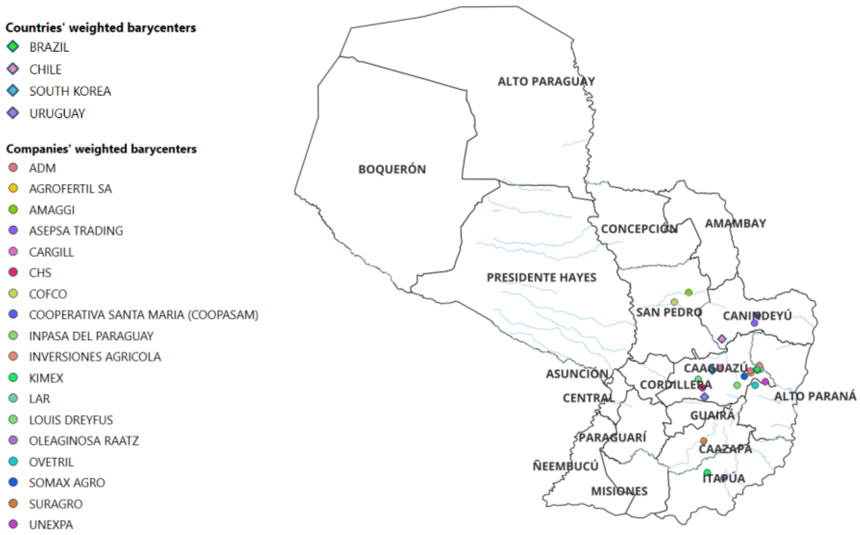


Figure 6.72: Paraguay, corn (2019). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

Tables 6.74 and 6.75 summarise statistics and weighted coordinates for five representative companies each.

Table 6.74: Paraguay, corn (2019). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Five examples.

COMPANY	**PERC_10** [m^3/ton]	**PERC_25** [m^3/ton]	**PERC_50** [m^3/ton]	**PERC_75** [m^3/ton]	**PERC_90** [m^3/ton]
AGROFERTIL SA	450	808	864	908	1039
CARGILL	847	862	896	926	956
ADM	847	862	896	926	1054
LAR	450	808	864	908	1039
AMAGGI	861	872	907	935	944

Table 6.75: Paraguay, corn (2019). Average uWF, weighted average uWF and weighted geographical coordinates of five traders.

COMPANY	**Average uWF** [m^3/ton]	**Weighted average uWF** [m^3/ton]	**Weighted LAT**	**Weighted LON**
COFCO	904	939	-24.0246	-56.5571
AMAGGI	904	924	-23.8701	-56.3239
CHS	890	914	-25.4012	-56.104
OLEAGINOSA RAATZ	896	896	-26.841	-55.76
CARGILL	896	882	-25.0808	-55.8119

Lastly, Louis Dreyfus virtual water trade is reported in Table 6.76, as illustrative example. Notably, South Korea was the only country relying on it.

Table 6.76: Paraguay, corn (2019). Relationship between the trader Louis Dreyfus and the country relying on it.

COUNTRYOFFIRSTIMPORT	**w_mean_uWF_tot** [m^3/ton]	**WF_tot** [m^3]
SOUTH KOREA	7.75E+02	8.11E+07

6.6.2 Soy

The last case analysed concerns soybean trade flows. Here, 14 out of the 16 major importing countries were studied (FAOSTAT, 2014-2019), along with the 15 top traders (Trase, 2019). In 2019, nor Germany not Mexico were involved in soybean export. Tables 6.77 and 6.78 show details. The last six companies reported in Table 6.78 were added to fulfil the local 80% constraint, with respect to Argentina, Turkey, Italy, Brazil and Spain.

Table 6.77: Paraguay, soy (2014-2019). Major importing countries (FAOSTAT).

IMPORTER	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
Argentina	1.07E+07	20.77	20.77	25.84
Russian Federation	5.60E+06	10.89	31.66	13.56
India	3.44E+06	6.69	38.35	8.32
Türkiye	2.55E+06	4.95	43.31	6.16
Italy	2.27E+06	4.41	47.72	5.49
Brazil	1.96E+06	3.80	51.52	4.73
Chile	1.95E+06	3.79	55.32	4.72
Netherlands	1.92E+06	3.74	59.05	4.65
Poland	1.68E+06	3.26	62.32	4.06
Peru	1.67E+06	3.24	65.56	4.03
Spain	1.66E+06	3.23	68.79	4.02
Bangladesh	1.58E+06	3.07	71.86	3.82
Germany	1.50E+06	2.92	74.78	3.63
United Kingdom of Great Britain and Northern Ireland	1.11E+06	2.15	76.93	2.68
Mexico	9.47E+05	1.84	78.77	2.29
Portugal	8.23E+05	1.60	80.37	1.99

Table 6.78: Paraguay, soy (2019). Major exporting companies (Trase).

EXPORTERGROUP	*SOY_EQUIVALENT_TONNES*	*PERC [%]*	*PERC_CUM [%]*	*PERC_REL [%]*
CARGILL	1.19E+06	18.88	18.88	19.55
SODRUGESTVO	8.24E+05	13.08	31.96	13.54
COFCO	6.77E+05	10.74	42.70	11.12
ADM	6.74E+05	10.70	53.40	11.08
LOUIS DREYFUS	5.17E+05	8.21	61.61	8.50
COMPANIA PARAGUAYA DE GRANOS	4.65E+05	7.38	69.00	7.65
VICENTIN PARAGUAY	3.79E+05	6.01	75.01	6.22
TRANS AGRO SA	2.80E+05	4.45	79.46	4.61
FRANCISCO VIERCI Y CIA	2.73E+05	4.34	83.80	4.50
BUNGE	2.00E+05	3.18	86.98	3.29
AGROFERTIL SA	1.97E+05	3.13	90.11	3.24
AMAGGI	1.89E+05	3.00	93.11	3.11
UNEXPA	9.28E+04	1.47	94.58	1.53
AGRO SILO SANTA CATALINA	7.12E+04	1.13	95.71	1.17
LAR	5.42E+04	0.86	96.57	0.89

As for corn, also this time the involved departments were 11 out of 17. Observing the colour ramp (Figure 6.73a), the two major productive sites were found in the southeastern corner of Paraguay.

These sites are reported in Table 6.79, additionally to Canindeyú. They accounted for 65% ($3.94 * 10^6\ tons$) of the soybean traded ($6.08 * 10^6\ tons$).

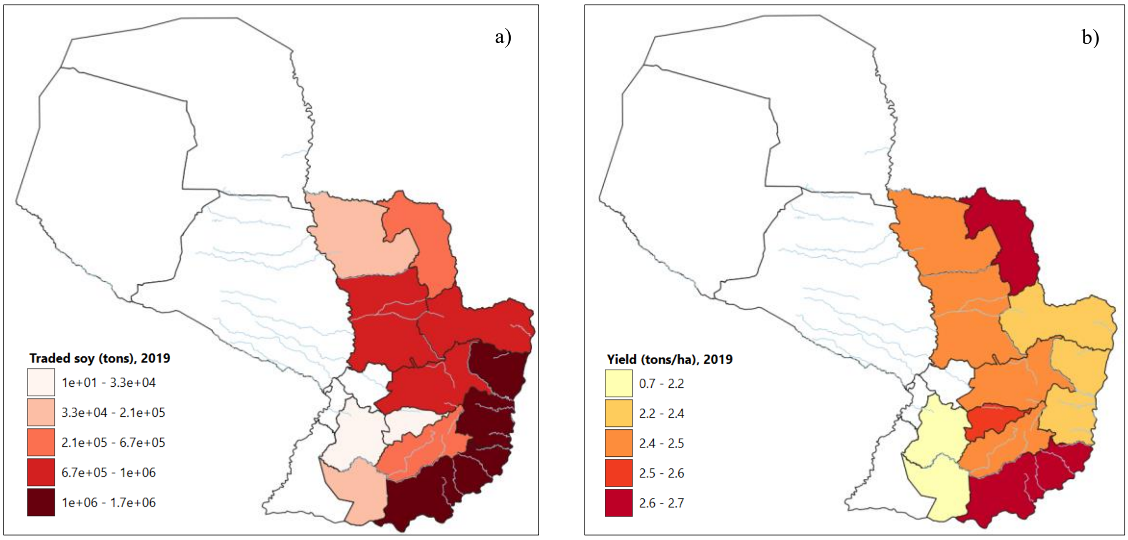


Figure 6.73: Paraguay, soy (2019). Traded tonnes (a) and yield values (b) for each involved department.

Table 6.79: Paraguay, soy (2019). First three producing departments. Exported tonnes and yield values are reported.

DEPARTMENTOFPRODUCTION	GEOCODE	SOY [tons]	YIELD [tons/ha]
ALTO PARANA	PY10	1.72E+06	2.25
ITAPUA	PY07	1.17E+06	2.63
CANINDEYU	PY14	1.05E+06	2.24

Available *ET* data (Appendix C, Figure C.32) were combined with yield values to obtain the unit water footprints illustrated in Figure 6.73. Data on blue water were provided for five departments only, and just in three cases (two of which are reported in Table 6.80) the value was greater than zero. Notably, the highest uWF was provided by green water only, for Paraguarí (Appendix C, Figure C.33).

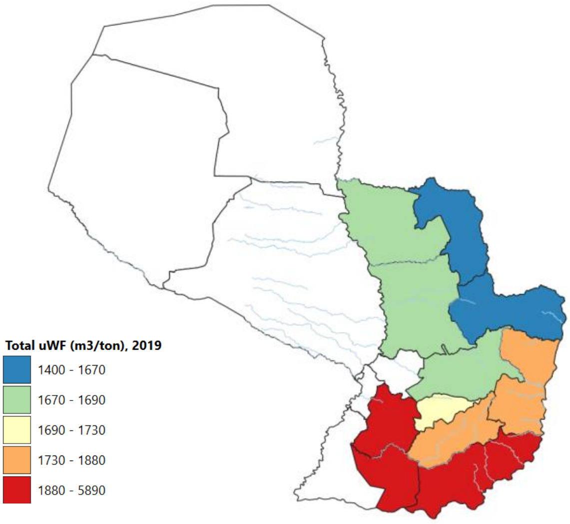


Figure 6.74: Paraguay, soy (2019). Total unit water footprint values at the department scale.

Table 6.80: Paraguay, soy (2019). Departments with the three highest uWF values.

DEPARTMENTOFPRODUCTION	**uWF_g [m^3/ton]**	**uWF_b [m^3/ton]**	**uWF_tot [m^3/ton]**	**SOY [tons]**
PARAGUARI	5.89E+03	NaN	5.89E+03	1.95E+01
MISIONES	2.49E+03	3.33E+02	2.82E+03	3.24E+04
ITAPUA	1.61E+03	2.68E+02	1.88E+03	1.10E+06

Subsequently, virtual water volumes were computed (Figure 6.75). In Appendix C, Figure C.34 shows green and water volumes.

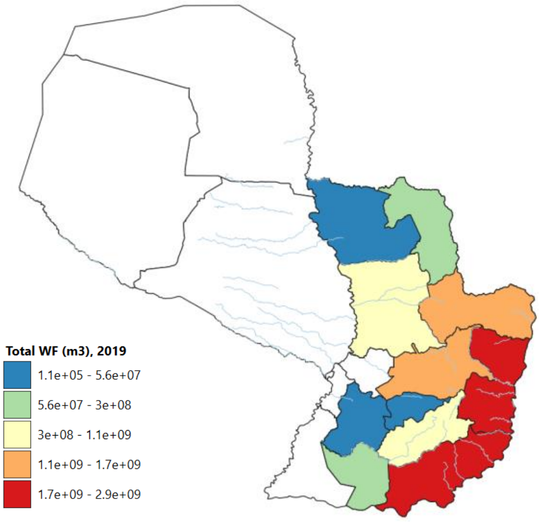


Figure 6.75: Paraguay, soy (2019). Total water footprint values at the department scale.

Table 6.81: Paraguay, soy (2019). Departments with the three highest WF values.

DEPARTMENTOFPRODUCTION	**WF_G [m^3]**	**WF_B [m^3]**	**WF_tot [m^3]**	**SOY [tons]**
ALTO PARANA	2.98E+09	0	2.98E+09	1.72E+06
ITAPUA	1.89E+09	3.15E+08	2.21E+09	1.17E+06
CANINDEYU	1.73E+09	1.62E+06	1.73E+09	1.05E+06

As appreciable in Table 681, the three departments with the highest *WFs* coincided with the ones shown in Table 6.79. Furthermore, Itapúa was recorded with the highest blue water footprint. Indeed, this site appears also in Table 6.80. The reported regions (Table 6.81) accounted for 66% $(6.91 * 10^9\ m^3)$ of virtual water traded $(1.05 * 10^{10}\ m^3)$.

Companies' and importers' statistics are illustrated in Figure 6.76.

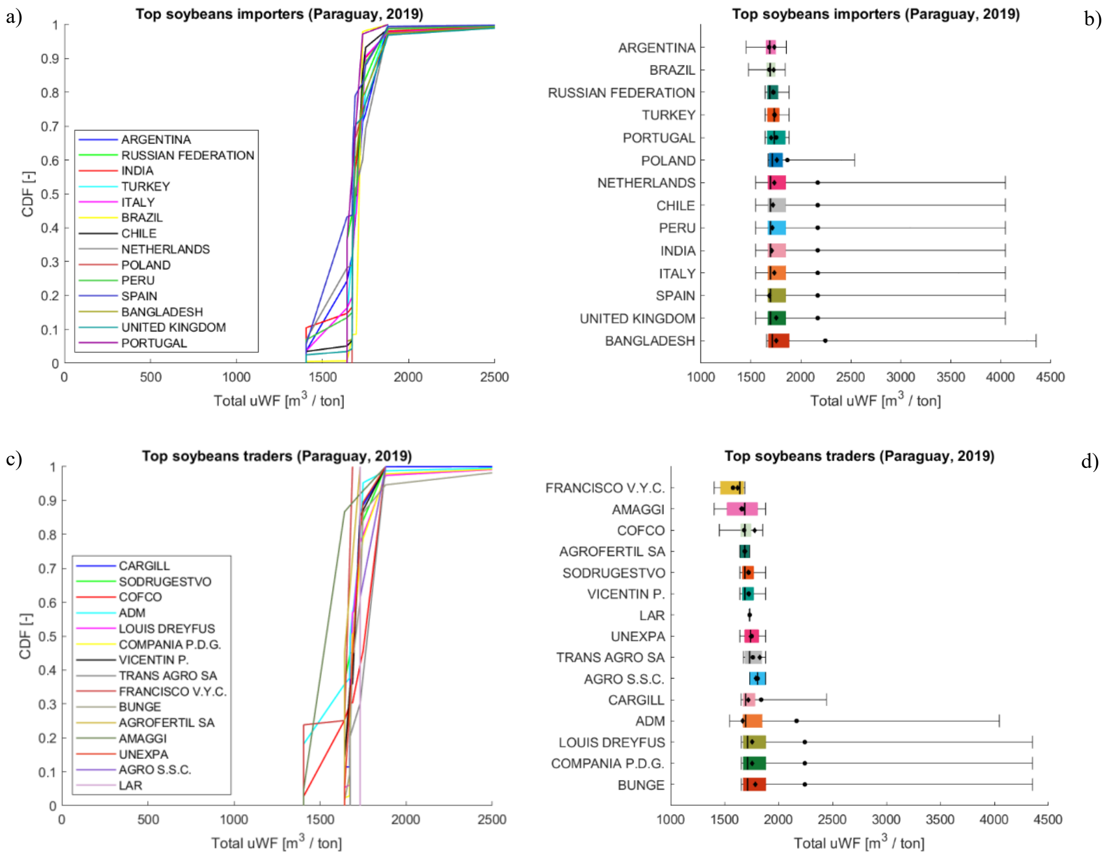


Figure 6.76: Paraguay, soy (2019). Cumulative distribution functions (a, c) and boxplots (b, d) of the major importing countries (a, b) and exporting companies (c, d).

Soybean trade in Paraguay was characterised by similar companies' and importers' distributions. As visible in Figure 6.76b-d, uWF distributions were mostly right skewed, with the exception of three traders (Francisco Vierci Y Cia, Amaggi and COFCO) and two importing countries (Argentina and Brazil). Among importers, Bangladesh had the highest average uWF ($2.24 * 10^3\ m^3/ton$), whereas Poland the greatest weighted value ($1.76 * 10^3\ m^3/ton$). On the other hand, the less water efficient traders were Bunge, Compania Paraguaya de Granos and Louis Dreyfus (average uWF of $2.24 * 10^3\ m^3/ton$), and Trans Agro SA (weighted uWF of $1.82 * 10^3\ m^3/ton$). Figure 6.77 illustrates the sourcing departments of Francisco Vierci Y Cia, who exerted the lowest pressure on water resources.

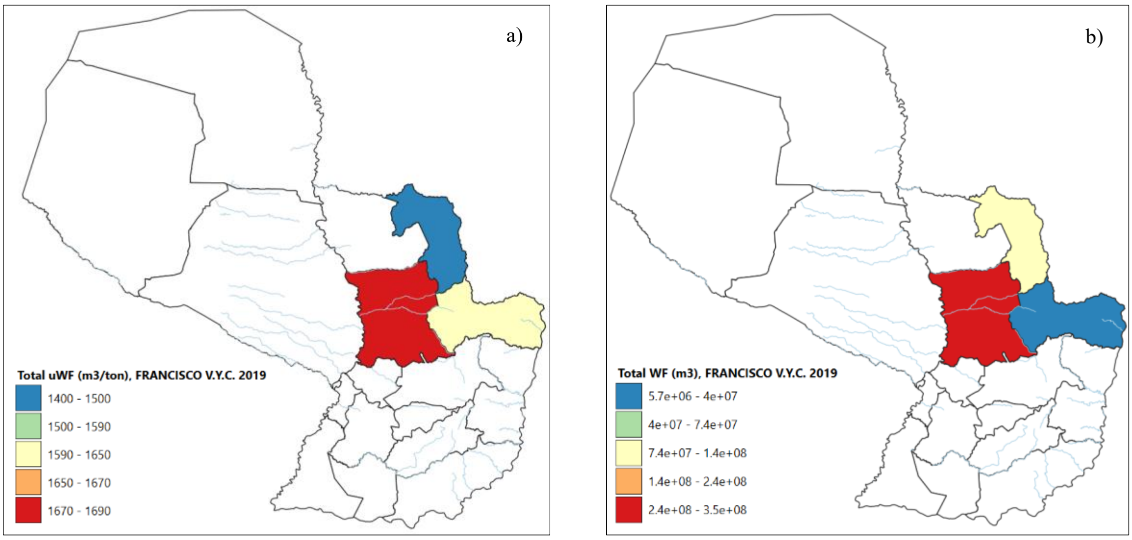


Figure 6.77: Paraguay, soy (2019). Total unit water footprint (a) and total water footprint (b) values of the departments supplying Francisco Vierci Y Cia.

Virtual water-weighted barycentres are represented in Figure 6.78, for companies and importers. Despite the majority of them fell within Caaguazú and Alto Paraná, a few exceptions are visible. Francisco Vierci Y Cia clearly relied on departments north of Caaguazú (as appreciable from Figure 6.77): its barycentre was found within San Pedro. By contrast, Trans Agro SA weighted barycentre fell in Itapúa, being the one furthest south. By the way, these two traders were the least and the most water demanding ones, in terms of weighted average *uWF*. COFCO (Caazapá) and Amaggi (Canindeyú) were the other exceptions. Furthermore, the range of latitude values was wider among traders' barycentres, as for the names introduced a few lines above. Barycentres and green *ET* data are shown together in Figure C.35, Appendix C.

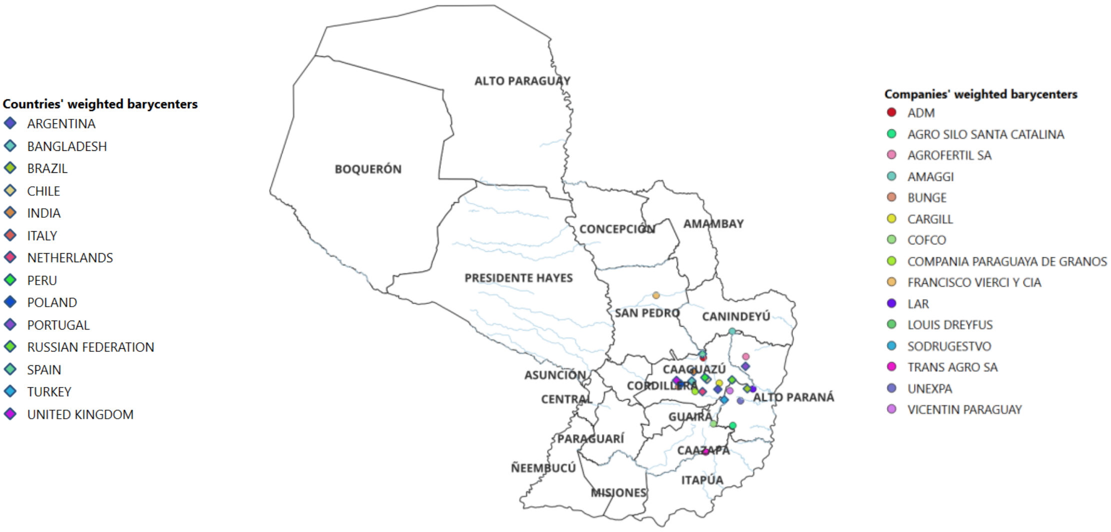


Figure 6.78: Paraguay, soy (2019). Virtual water-weighted barycentres of countries' and trading companies' virtual water trade.

To conclude, Tables 6.82 and 6.83 summarise statistic values and weighted coordinates, for three representative companies each.

Table 6.82: Paraguay, soy (2019). Values of the 10th, 25th, 50th, 75th, and 90th traders' percentiles. Three examples.

COMPANY	PERC_10 [m³/ton]	PERC_25 [m³/ton]	PERC_50 [m³/ton]	PERC_75 [m³/ton]	PERC_90 [m³/ton]
CARGILL	1653	1673	1695	1782	2444
SODRUGESTVO	1642	1666	1688	1769	1881
COFCO	1452	1650	1688	1745	1854

Table 6.83: Paraguay, soy (2019). Average uWF, weighted average uWF and weighted geographical coordinates of three traders.

COMPANY	Average uWF [m³/ton]	Weighted average uWF [m³/ton]	Weighted LAT	Weighted LON
TRANS AGRO SA	1762	1824	-26.39958083	-55.70888139
COFCO	1682	1781	-25.95352079	-55.58407474
COMPANIA PARAGUAYA DE GRANOS	2244	1758	-25.434667	-55.87743567

Chapter 7 – Discussion

Chapter 6 presented how virtual water volumes were associated with each trade flow of a selected crop, thus obtaining an overall estimate of the pressure exerted on local freshwater resources. The aim of Chapter 7 is to highlight similarities and major patterns across the involved countries. This is performed at three levels, which are 1) country, 2) crop, and 3) Transnational Corporation level. Water footprints are analysed focusing also on the biome of the producing region and its deforestation risks (Trase). Information on the biomes involved is provided by Trase, with the exception of Colombia (The Colombian Coffee Co.). Chapters 7.1 and 7.2 do not deal with cocoa trades from Brazil and Ivory Coast, as data are available only for one year in each country. This limitation prevents meaningful spatio-temporal comparisons. All of the following considerations, tables and maps were derived considering the major importers and traders reported in each subsection of Chapter 6. This allowed an in-depth understanding of the associated roles and possible changes in their supplying locations.

In Appendix D, time series show the exported tonnes and corresponding cultivated hectares, additionally to total *VWT* at the country scale. Moreover, the temporal evolution of unit and total *WFs* is reported for each involved biome. In Chapter 7.1, time series are reported for some representative cases. Throughout Chapter 7, soybean related results are taken multiple times as illustrative examples.

Note: in the following chapters, when referring to 'average uWF' or simply 'uWF', the term 'weighted' is implied.

7.1 Temporal behaviour and geographical heterogeneity of *uWFs*

Based on Trase data availability at the subnational scale, the temporal evolution of traded water volumes was studied. This chapter discusses about the differences in total exported tonnes and related average *uWFs* found for each combination crop-producing country. Additionally to the temporal variability, geographical heterogeneity is introduced based on the involved biomes, to enrich what discussed in Chapter 6 regarding the peculiarities at the production sites level. Notably, the processes of agricultural extensification and intensification showed significant differences from case to case, underlining the importance of site-specific actions to improve water management based on local features. This analysis also enabled to appreciate the differences of *uWF* values and *VWT* volumes between different crops. Crops with on average higher *uWFs* may have been associated with smaller *VWT* values than others, based on the magnitude of exports. Therefore, it is important to carefully consider both variables together to understand the overall magnitude of a crop in terms of water demand.

7.1.1 Argentina

In Argentina, the departments involved in soybeans exports remained almost the same in the five-year period. However, produced tonnes and corresponding cultivated hectares showed fluctuations (Figure 7.1a), according to annual climatic conditions (Chapter 5.1). In 2018, a minimum was registered for both variables, which dropped by 104.4% and 39%, respectively, if compared to 2019. Consequently, in 2018 the *VWT* at the national scale was the lowest one (– 39% compared to 2019, Figure 7.1b). From Figure 7.1b, it is observed that from 2015 to 2017 variations in *VW* volumes and

$uWFs$ were in phase. For instance, the growth in soybeans export and VWT reported for the year 2016 was associated with an increase in the cultivated area and of the average uWF. Conversely, values in the years 2018 and 2019 showed an out of phase behaviour. Notably, in 2018 the remarkable increment in unitary water requirements ($2.7 * 10^3\ m^3/ton$) was not coincident with a rise in production. This behaviour well explains the impact of drought periods on soybean cultivations. On the other hand, 2019 was characterised by a clear improvement: indeed, the growth in VWT corresponded to the lowest average uWF of the analysed period ($1.8 * 10^3\ m^3/ton$). These observations highlight the importance of considering the effect of climatic conditions on water requirements, additionally to market-related fluctuations.

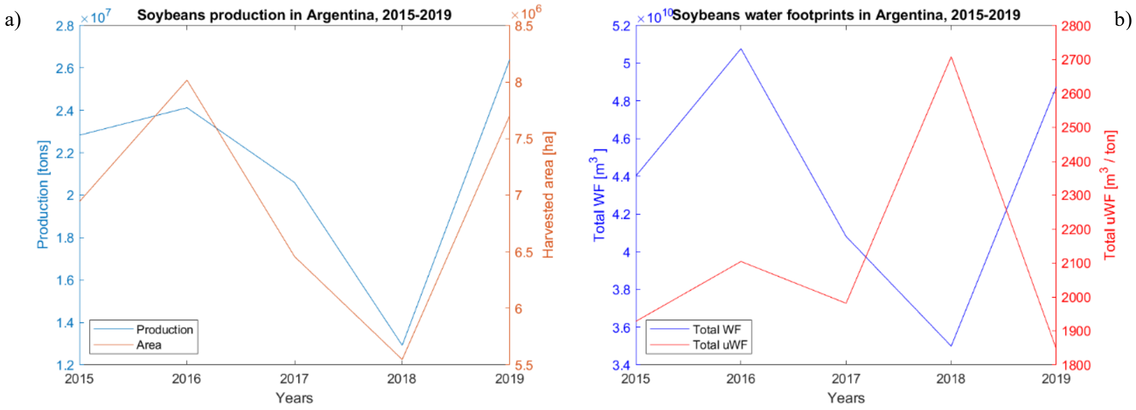


Figure 7.1: Argentina, soy (2015 - 2019). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right(b).

As presented in Chapter 6.1, uWF values detailed at the local scale demonstrated a considerable spatial variability, caused by site-specific environmental and climatic conditions. Departments with the highest water requirements were found in the southern Buenos Aires and northern Santa Fe provinces throughout the studied period, despite local yield improvements. On the other hand, most of the highly productive departments, also displacing considerable water volumes, were concentrated in Córdoba.

Further spatial analysis was conducted leveraging the insights provided by Trase on the departments’ biome. Total water volumes and average $uWFs$ were calculated for each of them. It emerged that the overall water consumption for soybean cultivations in La Pampa biome surpassed that of all other biomes. This evidence can be attributed to the extensive land utilization within the Argentine Pampas, which stands out as one of the world’s most productive rainfed agricultural regions (Holzman and Rivas, 2016). The second ecoregion showing considerable water exploitation was the dry forest Espinal, threatened by deforestation, agricultural expansion and soil degradation due to large-scale cattle ranching and irrigation-based agriculture (Guida Johnson and Zuleta, 2013). In Figure 7.2, the weighted average unit water footprints associated with each biome are shown. In particular, in 2018 Chaco Humedo emerged with the highest uWF ($5.5 * 10^3\ m^3/ton$, versus $2.6 * 10^3\ m^3/ton$ in La Pampa), indicating that the drought period had the greatest impact on this biome, which is typically characterised by high humidity. Instead, La Pampa and Espinal regions had always one of the lowest unitary water demands. Notably, biomes’ $uWFs$ had a range of variability larger than that of values at the country scale. This evidence further demonstrates the importance of studying these variables at several granularity levels.

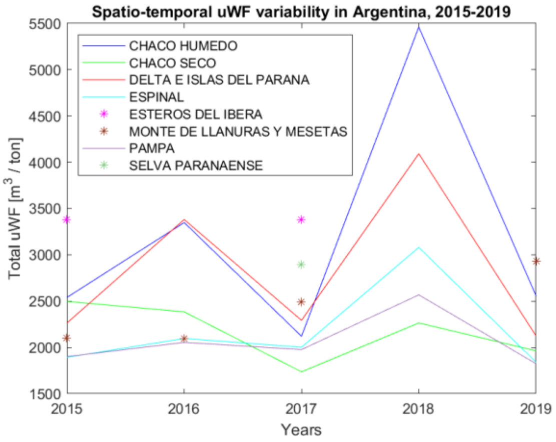


Figure 7.2: Argentina, soy (2015 - 2019). Temporal evolution of the weighted mean uWFs over each biome involved. Asterisks denote biomes that were absent in one or more years.

7.1.2 Bolivia

Soybean exports from Bolivia reduced in the two-year period (– 11.6%), despite the slight increase in cultivated hectares (+ 4.4% over 18 municipalities in 2021, 21 in 2020) (Appendix D, Figure D.1). Moreover, local *uWFs* saw a general growth, leading to an overall greater water volume displaced (+ 4.5%). Concerning biomes, most of the production was concentrated within the Chiquitano Dry Forest ecoregion, resulting in its higher water demand. However, the analysis of unit water footprints highlighted that the aforementioned biome and the Southwest Amazon Moist Forest faced almost an equal pressure on water resources ($1.3 - 1.5 * 10^3\ m^3/ton$, in 2020 and 2021 respectively) (Appendix D, Figure D.2).

7.1.3 Brazil

At present, Brazil has the most complete data availability at the subnational scale, allowing for comparisons across different crops. Regarding soybeans, the most critical one in terms of surface involved, an impressive land grabbing has occurred since the beginning of the 21st century (Chapter 5.7, Figure 5.10c). In the analysed period of seventeen years, a remarkable expansion of involved hectares (+ 162.5%) and growth in exported tonnes (+ 272.5%) characterised the major TNCs of 2020, as shown in Figure 7.3a. Consequently, total *VWT* increased (+ 158.3%, Figure 7.3b), being almost entirely contributed by green water. At the same time, average *uWF* values followed a decreasing trend. Inter-annual fluctuations might be explained by climatic variability as well as improvements adopted in water management. In particular, the greatest export and *VWT* were recorded in 2018, along with the lowest unitary water demand ($1.5 * 10^3\ m^3/ton$). The number of production sites involved in soybeans export to the considered importing countries almost doubled during the analysed period. This agricultural extensification, along with the intensification observed in the main production sites, highlights the urgent need for improved water management. The increase in virtual water displacement, despite the general decrease of *uWF* values, cannot be disregarded.

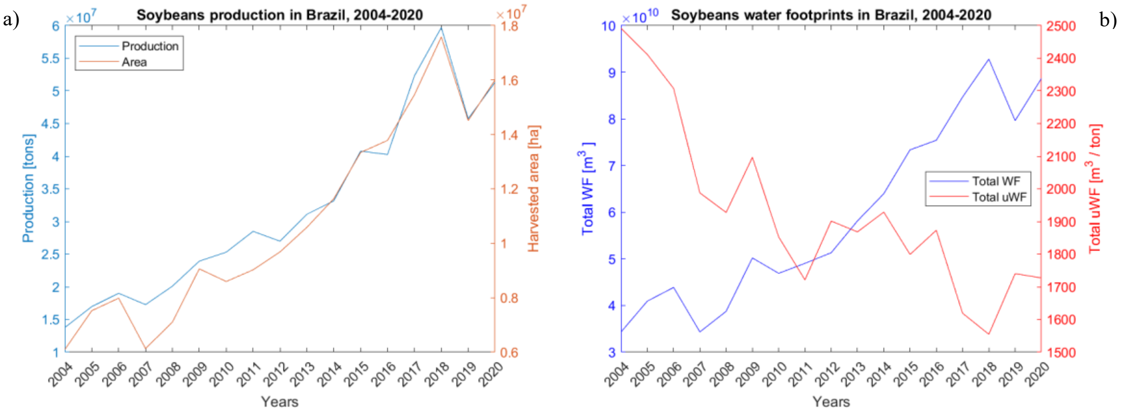


Figure 7.3: Brazil, soy (2004 - 2020). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right(b).

At the municipality level, the most critical values of *uWF* were predominantly found in Rio Grande do Sul. This evidence is explained by the high green and blue *ET* values (Appendix C, Figure C.20) mostly associated with low yields (Chapter 6.3.5, Figure 6.46b for 2020 data). The only exception was 2019, when some municipalities in Mato Grosso do Sul, São Paulo and Paraná experienced critical water requirements similar to those in Rio Grande do Sul. In this year, drought conditions caused consistent harvest losses. The analysis of biomes revealed that Mata Atlantica had the highest water requirement in 2004, while in 2020, Cerrado took over this distinction. According to Song et al. (2021), in the years 2001 to 2016 Cerrado experienced the most alarming soybean-driven deforestation among the South American biomes suitable for this crop. It was observed that Cerrado had the highest soybean gain as a direct driver of deforestation, whereas it was second to the Brazilian Amazon when considering soybean gain as a latent driver (Song *et al.*, 2021). From the analysis of unit water footprints in Figure 7.4b, it emerged that municipalities within the Pampas biome faced the most critical use of the water resource with a considerable variability over time. Conversely, Cerrado and Amazonia production sites showed an almost constant unitary water requirement.

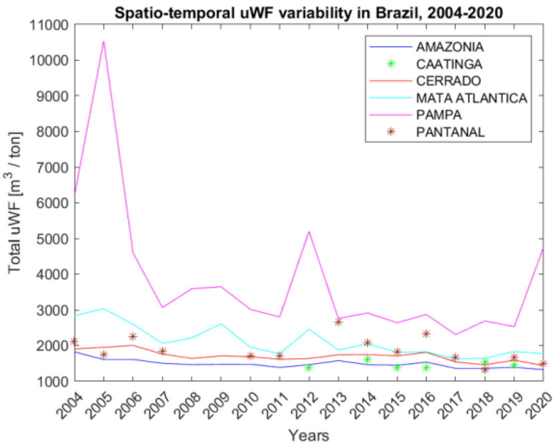


Figure 7.4: Brazil, soy (2004 - 2020). Temporal evolution of the weighted mean uWFs over each biome involved. Asterisks denote biomes that were absent in one or more years.

Considering coffee production, exports managed by the major traders of 2017 reduced by 6.8% compared to 2016. Cultivated hectares expanded (+ 5%) including more municipalities, yet highlighting an average yield reduction (– 11.2%). Despite the slight improvement in *uWF* values, the total *VWT* grew by 5.7%. This might be explained by a production shift towards more water demanding sites. Concerning biomes, the Brazilian coffee plantations supplying the considered actors were located in Cerrado and Mata Atlantica. This last ecoregion was found to have a more critical overall water requirement than Cerrado. Indeed, coffee exports were 90% (2016) and 74% (2017) higher in Mata Atlantica. Notably, unit water footprint increased in both biomes by 33.5% in Cerrado and 4.5% in Mata Atlantica. See Appendix D for related Figures D.3 and D.4.

Shifting the focus to corn, exports confirmed what observed in Chapter 5.3 (Figures 5.3a, 5.3c, 5.3e): in 2016, Brazil experienced a production drop of 25% and 29% compared to 2015 and 2017 harvests, respectively. Cultivated hectares expanded of 11.3% relative to 2017, yet the average yield was significantly lower (– 46% relative to 2017). The harvest drop was mainly caused by scarce precipitation during the growing period. Average $uWFs$ showed a slight improvement from 2015 to 2017, while VWT volumes remained almost unchanged. Looking at the municipal level, the overall geographical distribution of production sites in 2016 showed a different involvement of some states. Exports relied on a higher number of sites in Santa Catarina and Paraná, but less in Minas Gerais, Rio de Janeiro and Espírito Santo. In addition, the Pampas biome was involved only in 2016. This year again, local uWF values increased strongly in highly productive areas (Mato Grosso, Mato Grosso do Sul, Goiás, Maranhão), mostly in the Amazon and Cerrado ecoregions. Conversely, in the other two years analysed, these sites had generally $uWFs$ one order of magnitude lower than in 2016. Overall, corn production was mostly concentrated in municipalities in the Cerrado, which showed the highest water requirements over the three-year period. Nevertheless, Cerrado average uWF values were lower than those in Mata Atlantica but higher than in Amazonia (incidentally, irrigation is not required here). See Appendix D for related Figures D.5 and D.6.

Concerning cotton temporal variations, its production remained localized in approximately forty municipalities throughout the three-year period. Notably, exports grew by 44%, cultivated hectares were expanded by 30%, and a 10.6% yield improvement was observed. The $uWFs$ of the involved municipalities did not show considerable variations. Regarding the overall water volumes displaced, an increase of 26% was recorded, mostly given by the contribution of green water. Cotton production sites were almost entirely concentrated in the Cerrado, which consequently had the highest total water requirements. However, Cerrado average $uWFs$ remained the lowest among the other involved ecoregions. On the other hand, Caatinga was recorded with the highest average water demand per tonne. See Appendix D, Figures D.7 and D.8.

Given that multiple crops were mapped over Brazil, further analysis could be performed combining them. Using 2017 data as a representative example, the geographical distribution of production sites and corresponding VWT volumes was obtained, as presented in Figure 7.5. The aim was to identify the most involved areas in the export of coffee, corn, cotton, and soybeans altogether. The identified states were Mato Grosso, Rio Grande do Sul, Bahia, Mato Grosso do Sul, Paraná, Goiás, and Minas Gerais. Furthermore, it emerged that the highest total water demands were over the Cerrado and Mata Atlantica biomes. The analysis at the municipality level allowed to individuate Sorriso, in Mato Grosso, as the site from which the highest virtual water volume was displaced: $10^9\ m^3$ of water were involved in both the trade of corn and soybeans (1st producing site for both crops), while $10^8\ m^3$ in the cotton trade (12th producing site). Coffee, instead, was not produced there. Nevertheless, the weighted average uWF of Sorriso given by all the traded tonnes ($806\ m^3/ton$) was lower than that of the 90% of the municipalities analysed.

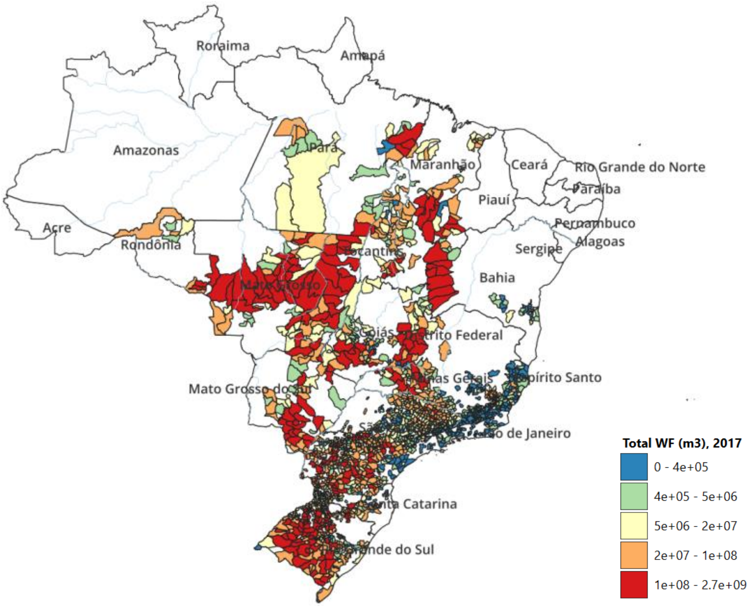


Figure 7.5: Brazil (2017). Total VWT associated to coffee, corn, cotton and soybeans exports.

7.1.4 Colombia

The precision of the temporal analysis for Colombian coffee was not equivalent to that of the other cases because the yield values did not vary over time. Consequently, the growth of exported tonnes (+ 165.1%) was followed by a proportional increase in the total VWT (+ 164.8%), as visible in Appendix D, Figure D.9. It is essential to note that the uWF values obtained at the department scale were considerably higher than those reported in other studies (Mekonnen and Hoekstra, 2010; Leal-Echeverri and Tobón, 2021). The lower than expected yield values might explain what observed. Agronet (2021) reports yields almost double if compared to those obtained with the MAPSPAM data, which suggests a probable overestimation of the total virtual water volumes. Although exports consistently increased, the overall weighted average unit water footprints showed both positive and negative variations. In particular, the lowest value was recorded in 2014 ($1.57 * 10^4\ m^3/ton$), whereas the highest in 2015 ($1.6 * 10^4\ m^3/ton$).

Regarding the involved biomes, Trase does not provide any specification. However, observing the producing departments, coffee growing areas were identified within three regions, in line with external sources (The Colombian Coffee Co.): the Andean (central), the Pacific (western), and the Caribbean (northern) regions. Each area was identified with water vulnerability: while unit water footprints were observed to be higher in the Caribbean region, due to irrigation requirements, the greatest water volumes were mostly required in Huila, Cauca and Tolima departments, the most productive ones (refer to figures in Chapter 6.4). Overall, it is expected that the risk of deforestation will increase by 2050 due to the combined effects of climate change and the growing demand for coffee (Trimmer C. and Goldstein A., 2020).

7.1.5 Paraguay

Concerning corn exports from Paraguay, the six-year period analysed saw a 67.5% increase in terms of tonnes and a 29.8% increase in cultivated hectares, resulting in an overall 29% yield improvement. However, exports did not grow steadily. In 2016, 2017, and 2018, the volume of traded tonnes was almost halved compared to 2019. The same is true for the total virtual water trade. Anyway, the VWT increased by only 29% despite the high growth in exports, thanks to improvements in the uWF values (– 29.5%). See trends in Appendix D, Figure D.10. Corn production sites were predominantly situated within the Mata Atlantica biome, with an overall water requirement two orders of magnitude greater than that recorded in Chaco Humedo.

Figure 7.6 reports the analysis of soybeans export. Between 2014 and 2019, the traded tonnes increased by 30%, while the cultivated area by 55.8%. This suggests a 16% drop in yield. Departments' *uWF* values slightly changed, whereas the total *VWT* grew by 55%. In 2019, the water volume marked a 15% increment compared to 2018, even though exports were 11.9% lower. Indeed, a sharp increase in the average *uWF* (+ 31%) is visible in Figure 7.6b. Drought during the soybean growth cycle was the cause.

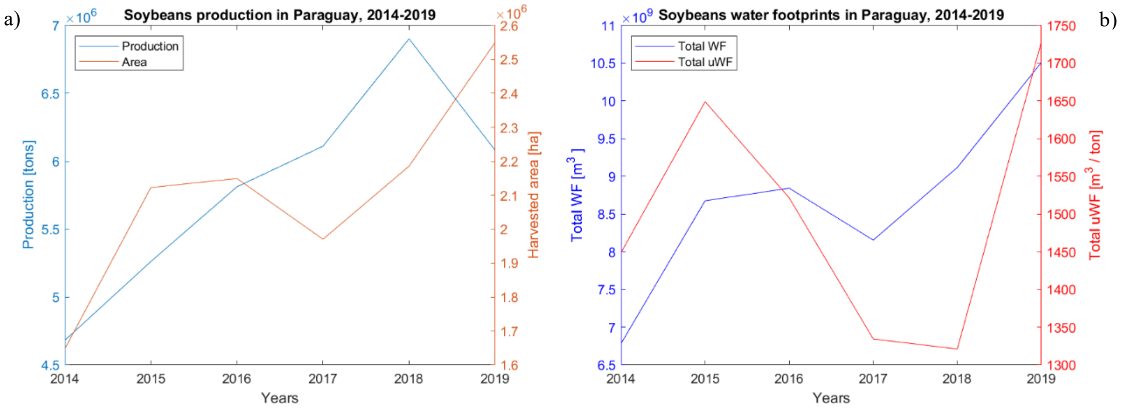


Figure 7.6: Paraguay, soy (2014 - 2019). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right(b).

Concerning the involved biomes, soybean fields were primarily located in Mata Atlantica, exposing the eastern side of the country to considerable water exploitation. Interestingly, *uWF* values were consistently lower in the Mata Atlantica than in the Chaco Humedo and Chaco Seco (Figure 7.7). The last two biomes are indeed less suitable for agricultural practices due to climatic reasons and water scarcity. Nevertheless, soybean has recently begun expanding within the Paraguayan Chaco, taking advantage of climatic changes, infrastructure improvements and technological support (Henderson *et al.*, 2021). Furthermore, according to Tyldesley M. (2021), exports from the Chaco region, especially from Chaco Seco, could be higher than declared. Despite the latter is predominantly producing soybeans for domestic consumption, the market has been experiencing rapid changes in the last years.

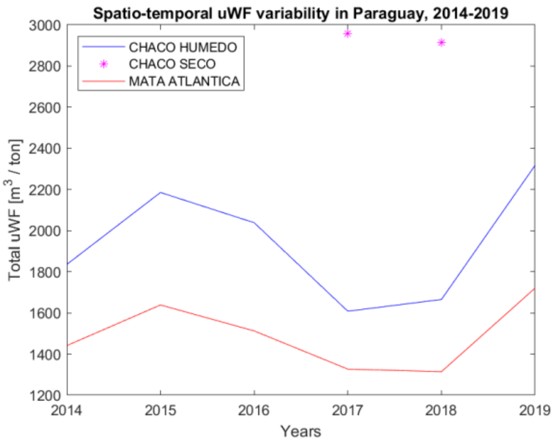


Figure 7.7: Paraguay, soy (2014 - 2019). Temporal evolution of the weighted mean uWFs over each biome involved. Asterisks denote biomes that were absent in one or more years.

Finally, the exports of corn and soybeans were considered together for the period of 2014 to 2019 (Appendix D, Figure D.12). It emerged that major virtual water volumes were displaced from the departments of Itapúa, Alto Paraná, Canindeyú and Caaguazú. They are all located in the Mata Atlantica biome.

7.2 Intercountry comparisons

In this subsection, similarities and peculiar features are discussed for each crop that was traced in more than one country. Specifically, Chapter 7.2 focuses on the weighted average uWF values observed at the national scale in distinct countries (same values introduced in Chapter 7.1), to increase awareness of the site-specific water requirements that the same crop has in different producing countries. Temporal variability is considered as well.

7.2.1 Coffee

For what concerns coffee production, some specifications are required. Regarding the crop's varieties, only Arabica beans are grown in Colombia, as they are well-suited to high altitude regions and cool climates. In contrast, Brazil grows both Arabica and Robusta beans, with Robusta being found in warmer areas and at lower altitudes. Specifically, Arabica is predominantly cultivated in the states of São Paulo and Minas Gerais, while Robusta in Espírito Santo and Rondônia, even though changes in suitability are expected due to climate change (Sustainable Coffee Challenge; Dias, Martins and Martins, 2024). Despite the fact that the same coffee variety is grown in Colombia and most of Brazil, notable differences apply in crop management. In Brazil, sun-grown intensive coffee plantations are generally found. On the other hand, shade-grown coffee has been traditionally prevalent in Colombia. Indeed, the analysis performed on coffee water footprints enabled to highlight a major difference between Brazil and Colombia production. As a result of the different agricultural practices and local climates, blue ET, and consequently blue $uWFs$, were significantly higher in Brazil. According to available ET data, almost all the Brazilian municipalities involved in the analysis relied on irrigation systems, with blue uWF values reaching $10^3\ m^3/ton$ (predominantly in the state of Minas Gerais). On the other hand, Cesar and La Guajira were the only Colombian departments observed with blue ET (blue uWF were around $10^2\ m^3/ton$ in this case).

Figure 7.8 reports the weighted average uWF values observed in the two countries. As explained in Chapter 7.1.4, values in Colombia might have been overestimated. Based on the CWASI database, it could be correct that they were one order of magnitude greater than those in Brazil, at the national level of analysis. However, according to Mekonnen and Hoekstra (2010), values in the two countries should be comparable at the subnational level, when considering the major productive sites.

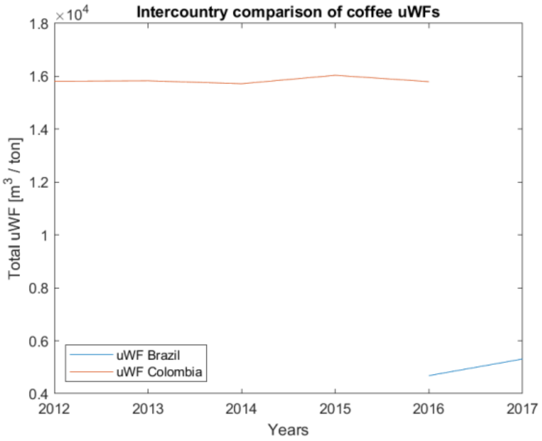


Figure 7.8: Coffee. Temporal evolution of weighted mean uWFs in Brazil and Colombia.

7.2.2 Corn

The temporal evolution of weighted average *uWFs* associated with corn production in Brazil and Paraguay is illustrated in Figure 7.9.

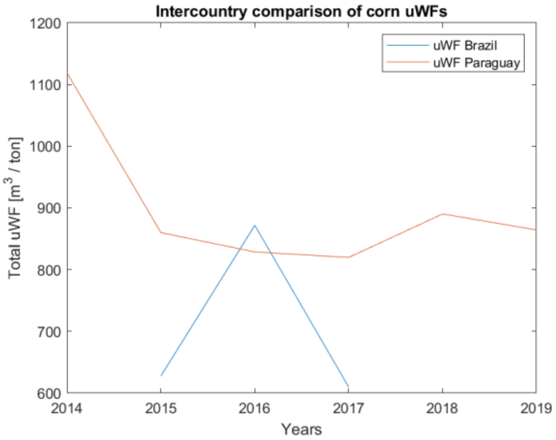


Figure 7.9: Corn. Temporal evolution of weighted mean uWFs in Brazil and Paraguay.

Apart from Brazil's peak value found in 2016, as discussed in Chapter 7.1.3, in Paraguay higher *uWFs* were observed. As corn *ET* data are very similar in both countries, the explanation is likely to be found in the yields of major producing areas in Brazil, which were higher than those in Paraguay. Indeed, their values reached approximately 7 ton/ha in Brazil, but 5 ton/ha in Paraguay. Municipalities in Mato Grosso, predominantly in the Cerrado, contributed the most to Brazil exports. Instead in Paraguay, the most productive departments were in the Mata Atlantica. The different biomes, with their peculiar climatic and environmental features, along with the different growing periods for the first and second crops, led to site-specific and variable water requirements. In particular, at the fine-scale, Brazil was observed with an intra-annual variability of *uWF* values wider than that of Paraguay, given that corn production was widespread throughout the Brazilian territory.

Figure 7.10 shows all production sites supplying the major TNCs in 2017. On panel a), the colour ramp identifies the total water requirement on each biome, whereas on panel b) total water footprints are reported for each production site, clearly illustrating spatial variability. In Figure 7.10a, the biome in common is represented with the same colour, despite the different *WF* associated with it.

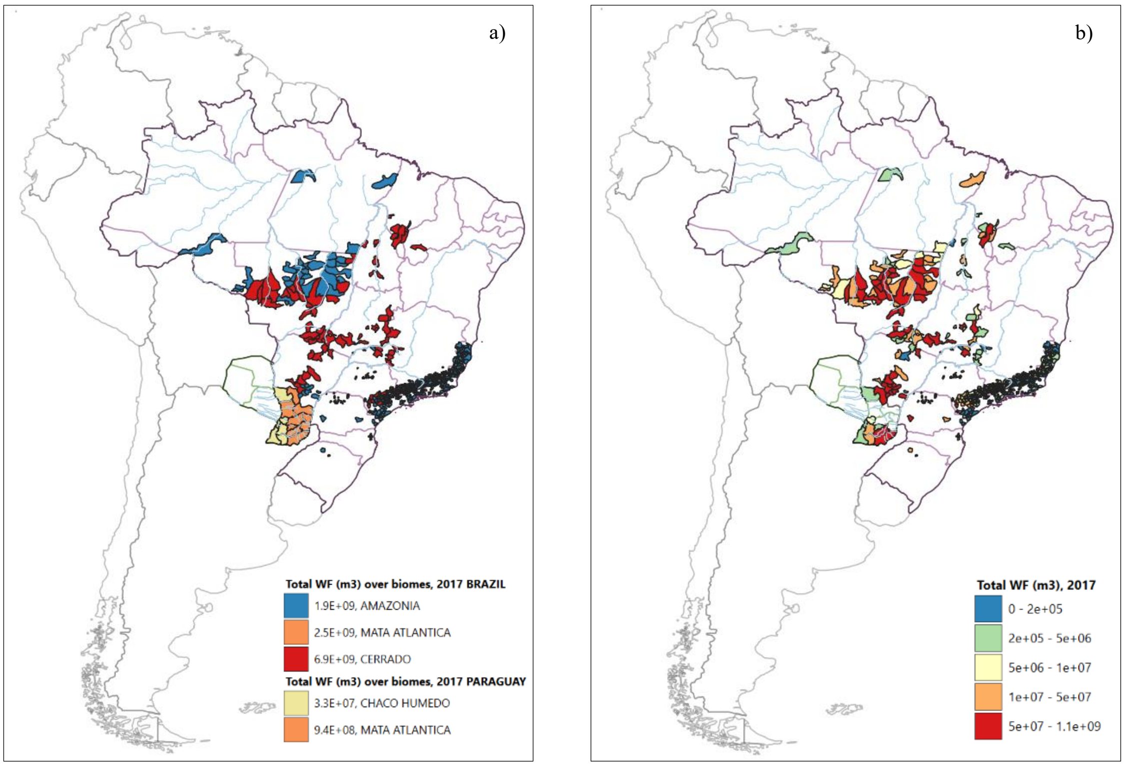


Figure 7.10: Southern America, corn (2017). Total water footprint over each biome involved (a) and total water footprint over each production site (b).

7.2.3 Soy

Global demand for soybean seeds is constantly increasing, leading to a geographic expansion of unique rapidity in South America (Chapter 5.7, Figure 5.10). Furthermore, Argentina, Bolivia, Brazil and Paraguay have been facing land grabbing and irregular land transfers (Norberg and Deutsch, 2023), due to the rapid establishment of new agricultural frontiers (Song *et al.*, 2021). These frontiers are mostly threatening the Brazilian Cerrado, and the Gran Chaco region in Argentina, Bolivia and Paraguay (NASA, 2022; Norberg and Deutsch, 2023).

From the analysis performed on each producer country, it emerged that country-specific major importers and traders, despite sourcing soybeans from different regions, relied on some shared biomes. Specifically, the Dry and Humid Chaco in Argentina, Bolivia and Paraguay; the Mata Atlantica in Brazil and Paraguay; and the Pampas in Argentina and Brazil. Figure 7.11a shows the overall water footprints on the involved biomes. The year under analysis is 2019 for Argentina, Brazil and Paraguay, and 2020 for Bolivia. The massive extension of soybean cultivations over each country emerged clearly, along with the concerning water exploitation concentrated in the Cerrado and Pampas. Analysing the water volumes associated with production sites (Figure 7.11b), it resulted that most of the trade was virtually displaced from areas in the Cerrado, Mata Atlantica, Pampas and Espinal. In Figure 7.11a, the same colour is used for biomes found in more than one country, despite the different *WF* associated with each of them.

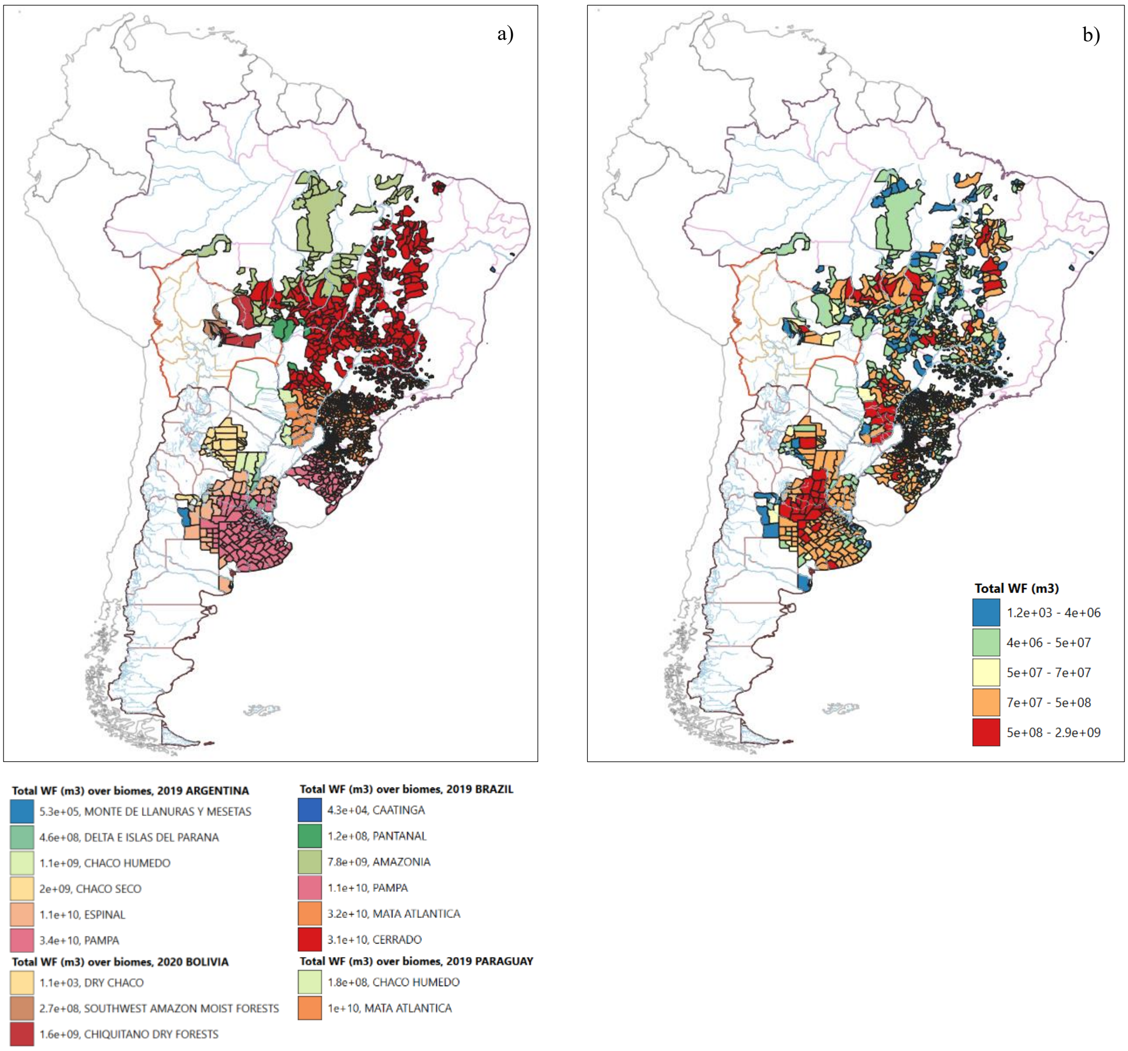


Figure 7.11: Southern America, soy (2019 and 2020). Total water footprint over each biome involved (a) and total water footprint over each production site (b). For Argentina, Brazil and Paraguay data are reported for the year 2019, whereas for Bolivia (red boundaries) for the year 2020.

Focusing on weighted average *uWF* values at the country scale, significant differences emerged between the four producers, as visible in Figure 7.12.

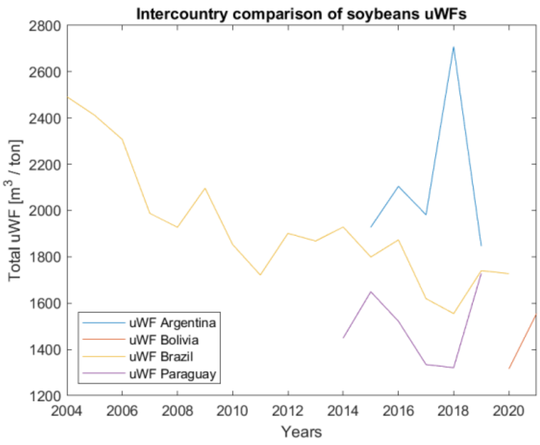


Figure 7.12: Soy. Temporal evolution of weighted mean uWFs in Argentina, Bolivia, Brazil and Paraguay.

In 2019, Argentina experienced the most consistent uWF variation among all those of the four countries, with the highest recorded value ($2.7 * 10^3\ m^3/ton$). It is worth noting that the values observed for Argentina, Brazil, and Paraguay were closest in 2019, with $1.85 * 10^3\ m^3/ton$, $1.74 * 10^3\ m^3/ton$ and $1.73 * 10^3\ m^3/ton$ respectively. When compared to the $uWFs$ of 2018, these values showed an improvement for Argentina and a worsening for Brazil and Paraguay. The explanation for the differences in response to drought periods in each country can be attributed to their specific geographical and climatic features. It is important to note that changes in biome can also affect the response to drought. In this specific case, Argentina experienced a prolonged drought in 2018 (as discussed in Chapter 7.1.1), while Brazil and Paraguay faced it the following year. A possible explanation could be found in the El Niño phenomenon as it affects differently South America. In terms of unit water demands, Paraguay and Bolivia had similar values. When comparing the years in common, Argentina had the highest values.

7.3 TNCs' role for the analysed crops

Chapter 7.3 represents the point of convergence of the entire thesis, where the considerations presented in previous Chapters 7.1 and 7.2 are combined with further study on the major Transnational Corporations. The first section is dedicated to the analysis of competitiveness in the market of each crop to unveil whether trades were controlled by a limited number of TNCs. The second section, instead, is focused on the spatio-temporal evolution of market shares taking only the four major traders, among the selected ones, for each combination crop-producer. This additional analysis is crucial in order to clearly understand whether the results reported in section 7.3.1 are truly indicative of market fragmentation, or whether this categorisation is merely a consequence of market expansion, but a few traders still cover most of the total shares. Finally, the third section focuses again on uWF values, this time in relation to TNCs. The objective was to emphasise the variability of values based on specific sourcing sites, thereby reinforcing the importance of evaluating results at the subnational level.

7.3.1 Market competitiveness: the HHI index

All the major traders presented in Chapter 6 were considered to analyse in a more complete way the temporal evolution of crop-specific markets. The Herfindahl–Hirschman index (HHI) was utilized to detect whether markets were fragmented or monopolised by specific companies. Final market descriptions were only partial as based on subsets of TNCs, which resulted in shares summations lower than one.

Table 7.1: Herfindahl-Hirschman index variations for the crops under analysis. The numbers within round brackets indicate how many TNCs were considered for the index computation.

	Soy (35)				**Coffee (34)**		**Corn (25)**		**Cotton (12)**
Years	**Argentina**	**Bolivia**	**Brazil**	**Paraguay**	**Brazil**	**Colombia**	**Brazil**	**Paraguay**	**Brazil**
2004			0.13						
2005			0.13						
2006			0.11						
2007			0.11						
2008			0.13						
2009			0.12						
2010			0.11						
2011			0.11						
2012			0.09			0.08			
2013			0.08			0.10			
2014			0.09	0.13		0.08		0.06	
2015	0.09		0.08	0.13		0.08	0.11	0.12	0.04
2016	0.09		0.08	0.13	0.05	0.10	0.10	0.04	0.06
2017	0.09		0.08	0.12	0.06		0.09	0.07	0.08
2018	0.10		0.08	0.12				0.08	
2019	0.09		0.07	0.10				0.08	
2020		0.20	0.08						
2021		0.19							

Table 7.1 summarises the HHI values obtained for the crops under analysis. Exception was made for cocoa, which could not be analysed over time. The market of cocoa had a HHI of 0.34 in Brazil and 0.13 in Ivory Coast, with respect to twelve traders. Hereafter, major findings are reported.

- Regarding soybeans export, Brazil and Paraguay experienced a progressive fragmentation of the market, as opposed to Argentina which reported only slight variations. In Bolivia, the highest HHI values were observed, even reaching in 2020 the 0.2 threshold indicating a *moderate* market concentration.
- In Colombia, values related to coffee oscillated over time but no clear trend could be detected.
- A notable change was detected for corn market in Paraguay from 2015 to 2016. Specifically, the HHI dropped from 0.12 to 0.04 which represented the maximum and minimum observed values, respectively. A deeper analysis of the Trase data revealed that the number of corn trade flows in 2016 almost doubled those of 2015 and they were handled by twenty-seven more companies. However, the traded tonnes exhibited a 14% drop, leading to the conclusion that in 2015 the market was indeed more concentrated in the hands of a few traders.
- Cotton exports from Brazil were controlled by a progressively lower number of traders.

According to accepted threshold values (‘Horizontal Merger Guidelines’, 2010), the coffee, corn and cotton markets can be defined as *not concentrated*. Soybean related outcomes showed variations from state to state, with HHI values ranging in the *not concentrated – moderately concentrated* thresholds. The market of cocoa in Brazil is the only one categorised as *highly concentrated*.

A precise interpretation of the obtained values is necessary. Despite being largely different from the unit, a few companies emerged as the most dominant in each case, holding a significant portion of the market share. However, when dealing with globally traded agricultural commodities at the rate of those analysed, it is natural that a vast number of companies are involved in their export, but the majority of them only hold a small share. Consider the case of soybeans export from Brazil in 2020, where five companies accounted for more than 50% of total exports and twelve for more than 80% over the 228 involved. Consequently, when computing the HHI based on subsets of companies, the value appears low, even though a few of them dominated the market. Therefore, it is important to conduct a more in-depth investigation, focusing on the market shares of the major traders, as discussed in Chapter 7.3.2. It is worth noting that the markets of the commodities analysed have indeed grown over the last few decades, with an increasing number of smaller traders emerging and competing alongside the most established names. For this reason, the word ‘fragmentation’ can lead to misunderstandings: a few TNCs still emerge and control most of each market, but the overall higher number of traders could lead to a kind of ‘market fragmentation’.

7.3.2 Market shares evolution for the major TNCs

For each combination crop-producer analysed, the four principal traders among those selected on the last year available were taken. The aim was to identify the predominant crop-specific actors operating in each market, specifically focusing on the evolution of their share, and understand whether the low HHI values presented in Chapter 7.3.1 truly indicate market fragmentation or they are a consequence of market expansion, which implies a higher number of TNCs involved. Appendix E presents stacked bar charts for each crop, except for soybeans, which is discussed in more detail here.

The major names emerged for soybeans export are ADM, Bunge, Cargill, COFCO, Hugo Spechar Gonzales – Granos, Industrias de Aceite S.A., Industrias Oleaginosas S.A., Louis Dreyfus, Sodrugestvo and Vicentin. Figure 7.13 illustrates their market shares in Argentina, Bolivia, Brazil and Argentina.

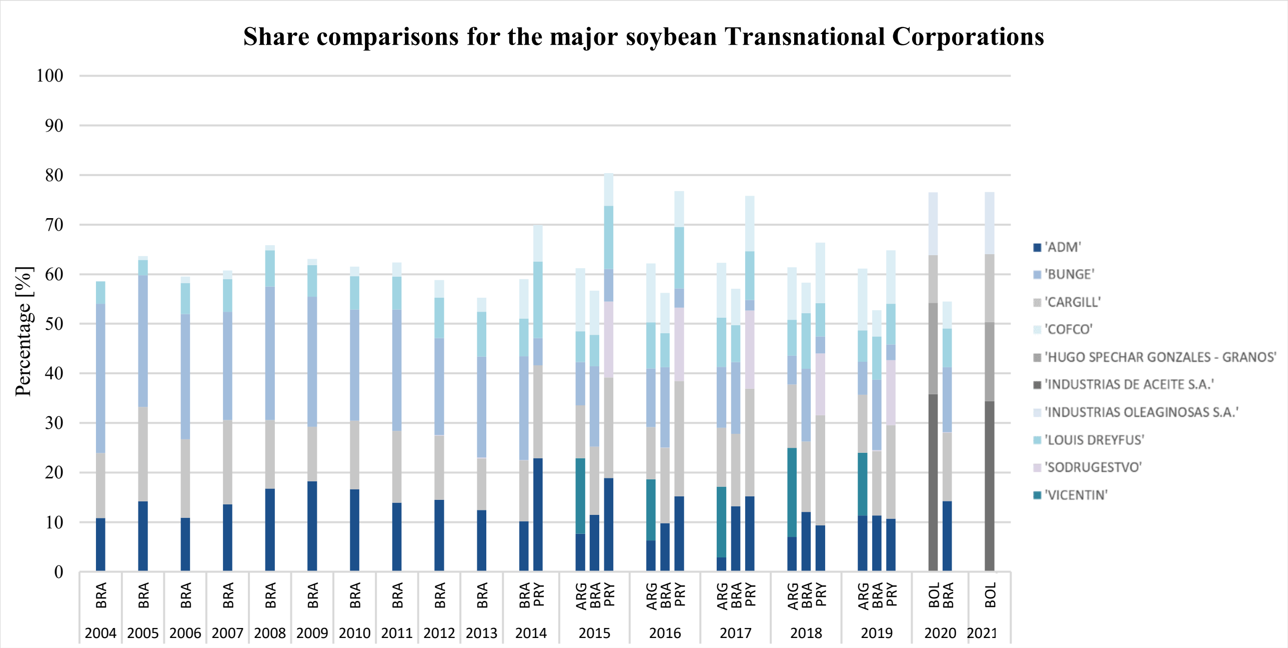


Figure 7.13: Argentina, Bolivia, Brazil and Paraguay. Market shares of the major soybean TNCs.

Notably, Cargill was the only giant agrobusiness involved in each producing country, confirming its relevance as one of the world's largest soybean traders. Furthermore, based on Trase knowledge, no other big company handled exports from Bolivia in the years 2020 and 2021. Together with Cargill, the traders ADM, Bunge, COFCO and Louis Dreyfus resulted to be responsible for 50 to 70% of total soybean exports each year. This evidence underlines how the soybean market is indeed concentrated in the hands of a few TNCs. According to Oliveira and Hecht (2017), during the first years of the 21st century, the ABCD firms controlled more than 75% of South America soybean exports, and if adding corn and wheat trades the percentage was around 70% (Clapp, 2016). It is therefore alarming that companies such as Bunge, Cargill, COFCO, and the less known Sodrugestvo have been discovered to be related to illegal deforestation, even though often indirectly (Jordan *et al.*, 2020; Wasley *et al.*, 2021; Chain Reaction Research, 2023; Global Witness, 2023; Radwin M, 2023).

Since each company showed inter-year variations in its market shares, illustrative time series are represented in Figure 7.14 to better appreciate spatio-temporal differences. The ABCD companies and COFCO were selected for this analysis, given their predominant role in soybeans export from Argentina, Brazil and Paraguay.

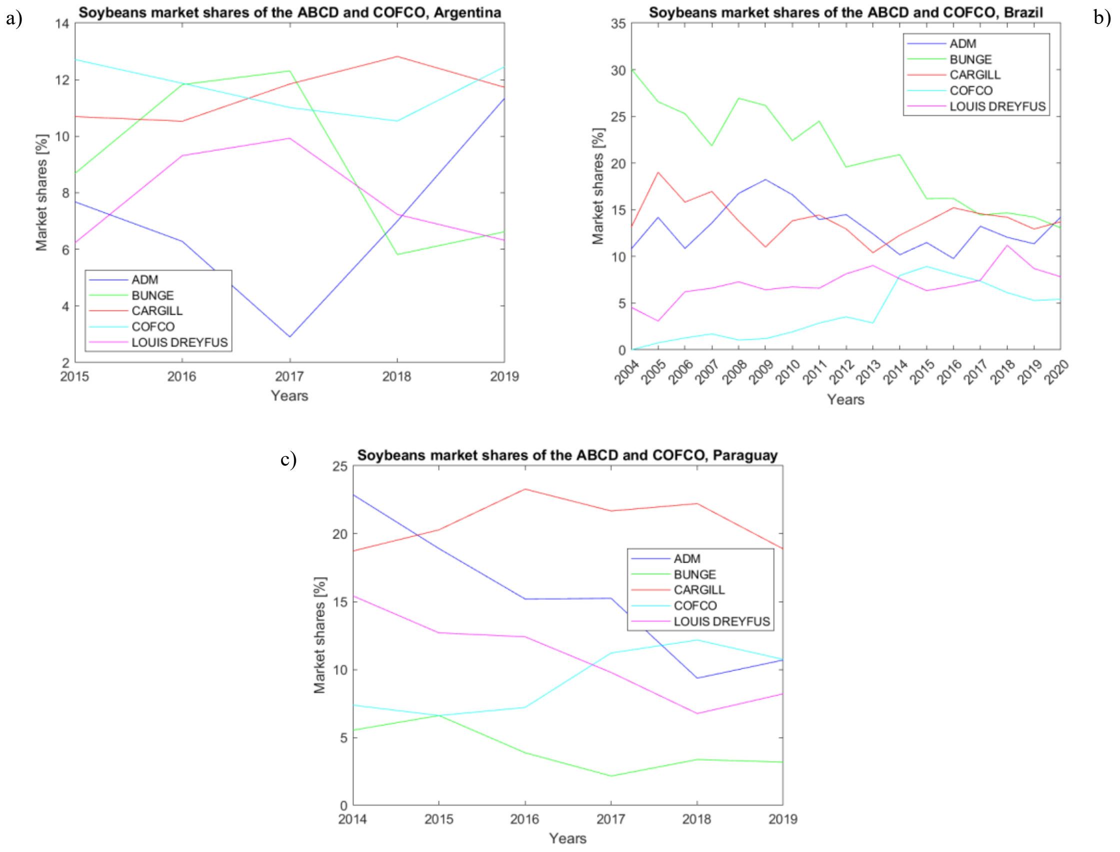


Figure 7.14: Argentina, Brazil and Paraguay. Temporal evolution of market shares for the major soybeans traders.

As visible in Figure 7.14b, in Brazil the shares of the analysed TNCs became progressively closer to each other. While in 2004 Bunge clearly dominated the market (30%), with time it lost power. This situation might also be related to the increasing weight of minor traders. The remaining four TNCs maintained their market shares quite consistently over time. ADM and Cargill fluctuated between 10% and 20%, Louis Dreyfus between 5% and 10%, and COFCO went from being absent in 2004 to becoming the fourth largest exporter in 2020 with a 5% share. These time series well explain the progressive market fragmentation observed in Brazil, as discussed in Chapter 7.3.1, in the sense that the clear dominance of a single trader disappeared over time. Conversely, the variations observed in Argentina (Figure 7.14a) do not suggest strong changes in the market from the beginning to the end of the period considered. Notably, Bunge and Louis Dreyfus had a similar trend, whereas ADM showed fluctuations exactly in the opposite directions, reaching the lowest share in 2017 (3%). Cargill and COFCO had the smallest range of variability (11 to 13%). Finally, Figure 7.14c shows that market shares in Paraguay tended to converge. This confirms the increase in market competitiveness already expressed by the drop in HHI values (Table 7.1, Soy). ADM and Louis Dreyfus became much less important, Bunge remained the most marginal trader, while COFCO maintained a strong position (around 20% of the total share).

In Brazil, ADM, Bunge and Cargill controlled 40 to 60% of the total market. This evidence allows to restate what previously introduced: despite the low HHI values observed in Brazil (Table 7.1, Soy), the soybeans market was indeed concentrated in the hands of a few TNCs. Figure 7.15 reports the total shares of the ABC companies together with the total number of TNCs involved in exports in each year. Overall, the ABC oligopoly tended to increase as the number of traders involved decreased, and vice versa. However, as the opposite behaviour was reported in 2007, 2009, 2017 and 2020, it is not easy to identify a general rule.

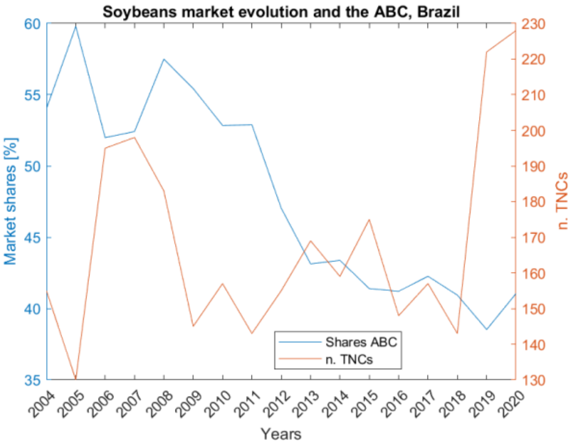


Figure 7.15: Brazil, soy (2004-2020). Comparison of the soybeans market shares of ADM, Bunge and Cargill with the total number of TNCs involved in each year.

On the other hand, in Argentina, apart from the ABCD and COFCO, Vicentin played a major role in soybeans export (Figure 7.13). In fact, it held the highest shares in each year, ranging from 12% to 18%. In Paraguay, instead, Sodrugestvo clearly affirmed its role from 2015 on, with shares comparable to those of the major agrobusinesses (from 12 to 16%).

Similar analyses were performed for the other crops. Major findings are reported.

- Cocoa trade exports from Brazil and Ivory Coast were consistently handled by the companies Barry Callebaut and Cargill, with market shares close to 40% (Brazil) and 20% (Ivory Coast) each. Furthermore, Joanes Industrial LTDA and, to a limited extent, Brandao Filhos SA exported cocoa beans from Brazil. On the other hand, importers from Ivory Coast also relied on Olam and Ecom.
- Concerning the major coffee traders from Brazil and Colombia, it emerged that Louis Dreyfus and Olam operated in both countries. However, the market shares of these traders were significantly lower than those of companies specialized on coffee trade, such as Carcafe LTD, Federacion Nacional de Cafeteros, and Racafe Y Cia SCA in

Colombia, while Cooperativa Regional de Cafeicultores, Stockler LTDA, and Terra Forte in Brazil. Overall, these companies accounted for 40 to 50% of exports in the considered years, showing slight variations in the corresponding percentages.

- Focusing on corn exports from Brazil and Paraguay, Cargill was found to handle around 10 to 20% of exports from both countries. ADM, Amaggi and Bunge were mainly active over Brazil, whereas LAR almost exclusively over Paraguay. Lastly, Agrofertil SA exported only from Paraguay, as a major company in the years 2018 and 2019. Altogether, these traders covered around 55% of Brazil corn export and 30 to 55% of Paraguay export.
- In 2017, the predominant cotton traders from Brazil were Amaggi, Bom Futuro Agricola LTDA, Cargill and SLC Agricola Pejucara LTDA. In the three-year period analysed, the influence of these four companies increased, accounting for around 25% of cotton exports in 2015 to almost 50% in 2017. Notably, SLC Agricola had the highest shares in each year (12 to15%), whereas Cargill had the lowest ones (4 to 9%).

Noteworthy, Cargill had a significant presence in all markets, except for coffee, confirming its remarkable importance as one of the biggest food companies. It is worth saying that this trader has been linked to illegal deforestation practices, sourcing soybeans directly from the Chiquitano region of Bolivia (Global Witness, 2023), and cocoa in Ivory Coast and Ghana, as well as palm oil in Indonesia and Malaysia from companies that rely on illegally cleared land (Jordan *et al.*, 2020; Lai, 2023).

As a conclusion, what emerges is that each market tended, to varying degrees, to be largely controlled by a limited number of traders. This evidence confirms the importance of the dedicate analysis of market shares, in addition to the HHI values presented in section 7.3.1. Moreover, it can be stated that, despite the undeniable relevance of the five agro-giants, i.e. the ABCD and COFCO, in dictating global standards and rules, several companies were involved in the trade of crops exposed to tropical deforestation risk. A significant distinction arises between the soybeans and corn markets, and the cocoa, coffee and cotton markets. While the commodities related to the former two crops are primarily traded within the newer feed industry, the latter three crops produce agricultural commodities with a much longer and established historical use for human consumption and the textile industry. In fact, specialised traders emerge in the cocoa and coffee markets, and to a minor extent in the cotton one. On the other hand, global agribusinesses largely trade soybeans and corn among other agricultural commodities.

7.3.3 Spatial and temporal changes in TNCs' *uWFs*

In Chapter 7.3.3, a further step was taken to obtain an overview of the Transnational Corporations that virtually displaced the greatest water volumes. Furthermore, importing countries that relied on these TNCs could be highlighted, with the aim of raising awareness of the local pressure generated by their agricultural demand.

7.3.3.1 The case of soy

Deepening the analysis of the ABCD and COFCO in soybeans exports started in Chapter 7.3.2, this section presents the results regarding the variations in the *VWT* and *uWF* values associated with each of the five traders. In Figure 7.16, values are illustrated for Argentina, Brazil and Paraguay from 2015 to 2019, which are the years in common. This enabled meaningful spatio-temporal comparisons.

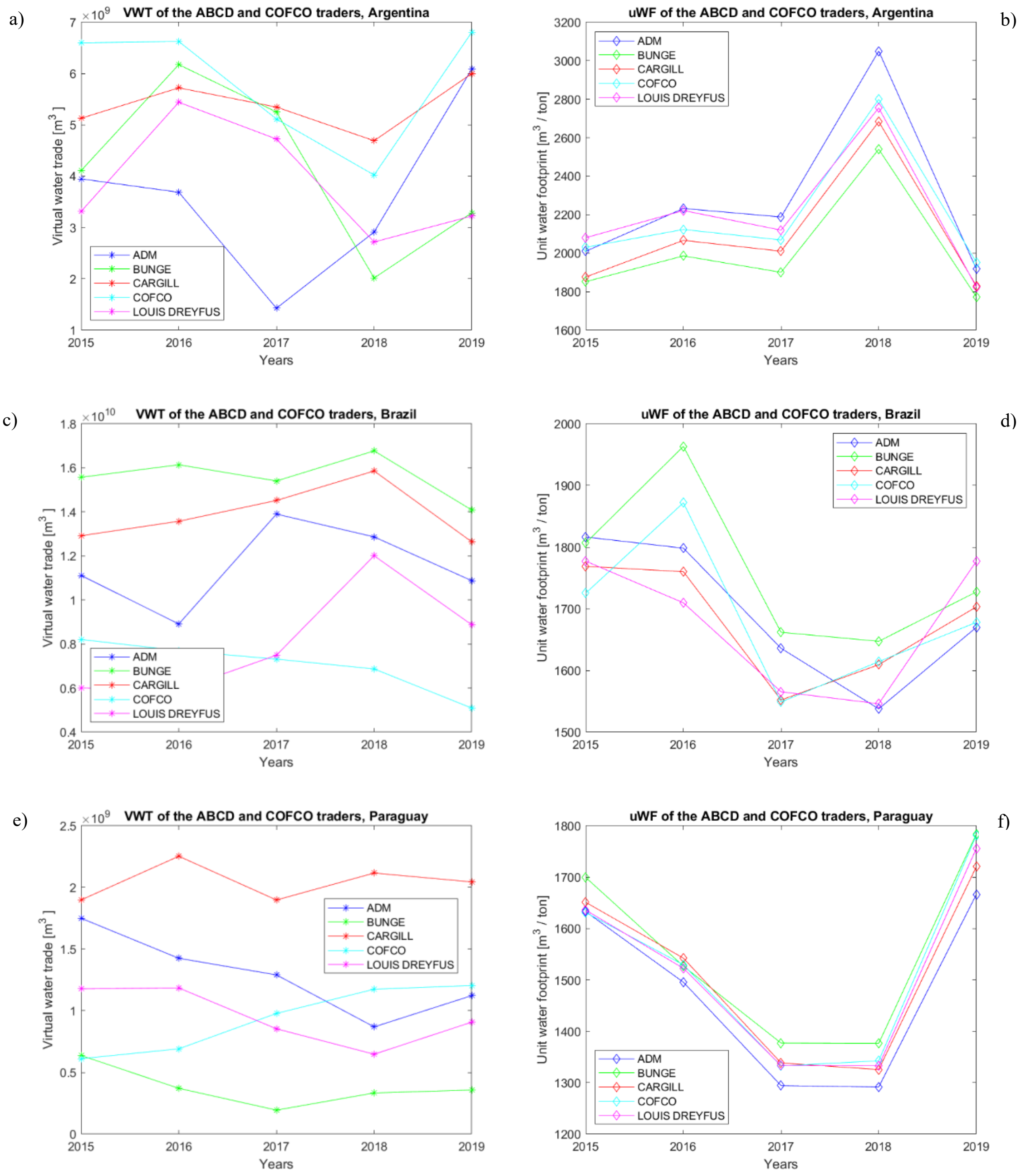


Figure 7.16: Water volumes related to the ABCD and COFCO in soybean trades, from Argentina (a, b), Brazil (c, d) and Paraguay (e, f).

As expected, the unit water footprint of each company was highly dependent on the producing country, according to site-specific water requirements and climatic events. The most critical values were observed for ADM in Argentina ($3.05 * 10^3\ m^3/ton$, Figure 7.16b), and Bunge in Brazil ($1.96 * 10^3\ m^3/ton$, Figure 7.1d) and Paraguay ($1.78 * 10^3\ m^3/ton$, Figure 7.16f). The corresponding years were 2018, 2016 and 2019, respectively. Cargill often showed a uWF lower than that of companies that exported less. These traders had the smallest range of variability of uWF values in Brazil, with an overall improvement over the analysed period. On the contrary, inter-annual variations were particularly marked in Argentina. Paraguay was the only country in which values slightly worsened by the end of the period (drought).

Additional considerations could be made on single traders with respect to different supplying countries. ADM was taken as illustrative example since in 2018 it reported the highest weighted average uWF in Argentina, but lowest in Brazil. Figure 7.17 shows the geographical position of its supplying sites along with the corresponding VW volumes displaced.

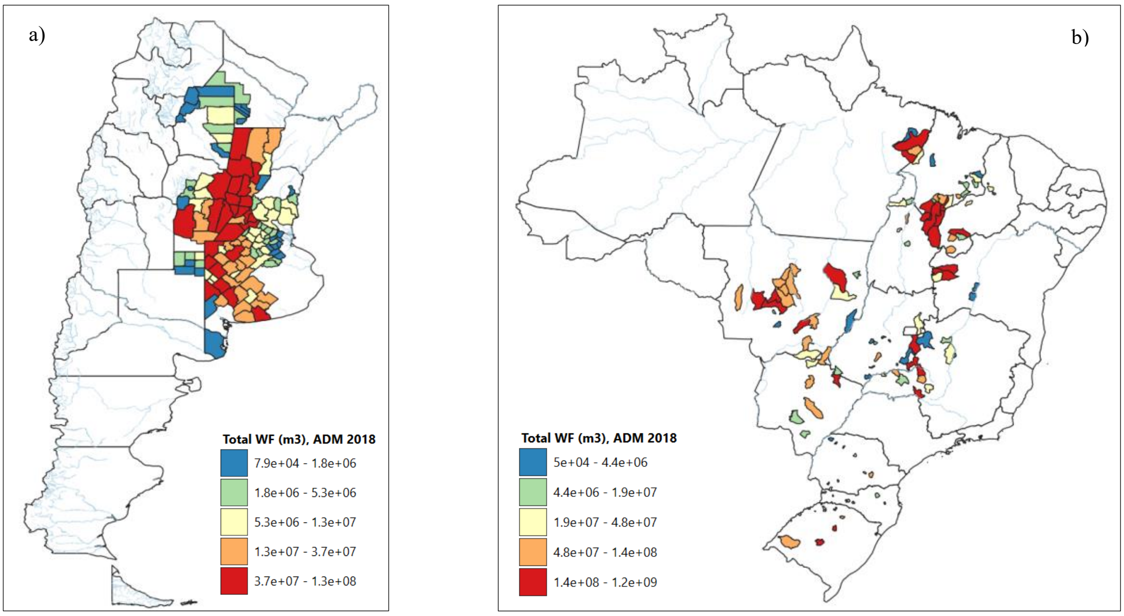


Figure 7.17: Argentina (a) and Brazil (b), soy (2018). ADM's virtual water trade at the subnational scale. Exports towards the major importing countries selected for Argentina and Brazil.

Certainly, climatic events considerably worsened the subnational uWF values in Argentina since, as already discussed, in 2018 a drought period affected the producing region. Nevertheless, it can be appreciated that ADM sourced from sites belonging to different ecoregions, without a geographical continuity from one country to the other one. In Argentina (Figure 7.17a), ADM predominantly relied on departments in La Pampa and Espinal, whereas in Brazil (Figure 7.17b) on municipalities in the Cerrado and Amazonia. The peculiar climatic and geographic features of these biomes inevitably contributed to strengthening the difference between the weighted average $uWFs$ observed. Moreover, the $uWFs$ of the involved sites were considerably different, with variability ranges of $1.3 - 9.5 * 10^3\ m^3/ton$ in Argentina, and $1.2 - 3.2 * 10^3\ m^3/ton$ in Brazil. The overall displacement of virtual water was however much higher in Brazil.

Figure 7.18 illustrates the spatio-temporal evolution of virtual water-weighted barycentres for the five companies. Notably, ADM's barycentre was the northernmost of all the considered companies in Brazil. This further confirmed what already discussed, explaining its different weighted average uWF values if compared to the ones found in Argentina. Any analysis at the subnational scale is indeed pivotal to understand differences.

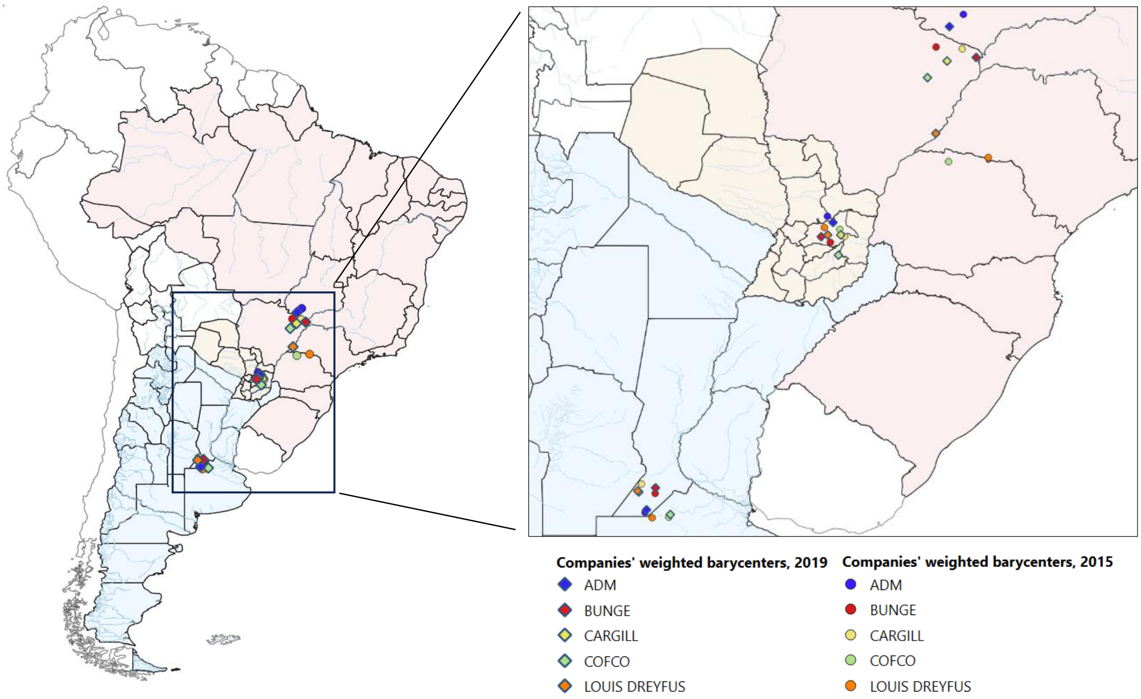


Figure 7.18: South America, soy (2015 – 2019). Virtual water-weighted barycentres of companies' virtual water trade. Barycentres are represented by diamonds in 2019, and circles in 2015.

From Figure 7.18, it also emerges that, in Brazil and Paraguay, COFCO was the trader that showed the greatest variation in its barycentres' location, while in Argentina it was Louis Dreyfus. The comparison between Figure 7.18b-d and Figure 7.18 confirm what observed throughout Chapter 6: moving southward in Argentina and Brazil, water efficiency decreases. In relation to biomes, these traders primarily exerted a pressure on the Argentinian Pampas, the Cerrado in Brazil, and the Mata Atlantica in Brazil and Paraguay.

To conclude the analysis on soybeans market, a few considerations on Vicentin and Sodrugestvo are added since they constituted the first and second traders in terms of exported tonnes from Argentina and Paraguay, respectively. Notably, Vicentin had the lowest unit water footprint in almost all the years. In 2019, for instance, Vicentin's *VWT* was 10% lower than COFCO's, despite its higher exports. This also had a clear effect on the importers' associated *uWF*. As for Sodrugestvo, its *uWFs* tended to converge with those of Cargill over time. Moreover, almost all of Sodrugestvo's export was to the Russian Federation, which relied almost entirely on this trader.

7.3.3.2 Considerations about the other crops

In this section, major findings are reported for the other crops analysed.

Taking into consideration the cocoa market in Brazil, it emerged that Barry Callebaut was associated to a virtual water volume 24% higher than that of Cargill, despite the comparable exported tonnes. Furthermore, it had the greatest weighted average *uWF* (Chapter 6.3.1, Figure 6.25d) among the three companies considered, since it supplied cocoa mainly from water-inefficient municipalities located in Bahia and, more generally, in the Mata Atlantica biome (considerable blue water requirements). Barry Callebaut exported predominantly to Argentina, which consequently had the highest weighted average *uWF* (Chapter 6.3.1, Figure 6.25b). On the other hand, the three major TNCs from Ivory Coast, i.e. Olam, Barry Callebaut and Cargill, displaced similar virtual water volumes, showing weighted average *uWFs* comparable to those of the other exporters. Notably, the three TNCs sourced mainly from the Eastern Guinean Forest biome, the one associated with the most critical deforestation exposure. The Netherlands imported significantly more from both Olam and Cargill compared to other countries.

Cooperativa Regional de Cafeicultores emerged as the first exporter of Brazilian coffee in 2016 and 2017, overtaking the second trader, Terra Forte, respectively by 37% and 45% in terms of tonnes and by 26% and 43% in terms of *VWT*. The United States and Germany were the primary destinations for their exports in both years. Concerning biomes, Mata Atlantica municipalities were the most exploited ones by Terra Forte and the two aforementioned importers, whereas Cooperativa Regional de Cafeicultores relied more on production sites in the Cerrado. Focusing on Colombia, Federacion Nacional emerged as the first exporter for both tonnes and *VWT* over the entire five-year period. Also, it was the major coffee supplier for Japan. Notably, the weighted average *uWF* of this trader was always lower than that of COFCO, despite the latter handled less exports. Concerning Olam and Louis Dreyfus, involved in the coffee trade in both Brazil and Colombia, it emerged that Olam was one of the major exporters from Brazil, whereas in Colombia Louis Dreyfus had a greater role. Interestingly, in Brazil Olam was recorded with the third-to-last weighted average *uWF* (Figure 6.31d, Chapter 6.3.2) over the twenty-six traders analysed.

Notably, most of the corn exports from Brazil were handled by the ABCD companies. On the other hand, despite having a role in 2015 and 2016 exports, COFCO appeared as a marginal trader in 2017. Bunge emerged as the most powerful agrobusiness, closely followed by Cargill and ADM. Among them, only ADM and Louis Dreyfus were associated with a blue *VWT*. The four companies mostly relied on municipalities in the Cerrado, which was indeed the most stressed ecoregion (Chapter 7.2.2, Figure 7.10). Moreover, ADM was supplied by more water demanding sites if compared to the other major traders, showing the highest *uWFs* among them. Regarding Paraguay, the importance of market players varied significantly over time. In 2014 and 2015, Cargill, COFCO, and Louis Dreyfus controlled most of the export. However, they progressively lost importance compared to the rising Agrofertil and LAR. Among the agro-giants, only ADM and Cargill maintained market shares similar to them. Corn demand of the major importer, Brazil, was mostly covered by Agrofertil and LAR over the entire period. It is worth saying that Brazil is not only contributing to massive corn expansion over its territory, but also over Paraguay due to its high imports. Nevertheless, Brazil's *uWF* values were observed to be the lowest among the other countries importing corn from Paraguay. This is explained by the lower water demand of the predominant sourcing sites of Agrofertil and LAR, which were Alto Paraná and Canindeyú. On the other hand, COFCO, Cargill, ADM and Louis Dreyfus often had some of the highest *uWFs*.

Brazil's cotton market was primary managed by the Brazilian SLC Agricola Pejucara and, among the well-known names, Louis Dreyfus. ADM and Cargill had a secondary role, whereas Bunge and COFCO almost did not take part in the market. Notably, Cargill was always recorded with the lowest weighted average *uWFs* with respect to the other mentioned companies. All the selected cotton importers are situated in Asia, as a result of the highly competitive textile industry that has been established in the region. In particular, Indonesia progressively increased its cotton demand, accounting for the largest number of tonnes and greatest *VWT* in 2017. This country was predominantly supplied by SLC Agricola Pejucara. It is worth noting that the weighted average *uWF* of this company had a non-negligible drop over time (– 27% from 2015 to 2017).

7.3.3.3 Integrated TNCs assessment at the subnational scale

All the presented considerations confirmed the importance of analysing temporal and spatial market fluctuations when dealing with agricultural commodities. Indeed, it is not straightforward to individuate a company that has high water requirements in absolute terms. Table 7.2 reports as an illustrative example Cargill’s average uWF values, weighted according to the exported tonnes. The choice of this company is justified by its relevance in the markets analysed (as discussed in Chapter 7.3.2), and its involvement in the deforestation phenomenon.

Table 7.2: Cargill. Temporal and spatial variability of crop-specific weighted average uWF values (m^3/ton). Numbers in red are those used in the discussion below.

	Soybean				**Cocoa**		**Corn**		**Cotton**
Years	**Argentina**	**Bolivia**	**Brazil**	**Paraguay**	**Brazil**	**Ivory Coast**	**Brazil**	**Paraguay**	**Brazil**
2004			2153						
2005			2145						
2006			2206						
2007			1882						
2008			1727						
2009			1870						
2010			1740						
2011			1627						
2012			1635						
2013			1796						
2014			1860	1361				1173	
2015	1876		1769	1651	17572		606	869	996
2016	2067		1760	1542			828	826	761
2017	2010		1552	1338			616	831	568
2018	2684		1609	1326				916	
2019	1830		1703	1720		15795		882	
2020		1321	1585						
2021		1565							

Inter-annual variability arose in exports from the same producing country due to annual variations in the local climatic conditions, as well as changes in traders’ reliance on specific production sites. This is evident from the shifts observed in the TNCs’ weighted barycentres (e.g. in Figure 7.18). It is noteworthy that differences exist for the same agricultural commodity exported from different countries. This suggests varying pressure levels exerted by the same trader in different locations. For example, Cargill’s uWF related to soybeans in 2017 was lower in Brazil than in Paraguay, but the opposite was true for corn exports. Consider the red-coloured numbers in Table 7.2. Further analysis should be conducted on countries that imported a specific commodity through the same trader but from different producing countries to further highlight case-by-case variations. In 2017, Cargill soybeans exports from Brazil to China and to Germany indeed showed relevant differences: $1562\ m^3/ton$ and $1719\ m^3/ton$, being respectively the largest and smallest soybeans importers in terms of tonnes. Furthermore, if focusing on China and comparing its uWF related to Brazil with the one associated with Argentina ($2323\ m^3/ton$), always in 2017, strong differences emerge. These numbers reinforce the importance of using a subnational level of analysis when studying the role of TNCs in the VWT. In each case, the specific supplying sites need to be identified to explain the non-negligible differences in weighted average $uWFs$.

To enable importing countries to make informed decisions when relying on a specific trader, deforestation exposure data should be combined with the knowledge of $uWFs$. Indeed, importers have the possibility to diversify across different companies and production areas, taking into account the site-specific environmental effects of agricultural practices. This approach further complicates the identification of a preferable exporter, as can be observed considering the pressure exerted by Cargill and Vicentin soybean exports in Argentina. Between 2015 and 2019, Vicentin was the top exporter in terms of tonnes, with average *uWFs* lower than those of Cargill. However, Vicentin had higher exposure to deforestation both in absolute terms and relative to the hectares associated with the company's sourcing sites. According to data availability, Almirante Brown, in the Chaco province, emerged with the highest number of hectares exposed to deforestation risk, each year and in the trade flows of both companies. The latest version of Trase only includes territorial deforestation for the Chaco province. Therefore, what discussed may change if the same variable was quantified for other provinces, particularly those in the Gran Chaco. It should be noted that this biome is responsible for the majority of deforestation in Argentina. In recent years, the Dry Chaco, located to the west, has been indeed subject to particularly intensive deforestation (Bracalenti *et al.*, 2023). Also in this case, the same study could be extended to importing countries. As illustrative example, China imports of soybeans from Argentina were considered. Interestingly, from 2015 to 2018 this country had the highest weighted average *uWF* (in 2019 it was second to Egypt) but lowest exposure to deforestation. These results can be explained by the way in which China relied on different traders. For instance, it was supplied mainly by ADM, COFCO and Cargill, and to a lesser extent by Vicentin, the former having higher *uWFs* and the latter having a higher exposure to deforestation. Overall, the country's weighted average *uWFs* varied over time without showing considerable improvements.

Finally, what emerged from the distribution of virtual water-weighted barycentres of importing countries and trading companies is that those of traders tended to be more geographically distributed, while importers' barycentres were closer to each other. This evidence was discussed by De Petrillo et al. (2023) with respect to Brazilian soybeans export, and it was further confirmed for each combination crop-producer considered in this thesis. Chapter 6 shows examples for the last available year of each combination. The statistical analysis performed also demonstrated these differences, with CDFs and boxplots much more similar among importing countries than traders. The observed behaviour is explicative of how single traders tended to control and rely on specific geographic areas, whereas countries generally showed more regionalised barycentres, diversifying across different companies.

The findings indicate that combining multiple data types is crucial to obtaining a comprehensive understanding of the role of Transnational Corporations in virtual water trade. It is essential to perform each analysis considering a subnational level of detail and the unit water footprint values of production sites. In fact, the water volumes virtually displaced are not meaningful on their own and must be accurately associated with the pressure exerted on local water resources. This approach enables to determine whether a high total water requirement is primarily due to high exports or high pressure. If the latter is the case, the most stressed production areas can be identified and the implementation of dedicated measures to improve water management can be considered.

Chapter 8 – Conclusions

Food production is strongly linked to factors detrimental to the well-being of the planet. Land clearing, forest loss, and the destruction of unique ecosystems that provide essential services are only a few examples. Among all, freshwater consumption for agricultural practices has become a topic of increasingly concern. Not only considering the projections of global population growth, but especially based on current utilisation patterns which are often characterised by water inefficiency. Moreover, the globalisation of food commodities has brought the attention to the concept of virtual water trade, directly related to water scarcity and water availability. Indeed, countries with highly suitable climatic conditions for globally demanded crops have started facing both land and water grabbing in the last decades. This has turned into widespread deforestation and massive use of local freshwater resources. Studies showing approximate values for grabbed water, given by rainfall and irrigation practices, are generally referring to the national scale (Rulli, Saviori and D'Odorico, 2013). Through the work done in the present thesis, results were not only scaled down to production sites, but they also considered the specific role of Transnational Corporations. Indeed, it is pivotal to obtain fine-scale high-resolution information about the virtual reallocation of water resources by means of international traders. This objective was achieved by merging 5 arc min grid level evapotranspiration data (Tuninetti *et al.*, 2015) with datasets providing trade data at the subnational level (Trase). The methodology used, developed by revisiting and generalising De Petrillo et al. (2023) work, allowed the spatial and temporal analysis of water requirements for the production of crops exposed to deforestation risk in countries located in tropical regions. This knowledge was further used for the virtual water trade assessment of major trading companies, which were selected according to a well-established threshold level. Flows of selected agricultural commodities were analysed with respect to their primary importing countries (FAOSTAT).

The need to focus on Transnational Corporations is explained by their key role in driving food supply chains. However, as long as profitability remains a major concern for trading companies, environmental and social pressures will continue to increase, along with externalities caused by the cost-benefit logic. Critical agricultural products have been turned into commodities, with consumers losing the perception of what they are really purchasing, within a market that renders these products fungible. In turn, trading companies keep on trying to maintain logistics and transportation costs as low as possible, often disregarding what the consequences are. Therefore, it has become increasingly crucial to raise awareness about the local pressure and resource utilisation related to globally demanded crops, starting from analysing traders' behaviour.

The analysis performed indicates that the ABCD agribusinesses, together with COFCO, were largely responsible for significant market shares. In particular, they emerged as the predominant actors in global soybeans export from Argentina, Brazil and Paraguay. However, a considerable number of lesser-known traders emerged alongside them, especially in the coffee and cocoa markets where several companies are specialised in the trade of these commodities. In all the considered cases, it was observed that the pressure exerted on local freshwater by traders, from the smallest to the largest ones, exhibited not negligible temporal variations. These were caused by changes in local water efficiencies or in the companies' supplying sites, or both. The dedicated in-depth study presented for Cargill and the examples reported for soybeans trade flows confirmed the importance of focusing on subnational information to grasp the heterogeneity of virtual water trade related aspects.

Investigating on Trase datasets, it was discovered that the geocodes provided for Ivory Coast departments were incorrect. Therefore, they were properly substituted based on OCHRA shapefiles. Moreover, outliers were identified in a few cases, with respect to yield values resulting from the declared exported tonnes and related cultivated hectares as reported by Trase. This circumstance were encountered for soybeans trade flows from Bolivia (2021) and Brazil (2020), and for Brazilian corn (2015). Decisions were made on a case-by-case basis to eventually remove trade data. Anomalies were detected in unit water footprint values as well, requiring dedicated upstream analysis of evapotranspiration data. Excessively high blue *ET* values were removed for soybeans in Brazil.

The major limit of this study was the application of time invariant yields in Colombia for the assessment of coffee unit water footprint values, at the subnational scale. Indeed, water requirements resulted much higher than those reported in other studies (Mekonnen and Hoekstra, 2010). For what concerns evapotranspiration data, future studies at the country scale should be better based on irrigation data available on national databases, therefore more updated and detailed. This would add a further degree of reliability and precision on final results.

Overall, this thesis work provides an in-depth analysis of the virtual water trade of major Transnational Corporations. It includes information on the total water volume virtually traded from all the supplying sites, the pressure exerted in terms of water required over each producing site and each biome, and the partitioning of *VW* trades to the importing countries relying on a given trader. Throughout temporal analysis, variations in the role played by traders are highlighted through changes in market shares and traded volumes. The case of Sodrugestvo in soybeans export from Paraguay is emblematic: in the five-year period analysed, this company went from not being involved in the market to becoming the second-largest exporter from the country. Concerning the analysis performed over biomes, it could be further combined with anthropogenic biomes data (Ellis and Ramankutty, 2008) to uncover the anthropomorphisation level of each natural area. Specifically, it would be meaningful to individuate whether a simultaneous land use change and agricultural expansion has occurred, at the subnational scale, combining this information with the observed changes in water requirements.

The results of traders' *VWTs* and *uWFs* detailed at the subnational scale are pivotal to enhance interventions and coordination in supply chain governance. Once the involved actors are aware of the local environmental issues related to their supplying choices, they might consciously operate and plan for improvements. Their key role in water stewardship is indeed becoming clearer, therefore enhancing dialogue between Transnational Corporations and initiatives like Trase is essential to elaborate on data and extract truthful information. TNCs have already started introducing annual Sustainability reports, as well as Water Security reports. The latter could be further enriched and developed joining the efforts of research entities and traders' transparency. It is worth mentioning CDP (Carbon Disclosure Project), a not-for-profit charity aiming to define the climatic and environmental impact of companies, comprising deforestation and water security issues. This international organisation is an example of how scientific data can be gathered and further elaborated to catalyse companies' actions towards more sustainable choices. Multiple levels of complexity characterise the virtual trade of water, from the precise understanding of water cycle's alterations due to climate and land use changes to the challenging traceability of commodity trade flows at the local scale. It is therefore essential that businesses and research improve cooperation towards a better use of water resources, or more broadly natural resources.

References

Agronet (2021) *Coffee Production and Coffee Growing Area in Colombia Departments*. Available at: https://www.agronet.gov.co/estadistica/Paginas/home.aspx?cod=1.

Allen, R.G., Pereira, L.S. and Raes, D. (1998) *Crop Evapotranspiration (guidelines for computing crop water requirements)*.

Astrakhantseva, E., Shipshova, O. and Antonova, M. (2019) *The role of transnational corporations in the globalization of the economy*.

Beck, H.E. *et al.* (2020) 'Publisher Correction: Present and future Köppen-Geiger climate classification maps at 1-km resolution'. Available at: https://doi.org/10.1038/s41597-020-00616-w.

Bracalenti, M.A. *et al.* (2023) *EGUsphere - The agricultural expansion in South America's Dry Chaco: Regional hydroclimate effects*. Available at: https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1427/.

Brezina, I. *et al.* (2016) 'Herfindahl–Hirschman index level of concentration values modification and analysis of their change', *Central European Journal of Operations Research*, 24(1), pp. 49–72. Available at: https://doi.org/10.1007/s10100-014-0350-y.

Carbon Disclosure Project *Companies - CDP*. Available at: https://www.cdp.net/en/companies.

Chain Reaction Research (2023) *Sodrugestvo: Soy Trader Linked to Brazilian Deforestation, Russian Finances - Chain Reaction Research*. Available at: https://chainreactionresearch.com/report/sodrugestvo-soy-brazilian-deforestation-russian-finances/.

Clapp, J. (2016) *Food.* 2nd ed.

Costa W (2021) *Paraguay on the brink as historic drought depletes river, its life-giving artery | Global development | The Guardian*. Available at: https://www.theguardian.com/global-development/2021/sep/27/paraguay-severe-drought-depletes-river.

CWASI *Download - CWASI Database - Water To Food*. Available at: https://www.watertofood.org/download/.

Czaplicki Cabezas, S. (2023) *The hidden crisis of deforestation in Bolivia - Insights - Trase*. Available at: https://trase.earth/insights/the-hidden-crisis-of-deforestation-in-bolivia.

Davey E (2018) *How Cocoa Farming Can Preserve Forests and Peace in Colombia | World Resources Institute*. Available at: https://www.wri.org/insights/how-cocoa-farming-can-preserve-forests-and-peace-colombia.

Dias, C.G., Martins, F.B. and Martins, M.A. (2024) 'Climate risks and vulnerabilities of the Arabica coffee in Brazil under current and future climates considering new CMIP6 models', *Science of The Total Environment*, 907, p. 167753. Available at: https://doi.org/10.1016/J.SCITOTENV.2023.167753.

Eisa, J. and White, N. (2018) *Coffee farmers struggle to adapt to Colombia's changing climate | PreventionWeb*. Available at: https://www.preventionweb.net/news/coffee-farmers-struggle-adapt-colombias-changing-climate.

Ellis, E.C. and Ramankutty, N. (2008) ‘Putting people in the map: Anthropogenic biomes of the world’, *Frontiers in Ecology and the Environment*. Ecological Society of America, pp. 439–447. Available at: https://doi.org/10.1890/070062.

European Commission *Glossary: Triad - Statistics Explained*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Triad.

Fama, M. and Conti, M. (2022) ‘Food security and agricultural crises in a “financialized food regime”’, *Cambio. Rivista sulle Trasformazioni Sociali*, 12(23). Available at: https://doi.org/10.36253/cambio-13164.

FAO (2004) *Fertilizer use by crop in Argentina. Chapter 1.* Rome. Available at: https://www.fao.org/3/y5210e/y5210e05.htm.

FAO and United Nations *UN Decade on Restoration*. Available at: https://www.decadeonrestoration.org/.

FAOSTAT *FAOSTAT*. Available at: https://www.fao.org/faostat/en/#data.

FAOSTAT, a *FAOSTAT. Crops and livestock products*. Available at: https://www.fao.org/faostat/en/#data/QCL.

Gardner, T. (2023) *Trase: Mapping the trade and financing of forest risk commodities*. Available at: https://www.sei.org/tools/trase/.

Gibbon, P. (2001) ‘Upgrading Primary Production: A Global Commodity Chain Approach’, *World Development*, 29(2), pp. 345–363. Available at: https://doi.org/10.1016/S0305-750X(00)00093-0.

Global Witness (2023) ‘Empty promises. Cargill, soy, banks and the destruction of Bolivia’s Chiquitano Forest’.

Global Yield Gap Atlas (2023) *Argentina - Global yield gap atlas*. Available at: https://www.yieldgap.org/argentina.

Godar, J. *et al.* (2015) ‘Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption’, *Ecological Economics*, 112, pp. 25–35. Available at: https://doi.org/10.1016/J.ECOLECON.2015.02.003.

Godar, J. *et al.* (2016) ‘Balancing detail and scale in assessing transparency to improve the governance of agricultural commodity supply chains’, *Environmental Research Letters*, 11(3). Available at: https://doi.org/10.1088/1748-9326/11/3/035015.

Greer, J. and Singh, K. (2000) *A Brief History of Transnational Corporations*. Available at: https://archive.globalpolicy.org/component/content/article/221-transnational-corporations/47068-a-brief-history-of-transnational-corporations.html.

Guida Johnson, B. and Zuleta, G.A. (2013) ‘Land-use land-cover change and ecosystem loss in the Espinal ecoregion, Argentina’, *Agriculture, Ecosystems & Environment*, 181, pp. 31–40. Available at: https://doi.org/10.1016/J.AGEE.2013.09.002.

Heilmayr, R. *et al.* (2020) ‘Brazil’s Amazon Soy Moratorium reduced deforestation’, *Nature Food*, 1(12), pp. 801–810. Available at: https://doi.org/10.1038/s43016-020-00194-5.

Henderson, J. *et al.* (2021) ‘The Paraguayan Chaco at a crossroads: drivers of an emerging soybean frontier’. Available at: https://doi.org/10.1007/s10113-021-01804-z/Published.

Hiba J (2022) *Heatwave and drought hit South America’s crops and economy*. Available at: https://dialogochino.net/en/agriculture/50488-drought-south-america-soy-maize-economy/.

Holzman, M. and Rivas, R. (2016) ‘Optical/Thermal-Based Techniques for Subsurface Soil Moisture Estimation’, *Satellite Soil Moisture Retrieval: Techniques and Applications*, pp. 73–89. Available at: https://doi.org/10.1016/B978-0-12-803388-3.00004-8.

Humanitarian Data Exchange *Welcome - Humanitarian Data Exchange*. Available at: https://data.humdata.org/.

Igini M (2023) *Deforestation in Colombia: An Intricate Story of Conflict and Power | Earth.Org*. Available at: https://earth.org/deforestation-in-colombia/.

Irwin A (2023) *Expeditions in post-war Colombia have found hundreds of new species. But rich ecosystems are now under threat*. Available at: https://www.nature.com/immersive/d41586-023-02300-6/index.html.

Jordan, L. *et al.* (2020) *Cargill: the company feeding the world by helping destroy the planet*, *UNEARTHED*.

Kalischek, N. *et al.* (2023) ‘Cocoa plantations are associated with deforestation in Côte d’Ivoire and Ghana’, *Nature Food 2023 4:5*, 4(5), pp. 384–393. Available at: https://doi.org/10.1038/s43016-023-00751-8.

Kordos, M. and Vojtovic, S. (2016) ‘ScienceDirect Transnational corporations in the global world economic environment’, *Procedia-Social and Behavioral Sciences*, 230, pp. 150–158. Available at: https://doi.org/10.1016/j.sbspro.2016.09.019.

Läderach, P. *et al.* (2013) ‘Predicting the future climatic suitability for cocoa farming of the world’s leading producer countries, Ghana and Côte d’Ivoire’, *Climatic Change*, 119(3–4), pp. 841–854. Available at: https://doi.org/10.1007/S10584-013-0774-8.

Lai, O. (2023) *13 Major Companies Responsible for Deforestation | Earth.Org*. Available at: https://earth.org/major-companies-responsible-for-deforestation/.

Leal *et al.* (2022) *The State of the World’s Mangroves 2022 | ICRI*. Available at: https://icriforum.org/the-state-of-the-worlds-mangroves-2022-report/.

Leal-Echeverri, J.C. and Tobón, C. (2021) ‘The water footprint of coffee production in Colombia’, *Revista Facultad Nacional de Agronomia Medellin*, 74(3), pp. 9685–9697. Available at: https://doi.org/10.15446/rfnam.v74n3.91461.

Lu, M. (2022) *These are the largest hydroelectric dams in the world | World Economic Forum*. Available at: https://www.weforum.org/agenda/2022/12/worlds-largest-hydroelectric-dams-renewable-energy/.

MAPSPAM *Home of the Spatial Production Allocation Model (MAPSPAM) | IFPRI INFO: Conversation – collaboration – community site*. Available at: https://mapspam.info/.

Marca País Colombia *Colombian Paramos That Have To Be Explored | Marca País Colombia*. Available at: https://www.colombia.co/en/colombia-country/environment/five-unmissable-colombian-paramos-begging-explored/.

Mekonnen, M.M. and Hoekstra, A.Y. (2010) *Value of Water Research Report Series No. 48 Volume 2: Appendices Value of Water*.

Mekonnen, M.M. and Hoekstra, A.Y. (2011) ‘The green, blue and grey water footprint of crops and derived crop products’, *Hydrol. Earth Syst. Sci*, 15, pp. 1577–1600. Available at: https://doi.org/10.5194/hess-15-1577-2011.

Mondelez International *Cocoa Life - Climate Change*. Available at: https://www.cocoalife.org/the-program/climate-change/.

NASA (2022) *The Spread of Soy in South America*. Available at: https://earthobservatory.nasa.gov/images/149621/the-spread-of-soy-in-south-america.

Nature and Culture International *Páramo Grasslands » Nature and Culture International*. Available at: https://www.natureandculture.org/wild-places/paramo-grasslands/.

Norberg, M.B. and Deutsch, L. (2023) ‘The regime of the third soybean cycle (1950–today)’, in *The Soybean Through World History*. Routledge, pp. 155–212. Available at: https://doi.org/10.4324/9780367822866-5.

OCHA *A Roadmap for the Evolution of HDX | OCHA*. Available at: https://www.unocha.org/publications/report/world/roadmap-evolution-hdx.

Oliveira, G.D.L.T. and Hecht, S.B. (2017) *Soy, Globalization, and Environmental Politics in South America. Routledge.* 1st ed.

Our World in Data *Our World in Data*. Available at: https://ourworldindata.org/.

Pacheco, P., Mertens, B. and Cruz, S. (2004) ‘Land use change and agricultural development’.

Peel, M.C., Finlayson, B.L. and Mcmahon, T.A. (2007) ‘Hydrology and Earth System Sciences Updated world map of the Köppen-Geiger climate classification’, *Hydrol. Earth Syst. Sci*, 11, pp. 1633–1644. Available at: www.hydrol-earth-syst-sci.net/11/1633/2007/.

Penalba, O.C., Bettolli, M.L. and Vargas, W.M. (2007) ‘The impact of climate variability on soybean yields in Argentina. Multivariate regression’, *Meteorological Applications*, 14(1), pp. 3–14. Available at: https://doi.org/10.1002/MET.1.

Pendrill, F. *et al.* (2022) ‘Disentangling the numbers behind agriculture-driven tropical deforestation’, *Science*, 377(6611). Available at: https://doi.org/10.1126/SCIENCE.ABM9267.

De Petrillo, E. (2021) ‘A step forward toward the high-resolution assessment of water footprint at the company’s scale’.

De Petrillo, E. *et al.* (2023) ‘International corporations trading Brazilian soy are keystone actors for water stewardship’. Available at: https://doi.org/10.1038/s43247-023-00742-4.

Prado, R.B. *et al.* (2012) ‘Mapping soil fertility at different scales to support sustainable Brazilian agriculture’.

Radwin M (2023) *Agro giant Cargill tied to deforestation in Bolivia’s Chiquitano forest*. Available at: https://news.mongabay.com/2023/09/agro-giant-cargill-tied-to-deforestation-in-bolivias-chiquitano-forest/.

Rausch L (2021) *Brazil's Amazon soy moratorium | WWF Forest Solutions*. Available at: https://forestsolutions.panda.org/case-studies/brazils-amazon-soy-moratorium.

Rulli, M.C., Saviori, A. and D'Odorico, P. (2013) 'Global land and water grabbing', *Proceedings of the National Academy of Sciences of the United States of America*, 110(3), pp. 892–897. Available at: https://doi.org/10.1073/PNAS.1213163110/-/DCSUPPLEMENTAL/ST01.DOC.

Scott M (2016) *Climate & Chocolate | NOAA Climate.gov*. Available at: https://www.climate.gov/news-features/climate-and/climate-chocolate.

SEI *Stockholm Environment Institute: bridging science and policy*. Available at: https://www.sei.org/.

Sgroi, L.C. *et al.* (2021) 'Characteristics of droughts in Argentina's core crop region', *Hydrol. Earth Syst. Sci*, 25. Available at: https://doi.org/10.5194/hess-25-2475-2021.

Shiferaw, B. *et al.* (2011) 'Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security', *Food Security*, 3(3), pp. 307–327. Available at: https://doi.org/10.1007/S12571-011-0140-5/TABLES/3.

Song, X.P. *et al.* (2021) 'Massive soybean expansion in South America since 2000 and implications for conservation', *Nature Sustainability*, 4(9), pp. 784–792. Available at: https://doi.org/10.1038/s41893-021-00729-z.

SPAM 2010 *Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0 - IFPRI HarvestChoice Dataverse*. Available at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PRFF8V.

Sustainable Coffee Challenge *Coffee production in the face of climate change: Brazil*, *THE IMPORTANCE OF COFFEE IN THE BRAZILIAN AGRICULTURAL SECTOR*.

Tandon A (2023) *South American drought in 2022 partly driven by 'triple-dip' La Niña - Carbon Brief*. Available at: https://www.carbonbrief.org/south-american-drought-in-2022-partly-driven-by-triple-dip-la-nina/.

The Colombian Coffee Co. *COFFEE GROWING REGIONS IN COLOMBIA – The Colombian Coffee Co.* Available at: https://thecolombiancoffeeco.com.au/coffee-growing-regions-in-colombia/.

The World Bank (2022) *Water in Agriculture*. Available at: https://www.worldbank.org/en/topic/water-in-agriculture.

Trase (no date) *Trase*. Available at: https://trase.earth/.

Trimmer C. and Goldstein A. (2020) *How to protect Colombia's forests as global demand for coffee soars*. Available at: https://trase.earth/insights/colombia-coffee-futures.

Tuninetti, M. *et al.* (2015) 'Global sensitivity of high-resolution estimates of crop water footprint', *Water Resources Research*, 51(10), pp. 8257–8272. Available at: https://doi.org/10.1002/2015WR017148.

Tyldesley M (2021) *Trase Insights - Soy deforestation risk in Paraguay continues despite decline*. Available at: https://insights.trase.earth/insights/soy-deforestation-risk-in-paraguay-continues-despite-decline/.

UN Environment Programme (2019) *Megadiverse Brazil: giving biodiversity an online boost*. Available at: https://www.unep.org/news-and-stories/story/megadiverse-brazil-giving-biodiversity-online-boost.

UNCTAD (2023) *TRADE AND DEVELOPMENT REPORT 2023 - Growth, Debt and Climate: Realigning the Global Financial Architecture*.

UNIDO *Water stewardship | UNIDO*. Available at: https://www.unido.org/our-focus/safeguarding-environment/resource-efficient-and-low-carbon-industrial-production/industry-and-adaptation/water-stewardship.

United Nations (1983) 'Draft United Nations Code of Conducts on Transnational Corporations'.

United Nations (2022) *'One Million Corals for Colombia': the largest ocean reef restoration project in the Americas | Un millón de corales por Colombia: El proyecto de restauración oceánica más grande de las Américas UN News*. Available at: https://news.un.org/en/story/2022/06/1121292.

U.S. Department of Justice and the Federal Trade Commission (2010) 'Horizontal Merger Guidelines'.

United Nations *Population | United Nations*. Available at: https://www.un.org/en/global-issues/population.

U.S. Department of Agriculture (a) *Argentina Soybean Area, Yield and Production*. Available at: https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=AR&crop=Soybean.

U.S. Department of Agriculture (b) *Southern South America - Mexico, Central America and Caribbean - Crop Production Maps*. Available at: https://ipad.fas.usda.gov/rssiws/al/ssa_cropprod.aspx.

Velpuri, N.M. and Senay, G.B. (2017) 'Partitioning Evapotranspiration into Green and Blue Water Sources in the Conterminous United States', *Scientific Reports*, 7(1). Available at: https://doi.org/10.1038/s41598-017-06359-w.

Wasley, A. *et al.* (2021) *Loophole Lets Soya Farmers Tear down the Amazon*, *Enterprises at Les Droits de l'Homme. Centre de Ressources sur les.* Available at: https://www.thebureauinvestigates.com/stories/2021-05-19/loophole-lets-soya-farmers-tear-down-the-amazon.

Watts J (2023) *Amazon deforestation falls over 60% compared with last July, says Brazilian minister | Amazon rainforest | The Guardian*. Available at: https://www.theguardian.com/environment/2023/aug/02/amazon-deforestation-falls-over-60-compared-with-last-july-says-brazilian-minister.

Weis, T. (2015) 'SFSGEC - Meatification and the madness of the doubling narrative', *Canadian Food Studies / La Revue canadienne des études sur l'alimentation*, 2(2), pp. 296–303. Available at: https://doi.org/10.15353/CFS-RCEA.V2I2.105.

Weis, T. (2016) *The Meatification of Diets*. Available at: https://www.researchgate.net/publication/343021406.

WWF a *The Pantanal: Saving the world's largest tropical wetland | Projects | WWF*. Available at: https://www.worldwildlife.org/projects/the-pantanal-saving-the-world-s-largest-tropical-wetland.

WWF b *Pantanal Programme | WWF*. Available at: https://wwf.panda.org/wwf_offices/bolivia/our_work/pantanal_programme/.

WWF c *Cerrado | Places | WWF*. Available at: https://www.worldwildlife.org/places/cerrado.

WWF d (2022) *Expansion of agriculture and livestock reduce biodiversity in the Cerrado and Amazon, study finds | WWF Brasil*. Available at: https://www.wwf.org.br/?81748/Expansion-of-agriculture-and-livestock-reduce-biodiversity-in-the-Cerrado-and-Amazon-study-finds.

Zibaoui, A. (2023) *The BRICS are shaking up the international system - ASCAME*. Available at: https://www.ascame.org/new/the-brics-are-shaking-up-the-international-system/.

Appendix A

Relevant maps are reported to clarify the differences between the dataset used by De Petrillo (2021) and De Petrillo et al. (2023) and the updated version (Trase), which was considered in the present thesis. Specifically, soybeans trade flows from Brazil were analysed.

Maps in Figure A.1 show the changes in terms of traded tonnes, with respect to the ten major importing countries and the nine related traders, as selected by De Petrillo et al. (2023). The year under study is 2018. It clearly emerges that Trase brought consistent updates to the original dataset. Data are shown for China, Netherlands, Spain, France, Thailand, Germany, Iran, South Korea, Italy and United Kingdom. The selected traders are Bunge, Cargill, ADM, Louis Dreyfus, Cofco, Glencore, Amaggi, Gavilon and Bianchini.

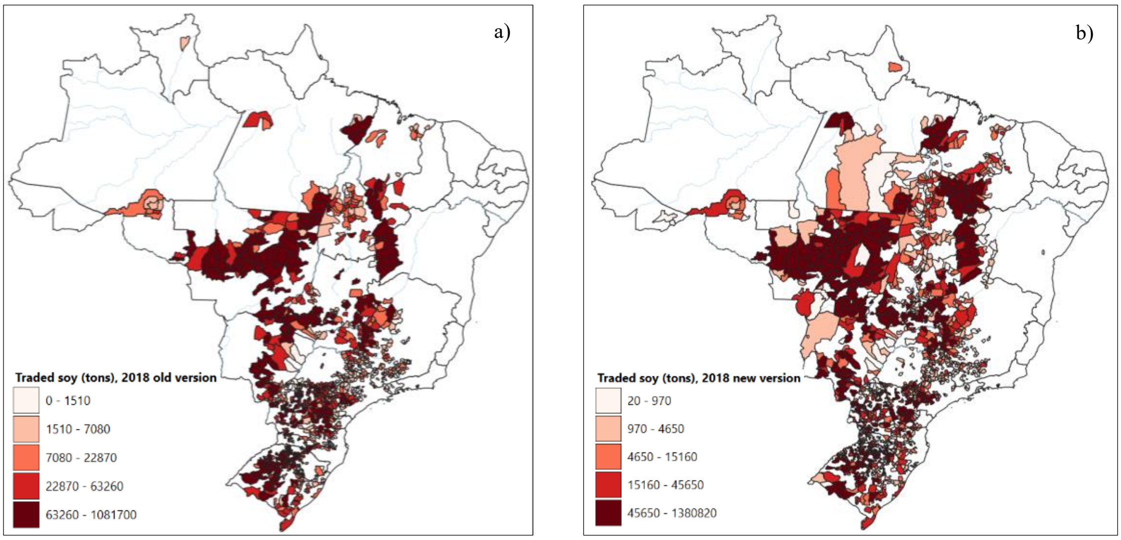


Figure A.1: Brazil, soy (2018). Comparison between the old dataset version (a) and the latest release (b).

On the other hand, the aim of Figure A.2 is to detect differences among years, within the same dataset version (2.6.0). The maps reported (2018, 2020) are meaningful for the eight top importing countries and the related major traders (thirteen and seventeen, respectively). Data are shown for China, Netherlands, Spain, Thailand, France, Germany, Iran and South Korea. In 2018, the most relevant traders were Bunge, Cargill, ADM, Louis Dreyfus, Cofco, Amaggi, Glencore, Gavilon, Coamo, Amaggi & LD Commodities, Bianchini, Caramuru and Cooperativa Agraria Agroindustrial. In 2020, instead, ADM, Cargill, Bunge, Louis Dreyfus, Cofco, Coamo, Amaggi, Gavilon, Engelhart, CHS, Glencore, Olam, Bianchini, Cooperativa Agraria Agroindustrial, Cervejaria Petropolis, Cocamar Cooperativa Agroindustrial and Bianchini SA Industria. Visible changes can be observed in almost all producing states. Furthermore, the number of involved municipalities increased from 1380 to 1630 during the two-year period.

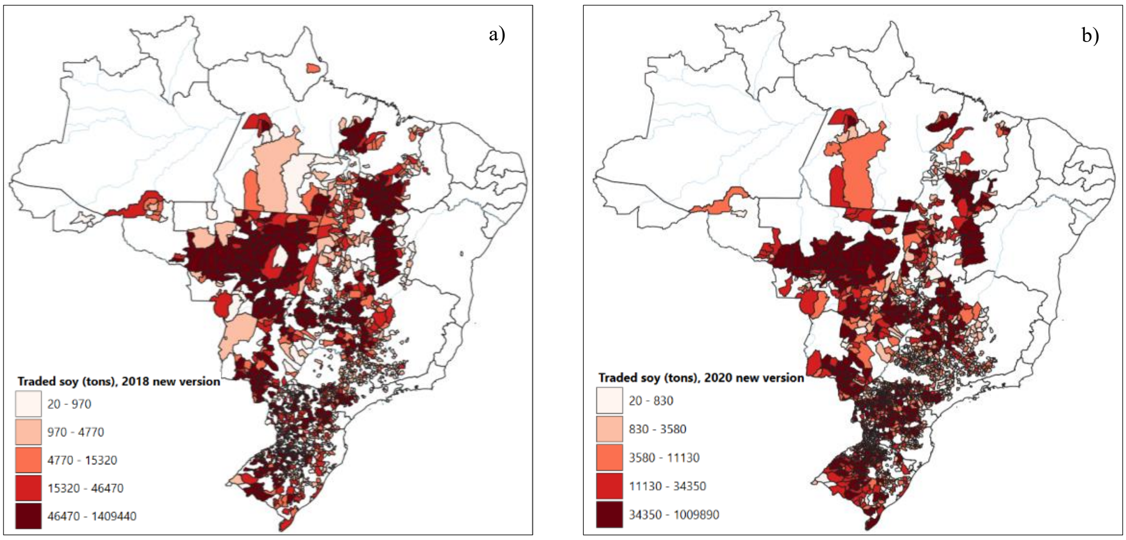


Figure A.2: Brazil, soy. Comparison between the municipalities involved in 2018 (a) and in 2020 (b), using the latest dataset available.

Appendix B

Whitin Appendix B, some details are given for the major Transnational Corporations. Furthermore, whenever available, links to companies' assessment reports are provided.

- *ADM*, Archer-Daniels-Midland Company: American multinational food processing and commodities trading corporation founded in 1902 and headquartered in Chicago, Illinois. The company provides a No-deforestation and Human Rights assessment Report, as well as a Corporate Sustainability Report for 2022.
  https://www.adm.com/globalassets/sustainability/sustainability-reports/adm-no-deforestation-and-human-rights-program-assessment-report-final.pdf
  https://www.adm.com/globalassets/sustainability/sustainability-reports/2022-reports/adm-2022-corporate-sustainability-report_final.pdf
- *AGD*, Aceitera General Deheza SA: Argentine agro-industrial complex dedicated to the production of proteins and vegetable oils , biodiesel and refined glycerin. It was founded in 1948.
- *Agrofertil SA*: founded in 1993, is one of Paraguay's leading crop input distributor and agronomic services companies. The company's headquarters are in Ciudad del Este, Paraguay.
- *Amaggi:* Brazilian commodities company involved in the soybean industry. It is the largest private producer of soybeans in the world. It was founded in 1977 and its headquarters are in Cuiabá, State of Mato Grosso, Brazil.
- *Barry Callebaut:* Swiss-Belgian cocoa processor and chocolate manufacturer. It was created in 1996 through the merging of the French company Cacao Barry and the Belgian chocolate producer Callebaut. Its headquarters are in Zürich, Switzerland.
- *Bunge* Global SA: global agribusiness and food company, incorporated in Geneva, Switzerland and headquartered in St. Louis, Missouri, United States. It was founded in 1818. Their Global Sustainability Report for 2022 is available at the following link.
  https://www.bunge.com/-/media/files/pdf/2022_non_deforestation_report
- *Cargill*: American global food corporation based in Minnetonka, Minnesota, and incorporated in Wilmington, Delaware. It was founded in 1865. The company provides the ESG report for 2023, available at the following link.
  https://www.cargill.com/sustainability/doc/1432249635993/2023-esg-report.pdf
- *Coamo Agroindustrial Coop:* Brazilian farming cooperative processing and trading in agricultural commodities. The cooperative is one of the top exporters of soy from Brazil.
- *COFCO*: Chinese state-owned food processing holding company. Its headquarters are in the COFCO Fortune Plaza in Chaoyang District, Beijing. It was founded in 1949.
  At the following link, COFCO sustainability report for 2022 is provided.
  https://www.cofcointernational.com/media/jval4ls5/7241-cofco-sr22-23-06-30-web.pdf
- *CHS:* diversified global agribusiness cooperative owned by farmers and local cooperatives across the United States.
- *Engelhart*: international commodity trading company, founded in 2013 by BTG Pactual Group.
- *Gavilon:* commodity management firm based in Omaha, Nebraska. The company is organized into two operating segments, which are Grain & Ingredients and Fertilizers. Its history dates back to 1874.

- *Glencore*: Swiss multinational commodity trading and mining company with headquarters in Baar, Switzerland. The current company was created in 2013, however originally founded in 1974.
- *Louis Dreyfus* Company B.V.: French merchant firm involved in agriculture, food processing, international shipping, and finance. Founded in 1851, its headquarters are in Rotterdam, Netherlands.
  The Sustainability report for 2022 is provided.
  https://www.ldc.com/wp-content/uploads/LDC-2022-Sustainability-Report_protected.pdf
- *Mitsui & Co,* Ltd: one of the largest sogo shosha in Japan; it is part of the Mitsui Group. Its headquarters are in Tokyo, Japan, and its foundation dates back to 1947.
- *Olam*: major food and agri-business company, operating in 60 countries and supplying food and industrial raw materials worldwide. Its value chain includes farming, origination, processing and distribution operations. It was founded in 1989 and has its headquarters in Singapore.
- *Perez Companc Family Group*: Argentinian holding company primarily involved the energy business, such as oil and gas, petrochemicals and electricity.
- *Sodrugestvo* Group: based in Luxembourg, it is an agro-industrial company, which specialise in soybean and rapeseed processing, purchasing of grains and oilseeds and distribution of those products to the end consumer. It was founded in 1994.
- *Vicentin*: Argentinian agro-industrial company active in textiles, agriculture, and agricultural products. It is a major player in the Argentinian soy market. Its headquarters are in Buenos Aires, Argentina. Currently, it has been threatened with bankruptcy.

Appendix C

In Appendix C, additional maps and plots are reported for each case analysed in Chapter 6. The aim is to provide an equal description to soybean in Argentina, according to site specific data availability.

Bolivia – soy 2021

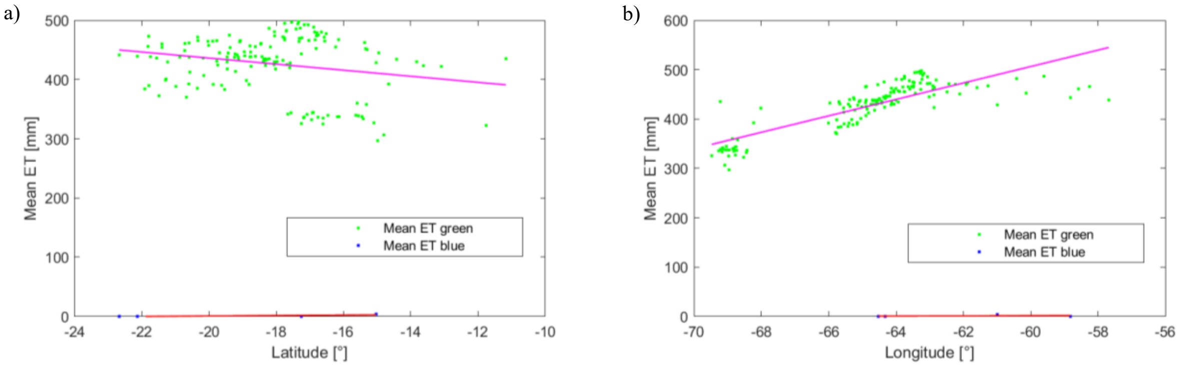


Figure C.1: Average evapotranspiration data for each Bolivian municipality. Geographical distribution is shown according to the latitude (a) and the longitude (b).

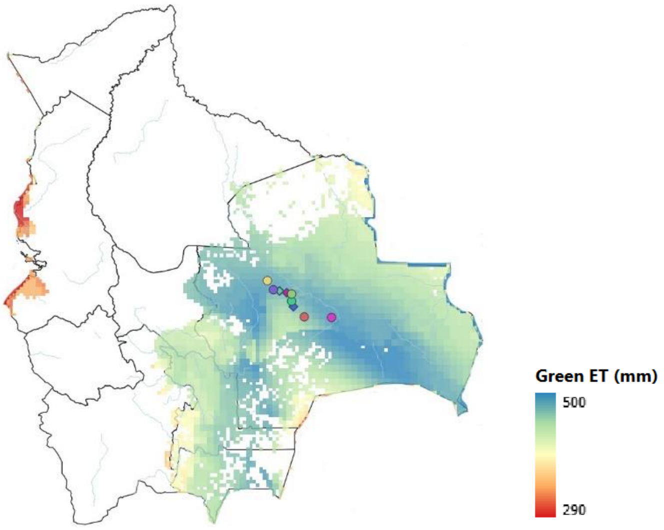


Figure C.2: Bolivia, soy (2021). Virtual water-weighted barycentres and green evapotranspiration data for soybeans.

Brazil – cocoa 2015

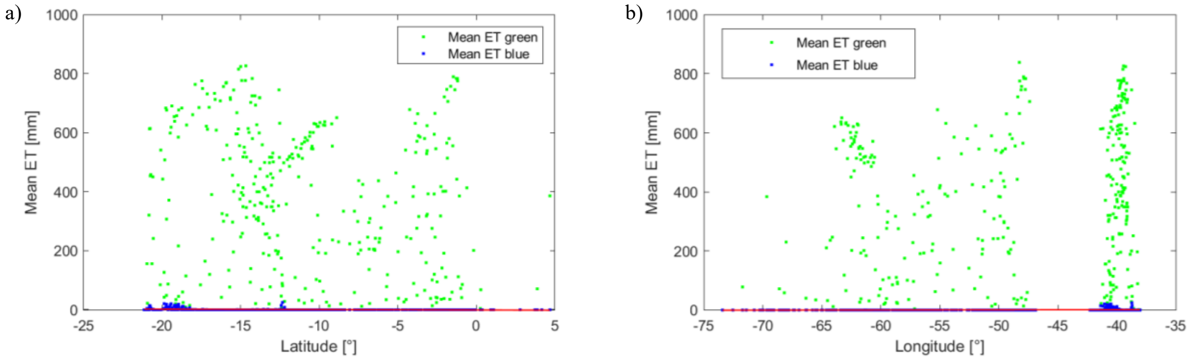


Figure C.3: Average evapotranspiration data for each Brazilian municipality. Geographical distribution is shown according to the latitude (a) and the longitude (b).

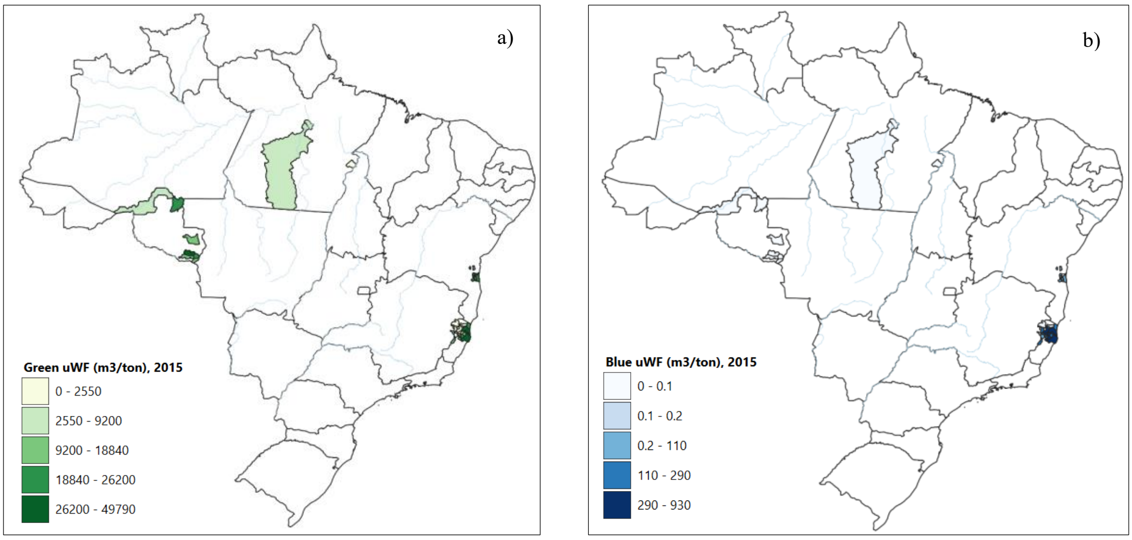


Figure C.4: Brazil, cocoa (2015). Green (a) and blue (b) unit water footprint values.

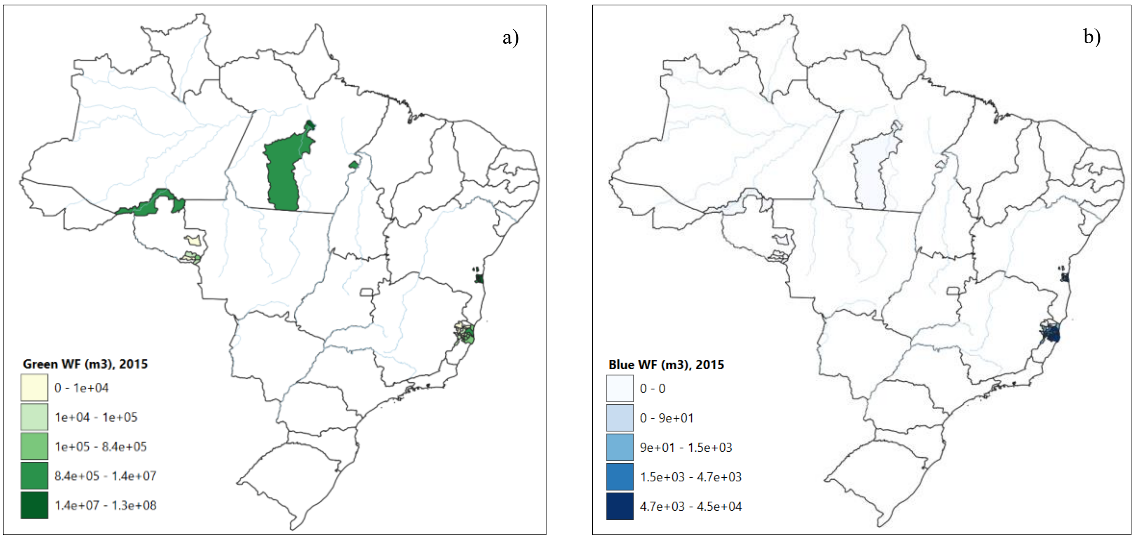


Figure C.5: Brazil, cocoa (2015). Green (a) and blue (b) water footprint values.

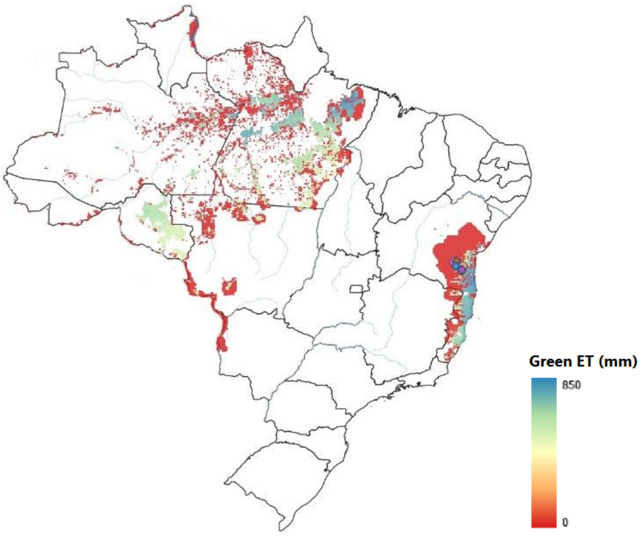


Figure C.6: Brazil, cocoa (2015). Virtual water-weighted barycentres and green evapotranspiration data for cocoa.

Brazil – coffee 2017

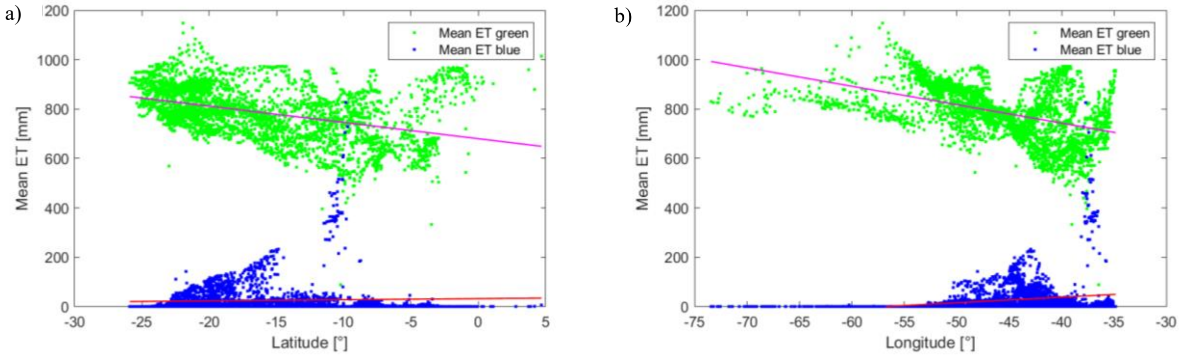


Figure C.7: Average evapotranspiration data for each Brazilian municipality. Geographical distribution is shown according to the latitude (a) and the longitude (b).

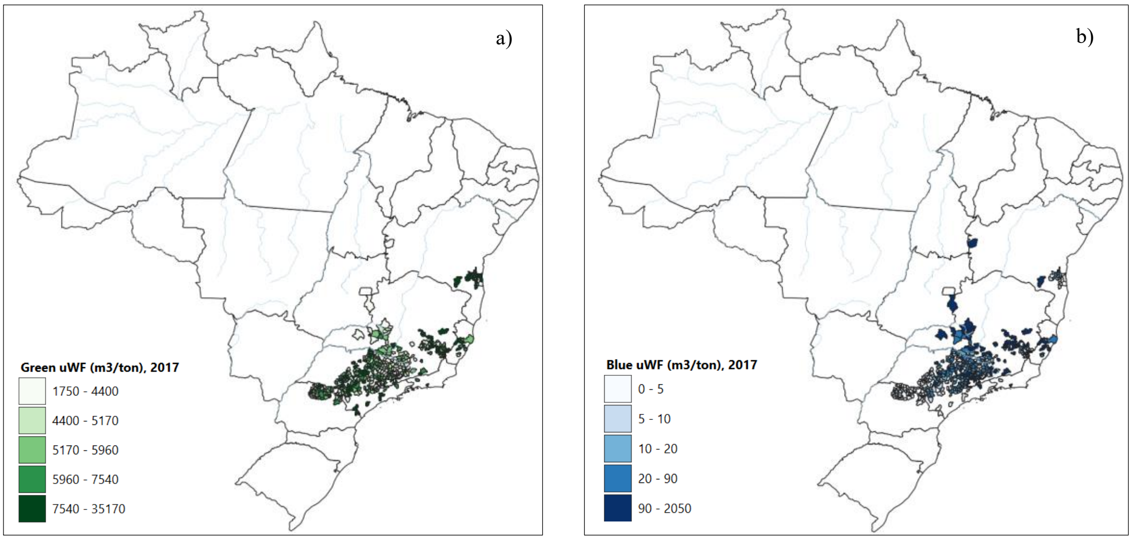


Figure C.8: Brazil, coffee (2017). Green (a) and blue (b) unit water footprint values.

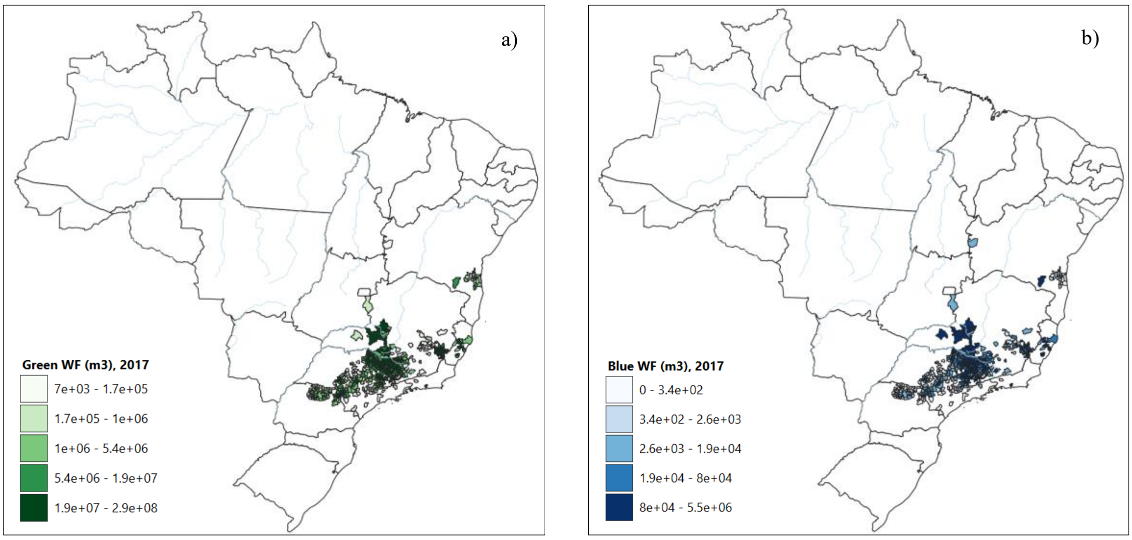


Figure C.9: Brazil, coffee (2017). Green (a) and blue (b) water footprint values.

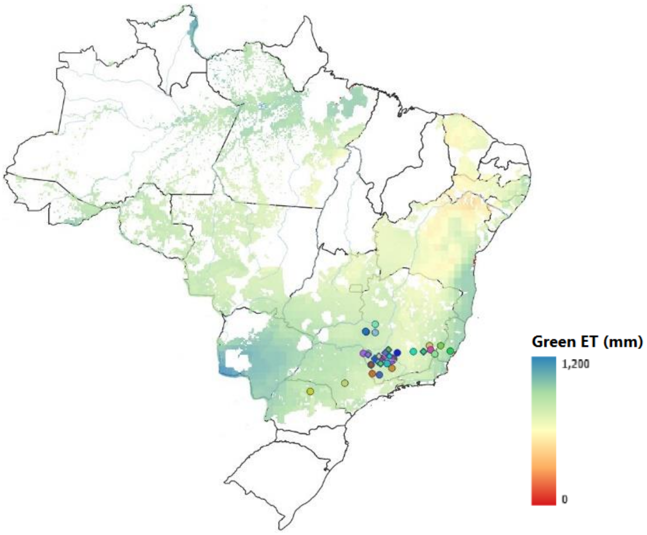


Figure C.10: Brazil, coffee (2017). Virtual water-weighted barycentres and green evapotranspiration data for coffee.

Brazil – corn 2017

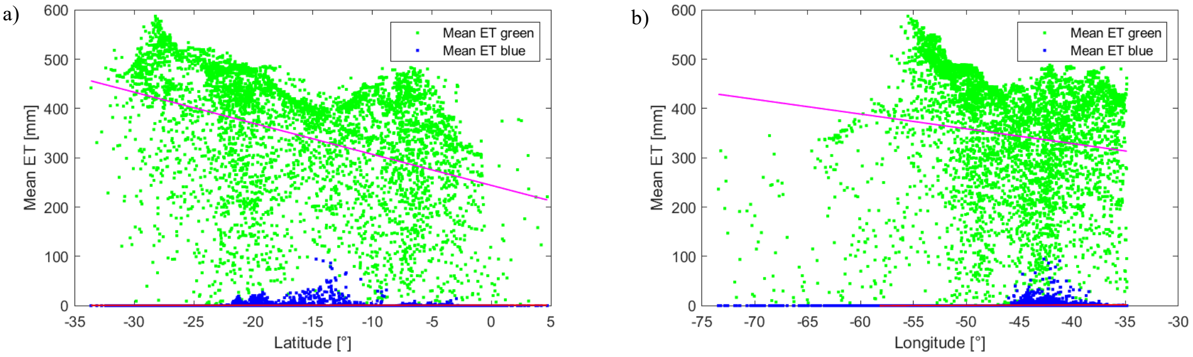


Figure C.11: Average evapotranspiration data for each Brazilian municipality. Geographical distribution is shown according to the latitude (a) and the longitude (b).

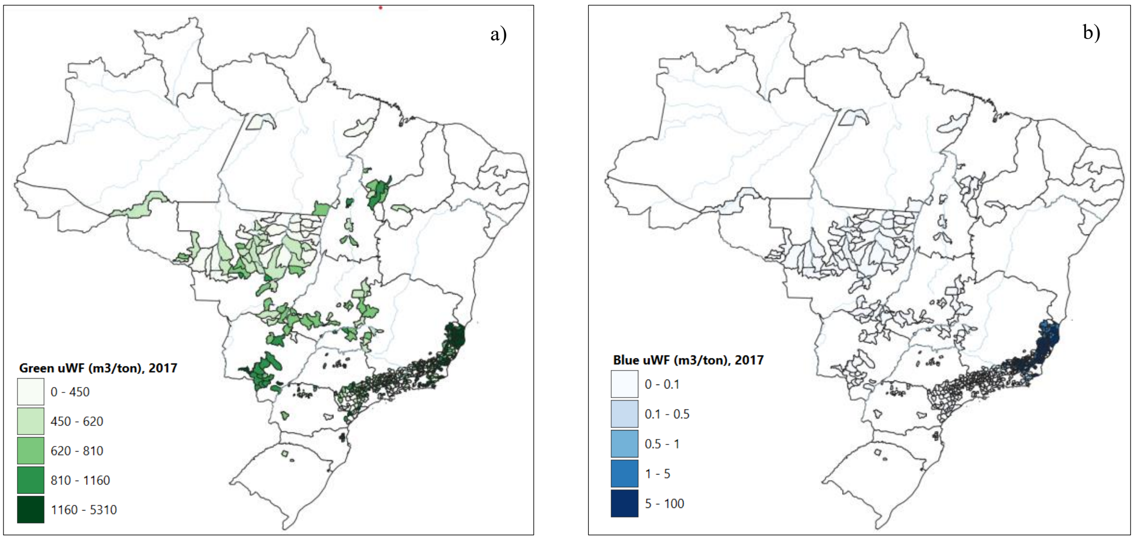


Figure C.12: Brazil, corn (2017). Green (a) and blue (b) unit water footprint values.

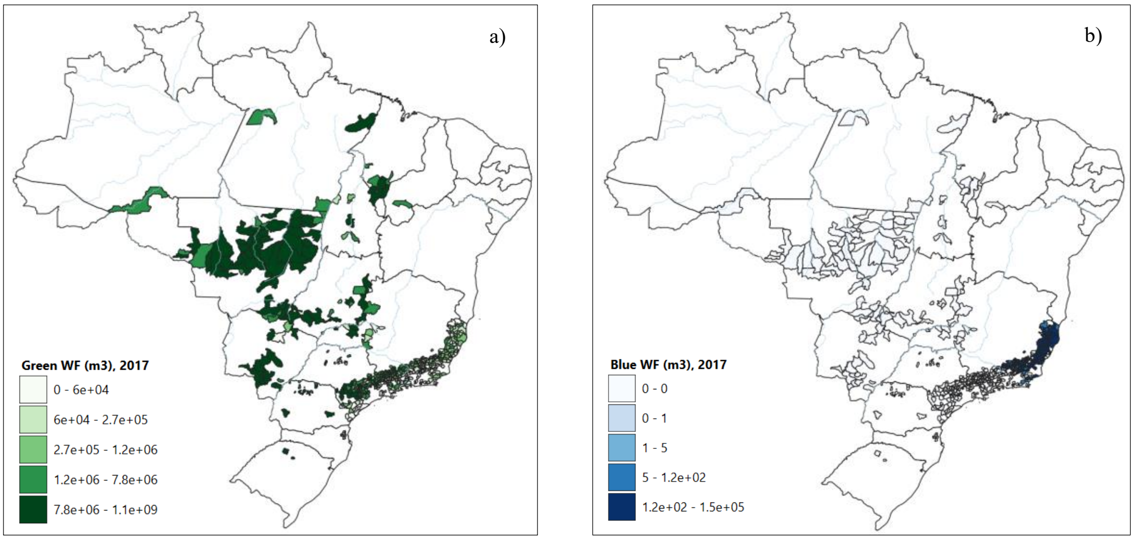


Figure C.13: Brazil, corn (2017). Green (a) and blue (b) water footprint values.

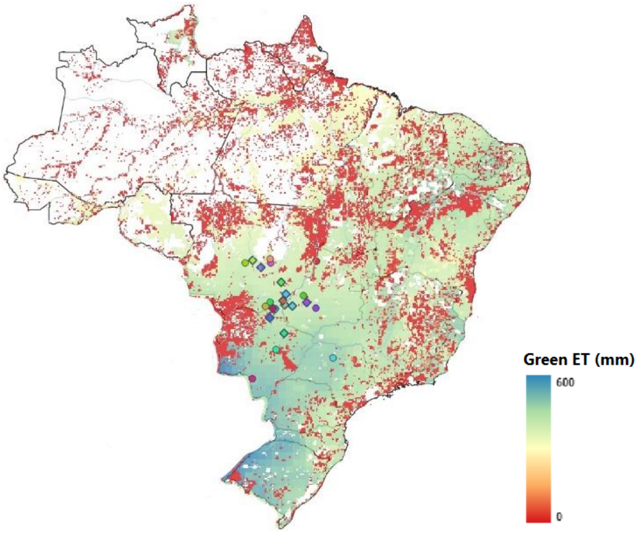


Figure C.14: Brazil, corn (2017). Virtual water-weighted barycentres and green evapotranspiration data for corn.

Brazil – cotton 2017

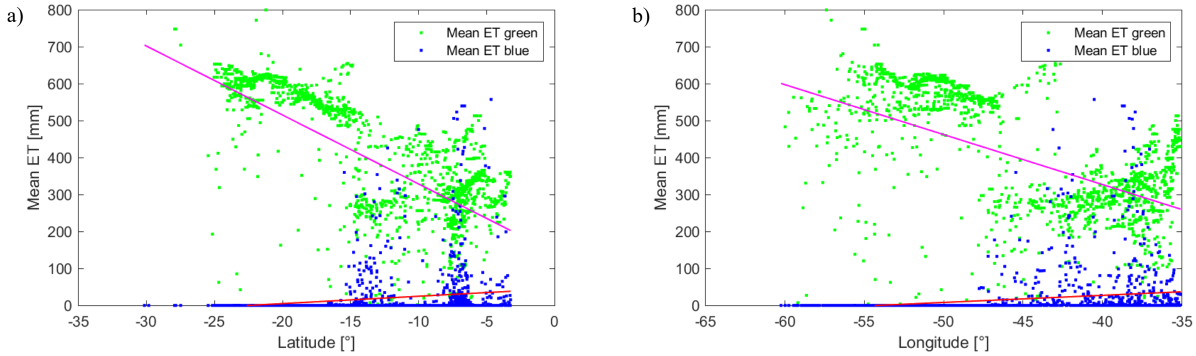


Figure C.15: Average evapotranspiration data for each Brazilian municipality. Geographical distribution is shown according to the latitude (a) and the longitude (b).

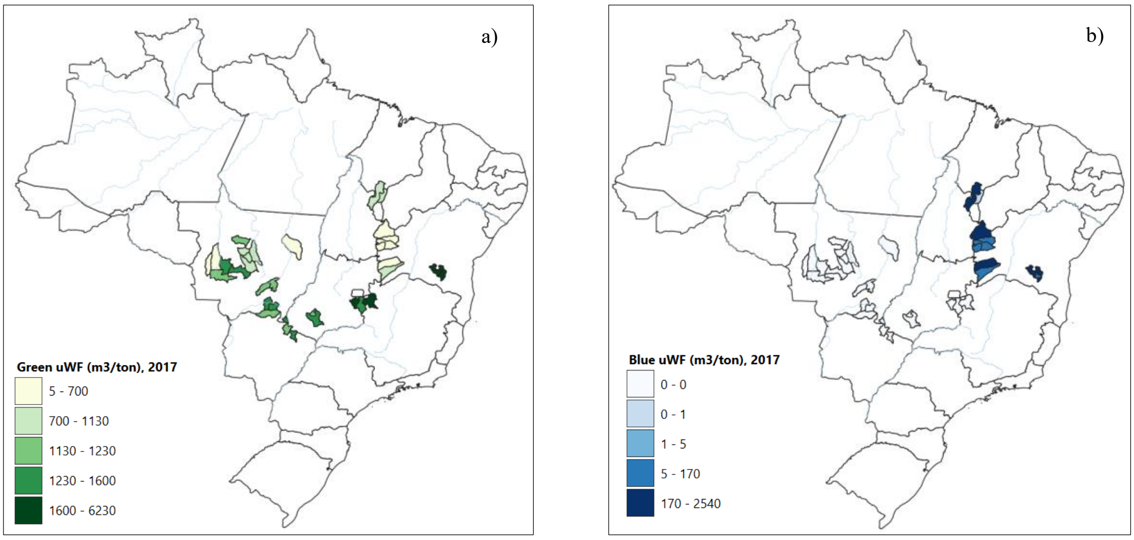


Figure C.16: Brazil, cotton (2017). Green (a) and blue (b) unit water footprint values.

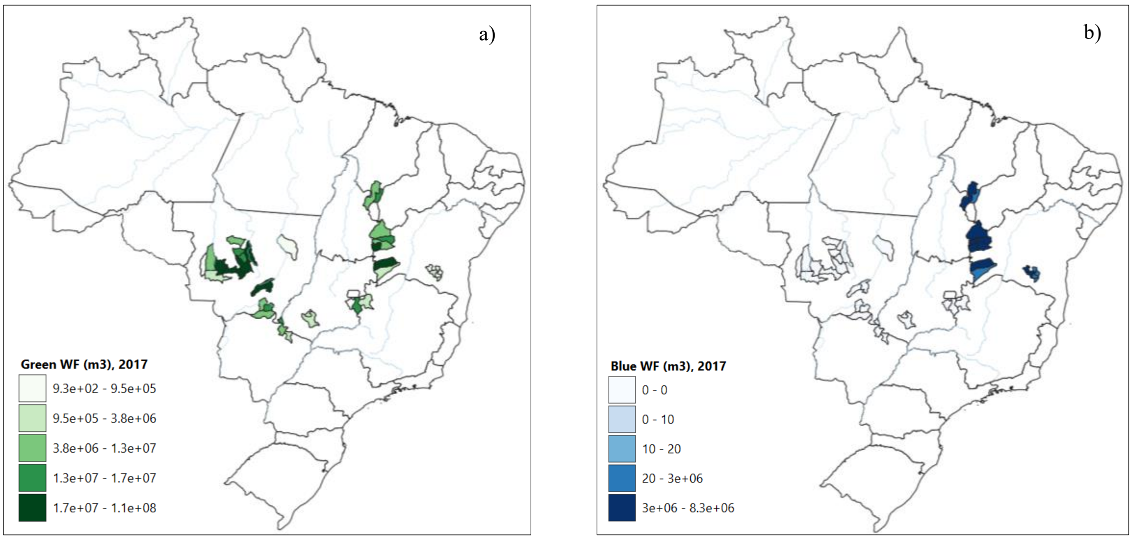


Figure C.17: Brazil, cotton (2017). Green (a) and blue (b) water footprint values.

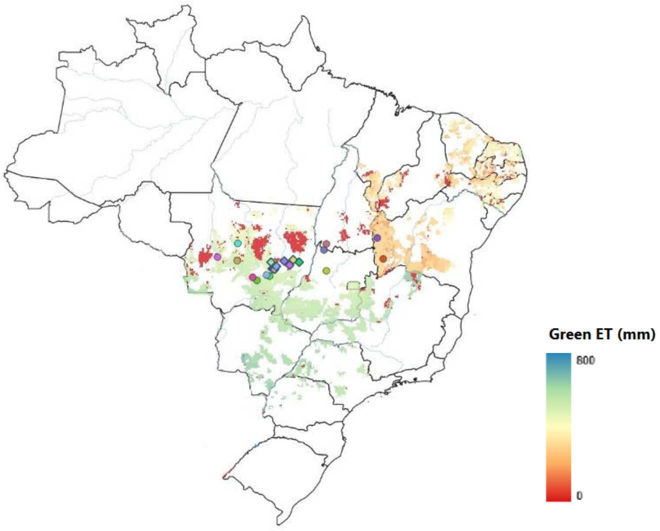


Figure C.18: Brazil, cotton (2017). Virtual water-weighted barycentres and green evapotranspiration data for cotton.

Brazil – soy 2020

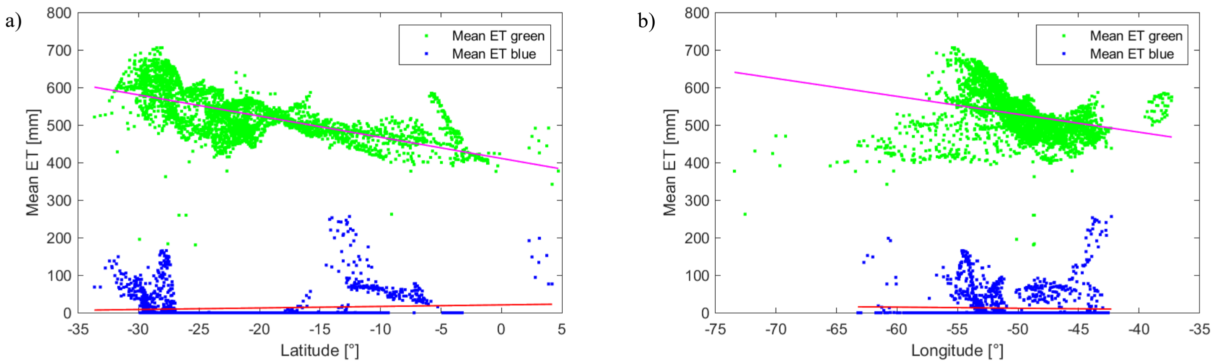


Figure C.19: Average evapotranspiration data for each Brazilian municipality. Geographical distribution is shown according to the latitude (a) and the longitude (b).

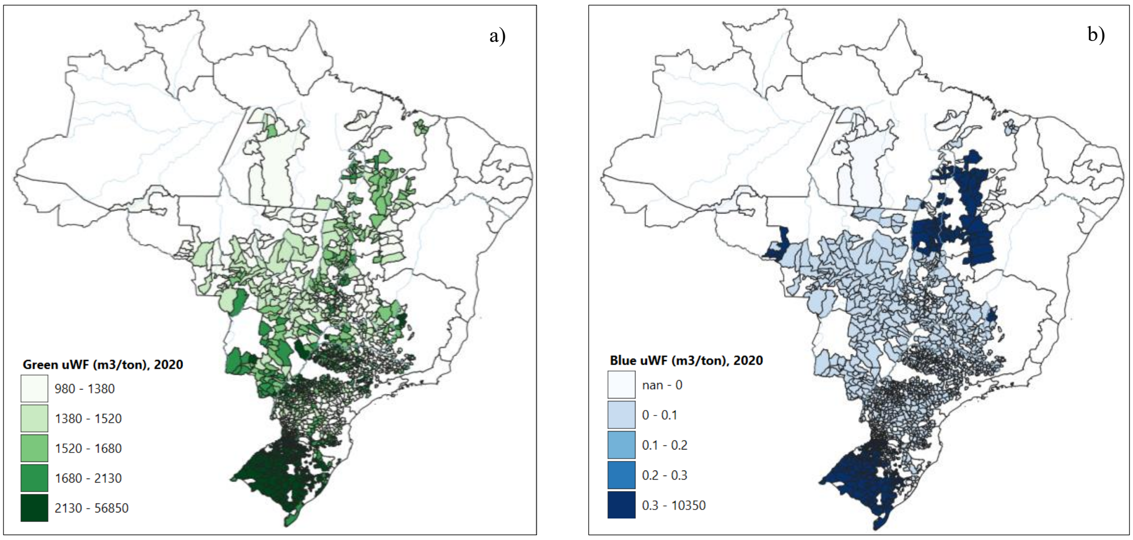


Figure C.20: Brazil, soy (2017). Green (a) and blue (b) unit water footprint values.

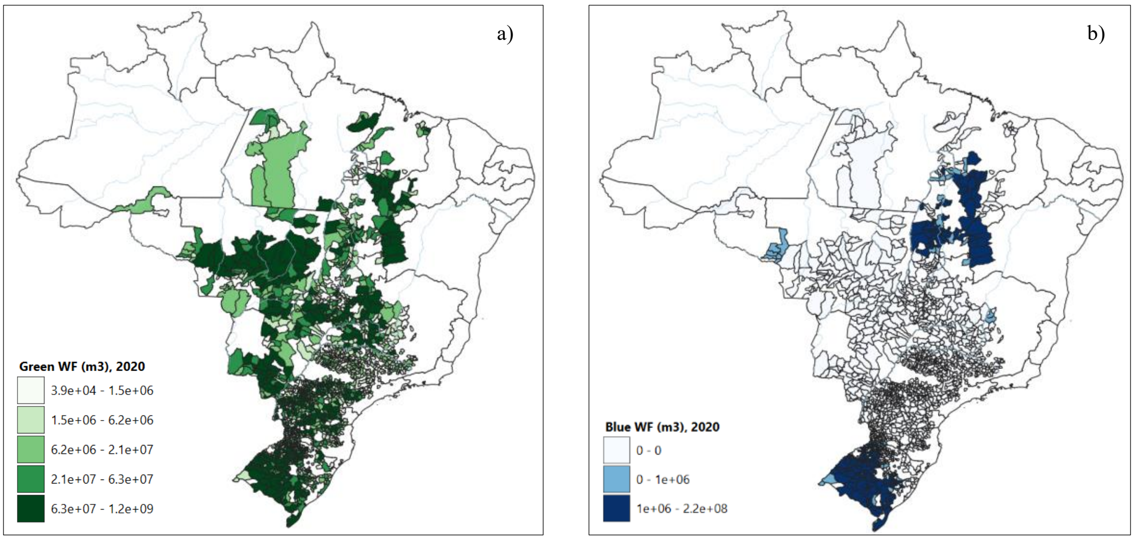


Figure C.21: Brazil, soy (2017). Green (a) and blue (b) water footprint values.

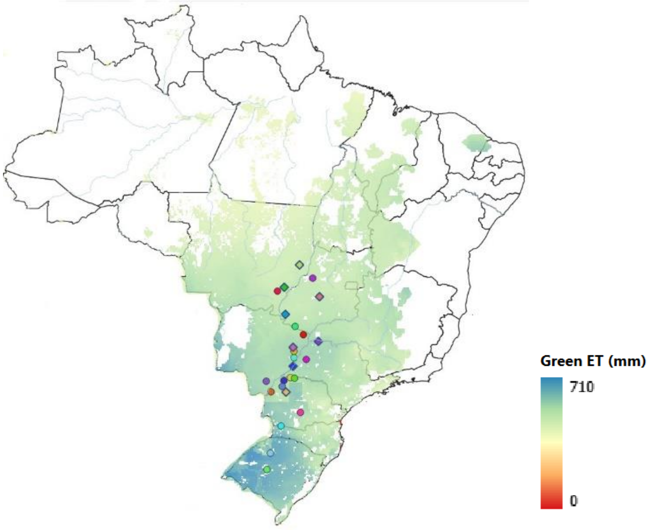


Figure C.22: Brazil, soy (2017). Virtual water-weighted barycentres and green evapotranspiration data for soy.

Colombia – coffee 2016

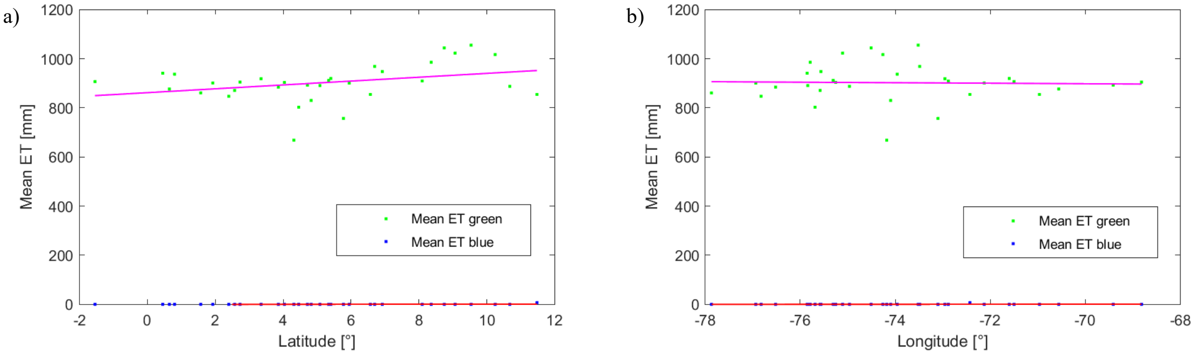


Figure C.23: Average evapotranspiration data for each Colombian department. Geographical distribution is shown according to the latitude (a) and the longitude (b).

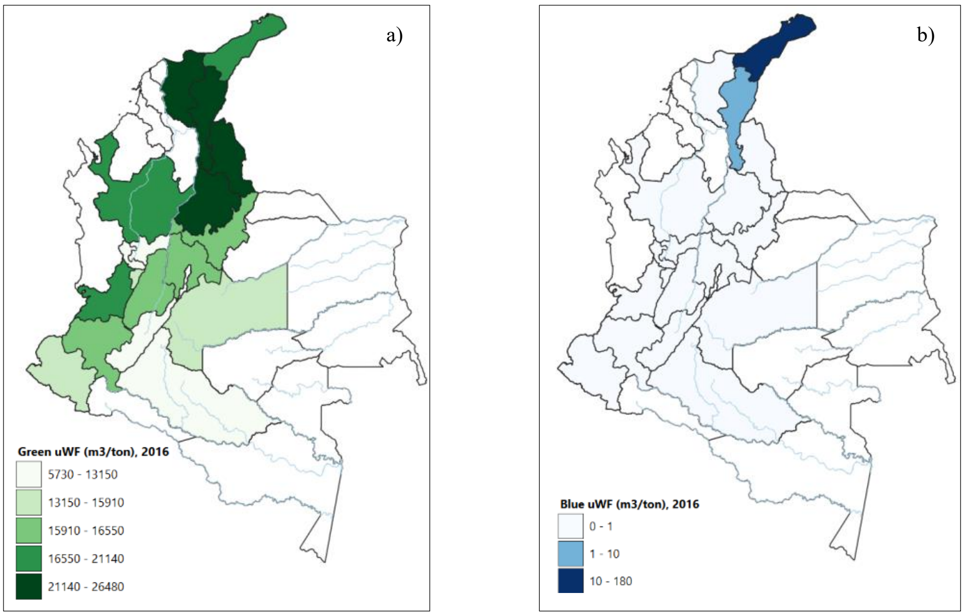


Figure C.24: Colombia, coffee (2016). Green (a) and blue (b) unit water footprint values.

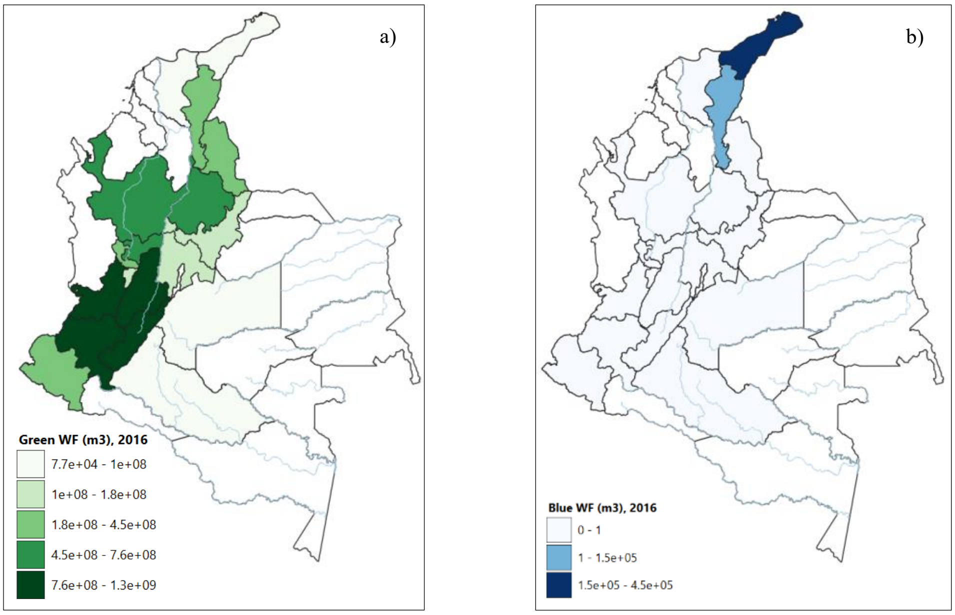


Figure C.25: Colombia, coffee (2016). Green (a) and blue (b) water footprint values.

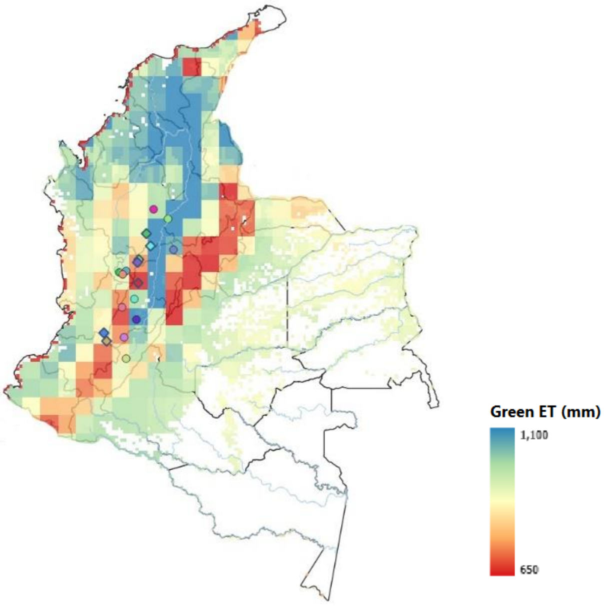


Figure C.26: Colombia, coffee (2016). Virtual water-weighted barycentres and green evapotranspiration data for coffee.

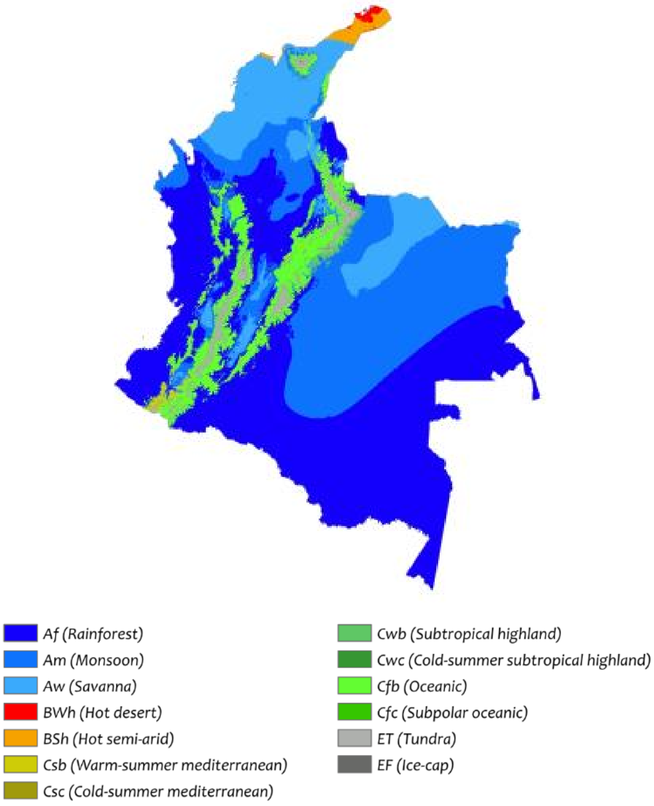


Figure C.27: Koppen climate types of Colombia (Beck et al.*, 2020).*

Ivory Coast – cocoa 2019

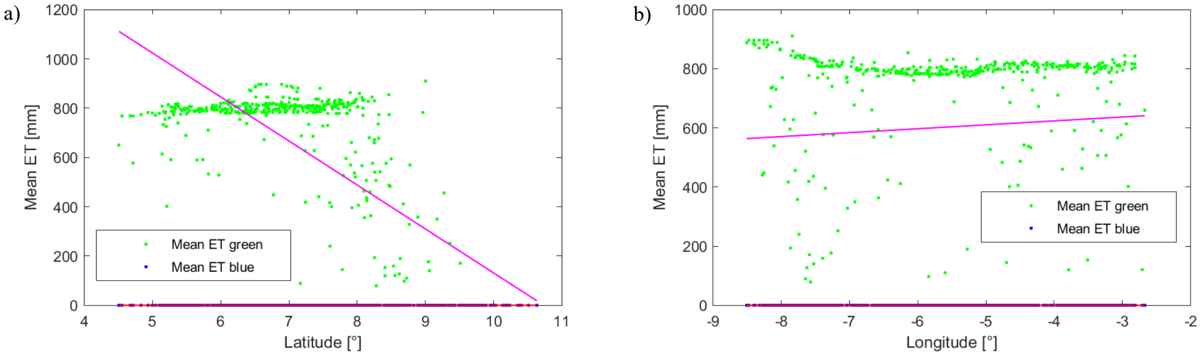


Figure C.28: Average evapotranspiration data for each Ivory Coast department. Geographical distribution is shown according to the latitude (a) and the longitude (b).

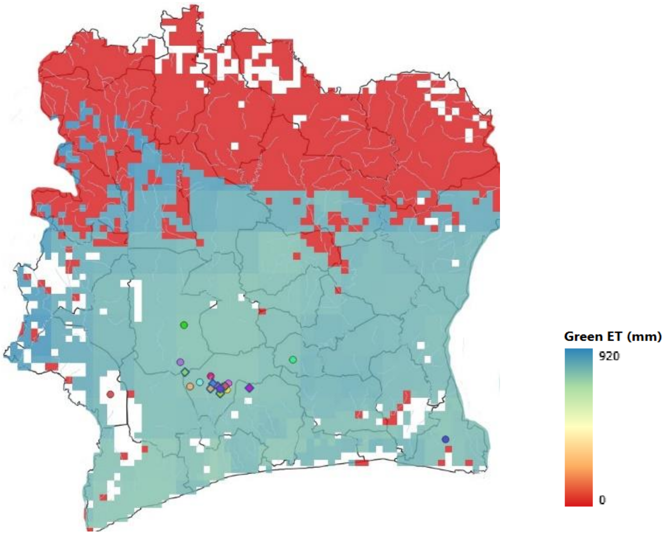


Figure C.29: Ivory Coast, cocoa (2019). Virtual water-weighted barycentres and green evapotranspiration data for cocoa.

Paraguay – corn 2019

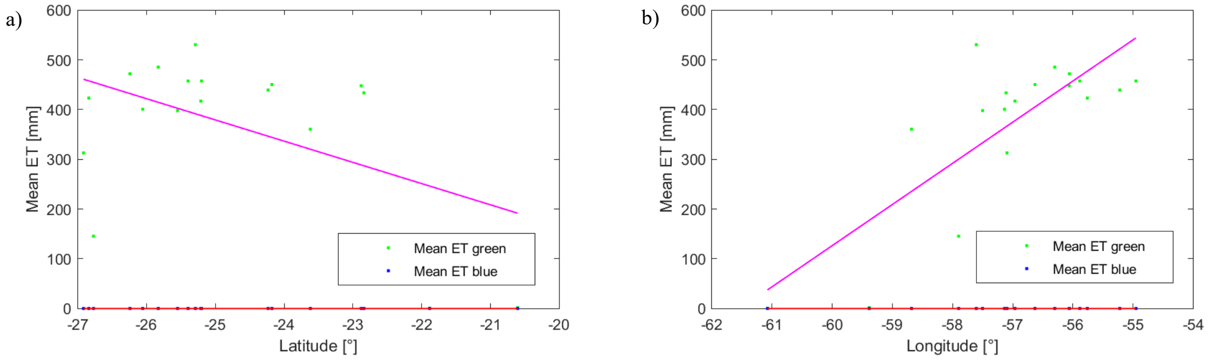


Figure C.30: Average evapotranspiration data for each Paraguayan department. Geographical distribution is shown according to the latitude (a) and the longitude (b).

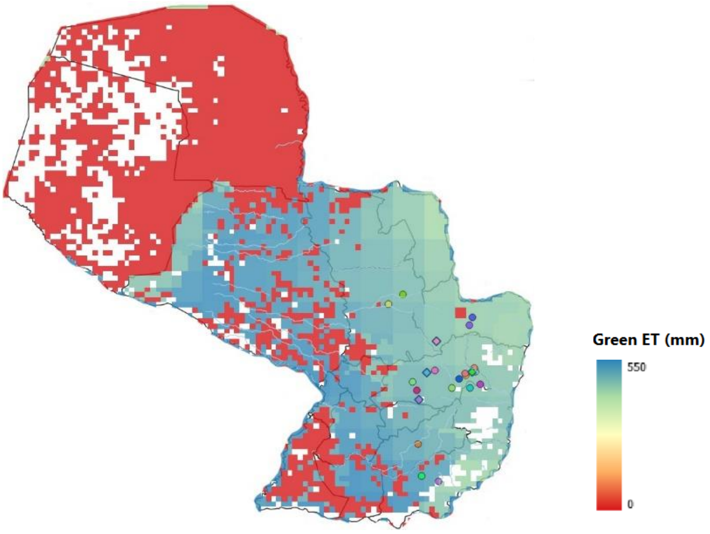


Figure C.31: Paraguay, corn (2019). Virtual water-weighted barycentres and green evapotranspiration data for corn.

Paraguay – soy 2019

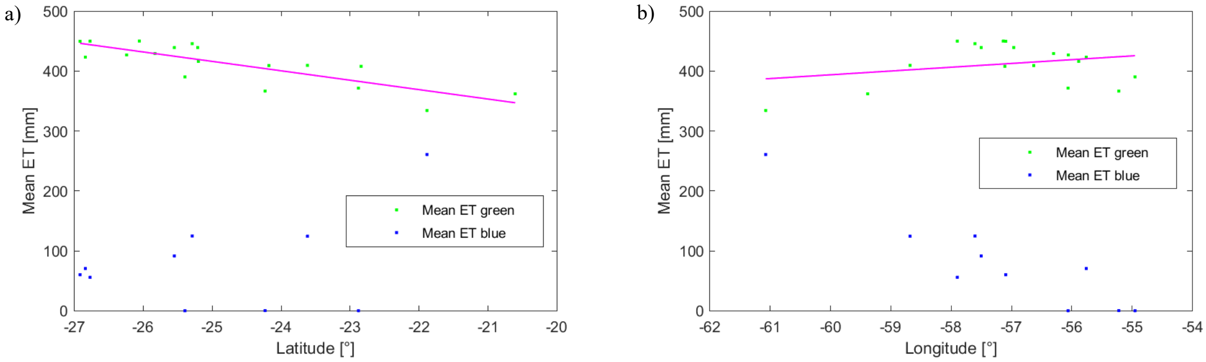


Figure C.32: Average evapotranspiration data for each Paraguayan department. Geographical distribution is shown according to the latitude (a) and the longitude (b).

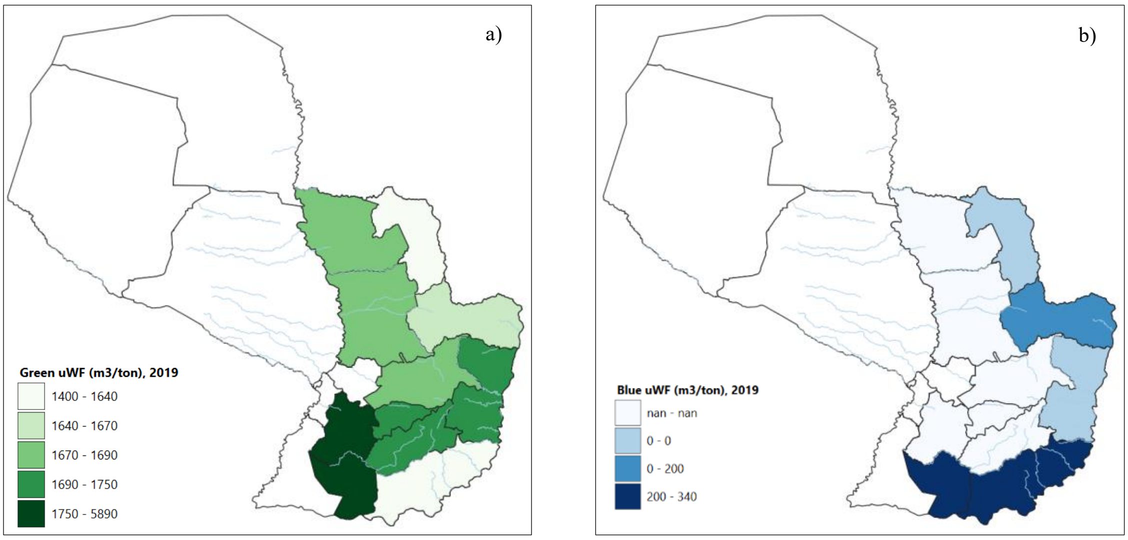


Figure C.33: Paraguay, soy (2019). Green (a) and blue (b) unit water footprint values.

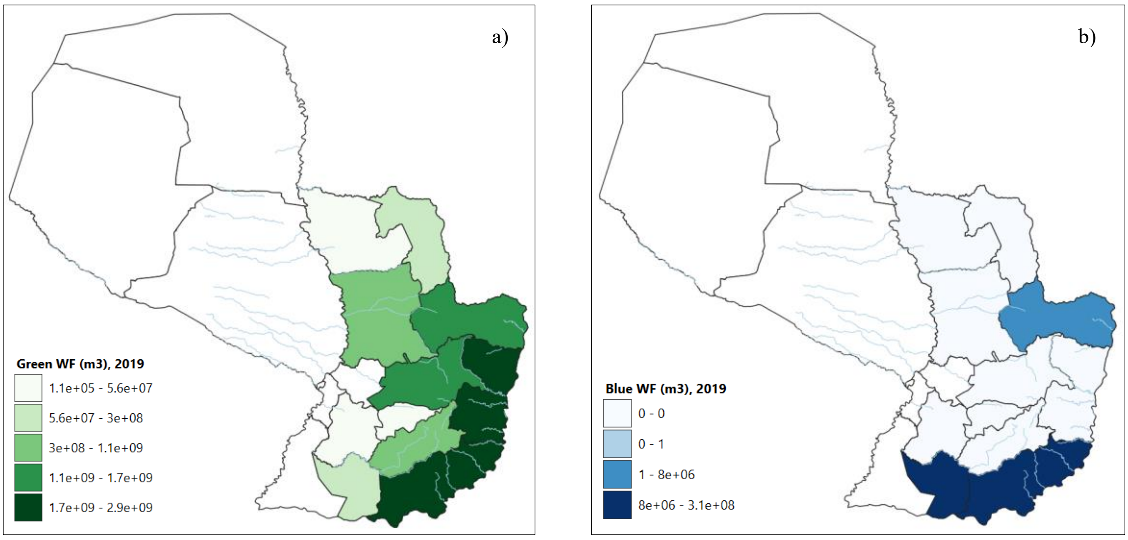


Figure C.34: Paraguay, soy (2019). Green (a) and blue (b) water footprint values.

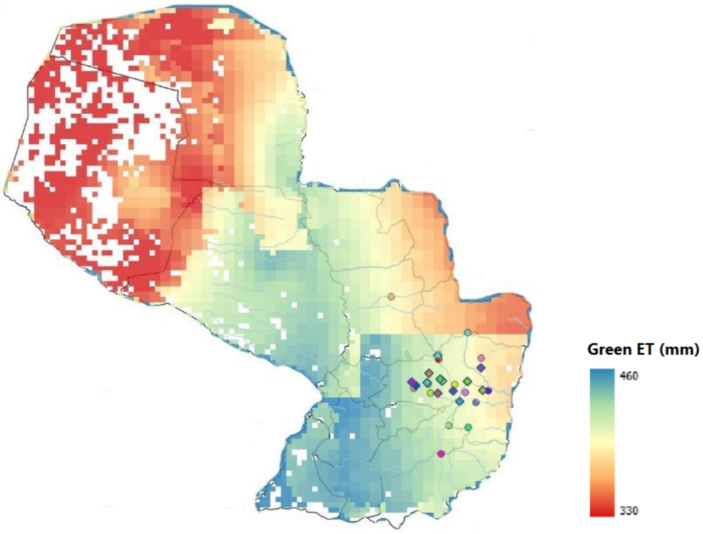


Figure C.35: Paraguay, soy (2019). Virtual water-weighted barycentres and green evapotranspiration data for soy.

Appendix D

Appendix D reports time series which include yearly exported tonnes, cultivated hectares and virtual water volumes. Moreover, temporal evolutions of water impact over each biome are reported.

Bolivia – soy 2020 / 2021

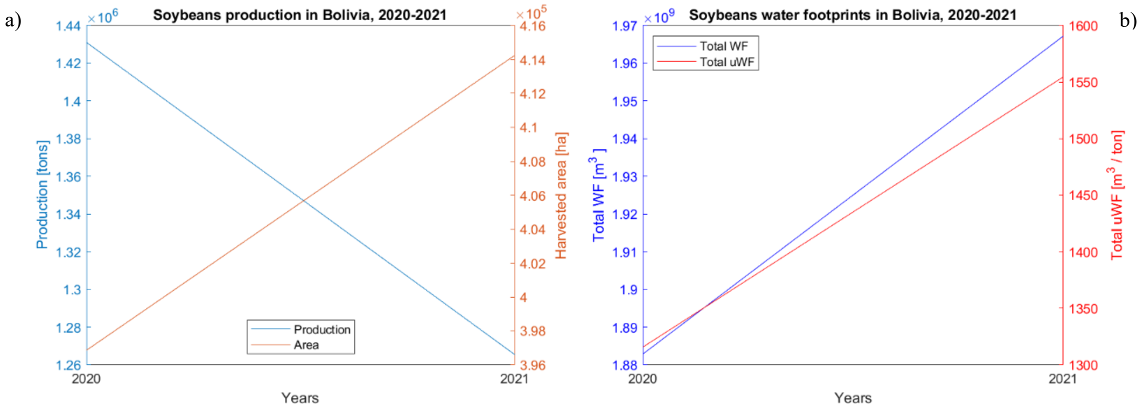


Figure D.1: Bolivia, soy (2020 - 2021). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right (b).

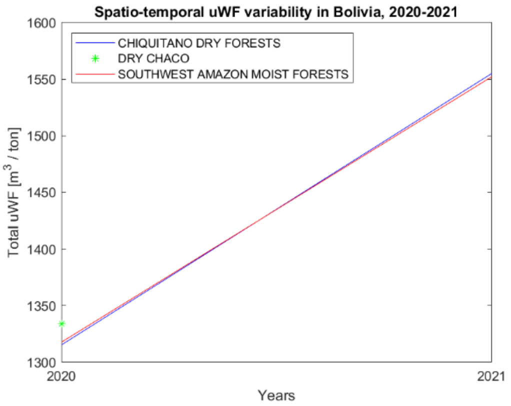


Figure D.2: Bolivia, soy (2020 - 2021). Temporal evolution of unit water footprint over each biome involved.

Brazil – coffee 2016 / 2017

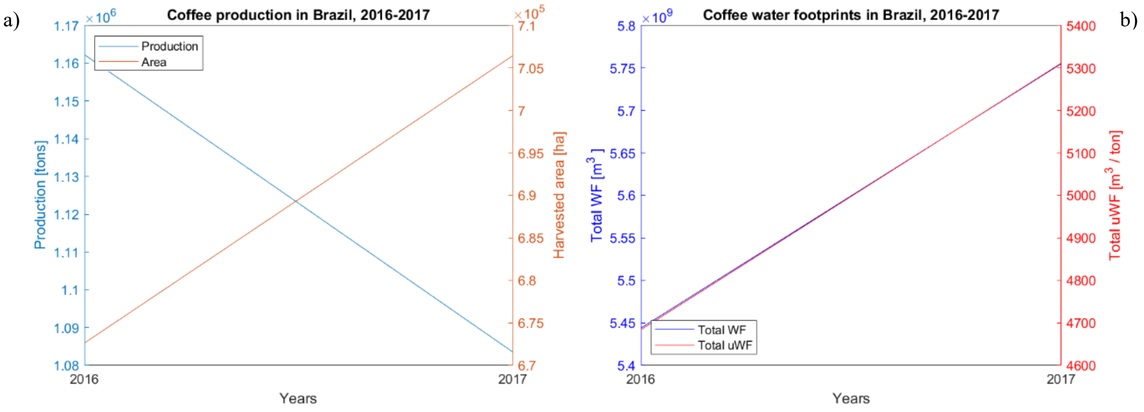


Figure D.3: Brazil, coffee (2016 - 2017). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right (b).

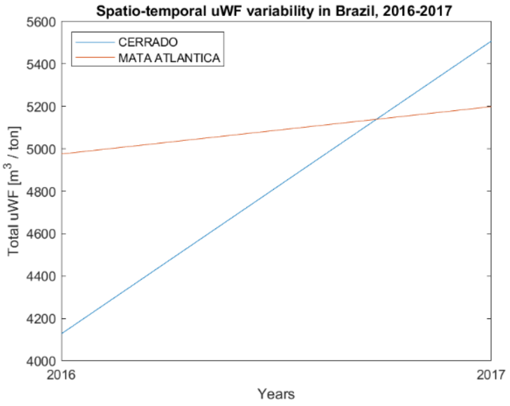


Figure D.4: Brazil, coffee (2016 - 2017). Temporal evolution of the weighted mean uWFs over each biome involved.

Brazil – corn 2015 / 2017

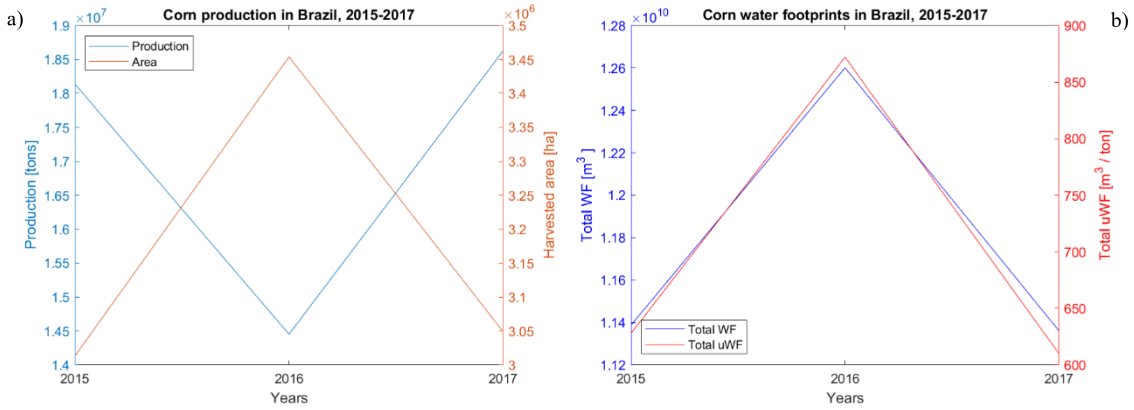


Figure D.5: Brazil, corn (2015 - 2017). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right (b).

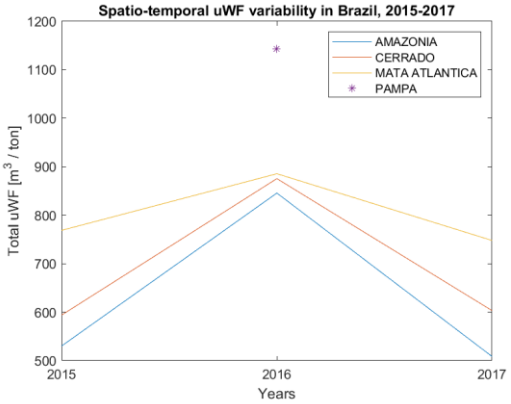


Figure D.6: Brazil, corn (2015 - 2017). Temporal evolution of the weighted mean uWFs over each biome involved.

Brazil – cotton 2015 / 2017

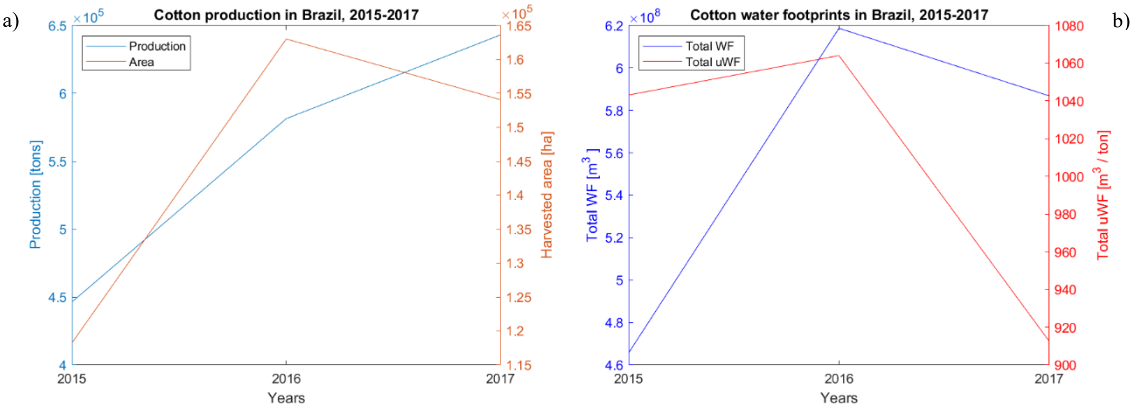


Figure D.7: Brazil, cotton (2015 - 2017). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right (b).

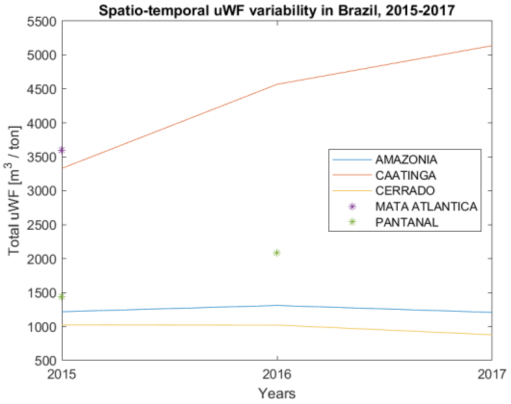


Figure D.8: Brazil, cotton (2015 - 2017). Temporal evolution of the weighted mean uWFs over each biome involved.

Colombia – coffee 2012 / 2016

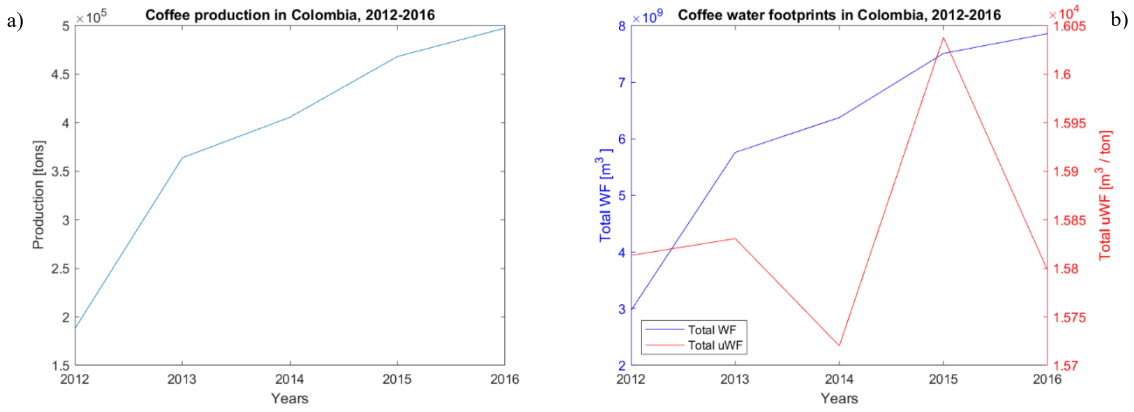


Figure D.9: Colombia, coffee (2012 - 2016). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right (b).

Paraguay – corn 2014 / 2019

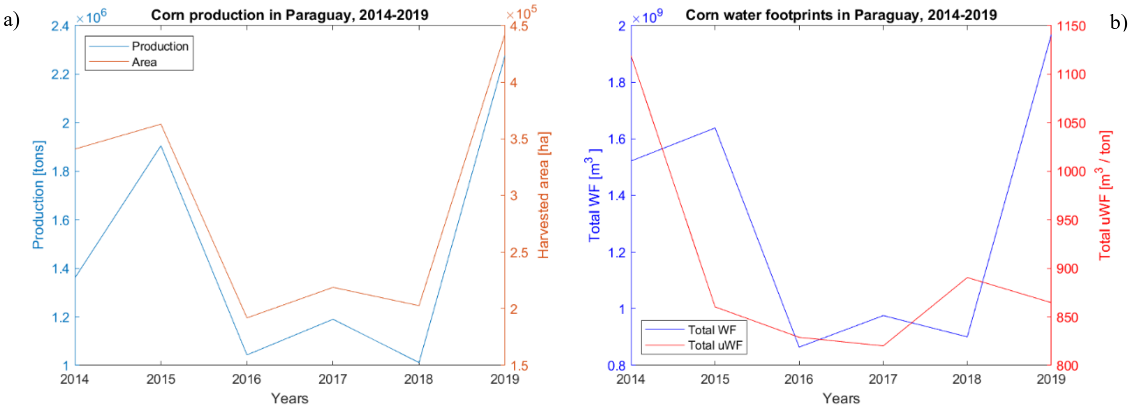


Figure D.10: Paraguay, corn (2014 - 2019). Yearly exported tons and cultivated hectares on the left (a). VWTs and weighted mean uWFs on the right (b).

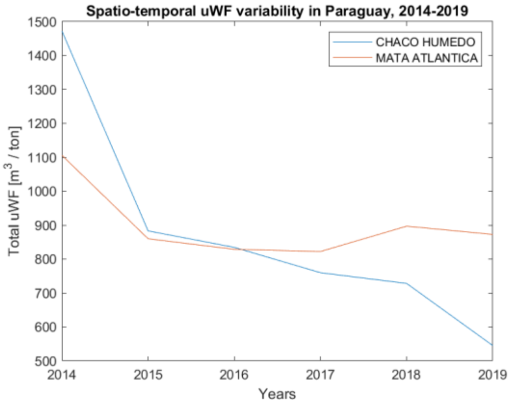


Figure D.11: Paraguay, corn (2014 - 2019). Temporal evolution of the weighted mean uWFs over each biome involved.

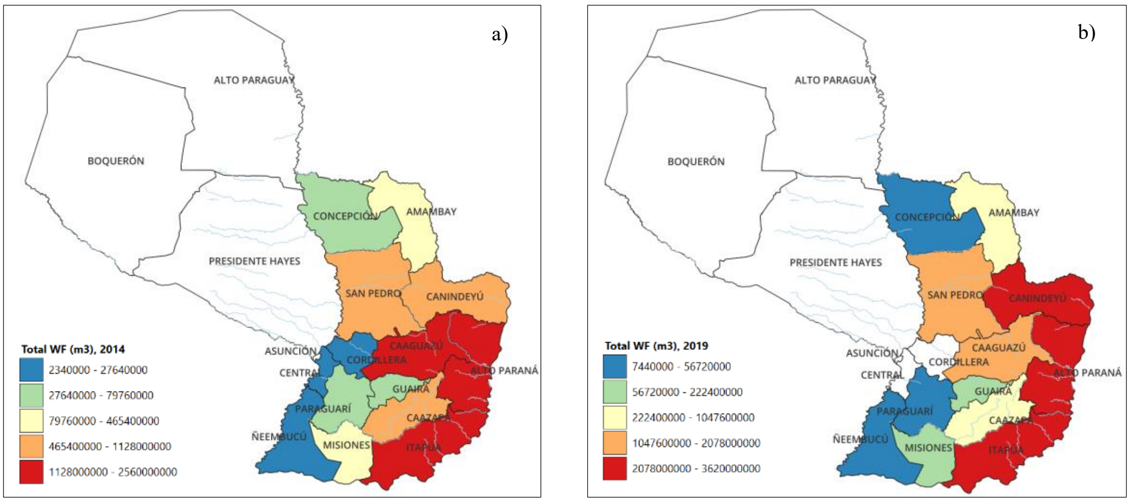


Figure D.12: Paraguay Total WF given by corn and soy in 2014 (a) and 2019 (b).

Appendix E

In Appendix E, the temporal evolution of agricultural markets is illustrated by means of stacked bar charts, related to the four major trading companies for each crop.

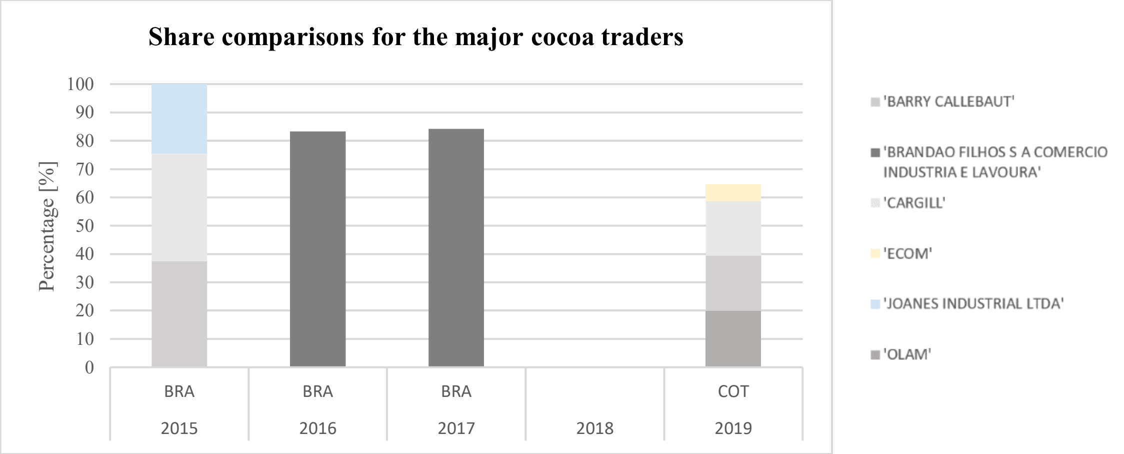


Figure E.1: Brazil and Ivory Coast. Shares of the major cocoa TNCs.

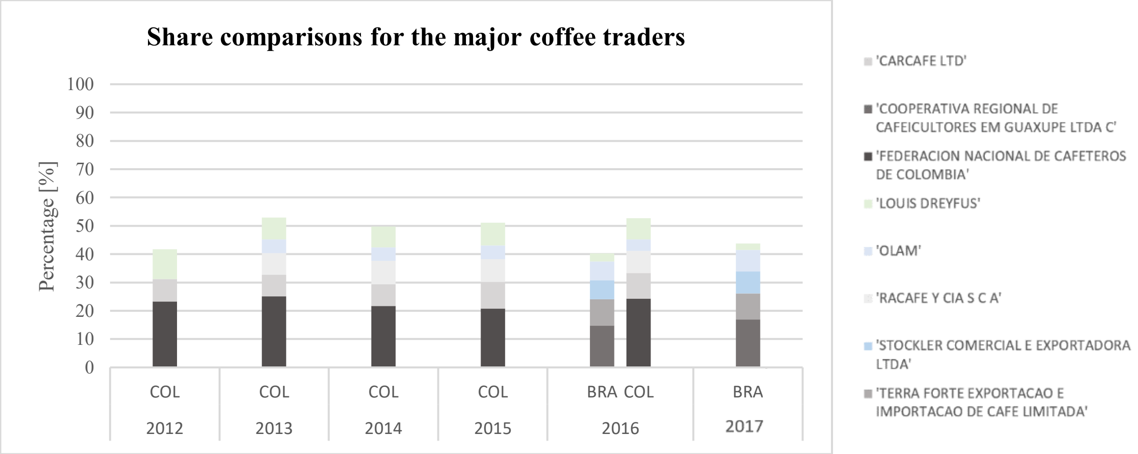


Figure E.2: Brazil and Colombia. Shares of the major coffee TNCs.

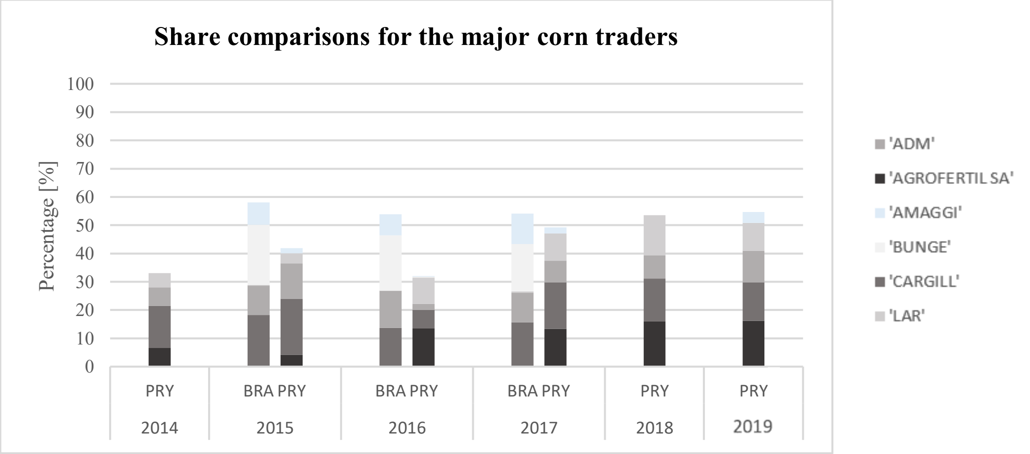


Figure E.3: Brazil and Paraguay. Shares of the major corn TNCs.

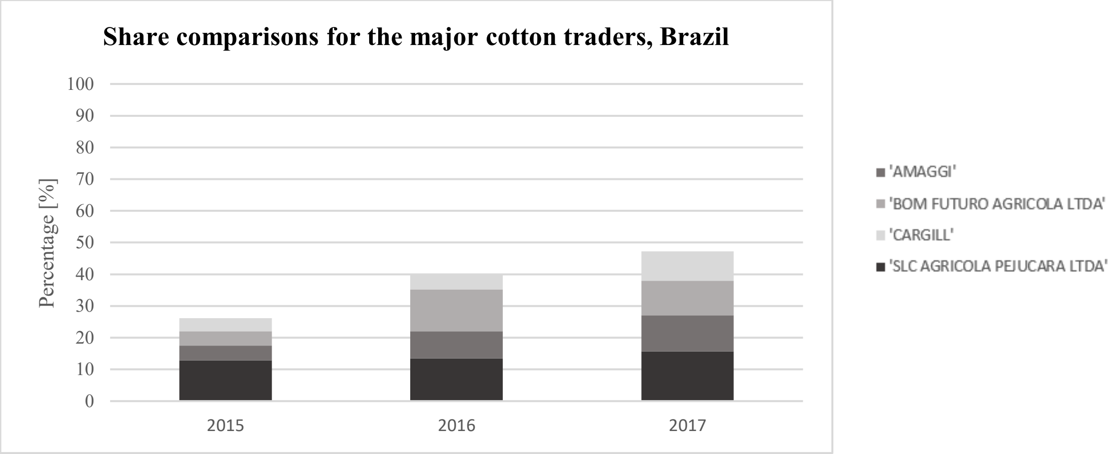


Figure E.4: Brazil. Shares of the major cotton TNCs.