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Economic implications of food-related virtual water trade

by

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Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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For my grandfather, who always believed in me.

Abstract

Many socio-economic and political factors drive food production, consumption, and trade, both locally and globally. The amount of food and agricultural products traded on the global market has doubled in the last 20 years; therefore, political boundaries do not coincide with the resources needed to sustain their own population. Some countries do not cultivate enough food to meet their needs and depend on imports to maintain food security. In contrast, others produce more than they need and turn to export-oriented activities to meet international demand for certain goods. Still, other countries may also reduce the domestic production of some goods to import them from abroad at a lower price, or sell abroad rather than domestically because this strategy allows them to gain larger profits.

Water plays a key role among the natural resources most commonly used in food production processes, and the notion of "virtual water" plays an essential role in shedding light on the movements throughout the water-food nexus. The virtual water content of a certain commodity is defined as the total volume of water required to produce it. It depends both on production conditions and on the efficiency and performance of irrigation systems. Therefore, what is traded on the international market are not just commodities, but also the water resources exploited during their production. Consequently, the availability of water resources has great influence on the competitiveness of a country on the international market, as well as on its own internal production capabilities. However, the trends recorded during the recent intensification of international trade have led to a growing disconnect between consumer demand for goods and services, and the intrinsic water value that these goods embed as a result of their production process.

This thesis investigates the water-food nexus from an economic perspective, exploring aspects of both food production and the related international virtual water trade. In particular, we aim to delve into the following issues: (i) within the water-price debate, we analyze whether agricultural commodity prices reflect the value of the water required to produce them; (ii) at the government policy level, we examine on a global scale the relationship between trade agreements and the topology of the agricultural trade network, investigating in terms of water productivity the differences between flows covered by trade agreements and those not covered; (iii) at the regional scale, through a simulation tool (the MAGNET model), we investigate the future developments of African virtual water flows and the effects of implementing the African Continental Free Trade Area (AfCFTA) on the African virtual water network; (iv) we develop an integrated communication strategy to outreach the people outside academy. More in detail:

(i) market dynamics can be associated with production and export choices, as well as with the price of agricultural products. In the continuing debate on whether water should be assigned an economic value, the question of whether water is reflected in the market prices of goods has not been fully addressed. Therefore, we investigate the relationship between water consumed in agricultural production and crop prices. In particular, we explore the relationship between farm gate prices and two environmental resources used in agricultural production: harvested area per tonne (land footprint) and water per tonne (water footprint). Initially, we focus on the relationship between crop water consumption in terms of water footprint and crop prices, finding a positive and statistically significant relationship. However, the literature argues that the value of water can be inextricably embedded in the value of land; both the size and regularity of food production depend on the presence of water in the land. Therefore, we analyze the water footprint in its two components: soil footprint and evapotranspiration. We find that the relationship between water footprint and crop prices is not fully incorporated in the role played by harvested area; the water component, in terms of evapotranspiration, seems to be correlated with price behavior, independently of the land footprint. The results illustrate an interesting aspect: paradoxically, only the prices of relatively less water-intensive goods show significant relationships with the water footprint of production; this allows us to hypothesize that different production and marketing structures influence the inputs taken into account in market prices. In fact, staple crops are often sold in competitive markets, where the amount of water used during production is positively associated with the crop price. In contrast, fewer producers grow cash crops and set prices according to international market factors;

(ii) as mentioned, the volume of agricultural products traded on the global market has multiplied in recent decades. In this scenario, governments play a crucial role at the policy level by establishing international agreements, thus defining the global market. We investigate the impact of trade agreements on the trade network of agricultural products to identify the relationships between market liberalization and food flows. In particular, we study whether the ratification of agricultural-oriented trade agreements is associated with changes in the food trade network (link establishment) and with flow increases through existing links. We find that implementing trade agreements tends to correlate with establishing new links and with commercial relationship persistence when two countries are already trading. First, the presence of a trade agreement shows a higher likelihood of continuing a commercial relationship over time. Second, compared to trade relationships not covered by the agreement, flows covered by trade agreements present higher flow values in both years with smaller inter-annual average flow variations. Moreover, from an environmental point of view, flows under trade agreements reveal higher economic (US\$/m^3) and nutritional (kcal/m^3) water productivity. Therefore, trade openness seems to promote higher water efficiency.

(iii) the African continent faces water scarcity problems, and the agricultural sector consumes much of the continent's water. Moreover, agricultural food trade triggers exchanges that transfer water resources to countries far from production. Based on these assumptions, we study the future developments of African virtual water flows and the effects of implementing the African Continental Free Trade Area (AfCFTA) on the virtual water network involving the African continent. Using the detailed virtual water production and trade matrices developed within the CWASI (Coping with water scarcity in a globalized world) project, we translate dollar projections obtained with MAGNET (Modular Applied GeNeral Equilibrium Tool) into virtual water. This dollar-to-water conversion allows us to capture production and trade projections in 2030 for a baseline scenario and an AfCFTA scenario removing tariff barriers. We then find that the base case projections to 2030 show significant increases in African production, especially in exports in extra-continental trade (51%) and intra-continental trade (34%). The implementation of the AfCFTA has the impact of reducing extra-continental exports almost in proportion to the increase in intra-continental trade. We also analyze the effect on virtual water of African economic regions and agricultural sectors to investigate whether the projected increases depend on region-specific or crop-specific factors.

(iv) All the studies described in this thesis are part of the European CWASI (Coping with water scarcity in a globalized world) project, founded by the European Council. In the last section of this work we discuss the dissemination strategies and communication framework created by our research group to successfully spread out five year of scientific research on the theme of water. During the CWASI project, we understood that the water-food nexus, and studies related to this concept, incorporate sub-

stantial environmental, economical and social dynamics. These dynamics and what we learned about them, have a huge influence on the contemporary world and society, and we felt it was necessary to maximise the chances to make these notions available for a wider and non-specialized audience. With our communication project, called WaterToFood, we create a multimedia platform to fulfill these goals, thanks to videos, an interactive online database, a curated magazine and constant social media coverage.

All in all, the common thread of this work is to analyse and interpret dynamics relative to water-footprint and virtual water using a multidisciplinary approach. The fulcrum is represented by the economic processes that lie behind the water-food nexus and its constant motion, but great importance in also given to the responsibilities that scientific research has toward society while disseminating its results.

Contents

Introduction

General Framework

In the modern world, consumption and production are the driving forces of the global economy[1] and are based on environmental resources. Virtually every product provided in an economy is composed to some extent of natural resources. Over time, increasing anthropogenic environmental pressures resulting from a growing population, economic development, and, most importantly, changes in consumption patterns have become increasingly relevant [1]. Moreover, due to international trade and globalization, the dynamics of countries around the globe are highly intertwined and interconnected: decisions, practices, strategies and priorities constantly influence and get influenced by global trade-regulated, social and political motions and fluctuations.

International trade plays a crucial role in making global production more efficient in economic terms, and it also has its weight in the natural resources exploitation and the way environmental issues are assessed. In this context, pursuing more prolific practices, production (and its potential environmental impacts) and consumption of goods and services naturally tend to take place in different locations, and, while this is effective in terms of trade, it may also produce a reduction on ecological pressure in one country at the cost of increasing impacts elsewhere [2, 3].

Food systems, in fact, depend on several natural resources: land, water, minerals, fossil fuels, biodiversity, and ecosystem services, which allows to perceive how food production is a major driver of a range of environmental impacts, such as loss of terrestrial and marine biodiversity, land degradation, water depletion, and greenhouse gas emissions [4, 5].
There are several reasons why pressure on environmental resources will increase in the coming years. Firstly, the world population is projected to reach almost 10 billion people by 2050. In a moderate economic growth scenario, this population increase will raise the global demand for agricultural products by 50% over current levels, intensifying pressure on already strained natural resources [4]. Secondly, rising incomes in a large number of developing countries lead to greater purchasing power. Increased income typically leads to diets that are richer in resource-intensive products, such

[1] https://unric.org/en/sdg-12/

as red meat and processed foods [6]. Finally, climate change will likely increase extreme weather events that will significantly impact the quality and quantity of natural resources, with severe consequences for the food system [7].

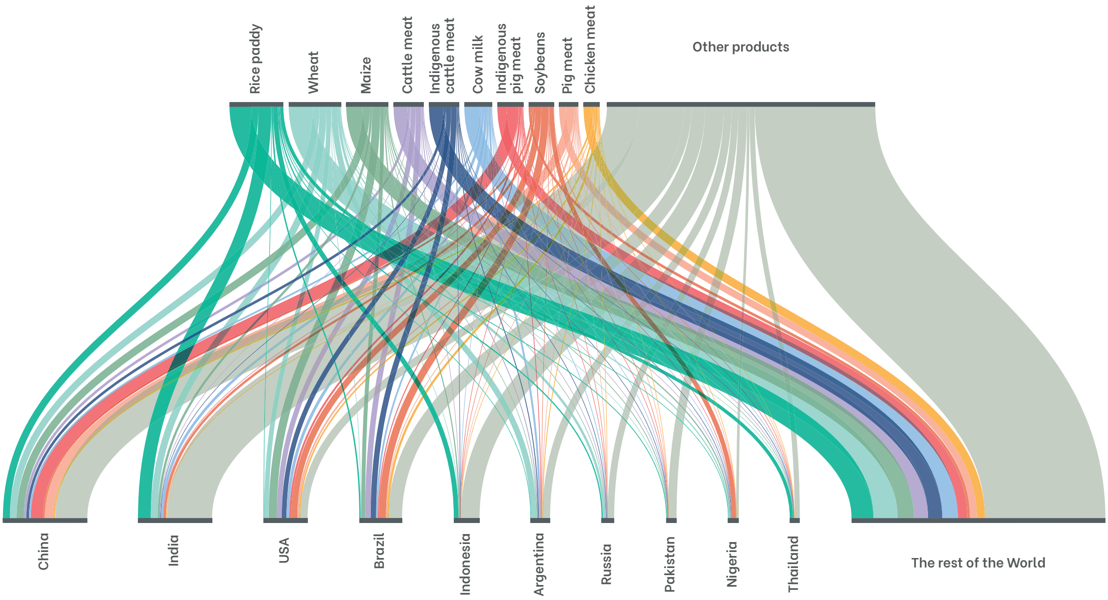

Figure 1: The top ten goods responsible for nearly 60% of the total water footprint of agricultural production and livestock in year 2011. Each bar represents the total water footprint of a given good, and it is evaluated as the sum of all the countries' water footprints, which contribute to global production. From each product, flows depart and connect to the ten top countries in terms of the water footprint of production. Image from *Water to Food. A Data-viz Book about the Water Footprint of Food Production and Trade [8].*

For these reasons, one of the keys to global sustainability lies in understanding the complex interdependencies between national food supply, international trade, and natural resources [9]. Among these, particular attention should be paid to water, an indispensable element for agricultural production. Food production can occur without land or direct sunlight, but water availability is an essential requirement of farming yields [10]. This fact prompted studies into the water footprint concept, which is the total volume of freshwater used along the production chain to obtain a good or service. The water footprint tool can be used to quantify the freshwater requirements of different processes. One may be interested in assessing the water footprint associated with producing a good, either along its entire supply chain or during one step of the process. Moreover, one can determine the water footprint of a group of consumers, a river basin, or a nation. The spatial and temporal scales of analysis of water footprint assessment depend on the research context [11]. To give an illustrative view of the volumes of water used in agriculture, Figure 1 shows the top ten products responsible for almost 60% of the total water footprint of agricultural production and livestock in 2011.

There are many socio-economic and political factors that influence the water footprint on a local and global scale [12–14], and increasing water stress has generated a debate about putting a price on water [15, 16].

Some scholars argue that assigning an economic value to water would improve the efficiency in its allocation, providing incentives for more sustainable patterns of consumption [17–19]. On the opposite side, other streams of thought argue that water should not be considered a private good because it is a fundamental human need and its allocation should not follow market dynamics [20–22]. In the context of this debate, some scholars claim that agricultural goods prices do not reflect correctly the amount of water used for their production [23, 24]. An important aspect to consider is the need to address the relationship between water content and economic value of crops and to discuss the grouping of behavior into the categories of subsistence and market crops [25].

Water used for food production moves virtually around the world due to the agri-food trade. This fact creates a virtual connection of water flowing from exporting (i.e., producing) to importing (i.e., consuming) countries, which is referred to as virtual water (VW) trade [26]. Figure 2 illustrates the most relevant virtual water flows in 2016 worldwide.

In recent years, the virtual water network related to internationally traded food products has been studied to reveal its temporal patterns and dynamics [27–29]. Through the integration of markets, production systems, and society's demands, globalization typically creates distant connections, socio-environmental interactions between natural and economic systems [30, 31]. he law of comparative advantage in economics states that countries tend to produce more of a good for which they can gain once traded, thus allocating production to export rather than local consumption. In these scenarios, governments play a crucial political role by establishing international agreements, thus defining and regulating the flows of the global market.

The implementation of trade agreements can have different impacts on the food market. On the network topology, the activation of an agreement

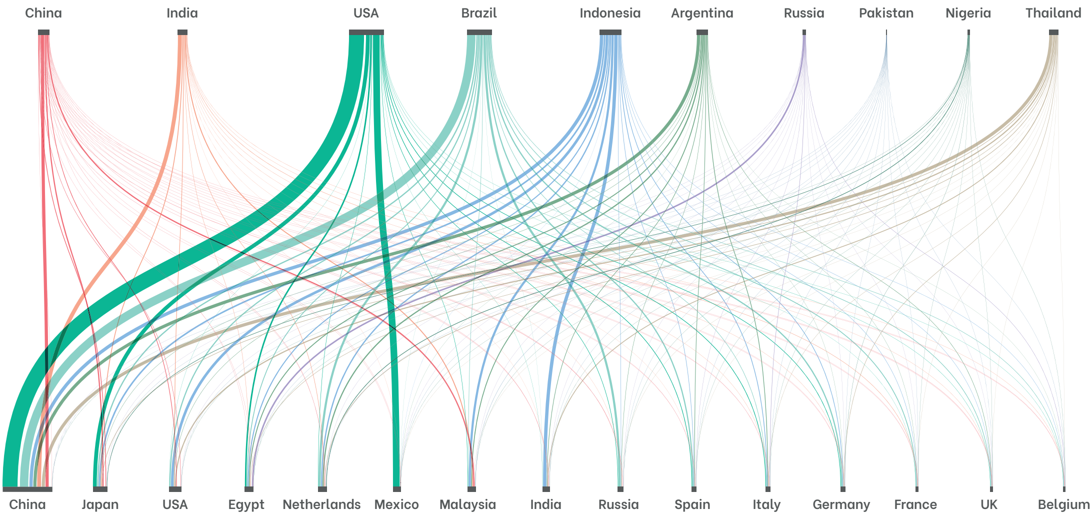

Figure 2: Virtual water's most relevant international flows, i.e., from the top ten exporters (on the bottom) to the top fifteen importers (on the top) in 2016. Each flow is proportional to the water volume embedded in the traded goods. This volume results from the traded quantity of a given good multiplied by its unit water footprint in the country of production (i.e., the country of origin). Image from *Water to Food. A Data-viz Book about the Water Footprint of Food Production and Trade [8].*

shows the probability of activating a new trade link by more than six times compared to the case of no agreement. Moreover, the flows of agricultural products covered by trade agreements show higher volumes, with smaller inter-annual fluctuations in flows, making the network more stable. More importantly, from an environmental point of view, agricultural commodity flows covered by trade agreements are more water-efficient, facilitating trade in crops with high water productivity values, perhaps revealing investments in water use efficiency due to increased economic value traded and higher export earnings of countries participating in trade treaties.

The progressive scarcity of water resources requires one to understand the increasing complexity that characterizes water's mobility patterns, common water use practices associated with these patterns, as well as traditions and social conventions that represent them, such as diets [32]. Trade plays a key role since food imports and exports are two of the main strategic development tools that countries use to maintain food security and improve their income generation. A country's ability to gain access to better market integration depends mainly on concluding trade agreements that, by reducing

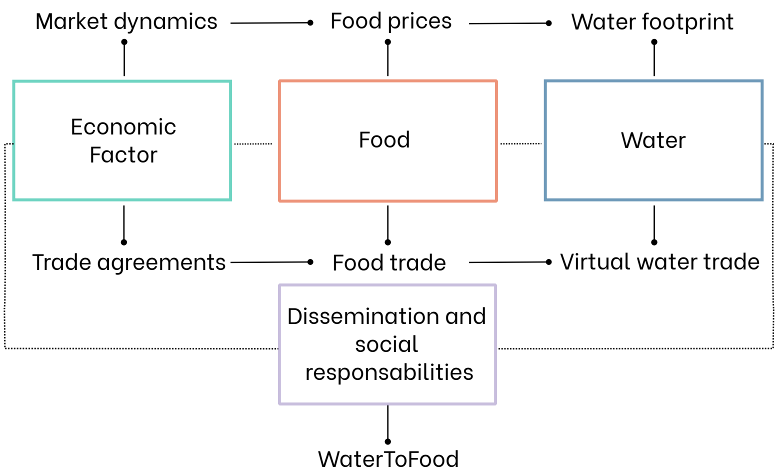

Figure 3: Map of the main key concepts of this thesis and their relationship.

tariff barriers, increase trade in goods by an average of 35%.[2] Recognizing water as an essential input necessary for production and economic growth is crucial when addressing the vulnerability of future economic activity to climate change and resource constraints, especially on the African continent [33]. The globalization of economic activities implies that countries should address resource exploitation and climate change through international agreements that sustainably coordinate their activities.

This dissertation touches on some of these issues from theoretical and empirical perspectives. Figure 3 shows the main topics touched upon in this thesis, as well as the relationships that link them. At a global level, economic factors, such as the prices of agricultural products or, in the context of international trade, the implementation of trade agreements, influence the dynamics of the water-food nexus. On a local scale, the liberalization of international trade affects future production and flows of agricultural products, thus also redefining the virtual water trade.

In addition, many countries still face severe difficulties in using water resources for human activities due to economic and infrastructural barriers, despite their level of water availability [33].

Finally, constantly working and interacting with a team that studies water from different perspectives brought out a question that soon became an urgency that we, as a collective, needed to assess. "How do we move

[2]https://www.worldbank.org/en/topic/regional-integration/brief/regional-trade-agreements

our studies, and the results that come with them, out of the academic environment and make them intelligible and approachable by people outside our niche, so that they can make informed decisions from an ethical, political, and economic point of view?". During the last two years, we undertook this major challenge creating a multimedia communication project and providing a cohesive and cross-disciplinary narration of all the research our team has carried out during the ERC Project "Coping with water scarcity in a globalized world". This has been one of the most challenging and diverse part of my PhD, but a necessary effort to put all my research in a wider perspective.

Overview of the following chapters

In the general context outlined in the previous section, in this thesis we have studied four aspects of the water-food nexus paying particular attention to some economic implications. The following chapters are devoted to describing each of the problems faced.

In **Chapter 1**, we explore if there is any significant relationship between crop prices and the volume of water embedded in the goods through their production processes, ideally providing incentives for more rational use of this resource, reducing waste and inefficiencies. Such practices would have immediate benefits for environmental sustainability, especially under climate change conditions and increased water scarcity. Based on these considerations, our work aims to understand whether water consumption in agricultural production is reflected in crop prices. On a regional scale, recent research has investigated the total water impact for almond production units to inform policymakers on water allocation in agricultural practices [34]. However, there is a lack of data-driven analysis on a global scale that investigates whether water is reflected in market prices of goods. To investigate this topic, we focus on twelve representative crops by analyzing their market prices from 1991 to 2016, collecting data from 162 countries in total. The correlation between water quantity and prices is considered throughout the analysis by splitting the water footprint into its two components of land footprint and evapotranspiration, and investigating the association between water scarcity and crop prices. We identify two different behaviors: staple crops (e.g., wheat, maize, soybeans, and potatoes) tend to reflect a significant relationship between the amount of water used during the production process and the prices of agricultural products. In contrast, cash crops (e.g., coffee, cocoa beans, tea, vanilla), which are not crucial in the human diet and are mainly produced for export, show weaker, if not non-existent, links between production water and global market prices. Although there may be different elements influencing the behavior of these two macro-crop categories, it is crucial to understand how water is linked to crop prices to embrace more efficient practices in water allocation and governance management, improving environmental sustainability in this field.

In **Chapter 2**, we focus on the global market for agricultural products. In particular, we study the relationship between trade agreements' presence and the activation of new trade ties and the increase in volumes traded, together with existing links from 1993 to 2015. We show through a data-driven approach that the activation of a trade agreement correlates with a more than six-fold increase in the probability of establishing a new trade link. At the same time, the presence of a trade agreement over time, not just its activation, is associated with higher volumes of traded goods, with a lower probability of deactivating the link. Trade links covered by agreements generally show higher flows and substantially reduced inter-annual fluctuations. From an environmental point of view, food trade involves a corresponding virtual trade in environmental resources. Translating the analysis in virtual water, we find that flows covered by trade agreements tend to trade products with higher water efficiency. The average economic water productivity of crops traded under trade agreements is 62% higher, indicating possible investments in water use efficiency due to increased income due to the higher economic value traded.
Finally, an analysis is reported to identify flow increases found under specific trade agreements, focusing on the role of trade openness on a global scale.

In **Chapter 3**, we investigate developments in agricultural production and trade on the African continent by 2030 and related virtual water trade. The African continent faces water scarcity with increasing pressure due to population growth and climate change. Water plays a key role in the processes required for agricultural production and food security. In this context, as the international food trade also virtually transfers water resources needed for agriculture from producing to consuming countries, a clear understanding of the African water-food nexus is needed to alleviate water-related issues on future food availability. Our study aims to investigate the future developments of African virtual water flows and the effects of implementing the African Continental Free Trade Area (AfCFTA) on the virtual water network involving the African continent.

To this end, we convert dollar projections obtained with MAGNET into virtual water, using detailed matrices of virtual water production and trade developed within the CWASI project. This dollar-to-water conversion allows us to capture production and trade projections in 2030 for a base case and an AfCFTA scenario by removing tariff barriers.

The baseline scenario projections to 2030 show significant increases in African production (26% increase in virtual water), exports in extra-continental trade (51%), and intra-continental trade (34%).

In the 2030 policy scenario, the most significant effect of AfCFTA implementation is the diversion of African exports. Removing tariffs increases intra-continental trade and slightly reduces exports to non-continental partners. Moreover, we diversify the impact on virtual water of different African economic regions and agricultural sectors to investigate whether the recorded increases depend on specific crops, allowing us to look more closely at the impact of changes in agricultural commodity trade on water demand.

Finally in **Chapter 4**, we present our scientific dissemination project, named "Water To Food"[3]. The dissemination of science is an essential vehicle for promoting and disseminating the new frontier of knowledge. It fosters a virtuous circle enabling researchers to engage with society and citizens to perceive the cultural and practical return on the resources that the community invests in research. Water To Food engages in the dissemination of the results achieved within the CWASI (Coping with water scarcity in a globalized world) project. The project, which has been funded by the European Research Council, pioneered the scientific research about the agricultural water consumption for food production and trade. Our outreach through Water To Food aims to shed light on the water-food nexus and the international commercial connections of virtual water, communicating and disseminating scientific research to the outside world to build an aware and proactive community.

[3] `https://www.watertofood.org/`

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Chapter 1

The work described in this chapter has been partially derived from paper [35].

Is water consumption embedded in crop prices? A global data-driven analysis

Agricultural production exploits about 70% of all water withdrawals around the globe. Still, to date, it is not clear if and how this water consumption is considered in the price of the primary agricultural goods. To shed light on this point, we analyze the farm gate prices of twelve representative crops in 1991-2016, considering data from 162 countries in total. The crop price correlation with the crop's water footprint is investigated, accounting for the country's water scarcity as a possible additional determinant of the price, while the land footprint is considered as a potential confounding factor. We find that the prices of staple crops (e.g., wheat, maize, soybeans, and potatoes) typically embed the amount of water used for their production. Differently, food products that do not contribute in an essential way to the human diet and whose production is more export-oriented (e.g., coffee, cocoa beans, tea, vanilla) exhibit weaker or negligible water-price relationship. These variations may be ascribable to specific market dynamics related to the two product groups. Staple crops are often sold in markets where producers are "price-takers", where the amount of water used during production in consistent with the final crop price. In contrast, cash crops are cultivated by fewer producers who set the prices depending on factors related to the international market. This mechanism seems to produce a crop price composition that is less correlated to production water.
Understanding different water impacts on crop prices may help increase efficiency in water allocation and governance decisions, aiming to improve environmental sustainability in this domain.

1.1 The water pricing debate

In recent years the concept of water availability has changed: for a long time, water was considered an infinite resource due to its renewability, but due to an increased awareness of the scarcity of this resource (in a usable form) in many areas of the world, this perception is not reasonable anymore [36–38].
Water is fundamental for all human activities, but agriculture consumes 70% of all freshwater withdrawals over the globe [39]. Most of the water used in agriculture derives directly from rainfall [40], and it is named *green* water. However, the volume of water extracted from rivers, lakes, and aquifers (*blue* water) for irrigation purposes also plays a fundamental role: even if the amount of irrigated land represents just 20% of the total land dedicated to agriculture, the food resources that it provides sums up to 40% of the global agricultural production [41, 42].

Every increase in the world population drives an increment in the demand for agricultural goods, which in turn requires water to be produced [43]. By 2050 the world's population will increase by approximately one-fourth concerning the current figure [44]. At the same time, an increase of one Celsius degree in global warming has been estimated to reduce the renewable water resource availability by 20% for almost 7% of the worldwide population [45]. Furthermore, the consumption of livestock products, whose production is significantly water-intensive, is growing as a result of higher incomes and urbanization processes that reshape people's diets [46]. Consistently to these projections, water withdrawals are expected to increase over time despite the improvement of technologies constantly. In the main food production areas of the world, water withdrawals from rivers, lakes, and aquifers are significantly reducing the freshwater reserves. This results in a quick and continuous deterioration of the water ecosystems, which are degrading at an even faster rate than other threatened environments [47–51].

In this picture of growing environmental stress due to over-exploitation of water resources, there has been an enduring debate of the possibility to attribute a price to water [15, 16, 52–54]. Some studies argue that assigning an economic value to water would improve the efficiency in the allocation of this resource, shifting its consumption towards more sustainable habits [17–19, 55, 56]. In this case, water would be treated as a private good where the price is decided by the interactions of different subjects on a competitive market. On the opposite side, other researchers argue that water should not be considered as a private good because it is a fundamental human need,

and its the allocation of this scarce resource should occur without necessarily involving monetary transactions, generating benefits for the whole society [20–22, 57, 58].
Other studies do not enter this discussion but declare that the one reason for the absence of economic value of water in agriculture is due to its direct link with the land in which it is embedded [59–61]. According to this point of view, the value of water would be implicit in the value of cultivable areas. Land with higher water availability has a greater opportunity cost than arid land [62]. Its possible alternative uses, in fact, determine its opportunity cost.

In the framework of this debate, some authors claim that agricultural product prices do not adequately reflect the amount of water used for their production [61, 63, 64]. However, there is a lack of large-scale data-driven analyses in this general debate. On a regional, single-crop scale, recent research [34] has investigated the total impact of water for almond production units in California, showing that there is a correlation between high prices of goods and high water content. Although this analysis's objective is different from ours, it provides an interesting indication of the correlation between crop water footprint and market prices of products. Global-scale multi-crop analyses are still lacking.
We aim to fill this gap by investigating the relationship between farm gate prices - i.e., the prices assigned to the agricultural goods that leave the farm and reach the first point of sale - and two environmental resources used for their production: water and harvested area, where the latter is considered to address its possible role as a factor confounding the price-water relation. We consider the water component both in terms of quantity utilized for each crop (crop water footprint) and of water scarcity per capita at a country level (according to the Falkenmark Water Stress Indicator [65]). The scale is global, with a country-scale resolution, and the period investigated is from 1991 to 2016.

1.2 Data and methods

1.2.1 Data

The data used in this study fall into six categories: agricultural production (in *tons*), farm gate price (in current *US$*), water footprint ($m^3/ton$), hectares harvested of each crop (ha/ton), evapotranspitation (mm/ha), and total per capita renewable water resource (m^3/pc).

All data we use are at the country scale and refer to annual values in the period from 1991 to 2016. All data except total water resource are also crop specific. The data-set includes 162 countries, covering all nations where data are available. Table 1.1 summarizes the main characteristics of the data sources used in this work.

The data regarding the production of goods and the harvested area are provided by the Food and Agricultural Organization of the United Nations' database [66]. For each crop, the database provides the quantity of tons ($Q_{cp}(t)$) and the amount of harvested hectares ($A_{cp}(t)$) of product p corresponding to the country c in the year t. The ratio between the harvested area and the tons produced allows us to consider an indicator called land footprint ($L_{cp}(t)$)[67], which is the reverse of the yield (ton/ha).

The economic value of agricultural production ($V_{cp}(t)$) in current *US$* is given by FAOSTAT and it refers to the price attributed to a ton of product when it leaves the farm and arrives at the first point of sale. It is called *Farm Gate Price*. The prices of goods widely vary among countries. To compare the prices of goods produced in different national markets that present distinct living standards and whose national currencies are subject to fluctuations of exchange rates, it is necessary to convert them into a common currency. In order to obtain a comparable price on the global market, we have divided the prices in current US dollars by the price level ratio[1] (plr_{ct}, in $US\$/Int\$$, see [68]). This conversion allows us to obtain a hypothetical currency that allows global comparison of prices, the PPP International Dollar ($P_{cp}(t)$), where PPP means *Purchasing Power Parity*. Finally, we deflated the international prices in PPP using the GDP deflator $defl_t^c$, published by FAOSTAT. Since the price level ratio already accounts for the country-wise fluctuations of inflation, we consider the USA deflator calculated by taking 2010 as the reference year ($defl_t^{USA}$). In this way, we obtain the prices deflated for every year and for each product ($P_{cp}^{(d)}(t)$), with

[1]The ratio indicates the number of dollars needed to buy a bundle of goods in a given country, compared to what would be necessary for buying the same bundle in the USA.

reference to the year 2010, according to

$$P_{cp}^{(d)}(t) = \frac{P_{cp}(t)}{defl_t^{USA}} \qquad t = 1991, ..2016. \tag{1.1}$$

The water footprint of an agricultural product is the amount of water used to produce one ton of that crop [69]. Water footprint data are available as a time average from 1996-2005 on WaterStat[2][69]. These data change in space but not overtime. In order to take into account the time dependence of the crop water footprint $F_{cp}(t)$, we use the data-set obtained through the so-called Fast Track approach [70] which transforms the above-mentioned data of the crop water footprint from constant to time-varying considering changes in agricultural yields. The data set is presented in [71].

Data of evapotranspiration (in mm/ha) would be available from many different sources in terms of potential evapotransporation. However, we are interested in actual evapotranspiration data, that we obtain through the relationship between the crop water footprint (in m^3/ton) and the land footprint (in ha/ton) as [72]

$$ET_{cp}(t) = \frac{1}{10}\frac{F_{cp}(t)}{L_{cp}(t)} \tag{1.2}$$

where the numerical factor 1/10 is introduced to obtain evapotranspiration expressed in mm.
In order to consider the overall water scarcity at a country level, we take into account the total renewable water resources (WR_c) [73], that is defined as the sum of the internal renewable water resources (IRWR) and of the external renewable water resources (ERWR). According to the Falkenmark Water Stress Indicator [65], we divide WR_c for the annual population $Pop_c(t)$ for each country obtaining the per capita water availability ($W_c(t)$). With the aim of considering an indicator that highlights the per capita water shortage instead of water abundance, we take the difference from the global maximum water availability. This water deficiency indicator ($D_c(t)$) is therefore obtained as:

$$D_c(t) = \max_c[W_c(t)] - W_c(t) \tag{1.3}$$

A heterogeneous set of agricultural products is selected: wheat, maize, rice paddy, soybeans, potatoes, apples, avocados, cocoa beans, green coffee,

[2]https://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/

Table 1.1: Variables and data sources considered in this work. The time interval reports the period available in the datasets. Links to the open source databases are reported.

Variable	Description	Source	n.Countries	Time interval
$V_{cp}(t)$	Value of agricultural production in current prices ($US\$/ton$)	FAOSTAT* (http://www.fao.org/faostat/en/#data/QV)	around 245	1991-2016
$Q_{cp}(t)$	Production quantity ($tons/yr$)	FAOSTAT* (http://www.fao.org/faostat/en/#data/QC)	around 245	1961-2017
$A_{cp}(t)$	Area harvested (ha)	FAOSTAT* (http://www.fao.org/faostat/en/#data/QC)	around 245	1961-2017
$Pop_c(t)$	Annual population	FAOSTAT* (http://www.fao.org/faostat/en/#data/OA)	around 240	1950-2017
$F_{cp}(t)$	Crop water footprint (m^3/ton)	CWASI [11] (https://watertofood.org/data/)	255	1961-2016
WR_c	Total annual renewable water resource ($10^9 m^3/yr$)	AQUASTAT** (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en)	200	1958-2017
prl_{ct}	Price level ratio of PPP conversion factor to the market exchange ($US\$/Int\$$)	World Bank (https://data.worldbank.org/indicator/PA.NUS.PPP)	264	1990-2017
$defl_t^c$	GDP deflator (base year varies by country)	FAOSTAT (http://www.fao.org/faostat/en/#data/PD)	around 212	1970-2017

* For the FAOSTAT database the number of countries changes according to the crop.

** For the Total Annual Renewable Water Resource, AquaStat provides data as a mean every 4 years.

cottonseed, tea, and vanilla (see Table 1.2). Four goods are staple crops (wheat, maize, rice paddy and soy beans) that, together with potatoes, cover roughly 60% of the global calorie intake [74]. Besides, we add other goods such as cocoa, cottonseed, tea, green coffee and vanilla whose large-scale cultivation is more oriented for export (commonly known as cash crops), and two fruit items (avocados and apples) characteristic of tropical and temperate areas, respectively. The selected crops exhibit wide variability in average water footprint and price (see Table 1.2). Also, the coefficients of variation of water footprint and prices (ratio of the standard deviation to the mean, both weighted upon production) span a wide range of values implying a large spatial and temporal heterogeneity for each crop.

The average of the economic water productivity (EWP), defined as the economic return of each product per unit of water used [75] (in Int\$/m^3), is obtained as the sum of the deflated global price of each product (in international dollars) for all years in all countries, divided by the total water footprint in all countries for each product over time.
If we calculate an average of the EWP for each of the two groups, staple and cash crops, we do not notice a relevant difference[3]. The interesting element to consider is that, although in the EWP clear patterns between the two

[3]It can be deduced that from the point of view of economic water productivity it seems convenient to grow crops products with low water footprint and higher economic value (such as apples and potatoes), although in reality, many more variables influence the decisions on crops selection. The whole process can be found in the Supplementary Material A.1.

Table 1.2: Basket of the products considered in this work. Columns report the global average crop water footprint (weighted on production) throughout the time period considered (1991-2016) and the global average price per ton (weighted on production), expressed both in International dollars and in US dollars (in parenthesis coefficients of variation CV_w across both countries and years are reported). The size of production in per capita terms is expressed as a global average between countries and years for each crop (kg/pc). The economic water productivity (EWP, in Int\$/m^3) shows the economic return of one cubic meter of water, different for each crop. The last column reports the number of producing countries within our dataset for each crop in 2016.

Product Description (n.FAOSTAT)	Water Footprint (m^3/ton)	Avg price (Int$)	Avg price (US $)	Avg Prod pc (kg/pc)	Avg EWP (Int$/$m^3$)	Num. Countries 2016
Apples (**515**)	646 (0.85)	1175 (0.67)	658 (0.56)	9.76	1.75	79
Avocados (**572**)	1112 (0.80)	1461 (0.53)	958 (0.64)	0.52	1.23	45
Cocoa, beans (**661**)	21711 (0.41)	3497 (0.56)	1535 (0.48)	0.58	0.15	34
Green coffee (**656**)	14739 (0.67)	3737 (0.64)	1865 (0.57)	1.16	0.23	46
Cottonseed (**328**)	3259 (0.62)	2016 (0.69)	972 (0.60)	9.78	0.55	57
Maize (**56**)	957(0.71)	374 (0.83)	216 (0.53)	112.73	0.38	125
Potatoes (**116**)	212 (0.46)	484 (0.64)	264 (0.59)	49.91	2.16	120
Rice, paddy (**27**)	2282 (0.53)	948 (0.53)	413 (0.96)	98.15	0.39	88
Soybeans (**236**)	2074(0.36)	545 (0.72)	369 (0.43)	31.23	0.27	73
Tea(**667**)	8409 (0.73)	4419 (0.89)	2178 (1.57)	0.61	0.47	33
Vanilla (**692**)	155587 (1)	12167 (1.6)	4348 (1.42)	0.001	0.07	5
Wheat (**15**)	1552 (0.46)	481 (0.72)	248 (0.39)	97.05	0.30	99

groups of products do not emerge, different trends can be observed in our analysis investigating the relationship between crop prices and water used. The per-capita production size for each crop was obtained through the sum for all years and all countries, of the total tons produced by each country for that crop, divided by the respective population. We notice that production in per capita terms is highly variable, spamming from more than 112 kg per capita for maize to 0.001 kg per capita for vanilla. The total amount of water actually used for each crop is of course given by the interplay between the water footprint and the production per capita. For example, in the case of vanilla, its enormous water footprint does not translate into large total volumes of water consumed due to low production, and consequently, per capita consumption, compared to other crops.

Finally, the crops are distinguished by the geographical distribution of their production (see Figure 1.1).

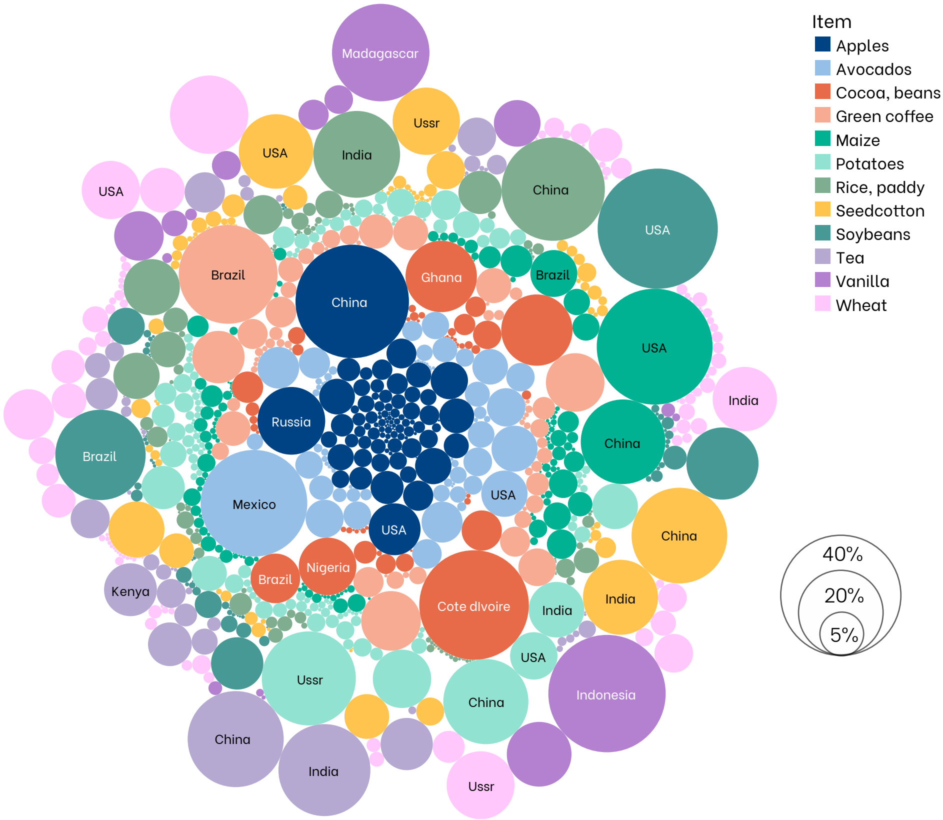


Figure 1.1: Main producing countries in the world divided by crop. The size of each circle represents the time-averaged (1991-2016) percentage of production of each country for each crop over the total production of all countries.

1.2.2 Methods

In order to investigate whether the water component is reflected in the market price of the basket of selected goods, we perform multivariate regressions, both considering all 12 crops together (all-product analysis) and for each crop separately (single-product analysis). The deflated International dollar ($P^{(d)}_{cp}(t)$) is considered as the dependent variable, and a set of different indicators are the explanatory variables (X_i). We consider a power-law relation between the dependent and the independent variables, that translates into a linear form upon log-transformation, namely

$$\log_{10} P^{(d)}_{cp}(t) = \beta_0 + \sum_{i=1}^{m} \beta_i \log_{10} X_i(t) + \epsilon \qquad (1.4)$$

where c runs over all 162 countries and t runs from 1991 to 2016, as explained in section 1.2.1. The set of explanatory variables (X_i), used alone ($m = 1$) or in multiple combinations ($m \neq 1$), includes the crop water footprint ($F_{cp}(t)$), the land footprint ($L_{cp}(t)$), the evapotranspiration ($ET_{cp}(t)$), and the per capita water deficiency indicator ($D_c(t)$). We include each explanatory variable step-wise in the model, keeping all the others constant, in order to detect the respective contribution in explaining the variance of the crop prices. The use of a logarithmic scale is justified by the fact that the quantities span different orders of magnitude. The regression coefficients are estimated with the weighted least square method. We run the regressions minimizing the sum of squared residuals weighted by the percentage of production for each country in every year with respect to the total tons produced by all the countries considered in the same year. In this way, we assign greater importance to the largest producers worldwide for each product. The statistically significant coefficients are identified by applying a Student's t-test with a 5% significance level.

The same regressions are performed also at an intra-product level in order to explore, for each crop, the associations between deflated price and the role of water, detached from the land, in terms of both quantity and scarcity. To explore the temporal stability of associations between variables, for each product we run 26 multivariate regressions across countries, one for each year taken into consideration in this study.
In order to compare the results of the different models we use the adjusted coefficient of determination (R^2_{adj})[4].

[4]The adjusted coefficient of determination (R^2_{adj}) quantifies the measure to which the regressor describes the variation of the dependent variable and considers both the number

1.3 Results

1.3.1 All-product analysis

Our analysis starts focusing on the relation between crop prices and crop water footprints. Figure 1.2 shows the scatter plot of these two variables considering all the products and all the years together. Different colors correspond to distinct crops and the size of the points represents the percentage of production of each country in every year referred to the global production of the same crop in the same year. The R^2_{adj} obtained from this first regression is 0.50.

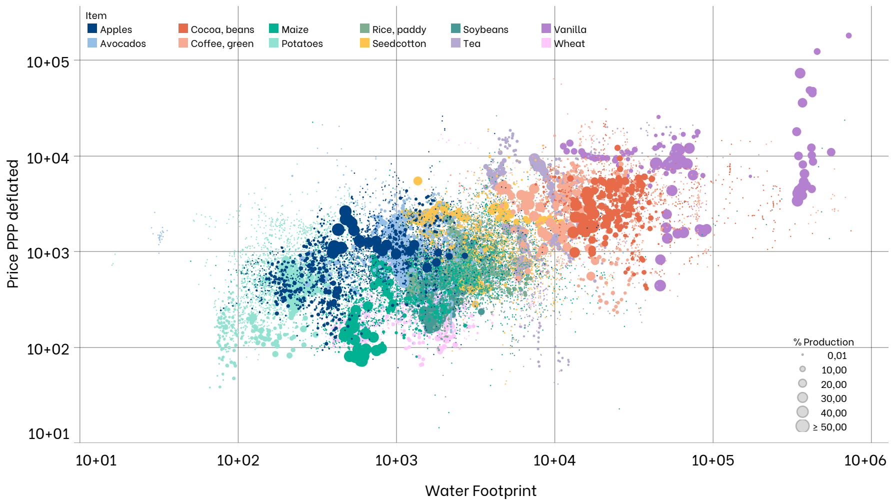


Figure 1.2: Relationship between deflated price in PPP, P_{cp} ($Int\$/ton$), and crop water footprint F_{cp} (m^3/ton). This scatterplot takes into account all crops, all countries, and all years. Each color represents a different crop. The size of the points represents the percentage of production of each country in every year on the total production of all nations in the same year of that crop. The green line represents the result of the weighted linear regression, Eq.(1.4), with $m = 1$ and $X_1(t) = F_{cp}(t)$.

The slope of the regression line is equal to 0.50 and significantly different from zero (p-value $\leq$ 0.05). If we convert the logarithmic values to an arithmetic scale we obtain

$$P^{(d)}_{cp} \propto F^{0.50}_{cp} \tag{1.5}$$

of independent variables and the sample size. Given the large sample size, however, its value is very similar to the standard R^2.

implying that the crop water footprint is correlated with the price, but the effect becomes smaller as the monetary value of the crops increases. This trend recalls the law of diminishing returns which argues that the additional profit obtainable from the increasing use of one production factor (keeping all the others constant) tends to progressively decrease [76].

The results in Figure 1.2 would suggest that water has a positive relation with the pricing behavior. However, as mentioned, many studies claim that the value of water is implicitly included in the value of arable land [59, 77]. To disentangle the roles of water and land, we investigate the possible relation between the hectares used to produce a ton of good and the respective amount of water needed. As it is shown in Figure 1.3, the two variables are strictly and positively correlated with a R^2_{adj} equal to 0.95. As a consequence,

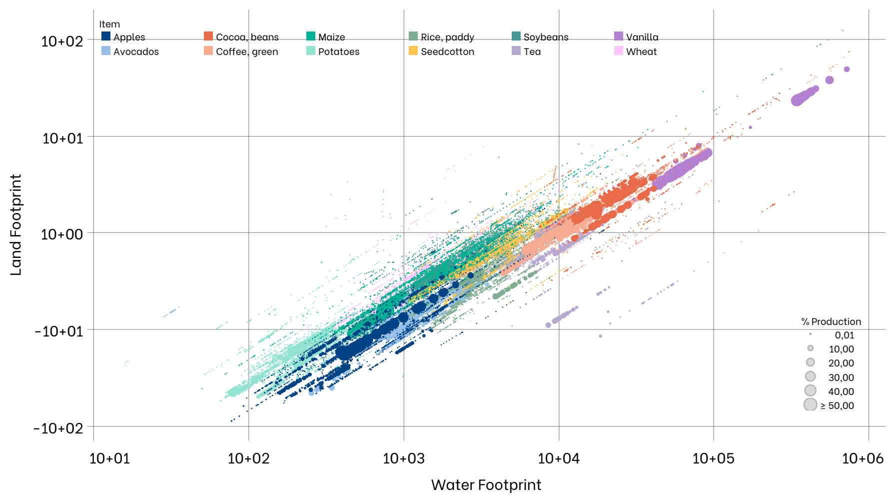


Figure 1.3: Scatter plot between land footprint, L_{cp}, and crop water footprint, F_{cp}.

it is questioned how much of the relationship previously found between deflated prices in PPP and crop water footprint is actually ascribable to the water component. For this reason, we analyze the association between the deflated price in PPP and the land footprint by applying the weighted regression framework of Eq.(1.4), with $m = 1$ and $X_1(t) = L_{cp}(t)$. Also in this case, the slope of the regression line is positive ($\beta_1 = 0.53$) and significantly different from zero. Converting the value to an arithmetic scale (i.e., $P_{cp}^{(d)} \propto L_{cp}^{0.53}$), the curve takes on the same diminishing return trend observed for the previous model. Therefore, one could hypothesize that the water footprint follows the behavior described in Eq.(1.7) because of its embeddedness in the land variable. Since land is an input of production with an existing market it is more expected to follow a law of diminishing returns in determining the output price than water, which is often not regulated by markets.

Nevertheless the ${R^2}_{adj}$ of the law $P_{cp}^{(d)} \propto L_{cp}^{0.53}$ is equal to 0.40, which is significantly lower than the coefficient of determination found for the regression with the crop water footprint as an explanatory variable (as shown in Table 1.4). This lower value suggests that a part of the variance of the dependent variable could be associated directly to the water component (see the Supplementary Material for a deeper investigation on the relation between land footprint and price, in Figure A.2).
In order to extract the information on the relation of the water component on deflated prices, we partition the water footprint into its two items, as derivable from Eq.(1.2): land footprint and evapotranspiration. We perform the multivariate regression in Eq.(1.4) with $m = 2$, $X_1(t) = L_{cp}(t)$ and $X_2(t) = ET_{cp}(t)$. The coefficient of determination is higher than those of the two previous models (${R^2}_{adj} = 0.53$) and the overall relation reads

$$P_{cp}^{(d)} \propto L_{cp}^{0.37} * ET_{cp}^{1.04} \tag{1.6}$$

The result reported in Eq.(1.6) indicates that keeping the cultivated land per ton constant, deflated prices increase almost linearly with evapotranspiration, underlining a well distinguishable role of the water component in terms of volume used during the production of a given crop. Finally, we investigate

Table 1.3: Results of univariate and multivariate regressions. All crops, all countries and all years are considered. The symbol (***) indicates the significant coefficients, identified by applying a Students t-test with a 5% significance level.

N.countries: 162 N.obs: 19981					
Explanatory Var.	$F_{cp}(t)$	$L_{cp}(t)$	$ET_{cp}(t)$	$D_c(t)$	R^2adj
Independent Var.					
$P_{cp}^d(t)$	0.50(***)				0.50
		0.53(***)			0.40
		0.37(***)	1.04(***)		0.53
		0.41(***)	1.01(***)	0.19(***)	0.57

whether water scarcity at the country level is correlated to the price behavior. In order to investigate the role of water shortage, the regression is performed by adding water deficiency as a third explanatory variable beyond land and evapotranspiration. The result, as shown in Table 1.4, indicates that water deficiency ($D_c(t)$) is positively and significantly correlated to price. This suggests that keeping the other variables unchanged, the deflated price growth could be related with the growth of per capita water scarcity. The value of the coefficient of determination $R^2{}_{adj}$ is larger than the one of the models that do not consider water deficiency (0.56). Also, in this case, the slope of evapotranspiration ($\beta_2 = 1.03$) remains stable compared to the previous regressions and still with almost-unitary value, confirming the linear relationship between the deflated prices and the volume of water used in production.

Sensitivity analysis for PPP price selection PPP prices are used to make the data more comparable across countries, eliminating the differences due to exchange rates. However, this conversion can lead to distortions in the analysis. On the one hand, PPP is more difficult to measure than market-based rates, and new price comparisons are only available at irregular intervals. On the other hand, the PPP conversion inflates emerging countries' prices, thus introducing spurious signals. To avoid distortions due to the PPP transformation of the economic values of agricultural products, we reproduced the regression using as dependent variable the deflated prices in US dollars $V^d_{cp}(t)$, i.e., the economic value of agricultural production in current dollars available on FAOSTAT before the transformation into international dollars. The sensitivity analysis of currency choice through the market exchange rate survey confirms the results found with PPP prices. However, it is more appropriate to use PPP prices as they allow us to equalize the purchasing power of different currencies and eliminate discrepancies in price levels between economically different countries [5].

Table 1.4: Results of univariate and multivariate regressions. All crops, all countries and all years are considered. The symbol (***) indicates the significant coefficients, identified by applying a Students t-test with a 5% significance level.

N.countries: 162 N.obs: 19981					
Explanatory Var.	$F_{cp}(t)$	$L_{cp}(t)$	$ET_{cp}(t)$	$D_c(t)$	$R^2 adj$
Independent Var.					
$V^d_{cp}(t)$	0.38(***)				0.40
		0.41(***)			0.32
		0.30(***)	0.78(***)		0.42
		0.30(***)	0.77(***)	0.03(***)	0.43

[5] https://www.worldbank.org/en/programs/icp8

1.3.2 Single-crop analyses

Regression analyses are also performed at the intra-product and intra-year level. By considering individual crops in single years, we examine the possible correlation of country-level crop price on the set of dependent variables considered in the all-product analysis. For each crop, we run 26 multivariate regressions, one for each considered year.
We describe in detail two illustrative examples for each product category: wheat and potatoes for staple crops, green coffee, and avocado for cash crops. The behavior of all 12 crops is summarized in Table 1.5.

Figure 1.4 shows the time variability of the regression coefficients, β_i, obtained for wheat, potatoes, green coffee, and avocados. For wheat the coefficients of the land footprint and water deficiency are positive and statistically significant throughout the time interval, indicating that as the explanatory variables increase the related prices increase as well. Instead, the evapotranspiration coefficients become statistically different from zero only after the year 2003. Although more specific research is needed for understanding changes over time in the significance of the independent variables of every crop, we formulate some hypotheses for the interpretation of this result. The change in the statistical relationship between evapotranspiration and wheat price can be explained by the combination of strong fluctuations in wheat prices since 2003 and increased variability in wheat evapotranspiration over the same period. Regarding potatoes, the coefficients of the three variables are for the most part positive and statistically significant, although water deficiency becomes significant only since the 2000s. This behavior could be ascribed to the fact that this indicator is gradually increasing over time because of the constant increase in the world population. As a result, the per capita water deficiency only starts to be reflected in market prices once it reaches higher values. At the same time, also the average price trend of potatoes encountered strong changes during the 2000s, and this may have influenced the relation between water deficiency and price.
For green coffee, a different behavior is observed; prices are almost never significantly positively correlated with land footprint and water scarcity, and evapotranspiration exhibits only 10 positive-valued and statistically significant coefficients. The evapotranspiration coefficient for green coffee loses significance around the 2000s. Therefore, for green coffee, a clear relationship between the considered variables does not emerge. This behavior is even sharper in the case of avocados where all the coefficients except one are not significantly different from zero. Table 1.5 illustrates the number of

Table 1.5: Crop-specific number of coefficients β_i that are positive and statistically significant in the 26 multivariate regressions (one for each year) adopting land footprint (L_{cp}), evapotranspiration (ET_{cp}) and water deficiency (D_c) for every single crop. For example, in the case of apples, coefficients are statistically significant in 26 years for land footprint, in 23 years for evapotranspiration and in 23 years for water deficiency. The last two columns indicate the average and standard deviation of the number of observations for each item.

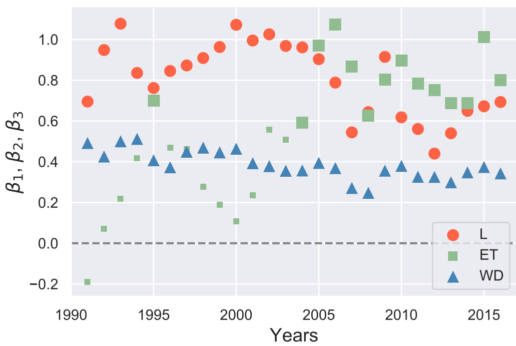
Crop	$L_{cp}(t)$ (ha/ton)	$ET_{cp}(t)$ (mm/ha)	$D_c(t)$ (m^3pc)	Avg N.obs	Std N.obs
Apples	26	23	23	74.54	8.02
Avocados	3	0	1	43.34	2.04
Cocoa beans	12	23	8	34.77	1.34
Green coffee	1	10	5	46.23	2.23
Cottonseed	0	3	26	57.53	2.53
Maize	26	0	26	118.15	9.33
Potatoes	26	26	11	110.65	11.53
Rice Paddy	11	0	16	82.31	6.50
Soybeans	26	25	14	69.96	2.53
Tea	24	2	11	32.15	6.51
Vanilla	6	1	0	5.73	0.45
Wheat	26	14	26	93.11	9.77

years for which the slope coefficients are positive and statistically significant for the three explanatory variables in the regression model for every crop in the sample. The main information captured from Table 1.5 is that we can distinguish two different behaviors.

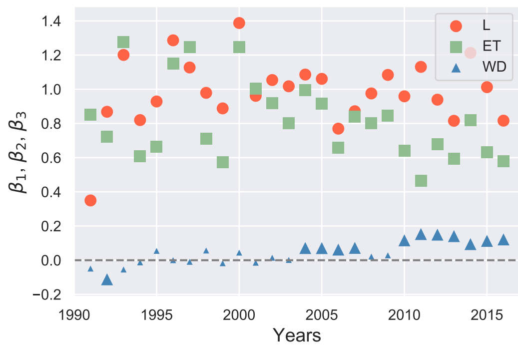
Products with lower water consumption and with a more spatial spread in the world - like wheat, potatoes, apples, and soybeans - show at least two out of three coefficients systematically significant over time. These crops are cultivated in a higher number of countries and are located in the bottom part of the data bundle in Figure 1.2. For this group of agricultural goods, we find a positive and increasing price-water relationship at an intra-product level.

On the contrary, the same relation does not hold for the most water demanding products in terms of water footprint. This group of crops (like vanilla, green coffee, and cottonseed) are cultivated in a lower number of countries, and in this case, the price-water relations are less clear at the intra-product level. These crops are placed on the top right section of the data bundle in the Figure 1.2 and, therefore, in the portion of the regression curve with the lower slope, if considered at an arithmetic scale.
The last two columns of the Table 1.5 show the mean and standard deviation of the number of observations for each crop. The fact that larger samples generally lead to more precise estimates determines whether the two different

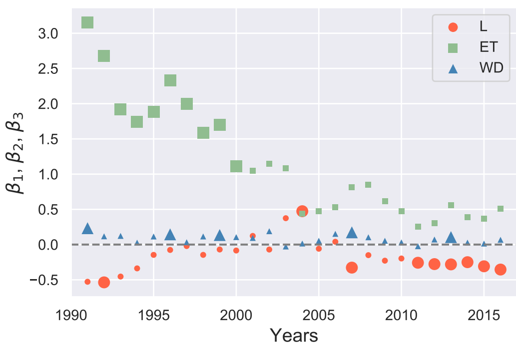
behaviors found can be associated with distortions arising from the number of observations. As we can see from the Table 1.5, this bias is evident in a case like Vanilla, which on average is produced in only five countries in the world. However, this is not systematic for all commercial crops. For this reason, we believe that the difference can not be determined exclusively by the lower precision of the estimate due to the number of observations since, for example, in the case of green coffee or cottonseed (cash crops), the sample sizes are not so different from those of soybeans or apples (staple crops).



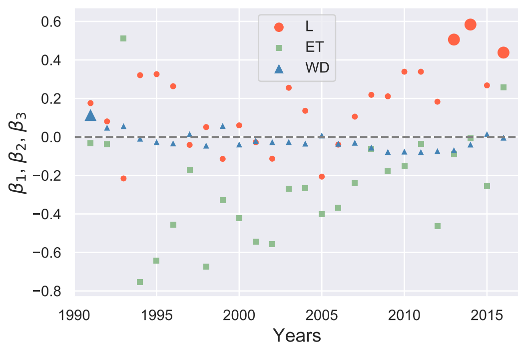
(a) Wheat



(b) Potatoes



(c) Green coffee



(d) Avocados

Figure 1.4: Time behavior of the coefficients β_i of the multivariate regression analysis in Eq. (1.4) (with area per ton, evapotranspiration and water deficiency as explanatory variables) for wheat (a), potatoes (b), green coffee (c) and avocados (d). The different coefficients are identified both by colour and by a different symbol. The larger (smaller) markers identify coefficient significantly (non-significantly) different from zero at a 5% level.

Focus on the blue water footprint

Water use studies distinguish so-called green water (i.e., rainfall) from blue water, which is irrigation water that is typically withdrawn from surface water bodies (rivers, lakes, etc.) and groundwater.

Separating a water footprint into green and blue water allows to see the differences between economic and environmental costs. First of all, blue water comes with its own opportunity cost - i.e., the best alternative use of water given up is of high value - therefore, there is a direct economic cost connected to the use of blue water, as irrigation requires infrastructure and energy not needed for the efficient use of rainfall. For this reason, we explored the relationship between blue water footprint (thus separating it from green) and crop prices.

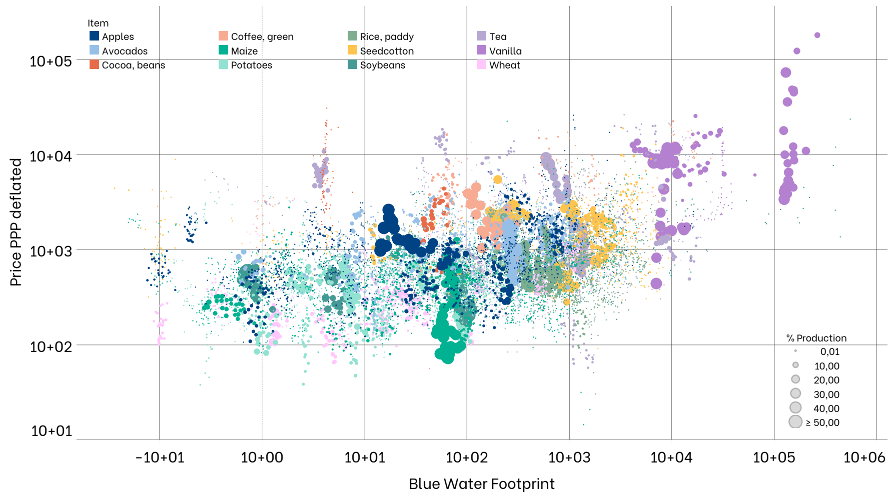


Figure 1.5: Relationship between deflated price in PPP, P_{cp} ($Int\$/ton$), and blue crop water footprint F_{cp} (m^3/ton). This scatterplot takes into account all crops, all countries, and all years. Each color represents a different crop. The size of the points represents the percentage of production of each country in every year on the total production of all nations in the same year of that crop. The green line represents the result of the weighted linear regression, Eq.(1.4), with $m = 1$ and $X_1(t) = F_{cp}(t)$.

As shown in Figure 1.5, the two variables show a positive relationship. The slope of the regression line is equal to 0.25 and significantly different from zero (p-value ≤ 0.05). If, as discussed for the total water footprint, we convert the logarithmic values to an arithmetic scale, we obtain

$$P_{cp}^{(d)} \propto BF_{cp}^{0.25} \tag{1.7}$$

which implies that the water footprint of blue crops is correlated with price, but the effect becomes less significant as the monetary value of the crops increases. However, the coefficient of determination is lower (R^2 =0.32) than the one obtained for the total crop water footprint. This result could be due to the smaller blue water volumes used for agriculture when compared with green water, and the lower overall availability of data.
Also, to investigate whether the blue water component alone has any impact in revealing the two different crop behaviors found in the single-crop analysis, Table 1.6 shows the weighted average for the total footprint and its two components: green and blue water footprint. The last column of the table shows the percentage of the blue water component of the total water footprint. It reveals no systematic classification of the two types of crops between irrigated and rain-fed. Therefore, the differences in the significance of the relationship, which allowed us to distinguish between the two kinds of products found in the single-crop analysis, do not seem to depend on the higher (or lower) composition of the water footprint types.

Table 1.6: The columns show the global average water footprint (total, green and blue) of the crops (weighted on production) for the entire period considered (1991-2016). The last column shows the blue water footprint as a percentage of the total.

Item	Water Footprint	Green Water Footprint	Blue Water Footprint	% of BWF on WF
Apples	645.78	495.98	127.71	19.78%
Avocados	1111.72	814.57	284.90	25.63%
Cocoa, beans	21711.12	26455.79	45.57	0.21%
Coffee, green	14738.51	10965.23	278.38	1.89%
Cotton seed	3258.92	2109.91	1069.54	32.82%
Maize	957.29	844.49	78.65	8.22%
Potatoes	212.25	174.80	34.32	16.17%
Rice, paddy	2282.44	1751.95	530.48	23.24%
Soybeans	2073.55	1979.90	69.73	3.36%
Tea	8409.42	6393.68	1463.19	17.40%
Vanilla	155587.16	104825.80	50761.36	32.63%
Wheat	1552.43	1252.16	362.31	23.34%

1.4 Discussion and conclusion

1.4.1 Discussion

The literature claims that many agricultural products are placed on the national and international markets at a price that does not include the amount of water used in their production cycle [61]. However, there are no large scale data-driven studies that analyze whether the water used for agricultural production is considered within the market prices on a global scale. Our work aims to fill this gap. We started our study focusing on the association between water footprint and crop prices, finding a statistically significant relationship, even if, as water footprint increases, crop prices tend to rise but at a progressively lower rate.

Literature claims also that the value of water is inextricably related to land [59, 78]. Taking this connection into account, we found that land footprint and crop prices are related, but crop prices are also significantly related to both water quantity (evapotranspiration) and water scarcity (water deficiency). Moreover, as water scarcity increases, crop prices tend to rise but progressively to a lesser extent.

We also carried out the study at single-crop level, in order to investigate the behavior of the variables considered within the production of each individual crop. The results allowed us to identify two main behaviors, with some crops confirming the significant price-water relation, and others providing less clear results. These two behaviors can be associated with two specific crop categories, generically referred to as staple and cash crops, respectively.

Staple crops represent a substantial part of the caloric requirements of many diets and are produced in large quantities. Wheat, maize, soya, rice, potatoes, and apples fall into this category. For staple crops (apart from rice), the water component has a significant relationship with their prices. Commercial crops require more water, and their production is smaller than that of staple crops and is concentrated in fewer countries. The literature suggests that a cash crop is a commodity that is grown almost exclusively for its economic value in the domestic and international markets [79]. For this group of products, the relationship between water (or land) use and price appear to be weaker than for the first category. Coffee, cocoa beans, cottonseed, tea, vanilla, and avocados, whose production is usually more export-oriented, belong to this category.

If we look at the relationship that emerged in Figure 1.2, expressed as an arithmetic scale, we see that marginal water productivity seems to be reflected in market prices for staple crops, whereas this is not the case for the so-called cash crops, which are at the top right of the data bundle. The reasons for this diversity can be manifold. On the one hand, the significance of the coefficients may be somewhat influenced by the different number of observations for some products belonging to the cash crops, such as vanilla. On the other hand, as the difference in the number of observations is not so systematic to distinguish the two types of crops behavior, we believe that among the reasons for this diversity, we can find the different production and sales dynamics of the two categories of crops. Although there are many exceptions, staple crops are often grown in more competitive market dynamics, where producers are more dependent on the value of inputs, including water, to maximize profits. In contrast, cash crops are produced by fewer firms that have the market power to set final prices according to the incentives provided by international trade trends, allowing them to decouple pricing from the quantity of some inputs, such as water.

Rice displays a peculiar behavior since it belongs to the staple crops category but it shows a pattern similar to the one of the cash crops. This may be due to a couple of different factors. Firstly, rice consumes more water than other staple crops and, therefore, it follows the law of decreasing marginal returns, for which the additional profit obtained from the increasing use of one production factor (keeping all the others constant) tends to progressively decrease. Secondly, although the water footprint of rice documented in the Asian regions (which are among the largest producers in the world) is high, relying extensively on irrigation water, on average it does not contribute excessively to water scarcity in the region, given the abundance of water resources (despite high heterogeneity within the area) [80]. This may lead to a detachment of the dynamics of water use for crop production from those linked to prices. Finally, more investigation is needed in analyzing the role of subsidies in the prices of irrigation water, that may lead to an under-representation of water in the final farm gate price of rice.

We also tentatively explored the economic water productivity intended as the monetary return obtained from one cubic meter of water for each crop [75], (as shown in Table 1.2, *EWP*). The average economic water productivity for staple crops in terms of dollars per cubic meter does not seem to differ significantly from the one obtained for cash crops. A larger water footprint per ton for cash crops does not seem to significantly affect their lower economic water productivity. The clear pattern found in the distinction of the two categories in the impact of water use on product prices does not seem to be found in the calculation of their economic productivity (see section A in Supplementary Material for more insights on economic water productivity).

1.4.2 Economic interpretation

Although the distinction between cash and staple crops is subject to the context in which it applies, it is useful in this analysis as it allows us to formulate a hypothesis for the understanding of the two macro behaviors [25].

Staple crops are often produced in situations of more competitive market dynamics, in which producers tend to be "price-takers", and the amount of water consumed in the production of crops finds a stable correlation with the final crops' prices. Differently, cash crops are often produced in situations of oligopsony and oligopoly, where the farm gate price is more influenced by few producing or trading firms that are in a "price-maker" position with respect to the international markets. In oligopsony, few companies buy cash crops from many small producers and re-sell them on the international market at a fixed price [81, 82]. In an oligopoly, few corporations are directly involved in the extensive production of those crops. In both cases, large firms own the market power for setting final prices according to the incentives provided by the international trade of those crops and can afford to decouple the price creation from the cost dynamics related to some inputs, such as water. The possibility to trade the cash crop products at a global scale determines both scale and quality of the production [83]. Paradoxically this process concerns those products that require relatively more water for their cultivation if compared to the others included in this study, as shown in Table 1.2. As an example of market concentration, 80 percent of all cocoa exported by Sierra Leone is handled by one single firm [84]. The few companies that produce cash crops have the freedom to decide the economic parameters of the commercialization processes and often agree on a common profit-maximizing strategy. This is the case of coffee, for instance, a crop that has experienced abrupt price changes over time [85]. The control on the coffee markets, in fact, is performed by a few corporate groups through a restriction of the export quotas with the aim of keeping the prices high [86, 87]. In this way, companies own market power over farmers and are able to appropriate the surplus generated by the exports. In our analysis, the dependent variable of the regression, the deflated crop price, tends not to grow above a certain threshold for products defined as cash crops and this may happen because it is less dependent from perfect competition dynamics.

1.4.3 Conclusion

With the present work, we have contributed to disclose the water-price relation for agricultural goods, addressing the problem with a data-based approach with data from the whole world. Through this method, we have found that some of the controversy characterizing the literature on this issue could be ascribed to the fact that different crops behave differently during the production and commercialization process, with the price of staple crops maintaining a positive correlation with the water used in their production. We believe this result could have relevant implications also in the debate on the possibility to explicitly attribute a monetary value to water used in agriculture. It lays the groundwork for future analyses of crop categories to explore in more detail the market mechanisms behind each of them. From a theoretical point of view, the result addresses the unequal consideration given to the different production inputs of crops, from which water is often excluded [64]. From a more practical standpoint, the result may help in designing targeted solutions for contexts in which a clear tendency of overuse of water is present.

More research focused on specific crops, their production processes, and the kind of producers involved is certainly needed. Should further results confirm the finding of the present study, we could argue that, instead of recommending blueprint solutions of water management to be applied to every cultivation, targeted policies could be designed according to the trends related to each crop category.

2

Chapter 2

The work described in this chapter has been partially derived from paper [88]

Role of trade agreements in the global cereal market and implications for virtual water flows.

Understanding the dynamics of food trade, which involves a corresponding virtual trade in environmental resources, is relevant to its effects on the environment. Among the socio-economic factors that interface with the international food market, trade agreements play a significant but poorly understood role in facilitating access to global trade. Focusing on global grain trade over the period 1993-2015, we investigate the role of trade agreements in enabling new linkages and increasing volumes traded and their environmental implications. Through a data-driven approach, we show that the activation of a trade agreement between countries is correlated with a more than six-fold increase in the probability of establishing a new linkage. Moreover, the presence of a trade agreement over time, and not just its activation, seems to be associated with greater market stability as we find a significantly lower probability of link deactivation. Trade links covered by agreements are associated with higher flows and smoother inter-annual fluctuations. In addition, flows covered by trade agreements are more water-efficient, stimulating the exchange of crops with high water productivity values. The average economic water productivity of crops traded under trade agreements increases by 62% when considering total virtual water and even by 93% when focusing on blue water.

2.1 Introduction

Agriculture for food production catalyzes the inputs and connections deriving from the intertwinement of a significant array of natural elements, such as soil composition, water availability, and climatic conditions [89, 90]. While theoretically renewable, these resources require proper management to promote practices that are sustainable over time [5]. In this context, food security requires countries to consider different options in order to maintain an equilibrium between productivity and environmental responsibilities connected to agricultural practices [91]. Environmental impact of food consumption is not a negligible problem: for example, the food system is responsible for 20-37% of the global carbon footprint [74, 92] and agriculture accounts for 70% of total water withdrawals [35, 93]. International trade plays a fundamental role in these strategies. During the last 20 years, the amount of crops traded among countries has more than doubled [74, 94, 95], and food trade now accounts for 23% of primary human food consumption. Food trade is induced by the fact that some countries do not produce enough food to meet their needs and depend on imported food to maintain food security. Other countries produce more than they need and export their surplus. Moreover, countries can reduce domestic food production to import goods produced abroad at a lower price, or can sell abroad rather than domestically the produced goods because this strategy allows them to make more profit [96]. Whatever the strategy pursued by countries, the key point for the purpose of this study is that trading any agricultural good implies a hidden exchange of the resources exploited in the goods' production. It follows that the study of the agricultural trading system is crucial also for understanding its consequences on environmental resources virtually transferred through the export and import of food. In the context of water, this concept translates into virtual water trade [26, 28], i.e. the amount of water used to produce agricultural goods virtually transferred from producing countries to consuming countries through trade in agricultural goods [97].

In the agricultural trade system, trade agreements play an increasingly essential role [98–100], reducing tariff barriers on both a regional and global scale. The food trade has become an integral part of trade agreements during the Uruguay Round, which began in 1986 and ended in April 1994, with the treaty's signing that led to the World Trade Organization (WTO). The evolution of trade agreements concerning the agricultural sector (according to the World Bank [101]) is shown in panel (a) of the Figure 2.2, where it is possible to notice the significant increase starting from 1994.

Some studies investigated the effect of trade agreements on the flow increase within the food trade [102–105]. Grant et al. [106] found that the average benefit of regional trade agreements (RTAs) was to increase the agricultural trade of members by 72%. Huchet-Bourdon et al. [107] showed that globally, RTAs tend to increase bilateral trade between member countries. Bureau and Jean [102] identified that RTAs boost agricultural and food exports by 22-31% after 5 years and 30-45% when wholly implemented. Furthermore, researchers examined the relationship between trade openness and water withdrawals [108–110]. Oki et al .[108] showed that the Middle East reduced its impact on water scarcity by importing water-intensive goods. Reimer found that in 1995, grain trade managed to save about 11% of the world's irrigation water volume [110]. On a regional scale, Dalin [28] identifies an intensification of North American domestic trade in virtual water consistent with the implementation of the US-Mexico agricultural trade agreement (part of the North American Free Trade Agreement) introduced in 1994.

With this work, we contribute to the literature through a data-driven, global-scale approach. By *ex-post* analysis, we test whether trade agreements are correlated with the activation of new linkages and increased trade in agricultural products and the water needed to produce them. Namely, assuming that agreements facilitate trade and influence the volumes traded across different links, we investigate whether the data support these hypotheses. We have two main objectives: (i) to investigate whether the operational activation of a trade agreement between two countries is related to establishing a new cereal flow link between the same countries (the so-called extensive margin in the economic literature)[1]; (ii) to study whether, in cases where a link already exists (i.e., when grains are already traded between two countries), a more significant volume of flow is observed for links covered by trade agreements (intensive margin). In our approach, agreements play the role of summary variables, bringing information on other aspects that, in turn, may determine their establishment (e.g., same language, historical background, geographical proximity, etc.). We are aware that establishing trade agreements and trade flows between countries may depend on these aspects. For this reason, our study aims to highlight a possible association between the implementation of a trade agreement and the creation of new links, and an increase in trade flows. This association

[1]Note that the year of "*operational activation*", corresponds to the moment when countries have declared their consent to be legally bound by a specific treaty, which may be different from the year of the actual entry into force of the entire agreement (for example, if some countries have entered the agreement after its establishment.)

cannot define a causal link between the two aspects (further analysis would be needed to investigate the causality of the two phenomena). Still, it can be a starting point to underline the positive relationship between food network growth and agreement implementation, mainly because it reveals interesting environmental implications, such as the virtual water trade. In fact, there are three innovative aspects in our analysis. The first is to examine the role of trade agreements from different perspectives, looking at grain flows in terms of kilocalories, dollars, and virtual water. This allows us to focus on the nutritional, economic, and environmental aspects of flows in the presence of RTAs, highlighting similarities and differences. The second aspect concerns the activation of links; we study not only whether RTAs are associated with higher volumes of traded grain, but also their correlation with changes in the topology of the trading network. Finally, the third new aspect concerns the type of data and its spatio-temporal scale considered. The analysis focuses on a global scale, considering all countries where information is available. The time interval covers 22 years, from 1993 to 2015, and includes the most important recent reforms in the agricultural sector. Our analysis is based on a dataset that combines the structure of trade agreements provided by the World Bank [111], data on grain trade flows from FAOSTAT, and data on virtual water flows from CWASI [11]. Among agricultural products, we focus on cereals as they are the most traded crop [112], accounting for more than half of the world's daily caloric intake [113].

2.2 Data

This study focuses on two types of data: (i) preferential trade agreements (PTAs) involving the agricultural sector and (ii) trade flows of cereal products.

2.2.1 Trade Agreement Data

About the preferential trade agreements, we use the dataset provided by the World Bank (1958-2015) [111] that collects information for all PTAs in force and which has been notified to the WTO until 2015 [101]. Minor changes are made to the original WB database to obtain more homogeneous clusters of trade treaties: since the WB database reports most European enlargements as individual treaties, we group them under the EC Treaty.

Similarly, we group other accessions and enlargements under the carrier treaty heading - e.g., EFTA and EAEU. The total number of agreements

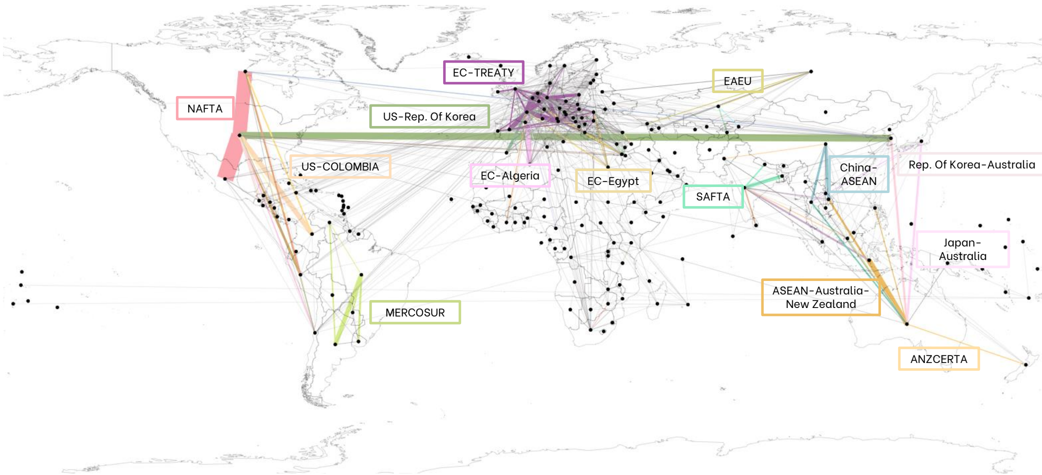


Figure 2.1: Trade flows of cereals in 2015 under trade agreements. The colors distinguish the different trade agreements whose flows make 80% of the total volume transited under trade agreements, the remaining links are in gray. The size of the links is proportional to the cereal flows in US$. The largest flow of cereals in 2015 was traded by NAFTA member countries.

explored in this analysis is 249 and a comprehensive list can be found in the Supplementary Material (Table 1).

We denote the matrix relating to trade agreements as $\mathbf{T}(t)$, in which $T_{ij}(t) = 1$ indicates the existence of a trade agreement between country i and country j at year t.

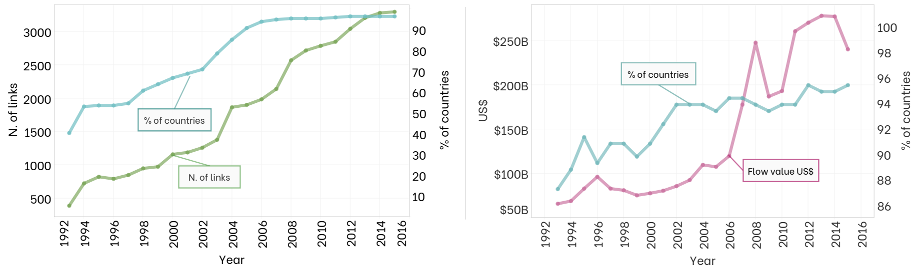
Since there is no specification at the product level, we assume that every agreement concerning the agricultural sector covers cereals [101]; this assumption is reasonable given the high percentage of grains in the global crop market. We conduct the analysis beginning in 1993 to consider individual countries resulting from the geopolitical dissolution of USSR, Czechoslovakia, and Yugoslavia. As an example, Figure 2.1 shows all cereal trade flows that transited under trade agreements in 2015.

2.2.2 Cereal Trade Data

In our analysis, we use detailed trade matrices provided by FAOSTAT [114], which report the bilateral trade flows of each cereal between countries in two units of measurement: weight (tonnes) and economic value (US $). To these units, we add the related flows (m^3) in terms of virtual water obtained from the CWASI database [11], which provides detailed matrices of water trade for each crop according to FAOSTAT classification. The added value of this database is to translate trade flows into virtual water flows by applying country specific coefficients (unit water footprint of supply) which account for the country originating the flow, by proportionally weighting the contributions from local production and import. This approach overcomes the problems due to re-export and gives a more accurate assessment of virtual water trade, with the correct identification of the countries of origin of the traded commodities. In this work, we focus on the total virtual water content and its two components: green water (due to rainfall) and blue water (provided by surface- and groundwater). For all three units of measurement (tonnes, US$ and m^3), data are cereal-specific and reported in the period 1993 – 2015 (see Table B.1 of the Supplementary Materials for the detailed list of cereals; notice that data refer to both primary and derived products).

For each cereal c at year t in the unit measure u, we define the matrix $\mathbf{F}$ recording the trade flow between countries. Therefore, the element $F_{ij}(c,t,u)$ of the (asymmetrical) matrix $\mathbf{F}$ represents the flow of cereal c at time t in the unit u that is traded from country i to country j. Countries' declarations sometimes present inconsistencies between importer and exporter countries, and, to reconcile the disparities, we replace the inconsistent flows with the average values reported by the two countries. Also, the smaller values in the dataset are potentially more error-prone. Accordingly, we exclude them from the analysis: we do not consider the import and export values lower than 10.000 dollars or lower than 1000 tons. Moreover, since we are interested in the overall volume exchanged between two countries, if we register both import and export flows between two countries, we sum together the two values. We obtain the exchange volume matrices equal to $S_{ij}(c,t,u) = F_{ij}(c,t,u) + F_{ji}(c,t,u)$, which we use to represent the trade flow for cereals. Therefore, the element $S_{ij}(c,t,u)$ of the symmetric matrix $\mathbf{S}$ reports the overall trade flow of cereal c in time t and unit u recorded between the two countries i and j. The matrix upon which our analyses will be performed is $\mathbf{V}(t,u)$, where $V_{ij}(t,u)$ is equal to $\sum_{c=1}^{23} S_{ij}(c,t,u)$ and represents the total volume of cereals traded in year t between two countries (i,j), in US$, Kcal, or m^3.

To provide results on cereal aggregation, we choose US dollars, Kcal, and m^3 of virtual water as our reference units. Tons are transformed in Kcal using the nutritional factors provided by FAO [115]. Panel (b) of the Figure 2.2 shows the evolution over time of the economic volume of cereals and the percentage growth of the countries that trade them.



(a) Evolution of trade agreements

(b) Evolution of cereal trade

Figure 2.2: Evolution of trade agreements and cereal trade over time. In panel (a), the blue line refers to the percentage of countries covered by at least one trade agreement out of a total of 196, while the green line shows the number of links in the global cereal trade covered by agreements. In panel (b), the blue line refers to the percentage of countries involved in grain trade out of the total number (196) of countries according to FAOSTAT. In contrast, the magenta line reports the total grain flow in economic terms, billions of US$.

2.3 Methods

The analysis focuses on two aspects:

(i) the activation of links; namely, whether operational activation or the existence of an agreement between two countries is associated with the creation of a new trade link. Contingency tables will be used to investigate this issue;

(ii) the assessment of flow changes occurring under a trade agreement; i.e., whether, in the case of existing links between two countries, the implementation of a trade agreement correlates with an increase in the flow volume of traded products.

2.3.1 Contingency Tables

Contingency tables describe the combined frequencies of two categorical variables:

Table 2.1: Example of a contingency table

		t	
		event A	*event B*
t-1	*event A*	10%	20%
	event B	30%	40%

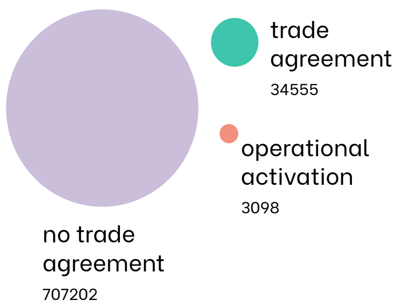
Table 2.1 shows an example of a contingency table where there are two events (A and B) that occur at two different times (*t* and *t-1*). This table shows the combined frequencies of events in the two different years: the first cell, for example, informs that in 10% of the total cases, event A occurred both in year *t* and in year *t-1*. By definition, the cell values sum to 100%. We use this tool to investigate whether the existence of an agreement correlates with the new trade links activation and to visualize the percentage of links that have persisted between one year and another. Therefore, event A represents the absence of cereal trade links, while event B represents the presence of trade links, considering two subsequent years (*t-1* and *t*). We apply contingency tables by dividing country pairs (i, j) into three different parts. Figure 2.3 clarifies the three sets considered:

(i) **No Trade agreements:** this set includes only cereal trade pairs where agreements are lacking at years *t-1* and *t*. This set also includes links where there is a switch-off from year *t-1* to year *t* of a trade agreement since this is found in just 111 cases;

(ii) **Operactional activation in year *t*:** this set covers trade pairs that signed an agreement at year t. We select only the first year in which a treaty exists between two given countries (at year t) to analyze whether we find any association between the signing of that specific agreement and the activation of an actual trade link between them;;

(iii) **Trade agreement in *t-1* and *t*:** this set contains trade links where an agreement exists in both years *t-1* and t. In this case, we investigate when two countries bonded by a trade agreement connect to a commercial relationship.

Figure 2.3: Partitions of all the trading country pairs considered in the analysis. The size of the bubbles is proportional to the number of country pairs included in each subset, listed under the names.



2.3.2 Flow variation index

To investigate differences in the inter-annual variation of flows in the three sets analysed, we introduce a metric as an index of flow variation. For each link (*i*,*j*), we define the index

$$\rho_{ij}(t,u) = \Delta_{ij}(t,u) - \Delta_w(t,u) \tag{2.1}$$

where

$$\Delta_{ij}(t,u) = \frac{V_{ij}(t,u) - V_{ij}(t-1,u)}{V_{ij}(t-1,u)} \cdot 100 \quad \text{and} \quad \Delta_w(t,u) = \frac{V_w(t,u) - V_w(t-1,u)}{V_w(t-1,u)} \cdot 100. \tag{2.2}$$

In Eq. (2.2), $V_w(t,u) = \sum V_{ij}(t,u)$ denotes the sum of all flows that are not covered by any treaty (i.e., *No Trade agreements* set). Therefore, in Eq.(2.1) and (2.2) the term $\Delta_{ij}(t,u)$ describes the percentage change in flow (measured with unit u) between year *t-1* and t for link (ij), while $\Delta_w(t,u)$ represents the worldwide variation corresponding to trade links not covered by treaties. Accordingly, positive values of the index ρ_{ij} indicate links where flow grew - in year t with respect to the previous year *t-1* - more than what happened (on average) worldwide along links where there are no agreements.

To investigate the inter-annual variation of flows covered by trade agreements, we calculate $\rho_{ij}(t,u)$, evaluating $\Delta_{ij}(t,u)$ on the three previously described sets, namely: *No trade agreements*, *Operational Activation in t*, and *Trade agreement in t-1 and t* (notice that the worldwide variation $\Delta_w(t,u)$ in Eq.(2.1) remains the same in each of the three sets).

2.4 Results

2.4.1 Link activation

Contingency tables corresponding to the three cases described in the method section are shown in Table 2.2. Table 2.2 is quite revealing in several ways. The most interesting aspect is that the highest probability of link establishment occurs when an agreement is activated (*Operational Activation in t*).

Table 2.2: Contingency tables. Each table refers to one of the three cases described in the Method section.

No Trade Agreement		**t**		
		no trade	trade	tot rows
t-1	no trade	94,3%	1,3%	95,6%
	trade	1,0%	3,4%	4,4%
	tot columns	95,3%	4,7%	100%

Operational Activation		**t**		
		no trade	trade	tot rows
t-1	no trade	75,3%	7,3%	82,6%
	trade	3,2%	14,2%	17,4%
	tot columns	78,5%	21,5%	100%

Trade Agreement in t-1 and t		**t**		
		no trade	trade	tot rows
t-1	no trade	66,9%	4,3%	71,2%
	trade	3,7%	25,1%	28,8%
	tot columns	70,6%	29,4%	100%

In this case, the probability of activation of a new link is 8.8% - namely, the ratio of new activation 7.3% to the total number of links that were not active at year t-1 (82.6%) - which is significantly higher than in the case of links not covered by a commercial agreement (*No Trade Agreement*), amounting to 1.4%.

Therefore, the findings show that operational activation is associated with the creation of new trade relations between two particular countries. The third set, which considers links where a trade agreement exists in both years *t-1* and *t* (*Trade Agreement in t-1 and t*), also shows a consistent activation probability, equal to 6%. This result confirms the assumption that the coverage of a commercial agreement, and not only its implementation, correlates the genesis of new links.

Moreover, Table 2.2 suggests some interesting considerations on trade persistence. To establish these probabilities, we focus on the row totals in which a trade relationship is present at year *t-1*, i.e., 28.8% in the case *Trade Agreement in t-1 and t.* The presence of an agreement influences in a positive way the probability of maintaining a trade relationship. In fact, when a trade agreement is present in both years, *t-1* and *t*, the probability to preserve the trade relationship is 87.1% ($\frac{25.1}{28.8} \cdot 100$), while when a trade agreement is activated at year *t*, the probability slightly decreases to 81.6%. In cases where trade agreements are missing (*No Trade Agreement in t*) we observe the probability of retaining a relationship decreases to 77.3%.

Another interesting aspect concerns the probability of link deactivation. Once more, the coverage of a trade agreement is related with a lower probability of deactivation of existing links. The ratio of the percentage of links that were active at year *t-1* and are no more active at year *t* to the total is 22.7% ($\frac{1}{4.4} \cdot 100$) in the case of a lack of agreement. This probability decreases to 18.4% ($\frac{3.2}{17.4} \cdot 100$) if we consider only the year of activation of the agreement (*Operational Activation*), and drops to 12.8% ($\frac{3.7}{28.8} \cdot 100$) when looking at agreements present in both years.

Together, these results provide insights into the role of trade agreements in the network topology of the grain trade. While the establishment of a trade agreement is associated with the potential for new trade links, the presence of the agreement in two consecutive years correlates with the maintenance of the existing relationship and a reduction in the likelihood of link shutdowns.

2.4.2 Flow variations

In this second part, we study whether there are differences in the volumes of flows traded between those covered by the trade agreement and those not covered by it analyzing the relationship between flows at time *t* and flows at time *t-1* in each of the three cases described in the Methods section-i.e., *No trade agreement*, *Operational activation in t*, and *Trade agreement in t-1 and t* - measured in US$, Kcal, and m^3 of virtual water.

Figure 2.4 shows three different scatterplots for each unit of measure (US$ and Kcal and m^3). The scatterplots are colored by Kernel Density Estimation (KDE), a non-parametric technique for probability density functions. KDE aims to take a finite sample of data and infer the underlying probability density function. Figure 2.4 relates the flows at time *t-1* with the flows at time *t*, both reported on a logarithmic scale since the quantities span several orders of magnitude. Let's start focusing on flows in terms of dollars and kilocalories. What stands out from the figure is the displacement

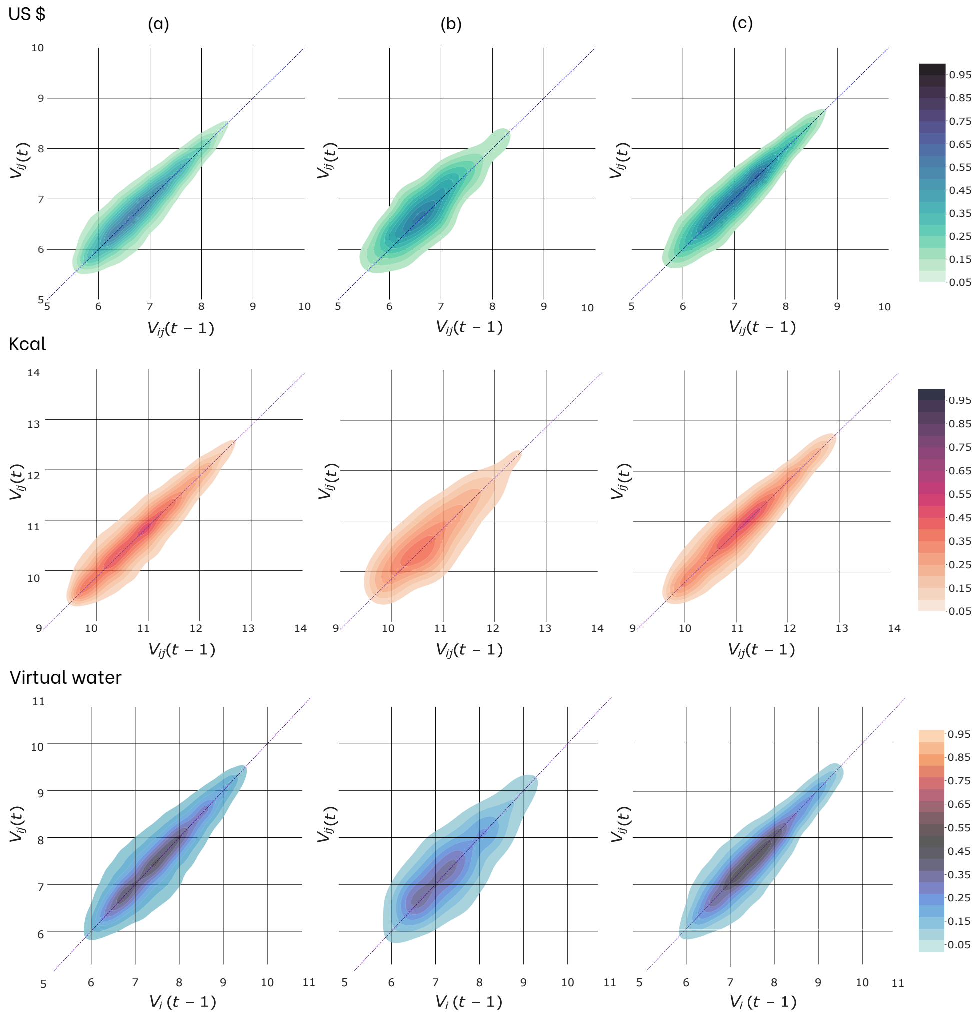


Figure 2.4: Kernel Density scatterplot between trade flows of cereals at time t (in the y-axis) and time *t-1* (in x-axis) for the three different sets: *No trade agreements* (column a), *Operational Activation in t* (b), and *Trade agreement in t-1 and t* (c). Panels in the first, second and third row refer to flows in US\$, Kcal, and virtual water (m^3), respectively. Flow values are shown on a logarithmic scale. The color bar indicates probability densities and the bisector is highlighted. Notice (i) the higher volumes in the case of flows covered by trade agreement and (ii) a a less relevant increase in volume when the flows are seen in the virtual water lens.

of the flows toward higher values when they are covered by trade agreements (*Trade Agreement in t-1 and t*), compared to the case where flows have no trade agreement. We have quantitative evidence of this result by looking at Table 2.3 where the average flows in both years are shown. The average values of flows in both US$ and Kcal are much higher when there is a trade agreement over time (*Trade agreement in t-1 and t*). Flows have an average value of $6.13 \cdot 10^7$\$, larger than the mean $3.05 \cdot 10^7$\$ achieved by flows not covered by a trade agreement. By comparing the distributions of the two distinct sets with different dimensions by applying the non-parametric Mann-Whitney test, we stand to evaluate this result as extremely significant (p-value approximately 0).

Moreover, while operational activation relates to an increased likelihood of new linkages in global grain trade, it does not appear to be correlated with increased flows. Indeed, the average value of flows in both years *t-1* and *t* are lower than those not covered by trade agreements.

Table 2.3: Average values of trade flows and flow variation index ρ_{ij} for each of the three sets, in US$ (a), Kcal (b), and Virtual water (VW, m^3). The bar indicates the average operator. The subscript w indicates the weighted average, where weights correspond to the flows at time *t-1* (i.e.,$V_{ij}(t-1)$). Values of ρ_{ij} is reported in percentage point (p.p). Table B.2 of the Supplementary Material provides the values of virtual water separated into the blue and green water components.

(a) US $

Operational Activation	
$\overline{V_{ij}}(t)$	$3.59 \cdot 10^7$
$\overline{\mid \rho_{ij} \mid}_w$	41.77 p.p
Trade Agreement in t-1 and t	
$\overline{V_{ij}}(t)$	$6.13 \cdot 10^7$
$\overline{\mid \rho_{ij} \mid}_w$	24.79 p.p
No Trade Agreement	
$\overline{V_{ij}}(t)$	$3.05 \cdot 10^7$
$\overline{\mid \rho_{ij} \mid}_w$	46.82 p.p

(b) Kcal

Operational Activation	
$\overline{V_{ij}}(t)$	$5.23 \cdot 10^{11}$
$\overline{\mid \rho_{ij} \mid}_w$	48.04 p.p
Trade Agreement in t-1 and t	
$\overline{V_{ij}}(t)$	$7.55 \cdot 10^{11}$
$\overline{\mid \rho_{ij} \mid}_w$	27.29 p.p
No Trade Agreement	
$\overline{V_{ij}}(t)$	$4.36 \cdot 10^{11}$
$\overline{\mid \rho_{ij} \mid}_w$	48.22 p.p

(c) VW m^3

Operational Activation	
$\overline{V_{ij}}(t)$	$1.98 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	43.10 p.p
Trade Agreement in t-1 and t	
$\overline{V_{ij}}(t)$	$2.56 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	40.07 p.p
No Trade Agreement	
$\overline{V_{ij}}(t)$	$1.94 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	54.99 p.p

The view appears slightly different if we look at the values in terms of virtual water (VW, m^3), i.e., the sum of the blue and green components. Flows with a trade agreement show higher average values than those not covered by agreements (see panel (c) of the Table 2.3), but the increase is significantly less than that recorded in the other two units (US$ and Kcal). The growth recorded in dollars is about 100%, while in virtual water terms, this increase is less than 30%. The next subsection will focus on this peculiar behavior, which reveals a different water content of traded goods along links covered or not by agreements.
Another significant result that emerges from the Figure 2.4 is the smaller width (around the bisector) of the cloud in the case of links covered by agreements in both years *t-1* and *t*. This is confirmed by comparing the

weighted average of the absolute value of the interannual flow change index $\overline{\rho_{ij}}_w$ (the weights are the flows exchanged in year *t-1*). Larger ρ_{ij} values correspond to larger average variations from year *t-1* to year *t*. Accordingly, we observe that in the presence of trade agreement at time *t-1* and *t* a smaller ρ_{ij} value of 24.79 percentage points (p.p) is found (see panel (a) of Table 2.3).

Considering all units (US$, Kcal, and m^3), this value is about half of the average inter-annual variation when there is no trade agreement. Hence, flows covered by a trade agreement experience more minor fluctuations, indicating more stable year-to-year variations.

2.4.3 Water productivity

In order to shed light on the response of virtual water to the agreement occurrence, we refer to water productivity (WP) [116], which is a measure of the output of a given agricultural system in relation to the water it consumes:

$$WP = \frac{Agricultural\ Ouput}{Water\ Use} \tag{2.3}$$

In particular, we consider the nutritional and the economic water productivity (NWP and EWP), that refer to the calories and dollars per unit of cubic meter of water, respectively.

Table 2.4: Average of nutritional (NWP, kcal/m^3) and economic (EWP, US$/m^3) water productivity (WP) for the total, blue and green virtual water.

	VW total		VW blue		VW green	
	NWP (kcal/m^3)	**EWP** (US$/$m^3$)	**NWP** (kcal/m^3)	**EWP** (US$/$m^3$)	**NWP** (kcal/m^3)	**EWP** (US$/$m^3$)
Operational Activation	2864.41	0.20	35192.40	2.45	3118.20	0.21
Trade Agreement in t-1 and t	3157.78	0.26	36790.92	3.02	3454.25	0.28
No trade agreement	2324.46	0.16	21839.35	1.56	2601.33	0.18

Table 2.4 shows that the nutritional water productivity (NWP) for the total virtual water is, on average, 35% higher in the flows under a trade agreement than in flows that are not under any treaty, while the economic water productivity (EWP) is 62% higher. We also analyze the two virtual water components, blue and green, separately. Interestingly, for blue water in the presence of a trade agreement, the NWP and the EWP for the flows covered by trade agreement are, on average, 68% and 93% higher than for the flows not covered by agreements. In other words, for one cubic meter of water used for grain production, more kilo-calories and dollars are

exchanged when an agreement is in place, and this difference is even more significant in terms of blue water.

We also investigate in detail which products contribute most to the imbalance between flows in terms of kcal or water. To this aim, Figure 2.5 reports the nutritional WP for each grain item distinguishing whether or not there is a commercial agreement (similar results occur if the economic WP is considered).

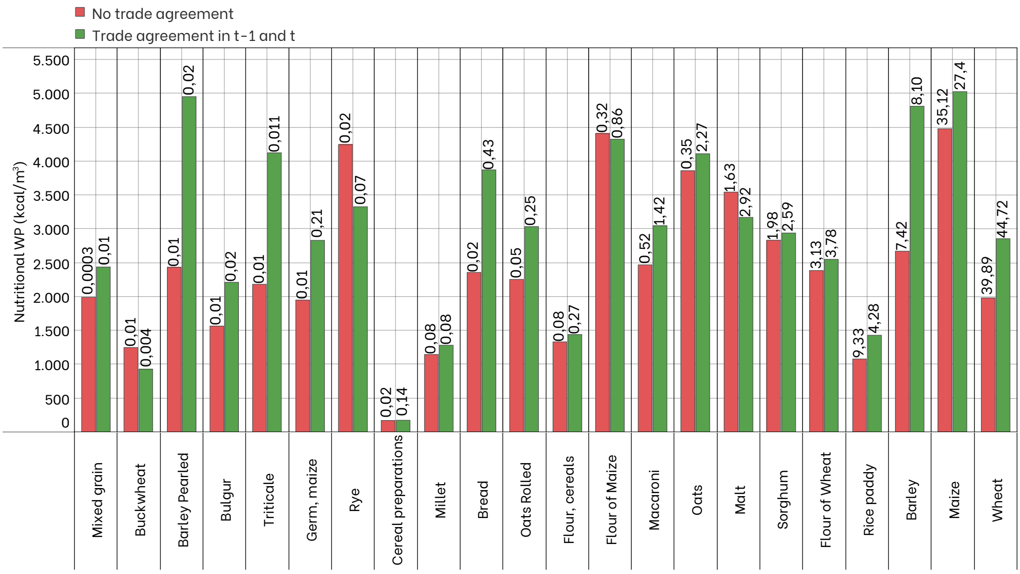


Figure 2.5: The bar chart shows the nutritional WP for each cereal product in the two sets of *Trade agreement in t-1 and t* (in green) and *No trade agreement* (in red). The number over the bars represents the percentage of kcal traded for each product compared to the total kcal of all cereals. Note that green bars are higher than the red ones in 80% of cases.

The figure highlights that generally the nutritional WP is higher in the case where flows are covered by trade agreements (green bars). The most noticeable cases are Maize and Wheat, which are also the most traded products: the value of nutronal WP increases from 1978 kcal/m^3 (*No trade agreement*) to 2851 kcal/m^3 in case of a trade agreement for Wheat, and from 4471 kcal/m^3 to 5026 for Maize.

A few products have a higher nutritional WP value when the flows are not involved in any treaty, e.g., Rye. This behavior can be traced back to a few flows that dominate the market between countries not linked by trade agreements. For example, trade in Rye in 2014 is attributable to just two major flows in terms of caloric intake relative to water quantity (notably, one between Germany and Japan, the other between Russia and Turkey).

Figure 2.5 clearly shows that grains characterized by greater water efficiency generally move along the links covered by agreements.

2.4.4 Flow increases under specific trade agreement

Our results show that links covered by agreements correlate with higher flows than links not covered by treaties. In this context, it is interesting to explore under which trade agreements the most significant flows increases occur. Accordingly, we use again the index (ρ) but now applying it at a trade agreement scale; we, therefore, focus on the overall flow changes that occurred (from year *t-1* to year *t*) between countries that are part of the same agreement; we define:

$$\rho_a(t) = \Delta_a(t) - \Delta_w(t) \tag{2.4}$$

where:

$$\Delta_a(t) = \frac{V_a(t) - V_a(t-1)}{V_a(t-1)} \cdot 100. \tag{2.5}$$

V_a stands for the cluster of flows between countries (i, j) falling under the trade agreement a, while t represents the year of entry into force of the agreement, and $\Delta_w(t)$ is defined as in Eq. (2.2) (i.e., it refers to average variation of non-agreement trade relationships). To evaluate ρ_a, we select active links in the year in which there is an entry force. Since there are trade treaties that came into effect before the considered time interval [1993 - 2015], these are not included in the analysis.

As a result, the total number of agreements selected for this analysis is 99, 61 of which show an increase (positive values of ρ_a). In contrast, the remaining 38 show a decrease in flow intensities relative to the overall trend. We present results for positive changes in ρ_a in the table, while trade agreements with negative values of ρ_a are reported in the supplementary material (Table 5). We provide this analysis in terms of economic flows (US$), but very similar results are obtained if calories ($kcal$) or virtual water (m^3) are chosen as units.

What stands out in the table is that most of the positive percentage changes occur in Europe and Central Asia. This may be due to long-term trade activities in Europe, supported by the countries' geographic proximity and the wide variety of political and economic treaties between them. Indeed, Europe is characterized by a fourfold increase in grain production since the

Table 2.5: Flow values in millions of dollars in year t and percent changes ρ_a from *t-1* to t for each trade agreement. Year t indicates the year of entry into force of the trade agreement. Colors highlight the geographical region as provided by the World Bank, considering most of the countries that are part of the trade agreement. In the case of a bilateral trade agreements, the geographical position of the first country mentioned in the actual name of the treaty is taken into account to assign the color. For each region, trade agreements are sorted in descending order according to the flow value ($ million). The color and orientation of the arrows classify the percentage changes into three categories: gray for a moderate increase concerning links not covered by agreements ($<$ 50% increase in flow intensity), yellow for strong increase (increase $\geq$ 50% and $<$ 100%), and green for sharp increase (increase $\geq$ 100%).

World Bank region	Name agreement	Year Entry Force	Flow intensity (millions $)	ρ_a p.p
Europe & Central Asia	EC-Algeria	2005	579,2	13
	CEFTA	2007	368,2	67
	EC-Morocco	2000	340,2	67
	EEA	1994	301,4	118
	EC-Cote d'Ivoire	2009	147,3	23
	EC-Cameroon	2009	146,1	6
	EC-CARIFORUM	2008	139,9	74
	EC-Bosnia Herzegovina	2008	123,0	99
	EC-Israel	2000	116,3	121
	EU - Republic of Moldova	2014	111,7	110
	EC-Turkey	1996	98,8	52
	EU - Colombia and Peru	2013	77,8	375
	EFTA - Mexico	2001	65,4	14
	EU - ESA Interim EPA	2012	63,7	0,3
	EC-South Africa	2000	59,6	111
	EU - Central America	2013	48,9	37
	EC-Croatia	2002	40,3	45
	EC-Lebanon	2003	16,9	6
	Turkey - Georgia	2008	14,8	273
	EU - Georgia	2014	12,6	14
	Turkey - FYR Macedonia	2000	8,6	34
	EC-Montenegro	2008	6,8	277
	EC-FYR Macedonia	2001	4,7	68
	Turkey - Mauritius	2013	1,8	140
	Turkey - Tunisia	2005	0,9	102
	EC-Faroe Islands	1997	0,6	12
South Asia	Pakistan - Malaysia	2001	34,0	28
	Pakistan - Sri Lanka	2005	15,0	62
	India-Singapore	2005	13,6	11
	India-Sri Lanka	2008	9,3	942
	India-Japan	2011	3,4	93

World Bank region	Name agreement	Year Entry Force	Flow intensity (millions $)	ρ_a p.p
East Asia & Pacific	ASEAN-Australia-New Zealand	2003	2080,6	45
	Korea, Republic of - Australia	2005	490,6	8
	ASEAN-India	2005	349,8	24
	Japan-ASEAN	2006	191,2	250
	Australia-Thailand	2006	184,5	62
	ASEAN-Korea	2006	45,0	91
	Korea, Republic of - Turkey	2008	19,3	188
	Thailand - New Zealand	2010	5,4	10
	PICTA	2010	5,1	167
	TPSEP	2010	1,4	33
	Korea, Republic of-Singapore	2010	0,8	37
	Japan-Malaysia	2013	0,5	14
	Korea, Republic of-India	2014	0,5	66
Latin America & Caribbean	CAFTA-DR	2002	847,4	43
	Mexico - Central America	2006	78,0	24
	Peru - Chile	2009	41,8	14
	Chile - Nicaragua	2010	4,6	2
	Panama - Peru	2012	1,9	27
	Chile - Guatemala	2012	1,5	53
	Chile - Costa Rica	2012	0,9	134
North America	NAFTA	1994	2215,3	37
	Canada - Colombia	2004	226,3	2
	US-Peru	2005	206,5	31
	US-Morocco	2006	197,8	98
	Canada-Peru	2009	173,7	53
	Canada-EFTA	2009	34,6	25
	US-Singapore	2009	15,0	21
	US-Australia	2011	5,9	142
	Canada - Panama	2013	2,2	34
Sub-Saharan Africa	COMESA	1994	161,5	154

1960s due to the adoption of the Common Agricultural Policy, which has intensified trade within Europe and to external markets [112].

A closer look at the table 2.5 shows that among the agreements with the most significant flows that have shown the greatest increases are EEA (European Economic Area) in Europe and Central Asia, Japan-ASEAN in East Asia and the Pacific, and COMESA in Sub-Saharan Africa.

The India-Sri Lanka agreement in Asia stands out above all others for the flow change value o(ρ_a) despite low flow intensity values. The treaty signed in 2013 between the EU - Colombia and Peru also shows significant variations in terms of the percentage of increase in flow, but the volume of the corresponding flow is lower than flows under other trade agreements. On the other hand, the North American Free Trade Agreement (NAFTA), which entered into force in 1994, has a lower ρ_a value, but the flows on which the variation is calculated are significantly higher.

2.5 Discussion

While the debate on the effectiveness of trade liberalization in agriculture is still open, we find evidence of the correlation that bilateral and regional treaties have on the growth of the global food network. Even if this increase could be influenced by several other aspects that occurred during the period analyzed (such as income and population growth [117]) and it is not possible to identify a causal link between the two phenomena, what emerges from our study is that the coverage of trade agreements is associated with changes in the topology of the food trade network.

This work argues that operational activation of an agreement is linked to a higher probability of generating new links and that flows covered by trade agreements have higher volumes of grain traded. Moreover, reducing trade barriers seems to be associated with more stable flows with a significant decrease in inter-annual fluctuations, supporting studies showing that highly connected relationships tend to improve the stability of agricultural trade [118–121]. All the results are data-driven, focusing on building a broad analysis from a spatial and temporal perspective. In fact, using cereals as proxies for the whole agricultural trade category, our data-based approach suggests that the implementation of trade agreements is positively combined with the establishment of new links: in the 1993-2015 period, the probability of activating a new trade link increases by more than 6 times (from 1.4% to 8.8%) compared to the case where no trade agreement is active, while the deactivation probability values for country pairs that activate new links is the same as the overall network disconnection probability (about 0.20). This suggests that, in the year of the trade agreement's implementation, the activation of a new link does not trigger an increase in the deactivation rate of other links; namely, trade agreements induce new partnerships and do not re-channel previous links. Furthermore, the presence of a trade agreement in both years *t-1* and *t* halves the probability of link deactivation.

We also discover a positive association between trade agreement implementation and the likelihood of continuing a commercial relationship even when two countries are already trading, showing flows with less inter-annual average variations.

A key point of our research concerns the environmental repercussions of the grain trade. The results show that under trade agreements, countries exchange crops with higher water productivity over crops traded along links not covered by any agreements. This behavior may be due to greater trade openness, allowing more investment in water-efficient systems. Water productivity differences between links covered or not by agreements are enhanced when blue water is focused on, indicating that countries linked by trade agreements can allocate irrigation water more efficiently by diverting water towards more proficient crops both nutritionally and economically. Among scholars, openness to international trade is often seen as a factor in economic growth [122]. Commercial agreements, in fact, help legislate and stabilize trade flows and politics, diminishing the uncertainty and providing the structure and information to make long term investments and decisions [123, 124].

Some studies suggest that trade leads to efficiency gains as resources are allocated in line with comparative advantage, shaped by differences in technology and relative factor endowments [125]. In agriculture, where differences in land and water and climate endowments across countries are significant, the gains from market openness and integration can be substantial [126]. Other studies argue that trade can induce technological change, transfer of technology, and sharing best practices between trading partners; therefore, leading to higher productivity and more efficient use of resources [127, 128].

Our study intertwines and strengthen other researches where the link between trade openness and water efficiency was investigated. For instance, Dang and Konar [129] shows that trade openness led to less water use in agriculture, reducing resource use. Kagohashi [32] deduces that the level of water consumption invariably decreases once water-rich and water-poor countries start trading, inferring that trade openness could reduce water consumption.

From an environmental point of view, international trade tends to have an explicit influence on the growth of externalities such as pollution and the deterioration of natural resources. At the same time, it also generates growth in production and trade, as well as the consequent relocation of production processes and regulations [89, 130, 131].

While this work has some relevant limitations, and we are aware the trade agreements have a tendency to be developed in contexts where a trade flow was already in place, it is still interesting to note through a data driven approach that flows covered by treaties privilege high-water-productivity grains.

Therefore, the results of this work highlight the importance of including the existence (or future stipulation) of trade agreements in the predictive models used to outline future global scenarios of virtual trade in environmental goods.

3

Chapter 3

This chapter chapter collects the results of a collaboration with the Wageningen University Research, Den Haag, Netherlands. A scientific article [132] is in preparation.

Scenarios for African virtual water trade and possible impacts of the African Continental Free Trade Agreement (AfCFTA)

Water scarcity is a major issue in the African continent and will likely get worst in the future due to population growth and climate change. In this context, the most significant portion of water consumed in Africa is pushed towards the agricultural sector. Since water resources are virtually transferred from production to consumption through the international trade of goods in which they are embedded, a clear understanding of the African water-food nexus is needed to alleviate water-related problems in this continent.

Starting from these assumptions, we study the future development of African virtual water flows, and the effects of the implementation of the African Continental Free Trade Area (AfCFTA) on the virtual water network involving the African continent.

To this end, we convert the projections in dollars obtained with MAGNET (Modular Applied GeNeral Equilibrium Tool) into virtual water, using detailed virtual water production and trade matrices developed within the CWASI project. This dollar-to-water conversion allows us to outline two 2030 scenarios: (i) a first scenario (which we will define as baseline) in which the activation of the agreement is not considered and (ii) a second scenario in which tariff barriers are removed and the AfCFTA is taken into account (this scenario will be called AfCFTA scenario).

3.1 Introduction

Water plays a key role in the processes necessary for food production and food security, and is therefore a crucial resource in the formation and sustainability of healthy local and global human environments [133]. As agricultural production accounts for 70% of all freshwater withdrawals globally [134], the food system is closely linked to water availability in producing countries. Global food trade implies the increasing globalization of water as a resource which is embedded in the commodities exchanged on the global market.

From this point of view, water scarcity is one of the main problems in the development of African countries. There are several socio-economic and environmental reasons why this continent in particular is subject to physical and economic water scarcity. Africa is the second driest continent in the world and its water resources are unevenly distributed: per capita availability varies from less than 500 m^3 in North African regions to 1700 m^3 in sub-Saharan Africa [135–138]. Moreover, the situation is expected to exacerbate in the future, where the pressure on the water system will increase substantially by 2050. Africa's population, in fact, is expected to grow to 2.4 billion by 2050, more than doubling the current 1.1 billion, and, in addition, the IPCC's 5th report states that rising temperatures caused by climate change will amplify the existing stress on Africa's water resources [135, 139]. Consequently, water scarcity poses a formidable threat in Africa as more than half the population relies on subsistence farming, and food security seems noticeably difficult to achieve in a continent where food production growth is lower than population growth [140].

In this context, our study intends to investigate possible future scenarios of virtual water trade in Africa, projecting the production and trade of commodities in 2030 and understanding the consequences on future agricultural water use. The concept of virtual water has been used by scholars and policy-makers in recent decades to study how the water resource moves around the world, embedded in the goods and services that exploit it during their production phase [61]. Virtual water is the volume of water needed to produce a specific good that is exchanged virtually when the product is traded on the market. The analysis of virtual water flows provides insights into environmental as well as socioeconomic aspects of global trade in agricultural goods, water management, and agricultural policy [11, 70].

In addition, we study the role of trade openness, as trade plays a primary role in this scenario: food imports and exports are, in fact, two of the main strategic development tools countries use to maintain food security and improve their income. Worldwide, a quarter of the food produced for human consumption is traded [141], and global and regional trade agreements are the preeminent legislative devices to regulate and encourage the generation of trade links and flows [107]. In this context, African intra-continental trade barely exceeds 10% of the total trade, and Africa's share in the total of global exports is only up to 2% [142]. The African Continental Free Trade Area (AfCFTA), implemented in 2021, is expected to increase trade within the African continent: in particular, inter-regional agricultural trade is expected to grow, improving the continent's efficiency and capacity to ensure food and nutrition security. The increase in the amount of food traded could also drive more significant trade in virtual water.

The implementation of the AfCFTA will directly impact the entire African economy, and not just the agricultural sector. This is why we decided to use the MAGNET model [143] - a recursive dynamic multi-regional Computable General Equilibrium (CGE) model with global coverage - to delve into Africa's trade projections and to investigate the impact of the AfCFTA on all trade flows. To explore the projections to 2030 and the impact of the AfCFTA on production and trade, we implement the second shared socio-economic pathway (SSP2) [144] and we aggregate single crops into agricultural sectors. To simplify the complexity of the network, we group 239 world countries into 16 regions (7 regions in Africa), as shown in Figure 3.1. This regional aggregation mainly refers to the economic (regional) agreements[1] in Africa and external trading routes and partners[2] (see the complete list of countries under the various aggregations in Table C.1 in the Supplementary Material).

In the existing literature, other CGE models have been adapted to include and explicit water resources used in the production processes [145, 146]. Since this methodology is commonly used for examining water supply shocks or water allocation in a general equilibrium context, CGE model parameters are usually obtained by calibration from national accounts data, which have the flaw to not incorporate information on sectoral water use. As a result, to assess the impact of water in production practices, some studies consider water as a factor related to land value [147], while others consider the water footprint of the produced goods [148]. In particular, Roson and Sartori (2015) estimated and analyzed virtual water trade and

[1] `https://au.int/en/organs/recs`

[2] The region names that we use are related to the main economic trading blocks of the region, but these are not the same thing. In our analysis, we make sure that countries that are normally considered part on multiple economic blocks figure just in a single one of these blocks, to avoid repetition.

supply shocks in the Mediterranean focusing on Italy, comparing the current situation with a hypothetical future scenario. On a small scale, Mellios et al. (2018) assigned national crop data at the basin level to determine the contribution of crop exports to water stress regions in Greece [149]. However, neither of these contributions consider possible virtual water flows changes overtime or make any distinction in the crop mix between production and trade. Our work differs from previous studies on this last point, and seeks to closely examine the impact of changes in trade in agricultural goods on water demand.

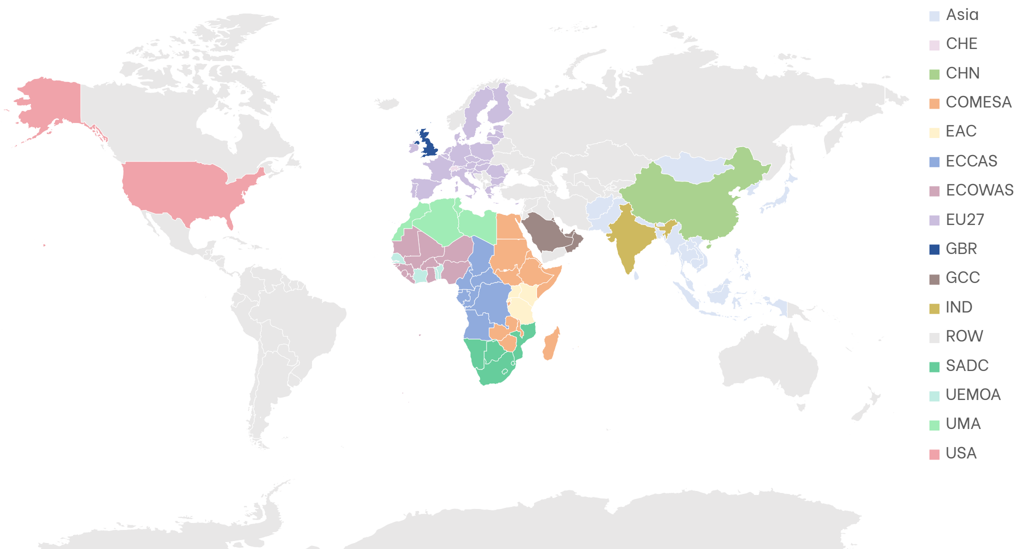


Figure 3.1: Map of the 16 regional subdivisions considered in this work. Notice that all the grey countries are included as Rest of the World.

In our analysis, we do not explicitly model water supply constraints, but nonetheless we simulate water use in agricultural production and trade, exploiting a detailed historical database. Furthermore, our study takes into account a wider spatial scale than previous contributions, examining the entirety of the African continent and its connections with external trading partners. Despite the large scale implemented, we are able to go in great detail on the water flows, considering the water demands of individual products. In fact, once we obtain the productions and flows in economic terms (dollars) from the MAGNET model, we translate them into virtual water. Specifically, we aim to illustrate the importance of considering the different country-specific and year-specific water footprints of food products using the information on virtual water content from the CWASI [11] database. The conversion of MAGNET model outputs into virtual water terms with the CWASI database is a significant innovation since, to our knowledge, no other CGE model has been integrated with such a detailed virtual water database.

3.2 Data and Methods

3.2.1 The CWASI database

The virtual water flows are available through the virtual water matrices developed within the EU-funded CWASI project[3]. The CWASI database contains over 30 years of virtual water trade (1986-2016) and 50 years of water footprint (1961-2016) related to agricultural products. The water footprint data include only primary products (167 crops), while the trade matrices also include derived products for 220 different goods. The database structure is mainly based on inputs provided by FAO, such as production in tons, bilateral trade matrix, yield, and hectares cultivated. The other key input is the water footprint data provided by Water Footprint Network, which published a large dataset for several primary and processed agricultural goods [72]. This database, called WaterStat, includes average values over the period 1996-2005. The CWASI dataset assumes that the time-variability of the water footprint, not detailed in WaterStat, is mainly driven by yield variations [71]. The resulting time-varying WFs are then applied to the FAO datasets on agricultural production, country exports, and reconstructed detailed trade matrices, thereby forming the CWASI database.

The virtual water content can be quantified in terms of green water and a blue water components depending on the origin of the water resource used for irrigation and food processing [69, 150]. Blue water in CWASI database is obtained as the virtual blue water content ratio to the total virtual water content, and both values are averaged over the period 1996-2005. Then, this fixed share is applied to the time-varying overall virtual water content, which was calculated through the Fast Track approach [70]. This is an approximation that does not take into account any changes in irrigation water supply from the averaged period of 1996 - 2005 [151].
For the purpose of our analysis, we take from the CWASI database two values of virtual water, relative to production and relative to trade flows, which we denote with C to highlight that it is data provided by the CWASI database, while W marks that we are dealing with water (m^3):

- $CW^{Pr}(p, c, t)$, equal to the total metric cubes used for the production of the good p, in the country c, in the year t.
- $CW^{Exp}(p, c, i, t)$, equal to the total metric cubes of the trade flow of the good p, from the producing country c to the importing country i,

[3] Data partially available in the download section of `https://www.watertofood.org/`

in the year t.

We take these two values in terms of both green and blue water. An illustrative example of how much the CW component can vary depending on whether we consider production or export, and depending on whether we consider green or blue water, is shown in the Figure 3.2. The figure shows the cubic meters of water used in production or export for each product included in the "Vegetable and fruits" sector for the African ECOWAS region.

Figure 3.2: Composition of individual items for ECOWAS Vegetables and Fruits sector in terms of green water (on the right) and blue water (on the left) for both production (on the top) and export (on the bottom). The size of the bubbles relates to the percentage of water (green or blue) exported (produced) by each item out of the total. The data refer to the base year (i.e., 2014). Note that green water represents 98% of the total water.

The importance of sector composition is evident; the cubic meters can change considerably between green and blue water and between production and export for each crop. For example, in Figure 3.2 cashew nuts account for only 9% of blue water and 7% of green water in production but account for 93% of blue virtual water exports and 97% of green virtual water exports. For this reason, it is essential to consider the different water needs of each crop.

3.2.2 The MAGNET model

The Modular Applied GeNeral Equilibrium Tool (MAGNET) model is a multi-regional general equilibrium model with global coverage and country-level details [143]. The MAGNET model is an extension of the standard GTAP model [152] in which various model extensions (modules) can be combined as required to examine the research question at hand. The core of the model is a social accounting matrix (SAM) that links value flows (payments and receipts) from production to consumption, including international trade. MAGNET uses a fully flexible constant elasticity production function (CES) that combines endowed factors of production (land, labour, and capital) with intermediate inputs to create goods produced for domestic consumption, as intermediate inputs for other domestic industries or for exports. The SAM contains bilateral trade flows where international trade is governed by the Armington hypothesis that treats goods of different origins as imperfect substitutes. Consumption in each region is governed by a representative household that collects all income from endowment inputs and taxes and distributes this income between private spending, government spending, and savings using a Cobb-Douglass expenditure function. Private consumption expenditure is allocated among commodities according to a non-homothetic CDE function. Government consumption is allocated across commodities according to fixed budget shares using a Cobb-Douglas expenditure function [143, 153]. MAGNET uses information from the IMAGE model [154] to estimate agricultural land availability and crop yields over time, as well as the intensification of pasture use and changes in livestock production systems consistent with the SSP2 [139] future narrative scenario.

We focus on the first eight sectors (as shown in Figure 3.3) according to the GTAP database [155]. In the CWASI database, these same sectors cover a total of 164 primary crops for the production side and 118 primary crops in international trade (see the complete list of commodities under the MAGNET-sector aggregations in Table C.2 in the Supplementary Material).

From the MAGNET model simulations, we consider two economic values concerning the production and trade flows, both in dollars. We denote these two values by M to indicate the source of the data and by D to show that they are US dollars:

- $MD^{Pr}(s, r, t)$ equal to the total dollars from the production of the sector s, in the economic region r, in the year t.

- $MD^{Exp}(s, r, i, t)$ equal to the total dollars from the trade flow of the sector s, from the producing region r, to the importing region i, in the year t.

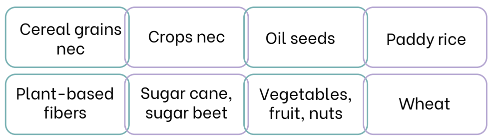


Figure 3.3: The first eight agricultural sectors of the GTAP database considered in this analysis. In the CWASI database, these sectors cover a total of 164 crops.

3.3 Dollar-water conversion

3.3.1 Determination of the conversion factor

From a methodological standpoint, we convert the base year dollar data (i.e., referred to 2014) and the 2030 dollar data simulated by the MAGNET model (considering both with-AfCFTA and without-AfCFTA implementation scenarios) into virtual water flows. In a nutshell, we use the production data and trade flows of the 8 different crop sectors in dollars for the base-year, and convert them to virtual water through detailed crop-specific water footprint data from the CWASI database.

We start by converting the production values provided by MAGNET as economic value of production (MD^{Pr}), in virtual water (m^3) by a suitable conversion factor ($m^3/US\$$).
In order to obtain the conversion factor, we use the virtual water values in the CWASI database and the corresponding crop-specific dollar values available from FAOSTAT. We calculate the conversion factor as a weighted average of all cubic meters needed for crop production within each sector over the respective production dollars. We define the production conversion

factor (fW^{Pr}) as follows:

$$fW^{Pr}(s,r,t) = \frac{\sum\limits_{c\in r}\sum\limits_{p\in s} CW(p,c,t)}{\sum\limits_{c\in r}\sum\limits_{p\in s} uD(p,c,t=2014)\cdot T^{Pr}(p,c,t)} \tag{3.1}$$

where f stands for conversion factor for water W that we use in order to convert dollars value in virtual water, Pr stands for production, uD is the ratio between dollars and tons typical of each product from the data available on FAOSTAT, and T represents the quantity of tons produced. Since our purpose is to show how the quantity and volume of the products have changed, we transform the values into dollars by reporting everything on the selected base year, i.e., 2014. The numerator of fW^{Pr} represents all the cubic metres relative to the production of sector s for region r, while the denominator includes all the dollars corresponding to the production of sector s for region r. Consequently, fW^{Pr} are the $m^3/US\$$ specific of the sector s for the region r at year t.

We calculate the conversion factor in terms of both green water and blue water and then obtain the following two factors:

$$fW_g^{Pr} \text{ for green water,}$$
$$fW_b^{Pr} \text{ for blue water.}$$

Conversion factors can have very different values depending on whether crops produced are also part of the export basket. This difference between production and export conversion factor is due to the diversity of the goods that make up these baskets, since just a portion of the produced goods are directed towards exports. For this reason, similarly to the Eq. (3.1), we need to calculate the conversion factor for trade flows as follows:

$$fW^{Exp}(s,r,t) = \frac{\sum\limits_{c\in r}\sum\limits_{p\in s}\sum\limits_{i\in r} CW(p,c,i,t)}{\sum\limits_{c\in r}\sum\limits_{p\in s}\sum\limits_{i\in r} uD(p,c,i,t=2014)\cdot T^{Exp}(p,c,i,t)} \tag{3.2}$$

Therefore, the numerator considers all the cubic meters of sector s exported from region r, while at the denominator there are all the export dollars of sector s from region r. With $c \in r$, we denote all countries importing from region r (without considering intra-regional flows). Again, fW^{Exp} is the specific $m^3/US\$$ of sector s from region r at time t, and we compute them in terms of both green water (fW_g^{Exp}) and blue water (fW_b^{Exp})[4].

[4]When the export fW^{Exp} data is missing, we substitute it with the corresponding fW^{Pr} of production in order to avoid losing the export dollar flows from MAGNET (this happens for the 5,5% of the data).

In this way, we obtain the conversion factors on each year t in [1986-1991] for production and all years t in [1986-1991] for trade flows. Since the conversion factor is calculated as a weighted average, we are able to assign an appropriate role to the crops that require more water (m^3) for the same economic unit produced (US$).

To obtain the conversion factors to convert the flows into dollars projected by MAGNET for the year 2030, we need to consider the conversion factor trend over time. For this purpose, we use ARIMA (AutoRegressive Integrated Moving Average), a statistical analysis model that uses time-series data to predict future trends. Furthermore, to exclude possible erroneous predictions of the ARIMA model, we impose that if the ratio $fW(s, r, t = 2030)/fW(s, r, t = 2014)$ is outside the range [0.5; 2.5], we substitute the value $fW(s, r, t = 2030)$ with the average of the conversion factor of the last 20 years [1996-2016] (this happens in the 3.5% of data).

3.3.2 MAGNET output conversion

Once we have obtained the conversion factors, both for the base year (2014) and for the scenario-year 2030, we convert the production dollars and trade flows obtained through the MAGNET model into virtual water values, both blue and green. For production, we have:

$$W^{Pr}_{g,b}(s, r, t) = MD^{Pr}(s, r, t) \cdot fW^{Pr}_{g,b}(s, r, t) \tag{3.3}$$

where W^{Pr} stands for the cubic metres of production water, in terms of green water (g) or in terms of blue water (b), for sector s in the region r for t=2014 and for t=2030.
Similarly, we calculate virtual water export flows as follows:

$$W^{Exp}_{g,b}(s, r, i, t) = MD^{Exp}(s, r, i, t) \cdot fW^{Exp}_{g,b}(s, r, t) \tag{3.4}$$

where W^{Exp} stands for the cubic metres of water exported, in terms of green water (g) and in terms of blue water (b), for crop sector s from region r, to the importing region i for t=2014 and for t=2030.

3.4 Results and discussion

We divide the results in two sections. First, we present the projections up to 2030 (baseline projection) and compare them with 2014 data (reference-year) for African production and exports in both dollar and virtual water terms. Secondly, we investigate the impact of AfCFTA implementation (policy scenario) on production and exports, exmining the effect of the tariff elimination policy on different agricultural sectors and the African virtual water network.

3.4.1 Evolution of African virtual water flows

Figure 3.4 shows the difference, measured in percentage points, between the 2030 and 2014 total production and export values for the African continent, both in dollars and in total water footprint (i.e., green and blue water together).

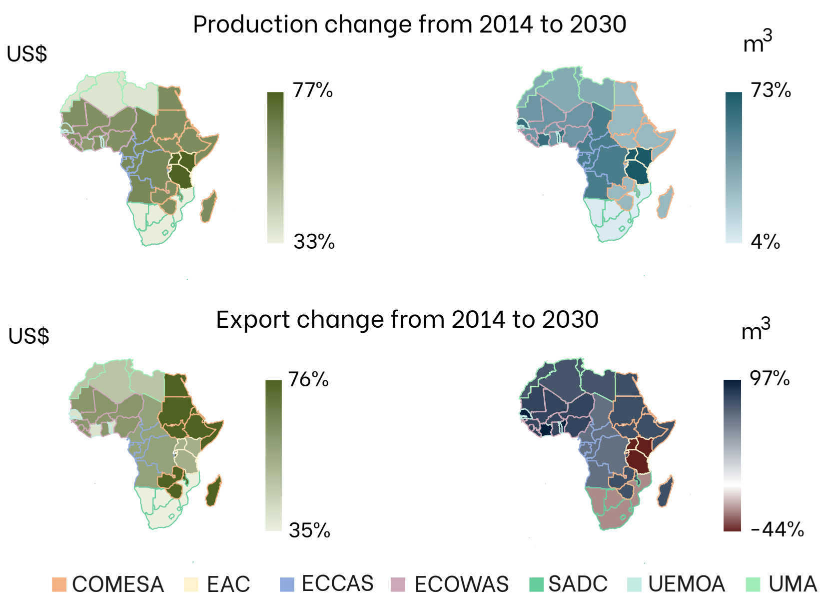


Figure 3.4: Two top graphs show the percentage change in dollars (right) and virtual water (left) of production from 2014 to 2030. The bottom two graphs show the percentage change of export in the same time range. The colours of the country borders distinguish each of the 7 African economic regions. See Figure C.3 in the Supplementary Material for separate export maps between green and blue water.

The top two panels show the percentage change in production that each of the 7 African regions would experience from 2014 to 2030 in terms of dollars (on the left) and virtual water (on the right). We observe that some regions would increase their agricultural production in 2030 more than others, and that this increase is also reflected in higher water demand, as in the case of the East African Community (EAC). Agricultural production is expected to become more concentrated in a few regions. In general, agricultural production increases mainly in the central African belt, i.e., in agro-ecological zones, which tend to be more suitable for intensive crop production due to the humid climate [156]. In contrast, the least growing areas in terms of production are those in northern and southern Africa, which are characterized by an arid or semi-arid climate [157].

However, values in dollars and in cubic meters of water do not always concur; for example, COMESA shows a significantly positive increase in economic terms (63.69%), but the growth in virtual water scores just a 29.15% increase. This difference reflects the importance of the diverse water demands related to each sector, as different products require different amounts of water for their production. Therefore, in 2030, COMESA is projected to increase the output of products with lower water consumption (such as the Cereal sectors).

While for production we have an increase in both economic and water terms, for exports the situation seems to be different (see two graphs at the bottom of the Figure 3.4). Increases in dollars do not systematically correspond to increases in virtual water, but in some cases, there are even decreases in virtual water exports.

Again, there is a clear differentiation of results at the level of economic regions: the most significant increase in dollars in exports is the COMESA region (60.11%), followed by the ECOWAS region (51.11%). Considering virtual water, the most significant impact is on exports from the UEMOA regions such as Senegal, Benin and Côte d'Ivoire, which increase their virtual water exports by 97.38%, probably because significant part of the trade consists in water-intensive crops such as cacao [158].

More interestingly, despite the overall dollar increase in exports registered from 2014 to 2030, we find significant reductions in water terms. For example, the East African Community (EAC) region shows a decrease in virtual water exports equal to 45.38%, due to the decline in the water footprint over time for some sectors (such as Crops nec). These results demonstrate the importance of weighting water demand differently for produced and exported quantities, as the composition of the export basket can vary from the production one. Virtual water projections for 2030, in fact, may differ significantly from dollar projections; in particular, regions that see a reduction in virtual water exported but an increase in dollar amounts exported are those regions for which the conversion factor shows a downward trend over time and thus a smaller value in 2030.

Therefore, both production and export projections to 2030 show generally significant increases compared to the reference-year, 2014. Consequently, it is interesting to further investigate the trade changes over time to point out any differences with trade destination area, or differences of the agricultural sector.

Figure 3.5: Million dollars for the base year (2014) and projections to 2030. Colours distinguish the different product aggregations. The left panel shows African intra-trade, the middle panel shows African exports to extra-continental partners, and the right panel shows African imports from extra-continental partners.

Figure 3.5 shows the growth of trade, both with continental and non-continental trading partners, breaking it down by agricultural sector. For intra-continental trade, since the flows are within the same continent, imports are equal to intra-continental exports (shown in the left panel of the Figure 3.5).

Projections up to 2030 show substantial increases in intra-continental trade (by 69%), exports to external partners (by 45%), and imports from non-African partners (by 32%).

Although intra-trade, when compared with trade towards external partners, accounts for just the 0.1% of the total projected dollars, the figure allows us to appreciate the different composition of the exchanged goods. The increase in intra-continental trade is the result of the predicted income growth that African regions will experience by 2030 (see Supplementary Material Table C.3), which allows a larger domestic market for previously export-oriented crops.

The results show a substantial difference between the composition of exports, both to intra-continental and extra-continental partners, and imports. On the one hand, African exports to non-continental and continental partners consist mainly of commercial crops, including cocoa, fruits, nuts, coffee, tea and spices, which account for about 50% of Africa's total agricultural exports [159]. On the other hand, most agri-food imports are staple food crops, such as wheat, rice and other cereals. These imports also differ in their origin: wheat comes mainly from Europe, rice from Asia and other cereals from the rest of the world, including Latin America, from which Africa imports large quantities of maize [160]. Imports of staple foods becomes necessary because, while agriculture is an important source of income for African countries, the sector is mainly made up of small farmers who grow a wide variety of low-yielding crops on small plots of land, using minimal amounts of fertilisers and pesticides, making the sector unproductive [159].

Similar results emerge for virtual water, as shown in Figure 3.6. For the intra-contiental trade, Plant-based fibers see the most significant increase for blue virtual water flows, and Oilseeds for the green water ones. For exports to non-continental partners in terms of blue water, we see an increase in exports of Plant-based fibers, while in terms of green water, there is a greater increase of the Crops nec sector.

The last two sets of panels on the right-hand side of Figure 3.6 show virtual water imports. Virtual blue water imported into African regions comes mainly from Paddy rice imports, while green water from Wheat imports. The rice trade and the embedded virtual water are essential for African countries, where imports cover a large part of their rice consumption. The African continent, particularly the sub-Saharan part of Africa, is recognized as a blue water-deficit region due to imports of rice [161]. Imported virtual green water is mainly incorporated into wheat and other grains, as staple crops such as wheat constitute the majority of African food imports [162].

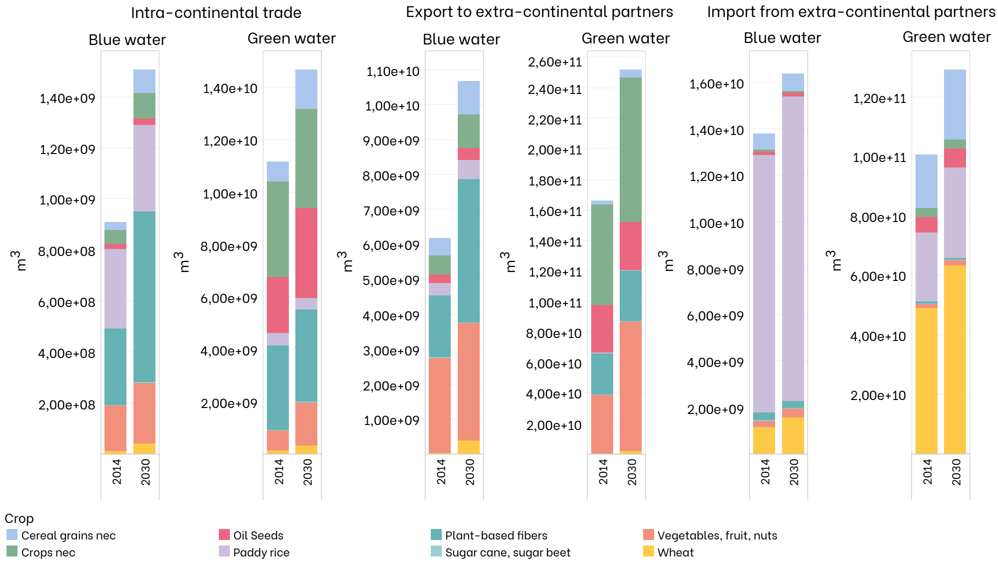


Figure 3.6: Results of virtual water (m^3) in terms of imports and exports by African continent for the base year (2014) and projections to 2030. The colors distinguish the different product aggregations. The first two sets show exports from the African regions in blue and green water terms to other African regions (intra-continental trade) and non-African trading partners (extra-contiental trade). The last two panels show the blue and green water imports in African regions from extra-continental partners.

We also investigate the evolution of the African virtual water network. Figure 3.7 shows how the virtual water flows between the 7 African regions change between 2014 and 2030. The evolution of the African virtual water network reveals essential differences in flows. For instance, the South African Development Countries (SADC) and East African Community (EAC) regions reduce their virtual water export to COMESA. Therefore, countries in the COMESA region reduce their virtual water imports in the 2030 projection. This is the result of regional production specialization; SADC increase dollar exports in the less water-demanding sectors. In contrast, some regions such as the UEMOA increase their contribution to continental virtual water trade; indeed, there is a significant increase in exports from this region to ECOWAS, which is projected to boost UEMOA role as an importer of virtual water. Increasing the exports of high water-demanding sectors such as cocoa, of which Ivory Coast (one of UEMOA countries) is the leading producer, has the consequence to increase water demand [163]. Therefore, the projections show both a diverse African trade network compared to 2014 and different export contributions of each region in the intra-trade market.

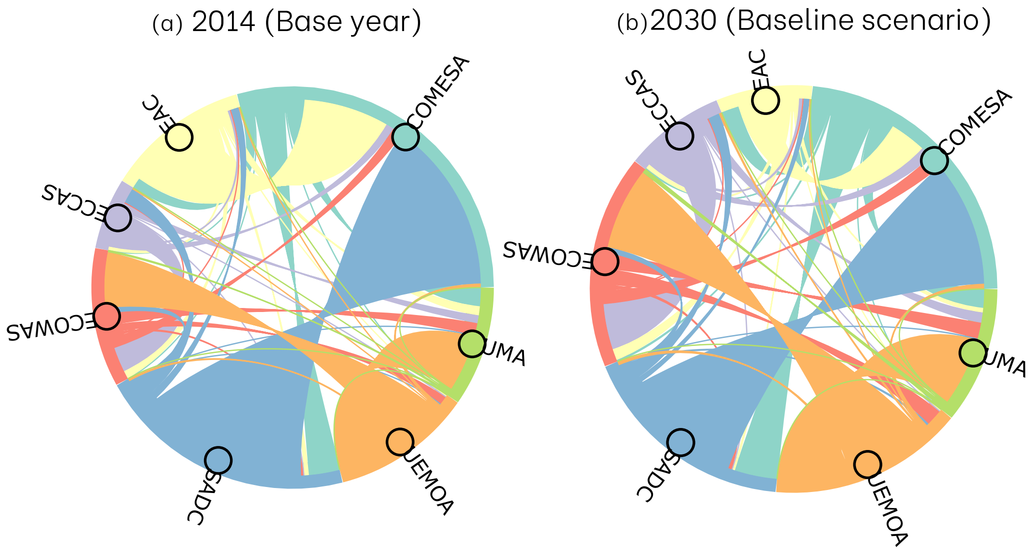


Figure 3.7: Total virtual water export flows (blue and green) among the 7 African regions. Panel (a) shows virtual water flows in 2014, while panel (b) shows simulated flows for 2030. Note that the simulated flows to 2030 (panel (b)) amount to a total of 34% increase compared to 2014 (panel (a)).

3.4.2 AfCFTA implementation

After analyzing the temporal evolution of African production and trade in our baseline scenario, we investigate the possible effects of the full implementation of the AfCFTA policy, modelled as the abolition of intracontinental tariffs.

Figure 3.8 shows the percentage change of production and exports between the policy scenario with AfCFTA implementation by 2030, compared to the baseline scenario for 2030. AfCFTA implementation triggers increased production, especially in southern Africa for primary agricultural products [164]. South African developing countries (SADCs) increase production through higher yields in sectors that require less water (higher water productivity), thereby reducing the total water footprint [165]. Compared to the scenario without policy implementation, the water footprint reduction is 0.67%.

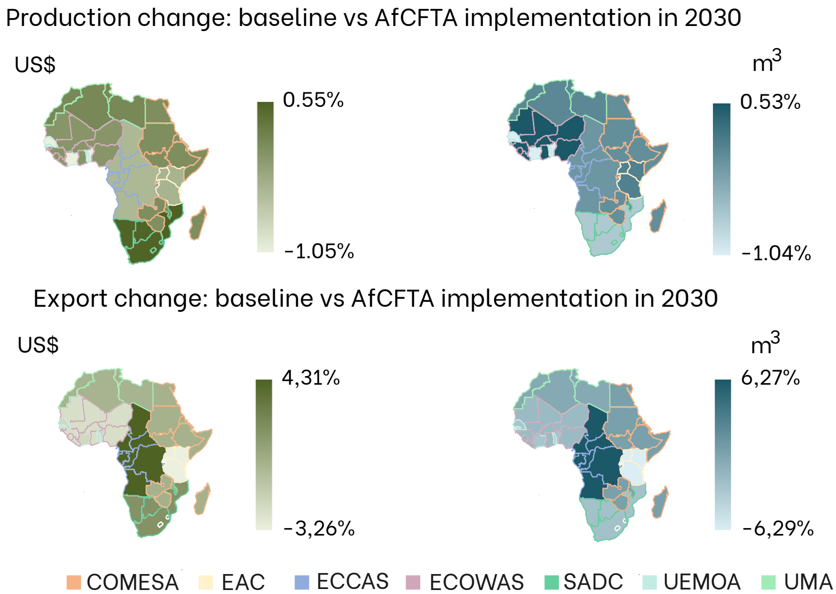


Figure 3.8: The top two graphs show the percentage change in the policy scenario compared to the baseline scenario in 2030 (m^3), both in dollars (on the left) and in virtual water (on the right). Similarly, the two graphs below show the percentage change in exports under the policy scenario. The colours of the country borders distinguish each of the 7 African economic regions. See Figure C.3 in the Supplementary Material for separate export maps between green and blue water.

The decrease in water used for production and the associated increase in economic value, show that the policy's implementation mainly facilitates the production of products with a lower water footprint.

The two bottom panels show the percentage changes in the implementation of the AfCFTA for export. Some regions increase their exports by 4.31%, such as ECCAS, with a corresponding increase in the total volume of water exported (6.27%). Similarly, regions that appear to be decreasing their exports in dollar terms (by 3.26%), such as EAC, also show a decrease in total virtual water exports (precisely 6.29%).

In contrast, the SADC region shows an increase in exported dollars (1.77%) for the implementation of the policy, but also a 2.58% decrease in virtual water exports. In fact, the SADC region increases the export of sectors with less water demand (such as vegetables and fruits) and decreases the export of water-demanding sectors such as Plant-based fibers and Oilseeds.

We now examine the impact of the AfCFTA on intra- and inter-continental on the 8 agricultural sectors. Figure 3.9 compares African dollars outflows and inflows between the 2030 baseline scenario (i.e., without policy implementation) and the AfCFTA policy scenario. Since the flows are within the same continent, imports will be equal to intra-continental exports (shown in the left panel of Figure 3.9).

First, we observe how the implementation is projected to lead to an increase in intra-continental trade and a reduction in extra-continental trade. Intra-continental trade in 2030 corresponds to 3.281 billion USD in the baseline scenario and 4.096 billion USD under the policy scenario with full implementation of the AfCFTA.

As far as extra-continental trade is concerned, the implementation of the AfCFTA is projected to reduce exports outside the continent by 3% in terms of US dollars. Among the most exported crops outside the continent in dollar terms there are the Crops nec sector, which include products such as tea, coffee, and cocoa, as well as the Vegetable and fruit sector, which consists of diverse products ranging from avocados to tomatoes and mangoes.

The implementation also impacts the extra-continental imports, which grow by $127 million compared to the baseline scenario. Extra-continental imports are driven by the increasing GDP of African regions, as shown in the Supplementary Material's Table C.3. The import increase, as shown in the right-hand panel of Figure 3.9, affects all the sectors analyzed, except the Vegetable and fruits and Crops nec ones, which register a decrease of 2.50% and 16.35% respectively, due to the increment in their production at the continental level (see Supplementary Material Figure C.2).

Accordingly, as an effect of the AfCFTA implementation, these two types of crops, which constitute the vast majority of the African extra-continental exports, are projected to be traded more consistently within the continent, as opposed to being exchanged on the global market.

In contrast to exports, among the most imported crops in economic value (US$) we find Wheat and Paddy Rice, followed by the Cereal grain nec category.

Similar results are also obtained in the dollar-to-water conversion, shown in Figure 3.10. The first clear feature is that implementing the AfCFTA policy increases virtual water exports (both blue and green) at the intra-continental level and decreases extra-continental exports, confirming the results already observed in dollars. At the intra-continental level, the implementation of the AfCFTA is projected to increase trade between African countries in terms of virtual water and especially in terms of green water. In particular, the comparison between the baseline scenario and the policy implementation shows that there is an increase of 27.70% in green water exports and 7.39% in blue water exports. At the extra-continental level, green water exports are projected to decrease by 3.40%, and blue water exports by 1.64%.

Figure 3.9: Results in millions of dollars for 2030 for baseline and policy scenario. Colours distinguish the different product aggregations. The left panel shows African exports to extra-continental partners, the central one the intra-continent trade, and the right panel shows African imports from extra-continental partners.

The last two sets of the panel in Figure 3.10 show the effects of the policy on imports from non-continental partners, which are barely noticeable in real terms. This result is consistent with the expectations: as intra-continental trade increases, fewer imports from extra-continental trading partners are coming into the continent.

The implementation of the AfCFTA in this modelling framework allows for an boost in the volumes of products already traded by African countries, outlining a clear commodity composition of African imports and exports, since, in this illustrative analysis, the impact of the agreement is only considered to complete removal of intra-African tariffs. However, it is noteworthy that African countries are actively using the AfCFTA as an opportunity to promote industrialization across Africa.

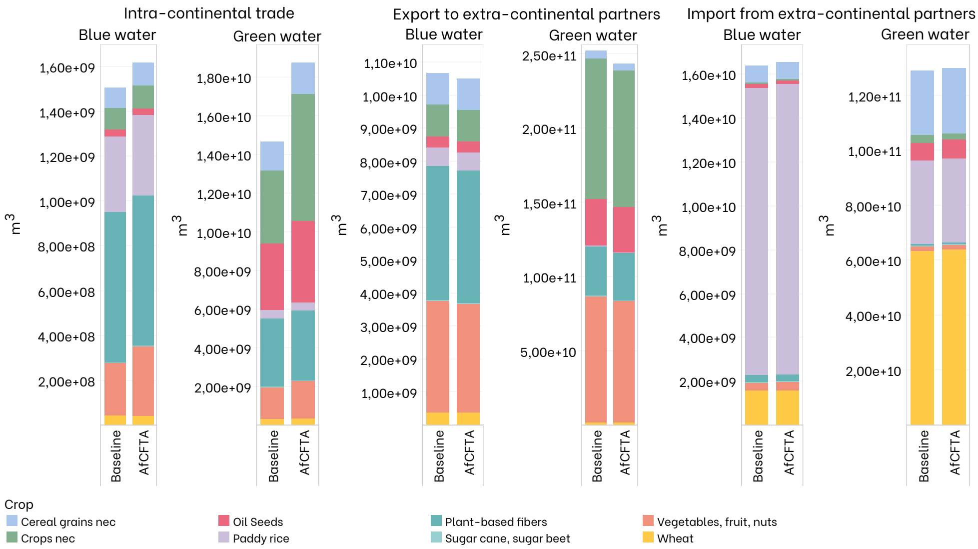


Figure 3.10: Virtual water results (m^3) in terms of imports and exports by African continent in 2030 both baseline and policy scenario. The colors distinguish the different product aggregations. The first two panels show exports from the African regions in blue and green water terms to other African regions (intra- trade) and non-African trading partners (extra-trade). The last two panels show the blue and green water results only referring to the import of the regions of the continent from non-African trading partners.

Therefore, in this analysis, we can only speak of a trade deal, as the impact of AfCFTA on investment in industrialization and progress within value chains is not assessed. Consequently, in the long run, this structural change could shift the observed composition of export-import baskets [166]. Furthermore, one of the objectives of the AfCFTA implementation is to make African economies less dependent on agriculture by augmenting the value-added shares in their production and thus boosting trade in processed foods more than the trade in primary agricultural products [164, 167].

Figure 3.11 shows the comparison of total virtual water flows (blue and green) between African regions in 2030 in the baseline and policy scenario. In terms of virtual water, it is interesting to note the growth in export flows for the UEMOA (West African Economic and Monetary Union) and ECCAS (Economic Community of Central African States) regions. These two regions are intensifying their exports of water-requiring products, particularly the

Oilseed sector for the ECCAS region and the Crops nec sector for the UEMOA region.

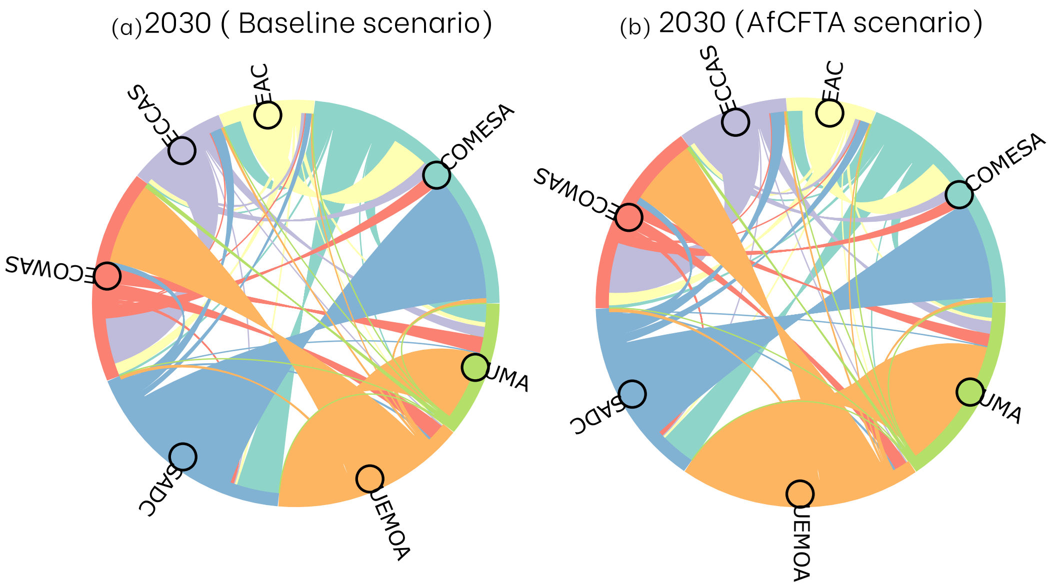


Figure 3.11: Total export virtual water flows (blue and green) between the 7 African regions. Panel (a) shows virtual water flows in 2030 for the baseline scenario, while panel (b) shows simulated flows for 2030 for the policy scenario. Note that the simulated flows to AfCFTA scenario (panel (b)) amount to a total of 26% increase compared to the Baseline (panel (a)).

In contrast, despite the overall increase in dollar exports, regions such as SADC reduce their virtual water exports under the policy scenario, because this region boosts exports in sectors that require less water, such as the Vegetable and Fruit or Cereal sectors. Furthermore, some regions extend their import from other continental RECs; this is the case, for example, of ECOWAS importing more virtual water from ECCAS and of UMA with a more significant flow from the UEMOA region.

3.5 Conclusion

Worldwide, the trade in agri-food has grown significantly over the last two decades, with a rate of almost 7% in real terms annually between 2001 and 2019[5]. In Africa we observe the same growth trend over the last 50 years, in which the agri-food market has seen constant increases both in exports (4%) and in imports (6%) [168].

Today, intra-continental trade in Africa barely exceeds 10% of Africa's total trade [168, 169]. However, in the coming years, the amount of food traded within African Regional Economic Communities (RECs) and outside the continent is expected to gradually increase, making it crucial to investigate future scenarios of African agricultural trade [170].

Agricultural trade consumes most water for the production of goods: worldwide, 70% of water withdrawals are consumed by the agricultural sector. In arid and semi-arid areas such as Africa, however, this percentage can rise to more than 90% [135]. Furthermore, the continuous escalation of the African population (up to 2 billion by 2050) and the volatility of harvests induced by climate change [171, 172] lead to expect a wider gap between food demand and supply, and therefore between water availability and water consumption.

In this work, we investigated future developments (2030) in African primary production and agricultural trade on the continent at the intra-continental and extra-continental scales. We studied these projections from an environmental perspective, converting the obtained dollar values into virtual water terms to explore possible developments of the African virtual water network in 2030. In addition, using the MAGNET model (that falls in the CGE class of economic models), we quantified the impact of trade policy changes in an illustrative policy scenario, investigating for the first time the impact of the AfCFTA on virtual water use for agricultural production and primary food trade.

The baseline scenario for 2030 (i.e., non-considering AfCFTA implementation) shows significant increases in African production (26% increment in virtual water), exports to extra-continental trade (51%), and intra-continental trade (34%). This pressure is not homogeneous in all African regions since agricultural production is concentrated above all in the West and Central Africa for climatic reasons and greater soil humidity [173]. Export projections lead to several questions about Africa's water future due to the high projected increase in virtual water exports. This water pressure

[5] https://www.oecd.org/agriculture/topics/agricultural-trade/

could be related to the agricultural products' specific characteristics that denote exports, i.e., export-oriented crops whose production demands high water contents. The different water pressure also depends on the type of crop produced. Despite being the second driest globally, the African continent is characterized by water-intensive agriculture (i.e., cotton, nuts, cocoa), that represents most of the African production and exports. Conversely, it imports staple foods, such as grains, that make up the majority of the kilocalories consumed [174].

The AfCFTA, established in 2018 and implemented in 2021, has received particular attention as a tool that can further integrate the African continent in terms of intra-continental trade. Indeed, although continental trade has increased in recent decades, trade flows have predominantly been within regional economic communities (RECs). The free trade area aims to expand intra-African trade, thus partially replacing the subdivisions of the various RECs [142].

Our modelling results show that the implementation of the AfCFTA has the most significant effect of diverting African exports. The reduction in extra-continental exports is projected to be, in percentage terms, almost proportional to the increase in intra-continental trade. The increase in intra-continental trade reflects greater access to the continental market by African countries. This intra-continental opening is positive from a water point of view since it allows for an increase in the water retained on the continent, which is particularly important for water-poor and vulnerable regions. In addition, the increased consumption of domestically produced crops does not result in the replacement of inter-continental imports but represents additional consumption for African populations. Furthermore, the dollar-water conversion allows us to analyze the virtual water impact of different economic regions and agricultural sectors in Africa, highlighting whether the recorded increases depend on specific crops. Given the expansion of agriculture, and the shift towards African countries becoming trade hubs outside their RECs, under the AfCFTA there is a need to support the competitiveness of agricultural sectors in the face of continental market opening. In order to take advantage of the rapid growth of the intra-African market and to be competitive, African agriculture must undergo a structural transformation involving a shift from subsistence-oriented production systems to more market-oriented systems [168].

Our methodology is subject to limitations and should be approached with the correct perspective in mind. CGE models outputs are highly dependent on the provided economic inputs and should not be considered as set-in-stone predictions of the future. The real value provided by MAGNET in this context is to quantify illustrative future scenarios and plausible impacts of trade liberalisation. Combining these with CWASI database allows for a wide array of specific water-related modifications to emerge. Moreover, it should be noted that, with this kind of model, we do not consider further policy changes, all of which are subject to uncertainty [142, 175].

This work is an initial investigation of future virtual water scenarios in Africa and the possible effects of continental trade liberalization under the AfCFTA. Future developments of this work also will explore outcomes in per capita terms, i.e. to understand the role of population growth in increasing trade within regions of the continent.

4

Chapter 4

4.1 Scientific dissemination project

There is increasing debate about a knowledge-based society and knowledge-based economy [176], as well as a discussion about the importance of critical discourse analyses in the development of these concepts [177, 178]. Therefore, it seems appropriate to dwell on the importance of scientific knowledge in society, since it greatly influences how our research is perceived and used outside of the academy. There seems to be relatively little interest, among scientists, to disseminate the results of their research and their ideas to a wide and general public. Their output tends to be, with few exceptions, mainly addressed to colleagues specialized in their disciplines, rather than to the general public of educated or simply intellectually interested people. While not always appropriate, making science accessible for all can be of great importance, but it often requires a great deal of effort. Unfortunately, dissemination practices are sometimes considered a distraction from research and its tight and competitive pace, but it is by turning science around and making it truly accessible, that the foundations are laid for knowledge to have wider repercussions and spread rapidly through society. Therefore, dissemination, communication, and technology transfer for universities and research institutes have been connected with research practices and high education tasks. Dissemination and technology transfer are the two main ways in which society benefits from scientific development and knowledge production [179]. Therefore, scientific culture is not an abstract asset but a strategic resource for countries' future. It is at the basis of its ability to innovate, produce and compete on the international environment. In recent years, the academic world has been under increasing pressure to focus on scientific research capable of incorporating the Third Mission (TM), which is defined as "a contribution to society" [180–182]. In this context, academia can be perceived as a crossroad of teaching, research, and TM.

The expression Third Mission, though, still carries some ambiguity: on the one hand, it is associated with concepts such as "entrepreneurial university" and "technology transfer", while, on the other, TM refers to a wide range of activities carried out by the academia to transfer knowledge to society, disseminate scientific results, promote innovation and social welfare, and form human capital [183].

In this context, our research group felt the urgency to look back and build a coherent narration regarding the European project we have been working on, excerpting the most important concepts we discussed throughout the whole "Coping with water scarcity in a globalized world" (CWASI) journey. The CWASI project, which started in 2015 and ended in 2020, addresses the globalization of water resources consumed and used for food production, using quantitative methods to study the effects of water changes on food security and conflicts related to the use of these resources. The project was carried out thanks to an ERC grant. The ERC itself is committed to sharing the results obtained and offers some interesting suggestions and guidelines to promote this effort. Based on these preliminary instructions, during the 2020 lockdown for the Coronavirus emergency, a clearer idea of how to communicate the results of this project outside the scientific world was conceived. From this idea, the WaterToFood project was created to make information about the water footprint in the food chain accessible through user-friendly communication tools and platforms. The key to the WaterToFood project is the belief that society as a whole should be involved in the protection and management of water resources, but that it is difficult to make informed decisions if the results of scientific research are not presented in an understandable way, seeking to raise awareness of the problem and provide tools to address it.

4.2 The context

In recent years we have observed a rapid and continuous development of communication technologies such as the internet and social media. The unprecedented potential of these tools has rapidly absorbed the function and purpose of simpler traditional media [184], creating a complex multidimensional ecosystem. Trying to cope with the complexity of this ecosystem requires to understand that, unlike in the past, creating a narrative about a topic in the contemporary world is impossible without interweaving different languages and stimuli [185]. The linearity of traditional media alone is not sufficient to adequately disseminate the results of research groups outside academia, and scholars should, therefore, focus part of their efforts on discerning how to provide intelligible and usable knowledge to society [186], creating new tools to manage complexity and raise awareness of critical issues.

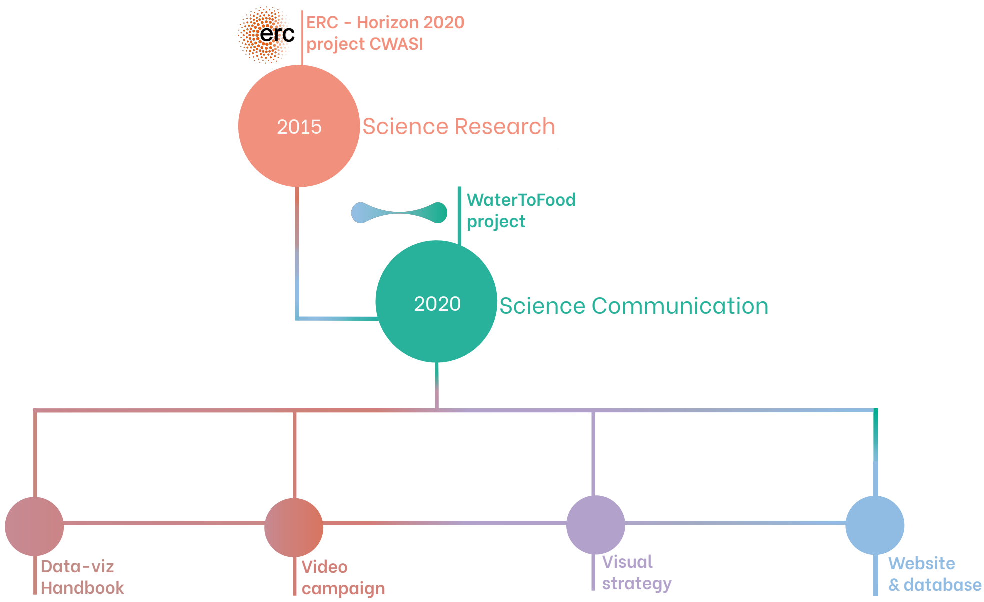


Figure 4.1: Communication project output and timeline

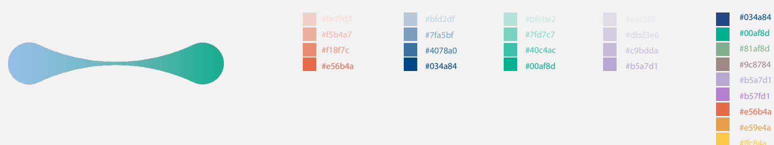
Starting from these assumptions, the WaterToFood team started to scan through all the material generated during five intense years of research to reinterpret it and make it understandable for a broader audience. Finding a coherent narration was essential, as well as creating a cohesive identity and meaning through different media, and reaching multiple degrees of elaboration and immediacy. To reach this goals, we decided to use a mix of strategies and concepts borrowed from research fields such as branding theory [187], visual identity studies [188, 189], experience design [190–192], and digital entrepreneurship [193, 194]. We created four different outputs, as shown in Figure 4.1, that contribute to bringing our research to society, each one with its purpose, target, language, and experience.
The following sections describe the various outputs of the project from a theoretical perspective, while the Textboxes provide insight specifically regarding the WaterToFood experience.

Water To Food: general overview

Water To Food was born in 2020 to bring to light the water-food nexus and the international commercial connections of virtual water, communicating and disseminating scientific research to the outside world to build an aware and proactive community. With the CWASI project ending in 2020, there was a need to disseminate and communicate the scientific results obtained to the general public. For this reason, we have enlisted the support of communication specialists to deploy diverse and interconnected strategies that provide easy access to scientific information, even by non-experts.
The first step was, therefore, to think of a gradual transformation of the external perception of the CWASI project into an authentic brand, able to express its contents clearly, coherently, and, to become transversely recognizable through the various media and to reach its potential target audience as widely as possible. We have projected this vision onto a system of concentric circles, at the center of which we have placed the visual identity.

4.2 Visual Identity

The brand contains the chromatic traits; it constitutes the first node around which the entire re-branding activity is woven, like a sort of genetic code that contains in its language the essential characteristics of the project's identity. A new typeface has been identified organically, which will be used transversely in all communications and compositions. A new color palette will be selected starting from the colors to which the project most often refers.



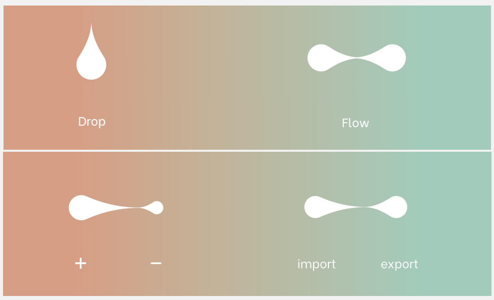
We started with the graphic work and the key element: the brand. The new design of the "Water To food" logo is the core of the revised visual identity (see box 4.2). Once this new graphic nucleus was composed, we were able to have the fundamental elements for the next steps; first of all, redesigning what in the digital sphere constitutes the centre of every communicative ramification: the `watertofood.org` website.

We have maintained the minimalist approach selected and worked to improve the structure of the general layout, giving a new style to the display of data, graphs, and tables. We have also refined the selection of images for previewing the various articles, implementing page loading performance, search engine indexing, and accessibility.

We then moved on to build the new database based on this new platform. Through essential programming work, we filtered the considerable amount of data managed by the project into a user-friendly, easily manageable, and attractively visualized interface, in complete continuity with the basic features already outlined above. We designed the new site by adapting it to the needs of the new users, modeling it to be easily consulted from any device, personal computer, tablet or smartphone, etc.

4.3 Logo

Starting from the shape of the drop, the logo was designed to represent the union of geographically distant natural resources. The two drops join together, forming a flow from one region to another. Since we are talking about international trade in our studies, the size of the logo can vary depending on the size of the import/export it is intended to represent.



After this first phase, we moved on to communicating the project to the outside world. The new website was the landing page for each successive phase of our work. The intention was to make the products immediately recognizable and linked by the user to the CWASI project and to accompany the user to a progressive deepening of the contents. Following these objectives, we built the structure of the animated video. The current communication context sees audiovisuals as one of the preferred channels for disseminating content, given the great immediacy of this language. We, therefore, created a video called "Main", the heart of the communication with a strong visual impact of the key message we proposed as WaterToFood: "Everything you do requires water to be done."

In parallel, we built the joint info-graphic project. The intention was to create an accurate book/report accessible to both an academic and non-academic target audience. Our research team proposed the contents themselves, doing editorial work on the texts, setting the general structure, and classifying the contents. The graphic design studio supported the contents by giving unity to the visual part and conforming different materials to a single visual identity to make this product impactful and recognizable through both digital and more traditional paper use. Starting from these assumptions and considering these contents, we then proceeded to the phase of involving an audience coming not only from the academic world but also from civil society. We have conceived a communication project whose ultimate goal is to reach an audience that is currently unfamiliar with the CWASI project. We then built a precise advertising strategy to increase user traffic both on social channels and on the new website through targeted sponsorships.

4.3 Communication output

4.3.1 Website

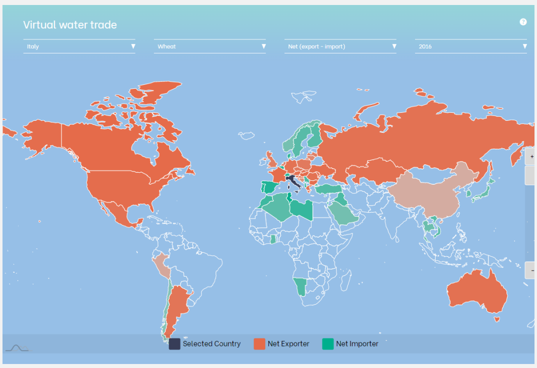
In recent years, concepts such as open science [195, 196] and interaction are finding their way into research methodologies and associated dissemination practices. Therefore, it is essential to gather information from different fields to make informed decisions and develop processes and technologies that take variables unique to the system in which they are implemented.

One of the essential resources created by the CWASI project is a database that contains over 30 years of virtual water trade data and 50 years of water footprints data related to agricultural products. The water footprint data include only primary products, while the trade matrices also include by-products for 290 different goods. The information collected in these matrices can provide a new interpretation for analyses related to water use and trade that would be difficult to be intelligible in a traditional context. An example of this is provided by one of the studies described previously in this thesis, the one dedicated to trade agreements in Africa, developed by combining the model known as MAGNET with the CWASI database. In this context, it was interesting to observe how the addition of the information gathered in our team's database produced different results that were more capable of describing the network dynamics of the relationships in Africa, taking into account the issue of water. Combining methods and knowledge are fundamental prerequisites for studies and academic environments that aim to understand how reality works.

The main problem we had to solve about WaterToFood was the accessibility of the data we produced over the years. On the one hand, we had to figure out how to organize the dataset to allow the user to request, filter, and select the data he/she needs. On the other hand, we had to build an effective interface, allowing immediate visualization of the information in the database and working on a functional user experience.

4.4 Play with data

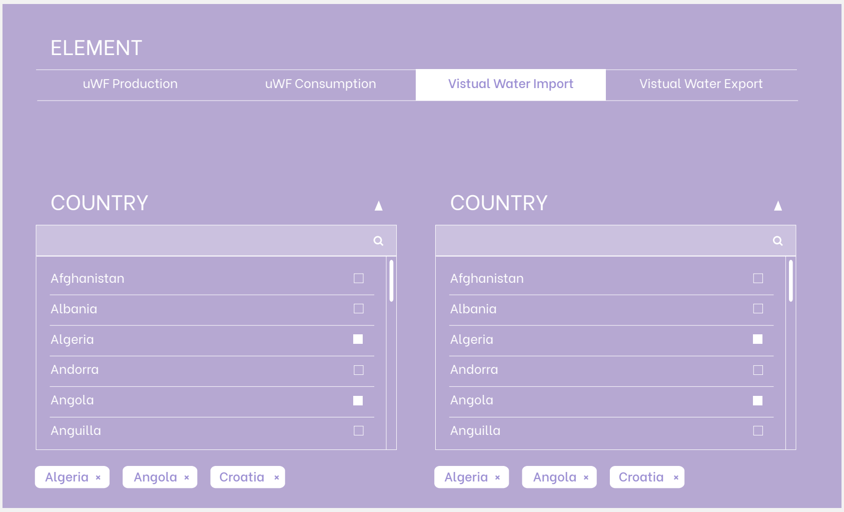
Given the main aim of WaterToFood, namely to make available to society data on the virtual water contained in the food consumed, we have created a user-friendly section on our website `watertofood.org`. The Play with data section allows querying the CWASI database directly through an interactive platform. Each user can access the Play with data section and check the value of a product's water footprint by analyzing the differences between production locations. Likewise, it facilitates selecting products whose virtual water trade you want to see on a global scale.



The result of this process is accessible on `watertofood.org`, a website that not only allows the user to select the data they want to download but also to visualize the information on a live map, providing the non-experts with a way to "play" with the data [197]. The site primarily aims to share knowledge with other researchers, companies, and policymakers in both the public and private sectors, promoting greater awareness of the hidden behavior of the water resource and how it is constantly being traded in the international context. Explaining these issues is highly relevant because it allows new questions to emerge, new needs to be revealed, and, consequently, the urgency of more effective projects. Therefore, making our database available and easily accessible is a crucial first step in this direction.

4.5 Download database

In the Download section, it is possible to download the data directly to the personal computer for research use. The online database offers the possibility of exporting data according to individual needs, selecting products or countries, or downloading the entire CWASI database via Bulk Download.

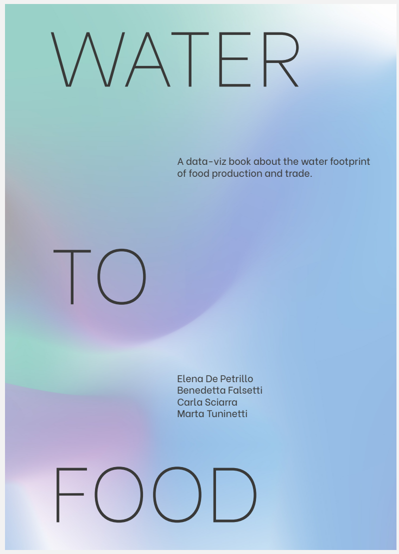


4.3.2 Handbook

Although the team had common goals and objectives, during an elaborate research project such as CWASI, it is common for scholars to study these topics by approaching them from different perspectives. For this reason, our team members decided to draw conclusions and present their findings collectively, seeking a shared logical thread and a coherent and effective view that could unite them. Faced with these needs, constructing a manual and a single guide containing our five years of research on these issues seemed the most effective idea for two fundamental reasons. First, this type of media allows for the unification of all components at the visual [198] level, adopting a language that allows the reader to interact in a defined way with the information. Second, it requires reasoning about the connections between these different perspectives and finding a functional synthesis that focuses on the central core.

4.6 Handbook

The handbook aims to bring together the group's research in a collection of data, images, and illustrations. To fully understand the concepts of water footprint and virtual water, it is necessary to consider other dimensions related to these dynamics, such as food trade, socio-economic and governance issues, resilience, vulnerability, and environmental impact. The graphs, data and illustrations in this book highlight how these dimensions are interlinked and provide useful information for addressing actions for change to take care of water resources in the global food system.



Link for the book preview:
Handbook

Specifically, in the handbook we constructed and produced, we identified five general dimensions that encapsulate much of the work done by individual research team members over the years. First, we introduce the concept of virtual water, explaining how it is calculated and providing a general historical context of the relationship between water and food. In the second chapter, we explore the implications of this relationship once we introduce the variable of international trade, i.e., the imports and exports of water resources inherent in the food that is traded on the global market. This perspective allows us to understand the complexity of relationships and flows between countries and provides the tools necessary to make these types of information intelligible. The third chapter addresses the implications of these flows and, in general, the water resource at the social, economic, and governance levels, thus providing links to the real world and the complex dynamics that populate it. The fourth chapter refers to water scarcity and shows the vulnerabilities and problems that arise from the relationship between populations, states, and water. Finally, the last chapter addresses the environmental impact of water use and the artificial solutions used to manage it. The book concludes with a reflection on the role of the consumer, providing tools and practices that, once framed in social, educational schemes, and economic processes, can lead to substantial change and overall improvement in the water situation.

The entire book shares a coherent tone of voice and leverages visuals and experience design to lead the reader through a wide range of topics, providing tools to understand their surroundings and facilitating this process through detailed data visualization [199].

4.3.3 Video campaign

The constant acceleration that characterizes the digital era requires the use of highly immediate communication formats [200, 201]. In this context, video is the most dynamic and engaging tool, given its ability to create a strong emotional impact in the shortest possible time, quickly providing access to the content. Of all the components of which WaterToFood is composed, the video component is undoubtedly the one that aims to reach the widest audience, introducing users to the topic and suggesting that they delve deeper through more detailed resources. One of the aims of the WaterToFood project is to encourage a change towards more sustainable lifestyles and decisions. Aware of the gradual shift to communication strategies more likely to induce a certain reaction in the viewer, our team has analyzed all the work done in five years from a different perspective, with more focus on how to maximize the results of the investment made by both the EU and the Politecnico di Torino. In fact, it is necessary to realize that exploring new communication channels, more current and content-oriented, is a responsibility of scholars and research groups once they engage in practices related to the dissemination of the results obtained. Without this awareness, it becomes difficult to think about taking knowledge outside the academy.

One of the fundamental pillars of WaterToFood as a dissemination project is to explain the often invisible concept of virtual water to anyone in less than a minute. For this reason, we had to solve the problem of synthesis and translation. We gravitated to a narrative capable of taking the concept of "water contained in the food we consume" to its extreme consequences in an ironic yet impactful way.

4.7 Video Campaign

The video made for the Water To Food communication campaign received the World Food Forum Film Festival award in the category "Best focus on agri-food system" with the following motivation: "for its originality and ability to communicate such an important message in a clear and direct way".

Link for the Videos:
Main Video & **Breakdown Video**

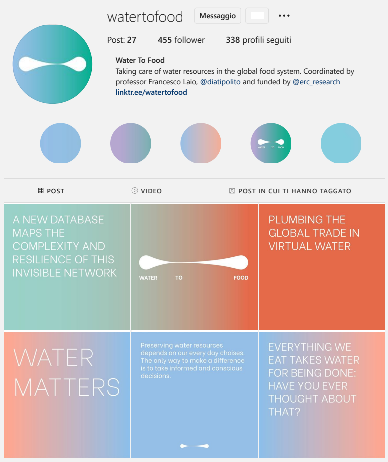
For the diffusion of WaterToFood, we made two different but complementary videos: in the first one, we aim to shock the viewer by confronting him with a paradoxical truth and igniting his curiosity towards something that seems impossible or that he would never have imagined; while in the second video we proceed deeper, always with a sarcastic and direct register, explaining and exemplifying what we visualized in the first clip. We try to bring the conversation on a common ground, translating the complexity of the research into ideas immediately understandable for most people and referring to activities that are part of everyone's daily life, such as going shopping. The videos were released on World Water Day, March 22, 2021, and remain the tool of first contact with most of the audiences who have shown interest in the project.

4.3.4 Public Relations e visual strategy

The fourth and final component of WaterToFood's dissemination strategy is its presence on social media, constant contact with all possible media, and participation in events and fairs. The potential of media and the ramifications associated with these types of communication tools are at the root of the idea of knowledge dissemination and organic transmission of different content as part of the same [202, 203] movement.

4.8 Social Strategy

The essential idea of the social strategy for WaterToFood is to be found precisely where any users interested in the topic are most likely to spend time, generating visibility on online communities and social media through integrated and organic communication management across all platforms. For this reason, WaterToFood is now active on all platforms: **Facebook**, **Instagram**, **Twitter**, and **LinkedIn**,



In order to increase the resonance of the project towards the outside world, it is indeed necessary to humanise the academy, to give a face to its achievements and to provide an easy and direct way to link the various aspects of the same project. It is, in fact, inefficient to think of being able to convey a clear message in today's world without using the tools that characterize it. For this reason, from the beginning of the outreach project, we have questioned the editorial line to follow, the platforms and messages to focus on, and the timeframe to use. Expanding the influence of a project in this type of media is not easy and requires a constant effort, spread over a long period, but at the same time, modern communication tools are necessary to reach as many people as possible.

Creating a coherent identity was probably the most important achievement we made out of the need to communicate with the outside world. It radically transformed the perspective from which we approach the data and results available to us. Building an identity is a particularly complex process because, at least in our case, it required a long process of introspection, which led to the construction of a coherent language across all components of our multidimensional narrative. In addition to this, it forced us to question the message we wanted to convey, and led us to place ourselves in a context outside of academia. Moreover, the relationships between the elements that make up contemporary complexity are decidedly more pronounced than within academia, where the fraction of highly specialized sectoral culture does not always allow for a collective interpretation of highly ramified phenomena, such as the exploitation of water resources.

4.4 Conclusion

The final result we obtained is the thread that ties the whole WaterToFood project together. Everything starts from the logo, which conceptually combines the drop, the symbol that characterizes water, with the pointers used as indicators on digital maps. The spaces on which the changes and global dynamics that have characterized recent history take place are our visualization tools. In the same way, colors, shapes, fonts and graphic elements run through all our work and allow us to find a location, show a defined identity and tell about a group and a project made of people and ideas that intertwine with each other.

Dissemination can be a process that brings enormous value to the research done and should not be underestimated, especially when it is developed following a multi-sectoral perspective that takes the conversation out of academia and seeks applications in the complexity of reality. There is also a notion of responsibility that should not be taken for granted when doing research. The academy requires more attention to its internal dynamics, which are often disconnected from what lies outside, and uses frameworks that are sometimes enclosed within this context. The knowledge that is developed within the academy needs to foster the ability to make informed decisions, providing awareness towards issues that affect everyday life in both the micro and the macro. Our outreach project has led us to approach all our work and research differently in an attempt to introduce it to the contemporary world. The topics covered remain part of a highly specialized thematic niche. However, it is up to the researcher to find a coherent conjugation in social, political, and communicative terms. If change starts from knowledge and problem explication, if design is a practice that, in general terms, responds to needs that are brought to the surface, then perhaps it is necessary for researchers to seek and find the connections necessary for their work to be more than just notional, but to have an operational conjugation.

5

Conclusions

Water-society links are a complex topic to study: it is a substance that, in its various shapes, traverses many areas of the academic landscape, and the ubiquitous and often invisible nature of water required the European Research Council to promote a project such as CWASI. Merging different perspectives in a multidisciplinary analysis - bringing together a variety of disciplines including hydrology, complex networks studies, social sciences, and economics - was the most effective way to provide a deeper and quantitative understanding of water's virtual movement and trade around the globe.

In this context, this thesis seeks to analyze the water-food nexus from a hybrid economic perspective to contextualize and interpret the various dynamics involved in agricultural production and trade. The thread connecting all the chapters of this thesis is the analysis and interpretation of the dynamics relative to water footprint and virtual water use and trade. In contrast, the core perspective of this work focuses on the economic processes underlying the water-food nexus and its movement through the commercialization of goods in the international agri-food trade market.

In the end, this work highlights the ubiquity of virtual water and its capillary diffusion throughout the market dynamics of the whole planet, both from a global standpoint and in smaller contexts, on a local scale. By analyzing the economic dimension through a data-driven approach, we managed to challenge some of the beliefs that underpin the study of the water footprint and the related trade, reaching the main outcomes that, in different forms, permeated this whole journey.

We find a consistent difference between staple and cash crops in terms of water-price ratio, and we discover that this relationship can be attributed to specificities in the production and marketing dynamics of the product types and not necessarily to the amount of resources expended in producing a given good. Apparently, the higher the production water footprint of a crop, the less it influences the crop's price on the global market, which means there is a detachment between the price formation and the cost of some inputs, such as water, for the most water-demanding crops. This different behavior may reflect the various market dynamics in which staple and cash crops are placed. Although further research is needed to understand these emerging behaviors, our results address the unequal consideration given to different crop production inputs, from which water is often excluded, and can help design targeted solutions for contexts with a clear tendency to overuse water such as cash crops.

We then shift our attention to the movement of water through the marketing of agricultural products on the international market and its strong influence on local scope economic trends. Interpreting specific signals from an economic point of view provides new perspectives and points of discussion in developing new possible water management policies.
In this context, governments play a crucial role at the political level, establishing international agreements and thus defining the global market. The presence - or entry into force - of trade agreements between two or more countries correlates with an increase in the volume of goods traded on the international market. Although this increase suggests a corresponding rise in virtual water traded, we find that flows covered by trade agreements are more stable and water-efficient because the crops changed through these flows have higher water productivity values.

Beyond international market dynamics, governance is crucial for water resources management. Despite their water availability, many countries still face severe difficulties using water resources for human activities due to economic and infrastructural obstacles. Shifting our attention from the global scale of international trade to a smaller scale characterized by significant water scarcity problems, we discover another interesting outcome. African countries, for instance, base their agri-food trade economies on the export of export-oriented products that are particularly water-demanding, thus making a more significant imprint on the delicate local water situation. This result shows how economics and trade policies involve the displacement of the virtual resource and how water management inextricably requires a strong interconnection of the various sciences to enable a comprehensive view of such a complex concept.

All the topics discussed in this thesis aim to explore possible economic behaviors that are related with the water-food nexus. These themes are increasingly common in contemporary debates because of their extreme importance in making the food chain sustainable and decreasing the impact on the environment. These studies must be accessible outside the academic environment, becoming tools that promptly inform change fostering responsible politics and behaviors. All in all, there will be no transition towards a more sustainable food supply chain without changing consumers' food choices. This is where the last chapter of this work comes in because it focuses on disseminating the results that our whole research team achieved during the years, working together on water-related issues under the common hat provided by the CWASI project. WaterToFood, the name of the whole communication project that we created, is conceived as a tool for scientific outreach. It comprises multiple parts with different aims that cooperate with harmony and purpose. We describe the intellectual and practical processes that allowed us to achieve this result, hoping to provide useful information and inspiration for whoever decides to take responsibility and put effort into disseminating their research.

Appendices

A

Appendix A

Economic return

Figure A.1 shows the relation between the global average per capita water footprint and the global average economic value derived from one cubic meter of water used for crop cultivation. The averages are calculated across countries. The economic value is expressed in deflated International dollars. Each point represents the annual value and colours distinguish the different products. Figure A.1 shows that staple crops exhibit a higher economic water productivity than the one of cash crops. This suggests that the economic water productivity is strongly linked to the quantities produced. Consequently, since staple crops are produced and consumed in large quantities, their average economic water productivity results higher than the others. The result is also influenced by the fact that staple crops present a lower water footprint per ton with respect to cash crops on average. We think that the information about the global average economic productivity adds an interesting dimension to our discussion. On average, the products for which we found that water was to some extent considered in the price (i.e. the staple) are the products that on average provide the greatest economic value per unit of water. For this reason, we added the global average economic water productivity (EWP) and the global average production per capita in kg over time to Table 1.2. The EWP is calculated as:

$$EWP(\frac{Int\$}{m^3}) = \frac{\sum_y \sum_c (\frac{Int\$}{ton}) \cdot ton}{\sum_y \sum_c (\frac{m^3}{ton}) \cdot ton} \tag{A.1}$$

Finally, although the suggestions on per capita dimension are very useful, we do believe that the analysis on the variables per ton is meaningful. Of course some crops are more produced and consumed per capita than others, for this reason we rule out this fact through the consideration of each variable per unit ton, in order to understand the relation water-price without the

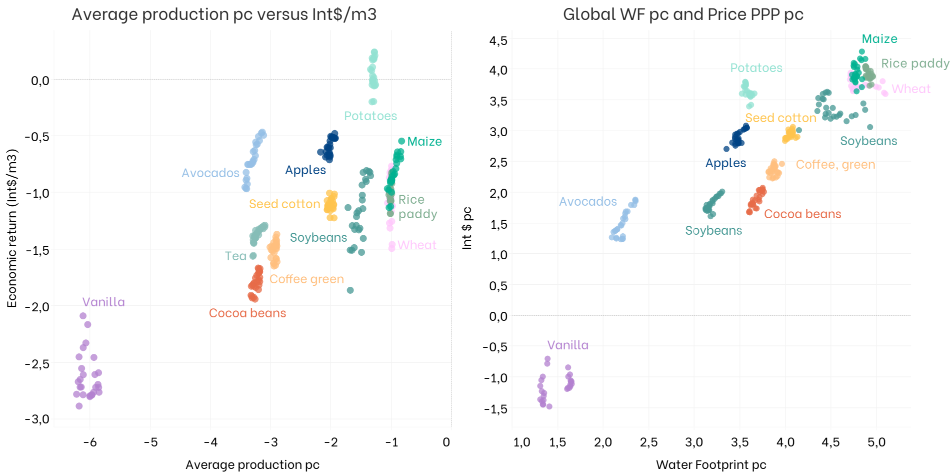


Figure A.1: Relationship between global average per capita water footprint and the global average economic value derived from one cubic meter of water used for crop cultivation.

influence of the quantity of production, which of course follows the quantity of consumption. Moreover, the water footprint metric (m^3/ton) is relevant since it is the core of our investigation on water-farm gate price relation in production. Consumption is a crucial domain as well of course, but it requires a completely different angle of research, for different reasons. First, the price payed by the consumer incorporates many other factors occurring along the long food value chain (from processing to marketing). Second, if on the one hand, decisions on production quantities are taken according to expected quantities of consumption worldwide, on the other hand consumption of one crop in one country includes also (and in the case of many crops, above all) imports. In this way we would consider information on a crop that is not produced in that country. Since water footprint is also country specific, the analysis would require more steps, that would be certainly feasible in a dedicated paper focusing on the virtual water trade, instead of on WF of production.

Land Footprint

We analyze the impact of the harvested area on the deflated price in PPP by applying the WLS estimator used previously for the crop water footprint (Eq: 1.4). The results obtained are similar: the angular coefficient of the regression is positive (0.53) and statistically significant. Also, in this case, the relationship is positive and it has a positive growth rate for crops that need a few hectares per ton for their production and that have a reduced monetary value as shown in Figure A.2. However, the same does not hold for products with greater intensity of harvested area and higher prices. Nevertheless the R^2_{adj} is equal to 0.40 (Table 1.4), which is lower

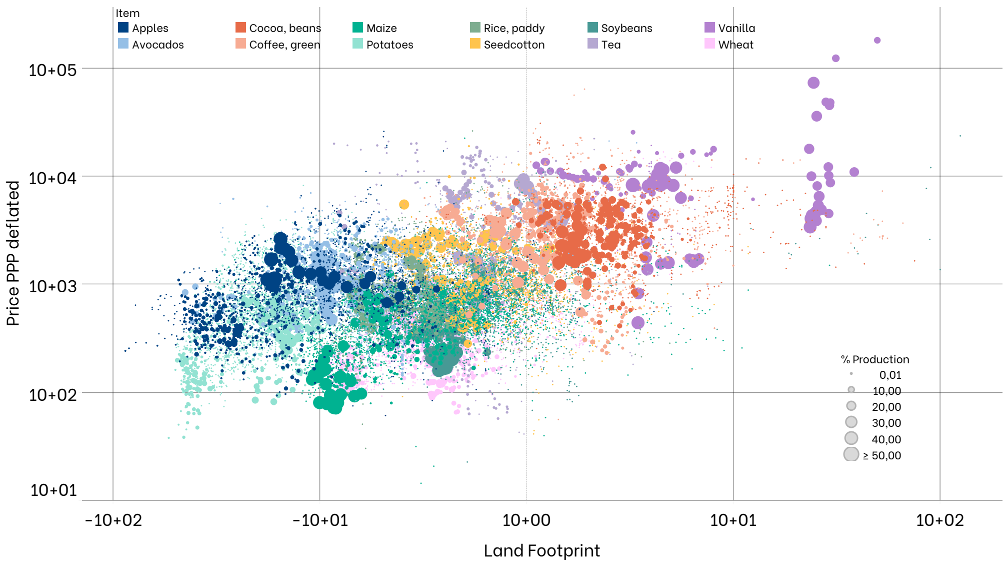
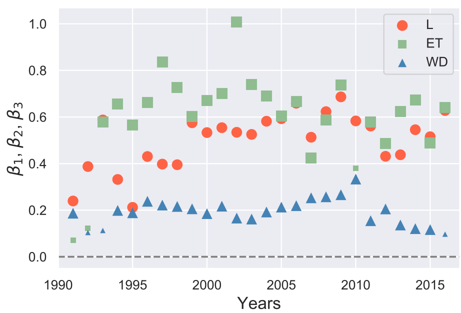
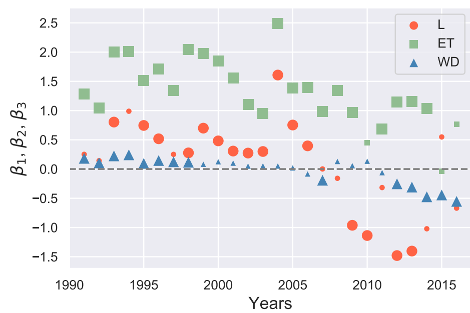


Figure A.2: Relationship between deflated price in PPP, P_{cp} ($Int\$/ton$), and land footprint L_{cp} (ha/ton). This scatter-plot takes into account all crops, all countries and all the years. Each color represents a different crop. The size of the points represents the percentage of production of each country in every year on the total production of all nations in the same year of that crop. The green line represents the result of the weighted linear regression, Eq.(1.4), with $m = 1$ and $X_1(t) = L_{cp}(t)$.

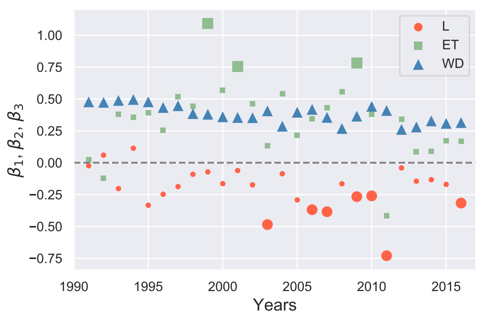
than the coefficient of determination found for the regression with the crop water footprint as an explanatory variable. This outcome suggests that a part of the variance of the dependent variable could be affected by the water component as an added value to the cultivated area. For this reason we partition the water footprint into its two components: harvested area and evapotranspiration.



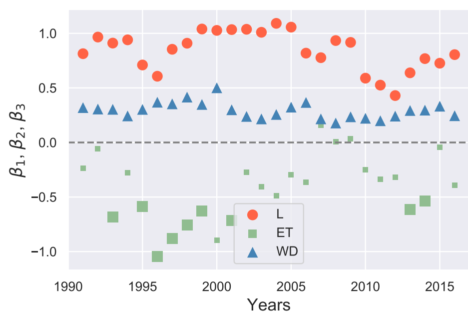
(a) Apples



(b) Cocoa beans

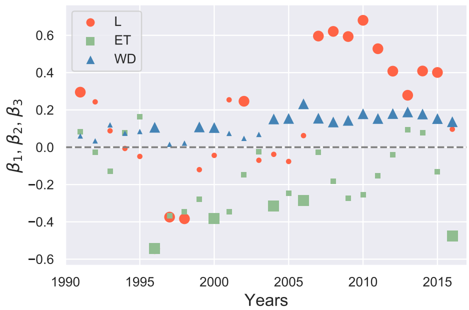


(c) Cotton seed

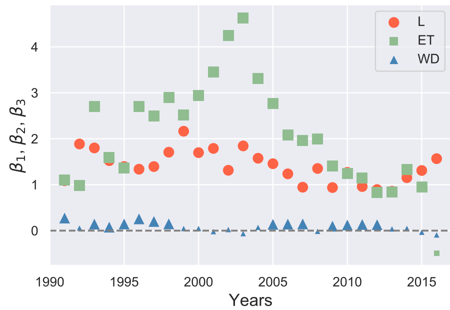


(d) Maize

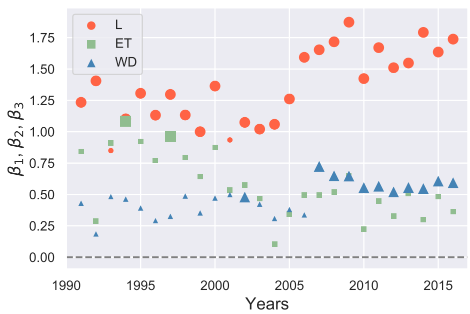
Figure A.3: Time behavior of the coefficients β_i of the multivariate regression analysis in Eq. (1.4) (with area per ton, evapotranspiration and water deficiency as explanatory variables). The different coefficients are identified both by colour and by a different symbol. The larger (smaller) markers identify coefficient significantly (non-significantly) different from zero at a 5% level.



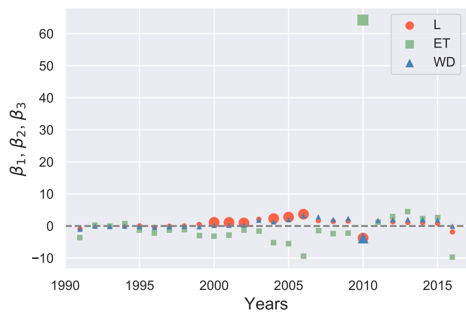
(a) Rice Paddy



(b) Soybeans



(c) Tea



(d) Vanilla

Figure A.4: Time behavior of the coefficients β_i of the multivariate regression analysis in Eq. (1.4) (with area per ton, evapotranspiration and water deficiency as explanatory variables). The different coefficients are identified both by colour and by a different symbol. The larger (smaller) markers identify coefficient significantly (non-significantly) different from zero at a 5% level.

B

Appendix B

Trade agreements

Table B.1: List of trade agreements considered in this study.

Trade Agreement	
Armenia - Kazakhstan	Chile - Guatemala (Chile - Central America)
Armenia - Moldova	Chile - Honduras (Chile - Central America)
Armenia - Russian Federation	Chile - Malaysia
Armenia - Turkmenistan	Chile - Mexico
Armenia - Ukraine	Chile - Nicaragua (Chile - Central America)
ASEAN-Australia-New Zealand	Chile - Viet nam
ASEAN-India	Chile-Australia
ASEAN-Korea	Chile-China
Australia - Papua New Guinea (PATCRA)	Chile-Japan
Australia-New Zealand (ANZCERTA)	Chile-Korea
Australia-Singapore	China - Costa Rica
Australia-Thailand	China - Macao, China
Brunei Darussalam - Japan	China-ASEAN
CAFTA-DR	China-Hong Kong
CAN	China-New Zealand
Canada - Chile	China-Pakistan
Canada - Colombia	China-Peru
Canada - Costa Rica	China-Singapore
Canada - Honduras	CIS
Canada - Israel	Colombia - Mexico
Canada - Jordan	Colombia - Northern Triangle
Canada - Panama	COMESA
Canada - Rep. of Korea	Costa Rica - Peru
Canada-EFTA	Costa Rica - Singapore
Canada-Peru	Dominican Republic - Central America
CARICOM	EAEC
CEFTA	East African Community (EAC)
Central American Common Market (CACM)	EC Treaty
CEZ	EC-Albania
Chile - Colombia	EC-Algeria
Chile - Costa Rica (Chile - Central America)	EC-Bosnia Herzegovina
Chile - El Salvador (Chile - Central America)	EC-Cameroon
EC-CARIFORUM	EFTA - Hong Kong, China
EC-Chile	EFTA - Jordan
EC-Cote d'Ivoire	EFTA - Lebanon
EC-Croatia	EFTA - Mexico
EC-Egypt	EFTA - Montenegro
EC-Faroe Islands	EFTA - Morocco
EC-FYR Macedonia	EFTA - Palestinian Authority
EC-Iceland	EFTA - Peru
EC-Israel	EFTA - SACU
EC-Jordan	EFTA - Serbia

Trade Agreement	
EC-Lebanon	EFTA - Singapore
EC-Mexico	EFTA - Tunisia
EC-Montenegro	EFTA - Ukraine
EC-Morocco	EFTA-Israel
EC-Norway	EFTA-Korea
CEMAC	Egypt - Turkey
ECOWAS	El Salvador - Honduras - Chinese Taipei
EC-Palestinian Authority	EU - Andorra
EC-South Africa	EU - Central America
EC-Switzerland Liechtenstein	EU - Colombia and Peru
EC-Syria	EU - ESA States Interim EPA
EC-Tunisia	EU - Georgia
EC-Turkey	EU - Korea, Republic of
EEA	EU - Papua New Guinea/Fiji
EFTA - Accession of Iceland	EU - Republic of Moldova
EFTA - Albania	Eurasian Economic Union (EAEU)
EFTA - Bosnia and Herzegovina	European Free Trade Association (EFTA)
EFTA - Central America (Costa Rica and Panama)	EU-San Marino
EFTA - Chile	EU-Serbia
EFTA - Colombia	Faroe Islands - Norway
EFTA - Egypt	Faroe Islands - Switzerland
EFTA - Former Yugoslav Rep. of Macedonia	GCC
Georgia - Armenia	Korea, Republic of - US
Georgia - Azerbaijan	Korea, Republic of-India
Georgia - Kazakhstan	Korea, Republic of-Singapore
Georgia - Russian Federation	Kyrgyz Republic - Armenia
Georgia - Turkmenistan	Kyrgyz Republic - Kazakhstan
Georgia - Ukraine	Kyrgyz Republic - Moldova
Guatemala - Chinese Taipei	Kyrgyz Republic - Russian Federation
Gulf Cooperation Council (GCC) - Singapore	Kyrgyz Republic - Ukraine
Hong Kong, China - Chile	Kyrgyz Republic - Uzbekistan
Hong Kong, China - New Zealand	Malaysia - Australia
Iceland - China	MERCOSUR
Iceland - Faroe Islands	Mexico - Central America
India - Bhutan	Mexico - Uruguay
India-Japan	NAFTA
India-Malaysia	New Zealand - Chinese Taipei
India-Singapore	New Zealand - Malaysia
India-Sri Lanka	New Zealand - Singapore
Israel - Mexico	Nicaragua - Chinese Taipei
Japan - Australia	Pacific Island Countries Trade Agreement (PICTA)
Japan - Peru	PAFTA
Japan-ASEAN	Pakistan - Malaysia
Japan-Indonesia	Pakistan - Sri Lanka
Japan-Malaysia	Panama - Chile
Japan-Mexico	Panama - Chinese Taipei
Japan-Philippines	Panama - Costa Rica (Panama - Central America)
Japan-Singapore	Panama - El Salvador (Panama - Central America)
Japan-Switzerland	Panama - Guatemala (Panama - Central America
Japan-Thailand	Panama - Honduras (Panama - Central America)
Japan-Viet Nam	Panama - Nicaragua (Panama - Central America)
Jordan - Singapore	Panama - Peru
Korea, Republic of - Australia	Panama - Singapore
Korea, Republic of - Turkey	Peru - Chile
Peru - Korea, Republic of	Turkey - Serbia
Peru - Mexico	Turkey - Syria
Peru - Singapore	Turkey - Tunisia

Trade Agreement	
Russian Federation - Azerbaijan	Turkey-EFTA
Russian Federation - Belarus	Ukraine - Azerbaijan
Russian Federation - Belarus - Kazakhstan	Ukraine - Former Yugoslav Rep. of Macedonia
Russian Federation - Kazakhstan	Ukraine - Moldova
Russian Federation - Republic of Moldova	Ukraine - Montenegro
Russian Federation - Serbia	Ukraine - Uzbekistan
Russian Federation - Tajikistan	Ukraine Tajikistan
Russian Federation - Turkmenistan	Ukraine-Belarus
Russian Federation - Uzkbekistan	Ukraine-Kazakhstan
Russian Federation-Ukraina	Ukraine-Turkmenistan
SACU	US - Colombia
SAFTA	US - Panama
Singapore - Chinese Taipei	US-Australia
Southern African Development Community	US-Bahrain
Switzerland - China	US-Chile
Thailand - New Zealand	US-Israel
Trans-Pacific Strategic Economic Partnership	US-Jordan
Treaty on a FTA between members of the CIS	US-Morocco
Turkey - Albania	US-Oman
Turkey - Bosnia and Herzegovina	US-Peru
Turkey - Chile	US-Singapore
Turkey - Former Yugoslav Republic of Macedonia	WAEMU
Turkey - Georgia	
Turkey - Israel	
Turkey - Jordan	
Turkey - Mauritius	
Turkey - Montenegro	
Turkey - Morocco	
Turkey - Palestinian Authority	

Flow variation and water productivity for blue and green virtual water.

The virtual water content can be quantified in green and blue water components, depending on whether the water is contributed by rainwater or by surface and groundwater used for irrigation and food processing. In this subsection we carry out the analysis by taking the two components of blue water and green water separately. Table B.2 shows in column (a) the results for total virtual water (blue and green together), in column (b) for blue water, and finally in column (c) for green water.

Table B.2: Average values of virtual water trade flows and flow variation index ρ_{ij} considering the total virtual water (blue and green together), and separately. The bar indicates the average operator. The subscript w indicates the weighted average, where weights correspond to the flows at time *t-1* (i.e.,$V_{ij}(t-1)$). Values of ρ_{ij} is reported in percentage point (p.p).

(a) VW m^3 tot

Operational Activation	
$\overline{V_{ij}}(t)$	$1.98 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	43.10 p.p
Trade Agreement in t-1 and t	
$\overline{V_{ij}}(t)$	$2.56 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	40.07 p.p
No Trade Agreement	
$\overline{V_{ij}}(t)$	$1.94 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	54.99 p.p

(b) VW m^3 blue

Operational Activation	
$\overline{V_{ij}}(t)$	$1.61 \cdot 10^7$
$\overline{\mid \rho_{ij} \mid}_w$	46.51 p.p
Trade Agreement in t-1 and t	
$\overline{V_{ij}}(t)$	$2.20 \cdot 10^7$
$\overline{\mid \rho_{ij} \mid}_w$	43.33 p.p
No Trade Agreement	
$\overline{V_{ij}}(t)$	$2.07 \cdot 10^7$
$\overline{\mid \rho_{ij} \mid}_w$	56.12 p.p

(c) VW m^3 green

Operational Activation	
$\overline{V_{ij}}(t)$	$1.82 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	44.74 p.p
Trade Agreement in t-1 and t	
$\overline{V_{ij}}(t)$	$2.34 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	40.55 p.p
No Trade Agreement	
$\overline{V_{ij}}(t)$	$1.74 \cdot 10^8$
$\overline{\mid \rho_{ij} \mid}_w$	55.40 p.p

The average volume of blue water when a trade agreement is present over time is slightly higher than when there is no agreement. This means that the differences in trading volumes observed in total water between flows covered and not covered by trade agreements, in addition to being smaller than those found in US$ and Kcal, are also almost exclusively due to green water.

Regional trade agreements presenting negative percentage variation of the flows.

Table B.3 displays the treaties that show a flow decrease from the year before the entry into force of the agreement, to the year after ratification. Notice that the ρ_a values are flow percentage variations in comparison to the fluctuations of the flows registered on links not covered by trade agreements. As mentioned in the Discussion section, a negative ρ_a value

Table B.3: Flow values in millions of dollars and negative percent changes ρ_a for each trade agreement. The colors are assigned according to the same procedure as in the Table 2.5. For each geographic area, trade agreements are sorted in descending order by flow value ($ million). The color and the orientation of the arrows classifies the percentage changes into three categories: gray for a slight decrease ($\leq -10\%$ decrease in flow intensity), yellow for strong decrease (decrease $\leq$ -10% and $\geq$ -50%), and red for extreme decrease (decrease $<$ -50%).

World Bank region	Name agreement	Year Entry Force	Flow intensity (millions $)	ρ_a p.p	Δ_a (%)
Europe & Central Asia	EU-Serbia	2010	272,0	-9	-9
	EC-Egypt	2004	147,4	-32	-13
	EU - Rep. of Korea	2011	110,5	-90	
	EC-Tunisia	1998	81,0	-20	-27
	EC-Chile	2003	32,1	-4	-1
	Turkey - Syria	2007	16,4	-105	-54
	EC-Albania	2006	12,8	-13	-8
	Turkey - Jordan	2011	7,2	-62	-26
	EC-Mexico	2000	7,1	-32	-34
	EC-Jordan	2002	4,9	-92	-84
	Turkey - Albania	2008	4,9	-44	1
	Turkey - Israel	1997	1,6	-51	-65
	EFTA - Egypt	2007	1,3	-74	-23
	Turkey - Morocco	2006	1,1	-68	-63
South Asia	SAFTA	2006	274,4	-7	-2
	India - Bhutan	2006	2,8	-54	-49
Middle East & North Africa	PAFTA	1998	151,6	-6	-13
	Egypt - Turkey	2007	71,9	-11	40
East Asia & Pacific	Rep. of Korea - US	2012	1558,8	-40	
	Japan - Australia	2015	368,9	-16	-26
	China-ASEAN	2005	355,2	-7	-12
	Japan-Thailand	2007	85,9	-14	36
	Australia-Singapore	2003	12,8	-18	-16
	Japan-Singapore	2002	8,1	-27	-19
	Japan-Indonesia	2008	7,9	-79	-34
Latin America & Caribbean	Chile - Viet nam	2014	7,5	-45	-50
	Peru - Mexico	2012	5,0	-2	3
	Chile - Colombia	2009	1,2	-28	-56
North America	US - Colombia	2012	286,6	-36	-31
	US - Panama	2012	106,8	-37	-32
	US-Jordan	2001	88,8	-1	4
	Canada - Rep. of Korea	2015	84,9	-46	-57
	US-Chile	2004	67,8	-69	-50
	Canada - Chile	1997	51,2	-41	-55
	Canada - Costa Rica	2002	6,3	-19	-12
	US-Oman	2009	2,8	-35	-62
Sub-Saharan Africa	SADC	2000	184,1	-0,1	-2,0
	CEMAC	1999	0,3	-68	-75

does not necessarily highlight a decrease, but indicates a lower increase compared to the average variation of non-agreement trade relationships. For this reason, differently from Table 2.5 we have also included the percentage change in the trade agreement (Δ_a).

In this way, we observe that some agreements, i.e., Japan - Thailand, register a flow increase of 36% compared to the year before the treaty was signed. The respective ρ_a value is -14 (p.p), which means that the change related to the trade treaty was smaller than the increase in flows that occurred in all links not covered by trade agreements.

Regional trade agreements variation of the flows in kcal and virtual water

The following tables show the treaties showing an increase or decrease in flows from the year before the agreement came into force to the year after ratification in the other units of measurement analyzed, namely kcal (see Tables B.4 and B.5) and virtual water (see Tables B.6 and B.7). Note that the values of ρ_a are percentage changes in flows compared to fluctuations in flows recorded on links not covered by trade agreements.

Table B.4: Flow values in kcal in year t and percent changes ρ_a from t-1 to t for each trade agreement. Year t indicates the year of entry into force of the trade agreement. Colors highlight the geographical region as provided by the World Bank, considering most of the countries that are part of the trade agreement. In the case of a bilateral trade agreements, the geographical position of the first country mentioned in the actual name of the treaty is taken into account to assign the color. For each region, trade agreements are sorted in descending order according to the flow nutritional value (kcal). The color and orientation of the arrows classify the percentage changes into three categories: gray for a moderate increase concerning links not covered by agreements (< 50% increase in flow intensity), yellow for strong increase (increase ≥ 50% and < 100%), and green for sharp increase (increase ≥ 100%).

World Bank region	Name agreement	Year	Flow intensity (kcal)	ρ_a
Europe & Central Asia	EC-Algeria	2005	1,14E+13	20,34
	EC-Morocco	2000	9,75E+12	8,97
	CEFTA	2007	4,39E+12	20,61
	EC-Israel	2000	2,98E+12	103,79
	EEA	1994	2,94E+12	8,93
	EU - Republic of Moldova	2014	1,64E+12	53,09
	EC-Cote d'Ivoire	2009	1,63E+12	15,22
	EC-Turkey	1996	1,52E+12	57,53
	EFTA - Mexico	2001	1,49E+12	93,52
	EC-Cameroon	2009	1,36E+12	21,79
	EC-Bosnia Herzegovina	2008	1,27E+12	86,10
	EC-Croatia	2002	8,61E+11	146,24
	EC-South Africa	2000	8,34E+11	351,00
	EC-CARIFORUM	2008	6,84E+11	48,17
	EU - Colombia and Peru	2013	4,54E+11	62,87
	EU - Central America	2013	3,24E+11	49,66
	EC-Chile	2003	3,03E+11	225,23
	EC-Albania	2006	1,81E+11	9,56
	Turkey - Georgia	2008	1,02E+11	38,18
	EC-FYR Macedonia	2001	9,79E+10	1039,69
	EU - Georgia	2014	9,36E+10	29,25
	EC-Montenegro	2008	4,13E+10	145,38
	Turkey - Mauritius	2013	1,72E+10	148,47
	Turkey - Tunisia	2005	1,64E+10	163,18
	EC-Faroe Islands	1997	1,07E+09	203,37
South Asia	India-Sri Lanka	2001	2,01E+11	61,82
	Pakistan - Sri Lanka	2005	1,63E+11	893,56
	India-Japan	2011	3,18E+10	79,41
Sub-Saharan Africa	COMESA	1994	3,93E+12	308,34

World Bank region	Name agreement	Year	Flow intensity (kcal)	ρ_a
East Asia & Pacific	ASEAN-Australia-New Zealand	2010	2,41E+13	40,06
	ASEAN-India	2010	4,65E+12	3,86
	Korea, Republic of - Australia	2014	4,49E+12	108,05
	Australia-Thailand	2005	2,55E+12	21,89
	Japan-ASEAN	2008	9,67E+11	62,09
	Japan-Thailand	2007	5,24E+11	104,10
	Australia-Singapore	2003	3,16E+11	19,93
	ASEAN-Korea	2010	2,61E+11	1,09
	Korea, Republic of - Turkey	2013	1,88E+11	9,86
	PICTA	2003	4,48E+10	414,46
	Thailand - New Zealand	2005	3,23E+10	51,49
	TPSEP	2006	9,73E+09	84,67
	Korea, Republic of-Singapore	2006	9,22E+09	63,65
	Japan-Malaysia	2006	7,88E+09	3,01
	Korea, Republic of-India	2010	6,14E+09	35,45
Latin America & Caribbean	CAFTA-DR	2006	1,49E+13	20,02
	Mexico - Central America	2012	5,54E+11	96,69
	Peru - Chile	2009	3,12E+11	31,90
	Panama - Peru	2012	9,79E+09	20,31
	Chile - Costa Rica	2002	9,74E+09	15,28
	Chile - Guatemala	2010	6,46E+09	12,40
North America	NAFTA	1994	5,42E+13	17,36
	US-Morocco	2006	5,08E+12	109,71
	US-Peru	2009	3,33E+12	48,98
	Canada-Peru	2009	2,18E+12	88,27
	US-Jordan	2001	2,02E+12	2,50
	US-Singapore	2004	2,50E+11	76,36
	US-Australia	2005	3,17E+10	62,52
	Canada - Panama	2013	1,13E+10	44,79

Table B.5: Flow values in kcal and negative percent changes ρ_a for each trade agreement. The colors are assigned according to the same procedure as in the Table 2.5. For each geographic area, trade agreements are sorted in descending order by flow nutritional value (kcal). The color and the orientation of the arrows classifies the percentage changes into three categories: gray for a slight decrease ($\leq -10\%$ decrease in flow intensity), yellow for strong decrease (decrease $\leq$ -10% and $\geq$ -50%), and red for extreme decrease (decrease $<$ -50%).

World Bank region	Name agreement	Year	Flow intensity (kcal)	Δ_a	ρ_a	World Bank region	Name agreement	Year	Flow intensity (kcal)	Δ_a	ρ_a
Europe & Central Asia	EU-Serbia	2010	4,41E+12	-27,56	-27,83	East Asia & Pacific	Rep. of Korea - US	2012	1,67E+13	-12,82	-14,34
	EC-Egypt	2004	3,14E+12	-92,62	-104,65		China-ASEAN	2005	4,79E+12	-21,58	-27,66
	EC-Tunisia	1998	2,13E+12	-7,11	-0,004		Japan - Australia	2015	3,88E+12	-66,27	-66,53
	EU - Korea, Republic of	2011	1,15E+12	-40,91	-44,11		Japan-Singapore	2002	1,63E+11	-6,83	-18,86
	EU - ESA Interim EPA	2012	5,09E+11	-12,30	-12,96		Japan-Indonesia	2008	4,96E+10	-36,82	-48,75
	Turkey - Syria	2007	2,31E+11	-42,77	-51,62	Latin America & Caribbean	Chile - Viet nam	2014	4,25E+10	-20,70	-18,88
	EC-Mexico	2000	1,36E+11	1,13	-10,80		Peru - Mexico	2012	3,78E+10	-12,09	-24,02
	EC-Lebanon	2003	1,22E+11	-66,03	-69,46		Chile - Nicaragua	2012	2,63E+10	-46,62	-50,27
	Turkey - FYR Macedonia	2000	8,48E+10	-16,37	-13,78		Chile - Colombia	2009	1,13E+10	-11,87	-23,80
	EC-Jordan	2002	5,50E+10	-40,92	-41,18	North America	US - Colombia	2012	2,46E+12	-39,71	-44,79
	Turkey - Jordan	2011	3,70E+10	-23,50	-26,70		Canada - Colombia	2011	2,14E+12	-0,66	-4,08
	Turkey - Albania	2008	3,59E+10	-65,88	-70,96		Canada - Chile	1997	9,96E+11	-12,01	-24,04
	Turkey - Israel	1997	2,39E+10	-57,27	-60,70		US - Panama	2012	9,35E+11	-58,67	-64,74
	Turkey - Morocco	2006	2,08E+10	-68,78	-67,33		Canada - Rep. of Korea	2015	8,18E+11	-5,45	-3,62
	EFTA - Egypt	2007	1,13E+10	-77,94	-86,79		US-Chile	2004	2,94E+11	-42,39	-54,32
South Asia	SAFTA	2006	4,02E+12	-53,02	-51,58		Canada-EFTA	2009	2,63E+11	-44,31	-56,24
	Pakistan - Malaysia	2008	1,70E+11	-9,76	-11,27		Canada - Costa Rica	2002	1,14E+11	-74,88	-75,16
	India-Singapore	2005	1,09E+11	-26,37	-26,63		US-Oman	2009	2,70E+10	-57,08	-55,25
	India - Bhutan	2006	3,71E+10	-20,11	-18,66	Sub-Saharan Africa	SADC	2000	2,36E+12	-60,06	-65,98
Middle East & North Africa	PAFTA	1998	1,57E+12	-21,21	-30,05		CEMAC	1999	3,80E+09	-22,50	-25,70
	Egypt - Turkey	2007	4,48E+11	-35,96	-36,62						

Table B.6: Flow values in virtual water in year t and percent changes ρ_a from t-1 to t for each trade agreement. Year t indicates the year of entry into force of the trade agreement. Colors highlight the geographical region as provided by the World Bank, considering most of the countries that are part of the trade agreement. In the case of a bilateral trade agreements, the geographical position of the first country mentioned in the actual name of the treaty is taken into account to assign the color. For each region, trade agreements are sorted in descending order according to the virtual water value (km^3). The color and orientation of the arrows classify the percentage changes into three categories: gray for a moderate increase concerning links not covered by agreements ($< 50\%$ increase in flow intensity), yellow for strong increase (increase $\geq 50\%$ and $< 100\%$), and green for sharp increase (increase $\geq 100\%$).

World Bank region	Name agreement	Year Entry Force	Flow Intensity (km3)	ρ_a
Europe & Central Asia	EC-Algeria	2005	2 195 650,95	20,23
	CEFTA	2007	1 732 880,54	55,89
	EC-Morocco	2000	1 618 252,96	57,99
	EU - Republic of Moldova	2014	703 721,17	16,86
	EEA	1994	620 979,66	113,23
	EFTA - Mexico	2001	589 784,20	54,09
	EC-Israel	2000	548 680,52	33,83
	EC-CARIFORUM	2008	397 392,04	135,04
	EC-South Africa	2000	337 083,15	45,32
	EC-Turkey	1996	313 280,31	71,03
	EC-Cote d'Ivoire	2009	267 392,62	148,58
	EC-Bosnia Herzegovina	2008	266 775,84	239,09
	EC-Cameroon	2009	232 865,57	38,96
	EC-Croatia	2002	209 603,27	189,22
	EU - Colombia and Peru	2013	100 853,88	10,69
	Turkey - FYR Macedonia	2000	95 529,35	175,66
	EC-Chile	2003	61 173,06	306,20
	Turkey - Georgia	2008	60 543,54	10,25
	EU - Central America	2013	58 265,39	51,10
	EC-FYR Macedonia	2001	14 897,30	692,38
	EFTA - Egypt	2007	11 826,40	165,66
	EC-Faroe Islands	1997	10 430,40	153,20
	Turkey - Tunisia	2005	9 796,19	166,66
	EC-Montenegro	2008	9 416,05	217,40
	Turkey - Mauritius	2013	8 962,08	1238,21
South Asia	Pakistan - Sri Lanka	2005	395 296,00	1348,11
	India-Sri Lanka	2001	71 981,29	944,43
	India-Japan	2011	14 775,13	62,12

World Bank region	Name agreement	Year Entry Force	Flow Intensity (km3)	ρ_a
East Asia & Pacific	ASEAN-Australia-New Zealand	2010	17 370 625,04	49,12
	Australia-Thailand	2005	1 793 518,35	123,94
	Japan-ASEAN	2008	810 244,67	181,37
	Australia-Singapore	2003	352 642,73	94,17
	ASEAN-Korea	2010	224 152,20	207,83
	Korea, Republic of - Turkey	2013	91 434,45	30,27
	PICTA	2003	39 972,58	452,85
	TPSEP	2006	4 701,47	42,40
	Korea, Republic of-Singapore	2006	4 590,02	100,53
	Japan-Malaysia	2006	3 725,61	201,09
	Korea, Republic of-India	2010	3 583,17	28,08
Latin America & Caribbean	CAFTA-DR	2006	4 997 760,12	31,91
	Mexico - Central America	2012	197 495,22	25,82
	Peru - Chile	2009	131 878,26	30,76
	Chile - Colombia	2009	4 878,55	36,24
	Chile - Guatemala	2010	3 753,22	37,71
	Chile - Costa Rica	2002	3 205,00	58,84
North America	NAFTA	1994	16 671 019,17	15,21
	US-Jordan	2001	1 353 620,37	32,96
	US-Morocco	2006	1 114 702,48	137,82
	US-Peru	2009	955 468,66	15,51
	Canada-Peru	2009	685 669,09	97,12
	Canada-EFTA	2009	108 985,29	11,22
	Canada - Costa Rica	2002	58 082,40	107,92
	US-Australia	2005	15 252,82	183,31
Sub-Saharan Africa	COMESA	1994	3 696 299,92	478,72

Table B.7: Flow values in virtual water and negative percent changes ρ_a for each trade agreement. The colors are assigned according to the same procedure as in the Table 2.5. For each geographic area, trade agreements are sorted in descending order by flow virtual water value (km^3). The color and the orientation of the arrows classifies the percentage changes into three categories: gray for a slight decrease ($\leq -10\%$ decrease in flow intensity), yellow for strong decrease (decrease $\leq$ -10% and $\geq$ -50%), and red for extreme decrease (decrease $<$ -50%).

World Bank region	Name agreement	Year	Flow intensity (km^3)	Δ_a	ρ_a
Europe & Central Asia	EU-Serbia	2010	1 320 862,61	-28,43	-22,18
	EC-Egypt	2004	768 113,18	-28,18	-24,53
	EC-Tunisia	1998	365 679,73	-11,48	-12,22
	EU - Korea, Republic of	2011	260 570,49	-72,99	-72,69
	Turkey - Syria	2007	114 364,71	-66,05	-81,12
	EU - ESA Interim EPA	2012	100 776,06	-6,06	-28,52
	EC-Albania	2006	49 086,86	-15,89	-13,64
	EC-Lebanon	2003	43 017,93	-8,96	-2,21
	EC-Jordan	2002	25 448,39	-81,22	-96,55
	EC-Mexico	2000	21 684,54	-68,48	-71,15
	Turkey - Albania	2008	21 379,75	-48,27	-44,02
	Turkey - Jordan	2011	15 626,97	-64,83	-64,53
	Turkey - Israel	1997	14 974,90	-62,35	-67,24
	EU - Georgia	2014	13 571,71	-14,27	-17,76
	Turkey - Morocco	2006	8 033,64	-63,11	-60,85
South Asia	SAFTA	2006	3 001 215,56	-21,78	-19,52
	Pakistan - Malaysia	2008	160 682,90	-5,98	-1,72
	India-Singapore	2005	71 388,93	-42,17	-43,13
	India - Bhutan	2006	33 765,10	-50,93	-48,67
Middle East & North Africa	PAFTA	1998	1 113 969,65	-56,86	-57,60
	Egypt - Turkey	2007	231 390,10	-39,62	-54,69
Sub-Saharan Africa	SADC	2000	1 143 840,31	-40,29	-42,96
	CEMAC	1999	1 508,46	-55,06	-52,77
East Asia & Pacific	Korea, Republic of - US	2012	5 286 039,24	-10,88	-33,34
	China-ASEAN	2005	2 471 263,83	-23,81	-24,77
	Korea, Republic of - Australia	2014	2 437 485,22	-0,59	-4,08
	Japan - Australia	2015	2 255 693,21	-18,70	-20,70
	ASEAN-India	2010	2 188 885,93	-21,33	-15,08
	Japan-Thailand	2007	500 420,16	4,29	-10,79
	Japan-Singapore	2002	111 477,86	-7,81	-23,14
	Thailand - New Zealand	2005	33 683,03	0,37	-0,59
	Japan-Indonesia	2008	24 213,75	-73,00	-68,75
Latin America & Caribbean	Chile - Viet nam	2014	20 217,80	-48,30	-51,79
	Peru - Mexico	2012	13 674,82	-27,49	-49,95
	Chile - Nicaragua	2012	9 494,91	15,51	-6,95
	Panama - Peru	2012	4 578,51	16,54	-5,92
North America	US - Colombia	2012	1 021 726,85	-34,81	-57,27
	Canada - Colombia	2011	653 202,68	-2,56	-2,26
	Canada - Chile	1997	453 935,77	-26,25	-31,14
	US - Panama	2012	395 690,61	-18,92	-41,38
	Canada - Rep. of Korea	2015	245 659,13	-60,07	-62,06
	US-Chile	2004	117 253,04	-77,60	-73,95
	US-Singapore	2004	80 858,00	-14,40	-10,75
	US-Oman	2009	6 683,22	-9,98	-9,57
	Canada - Panama	2013	3 032,15	-12,80	-4,90

C

Appendix C

MAGNET aggregation: list of countries

Table C.1: List of countries considered in this study with their aggregation under the MAGNET- economic region.

MAGNET aggregation	Country name
Asia	Afghanistan
Asia	Bangladesh
Asia	Bhutan
Asia	Brunei Darussalam
Asia	Cambodia
Asia	Korea DPR
Asia	Indonesia
Asia	Japan
Asia	Laos
Asia	Malaysia
Asia	Maldives
Asia	Mongolia
Asia	Myanmar
Asia	Nepal
Asia	Pakistan
Asia	Philippines
Asia	Korea R
Asia	Singapore
Asia	Sri Lanka
Asia	Thailand
Asia	Timor-Leste
Asia	Vietnam
Asia	China, Hong Kong SAR
Asia	China, Macao SAR
Asia	China, Taiwan Province of
CHE	Switzerland
CHN	China
COMESA	Burundi
COMESA	Comoros
COMESA	Djibouti
COMESA	Egypt
COMESA	Eritrea
COMESA	Ethiopia
COMESA	Madagascar
COMESA	Malawi
COMESA	Mauritius
COMESA	Seychelles
COMESA	Somalia
COMESA	South Sudan
COMESA	Sudan
COMESA	Zambia
COMESA	Zimbabwe
COMESA	Ethiopia PDR
COMESA	Mayotte
COMESA	Sudan (former)

MAGNET aggregation	Country name
EAC	Kenya
EAC	Rwanda
EAC	Uganda
EAC	Tanzania
ECCAS	Angola
ECCAS	Cameroon
ECCAS	Central African Republic
ECCAS	Chad
ECCAS	Republic of the Congo
ECCAS	Democratic Republic of the Congo
ECCAS	Equatorial Guinea
ECCAS	Gabon
ECCAS	Sao Tome and Principe
ECOWAS	Burkina Faso
ECOWAS	Cape Verde
ECOWAS	Gambia
ECOWAS	Ghana
ECOWAS	Guinea
ECOWAS	Guinea-Bissau
ECOWAS	Liberia
ECOWAS	Mali
ECOWAS	Mauritania
ECOWAS	Niger
ECOWAS	Nigeria
ECOWAS	Sierra Leone
ECOWAS	Saint Helena,Asc. and Tr. da Cunha
EU27	Austria
EU27	Belgium
EU27	Bulgaria
EU27	Croatia
EU27	Cyprus
EU27	Czechia
EU27	Denmark
EU27	Estonia
EU27	Finland
EU27	France
EU27	Germany
EU27	Greece
EU27	Hungary
EU27	Ireland
EU27	Italy
EU27	Latvia
EU27	Lithuania
EU27	Luxembourg
EU27	Malta

MAGNET aggregation	Country name
EU27	Netherlands
EU27	Poland
EU27	Portugal
EU27	Romania
EU27	Slovakia
EU27	Slovenia
EU27	Spain
EU27	Sweden
EU27	Guadeloupe
EU27	Martinique
EU27	Reunion
GBR	UK
GCC	Bahrain
GCC	Kuwait
GCC	Oman
GCC	Qatar
GCC	Saudi Arabia
GCC	UAE
IND	India
ROW	Albania
ROW	Andorra
ROW	Antigua and Barbuda
ROW	Argentina
ROW	Armenia
ROW	Australia
ROW	Azerbaijan
ROW	Bahamas
ROW	Barbados
ROW	Belarus
ROW	Belize
ROW	Bolivia
ROW	Bosnia and Herzegovina
ROW	Brazil
ROW	Canada
ROW	Chile
ROW	Colombia
ROW	Cook Islands
ROW	Costa Rica
ROW	Cuba
ROW	Dominica
ROW	Dominican Republic
ROW	Ecuador
ROW	El Salvador
ROW	Faroe Islands
ROW	Fiji

MAGNET aggregation	Country name
ROW	Georgia
ROW	Grenada
ROW	Guatemala
ROW	Guyana
ROW	Haiti
ROW	Honduras
ROW	Iceland
ROW	Iran
ROW	Iraq
ROW	Israel
ROW	Jamaica
ROW	Jordan
ROW	Kazakhstan
ROW	Kiribati
ROW	Kyrgyzstan
ROW	Lebanon
ROW	Marshall Islands
ROW	Mexico
ROW	Micronesia
ROW	Monaco
ROW	Montenegro
ROW	Nauru
ROW	New Zealand
ROW	Nicaragua
ROW	Niue
ROW	Macedonia
ROW	Norway
ROW	Palau
ROW	Panama
ROW	Papua New Guinea
ROW	Paraguay
ROW	Peru
ROW	Moldova
ROW	Russian Federation
ROW	Saint Kitts and Nevis
ROW	Saint Lucia
ROW	Saint Vincent and the Grenadines
ROW	Samoa
ROW	San Marino
ROW	Serbia
ROW	Solomon Islands
ROW	Suriname
ROW	Syria
ROW	Tajikistan
ROW	Tokelau

MAGNET aggregation	Country name
ROW	Tonga
ROW	Trinidad and Tobago
ROW	Turkey
ROW	Turkmenistan
ROW	Tuvalu
ROW	Ukraine
ROW	Uruguay
ROW	Uzbekistan
ROW	Vanuatu
ROW	Venezuela
ROW	Yemen
ROW	American Samoa
ROW	Anguilla
ROW	Antarctica
ROW	Aruba
ROW	Bouvet Island
ROW	British Indian Ocean Territory
ROW	British Virgin Islands
ROW	Cayman Islands
ROW	Christmas Island
ROW	Cocos Islands (Keeling)
ROW	Falkland Islands (Malvinas)
ROW	French Guiana
ROW	French Polynesia
ROW	French Southern and Antarctic Territories
ROW	Gibraltar
ROW	Guam
ROW	Heard and McDonald Islands
ROW	Holy See
ROW	Liechtenstein
ROW	Montserrat
ROW	Netherlands Antilles
ROW	New Caledonia
ROW	Norfolk Island
ROW	Northern Mariana Islands
ROW	Occupied Palestinian Territory
ROW	Pitcairn Islands
ROW	Puerto Rico
ROW	South Georgia and the South Sandwich Islands
ROW	Svalbard and Jan Mayen Islands
ROW	Turks and Caicos Islands
ROW	United States Minor Is.
ROW	Wallis and Futuna Islands
SADC	Botswana
SADC	Swaziland

MAGNET aggregation	Country name
SADC	Lesotho
SADC	Mozambique
SADC	Namibia
SADC	South Africa
UEMOA	Benin
UEMOA	Côte d'Ivoire
UEMOA	Senegal
UEMOA	Togo
UMA	Algeria
UMA	Libya
UMA	Morocco
UMA	Tunisia
UMA	Western Sahara
USA	USA

List of commodities

The table below shows the individual products in CWASI for each sector considered in the MAGNET model. The binary value (0;1) in the production and trade columns indicates where the data is present in the CWASI database (e.g., only in production values, trade values, or both).

Table C.2: List of CWASI products considered in this study with their aggregation under the MAGNET- sectors.

Commodity name	FAO code	MAGNET sector	in Production	in Trade
Wheat	15	Wheat	1	1
Rice, paddy	27	Paddy rice	1	0
Barley	44	Cereal grains nec	1	1
Maize	56	Cereal grains nec	1	1
Rye	71	Cereal grains nec	1	1
Oats	75	Cereal grains nec	1	1
Millet	79	Cereal grains nec	1	1
Sorghum	83	Cereal grains nec	1	1
Buckwheat	89	Cereal grains nec	1	1
Quinoa	92	Cereal grains nec	1	0
Fonio	94	Cereal grains nec	1	1
Triticale	97	Cereal grains nec	1	1
Canary seed	101	Cereal grains nec	1	1
Mixed grain	103	Cereal grains nec	1	1
Cereals, nes	108	Cereal grains nec	1	0
Potatoes	116	Vegetables, fruit, nuts	1	1
Sweet potatoes	122	Vegetables, fruit, nuts	1	1
Cassava	125	Vegetables, fruit, nuts	1	1
Yautia (cocoyam)	135	Vegetables, fruit, nuts	1	0
Taro (cocoyam)	136	Vegetables, fruit, nuts	1	0
Yams	137	Vegetables, fruit, nuts	1	0
Roots and Tubers, nes	149	Vegetables, fruit, nuts	1	1
Sugar cane	156	Sugar cane, sugar beet	1	0
Sugar beet	157	Sugar cane, sugar beet	1	1
Beans, dry	176	Vegetables, fruit, nuts	1	1
Broad beans, horse beans, dry	181	Vegetables, fruit, nuts	1	1
Peas, dry	187	Vegetables, fruit, nuts	1	1
Chick peas	191	Vegetables, fruit, nuts	1	1
Cow peas, dry	195	Vegetables, fruit, nuts	1	0
Pigeon peas	197	Vegetables, fruit, nuts	1	0
Lentils	201	Vegetables, fruit, nuts	1	1
Bambara beans	203	Vegetables, fruit, nuts	1	1
Vetches	205	Vegetables, fruit, nuts	1	1
Lupins	210	Vegetables, fruit, nuts	1	0
Pulses, nes	211	Vegetables, fruit, nuts	1	0
Brazil nuts, with shell	216	Vegetables, fruit, nuts	1	0
Cashew nuts, with shell	217	Vegetables, fruit, nuts	1	1
Chestnuts	220	Vegetables, fruit, nuts	1	1
Almonds, with shell	221	Vegetables, fruit, nuts	1	0

Commodity name	**FAO code**	**MAGNET sector**	**in Production**	**in Trade**
Walnuts, with shell	222	Vegetables, fruit, nuts	1	1
Pistachios	223	Vegetables, fruit, nuts	1	1
Kolanuts	224	Vegetables, fruit, nuts	1	1
Hazelnuts, with shell	225	Vegetables, fruit, nuts	1	0
Arecanuts	226	Vegetables, fruit, nuts	1	0
Nuts, nes	234	Vegetables, fruit, nuts	1	0
Soybeans	236	Oil seeds	1	1
Groundnuts, with shell	242	Oil seeds	1	0
Coconuts	249	Crops nec	1	1
Oil, palm fruit	254	Oil seeds	1	0
Olives	260	Vegetables, fruit, nuts	1	1
Karite Nuts (Sheanuts)	263	Oil seeds	1	0
Castor oil seed	265	Oil seeds	1	0
Sunflower seed	267	Oil seeds	1	1
Rapeseed	270	Oil seeds	1	1
Tung nuts	275	Oil seeds	1	0
Jojoba seed	277	Oil seeds	1	0
Safflower seed	280	Oil seeds	1	0
Sesame seed	289	Oil seeds	1	1
Mustard seed	292	Oil seeds	1	1
Poppy seed	296	Oil seeds	1	1
Melonseed	299	Oil seeds	1	0
Tallowtree seed	305	Oil seeds	1	0
Kapok fruit	310	Oil seeds	1	0
Kapokseed in shell	311	Oil seeds	1	1
Seed cotton	328	Crops nec	1	0
Cottonseed	329	Oil seeds	1	1
Linseed	333	Oil seeds	1	1
Hempseed	336	Oil seeds	1	0
Oilseeds, Nes	339	Oil seeds	1	1
Cabbages and other brassicas	358	Vegetables, fruit, nuts	1	1
Artichokes	366	Vegetables, fruit, nuts	1	1
Asparagus	367	Vegetables, fruit, nuts	1	1
Lettuce and chicory	372	Vegetables, fruit, nuts	1	1
Spinach	373	Vegetables, fruit, nuts	1	1
Cassava leaves	378	Vegetables, fruit, nuts	1	0
Tomatoes	388	Vegetables, fruit, nuts	1	1
Cauliflowers and broccoli	393	Vegetables, fruit, nuts	1	1
Pumpkins, squash and gourds	394	Vegetables, fruit, nuts	1	1

Commodity name	FAO code	MAGNET sector	in Production	in Trade
Cucumbers and gherkins	397	Vegetables, fruit, nuts	1	1
Eggplant-baseds (aubergines)	399	Vegetables, fruit, nuts	1	1
Chillies and peppers, green	401	Vegetables, fruit, nuts	1	1
Onions (inc. shallots), green	402	Vegetables, fruit, nuts	1	1
Onions, dry	403	Vegetables, fruit, nuts	1	1
Garlic	406	Vegetables, fruit, nuts	1	1
Leeks, other alliaceous vegetables	407	Vegetables, fruit, nuts	1	1
Beans, green	414	Vegetables, fruit, nuts	1	1
Peas, green	417	Vegetables, fruit, nuts	1	1
Vegetables, leguminous nes	420	Vegetables, fruit, nuts	1	0
String beans	423	Vegetables, fruit, nuts	1	0
Carrots and turnips	426	Vegetables, fruit, nuts	1	1
Okra	430	Vegetables, fruit, nuts	1	0
Maize, green	446	Vegetables, fruit, nuts	1	1
Mushrooms and truffles	449	Vegetables, fruit, nuts	1	1
Chicory roots	459	Vegetables, fruit, nuts	1	0
Carobs	461	Vegetables, fruit, nuts	1	0
Vegetables fresh nes	463	Vegetables, fruit, nuts	1	1
Bananas	486	Vegetables, fruit, nuts	1	1
Plantains	489	Vegetables, fruit, nuts	1	1
Oranges	490	Vegetables, fruit, nuts	1	1
Tangerines, mandarins, clem.	495	Vegetables, fruit, nuts	1	1
Lemons and limes	497	Vegetables, fruit, nuts	1	1
Grapefruit (inc. pomelos)	507	Vegetables, fruit, nuts	1	1
Citrus fruit, nes	512	Vegetables, fruit, nuts	1	0
Apples	515	Vegetables, fruit, nuts	1	1
Pears	521	Vegetables, fruit, nuts	1	1
Quinces	523	Vegetables, fruit, nuts	1	1
Apricots	526	Vegetables, fruit, nuts	1	1
Sour cherries	530	Vegetables, fruit, nuts	1	1
Cherries	531	Vegetables, fruit, nuts	1	1
Peaches and nectarines	534	Vegetables, fruit, nuts	1	1
Plums and sloes	536	Vegetables, fruit, nuts	1	1
Stone fruit, nes	541	Vegetables, fruit, nuts	1	0
Fruit, pome nes	542	Vegetables, fruit, nuts	1	0
Strawberries	544	Vegetables, fruit, nuts	1	1
Raspberries	547	Vegetables, fruit, nuts	1	0
Gooseberries	549	Vegetables, fruit, nuts	1	1
Currants	550	Vegetables, fruit, nuts	1	1

Commodity name	FAO code	MAGNET sector	in Production	in Trade
Blueberries	552	Vegetables, fruit, nuts	1	1
Cranberries	554	Vegetables, fruit, nuts	1	1
Berries Nes	558	Vegetables, fruit, nuts	1	0
Grapes	560	Vegetables, fruit, nuts	1	1
Watermelons	567	Vegetables, fruit, nuts	1	1
Other melons (inc.cantaloupes)	568	Vegetables, fruit, nuts	1	1
Figs	569	Vegetables, fruit, nuts	1	1
Mangoes, mangosteens, guavas	571	Vegetables, fruit, nuts	1	1
Avocados	572	Vegetables, fruit, nuts	1	1
Pineapples	574	Vegetables, fruit, nuts	1	1
Dates	577	Vegetables, fruit, nuts	1	1
Persimmons	587	Vegetables, fruit, nuts	1	1
Cashew apple	591	Vegetables, fruit, nuts	1	1
Kiwi fruit	592	Vegetables, fruit, nuts	1	1
Papayas	600	Vegetables, fruit, nuts	1	1
Fruit, tropical fresh nes	603	Vegetables, fruit, nuts	1	1
Fruit Fresh Nes	619	Vegetables, fruit, nuts	1	1
Coffee, green	656	Crops nec	1	1
Cocoa beans	661	Crops nec	1	1
Tea	667	Crops nec	1	1
Maté	671	Crops nec	1	1
Hops	677	Vegetables, fruit, nuts	1	1
Pepper (Piper spp.)	687	Crops nec	1	1
Chillies and peppers, dry	689	Crops nec	1	1
Vanilla	692	Crops nec	1	1
Cinnamon (canella)	693	Crops nec	1	1
Cloves	698	Crops nec	1	1
Nutmeg, mace and cardamoms	702	Crops nec	1	1
Anise, badian, fennel, corian.	711	Crops nec	1	1
Ginger	720	Crops nec	1	1
Spices, nes	723	Crops nec	1	1
Peppermint	748	Crops nec	1	1
Cotton lint	767	Plant-based fibers	1	1
Flax fibre and tow	773	Plant-based fibers	1	1
Hemp Tow Waste	777	Plant-based fibers	1	0
Kapok fibre	778	Plant-based fibers	1	1
Jute	780	Plant-based fibers	1	1
Other Bastfibres	782	Plant-based fibers	1	0
Ramie	788	Plant-based fibers	1	0
Sisal	789	Plant-based fibers	1	0
Agave Fibres Nes	800	Plant-based fibers	1	0
Manila Fibre (Abaca)	809	Plant-based fibers	1	1
Coir	813	Plant-based fibers	1	0
Fibre Crops Nes	821	Plant-based fibers	1	0
Tobacco, unmanufactured	826	Crops nec	1	1
Natural rubber	836	Crops nec	1	1
Gums, natural	839	Crops nec	1	0

MAGNET Food security trends 2020-2030

Table C.3 shows that over the coming decade 2020-2030, even without the implementation of the AfCFTA food security is expected to increase for all regions in the African continent. Income per capita increases and average food prices decrease. This results in a wealthier average population which spends a smaller share of income on food despite a significant increase in food consumption. MAGNET result Food Security Trends percentage change 2020-2030 (no AfCFTA).
Disposable income per capita = (VDPA + VIPA) / pop.
Where VDPA stands for *domestic purchases, by households, at agents' prices* and VIPA for *import purchases, by households, at agents' prices.*
All indicators increase significantly for all regions, particularly income.

Table C.3: MAGNET result Food Security Trends percentage change 2020-2030 (no AfCFTA), African regions

	Disposable income per capita	Average Food Prices	Share of food expenditure in total disposable income	Food consumption per capita
UMA	22.74	-9.56	-13.44	17.86
UEMOA	93.98	-0.71	-24.85	42.29
ECOWAS	30.72	-5.24	-8.94	24.40
ECCAS	12.41	-9.37	-7.10	14.80
COMESA	40.20	-4.87	-12.20	26.90
EAC	39.98	-5.85	-12.95	28.24
SADC	24.41	-6.27	-16.49	10.29

ECOWAS production's conversion factor forecast

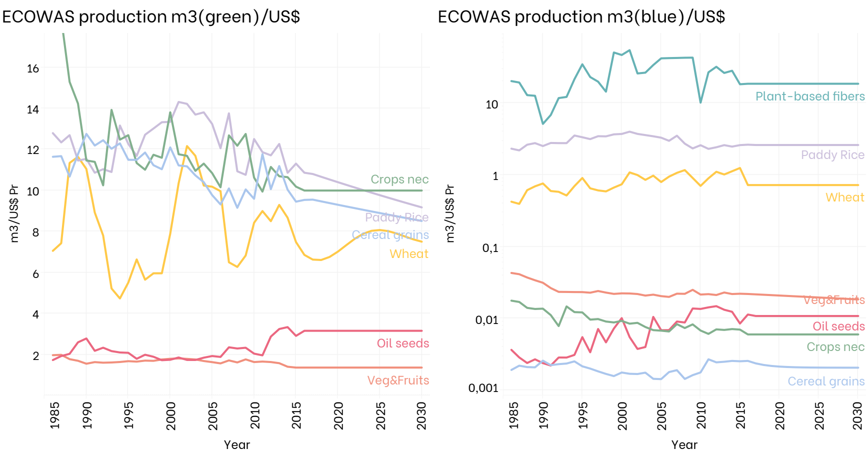


Figure C.1: An illustrative example of a time series forecast using ARIMA for ECOWAS production's conversion factor (m^3/US). The different colors highlight the agricultural sectors.

African production scenario for 2020 and 2030

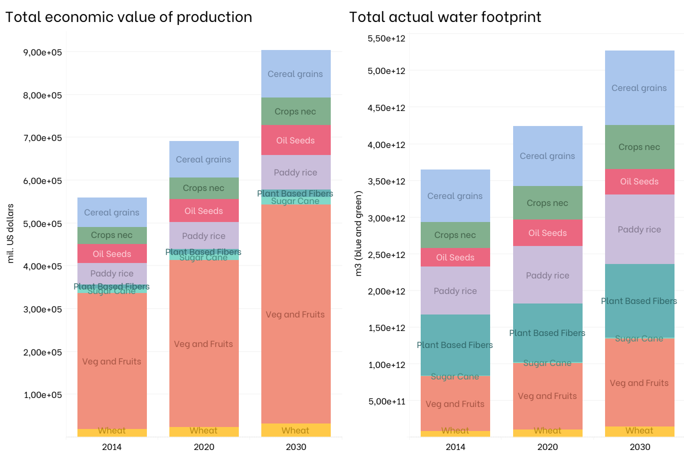


Figure C.2: Simulation of African production for the years 2020 and 2030, based on dollars produced in 2014. Colours distinguish each sector. The left panel shows the simulations in dollars, the right panel in total water footprint (blue water and green water).

Export change in the two scenarios in terms of green and blue water

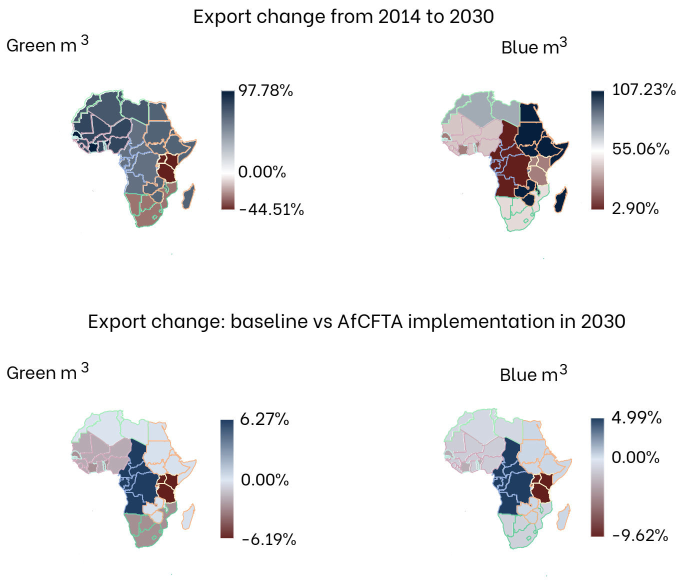


Figure C.3: Two top graphs show the percentage change in virtual water exports in terms of green water (on the left) and blue water (on the right) from 2014 to 2030. Similarly, the two graphs below show the percentage change in exports under the policy scenario. The colours of the country borders distinguish each of the 7 African economic regions.

Nomenclature

c	country
p	agricultural product
t	year
u	unit of measure
Q_{cp}	Quantity of tons
A_{cp}	Harvested hectares
F_{cp}	Water Footprint (m^3/ton)
L_{cp}	Land footprint (ton/ha)
V_{cp}	Economic Value of Production (current US$)
plr_{ct}	Price level ratio (US$/Int$)
PPP	Purchasing Power Parity
$defl^{(USA)}$	USA deflator calculated by taking 2010 as reference year
$P_{cp}{}^{(}d)$	Price deflated with reference year 2010 (Int $)
ET_{cp}	Evapotranspitation
Pop_c	Population
WR_c	Total renewable resources
D_c	Water deficiency indicator
EWP	Economic Water Productivity ($Int\$/m^3$)
$RTAs$	Regional Trade Agreements
$PTAs$	Preferential Trade Agreements
WTO	World Trade Organization
i	Exporter country
j	Importer country
F_{ij}	Matrix flow of cereal (from i to j)
S_{ij}	Matrix flow of cereal (sum of quantity from i to j and quantity from j to i)
V_{ij}	Matrix flow of cereal in US$ or Kcal
ρ_{ij}	Interannual flow variation
Δ_{ij}	Percentage change in flow for each link (ij)

KDE	Kernel Density Estimation
Δ_w	Worldwide percentage change
WP	Water productivity
ρ_a	Interannual flow variation (trade agreement level)
Δ_a	Percentage change in flow for each trade agreement
$AfCFTA$	African Continental Free Trade Area
$RECs$	Regional Economic Communities
CGE	Computal General Equilibrium
$CWASI$	Coping with water scarcity in a globalized world
SSP	Shared Socioeconomic Pathways
$MAGNET$	Modular Applied GeNeral Equilibrium Tool
$GTAP$	Global Trade Analysis Project
s	MAGNET crop sector
r	Producing region
i	Importing region
CW^{Pr}	CWASI Water Footprint (m^3)
CW^{Exp}	CWASI Virtual Water (m^3)
MD^{Pr}	MAGNET Production economic value (US$)
MD^{Exp}	MAGNET Export economic value (US$)
fW	Water conversion factor ($m^3/US\$$)
W^{Pr}	Production MAGNET dollars conversion in water (m^3)
W^{Exp}	Expor MAGNET dollars conversion in water (m^3)

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References

1. Lucas, P. & Wilting, H. *Using Planetary Boundaries to Support National Implementation of Environment-related: Sustainable Development Goals: Background Report* (PBL Netherlands Environmental Assessment Agency, 2018).
2. Wiedmann, T. & Lenzen, M. Environmental and social footprints of international trade. *Nature Geoscience* **11,** 314–321 (2018).
3. Sarkodie, S. A. Environmental performance, biocapacity, carbon & ecological footprint of nations: drivers, trends and mitigation options. *Science of the Total Environment* **751,** 141912 (2021).
4. FAO *et al.* The future of food and agriculture–Trends and challenges. *Annual Report* (2017).
5. Hajer, M., Westhoek, H., Ingram, J., Van Berkum, S. & Özay, L. *Food systems and natural resources* (United Nations Environmental Programme, 2016).
6. Vasileska, A. & Rechkoska, G. Global and regional food consumption patterns and trends. *Procedia-Social and Behavioral Sciences* **44,** 363–369 (2012).
7. Pingali, P., Aiyar, A., Abraham, M. & Rahman, A. in *Transforming Food Systems for a Rising India* 241–275 (Springer, 2019).
8. De Petrillo, E., Falsetti, B., Sciarra, C. & Tuninetti, M. *Water to Food. A Data-viz Book about the Water Footprint of Food Production and Trade.* (ISBN: 9791220096362, 2021).
9. Seekell, D., D'Odorico, P. & MacDonald, G. K. Food, trade, and the environment. *Environmental Research Letters* **13** (2018).
10. Wetser, K., de Miguel Garcia, A., Smit, A., Wilbers, G. & Wolters, W. *What is the role of water in the global food challenge?* tech. rep. (Wageningen Environmental Research, 2020).
11. Tamea, S., Tuninetti, M., Soligno, I. & Laio, F. Virtual water trade and water footprint of agricultural goods: the 1961–2016 CWASI database. *Earth System Science Data* **13,** 2025–2051 (2021).

12. D'Odorico, P., Laio, F. & Ridolfi, L. Does globalization of water reduce societal resilience to drought? *Geophysical Research Letters* **37** (2010).
13. Fracasso, A., Sartori, M. & Schiavo, S. Determinants of virtual water flows in the Mediterranean. *Science of The Total Environment* **543,** 1054–1062 (2016).
14. Tamea, S., Carr, J., Laio, F. & Ridolfi, L. Drivers of the virtual water trade. *Water Resources Research* **50,** 17–28 (2014).
15. Young, R. & Loomis, J. *Determining the Economic Value of Water: Concepts and Methods* (Washington, D.C., RFF Press, 2014).
16. Rey, D., Pérez-Blanco, C. D., Escriva-Bou, A., Girard, C. & Veldkamp, T. I. Role of economic instruments in water allocation reform: lessons from Europe. *International journal of water resources development* **35,** 206–239 (2019).
17. Subramanian, A. *Water pricing experiences: An international perspective* (World Bank, 1997).
18. Rogers, P., De Silva, R. & Bhatia, R. Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. *Water policy* **4,** 1–17 (2002).
19. Gómez Gómez, C. M., Pérez-Blanco, C. D., Adamson, D. & Loch, A. Managing water scarcity at a river basin scale with economic instruments. *Water Economics and Policy* **4,** 1750004 (2018).
20. Brentwood, M. & Robar, S. F. *Managing common pool groundwater resources: an international perspective* (Greenwood Publishing Group, 2004).
21. Savenije, H. H. Why water is not an ordinary economic good, or why the girl is special. *Physics and Chemistry of the Earth, Parts A/B/C* **27,** 741–744 (2002).
22. Perry, C. J., Seckler, D., Rock, M. T. & Seckler, D. W. *Water as an economic good: A solution, or a problem?* (International Water Management Institute, 1997).
23. Hung, A. H. P. Virtual water trade a quantification of virtual water flows between nations in relation to international crop trade (2002).
24. Editorial, N. F. *The true cost of food, Nature Food* `https://doi.org/10.1038/s43016-020-0070-5`..

25. Gower, D. B., Dell'Angelo, J., McCord, P. F., Caylor, K. K. & Evans, T. P. Modeling ecohydrological dynamics of smallholder strategies for food production in dryland agricultural systems. *Environmental Research Letters* **11,** 115005 (2016).
26. Graham, N. T. *et al.* Future changes in the trading of virtual water. *Nature communications* **11,** 1–7 (2020).
27. Carr, J. A., D'Odorico, P., Laio, F. & Ridolfi, L. Recent history and geography of virtual water trade. *PloS one* **8,** e55825 (2013).
28. Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A. & Rodriguez-Iturbe, I. Evolution of the global virtual water trade network. *Proceedings of the National Academy of Sciences* **109,** 5989–5994 (2012).
29. Tuninetti, M., Tamea, S., Laio, F. & Ridolfi, L. To trade or not to trade: link prediction in the virtual water network. *Advances in Water Resources* **110,** 528–537 (2017).
30. Liu, J. *et al.* Framing sustainability in a telecoupled world. *Ecology and Society* **18** (2013).
31. Oberlack, C. *et al.* Polycentric governance in telecoupled resource systems. *Ecology and Society* **23** (2018).
32. Kagohashi, K., Tsurumi, T. & Managi, S. The effects of international trade on water use. *PloS one* **10,** e0132133 (2015).
33. Marson, M. & Savin, I. Ensuring sustainable access to drinking water in Sub Saharan Africa: Conflict between financial and social objectives. *World Development* **76,** 26–39 (2015).
34. Fulton, J., Norton, M. & Shilling, F. Water-indexed benefits and impacts of California almonds. *Ecological Indicators* **96,** 711–717 (2019).
35. Falsetti, B., Vallino, E., Ridolfi, L. & Laio, F. Is water consumption embedded in crop prices? A global data-driven analysis. *Environmental Research Letters* **15,** 104016 (2020).
36. Crase, L., Cooper, B. & Burton, M. From Sharing the Burden of Scarcity to Markets: Ill-Fitting Water Property Rights and the Pressure of Economic Transition in South Asia. *Water* **11,** 1294 (2019).
37. Soto Rios, P. C., Deen, T. A., Nagabhatla, N. & Ayala, G. Explaining Water Pricing through a Water Security Lens. *Water* **10,** 1173 (2018).
38. Pereira, L. S., Cordery, I. & Iacovides, I. *Coping with water scarcity: Addressing the challenges* (Springer Science & Business Media, 2009).

39. FAO. Water for Sustainable Food and Agriculture. *A report produced for the G20 Presidency of Germany* (2017).

40. Rost, S. *et al.* Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research* **44** (2008).

41. Mancosu, N., Snyder, R. L., Kyriakakis, G. & Spano, D. Water scarcity and future challenges for food production. *Water* **7,** 975–992 (2015).

42. Dowgert, M. F. & Fresno, C. *The impact of irrigated agriculture on a stable food supply* in *Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney, NE* (2010), 24–25.

43. Hejazi, M. I. *et al.* Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. *Hydrology and Earth System Sciences* **18,** 2859–2883 (2014).

44. United Nations. World Population Prospects 2019: Highlights (2019).

45. Klein, R. J. *et al.* Climate Change 2014: Impacts, Adaptation and Vulnerability. *Intergovernmental Panel on Climate Change. Part A: Global and Sectoral Aspects; Field, CB, Barros, VR, Dokken, DJ, Mach, KJ, Mastrandrea, MD, Bilir, TE, Chatterjee, M., Ebi, KL, Estrada, YO, Genova, RC, et al., Eds* (2014).

46. Molden, D. *et al.* Trends in water and agricultural development. *London, Earthscan* (2007).

47. Liu, J. *et al.* Achieving sustainable irrigation water withdrawals: global impacts on food security and land use. *Environmental Research Letters* **12,** 104009 (2017).

48. Vörösmarty, C. J. *et al.* Global threats to human water security and river biodiversity. *Nature* **467,** 555 (2010).

49. Soligno, I., Ridolfi, L. & Laio, F. The environmental cost of a reference withdrawal from surface waters: Definition and geography. *Advances in Water Resources* **110,** 228–237 (2017).

50. Boretti, A. & Rosa, L. Reassessing the projections of the World Water Development Report. *Clean Water* **2,** 1–6 (2019).

51. Dubois, O. *et al.* *The state of the world's land and water resources for food and agriculture: managing systems at risk.* (London, Earthscan, 2011).

52. Imbulana, K., Droogers, P. & Makin, I. W. *World water assessment programme Sri Lanka case study: Ruhuna Basins* (International Water Management Institute, 2002).

53. Miller, R. W. Book review of Griffin RC "Water resource economics. The analysis of scarcity, policies, and projects" MIT Press. *Electronic Green Journal,* 2 (2007).

54. Ostrom, V. The political economy of water development. *The American Economic Review* **52,** 450–458 (1962).

55. Ward, F. A. & Michelsen, A. The economic value of water in agriculture: concepts and policy applications. *Water policy* **4,** 423–446 (2002).

56. Ziolkowska, J. R. Shadow price of water for irrigation: a case of the High Plains. *Agricultural Water Management* **153,** 20–31 (2015).

57. Stiglitz, J. E. & Rosengard, J. K. *Economics of the public sector: Fourth international student edition* (WW Norton & Company, 2015).

58. McNeill, D. *Water as an economic good* in *Natural Resources Forum* **22** (1998), 253–261.

59. Bjornlund, H. & O'Callaghan, B. A comparison of implicit values and explicit prices of water. *Pacific Rim Property Research Journal* **11,** 316–331 (2005).

60. Buck, S., Auffhammer, M. & Sunding, D. Land Markets and the Value of Water: Hedonic analysis using repeat sales of farmland. *American Journal of Agricultural Economics* **96,** 953–969 (2014).

61. Hoekstra, A. Virtual water: An introduction. *Virtual water trade* **13,** 108 (2003).

62. Msangi, S. & MacEwan, D. in, 77–79 (Springer, 2019).

63. Hoekstra, A. Y. Water footprint assessment: evolvement of a new research field. *Water Resources Management* **31,** 3061–3081 (2017).

64. The true cost of food. *Nat Food 1, 185 (2020).* **1** (2020).

65. Falkenmark, M., Lundqvist, J. & Widstrand, C. *Macro-scale water scarcity requires micro-scale approaches: Aspects of vulnerability in semi-arid development* in *Natural resources forum* **13** (1989), 258–267.

66. FAOSTAT. *FAO Statistical Database (FAOSTAT). ICTUpdate.* 2019.

67. Hogeboom, R. & Hoekstra, A. Water and land footprints and economic productivity as factors in local crop choice: the case of silk in Malawi. *Water* **9,** 802 (2017).

68. WorldBank. *World Bank Open Data* `https://data.worldbank.org/indicator/pa.nus.pppc.rf`. 2019.

69. Mekonnen, M. M. & Hoekstra, A. Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences* **15,** 1577–1600 (2011).

70. Tuninetti, M., Tamea, S., Laio, F. & Ridolfi, L. A Fast Track approach to deal with the temporal dimension of crop water footprint. *Environmental Research Letters* **12** (2017).

71. Tamea, S., Soligno, I., Marta, T. & Laio, F. Virtual water trade and consumptive water footprint of agricultural products: the 1961-2016 CWASI database. *Water Resources Research, under review.* (2019).

72. Hoekstra, A. Y., Chapagain, A. K., Mekonnen, M. M. & Aldaya, M. M. *The water footprint assessment manual: Setting the global standard* (Routledge, 2011).

73. AQUASTAT. *FAO's Global Information System on Water and Agriculture* 2019.

74. D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L. & Vandoni, S. Feeding humanity through global food trade. *Earth's Future* **2,** 458–469 (2014).

75. Molden, D. *et al. Pathways for increasing agricultural water productivity* tech. rep. (International Water Management Institute, 2007).

76. Krugman, P., Wells, R. & Graddy, K. The essentials of economics, Chapter 3. *New York: WorthPublishers* (2011).

77. Dell'Angelo, J., Rulli, M. C. & D'Odorico, P. The global water grabbing syndrome. *Ecological Economics* **143,** 276–285 (2018).

78. Hodgson, S. *Land and Water-the Rights Interface* **84** (Food & Agriculture Organization, 2004).

79. Babu, S., Gajanan, S. & Sanyal, P. Chapter 3 Effects of commercialization of agriculture (shift from traditional crop to cash crop) on food consumption and nutrition-application of chi-square statistic. *Food Security, Poverty and Nutrition Policy Analysis,* 63–91 (2014).

80. Chapagain, A. & Hoekstra, A. The green, blue and grey water footprint of rice from both a production and consumption perspective. Value of water research Report Series No. 40. *Delft, Netherlands: UNESCO-IHE Institute for Water Education* (2010).

81. Porto, G., Chauvin, N. D., Olarreaga, M., *et al. Supply chains in export agriculture, competition, and poverty in Sub-Saharan Africa.* (International Bank for Reconstruction and Development, World Bank, 2011).

82. Piyapromdee, S., Hillberry, R. & MacLaren, D. 'Fair trade'coffee and the mitigation of local oligopsony power. *European Review of Agricultural Economics* **41,** 537–559 (2013).

83. Fafchamps, M. Cash crop production, food price volatility, and rural market integration in the third world. *American journal of agricultural economics* **74,** 90–99 (1992).

84. Bulte, E., Richards, P., Voors, M., *et al.* Institutions and Agrarian Development. *Palgrave Studies in Agricultural Economics and Food Policy* (2018).

85. Henkel, M. *21st Century Homestead: Sustainable Agriculture I* (Lulu. com, 2015).

86. Distefano, T., Chiarotti, G., Laio, F. & Ridolfi, L. Spatial Distribution of the International Food Prices: Unexpected Heterogeneity and Randomness. *Ecological economics* **159,** 122–132 (2019).

87. Gilbert, C. L. & Morgan, C. W. Food price volatility. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365,** 3023–3034 (2010).

88. Falsetti, B., Ridolfi, L. & Laio, F. Role of trade agreements in the global cereal market and implications for virtual water flows. *In Preparation* (2021).

89. Dalin, C. & Rodrıguez-Iturbe, I. Environmental impacts of food trade via resource use and greenhouse gas emissions. *Environmental Research Letters* **11,** 035012 (2016).

90. Ritchie, H. & Roser, M. Environmental impacts of food production. *Our World in Data.* https://ourworldindata.org/environmental-impacts-of-food (2020).

91. El Bilali, H., Callenius, C., Strassner, C. & Probst, L. Food and nutrition security and sustainability transitions in food systems. *Food and energy security* **8,** e00154 (2019).

92. Crippa, M. *et al.* Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food* **2,** 198–209 (2021).

93. Dubey, P. K. *et al.* Planet friendly agriculture: Farming for people and the planet. *Current Research in Environmental Sustainability* **3,** 100041 (2021).

94. Carroll, E. *et al.* The state of agricultural commodity markets 2018: agricultural trade, climate change and food security. *The state of agricultural commodity markets 2018: agricultural trade, climate change and food security.* (2018).

95. Traverso, S. & Schiavo, S. Fair trade or trade fair? International food trade and cross-border macronutrient flows. *World Development* **132,** 104976 (2020).

96. Porkka, M., Guillaume, J. H., Siebert, S., Schaphoff, S. & Kummu, M. The use of food imports to overcome local limits to growth. *Earth's Future* **5,** 393–407 (2017).

97. Allan, J. A. Virtual water-the water, food, and trade nexus. Useful concept or misleading metaphor? *Water international* **28,** 106–113 (2003).

98. D'Odorico, P. *et al.* Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts. *Environmental Research Letters* **14,** 053001 (2019).

99. Clapp, J. *The State of Agricultural Commodity Markets 2015–16. Rome, Italy* tech. rep. (I5222E/1/12.15, 2015).

100. Martin, W. *Agricultural trade and food security* tech. rep. (ADBI Working Paper, 2017).

101. Hofmann, C., Osnago, A. & Ruta, M. *Horizontal depth: a new database on the content of preferential trade agreements* (The World Bank, 2017).

102. Jean, S. & Bureau, J.-C. Do regional trade agreements really boost trade? Evidence from agricultural products. *Review of World Economics* **152,** 477–499 (2016).

103. Lambert, D. & McKoy, S. Trade creation and diversion effects of preferential trade associations on agricultural and food trade. *Journal of Agricultural Economics* **60,** 17–39 (2009).

104. Mujahid, I. & Kalkuhl, M. Do Trade Agreements Increase Food Trade? *The World Economy* **39,** 1812–1833 (2016).

105. Studnicka, Z., Thierie, W. & Van Hove, J. The impact of regional trade agreements on European exports. *International Economics and Economic Policy* **16,** 467–488 (2019).

106. Grant, J. H. & Lambert, D. M. Do regional trade agreements increase members' agricultural trade? *American journal of agricultural economics* **90,** 765–782 (2008).

107. Huchet-Bourdon, M., Le Mouel, C., Peketi, M., *et al. The impact of regional trade agreements on agrifood trade flows: The role of rules of origin* tech. rep. (2016).

108. Oki, T. *et al. Virtual water trade to Japan and in the world* in *Hoekstra, AY 'Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade', Value of Water Research Report Series* **12** (2003).

109. De Fraiture, C., Cai, X., Amarasinghe, U., Rosegrant, M. & Molden, D. *Does international cereal trade save water?: the impact of virtual water trade on global water use* (Iwmi, 2004).

110. Reimer, J. J. On the economics of virtual water trade. *Ecological Economics* **75,** 135–139 (2012).

111. Hofmann, C., Osnago, A. & Ruta, M. *A New Database on the Content of Preferential Trade Agreements* `https://datacatalog.worldbank.org/dataset/content-deep-trade-agreements`. 2017.

112. Dupas, M.-C., Halloy, J. & Chatzimpiros, P. Time dynamics and invariant subnetwork structures in the world cereals trade network. *PloS one* **14,** e0216318 (2019).

113. Awika, J. M. in *Advances in cereal science: implications to food processing and health promotion* 1–13 (ACS Publications, 2011).

114. FAOSTAT. *Detailed trade matrix* `https://www.fao.org/faostat/en/#data/TM`.

115. FAO. *Nutritive Factors* `https://www.fao.org/economic/the-statistics-division-ess/publications-studies/publications/nutritive-factors/en/`.

116. Kijne, J. W., Barker, R. & Molden, D. J. *Water productivity in agriculture: limits and opportunities for improvement* (Cabi, 2003).

117. Peterson, E. W. F. Trade Agreements: Impacts of the Uruguay Round and Prospects for the Future. *Choices* **30,** 1–7 (2015).

118. Dithmer, J. & Abdulai, A. Does trade openness contribute to food security? A dynamic panel analysis. *Food Policy* **69,** 218–230 (2017).

119. Fair, K. R., Bauch, C. T. & Anand, M. Dynamics of the global wheat trade network and resilience to shocks. *Scientific reports* **7,** 1–14 (2017).

120. Matthews, A. Trade rules, food security and the multilateral trade negotiations. *European Review of Agricultural Economics* **41,** 511–535 (2014).

121. Rutten, M., Shutes, L. & Meijerink, G. Sit down at the ball game: How trade barriers make the world less food secure. *Food Policy* **38,** 1–10 (2013).

122. Irwin, D. A. Does trade reform promote economic growth? A review of recent evidence (2019).

123. Rodrik, D. What do trade agreements really do? *Journal of economic perspectives* **32,** 73–90 (2018).

124. Potier, M. & Less, C. T. Trade and Environment at the OECD. `https://www.oecd-ilibrary.org/content/paper/235751371440` (2008).

125. Wichelns, D. Virtual Water and Water Footprints: Overreaching Into the Discourse on Sustainability, Efficiency, and Equity. *Water Alternatives* **8** (2015).

126. Martin, W. A research agenda for international agricultural trade. *Applied Economic Perspectives and Policy* **40,** 155–173 (2018).

127. Grossman, G. M. & Krueger, A. B. *Environmental impacts of a North American free trade agreement* 1991.

128. Le Vernoy, A. *The trade and water nexus* tech. rep. (ADBI Working Paper, 2017).

129. Dang, Q. & Konar, M. Trade openness and domestic water use. *Water Resources Research* **54,** 4–18 (2018).

130. Abman, R. & Lundberg, C. Does free trade increase deforestation? the effects of regional trade agreements. *Journal of the Association of Environmental and Resource Economists* **7,** 35–72 (2020).

131. Balogh, J. M. & Jámbor, A. The environmental impacts of agricultural trade: A systematic literature review. *Sustainability* **12,** 1152 (2020).

132. Falsetti, Benedetta and Levin-Koopman, Jason and Carrico Caitlyn and Ridolfi, Luca and Laio, Francesco. African virtual water projections and possible impacts of African Continental Free Trade Agreement (AfCFTA). *Work in progress* (2022).

133. Vilakazi, N., Nyirenda, K. & Vellemu, E. in *Food Security in Africa* (IntechOpen, 2019).

134. Barrett, C. B. Overcoming global food security challenges through science and solidarity. *American Journal of Agricultural Economics* **103,** 422–447 (2021).

135. Tuyishimire, A. *et al.* Drivers of the increasing water footprint in Africa: The food consumption perspective. *Science of The Total Environment* **809,** 152196 (2022).

136. Leal Filho, W. *et al.* Understanding responses to climate-related water scarcity in Africa. *Science of the Total Environment* **806,** 150420 (2022).

137. Nguimalet, C.-R., Mahe, G., Laraque, A., Orange, D. & Yakoubou, B. M. Note sur le changement climatique et la gestion des ressources en eau en Afrique: Repenser l'usage et l'amélioration des services éco-systémiques d'eau. *Geo-Eco-Trop* **40,** 317–326 (2016).

138. Molden, D., De Fraiture, C. & Rijsberman, F. Water scarcity: the food factor. *Issues in Science and Technology* **23,** 39–48 (2007).

139. Lal, R. *et al.* Climate change and multi-dimensional sustainability in African agriculture. *Columbus: Springer* (2016).

140. LA BANQUE AFRICAINE, D. D. P. & BANKGROUP, A. The Africa water vision for 2025: Equitable and sustainable use of water for socioeconomic development.

141. Distefano, T., Laio, F., Ridolfi, L. & Schiavo, S. Shock transmission in the international food trade network. *PloS one* **13,** e0200639 (2018).

142. Fusacchia, I., Balié, J. & Salvatici, L. The AfCFTA impact on agricultural and food trade: a value added perspective. *European Review of Agricultural Economics* (2021).

143. Woltjer, Gerard Bastiaan and Kuiper, Marijke and Kavallari, Aikaterini and van Meijl, Hans and Powell, JP and Rutten, MM and Shutes, LJ and Tabeau, AA. *The MAGNET model: Module description* tech. rep. (LEI Wageningen UR, 2014).

144. O'Neill, B. C. *et al.* The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global environmental change* **42,** 169–180 (2017).

145. Berck, P., Robinson, S. & Goldman, G. in *The economics and management of water and drainage in agriculture* 489–509 (Springer, 1991).

146. Ponce, R., Bosello, F. & Giupponi, C. Integrating water resources into computable general equilibrium models-a survey (2012).

147. Calzadilla, A., Rehdanz, K., Tol, R. S., *et al. The GTAP-W model: accounting for water use in agriculture* tech. rep. (Kiel Working Paper, 2011).

148. Roson, R. & Sartori, M. in *The Water We Eat* 159–174 (Springer, 2015).

149. Mellios, N., Koopman, J. F. & Laspidou, C. Virtual crop water export analysis: the case of Greece at River Basin district level. *Geosciences* **8,** 161 (2018).

150. Tuninetti, M., Tamea, S., D'Odorico, P., Laio, F. & Ridolfi, L. Global sensitivity of high-resolution estimates of crop water footprint. *Water Resources Research* **51,** 8257–8272 (2015).

151. Soligno, I. Spatial and temporal patterns of global freshwater use for food production and trade. *Diss. Politecnico di Torino* (2019).

152. Hertel, T. W. *Global trade analysis: modeling and applications* (Cambridge university press, 1997).

153. Frank, Stefan and Havlık, Petr and Tabeau, Andrzej and Witzke, Peter and Boere, Esther and Bogonos, Mariia and Deppermann, Andre and van Dijk, Michiel and Höglund-Isaksson, Lena and Janssens, Charlotte and others. How much multilateralism do we need? Effectiveness of unilateral agricultural mitigation efforts in the global context. *Environmental Research Letters* **16,** 104038 (2021).

154. Stehfest, E., van Vuuren, D., Bouwman, L. & Kram, T. *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications* (Netherlands Environmental Assessment Agency (PBL), 2014).

155. Aguiar, A., Chepeliev, M., Corong, E., McDougall, R. & Mensbrugghe, D. van der. The GTAP Data Base: Version 10. *Journal of Global Economic Analysis* **4,** 1–27 (2019).

156. Wilkus, E., Roxburgh, C. & Rodriguez, D. Understanding household diversity in rural eastern and southern Africa (2019).
157. Lancelotti, C. & Biagetti, S. Mapping Food Production in Hyper-Arid and Arid Saharan Africa in the Holocene—A View from the Present. *Quaternary* **4,** 13 (2021).
158. Raimondi, V. & Scoppola, M. The impact of foreign land acquisitions on Africa virtual water exports. *Ecological Economics* **193,** 107316 (2022).
159. Moyo, J. M., Bah, E. & Verdier-Chouchane, A. Transforming Africa's agriculture to improve competitiveness. *The Africa competitiveness report 2015* **37** (2015).
160. Zhai, R., Tao, F., Lall, U. & Elliott, J. Africa would need to import more maize in the future even under 1.5 C warming scenario. *Earth's Future* **9,** e2020EF001574 (2021).
161. Philippidis, G., Pérez, H. F., de Renterıa, P. G., M'barek, R. & López, A. I. S. Eating your greens: a global sustainability assessment. *Resources, Conservation and Recycling* **168,** 105460 (2021).
162. Food & of The United Nations, A. O. *Why has Africa become a net food importer? Explaining Africa agricultural and food trade deficits* 2011.
163. Wessel, M. & Quist-Wessel, P. F. Cocoa production in West Africa, a review and analysis of recent developments. *NJAS-Wageningen Journal of Life Sciences* **74,** 1–7 (2015).
164. Simola, A., Boysen, O., Ferrari, E., Nechifor, V., Boulanger, P., *et al. Potential effects of the African Continental Free Trade Area (AfCFTA) on African agri-food sectors and food security* tech. rep. (Joint Research Centre (Seville site), 2021).
165. Fischer, G. & Tramberend, S. South African agriculture towards 2030/50 (2019).
166. Apiko, P., Woolfrey, S. & Byiers, B. *The promise of the African Continental Free Trade Area (AfCFTA)* tech. rep. (ECDPM Discussion paper, 2020).
167. Fofack, H. Making the AfCFTA work for 'The Africa We Want'. *Brooking Africa Growth Initiative Working Paper* (2020).

168. FAO & AUC. *The Framework for Boosting Intra-African Trade in Agricultural Commodities and Services* tech. rep. (https://doi.org/10.4060/cb3172en, 2021).

169. Jung, J. W. The impact of trade liberalization in Africa. *KIEP Research Paper. Working paper,* 17–05 (2017).

170. FAO Regional Conference for Africa. *Intra-Africa Trade in Food and Agriculture: Issues, Challenges and Prospects in the Context of the African Continental Free Trade Area (AfCFTA)* tech. rep. (https://www.fao.org/3/nc707en/nc707en.pdf, 2020).

171. Ezeh, A., Kissling, F. & Singer, P. Why sub-Saharan Africa might exceed its projected population size by 2100. *The Lancet* **396,** 1131–1133 (2020).

172. FAO. *Climate change in Africa: the threat to agriculture* 2009.

173. Mechiche-Alami, A. & Abdi, A. M. Agricultural productivity in relation to climate and cropland management in West Africa. *Scientific reports* **10,** 1–10 (2020).

174. Gebremedhin, S. & Bekele, T. Evaluating the African food supply against the nutrient intake goals set for preventing diet-related non-communicable diseases: 1990 to 2017 trend analysis. *Plos one* **16,** e0245241 (2021).

175. Tröster, B. & Janechová, E. *The long journey towards Pan-African integration: The African Continental Free Trade Area and its challenges* tech. rep. (ÖFSE Briefing Paper, 2021).

176. Menkhoff, T., Chay, Y. W., Evers, H.-d. & Pang, E. F. *Beyond the knowledge trap: Developing asia's knowledge-based economies* (World Scientific, 2011).

177. Cummings, S., Regeer, B., De Haan, L., Zweekhorst, M. & Bunders, J. Critical discourse analysis of perspectives on knowledge and the knowledge society within the Sustainable Development Goals. *Development Policy Review* **36,** 727–742 (2018).

178. Gee, J. P. & Handford, M. *The Routledge handbook of discourse analysis* (Routledge, 2013).

179. Mormina, M. Science, technology and innovation as social goods for development: rethinking research capacity building from sen's capabilities approach. *Science and Engineering Ethics* **25,** 671–692 (2019).

180. Compagnucci, L. & Spigarelli, F. The Third Mission of the university: A systematic literature review on potentials and constraints. *Technological Forecasting and Social Change* **161,** 120284 (2020).

181. Urdari, C., Farcas, T. V. & Tiron-Tudor, A. Assessing the legitimacy of HEIs' contributions to society: the perspective of international rankings. *Sustainability Accounting, Management and Policy Journal* (2017).

182. Abreu, M., Demirel, P., Grinevich, V. & Karataş-Özkan, M. Entrepreneurial practices in research-intensive and teaching-led universities. *Small business economics* **47,** 695–717 (2016).

183. Mora, J.-G., Ferreira, C., Vidal, J. & Vieira, M.-J. Higher education in Albania: developing third mission activities. *Tertiary Education and Management* **21,** 29–40 (2015).

184. Voithofer, R. Designing new media education research: The materiality of data, representation, and dissemination. *Educational Researcher* **34,** 3–14 (2005).

185. Morin, M.-E. Cohabitating in the globalised world: Peter Sloterdijk's global foams and Bruno Latour's cosmopolitics. *Environment and Planning D: Society and Space* **27,** 58–72 (2009).

186. Elliott, K. C. & Resnik, D. B. Making open science work for science and society. *Environmental health perspectives* **127,** 075002 (2019).

187. Bastos, W. & Levy, S. J. A history of the concept of branding: practice and theory. *Journal of Historical Research in Marketing* (2012).

188. Coman, C., Bularca, M. C. & Angela, R. Constructing and Communicating the Visual Identity of a University. Case Study: Visual Identity of Transilvania University of Brasov. *Sustainability* **13,** 7145 (2021).

189. Skaggs, S. Visual identity: systems and semiotics. *The American Journal of Semiotics* **34,** 313–330 (2019).

190. Hassenzahl, M. User experience and experience design. *The encyclopedia of human-computer interaction* **2** (2013).

191. Harutyunyan, N. & Riehle, D. *User experience design in software product lines* in *Proceedings of the 52nd Hawaii International Conference on System Sciences* (2019).

192. Lin, Y.-T. & Hertzum, M. *How Do Designers Make User-Experience Design Decisions?* in *International Conference on Human-Computer Interaction* (2020), 188–198.

193. Elia, G., Margherita, A. & Passiante, G. Digital entrepreneurship ecosystem: How digital technologies and collective intelligence are reshaping the entrepreneurial process. *Technological Forecasting and Social Change* **150,** 119791 (2020).

194. Sahut, J.-M., Iandoli, L. & Teulon, F. The age of digital entrepreneurship. *Small Business Economics* **56,** 1159–1169 (2021).

195. Hampton, S. E. *et al.* The Tao of open science for ecology. *Ecosphere* **6,** 1–13 (2015).

196. Stilgoe, J., Lock, S. J. & Wilsdon, J. Why should we promote public engagement with science? *Public understanding of science* **23,** 4–15 (2014).

197. Ross-Hellauer, T. *et al. Ten simple rules for innovative dissemination of research* 2020.

198. Meyer, R. E., Höllerer, M. A., Jancsary, D. & Van Leeuwen, T. The visual dimension in organizing, organization, and organization research: Core ideas, current developments, and promising avenues. *Academy of Management Annals* **7,** 489–555 (2013).

199. Segel, E. & Heer, J. Narrative visualization: Telling stories with data. *IEEE transactions on visualization and computer graphics* **16,** 1139–1148 (2010).

200. Ramlatchan, M. & Watson, G. S. Enhancing instructor credibility and immediacy in online multimedia designs. *Educational Technology Research and Development* **68,** 511–528 (2020).

201. Bialowas, A. & Steimel, S. Less Is More: Use of Video to Address the Problem of Teacher Immediacy and Presence in Online Courses. *International journal of teaching and learning in higher education* **31,** 354–364 (2019).

202. Spence, M. & Essoussi, L. H. SME brand building and management: an exploratory study. *European Journal of Marketing* (2010).

203. Cawsey, T. & Rowley, J. Social media brand building strategies in B2B companies. *Marketing Intelligence & Planning* (2016).