POLITECNICO DI TORINO

Master of Science in Engineering and Management

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Economic Valuation of Blue Water in the Global Food Trade

Supervisors

Luca Ridolfi
Francesco Laio
Paolo D'Odorico

Student

Manuela Busca

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Introduction

Water has always been necessary for life and has supported civilizations' development and population. Thus, over time, different technologies to manage water have been developed. In the last century global population increased dramatically from about 1.6 billion to 6.1 billion and nine billion people are projected to be living on the planet in 2050 (*United Nations 2015*, *10 billion by 2050*). Despite the massive technological progress of the twentieth century, experts agree that the planet is now facing a water crisis. This term refers to problems such as local water scarcity, climate change, ability to grow enough food and agricultural yield, inefficiency and inequity in fresh water distribution, pollution and access to save water for human health (*Anisfeld, 2010*). The vast and urgent problems lead to a growing importance of water management for all of the human beings in order to put an effort towards new multidisciplinary approaches and solutions.

It is important to notice that, in spite of the attention of water saving in the domestic use, this is not the main scope of the problem of water crisis. Indeed, we use much more water indirectly, i.e. the virtual water content of goods that we consume. The largest societal use of water is the consumption for food production in order to feed humanity (*Falkernmark and Rockström, 2004)* and crop irrigation represents the 70% of the overall freshwater withdrawal for human use. In the light of this fact, the concept of water footprint has become a matter of wide interest for the scientific community. Water footprint of a good, in particular food, means the overall amount of water used in its entire production process. This can be seen as a measure of our impact on water resources available on the planet Earth.

It is well known that water is a natural primary good, not substitutable and its scarcity (absolute or relative) depends on both natural processes and economic factors. Furthermore, the demand of water is inelastic due to the fact that it is scarce and not substitutable, thus its demand is not influenced by price variations. Another important peculiarity of water is the fact that it is not directly transportable, relating to enormous costs of hydraulic works.

Upon those considerations the concept of virtual water trade arises. Indeed, the 20% of the global water use is traded as virtual water, especially in the trade of food commodities. The global food trade can be considered as a way of meeting the demand for food in overpopulated and water scarce countries (*Allan, 2008*) and the corresponding virtual water trade has been declared as a way of saving water and matching demand and supply of water in scarce regions (*Hoekstra and Chapagain, 2008*).

Though, water globalization and trade lead to an economic consideration of the good itself. For instance, a recent study (*Debaere, 2014*) explains, through a regression model, that water is a source of comparative advantage. The concept of comparative advantage in economics is generally referred to the international trade of a good and it states that, in free trade, an actor of the economic system will produce more and consume less of a good or commodity for which it has a comparative advantage. Hence, an agent with a comparative advantage over others in the production process of a good will have a lower opportunity cost or a lower relative marginal cost prior to trade.

In the water case, it means that water abundant countries tend to export more water intensive products and water scarce countries tend to export less water intensive goods.

Nevertheless, there are negative exceptions and implications of water use in the global water trade. For example, globalization disconnects the population from regional sustainable water use (*D'Odorico et al., 2010*).

Furthermore, water price does not have the true reflection of its real opportunity cost and it is subject of tragedy of commons that describe the reason why water is freely overconsumed. Indeed, the accounted cost of water does not have a great impact in the pricing process of the food commodity or good and generally has not a significant impact. Water is necessary for life and so it is strongly correlated to the human right of health. This does not lead to the consideration that water should not be priced but that, upon regulation by institutions, the consumer has the right to affordable access to fresh water thanks to affordability policies as in the case of food prices, maintained artificially low thanks to subsidies to the agriculture industry (*Anisfeld, 2010*).

The water price normally reflects extraction cost, maintenance cost of the delivery infrastructure and treatments cost. But, as for other goods, the value of the water itself as a raw material should be considered. In the economic environment this value arises from the marginal cost of water distribution and the opportunity cost of water use.

In this work, instead, we developed an innovative method with an engineering basis starting from considering the yield of water in the agriculture production. In fact, the goal of this study is to analyze *a posteriori* the economic return on the investment of a unit of irrigation's water. The innovative connotation of the method corresponds to the separation of the green and blue water content while considering the economic yield of water in the crop production and trade and in the incremental analysis of the production yield of irrigated lands. Water, indeed, can be divided into three components: green, blue and grey (*Hoekstra et al., 2011*). Green water, in essence, is the precipitation on land, blue water is embodied by fresh water available in surface basins such as lakes and rivers or groundwater and, lastly, grey water refers to the fraction of freshwater polluted due to the production of a good over its full supply chain.

Irrigation in agriculture has rapidly grown in the last decades and it has been estimated that one third of harvested lands in the world are subjected to irrigation for crop production (*Shah, 2014*). Additionally, 70% of the irrigated land is concentrated in Asia, where irrigation is a matter of fundamental importance in order to guarantee food security. The irrigated share of land seems to be five times the one of the early 20th century (same as water consumption) and nowadays the 17% of this land share produce the 40% of the global food production.

In this study blue water used for irrigation has a central role. Indeed, the goal of this work is to estimate the economic value of blue water through the production yield of irrigated lands compared to rainfed lands in the crop production and then in the virtual water trade, i.e. considering the global food trade. In other words, the behavior of irrigation's water will be observed through all the stages of the supply chain of a crop. Therefore, the embodied water of a crop at the selling stage turns into an economic revenue through the price of the good. In this work it will be estimated, assuming other production inputs as constants, how much is rentable irrigating harvested areas with additional blue water. Basically, this means to observe which is the economic yield of water *a posteriori* in the food market and which is the behavior of this parameter in the global context. This value embodies the economic return on the investment of water for farmers, so it represents their maximum willingness to pay for water itself as a raw material.

Finally, it is notable to consider water pricing as a matter of importance especially in the light of the emergent trend of water markets. Water markets are relatively new and increasingly popular and they were born as a solution for fighting the growing water scarcity in some regions of the world. They consist of a voluntary exchange of water rights between buyers and sellers. In a recent study Debeare et al. described seven cases of water markets, with the Murray-Darling Basin in Australia as the most important and the most structured water market (*Debaere et al., 2014*). The price of water in those markets is not always explicit and techniques for the determination of the price are not always clear. Thus, water pricing is not just a topic referred to the virtual water trade context but it is becoming a real subject with a direct consequence.

Main general concepts, namely water footprint, the globalization of water as a response to scarcity and the logic of water markets, will be illustrated in the first chapter. The second chapter will be about the data used as a pillar of this work and their first analysis. The method will be illustrated in the third chapter in two sections: the first section about the global crop production and the second about global crop trade.

Results about global crop production will be shown in the fourth chapter, meanwhile the fifth chapter will be about the global crop trade.

Eventually, the sixth chapter will show the main evidences and take-away resulting from the analysis of the previous chapters.

The innovative method in this study has been developed in collaboration with University of California, Berkeley as a result of a visiting period in the Environmental Science, Policy and Management department of U.C. Berkeley.

1 General Framework

1.1 Water Footprint

The 'water footprint' concept was introduced by Hoekstra in 2002 (*Hoekstra, 2003*) and it leads to the idea of water use upon the entire supply chain, indeed this indicator considers the indirect water use of consumers and producers along with the direct use. Thus, water footprint is an indicator of water resources' usage beyond the traditional idea of water withdrawal as a measure of consumption.

Water has been divided into the three components: green, blue and grey (*Hoekstra et al., 2011*). Green water basically is the precipitation on land that does not contribute to the supply of ground water, though it is retained in the soil or temporary maintained on the surface of land or vegetation. Hence, this component of water evaporates or transpires through seedlings. Eventually, precipitation contribute to crop growth even if not all green water is absorbed from crop due to regular evaporation from the soil and a disconnection between periods of the year and areas suitable for agriculture.

Instead, blue water is embodied by fresh water available in surface basins such as lakes and rivers, or groundwater. This kind of water has a crucial role in crop production and agriculture because it is constantly available. Thanks to that it is possible to use blue water as a supplement, through irrigation, in case of lack of rain and precipitation.

Lastly, grey water refers to the fraction of freshwater polluted due to the production of a good over its full supply chain.

Thus, it is possible to classify water footprint in the corresponding green, blue and grey compositions. Firstly, the green water footprint means the consumption of rain water that does not become run-off. Secondly, blue water footprint refers to the consumption of fresh water from basins and groundwater along the supply chain of a good. Lastly, grey water footprint is defined as the overall amount of fresh water required to assimilate the quantity of pollutants that arise in the production process, given natural ambient water quality standard. Figure 1 illustrates the scheme of the composition of water footprint.

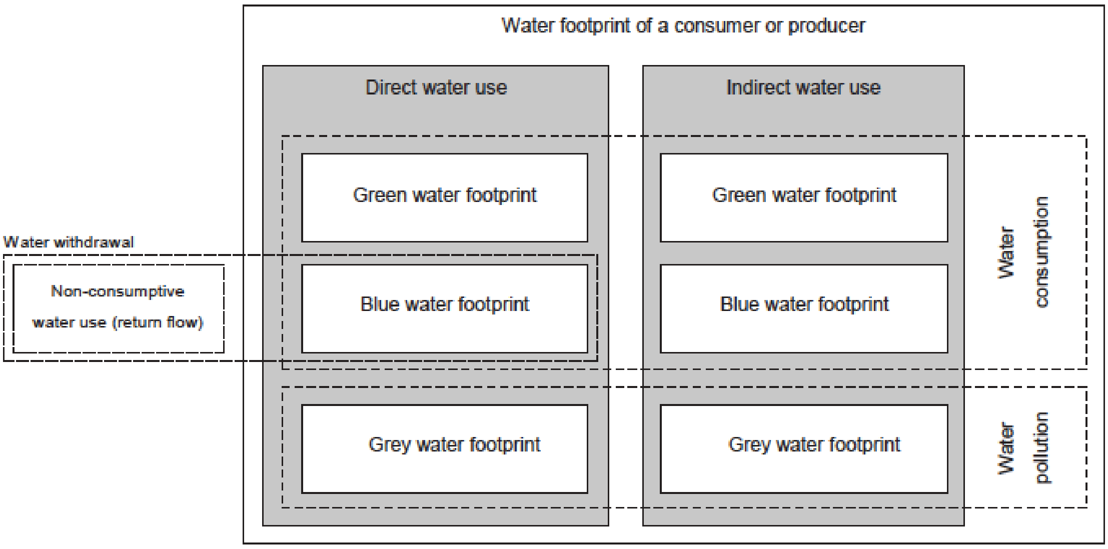

Figure 1: Schematic representation of the three components of water footprint. The return flow (the non-consumptive part of water withdrawals) is not part of the water footprint. The indirect component, instead, has been included contrary to the traditional measure of water withdrawal. Source: The Water Footprint Assessment Manual.

The most important differences between the concept of water footprint and water withdrawal are the followings:

- water footprint does not incorporate blue water insofar due to the fact that this kind of water is returned to initial source;
- water footprint includes blue, green and grey components;
- water footprint considers both the direct water use and indirect water use.

Water footprint is hence the measure of humanity's requirement of fresh water. In order to better understand this important requirement, the process of water evapotranspiration needs to be first explained. The process of evapotranspiration consists of the evaporation of water from the soil and water surfaces as a result of wind and solar energy plus the transpiration of water in the soil through the stomata on the leaves of plants, eventually released into the atmosphere. The quantity of water in the atmosphere, hence, increases with the evapotranspiration process but decreases through precipitation. Due to the complex pattern of vapor movement around the globe within atmosphere, the water that evaporates in one place does not always return in the same place through precipitation. Since in the long run precipitation generally exceeds evapotranspiration, there is a phenomenon of water surplus

on land that gives rise to run-off. This run-off water from land eventually converges into the ocean through rivers and groundwater flow. As a result, in oceans the phenomenon of evaporation surplus exists. Thus, there is an all embracing net transport of water between oceans and land through the atmosphere. Hence, the overall volume of water on Earth stays more or less equal. Although there is the water cycle, availability of fresh water is not unlimited. Indeed, the withdrawal of water per year for domestic, agriculture and industrial issues must not exceed the annual replenishment rate. Water footprint accounting embodies the measure for responding to the following question: is man's consumption of fresh water flow in a certain period sustainable compared to the availability of it in the same period?
For instance, the freshwater withdrawal process by humans compared to the hydrological cycle can be explained through a river basin case (Figure 2), i.e. the entire geographical surface drained by a river. All run-off from a catchment area, which is another term for river basin, converges to the same outlet. The overall annual water availability of this area is the total annual amount of precipitation, that will eventually leave the basin through run-off from catchment and evapotranspiration. Both the run-off and the evaporative flow can be used by humans. Specifically, the green water footprint consists to the human appropriation of the evaporative flow, mainly for crop production and the blue water footprint consists in the consumption of the run-off, thus the run-off does not return back to the catchment area.

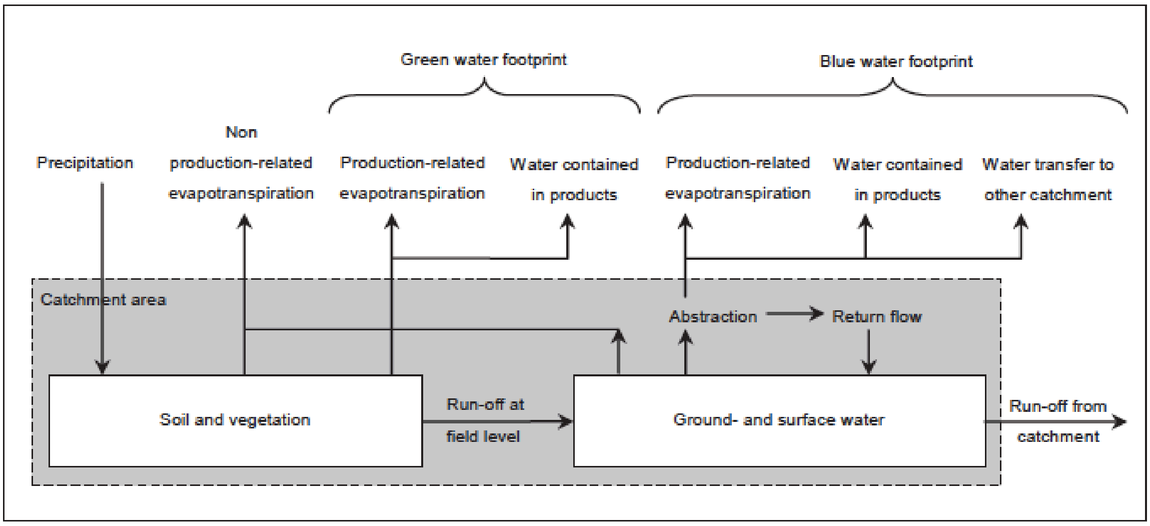

Figure 2: Green and blue water footprint compared to the water balance of a catchment area, i.e. river basin. Source: The Water Footprint Assessment Manual.

After having introduced the water footprint concept specifically, it is important to notice that, in spite of the attention of water saving in the domestic use, this is not the main scope of the water case as water consumption refers mainly to the fact that we use much more water indirectly. The largest societal use of water is the consumption for food production in order to feed humanity (*Falkernmark and Rockström, 2004*). In fact, crop irrigation represents the 70% of the overall freshwater withdrawal for human use. In the light of that, the concept of water footprint of an agriculture product has become a matter of wide interest of the scientific community. In the case of crops, water footprint is expressed in m^3/ton.

Water used in the crop production depends on the quantity of water necessary in the evapotranspiration process in the ideal settings (without limits for plant growth) during the whole plant life cycle and the real available quantity of water in the soil, i.e. green water represented by precipitations and blue water embodied by irrigation.

The estimation of evapotranspiration of crops has been developed by Mekonnen (*Mekonnen and Hoekstra, 2011*) following the methods of the reference study of Richard Allen (*Allen et al.,1998; FAO*).

Furthermore, 5x5 arc min model has been used which has been considered the hydric balance for each cell of the model considering local climate conditions, soil conditions and fertilizers.

Eventually, the estimation of the water footprint (*WFP*) has been calculated as the water consumption for crop production (*WC, m^3/ha*) divided by the crop production yield (*Y, ton/ha*) in the formula

$$WFP = \frac{WC}{Y} \qquad \left[\frac{m^3}{ton}\right] \tag{1}$$

In conclusion, contrary to the common sense, it is possible to affirm that humanity consumes more water indirectly in order to be fed than for domestic use. In fact, the water foot print resulting from domestic use, composed by activities such as drinking, washing and cooking, is equal to 152 m^3 per capita per year. Whereas, the overall per capita blue water footprint is 982 m^3 per year, by far greater than the water footprint corresponding to the domestic use.

Some examples in order to better comprehend the impact of food on water resources:

in a cup of coffee there are 140 liters of embodied water, 135 in one egg, 2400 in a hamburger, 40 in a slice of bread and 70 in an apple. Therefore, the concept of water footprint is necessary and fundamental in understanding the dependence of humanity on hydrological systems and the impact of human lifestyle on them.

1.2 Globalization of Water and Global Food Trade

The scarcity of water at the global and country scale has been calculated in a study of Shimon C. Anisfeld (*Anisfeld, 2010*) through two indicators (Falkenmark and WTA indicators).
At the global scale the calculation of water scarcity indicators leads to the fact that Earth is not in a situation of water scarcity, at the country scale it is possible to observe that the majority of countries are not water scarce, but 45 countries have a relevant water stress level, with 19 in a severe situation. These are especially Middle Eastern, North African countries or small islands with low levels of water resources.
In several studies, the concept of virtual water has been used in order to influence consumption, production and trade policies of goods, taking into account their water footprints (*Hoekstra, 2005*), such as delocalizing the production of water intensive agriculture goods in water abundant regions or changing eating habits of society (for instance a vegetarian diet has a lower water footprint due to the fact that livestock production requires more water considering the direct and indirect use) in order to reduce pressure on local water available resources.
The scientific community has focused its effort in the analysis of the virtual water flows between nations. In the past years it has been shown that the overall sum of global virtual water flows is in the range of 1,000 – 2,000 billion cubic meters per year i.e. the 1-2% of the precipitation above the globe is used to produce commodities for export. This amount can be compared to more than the annual runoff volume of a huge river as the Ganges-Brahmaputra.
The term “virtual-water trade” was introduced for the first time in the 2002 (*Hoekstra and Hung, 2002*). This term was criticized because trade is normally referred to real things and that it was better to consider food trade with a corresponding virtual-water transferor flow.
Although the term was avoided in 2003, the virtual water trade is a phrase that pops up frequently nowadays and in this study it will be used in parallel to the food trade concept.
The virtual water flows (m^3/yr) is calculated as good trade (ton/yr) multiplied by the associated virtual water footprint (m^3/ton).
Therefore, the World Water Council in 2004 underlined the importance of conscious consumers’ strategic choice of importing services and goods under a sustainable optic.
For instance, some countries in a water stress situation (Middle Eastern and North African countries) tend to import water intensive products in a water saving logic (*Allan, 1997*) and this is much more relevant if the country is saving blue water.

For the sake of investigating the role of the global food trade, another study of Hoekstra has been considered (*Hoekstra et al., 2008*). In the period 1997-2001 the virtual water flows in the global food trade (agriculture products) consisted more than 60% of the entire amount of virtual water and exchanged goods embodied the 16% of the global water consumption.
Thus, the global food trade can be considered as a way of meeting the demand for food in overpopulated and water scarce countries and the corresponding virtual water trade has been declared as a way of saving water and matching demand and supply of water in scarce regions (*Hoekstra and Chapagain, 2008*).
Therefore, the virtual water is well connected to global food trade due to the fact that water is not directly transportable for economical and logistics issues. In the light of this, we should consider what is the impact of water resources in the global food trade. Indeed, local water scarcity is not the only factor in the food commodities and crops trade. The study conducted by DIE[1] (*Horlemann et al., 2006*) shows the theory of comparative advantage in the global food trade. The concept of comparative advantage in economics is generally refers to the international trade of a good and it states that, in free trade, an actor of the economic system will produce more and consume less of a good or commodity for which it has a comparative advantage. Hence, an agent with a comparative advantage over others in the production process of a good will have a lower opportunity cost or a lower relative marginal cost prior to trade. Therefore, in the DIE study, along with demand and offer for a food commodity analysis, factors such as labor force, available capital and arable land have been taken into account. Thus, it seems reasonable to account the economic value of water as a source of comparative advantage. Actually, water has an economically relevant value just in those cases in which the offer is scarce compared to demand, in all the other cases water price does not have the true reflection of its real opportunity cost (*Debaere, 2014*) and it is subject to tragedy of commons that describe the reason why water is freely overconsumed.
Nevertheless, there are several studies that demonstrate how virtual water flows are positively correlated to water mismatches, indeed water abundant countries tend to export more water intensive products and water scarce countries tend to export less water intensive goods but the leading factors still remain capital and skilled work.
Eventually virtual water could have a role in the better allocation and management of local water resources but does not always affect how production and commercial strategies come

[1] Deutshes Intitute für Entwicklungspolitik – German Institute of Development

to be determined (*Wichelns, 2003*) because the water footprint does not reflect opportunities cost and production technology. For instance, considering the rice case, it has been noticed that even if it is a water intensive crop its production is concentrated in regions with lower opportunity cost (i.e. humid regions) without taking into account the water efficiency.

Considering the global food trade of agriculture products, that refers to economics and politics in a complex pattern, the impact of virtual water or water footprint can be overestimated. Indeed, a study of the IWMI[2] *(Molden et al., 2004*) shows that there is not a linear relationship between scarcity of fresh water resources in a country and water saving due to global trade. The majority of exchanges in the global pattern are affected by other factors, and in the future scenario projections suggest that the 60% of crop trade will be not related to water scarcity.

Furthermore, a study leaded in 2013 (*Carr et al., 2013*) described that the virtual water trade has substantially increased in the last few decades, considering that the overall virtual water transfer, in terms of both volume and numbers of links (exchanges in the global network), has almost doubled in the range of years 1986-2010 (Figure 3). The virtual water network has also changed in terms of geography, indeed the virtual water trade depends more and more on few big exporters since the ratio between net importers and net exporters has significantly increased from 1.2 to 2. For instance, China in 1986 was a big net exporter of virtual water and in 2010 became the main net importer of virtual.

Instead, generally the overall transfer of water due to staple crops have remained essentially the same over the period from 1986 to 2010.

Actually, the majority of countries in this period show a situation slightly changed in term of variation of water flows, meanwhile substantial variation affected few countries, indeed there is a small group of countries controlling wide exports of virtual water so that importers cannot diversify their providers. Anyway the dynamics of the controls in both commodity trade and virtual water trade remains not well understood.

[2] International Water Management Institute

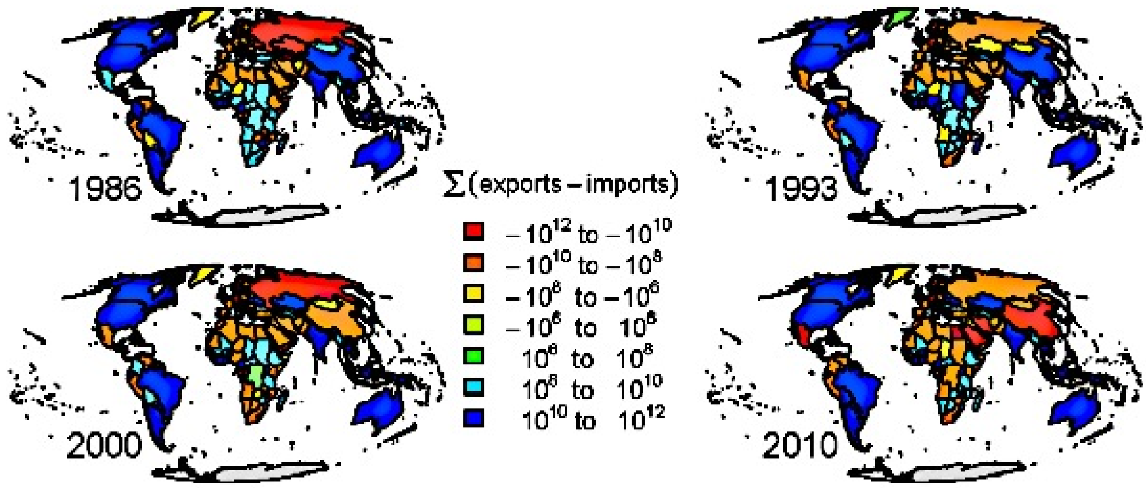

Figure 3: The virtual water import-export balance(m3) for the years 1986,1993,2000 and 2010. The global transfer has more than doubled. Source: Carr et al.,2013.

Table 1 shows the most significant net importers (top of the list) and net exporters (bottom of the list) for the period 1986-2010. As said before, over time China became the first net importer. Both Italy and Germany increased their net import. USA remained one of the biggest importers along with Argentina and Brazil. Canada and Indonesia became part of the top 5 respectively in 2000 and 2010. Generally, the export of the main exporters increased a lot, more than doubled.

Table 1: The global ranking of the top 5 net importers (above) and the top 5 net exporters (below) and the corresponding balance of virtual water export ($10^{11}m^3$) for the years1986, 1993, 2000, 2010. Source: Carr et al.,2013.

Rank	1986 Balance		1993 Balance		2000 Balance		2010 Balance	
1	Japan	−0.77	Japan	−0.85	Japan	−0.88	China, mainland	−2.43
2	USSR	−0.54	Germany	−0.48	Germany	−0.49	Japan	−0.91
3	Italy	−0.37	Italy	−0.36	Italy	−0.45	Germany	−0.64
4	Germany	−0.32	Republic of Korea	−0.34	Russian Federation	−0.44	Iran	−0.58
5	United Kingdom	−0.23	Russian Federation	−0.29	Republic of Korea	−0.38	Italy	−0.55
1	United States of America	0.85	United States of America	1.04	United States of America	1.15	Brazil	1.87
2	Australia	0.60	Argentina	0.53	Argentina	0.99	United States of America	1.1.55
3	Argentina	0.44	Australia	0.40	Australia	0.79	Argentina	1.48
4	Thailand	0.34	Brazil	0.39	Brazil	0.58	Indonesia	0.84
5	Brazil	0.33	India	0.33	Canada	0.44	Canada	0.72

1.3 Water Markets

In the light of the fact that water footprint and global food trade are not always effective in the better allocation of water resources and that water governance of the existing systems are proving to be quite ineffective as a response to water scarcity. In this section a relatively new and of rising popularity tool in the pattern of local water scarcity will be described.
As the IWMI declared in 2007, at the global scale we are not running out of water. Indeed, the problem about water availability is connected to space and time mismatching. In the last few years there have been economic innovations to manage water besides engineering and technological solutions. In this context strategies in order to manage the demand of water have been developed, such as conscious strategies in the the food trade pattern (not always effective) and water markets. This concept consists of a formal system of regulations and rules in order to govern the activity of exchanging (buying, selling or leasing) water rights independent of land rights. The flexibility of this relatively new tool is restricted by infrastructures capable of storing and transporting water. Furthermore, governmental limitations on water volumes can be an obstacle in this trade.
A recent study (*Debeare et al., 2014*) analyzed seven water markets: four in the United States (the Northern Colorado Water Conservancy District, the Edwards Aquifer of Texas, the Columbia River basin in the Pacific Northwest, and the Central Valley / San Joaquin River of California), one in Chile, the Murray-Darling Basin in Australia and the Santiago River basin in Mexico. The study focused on the capability of these markets to face the problem of water scarcity while taking into account the economic and the ecological benefits, examining them as cap-and-trade systems. This means that a community or a government can impose a cap (a limit) upon the water use within a specific source of freshwater. This is supposed to stop the *tragedy of the commons*, i.e. to limit the phenomenon of individuals pursuing their self-interest in overconsuming a free and scarce resource against the long-term interest of society (because they do not sustain the full cost of their actions). In considering water markets as a management strategy in the study conducted by Debeare, it has been also examined whether water used remained under the cap, thus what is obtained is a system of water trade that is sustainable.
In the study two markets, Northern Colorado Water Conservancy District (Figure 4) and Edwards Aquifer of Texas, resulted in effectively limiting water use through regulatory control of water use and allocation.

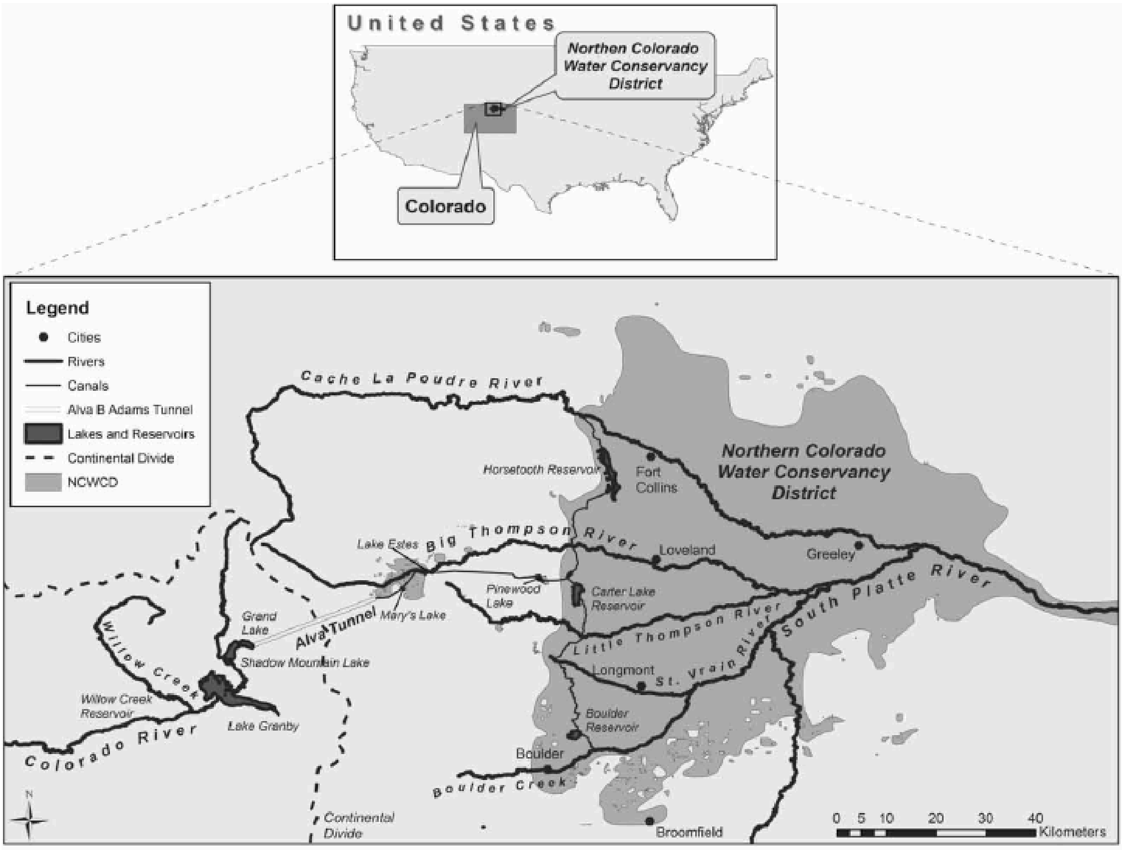

Figure 4: The Northern Colorado Water Conservancy District, NCWCD. (Debeare et al., 2014).

Nevertheless, the study underlines the complexity in water markets transactions such as high variability of prices. For instance, in the light of the fact that transportation costs are high compared to water's value at the source, during a specific week in 2015 (April 15th) the cost of permanent water right varied from 4.26 USD/m^3 (average value) in the Edwards Aquifer to 19.70 USD/m^3 in the NCWCD and 1.20 USD/m^3 in the Murray-Darling Basin. Anyway these regional differences among water prices in different markets do not necessarily mean that the allocation of water is inefficient.

Eventually, water markets seem to move towards sustainable and efficient water use when there are regulation policies in order to settle a cap on the water rights and volumes.

These considerations about water prices in arising water markets referred to specific local situations. Nevertheless, it underlines the existence of a real water trade, along with the virtual water trade, that leads to considerations and issues about water price as a raw material aside from costs of transportation and infrastructure system.

2 Data and Preliminary Analysis

In this chapter all the variables used for this study will be illustrated and described. The scope is composed by the agricultural production context and the global food trade. Indeed, the economic valuation of water in this study refers to the economic yield in the agriculture industry that represent the 70% of the overall withdrawal of fresh water.
The sources of the data sets of reference will be shown, together with preliminary analysis and distributions of data. This will make the comprehension of the chapter about methods easier in which those inputs are used to describe techniques in order to achieve the goals of this work. The reference year taken into account of this work is 2000, which is the year with the most availability of data about agriculture, production and water footprints. This means that all the analysis is focused on a spatial investigation on the differences between countries and their behavior.

2.1 Water Footprint

The reference data set for water footprint values arises from the Water Footprint Network, i.e. waterfootprint.org. The virtual platform in question is a scientific community composed by companies, organization and individuals with the aim of solving world's water crisis issues using science-based practical solutions to manage water resources. Specifically, water footprint of products has been withdrawn from the National Water Footprint Accounts: the green, blue and grey water footprint of production and consumption (*Mekonnen and Hoekstra, 2011*). The products used in this study are the four main staple crops namely wheat, rice, maize and soybeans that together consist in the 50% of the global consumption of calories in the traditional human diet as depicted in a recent study (*D'Odorico et al., 2014*). Table 2 has been picked from the same study in order to better show the composition of the caloric intake.

Table 2: The Major Food Commodities that Explained the 80% of the Total Food Calories Produced (D'Odorico et al., 2014).

Production													
1986							2009						
	Food Cal		Protein					Food Cal		Protein			
Commodity	% Cal	Cum.	% Prot.	Cum	β	WUE	Commodity	% Cal	Cum.	% Prot	Cum.	β	WUE
Wheat	23.7	23.7	19.7	19.7	0.78	1.321	Wheat	20.4	20.4	17.2	17.2	0.81	1.321
Rice (milled equivalent)	18.4	42.1	11.6	31.3	0.95	0.970	Rice (milled equivalent)	16.1	36.5	10.4	27.6	0.88	0.970
Maize	9.7	51.9	10.7	42.0	0.33	1.298	Maize	12.8	49.3	12.7	40.2	0.40	1.298
Soy beans	5.3	57.2	14.2	56.3	0.97	0.356	Soybean	8.0	57.2	20.5	60.8	0.96	0.356
Sugarcane	4.7	61.9	0.7	57.0	0.97	0.752	Sugarcane	5.4	62.7	0.8	61.6	0.98	0.752
Pig meat	3.4	65.3	3.0	60.0	1.00	0.834	Pig meat	3.8	66.5	3.2	64.8	1.00	0.834
Sugar beet	3.3	68.6	1.48	61.5	0.96	2.465	Rape and mustard seed	3.1	69.6	2.9	67.8	0.91	1.515
Barley	2.6	71.3	5.52	67.0	0.26	1.342	Potatoes	2.1	71.8	1.1	68.8	0.86	1.782
Potatoes	2.5	73.7	1.24	68.3	0.74	1.782	Barley	2.1	73.8	2.5	71.3	0.38	1.342
Sorghum	1.9	75.6	2.1	70.4	0.46	0.674	Poultry meat	1.9	75.7	2.5	73.8	0.99	0.616
Rape and mustard seed	1.6	77.2	1.5	71.9	0.93	1.515	Vegetables, other	1.8	77.5	0.8	74.7	0.94	0.465
Groundnuts (shelled eq)	1.4	78.7	1.5	73.5	0.99	0.918	Sugar beet	1.7	79.2	0.7	75.4	0.94	2.465
Bovine meat	1.4	80.0	3.7	77.3	1.00	0.141	Groundnuts (shelled eq)	1.5	80.7	1.6	77.0	0.96	0.918

[a]For each of these commodities we also report their contribution to the total production of protein for human consumption (expressed as a % of the total) and the cumulated contribution. These values are based on production data (P^f) for direct human consumption (i.e., excluding secondary products, feed and other nonfood uses); β is the fraction of food production that is available for human consumption. Water use efficiency (WUE) is expressed in kcal/L.

Nevertheless, the dataset in consideration, is referred to a study that estimates globally green, blue and grey water footprint of 126 crops and more than 200 derived crop products as an average value over the period 1996-2005 (centered in 2000), with a high-resolution approach (5 by 5 arc minute grid) (*Mekonnen and Hoekstra, 2011*). This model has been built on the basis of the daily soil water balance and weather conditions for each grid cell. Furthermore, it has been used the water footprint assessment framework as described in the guideline of the Water Footprint Network. Hence, those values have been taken into account in this study as estimations for the year 2000 in the country scale, even if conditions inside a country can be heterogeneous.

In this study green water and blue water footprint have been taken into account with an emphasis on the blue component. In fact, the blue water footprint express the quantity of irrigation needed to grow a certain crop.

Figure 5 shows the spatial distribution of blue water footprints in the year 2000 for the four staple crops. In the wheat, maize and soybeans cases the majority of countries show spatial homogeneity of the parameter in object with a value less or equal to 200 m^3 of blue per ton. Exceptions are India, Nepal, Pakistan and Saudi Arabia for wheat, Kazakhstan, Uzbekistan, Turkmenistan and Sudan for maize, Turkmenistan, Azerbaijan, Tajikistan, Tunisia and Lebanon for Soybeans. Rice, compared to the other three staple crops, has, generally, a higher blue water footprint. Indeed, rice production is notable to require more water from irrigation respect other crops, so that the majority of countries show values between 1000 and 2000 cubic meters per ton of production. In the rice case the least blue water efficient countries are Kazakhstan, Uzbekistan, Turkmenistan, Namibia, Botswana and Lesotho. Generally, European countries are the most efficient in the use of water for irrigation as a result of production quantities.

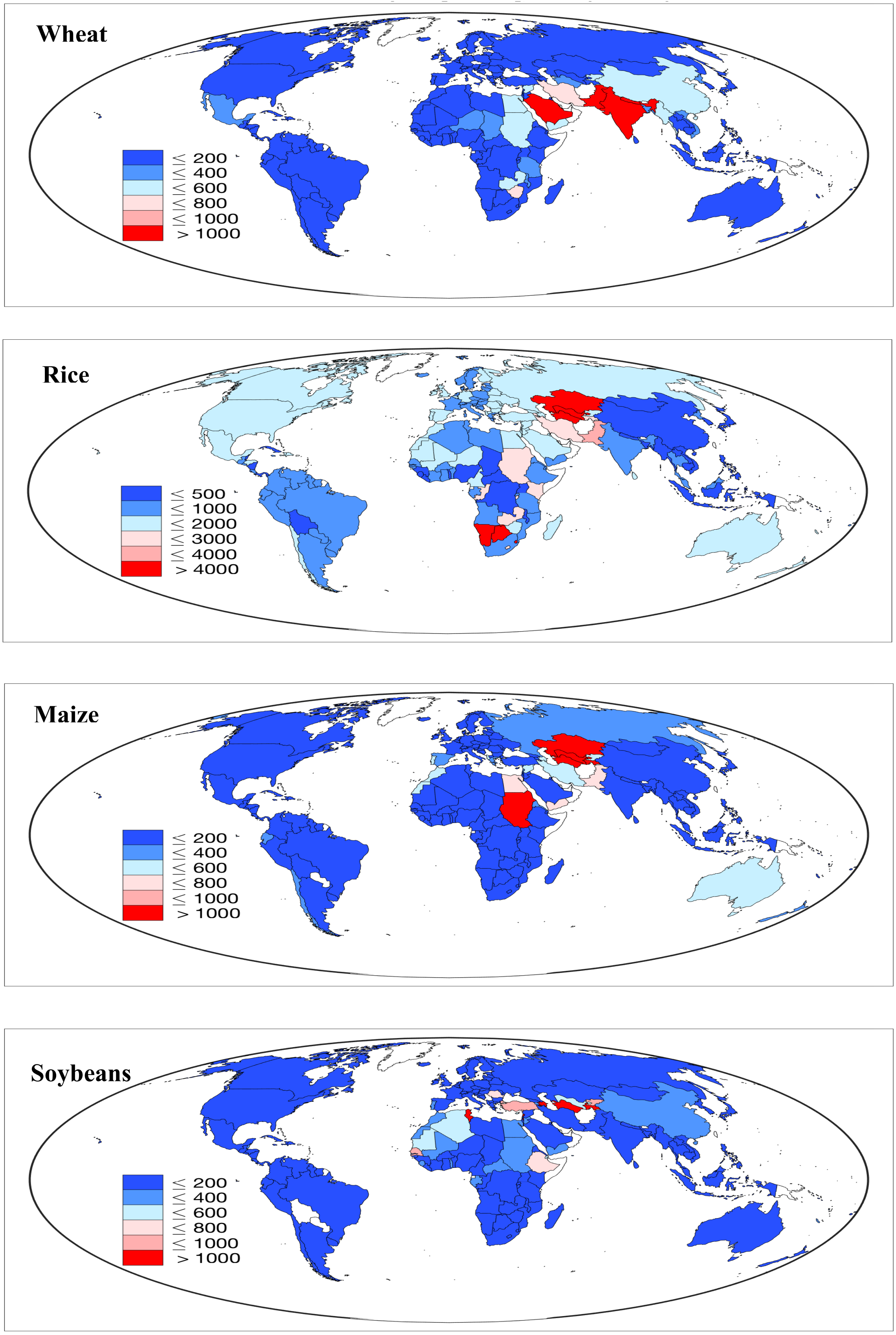

Figure 5:Maps of Blue Water Footprint of Wheat, Rice, Maize and Soybeans in 2000.

2.2 Production and Farm-gate Prices

The data set referenced in this section arises from the FAOSTAT collection of data. The Food and Agriculture Organization (FAO) is a specialized section of the United Nations that leads international efforts to fight hunger in the world. The goals of this agency are food security for all, high-quality food and healthy lives summarized as Zero-Hunger World.

FAO also develops methods, standards and techniques for food and agriculture statistics including data collection, validation and analysis.

Data of production quantities for each producer country are for the year 2000 and are the actual values expressed in tons per year. The quantities of wheat, rice, maize and soybeans used are in the country scale.

Farm-gate prices refer to the value in USD of a ton of a specific crop that represents the prices received by farmers for primary crops as collected at the initial sale. They are lower with respect to retail prices because they are set at the first stage of the supply-chain. Farm-gate prices withdrawal from FAOSTAT database are the average values accounted in a country for 2000.

In the case the price data are not available for the corresponding accounted production data, the statistics division of FAO estimates the missing value through a specific method illustrated in 'Methods and standards', which means:

- taking into account that similar goods follows the same behavior;
- using PPI (Producer Price Index) for the estimation, that expresses the annual variation with respect to a reference year;
- applying similar indexes to PPI (CPI, GDP deflator).

Nevertheless, in 2000 the most produced crop is rice with a global production of around 599 million tons, followed by maize (592 million tons), then wheat with 585 million tons and eventually soybeans with an overall production of 161 million tons.

The highest value of farm-gate price among the four staple crops in terms of weighted average, is 213 USD/ton in the rice case. Generally, the majority of countries have a farm-gate price (in all the cases) close to the average. For instance, in the wheat case the weighted average farm-gate price is equal to 188 USD/ton and, as exhibited in Figure 6, the majority of countries have a farm-gate price in the range from 100 to 200 USD/ton. In the Rice and soybeans cases farm-gate prices show a range up to 2500 USD/ton, anyway the majority of countries have farm-gate less than 500 USD/ton. Rice case show an exponential distribution while the rice distribution is not very clear. In the maize case the distribution is very similar to the distribution of farm-gate prices in the wheat case.

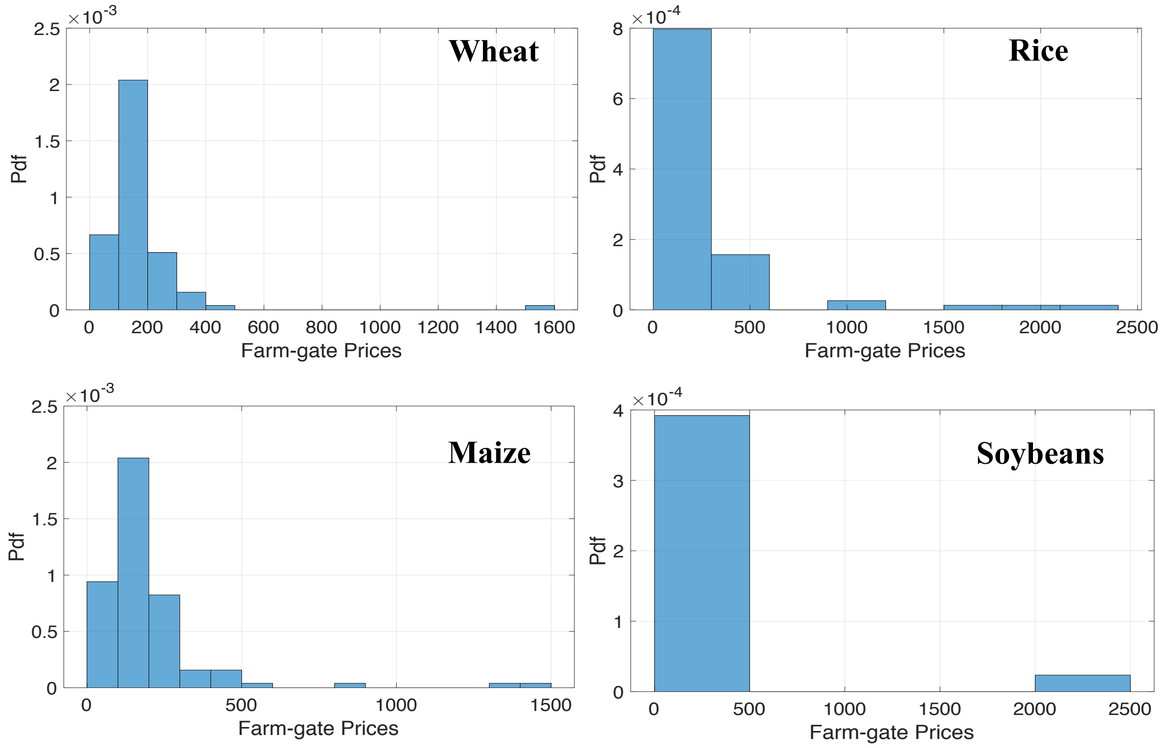

Figure 6:Farm-gate prices probability distribution function of wheat, rice, maize and soybeans (2000)

Generally big producers of a crop are just a restricted group of countries. For instance, the biggest producers of wheat are China, India and USA and the biggest producers of maize are USA and China with amounts greater than 50 million tons (as in Figure 7). Furthermore, big producers do not have a farm-gate prices with high values, but under the average (not weighted). In fact, the farm-gate price of USA in the maize case, which in 2000 produced 251 million tons, was 73 USD/ton against an average value of 201 USD/ton. The overall production in USA in the maize case in 2000 consists in the 43% of the global maize production and for this reason (its weight in term of production) the weighted average farm-gate price is lower (149 USD/ton) than the not weighted value.

This behavior seems to be reasonable in light of the fact that prices reflect the dynamic of economies of scale, according to which big producers reduced costs per unit that arise from the increased total output of a product.

In the rice case, China India and Indonesia have production greater than 50 million tons meanwhile, in the soybeans case the only country with a essentially great production is USA.

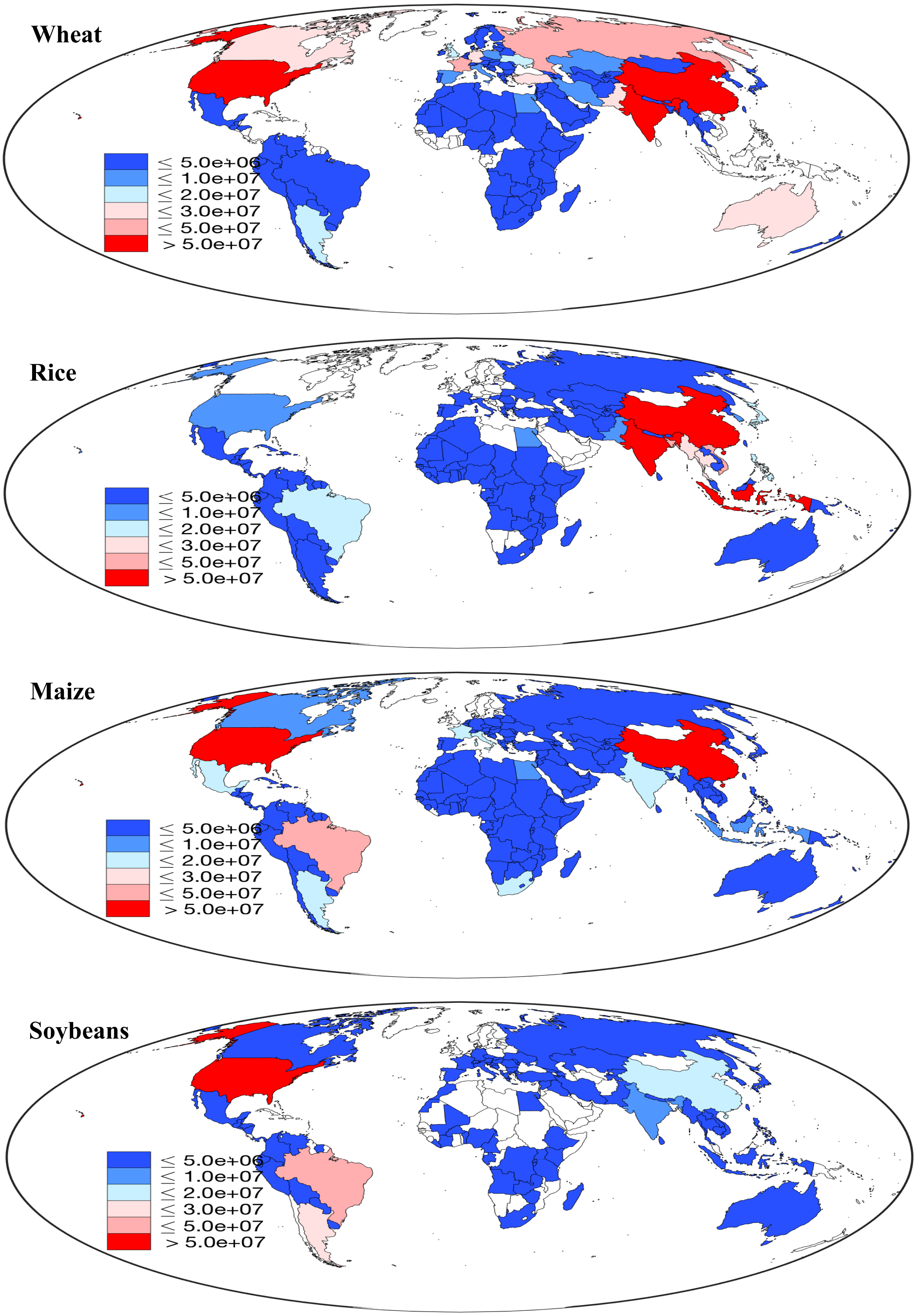

Figure 7: World maps of the production quantities of wheat, rice, maize and soybeans in 2000.

2.3 Yields and Areas

Crop production yields in agriculture refer to the production amount of tons per hectare. Meanwhile areas refer to the harvested hectares of land. Those parameters can be divided into rainfed yields in corresponding rainfed areas and irrigated yields in the corresponding irrigated areas. Of course, irrigated lands are also exposed to rain, therefore, the irrigated component also takes into account the green water. The data set of reference has been withdrawn from GAEZ platform (Global Agro-Ecological Zones) that is collocated inside of the Food and Agriculture Organization of United Nations platform.

Dataset for both rainfed and irrigated yields, and dataset for the areas, both rainfed and irrigated, are referred to actual values in the year 2000 calculated by 5 arc-min grid-cell model following procedures of GAEZ Module VI (actual yield and production) in which statistics arises mainly from FAOSTAT and the FAO study AT 2015/30.

The two main stages of this method are the estimation of shares of rainfed or irrigated harvested land (5 arc-min grid-cell) and the estimation of areas, yields and production quantities in the rainfed and irrigated harvested land shares. The details of this technique can be found in the GAEZ v.3.0 Global Agro Ecological Zones.

Therefore, for the sake of understanding the dimension of the instance values of both irrigated and rainfed yields will be described.

At first, Figure 8 exhibits the probability distribution function of rainfed yields, respectively for wheat, rice, maize and soybeans. The average value of irrigated yield is almost the same in wheat, rice and maize case, as illustrated in Table 3, while soybeans case is lower (equal to 1.568 ton/ha). Maize first and wheat second, show the most spread out distributions with high values of standard deviation, i.e. respectively 2.483 and 1.957 ton/ha. All the distributions show an asymmetric behavior, especially in the maize case that seems to be well approximated with an exponential distribution, while others seem to follow a lognormal trend.

Figure 9, meanwhile, exhibits the distribution among nations of irrigated yield for the four staple crops. As expected, in average values are higher than rainfed averages, indeed they vary from 2.188 ton/ha (soybeans) to 4.976 ton/ha (maize). The soybeans case is the leas spread with the lowest standard deviation (as it is shown in Table 3). Rice distribution shows a sort of normal distribution. Maize shows the most asymmetric distribution that can be approximated, as in the previous case, with an exponential distribution. The yield of irrigated maize is the most spread out also in this case.

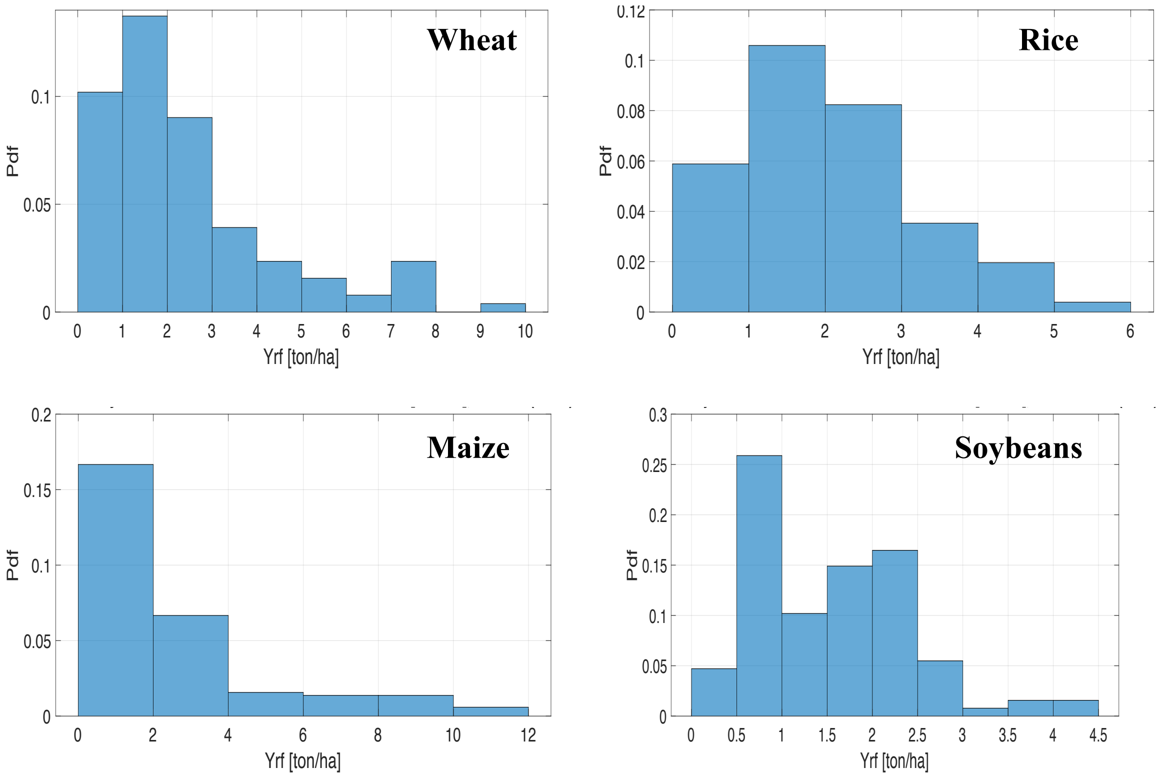

Figure 8: Probability distribution function of rainfed yield for wheat, rice, maize and soybeans in 2000.

Parameter	Crop	Global Average	Global Standard Deviation
Yirr [ton/ha]	Wheat	3.69	1.98
	Maize	4.98	3.44
	Rice	3.84	1.69
	Soybeans	2.19	0.75
Yrf [ton/ha]	Wheat	2.46	1.96
	Maize	2.65	2.48
	Rice	2.11	1.15
	Soybeans	1.57	0.85

Table 3: Global Average and Global Standard Deviation of Irrigated Yield and Rainfed Yield.

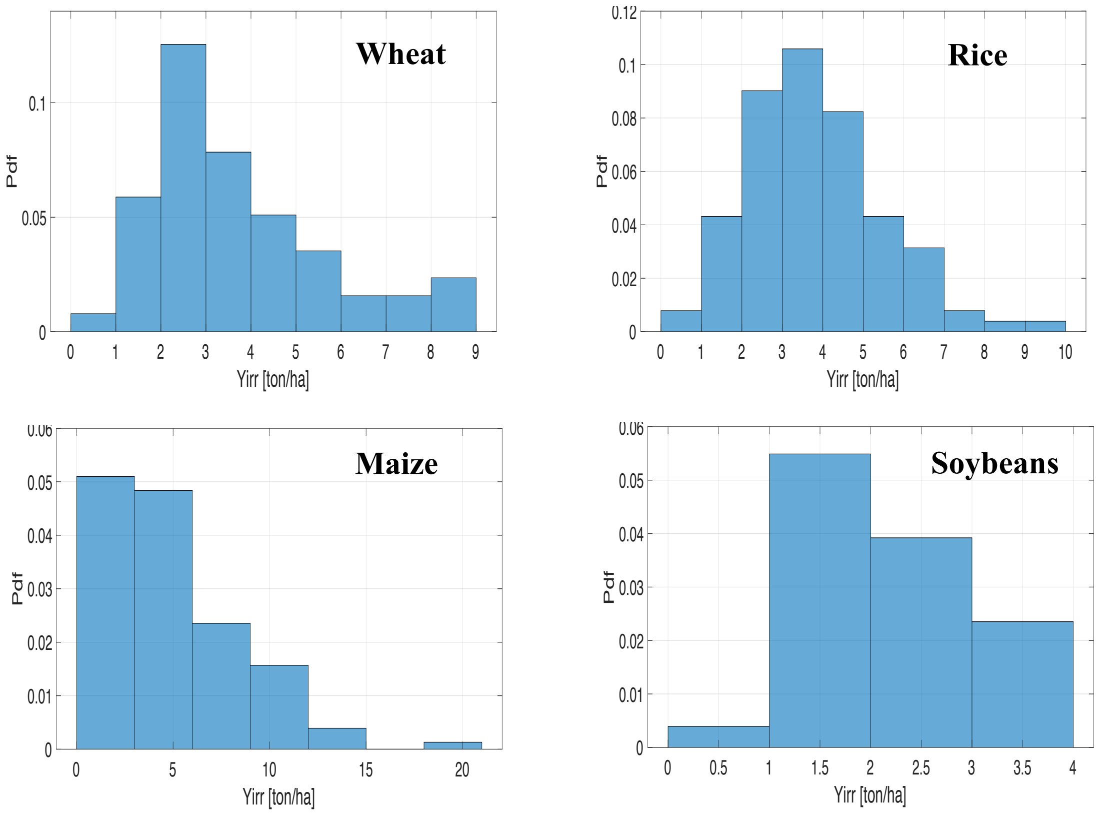

Figure 9: Probability distribution function of irrigated yield for wheat, rice, maize and soybeans in 2000.

Figure 10 exhibits the world maps of rainfed yield and irrigated yield respectively for wheat, rice, maize and soybeans in the year 2000. In the wheat case Europeans countries are the most efficient in both cases (rainfed and irrigated) with yields greater than 5 tons/ha. Among the big producers of wheat, namely China, India and USA, USA is the most efficient in both rainfed and irrigated production, followed by China and India. Generally, it is possible to affirm that irrigated yields are punctually (for each country) higher than rainfed yields.

Rice and maize show highest values of irrigated yields, in a lot of producer countries greater that 5 tons/ ha, while irrigated yields in the soybeans case are the lowest.

Moreover, in the rice case there are more countries that produce irrigated rice instead of rainfed rice, meanwhile in the soybeans case there are more countries that produce rainfed soybeans with respect to irrigated soybeans.

Generally, dry countries such as the Northern Africans have low rainfed yields of production for all the four staple crops and in some cases they do not produce the rainfed crops due to scarce precipitation. Brazil do not produce both irrigated wheat and irrigated soybeans. If in the soybeans case the rainfed yield of Brazil is higher than the majority of the irrigated yield of other countries, this is not true in the wheat case.

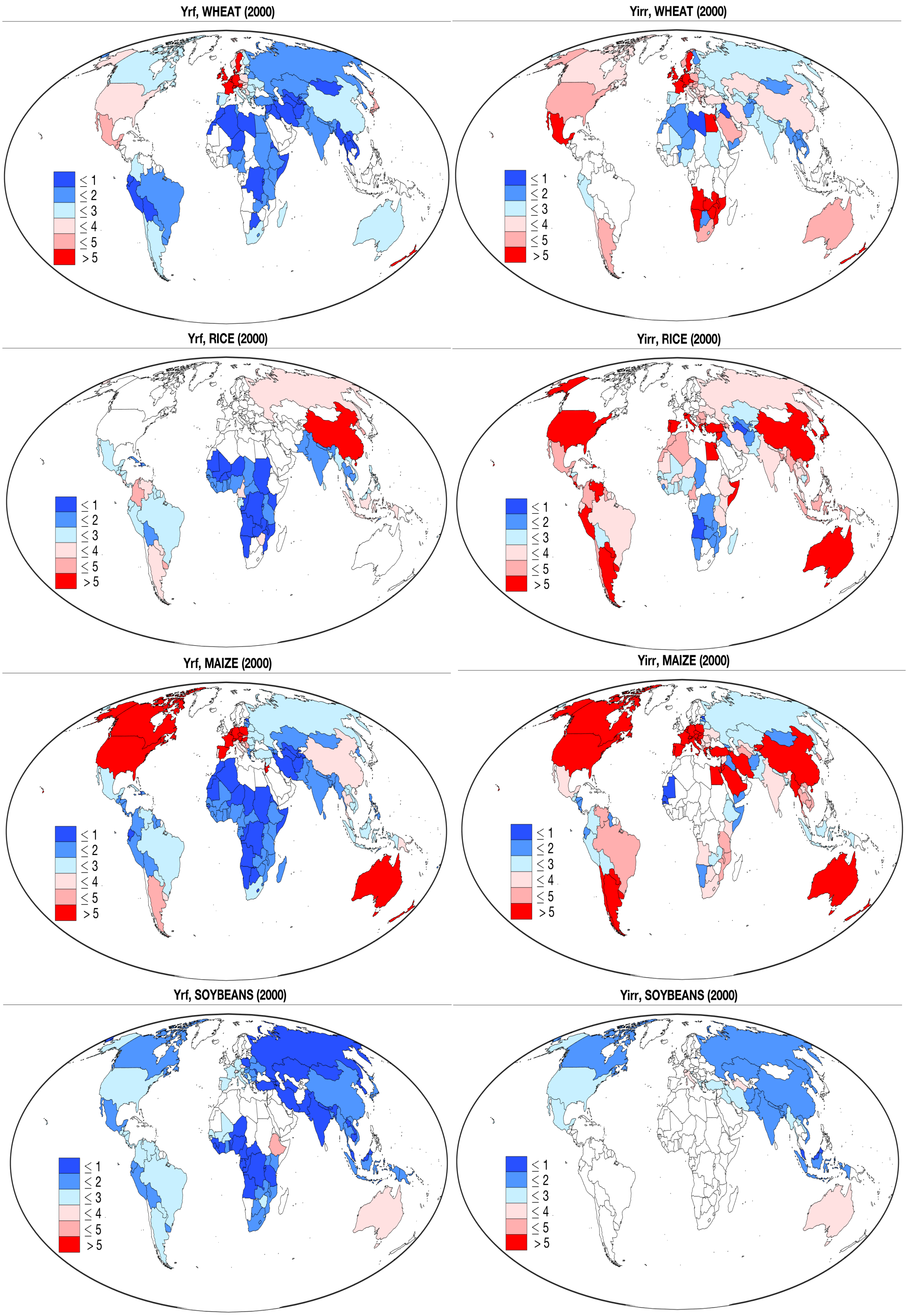

Figure 10: World maps of rainfed yield and irrigated yield (ton/ha) for wheat, rice, maize and soybeans in 2000. Countries depicted in white do not produce the corresponding crop.

2.4 Trade Quantities and Trade Prices

Trade parameters such as exchanged quantities and corresponding prices have been withdrawn from FAOSTAT in the trade section. Indeed, it is possible to get those data as a trade matrix of each product (wheat, rice, maize and soybeans for this study) of the year in question (2000). In each cell (*i,j*) of the trade quantities matrix the amount of tons exchanged between the exporting country (*i*) and the importing country (*j*) has been illustrated. The structure is the same for the trade price matrix in which each cell represents the price of a ton of the crop in object exported by the country (*i*) and imported by another country (*j*).

The trade database is affected by a problem of correspondence between the exporting matrix and the importing matrix, recognized by the technical staff of FAOSTAT itself. In order to solve this issue, both trade prices and trade quantities have been adjusted by an average matrix in which each cell is the average value of the exporting and importing ones.

Furthermore, trade prices in USD are real, indeed they have been deflated in accordance with the global annual average.

Comparing trade prices to farm-gate prices, at first it seems that there are punctual differences but in average they are substantially the same. Indeed, for instance, in the wheat case, the global weighted average of farm-gate prices in 2000 (the weight of each country has been considered the overall production of the country) is equal to 118 USD/ton, same as the global weighted average of trade prices (where the weight of each price has been considered the amount of quantities exchanged between the exporter and the importer).

In order to observe the behavior of the trade prices in wheat case, Figure 11 shows them as a function of farm-gate prices. The size of the bubble is proportional to the quantity of crop traded in the peculiar exchange. The majority of the bubbles, especially the most significant, are localized along the bisector as a proof of the fact that trade prices are not so far from the farm-gate prices. This sounds reasonable in the light of the peculiarity of these crops: food commodities do not have a high added value that can determine a higher price of sell out. The sum of all the bubbles in the diagram is equal to the global trade of wheat in 2000; this amount is almost equal to 119 million tons corresponding to the 20% of the global wheat production in 2000. Figure 12 shows that trade prices of rice are generally above the bisector (greater that farm-gate prices) and in average they slightly higher than farm-gate prices since the weighted average of rice farm-gate price is equal to 171 USD/ton compared to a weighted average of farm-gate price equal to 214 USD/ton. Rice in 2000 has been traded at an amount

equal to the 4% of its overall production and there are more exchanges as a number of links but with corresponding smaller quantities with respect to the other crops.
Meanwhile maize farm-gate prices seem to be higher than trade prices (farm-gate equal to 149 USD/ton and trade price equal to 102 USD/ton) in terms of weighted average with a global export equal to the 14% of its global production. Anyway, Figure 13 shows that biggest exchanges have trade prices really close to the farm-gate prices. In this case there are also big exchanges with a trade price less than farm-gate price. This can be explained by the fact that this farm-gate is substantially greater than the global average and hence not competitive in the global market. Therefore, in the trade context the price is generally set by the market (matching demand and supply) in a competitive environment.
The soybeans case does not delineate a difference in weighted average between the two prices, indeed both are equal to 185 USD/ton, with a global export share equal to 30%. Moreover, also Figure 14 shows that trade prices are substantially equal to farm-gate prices for the most significant exchanges and that they are almost all included in the range from 150 USD/ton to 200 USD/ton.

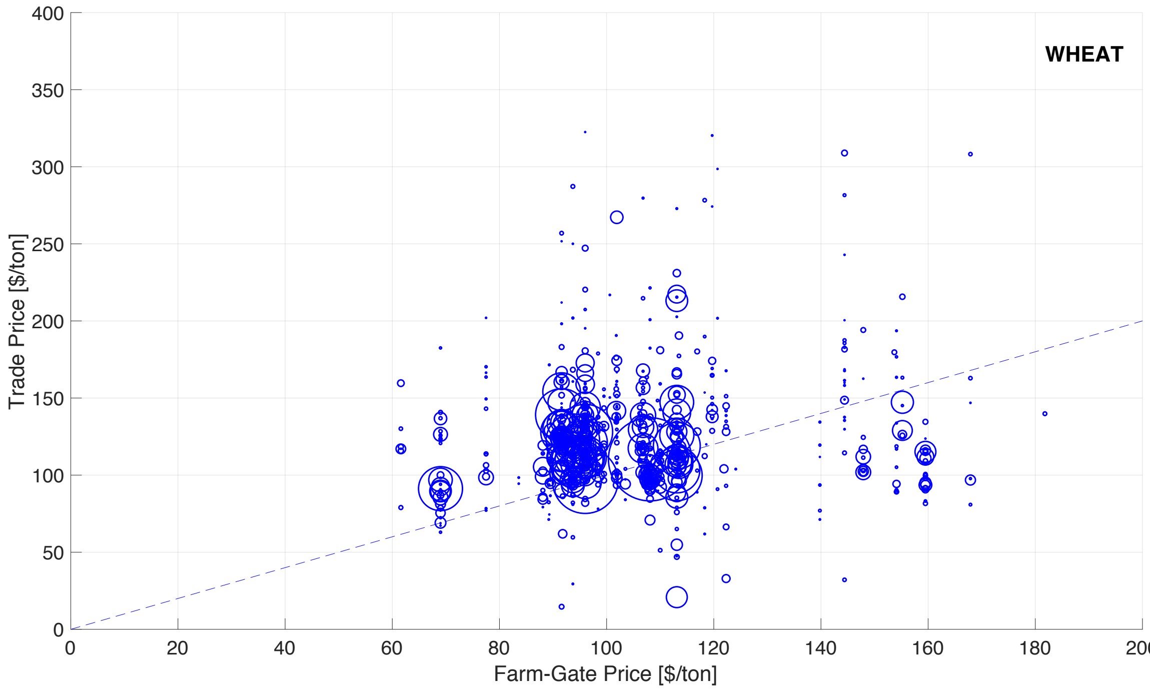

Figure 11: Trade prices as a function of farm-gate prices in the wheat case in the year 2000

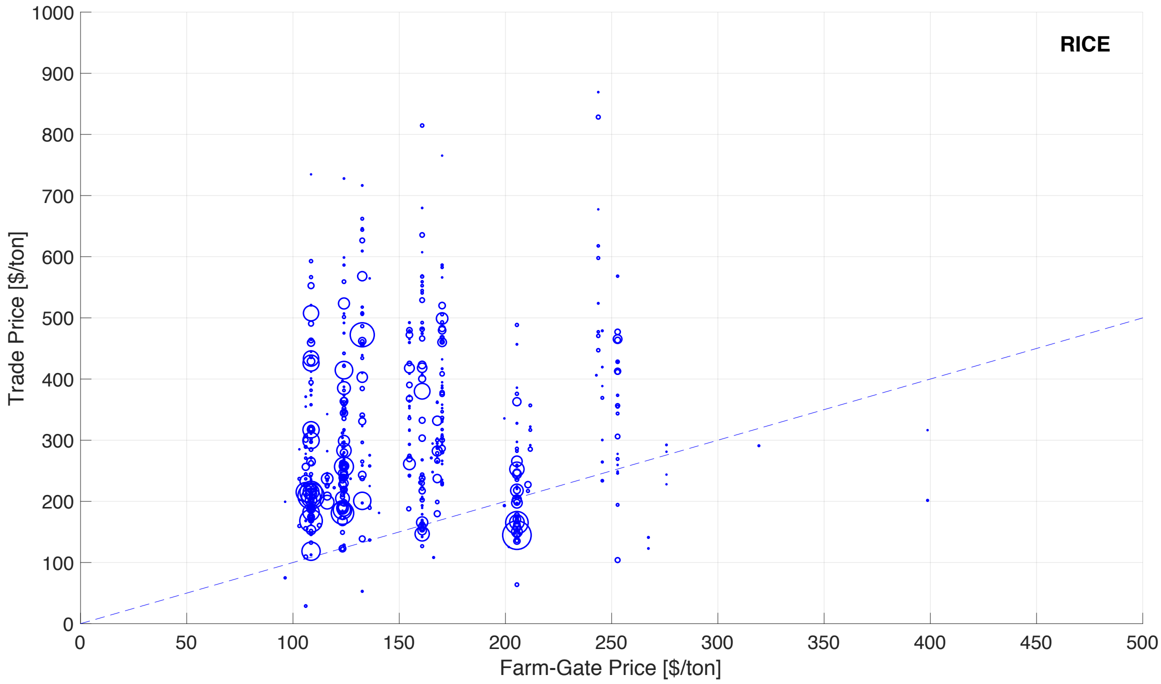

Figure 12: Trade prices as a function of farm-gate prices in the rice case in the year 2000

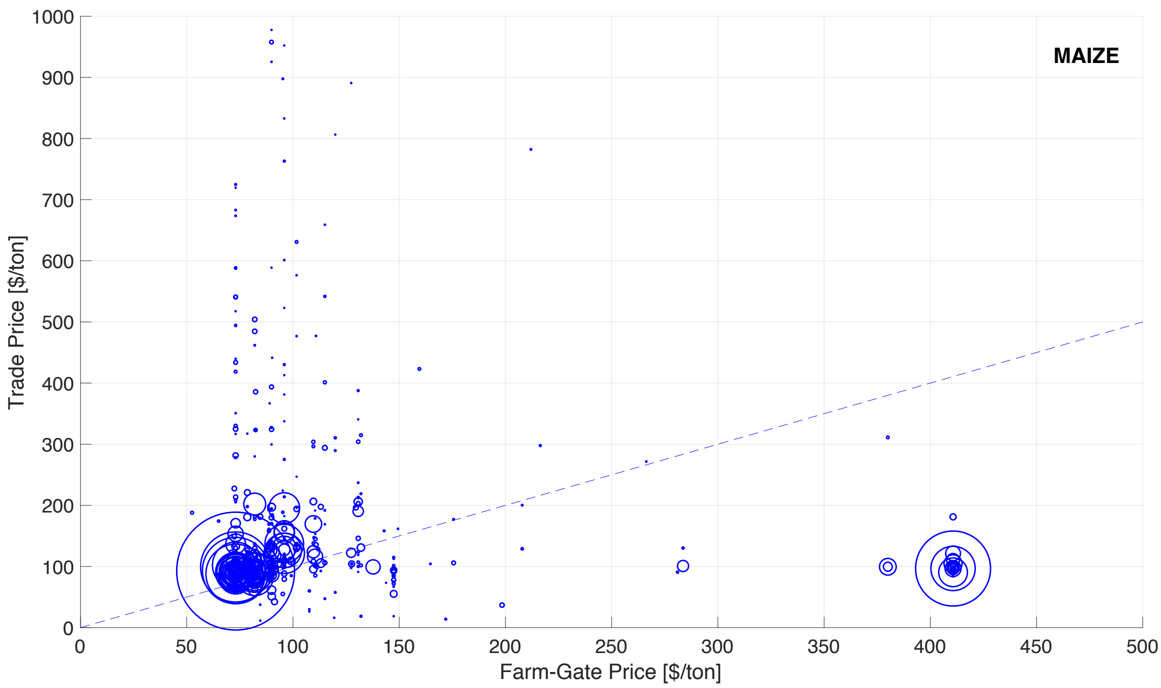

Figure 13: Trade prices as a function of farm-gate prices in the maize case in the year 2000

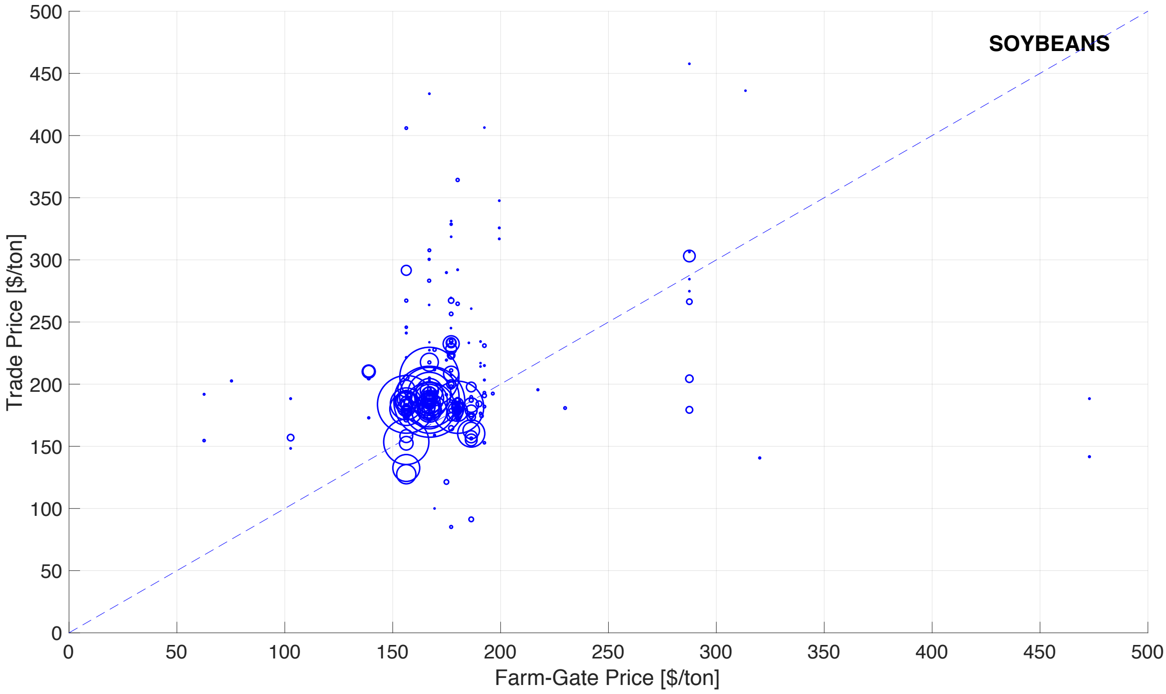

Figure 14: Trade prices as a function of farm-gate prices in the soybeans case in the year 2000.

Thought, it could have been logical to expect trade prices greater than farm-gate prices, but they actually do not follow a specific behavior in aggregate. Indeed, a recent study of Distefano describes the randomness of the distribution of prices at the country scale (*Distefano et al., 2018*). In the study this phenomenon can be explained through the consideration that the average prices at country scale aggregate the heterogeneity that exists at a smaller scale considering together completely different situations or economic actors, such as companies with different dimension. Furthermore, there are also counter-cyclical policies according to which, for instance exporters could set restrictions in order to obtain higher prices to importers. Eventually, consideration needs to be given to the fact that the country scale aggregate price does not show the heterogeneity among products of different levels of quality within the same category of a good.

3 Methods

Estimating the value of water is a complex task due to the fact that water does not have a direct price referred to the raw material. In fact, water is a natural good necessary for life and it is considered a basic human right (right of health established in the International Covenant on Economic Social and Cultural Rights 1976). Otherwise, it has also an economic connotation related to equitably, efficiency and allocation issues. It is due to this connotation that since the International Conference on Water and the Environment in Dublin in January 1992, water has been recognized as a good with economic value (*Anisfeld, 2010*).

There are different points of view about water pricing. At first, it is intuitive to think that water should be free since it is nature's gift that belongs to the public. But, upon reflection, it is also logical to consider extraction cost, the cost associated with the maintenance of the delivery infrastructure system and treatments cost. However, the economist point of view includes also the value of the raw natural water itself, that must be compared to the marginal cost of water distribution (What is the distribution cost associated with the last increment of water?) and the opportunity cost (What is the value related to the other uses of water?). This approach could sound coldhearted, but after a deeper reflection it can be considered similar to two other cases: oil and food. Oil, which like water is a naturally available resource, however this fact does not justify the absence of an economic value attached to oil. Food too like water and oil is another naturally available resource, key to human survival but, in spite of that, markets set prices for it. On the other end, hopefully it is encouraging to see that in many countries prices have been maintained artificially low thanks to affordability policies and subsidies to the agriculture industry (*Anisfeld, 2010*).

Furthermore, there are other questions about water pricing associated with the huge variety of water uses, the nature of water sources ownership and the natural monopoly in the water delivery market.

Nevertheless, the goal of this study is the economic valuation of water, i.e. water pricing, under a new point of view.

Therefore, in the following analysis the engineer point of view in evaluating water is showcased. Firstly, it has been considered that the largest societal use of water is the

consumption for food production (*Falkernmark and Rockström, 2004*) and in particular crop irrigation represents 70% of the overall freshwater withdrawal for human use. Thus, the scope of this study is the agriculture industry, considering crop production and trade.
Before proceeding with the description of the method, it is interesting to consider that the value of a resource can be accounted for its economic yield or the value that that resource can produce. In other words, this means to evaluate what is the economic return on investment of a unit of the specific resource considered.

3.1 The Global Crop Production

Therefore, for the sake of the estimation of water economic value in the agriculture, the blue water productivity in terms of additional production quantity has a crucial role. In fact, the increase of crop production yields can rely heavily on additional irrigation water, especially in such areas where the actual rainfed yield is far away from the potential yield. This approach leads to the fact that an additional amount of blue water can bring an improvement in production expressed in an added revenue. Therefore, the maximum value that a farmer would be willing to pay for blue water is the economic return of the blue water minus the eventual cost that arises from providing an additional unit of water. In this case, due to the structure of data, values are estimated for countries in which crops have been already irrigated and so the cost of the irrigation system is defined as a sunk cost. Which means that the irrigation system infrastructure cost does not affect the choice of delivering less or more water because it has already been accounted for in a previous period. What can affect the decision of using more water could be the additional cost of maintenance of the system per additional cubic meter released and the cost of an eventual extension of the irrigation system infrastructure. These last costs have not been considered in this chapter since there are not enough data available at country scale.
Thus, speaking about the production gain due to irrigation there have been considered two scenarios in the crop production:

- The real scenario composed by actual rainfed harvested areas (A_R) and irrigated harvested areas (A_I), measured in hectares, with the corresponding actual rainfed yield (Y_R) and irrigated yield (Y_I), expressed in tons per hectare;

- An *all rainfed* scenario, where the overall amount of harvested areas is considered not irrigated and, therefore, the yield is the rainfed one.

Hence, the overall production (*PR*) in the real scenario will be express as

$$PR_{k,i} = (Y_{R,k,i} \cdot A_{R,k,i}) + (Y_{I,k,i} \cdot A_{I,k,i}) \qquad [ton]; \tag{2}$$

meanwhile the production in the *all rainfed* scenario (PR_{all}) will be calculated as

$$PR_{all,k,i} = (Y_{R,k,i} \cdot A_{R,k,i}) + (Y_{R,k,i} \cdot A_{I,k,i}) = Y_{R,k,i} \cdot (A_{R,k,i} \cdot A_{I,k,i}) \qquad [ton], \tag{3}$$

where k (k=1:4) and i (i=1:255) are respectively the staple crops (wheat, rice, maize and soybeans) and the 255 countries taken into account for this study.

Eventually, the increase in crop production (ΔPR) resulting from irrigation will be the difference between the real production and the production in the *all rainfed* scenario as

$$\Delta PR_{k,i} = \left(Y_{I,k,i} - Y_{R,k,i}\right) \cdot A_{I,k,i} \qquad [ton]; \tag{4}$$

where, assuming other factors as constants, the difference of irrigated yield and rainfed yield is the additional amount of tons per hectare of a certain crop (k) within a country (i) due to the use of blue water for irrigation in a year.

This increase is the first factor in equation (4) and it can be expressed as

$$\Delta Y_{k,i} = \left(Y_{I,k,i} - Y_{R,K,i}\right) \qquad [ton/ha]\,. \tag{5}$$

That means that lands that have been irrigated are expected to be more productive than rainfed ones. In the wheat production, for instance, the Y_R of China in 2000 is equal to 2.31 ton/ha, while its Y_I is equal to 3.64 ton/ha. In this case the ΔY will be equal to 1.33 ton/ha as a measure of additional amount of tons in irrigated harvested lands.

Therefore, in order to confront the additional amount of production (ΔPR) of different countries, taken into account the blue water efficiency, the additional production has to be normalized by the total consumption of cubic meters of blue water.

This leads to the blue water productivity increase (BWP) as the additional amount of tons of crop (k) per water unit [m^3] in a country (i), i.e. the additional production that arise from using a particular amount of blue water.

This amount can be estimated as the production increase (equation 4) divided by the blue water overall consumption (BW) in cubic meters, as

$$BWP_{k,i} = \frac{\Delta PR_{k,i}}{BW_{k,i}} = \frac{\left(Y_{I,k,i} - Y_{R,k,i}\right) \cdot A_{I,k,i}}{BW_{k,i}} \qquad [ton/m^3]. \tag{6}$$

Thus, the total consumption (BW) of blue water used in the corresponding irrigated lands lands has been calculated as

$$BW_{k,i} = BWF_{k,i} \cdot PR_{k,i} \qquad [m^3]\,, \tag{7}$$

Where $BWF_{k,i}$ $[m^3/ha]$ is the blue water footprint for each crop (k) within the specific country (i) and $PR_{k,i}$ $[ton]$ is the overall actual (real) production (rainfed and irrigated as in equation 2) of a certain crop within the country in a year.

Therefore, blue water productivity increase can be seen as a measure of blue water yield, taking into account the combination of the production efficiency and the water efficiency.

The more a country is efficient in the production of irrigated lands the more it will obtain extra tons of crop.

For the sake of investigating a measure of price for water, the focus will shift to the increase of economic value that is possible to extract from the injection of blue water in the production system. This analysis will make it is possible to obtain an economic valuation of the increase of productivity resulting from irrigation transforming the extra amount of tons of crop in extra income of USDs. Indeed, with all other production factors constant among irrigated and rainfed production, the extra value obtained from the sale of extra tons resulting from irrigation (through the price of the crop) will be the economic return of water, i.e. the economic yield.
This value normalized by the overall amount of BW, namely the Blue Water Unit Value for each crop (k) in the country (i) is

$$BWUV_{k,i} = P_{FG,k,i} \cdot BWP_{k,i} \qquad [\$/m^3] , \tag{8}$$

where $P_{FG,k,i}$ is the farm-gate price, i.e. the value of a ton of a certain food commodity (k) in USD exiting the production step, in the value-chain process, within the country (i).
Basically the $BWUV_{i,c}$ is the productivity increase of the blue water in terms of production multiplied by the value of a ton of the crop.
Developing the numerator and denominator, $BWUV_{k,i}$ can be written as

$$BWUV_{k,i} = P_{FG,k,i} \cdot \frac{\left(Y_{I,k,i} - Y_{R,k,i}\right) \cdot A_{I,k,i}}{BWF_{k,i} \cdot PR_{k,i}} \qquad [\$/m^3] . \tag{9}$$

In the interest of comparing blue and green water, it has been calculated also the economic value of the latter. Even if, in this case, Green Water Unit Value ($GWUV$) will not be seen in the logic of price but as a gross economic yield. Thus the economic value of green water will be calculated as a measure of benchmark in terms of gross productivity.
Indeed, the BWUV can be seen as the incremental productivity in terms of tons, and due to that reason (the incremental logic) it will be seen as the net added value of blue water. Thus, it can also be seen as the cap value that a farmer could pay blue water in irrigation, as it is

the net economic return (the increment of production is just due to additional irrigation, while other factors are constant) of a unit of blue water used in agriculture for crop production.
In the light of this, Green water unit value can be expressed as

$$GWUV_{k,i} = \frac{P_{FG,k,i}}{GWF_{k,i}} \qquad [\$/m^3]; \tag{10}$$

where the numerator is simply composed by the farm-gate price of the crop (k) within the country (i) in USD/ton, while the denominator is the Green Water Footprint of the crop (k) within the country (i). In fact, in this case it has been simply considered the dollars resulting from the sale of a ton of crop divided by its green water footprint.

3.2 The Global Crop Trade

Once the value of blue water in the crop production context has been estimated, it is of interest to investigate this parameter in the global food trade.

Using the same logic as in the global crop production, it will be possible to estimate the correspondent value of a unit of blue water in the global trade. This means using the same productivity of blue water estimated in the production environment, described in the previous section, but using trade prices instead of farm-gate prices.

In this case, the issue consists in the fact that for each country there will be a set of trade prices, i.e. one for each exchange with a different country.

Thus, it is possible to obtain a singular value of water for each exchange between countries and this lead to a set of numbers of $BWUV$ for each exporting country.

Therefore, they have been defined exporter countries with the index i (i=1:255), importer countries with the index j (j=1:255), and eventually the index k refers, as in the production case, to the four staple crops in object (k=1:4). The vector of exporters and importers is composed by the same list of countries. For this reason, all the parameters will be calculated as matrixes 255x255 where not always the cells are all full, or rather there will be a lot of cell equal to 0 because not all the countries have trade with every country.

All the following matrixes will be calculated for each crop k.

Hence, $BWUV\_TR_{i,j}$ is the matrix of blue water unit value in the global trade that arises in the exchange of a crop (k) between the exporter country (i) and the importer country (j), calculated by multiplying the trade price with of the exchange (i,j) by the blue water productivity of the exporter, as

$$BWUV\_TR_{i,j} = P_{TR,i,j} \cdot BWP_i \qquad [\$/m^3]\ , \quad \forall k \tag{11}$$

where $P_{TR,i,j}$ [$] is the matrix (255x255) of trade prices of a crop (k) exchanged between the exporter (i) and the importer (j) and BWP_i $[ton/m^3]$ is the vector (255x1) of blue water productivity calculated in the production stage of a crop (k) within the exporter (i).

Furthermore, it is possible to estimate the amount of blue water globally traded that is used in irrigation. Indeed, each amount of crop (k) exchanged from the exporter (i) to the importer (j) leads to the virtual blue water content of each link, the matrix of Blue Water Traded (BW_TR), calculated as

$$BW\_TR_{i,j} = BWF_i \cdot TR_{i,j} \qquad [m^3]\,, \quad \forall k \tag{12}$$

i.e. multiplying the vector of blue water footprint (BWF, 255x1) by $TR_{i,j,k}$, that is the square matrix (255x255) of the amount of tons of a crop (k) exchanged between the exporter (i) and the importer (j), so that it is possible to estimate the virtual cubic meters of water traded resulting from irrigation.

In order to investigate the economic relevance of the blue water trade, it is also possible to estimate the value of each link, thus the matrix of Blue Water Value Traded ($BWV\_TR_{i,j}$, 255x255), multiplying the blue water traded $BW\_TR_{i,j}$ by the corresponding unit value $BWUV\_TR_{i,j}$, as

$$BWV\_TR_{i,j} = BW\_TR_{i,j} \cdot BWUV\_TR_{i,j} \qquad [\$], \quad \forall k \tag{13}$$

Both BW_TR and BWV_TR are square matrixes with dimension equal to 255x255.

In conclusion, the unit value of blue water in trade is expected to be comparable to the one in the production case due to the fact that in both of the cases the basis is the productivity in terms of yield. The only discrepancy is the difference between farm-gate and trade prices, but this has been already discussed in the previous chapter.

4 Results of Blue Water Valuation in the Global Crop Production

In this chapter the results of the analysis in the global crop production context will be illustrated.

The spatial distribution of parameters will be illustrated through maps and plots. The behavior of blue water value in the crop production will be study and, eventually, the relationship between parameters in order to understand the global trend will be analyzed.

4.1 Distribution of Blue Water Productivity and Blue Water Unit Value

In order to introduce the dimension of the issue, Table 4 shows the parameters Blue Water Productivity (*BWP*), Green Water Unit Value (*GWUV*) and Blue Water Unit Value (*BWUV*) for the four staple crops (namely wheat, rice, maize and soybeans). Thus, the minimum, the maximum, the weighted average and weighted standard deviation have been accounted for. Therefore, it is possible to observe almost the same order of magnitude among the different crops for each parameter, so that in average there are not substantial differences between the four different crops. In order to obtain representative estimation of the parameters, averages and standard deviations are calculated between countries taking into account that each country has a different importance. In fact, the weight has been considered as the overall amount of blue water in cubic meters consumed in the year 2000 within nations for agricultural use for Blue Water Productivity and Blue Water Unit Value, meanwhile the weight of Green Water Productivity is the overall amount of green water in cubic meters in 2000 within a country. It means that the more a country uses blue water the more relevant it will be in the estimation of the average of Blue Water Productivity and the average of Blue Water Unit Value, in order to filter not significant contributions. Averages of blue water productivity (*BWP*) are roughly very similar between crops (wheat, rice, maize and soybeans) with the highest value (in average) being found for the case of maize (0.001 ton/m^3). The corresponding weighed standard deviations are significantly high and it means that values are widespread and that there is a substantial geographical heterogeneity. Furthermore, estimations of Blue Water Unit Value (*BWUV*) approximately vary from 0.036 USD/m^3 (soybeans) to 0.190 USD/m^3 (maize). The corresponding weighed standard deviations are high, in particular they are higher than the corresponding averages, with a coefficient of variation greater than the unit. This underlines a great level of dispersion of data around the mean. Green Water Unit Value (*GWUV*) numbers are included in the range of BWUV values and vary from 0.049 USD/m^3 (soybeans) to 0.165 USD/m^3 (maize). The weighted standard deviation of *GWUV* is, crop by crop, a slightly lower than the weighted standard deviation corresponding to the *BWUV* with the exception of rice.

Parameter	Crop	Minimum Value	Maximum Value	Weighted Average	Weighted Standard Deviation
BWP [ton/m^3]	Wheat	$4.23 \cdot 10^{-8}$	0.09	$5.19 \cdot 10^{-4}$	$7.20 \cdot 10^{-4}$
	Maize	$1.11 \cdot 10^{-7}$	0.04	$1.00 \cdot 10^{-3}$	$1.00 \cdot 10^{-3}$
	Rice	$1.38 \cdot 10^{-7}$	$2.00 \cdot 10^{-3}$	$3.57 \cdot 10^{-4}$	$2.201 \cdot 10^{-4}$
	Soybeans	$4.44 \cdot 10^{-8}$	0.02	$1.61 \cdot 10^{-4}$	$4.74 \cdot 10^{-4}$
GWUV [\$/m^3]	Wheat	0.02	0.90	0.10	0.08
	Maize	0.01	3.78	0.17	0.16
	Rice	0.02	2.41	0.12	0.29
	Soybeans	0.02	0.61	0.05	0.03
BWUV [\$/m^3]	Wheat	$4.58 \cdot 10^{-6}$	7.82	0.07	0.08
	Maize	$1.24 \cdot 10^{-5}$	4.34	0.19	0.24
	Rice	0.01	2.52	0.06	0.18
	Soybeans	$7.14 \cdot 10^{-5}$	5.47	0.04	0.16

Table 4: Calculated values of Blue Water Productivity (BWP), Green Water Unit Value (GWUV) and Blue Water Unit Value (BWUV) in 2000. The weight in the estimation of the average and standard deviation is the total amount of blue water withdrawal inside the country for the year in cubic meters (BW m^3) for BWP and BWUV, meanwhile the weight of the average and standard deviation of GWUV is the overall amount of green water within the country for the year.

Before proceeding, it is important to remind that only countries with both irrigated and rainfed lands for the same crop will be represented, indeed the basis of this analysis is the increase of production yield and this can be calculated just for the cases where data of rainfed and irrigated yields is available.

Therefore, in order to better comprehend the distributions of *BWP*, i.e. the additional tons per cubic meter of blue water, distributions for wheat, rice, maize and soybeans will be illustrated in Figure 15. They show bar diagrams of Blue Water Productivity in terms of tons per m^3 and in correspondence of each bar, a bubble proportional to Blue Water (*BW*) appears. BW embodies the total amount of fresh water (m^3) withdrawn for agriculture within the country in 2000.

Generally, for all the four staple crop, it seems that countries with higher values are not significant from the stand point of Blue Water, thus they are little consumers of blue water. The case of Bulgaria stands out due to the great difference with other countries. Analyzing the components of the parameter *BWP*, it arises that the blue water foot print accounted in the National Water Footprint Accounts for Bulgaria is really low (equal to 1). Due to the structure of calculations this contribution lead to a considerably high value. Bulgaria is not a big consumer of blue water, thus its contribution to the average value is not really significant. For this reason, the bar diagram of wheat has an upper limit of 0.2 ton/m^3 for *BWP*, meanwhile Bulgaria shows a value equal to 0.9 ton/m^3.

In the rice case, countries have more homogeneous behavior and there are not isolated picks. Generally big consumers, for all the crops, tend to be not so efficient in the increase of yield. Furthermore, this could also be the result of high heterogeneity within the country itself therefore, within the same country there can be high rainfed yields in florid areas with abundant precipitations and high irrigated yields in dry lands. Indeed, in both cases, the biggest consumers of blue water (India, China and Pakistan) are wide countries with different climatic zones within while yields values, in this study, are overall weighed averages.

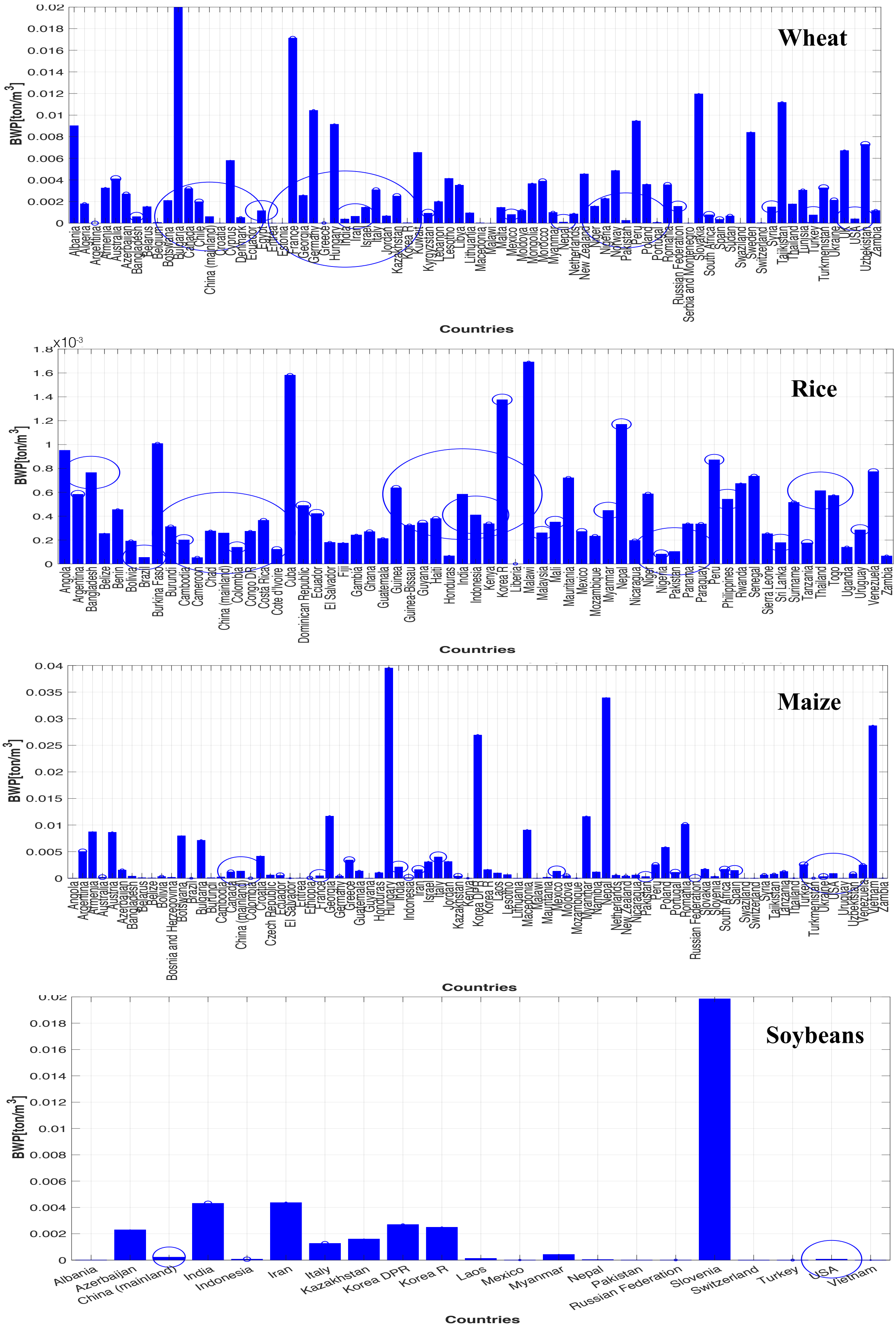

Figure 15: Bar diagrams of Blue Water Productivity Increase for wheat, rice, maize and soybeans in 2000. Bubble size proportional to the overall withdrawal of blue water within the country for the production of the corresponding crop.

Figure 16 shows the spatial distribution of the parameter mapped worldwide, respectively for wheat, rice, maize and soybeans.
The maps depicted in Figure 16 show values for countries that grow both irrigated and rainfed crops, in fact they have been calculated starting from the increase of production yield, that is the difference between irrigated and rainfed yields. So, countries that present just one of those values (e.g. they are just growing irrigated rice) have been excluded from the analysis.
Wheat and maize maps show a similar distribution, where the majority of countries present values equal or less then 0.002 ton/m^3. Furthermore, countries that grow both irrigated and rainfed wheat and maize are generally the same. Irrigated and rainfed rice have both grown in the same country just in the central southern part of the globe. For example, Italy is a producer of rice but does not show value of blue water productivity for it because Italy grows irrigated rice. Thus, due to the structure of the evaluation model and data available, calculating the parameter was impossible.
The Blue Water Productivity values for soybeans are available, contrary to the rice case, in the northern part of the globe.
As opposed to wheat, rice and maize cases, India shows high productivity in terms of tons per cubic meter of blue water in the soybeans case (BWP greater than 0.003 ton/m^3) even if the soybeans numbers are generally lower than the other crops.

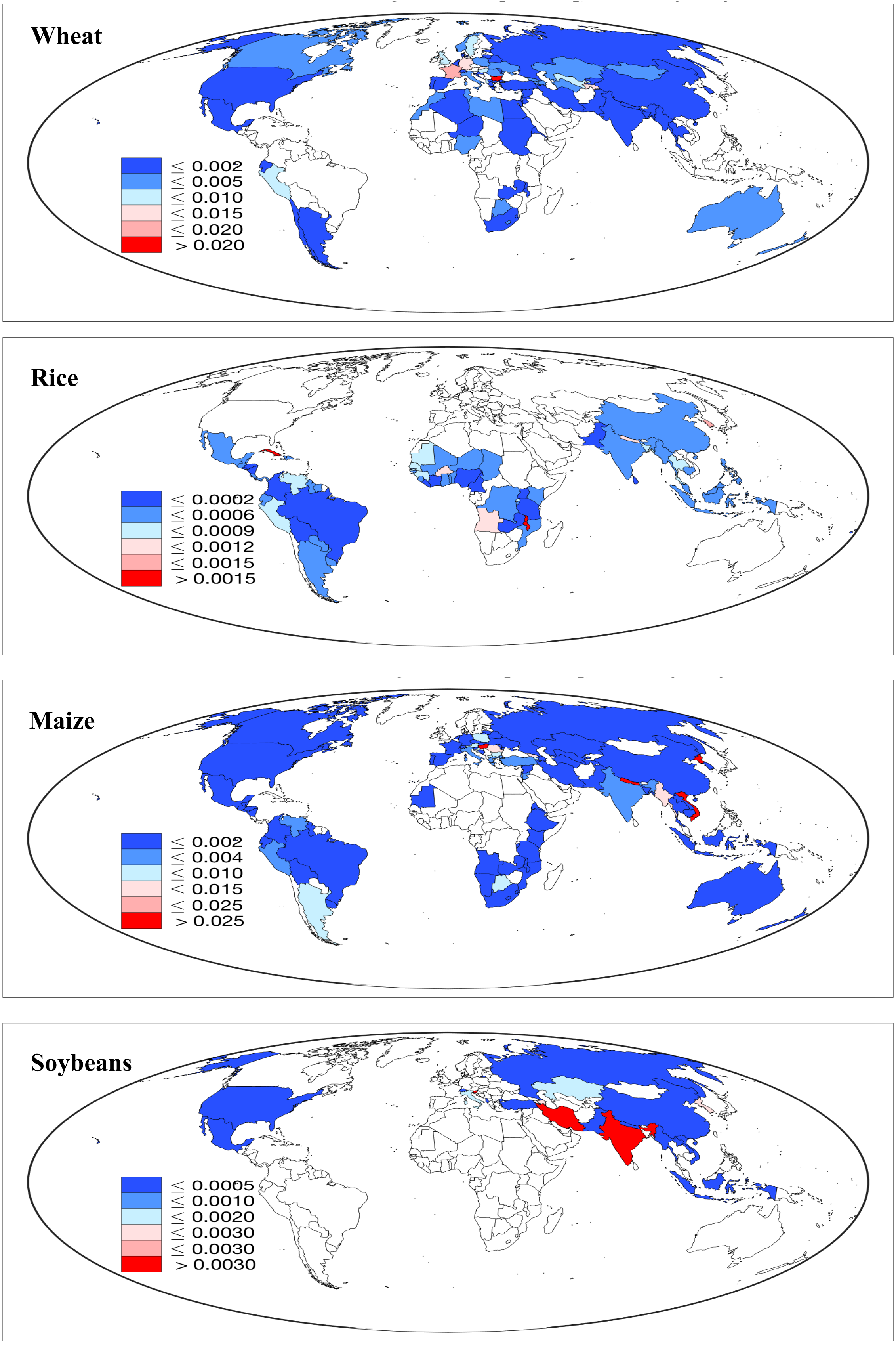

Figure 16: World Maps of Blue Water Productivity for Wheat, Rice, Maize and Soybeans in 2000. Countries that do not produce both rainfed and irrigated crops are depicted in white.

As shown in Table 4, weighted average values of Blue Water Productivity in the year 2000 are almost the same. But punctually the situation is different. For example, in the case of wheat Blue Water Productivity shows the biggest range but not the biggest weighted standard deviation (that is the largest in the maize case). Nevertheless, the majority of countries have low values.

Furthermore, in order to compare the crops global aggregate values of production have been reported along with blue water withdrawal and green water withdrawal. For instance, maize is the crop with the highest average of blue water productivity even if maize and soybeans, as shown also in Table 5, are the least irrigated amongst the four staple crops, meanwhile rice and wheat, that have the lowest averages, are the most irrigated. The biggest global amount of water withdrawal is $3.158 \cdot 10^{11}$ m^3 for the irrigation of rice. Indeed, rice is the most water intensive among the main four staple crops. In the year 2000 rice seems to be the most produced crop with almost 700 millions of tons.

Parameter	Crop	Global Aggregate
BW [m³]	Wheat	$194,270 \cdot 10^6$
	Maize	$41,829 \cdot 10^6$
	Rice	$315,800 \cdot 10^6$
	Soybeans	$18,811 \cdot 10^6$
GW [m³]	Wheat	$721,000 \cdot 10^6$
	Maize	$538,970 \cdot 10^6$
	Rice	$1,060,800 \cdot 10^6$
	Soybeans	$612,450 \cdot 10^6$
PR [ton]	Wheat	$585 \cdot 10^6$
	Maize	$592 \cdot 10^6$
	Rice	$599 \cdot 10^6$
	Soybeans	$161 \cdot 10^6$

Table 5: Global Aggregate values of Blue Water withdrawal, Green Water total consumption and Crop Production in 2000.

Now the Blue Water Unit Value will be brought into attention as it has a central role in this study. This parameter has a behavior similar to Blue Water Productivity, in fact they are proportional. At first, distributions in Figure 17 show for each crop the behavior of *BWUV*. Reminding that weighed averages are 0.068 USD/m^3 for wheat, 0.061 USD/m^3 for rice, 0.190 USD/m^3 for maize and 0.036 USD/m^3 for soybeans and corresponding weighed standard deviations are 0.078, 0.182, 0.240 and 0.162 (USD/m^3), it is possible to notice that even if the probability function distribution of wheat seems the more spread, actually the weighed standard deviation is the lowest between the four staple crops. In fact, the value of Bulgaria (almost 8 USD/m^3) is not relevant due to its little contribution in the irrigation water withdrawal. In general, distributions are similar and show an asymmetric behavior due to the fact that there is major probability of having values in the left side of the distribution, with relatively thin right tail. The distributions seem to be well approximated by exponential trends.

The majority of countries have values close to the average for all the four cases.

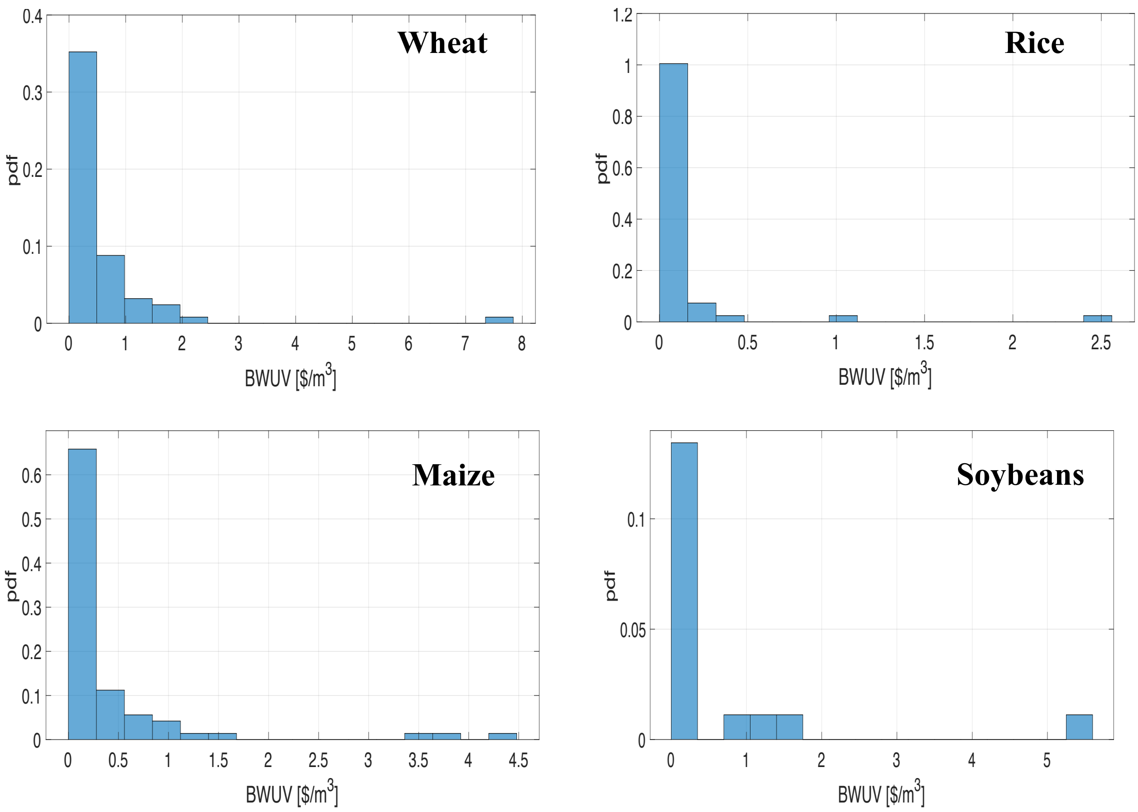

Figure 17: Probability Distribution Functions of BWUV for Wheat, Rice, Maize and Soybeans in 2000.

Figure 18, Figure 19, Figure 20 and Figure 21 illustrate respectively Blue Water Unit Value of wheat, rice, maize and soy of each country in 2000, and the triangle size represents the overall withdrawal of blue water within the country as a measure of weight of single estimated parameters. As well as *BWP*, the highest value of *BWUV* is again for the case of Bulgaria and this anomaly is explained through the considerable contribution of an extreme low value of Blue Water Footprint. In fact, the composition of the total water footprint of this country is almost all Green Water (Green Water Footprint equal to 1,472 m^3/ton, Blue Water Footprint equal to 1 m^3/ton and Grey Water Footprint equal to 367 m^3/ton). In order to make the diagram readable, the cutoff value for *BWUV* has been set at 3 USD/m^3, meanwhile Bulgaria shows a value equal to 7.8 USD/m^3.

In the rice case, the highest number (2.5 USD/m^3) is shown by the Republic of Korea. In this instance, the main contribution of this is the relatively high Farm-Gate Price equal to 1,833.7 USD/ton while the global average value (not weighed) is close to 300 USD/ton. In the maize production, Hungary, Nepal and Vietnam show values equal or greater than 3.5 USD/m^3 due too high BWP values, indeed they have productivities greater that 0.03 additional tons per m^3 of blue water.

Finally, in the soybeans case, there are less data accounted and so less values to observe. The Republic of Korea, similar to the case of rice, presents the greatest value (more than 5 USD/m^3) again for the high Farm-Gate Price (2,201.6 USD/ton) with respect to the global average of 341 USD/ton. Furthermore, it is important to note that countries with highest values of Blue Water Unit Value do not represent big consumers of blue water. On the contrary, countries with wide amount of blue water withdrawal for irrigation show relatively low numbers even less than averages.

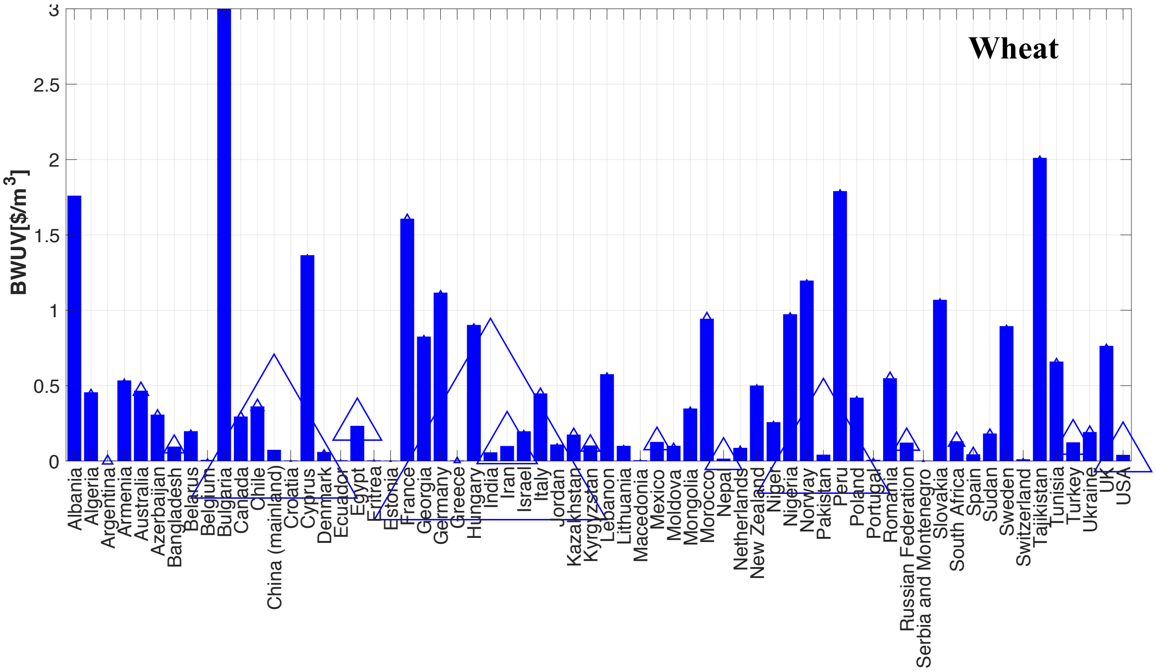

Figure 18: Bar diagram of Blue Water Unit in 2000, Wheat.

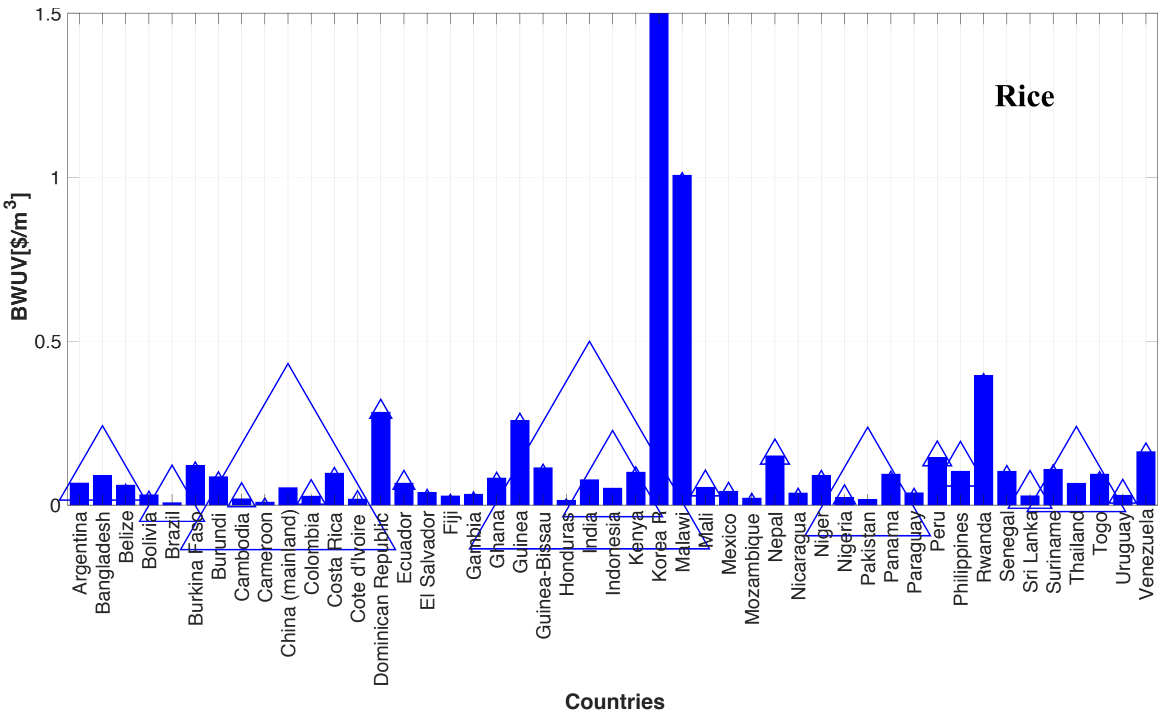

Figure 19: Bar diagram of Blue Water Unit in 2000, Rice.

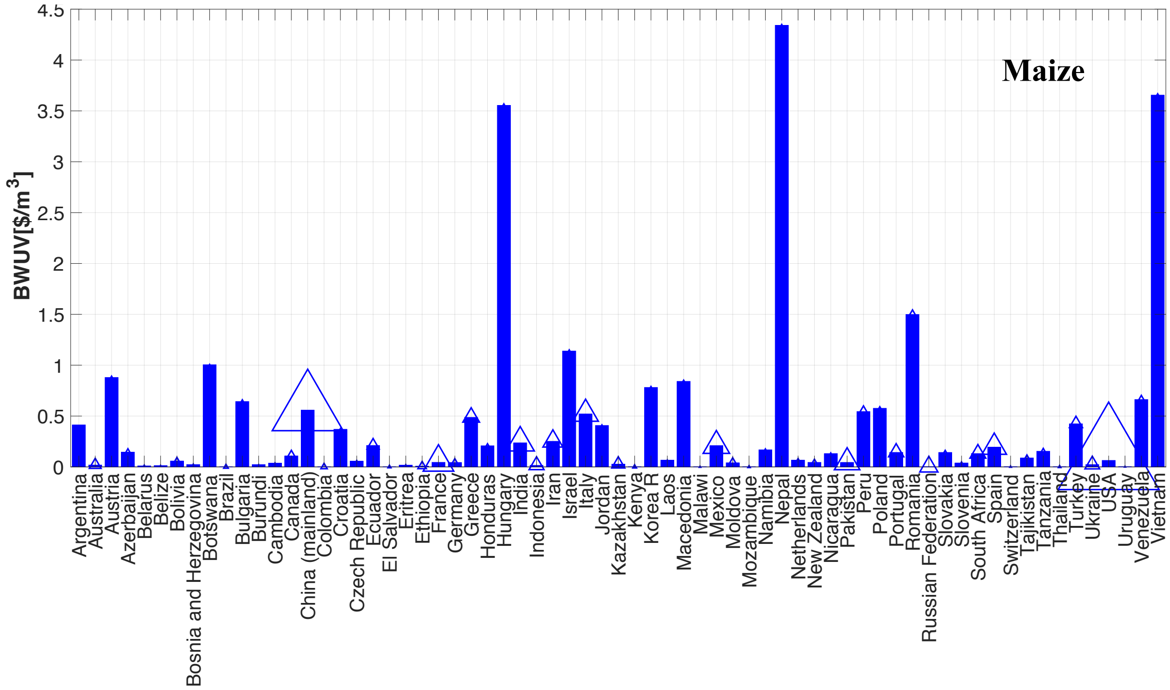

Figure 20: Bar diagram of Blue Water Unit in 2000, Maize.

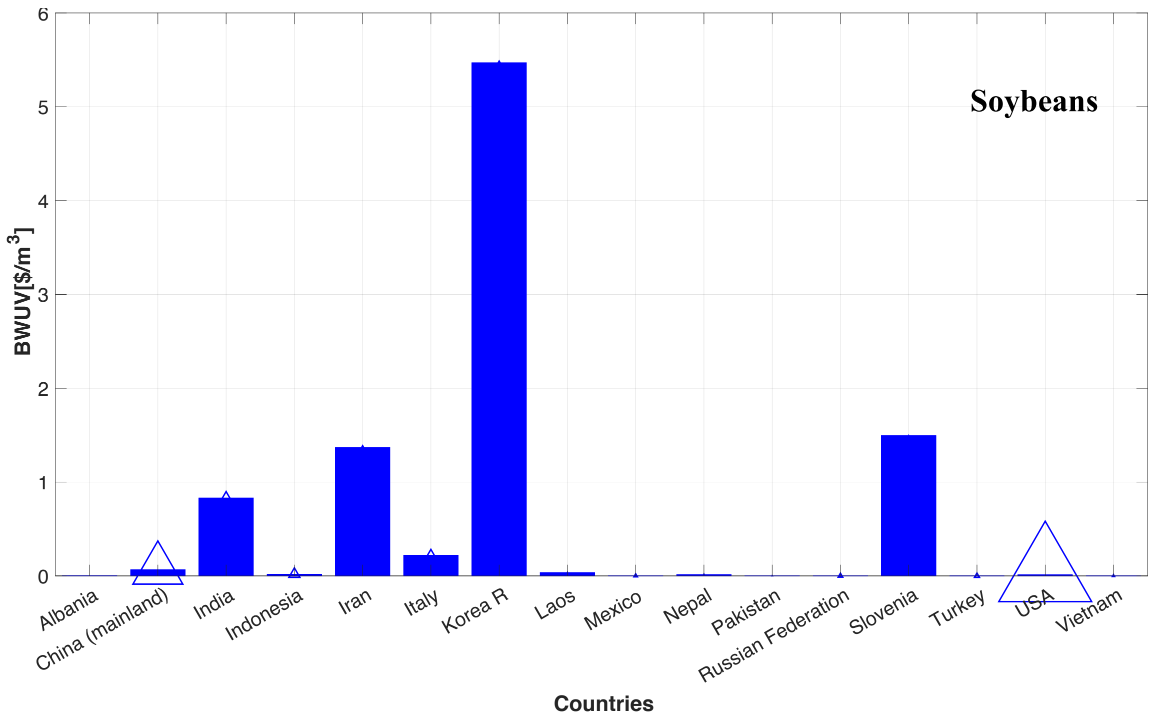

Figure 21: Bar diagram of Blue Water Unit in 2000, Soybeans.

Figure 22 shows the worldwide distribution Blue Water Unit Value for all the four staple crops. In the wheat case the majority of countries have values less or equal the 0.2 USD (weighted average equal to 0.07 USD/m^3). Bulgaria, Peru, Tajikistan and France report the highest water value estimation as a combination of water productivity and farmg-ate prices.
In the rice case, the range of *BWUV* is smaller and the majority of counties show values less than 0.10 USD/m^3.
Maize and soybeans show wide ranges of Blue Water Unit Value and, especially in maize case, the majority of countries have a value less than 0.25 USD/m^3.
In order to compare yields of blue water and green water, Figure 23 illustrates the world maps of Green Water Unit Value in 2000 respectively for wheat, rice, maize and soybeans. For instance, in the wheat case there are no significant differences in terms of weighted average, 0.07 USD/m^3 for Blue Water and 0.09 USD/m^3 for Green water, but there are substantial variations considering country by country situations.
Furthermore, Generally the global distribution of *BWUV* is more spread out compared to the *GWUV* global distribution, especially because the maximum values of *BWUV* are higher than the *GWUV* ones. But there are not significant differences in terms of weighted dispersion, for instance in the wheat case the distribution of Green Water Unit Value has a weighed standard deviation equal to 0.074 USD/m^3 while the weighted standard deviation of Blue Water Unit Value is equal to 0.078 USD/m^3.

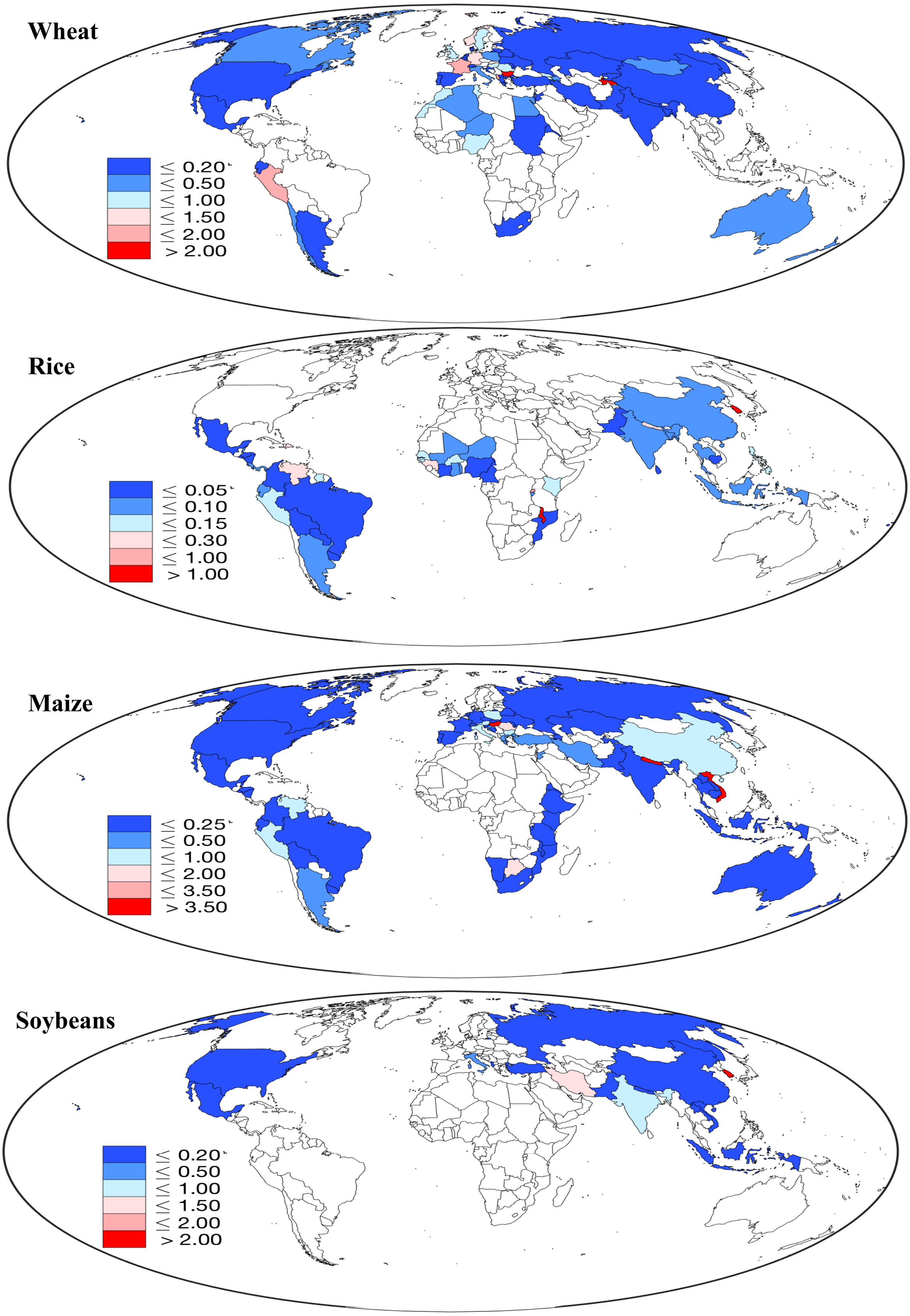

Figure 22: World maps of Blue Water Unit Value, respectively for Wheat, Rice, Maize and Soybeans in 2000. Countries that do not have both irrigated and rainfed production of a crop are represented in white.

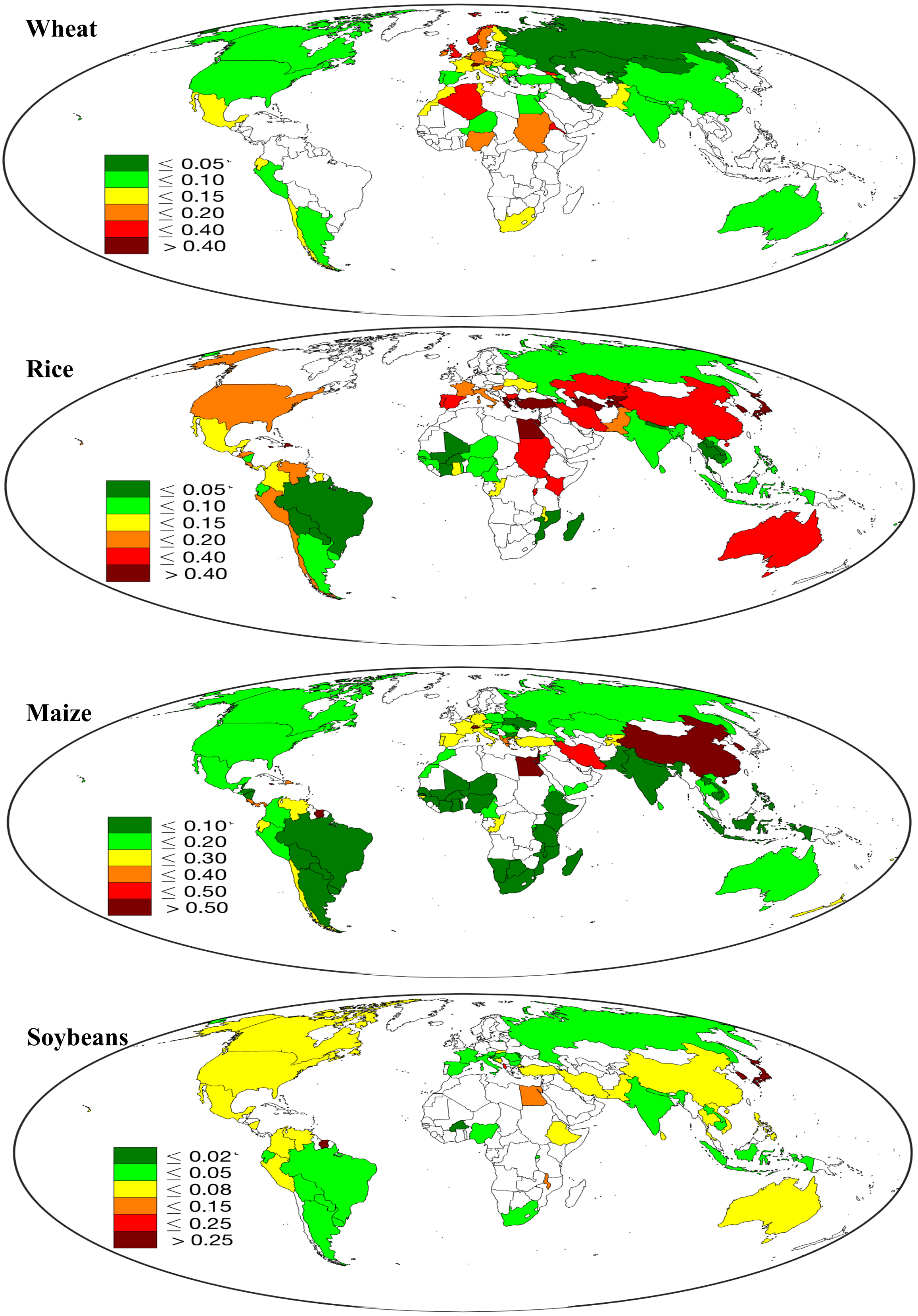

Figure 23: World maps of Green Water Unit Value in 2000 respectively for Wheat, Rice, Maize and Soybeans. Countries that do not have rainfed production of a crop are represented in white.

In order to compare blue water to green water Figure 24 exhibits the bar diagrams of Water Unit Value Ratio respectively for wheat, rice, maize and soybeans for the year 2000. It illustrates how many times the value of blue water is greater than the value of green water calculated in this work. Big consumers of blue water like India, China and Pakistan that have generally, a ratio equal to the unit in the wheat case. The ratio of Bulgaria for wheat (more than 100 times) reflects the considerations made about the composition of its water footprint. Indeed, the Green Water Footprint is considerably greater than the Blue Water Footprint and this relationship in the denominator of both the *BWUV* and the *GWUV* formula makes this *BWUV/GWUV* ratio so high. The magnitude of the scale in the ordinate of the maize diagram is comparable to that of wheat. The case of the great value of the ratio in Nepal for the maize case (98 times) follows the same logic as the case of Bulgaria in the wheat case, in fact the blue water component of water footprint is really low compared to that of green water.

The scale of the ratio in the rice case generally is less than the wheat or maize scale. The Malawi case in which the number is considerably higher with respect to others seems to derive from the wide productivity of irrigated lands compared to the rainfed lands.

Lastly, soybeans ratio is generally higher than rice's one. India, contrary to wheat case, presents a high value, in fact the *BWUV* is 25 times the *GWUV*, while in the wheat production it is more or less equal to the unit.

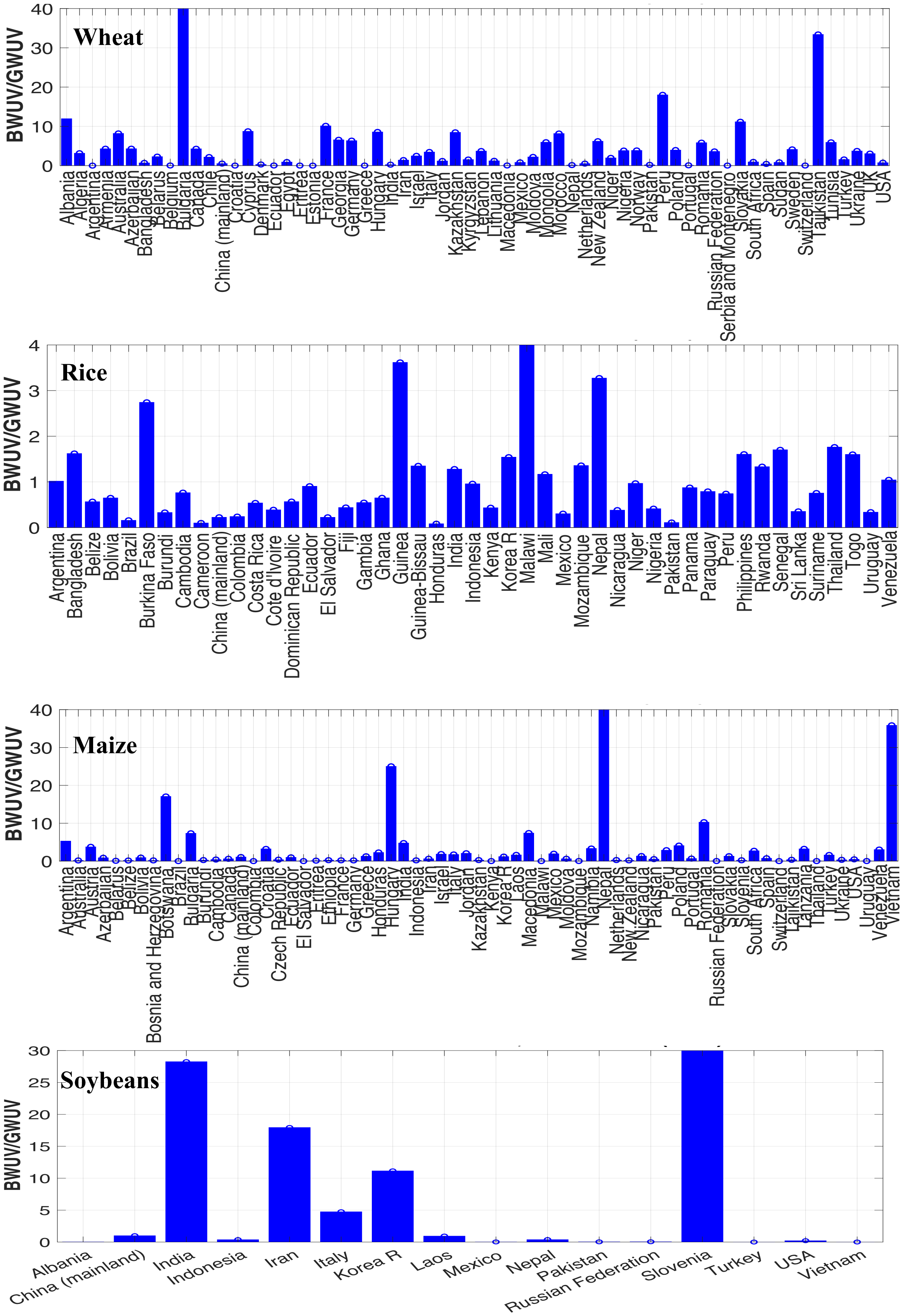

Figure 24: Bar diagrams of the ratio between Blue Water Unit Value and Green Water Unit Value for Wheat, Rice, Maize and Soybeans in 2000

Furthermore, for the sake of understanding the global trend of the ratio between *BWUV* and *GWUV*, Figure 25, Figure 26, Figure 27 and Figure 28, respectively for wheat, rice, maize and soybeans, exhibit bubble plots of Blue Water Unit Value as a function of Green Water Unit Value with the bubble size proportional to the ratio *BW/GW*, i.e. the ratio between the total blue water consumption and the total green water consumption within each country as a measure of relevance in the global pattern. In all of the diagrams it is outlined that the ratio between *BWUV* and *GWUV* is more or less equal to the unit for the countries with the bigger ratio *BW/GW*, indeed they are distributed along the bisector. Countries with a relative high value of *BWUV* respect *GWUV* are the ones with little *BW/GW*, in fact the ratio *BWUV/GWUV* is proportional to *GWF/BWF* (Green Water Footprint divided by Blue Water Footprint) as the structure of calculation illustrated in the methods chapter. So that the more a country uses blue water the more its economic value is comparable to the green water value.

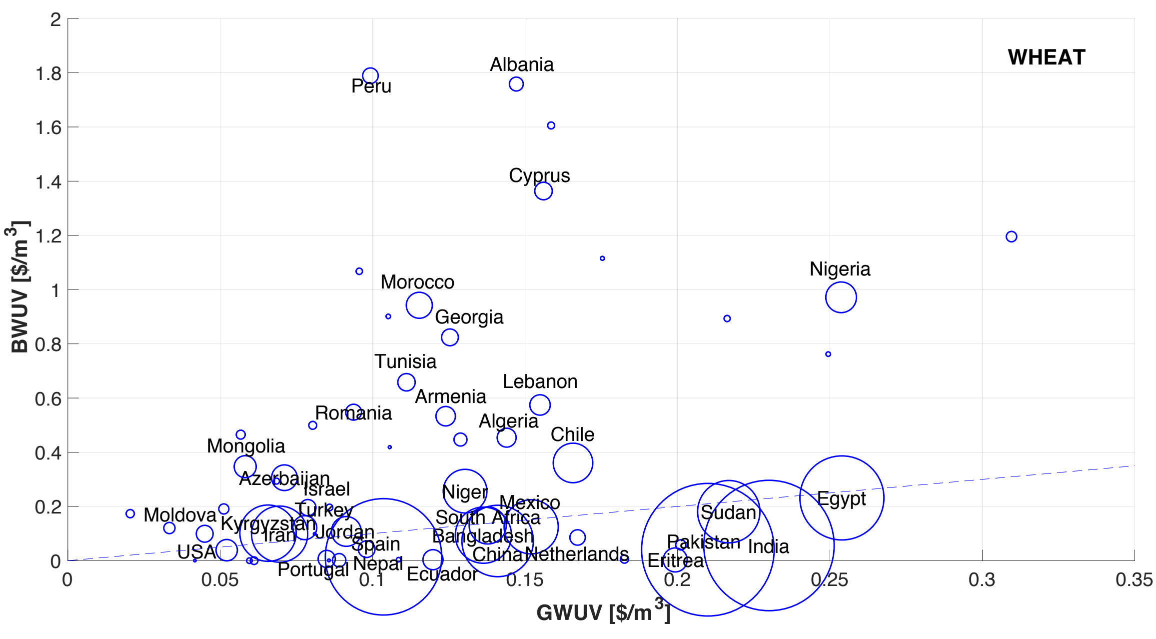

Figure 25: Blue Water Unit Value VS Green Water Unit Value in 2000 (WHEAT). Bubble size proportional to the ratio between the total amount of Blue Water and the total Amount of Green Water used in the wheat production within the country for the whole year.

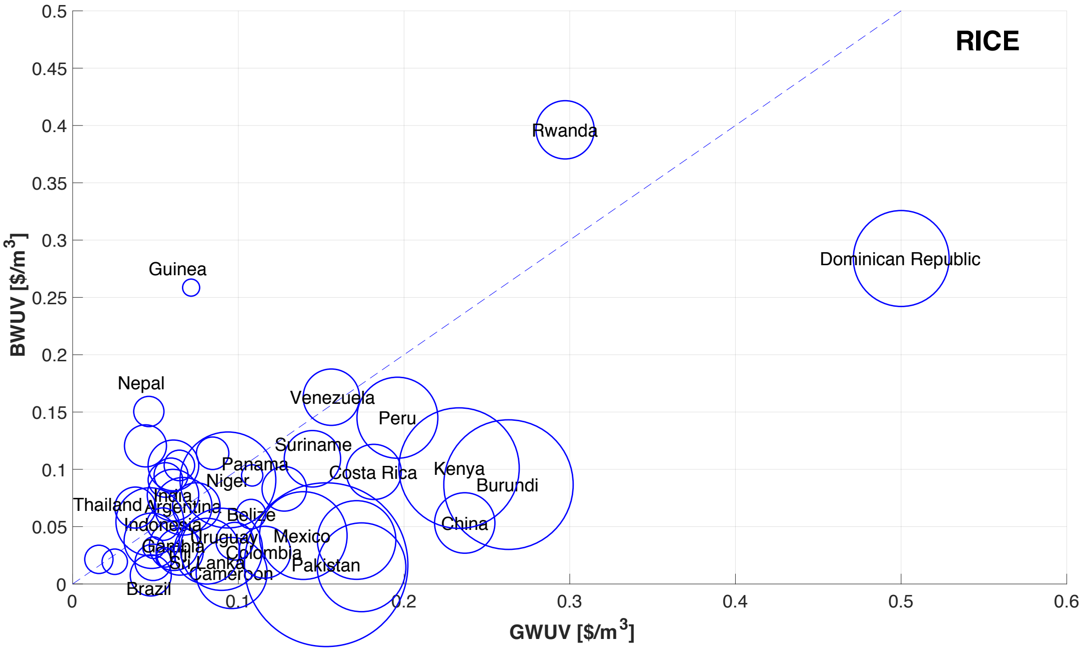

Figure 26: Blue Water Unit Value VS Green Water Unit Value in 2000 (RICE). Bubble size proportional to the ratio between the total amount of Blue Water and the total Amount of Green Water used in the rice production within the country for the whole year.

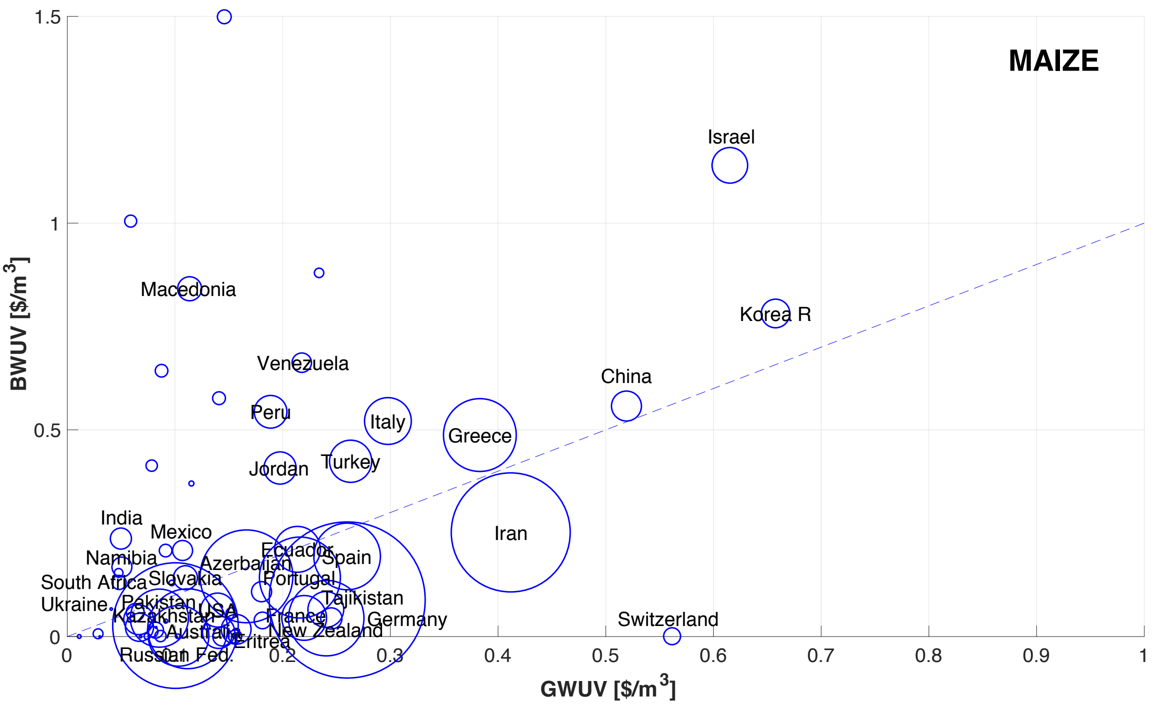

Figure 27 Blue Water Unit Value Vs Green Water Unit Value in 2000 (MAIZE). Bubble size proportional to the ratio between the total amount of Blue Water and the total Amount of Green Water used in the maize production within the country for the whole year.

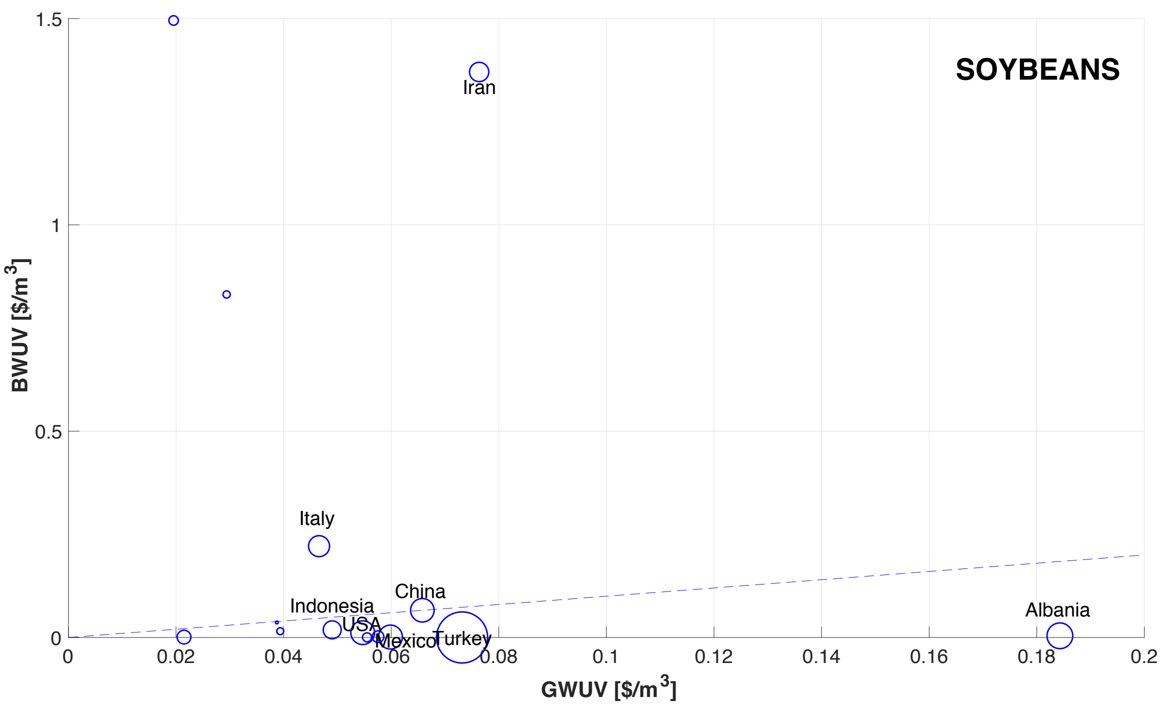

Figure 28: Blue Water Unit Value Vs Green Water Unit Value in 2000 (SOYBEANS). Bubble size proportional to the ratio between the total amount of Blue Water and the total Amount of Green Water used in the soybeans production within the country for the whole year.

4.2 Relationship among Blue Water Unit Value, Production Yield and Blue Water Consumption

After having described how Blue Water Unit Value is distributed among nations, the second step is to investigate if there are interesting relationships among *BWUV* and other parameters such as yields and consumptions of blue water and green water. For the sake of that there will be illustrated several bubble plots with the possibility to observe three dimensions at time.

4.2.1 Increase of Production Yield VS Blue Water Share

Thus, at first, it has been investigated, through a bubble plot, the relationship between the production yield ratio and the blue water share. The production yield ratio is the difference between irrigated and rainfed yield divided by rainfed yield, that means the increase of production yield in relation to rainfed yield and the share of blue water is the fraction of blue water with respect to the total water withdrawal (*BW/BW+GW*). In order to determine a measure of importance and weight of countries the bubble size is proportional to the overall production of the crop in object in within a country in 2000.

Figure 29 exhibits the case of wheat. Even if there are some countries that follow an ascending trend, the pattern is not really clear and countries with the same share of blue water, especially low values, seem to have considerable different behaviors of the yield ratio. Thus, it is not possible to affirm that countries with little consumptions of blue water with respect to the total amount, have low or high values of yield ratio. Meanwhile, for countries with bigger blue water shares, greater than 20%, it is possible to notice relatively high values of yield ratio (generally greater that an increase of 50% respect the rainfed yield) with the exception of Nepal, that, furthermore, is a little producer of wheat.

The biggest producer of wheat in 2000 are China, India and United States and they present different situations. For instance, USA does not use a lot of blue water in the wheat production (a share less than 10%) and has an increase of yield of 30%. China that has a blue water share of 35% has a yield ratio greater that 50%. Eventually, India that is one of the biggest consumer of blue water together with Pakistan (more than 60% of blue water share) has a yield increase of almost 130% with irrigation. Hence, for big producers of wheat an ascending relationship seems to be present between the parameters in object.

The case of rice is illustrated in Figure 30. Also, in this instance the pattern is not perfectly clear at first sight. In fact, contrary to wheat, for countries with a share less than 30% of blue water there is an ascending relationship, but then there are countries that invert the trend. For instance, China, that is also the biggest producer, has a blue water share greater that 30% (a substantial quantity of blue water) but has a yield increase considerably low (less than 20%) in a production in which yield increase due to the fact that irrigation is really high. In fact, the increase of yield production due to irrigation with respect to the rainfed yield reaches values greater than 160% as for the case of Peru. Sri Lanka, Uruguay and Pakistan that are not bigger producers but, together with China, present values of yield ratio less than 60% meanwhile their consumption of blue water is consistently high in the rice production (respectively 35% for Sri Lanka, 45% for Uruguay and more than 75% for Pakistan). India is the second biggest producer of rice and it shows values of almost 25% of blue water share and an increase of yield of 130% with irrigation.

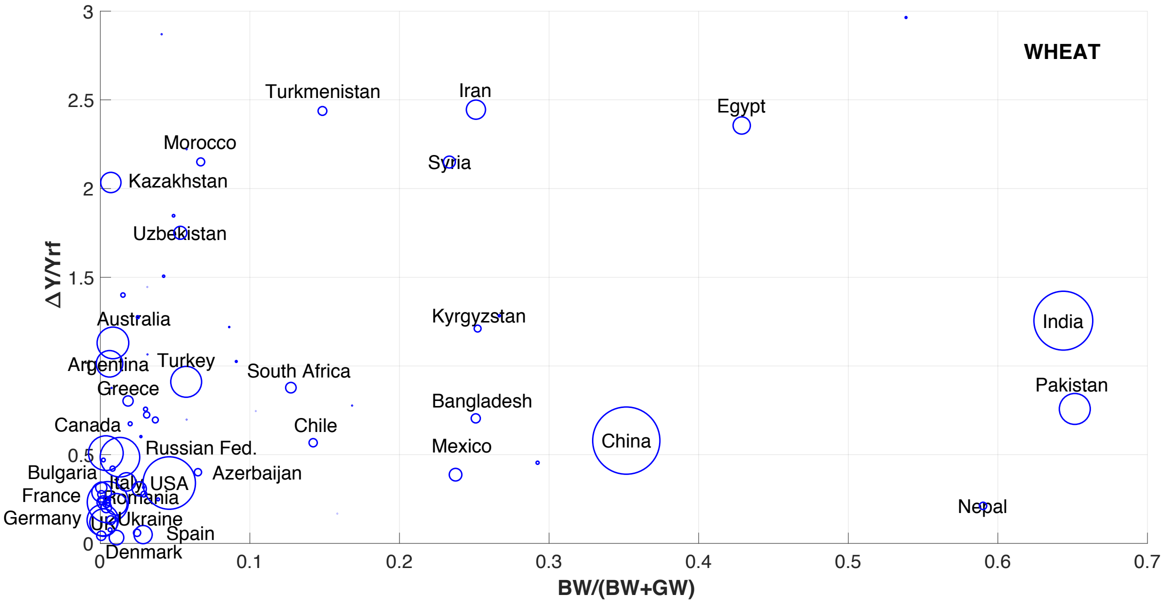

Figure 29: Production Yield Ratio VS Blue Water Share in 2000, WHEAT. Bubbles represent the total production of wheat (tons) in 2000 within the country.

Furthermore, Figure 31 exhibits the pattern of these parameters in the production of maize. Iran has been removed from the diagram for representative reasons, indeed its value of yield ratio is out of scale compared to the others (1293%) due to an accounted value of rainfed yield extremely low. This country is, indeed, a big consumer of blue water with a share of blue water equal to 60%. The relationship between the yield ratio and the blue water share is not clear at all, worse than the rice and wheat case. Biggest producers, namely USA and China, have water shares around 10% and low values of yield increase (less that 50%) compared to the others.

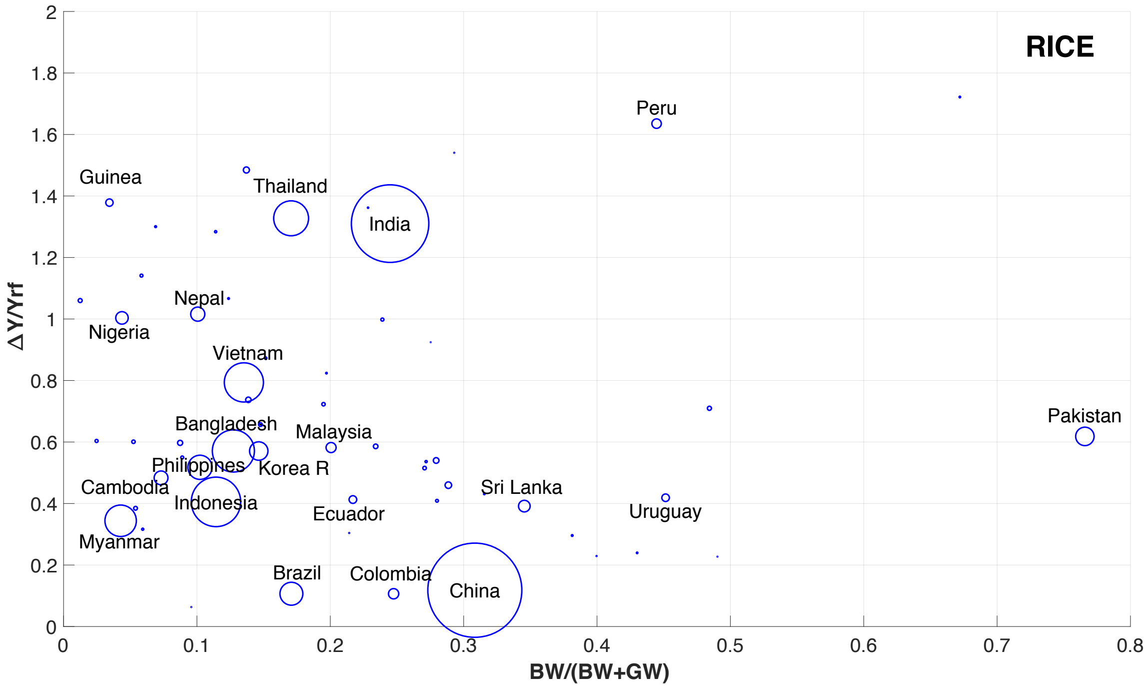

Figure 30: Production Yield Ration VS Blue Water Share in 2000, RICE. . Bubbles represent the total production of rice (tons) in 2000 within the country.

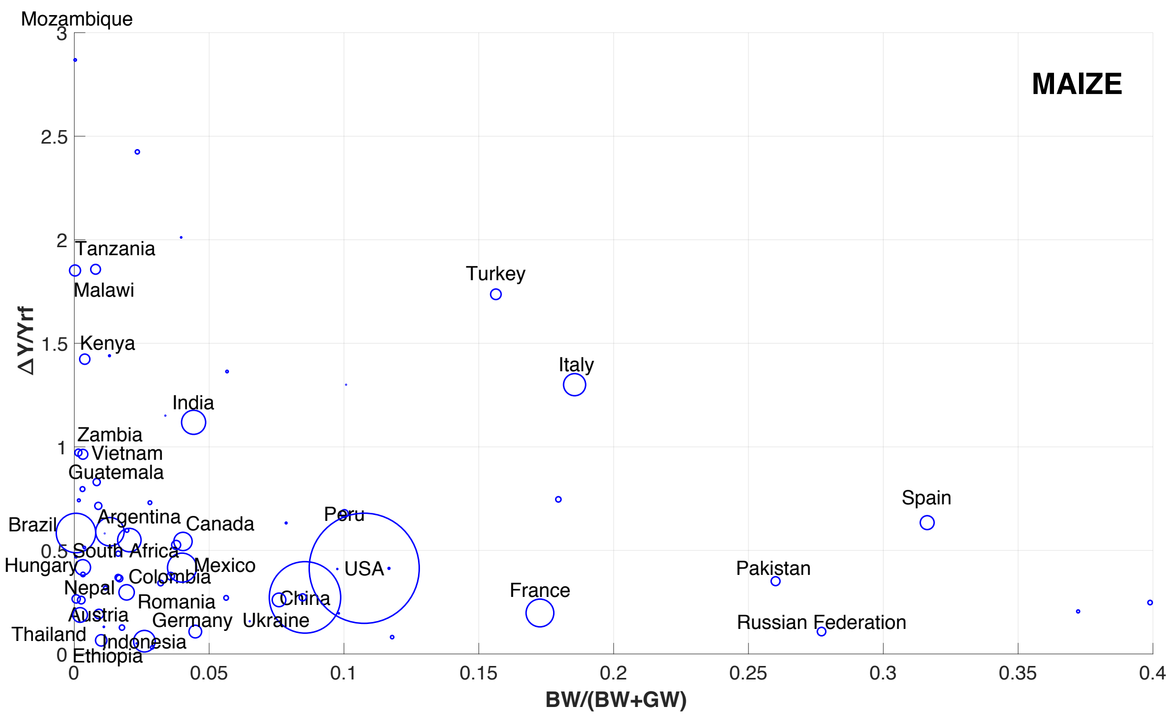

Figure 31: Production Yield Ration VS Blue Water Share in 2000, MAIZE. Bubbles represent the total production of maize (tons) in 2000 within the country.

Italy, for instance, has a blue water share for maize production about 20% and an increase in the production yield of 130%, which is pretty significant.

Eventually, soybeans pattern for the relationship between production yield ratio and blue water share is relatively confused, as Figure 32 does not show any considerable trend. USA and China remain the biggest producer and they are located in a similar situation: 5% of blue water share for soybeans production and around 25% of yield ratio. This crop is the least irrigated one and the increase of yield in this situation is in a range up to 250%.

It is possible to affirm that generally dry countries have higher yield increase ratios because rainfed lands are not actually productive and the gap between rainfed and irrigated lands in terms of productivity is substantial. In fact, in the upper part of diagrams there are countries such as Egypt, Iran, Syria, Turkey and Greece. Rice case makes an exception due to the fact that dry countries do not grow rainfed rice.

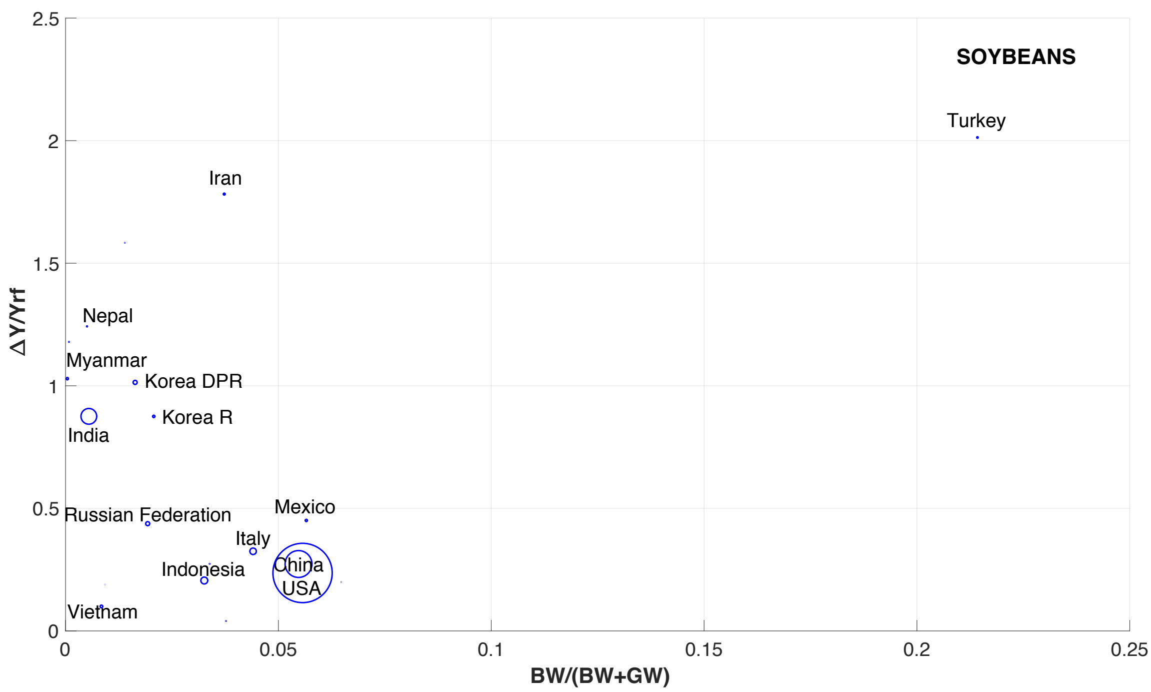

Figure 32: Production Yield Ration VS Blue Water Share in 2000, SOYBEANS. Bubbles represent the total production of soybeans (tons) in 2000 within the country.

4.2.2 Blue Water Unit Value VS Increase of Production Yield

Another interesting consideration is the relationship between the Blue Water Unit Value and the yield ratio. For the sake of it, there have been plotted the bubble diagrams for the four crops in object with the *BWUV* in ordinate and the yield ratio in abscissa. Hence, Figure 33 exhibits the case of wheat with an unclear pattern. Indeed, it is not possible to identify a relationship between the parameters since countries within the same range of yield ratio show both high and low numbers of *BWUV*. For representative reasons, in the diagram it has not been considered the case of Bulgaria because its *BWUV* is out of scale. Thus the second highest value is France (1.6 USD/m^3) with a yield ratio that is relatively low (less than 30%), as for the case of Bulgaria. Biggest producers, namely China, India and USA, with different value of yield ratio, have all low *BWUV* (less than 0.2 USD/m^3) below the average. Nevertheless, there are other relatively big producers such as France, Germany and Australia with a wide range of BWUV which vary from 1.6 to 0.5 USD/m^3.

Meanwhile the rice case seems to show an ascending trend (Figure 34) within countries with relatively low *BWUV*. The Republic of Korea has not been taken into account in the diagram because the really high value of *BWUV* was out of scale.

In the maize production, Figure 35, *BWUV* and yield ratio have the same confused pattern as the wheat case, but all the big producers have a relatively low *BWUV*, less than 0.5 USD/m^3, with the exception of China with a *BWUV* greater than 0.5 USD/m^3.

As well as for wheat and maize, the pattern in the soybeans case is confused (Figure 36). The highest value of *BWUV* (5 USD/m^3) is related to an average yield ratio of around 90%. The biggest producers, namely USA and China, have both a really low *BWUV* and a corresponding low yield ratio (less than 30%).

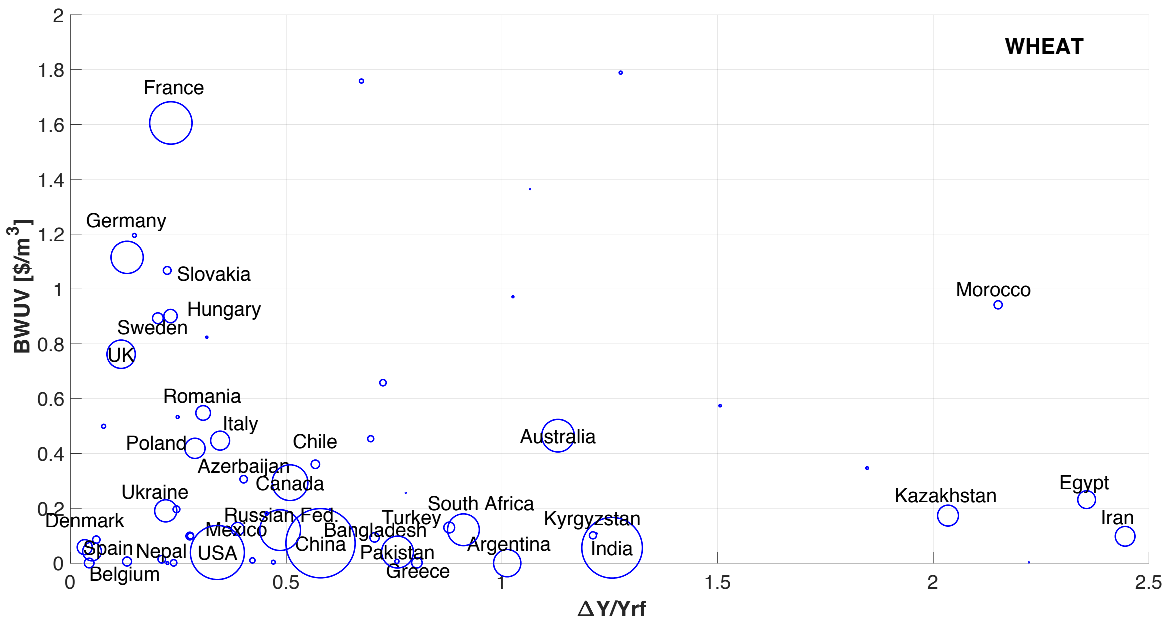

Figure 33: Blue Water Unit Value VS Yield Ratio in 2000, WHEAT. Bubbles represent the total production of wheat (tons) in 2000 within the country.

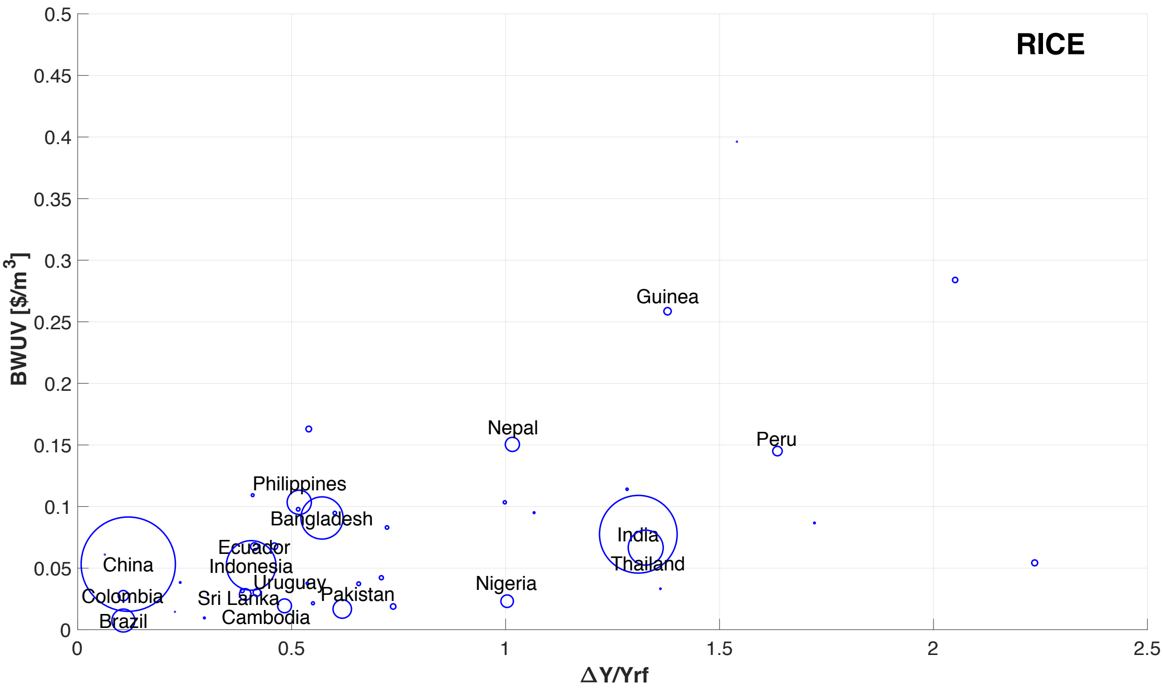

Figure 34: Blue Water Unit Value VS Yield Ratio in 2000, RICE. Bubbles represent the total production of rice (tons) in 2000 within the country.

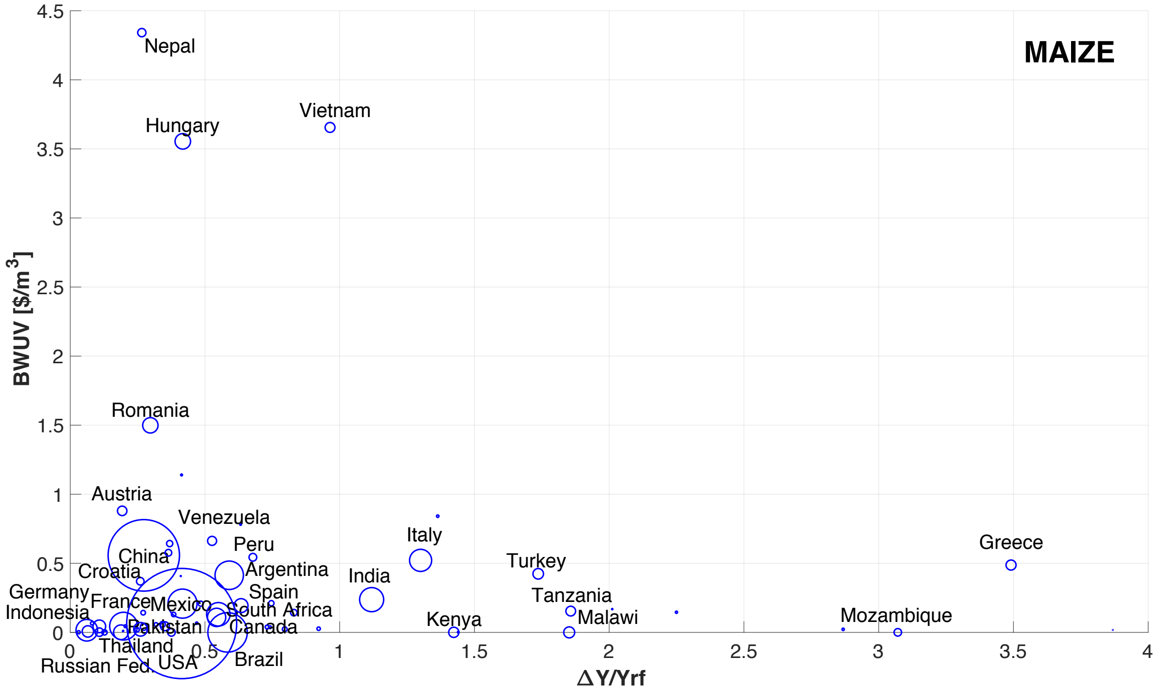

Figure 35: Blue Water Unit Value VS Yield Ratio in 2000, MAIZE. Bubbles represent the total production of maize (tons) in 2000 within the country.

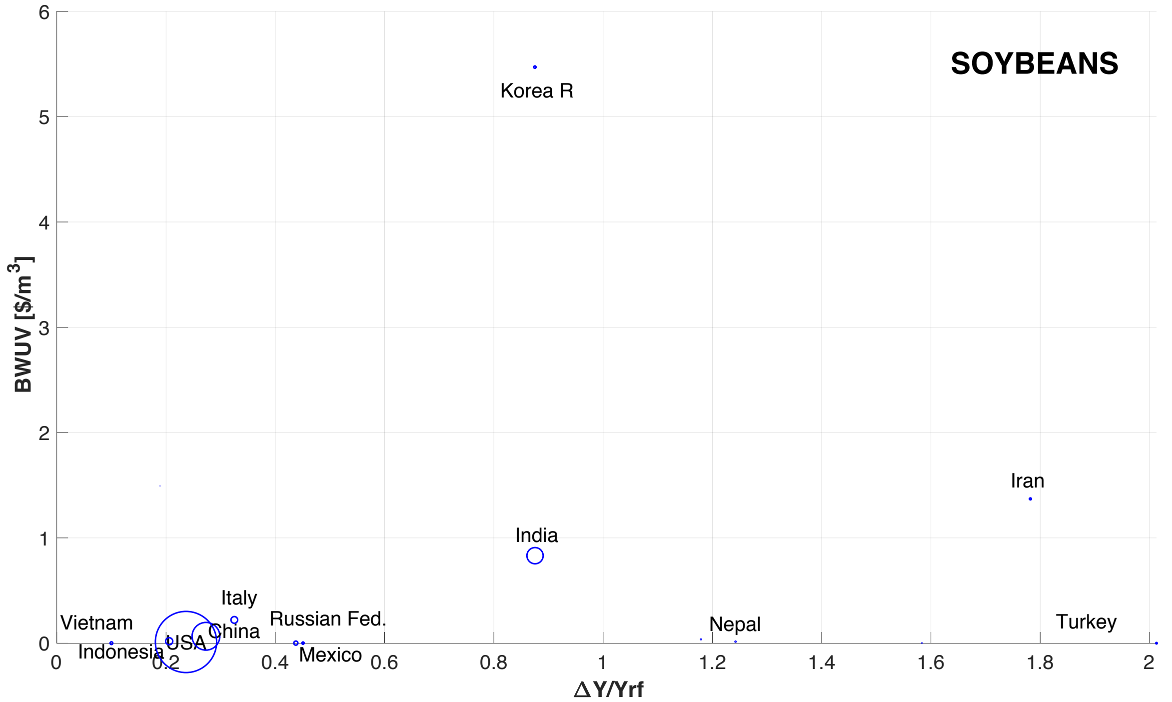

Figure 36: Blue Water Unit Value VS Yield Ratio in 2000, SOYBEANS. Bubbles represent the total production of soybeans (tons) in 2000 within the country.

Therefore, generally it is not possible to affirm that the component of yield increase is the main factor of *BWUV*, as there is not an ascending trend between them. Just the behavior in the rice case outlines a sort of ascending trend.

4.2.3 Blue Water Unit Value VS Blue Water Share

Lastly, the relationship between the *BWUV* and the blue water share has been investigated. Figures 37, Figure 38, Figures 39 and Figures 40 illustrate bubbles plots, respectively for wheat, rice, maize and soybeans with *BWUV* in ordinate and the Blue Water Share in abscissa, while the bubble size is proportional to the overall amount of production in terms of tons within each country in 2000. For all these crops, with the exception of rice that does not show any trend, there is a sort of inverse correlation between the two parameters since there is a relative predominance of the contribution of blue water footprint in the estimation of blue water value. Due to the fact that in the structure of this estimation blue water footprint is present in the denominator of *BWUV* this inverse relationship shows up in the diagram.

For instance, in the wheat case, countries such France, Germany, Slovakia, Hungary and Morocco, with a *BWUV* above the average have relatively low blue water shares. Same as in the maize production, where Vietnam, Hungary and Nepal, with the highest values of *BWUV* (greater than 3.5 USD/m^3) show little shares of blue water, less than 3%.

The Republic of Korea in both Rice and Soybeans cases has high *BWUV*, mainly due to high farm-gate prices with respect to the average, and has little share of blue water, respectively 15% and less than 5%.

In the wheat diagram, Nepal, India and Pakistan with the greatest blue water share for wheat production (around 60%) show significantly low *BWUV*, less than 0.1 USD/m^3.

Pakistan shows the same behavior in the rice case with almost 80% of blue water share for the rice production and a *BWUV* less than 0.01 USD/m^3.

In the maize case countries with greatest blue water shares such as Iran, Greece and Spain have *BWUV* equal or less than 0.5 USD/m^3, that is below the global weighed average 0.19 USD/m^3.

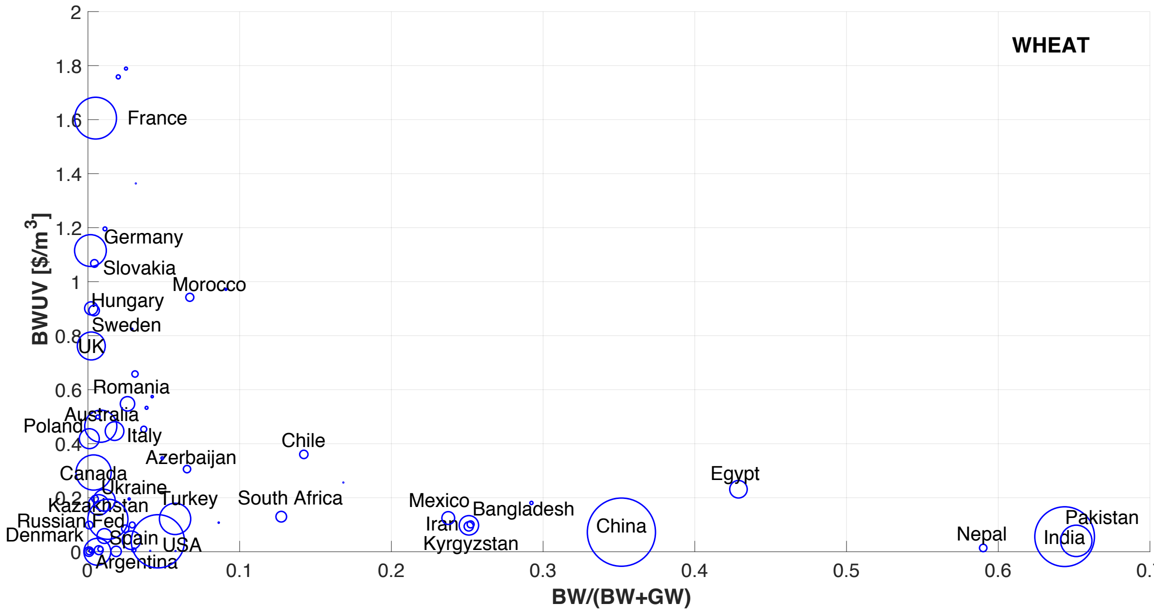

Figure 37: Blue Water Unit Value VS Blue Water Share in 2000, WHEAT. Bubbles represent the total production of wheat (tons) in 2000 within the country.

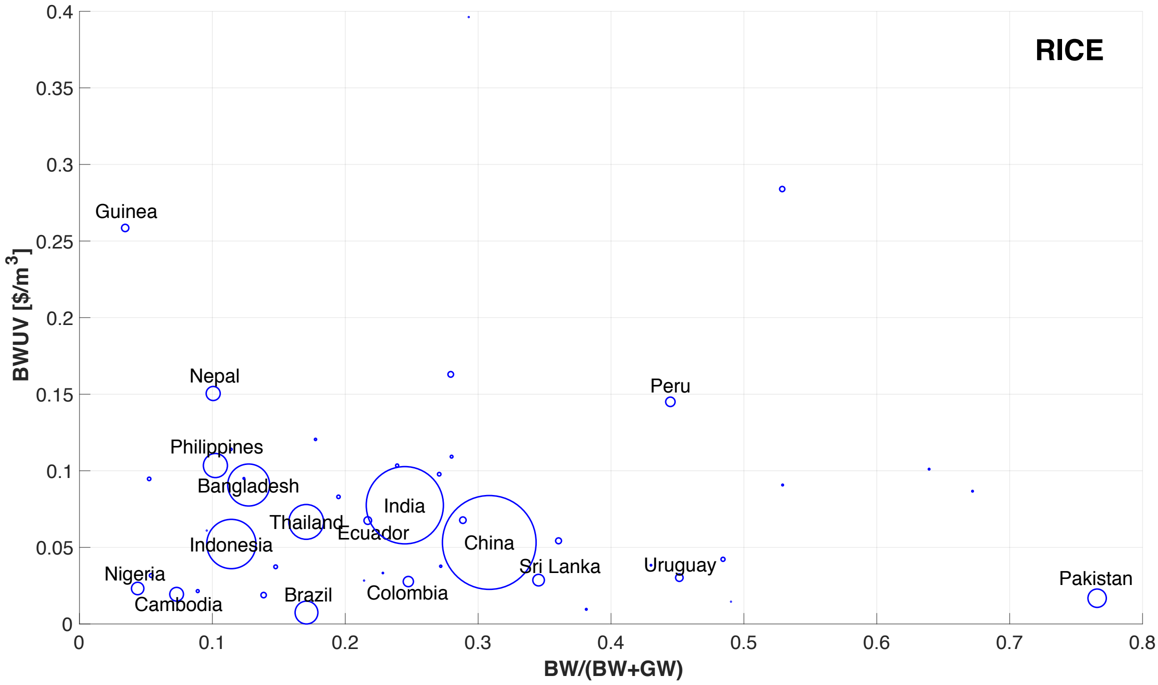

Figure 38: Blue Water Unit Value VS Blue Water Share in 2000, RICE. Bubbles represent the total production of rice (tons) in 2000 within the country.

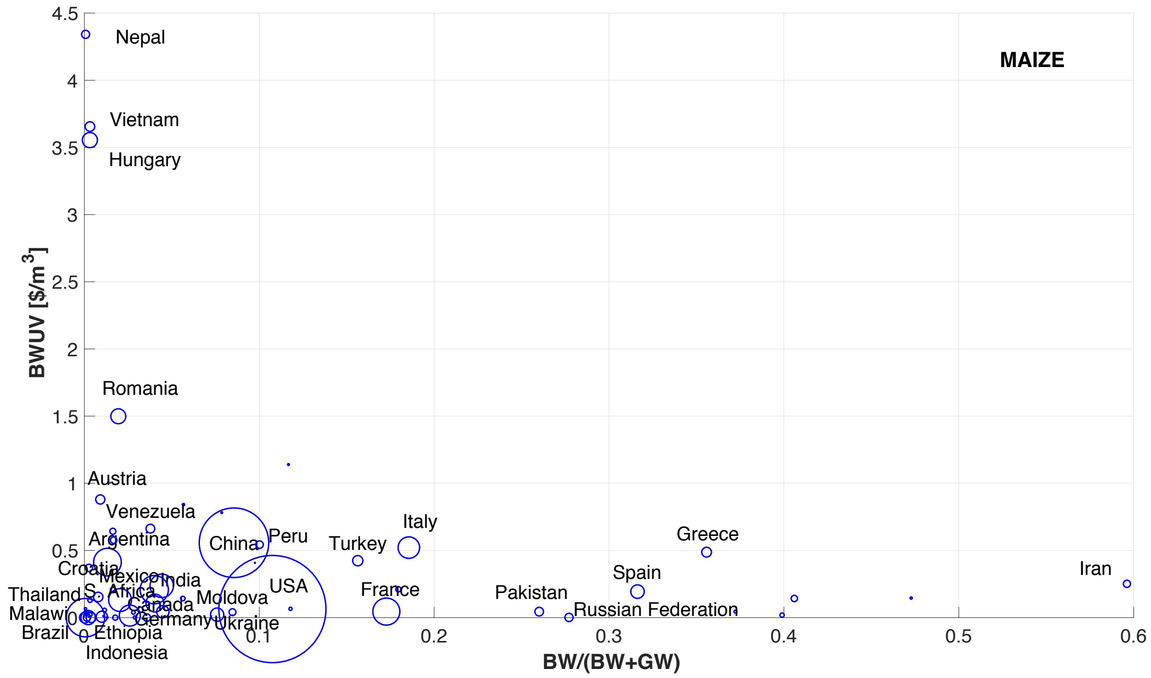

Figure 39: Blue Water Unit Value VS Blue Water Share in 2000, MAIZE. Bubbles represent the total production of maize (tons) in 2000 within the country.

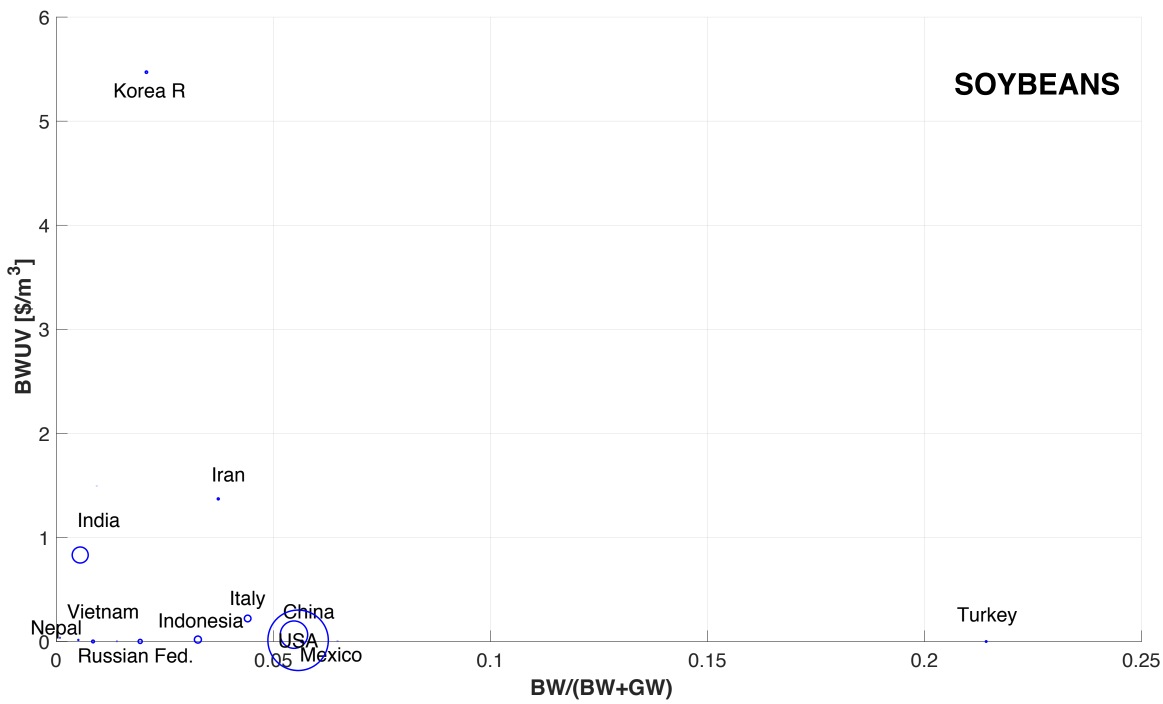

Figure 40: Blue Water Unit Value VS Blue Water Share in 2000, SOYBEANS. Bubbles represent the total production of soybeans (tons) in 2000 within the country.

Therefore, generally it seems that countries that use huge amounts of blue water for irrigation in the crop production do not have a corresponding high economic value for this water. Thus, all the diagrams outline an inverse proportionality trend so that the more a country uses blue water in relation to blue water, the less the country manages to make blue water rentable.

For the sake of better outlining the relationship between blue water share and its economic value Figure 41, Figure 42, Figure 43 and Figure 44 exhibit same diagrams but with Blue Water Footprint instead of Blue Water Share in abscissa. As expected, they show the same relationship of inverse proportionality, with the exception of rice that does not present a clear pattern of inverse proportionality.

Eventually, it is possible to affirm that countries that are more efficient in the use of blue water to produce a certain amount of crop can be more efficient also in the profitability of it. Thus, the more a country can improve the production yield of a crop using the least quantity of blue water per ton of it, the more the country can manage to make water profitable in economic terms.

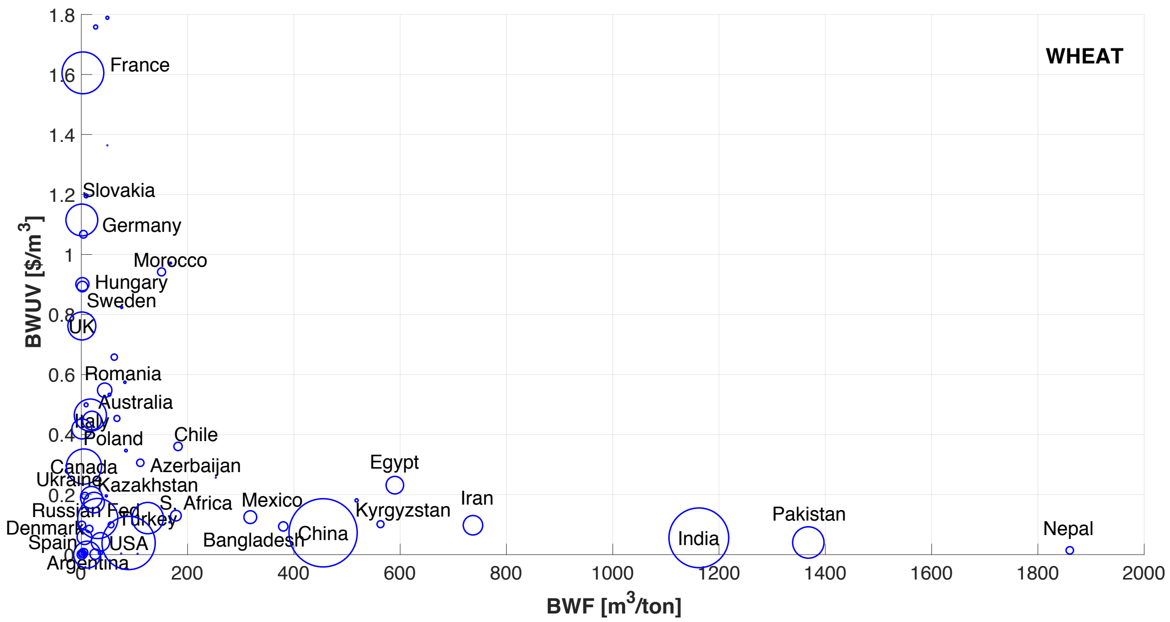

Figure 41: Blue Water Unit Value VS Blue Water Footprint in 2000, WHEAT. Bubbles represent the total production of wheat (tons) in 2000 within the country.

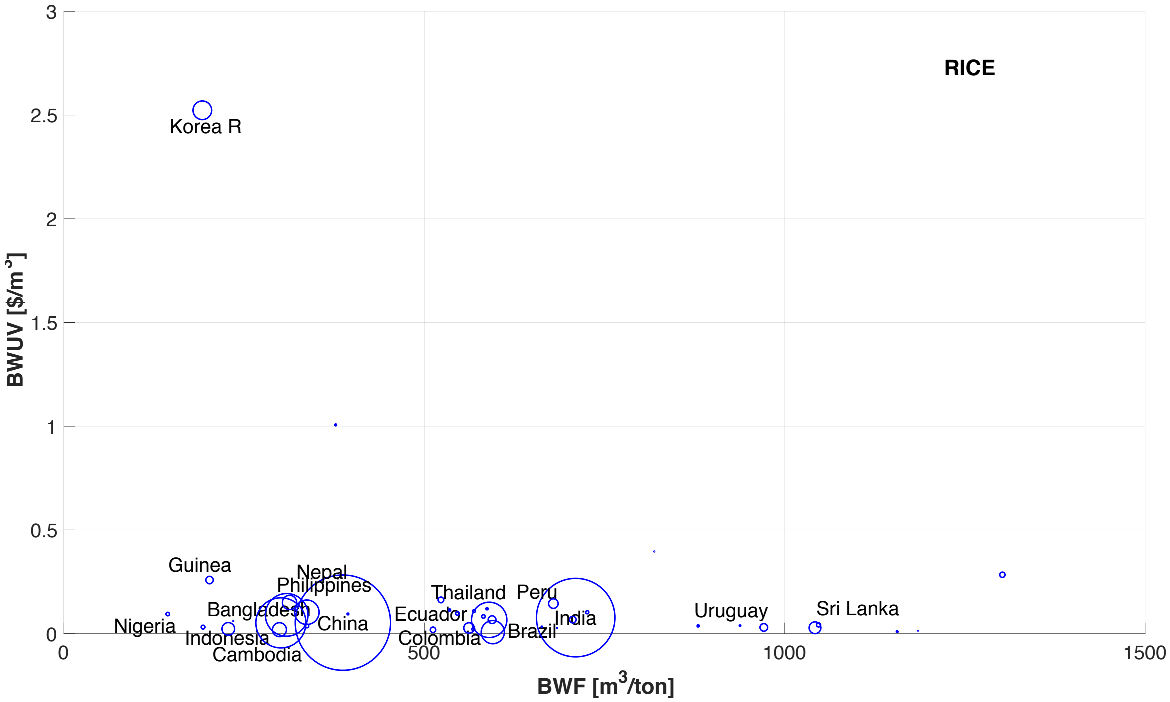

Figure 42: Blue Water Unit Value VS Blue Water Footprint in 2000, RICE. Bubbles represent the total production of rice (tons) in 2000 within the country.

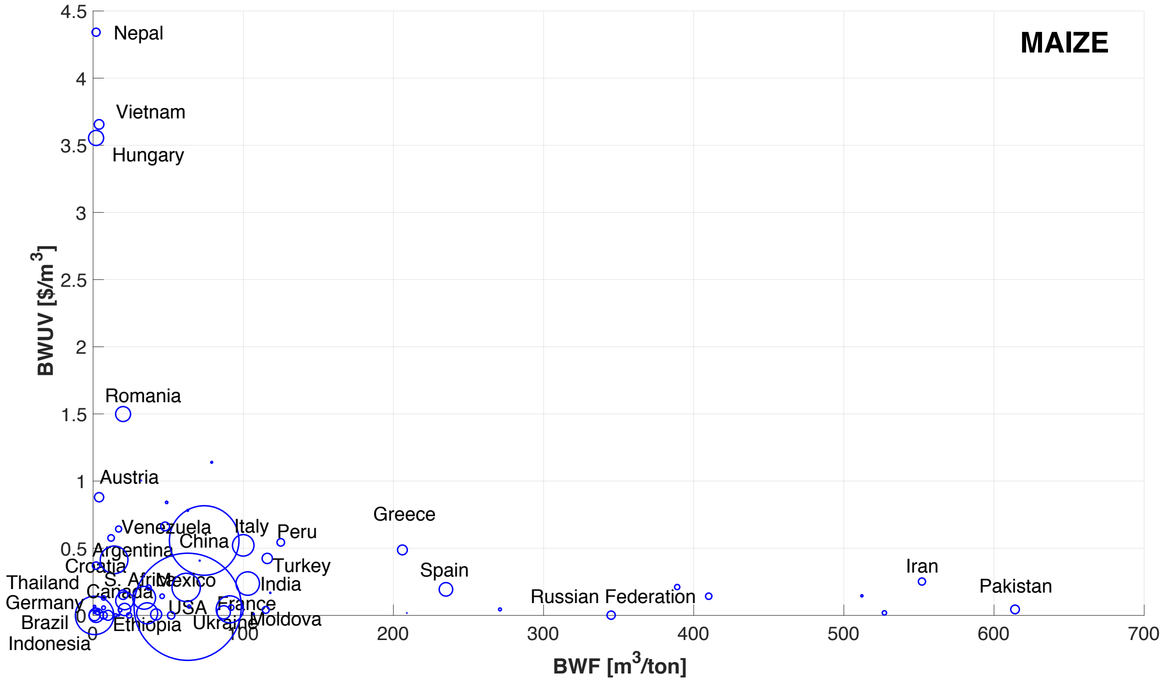

Figure 43: Blue Water Unit Value VS Blue Water Footprint in 2000, MAIZE. Bubbles represent the total production of maize (tons) in 2000 within the country.

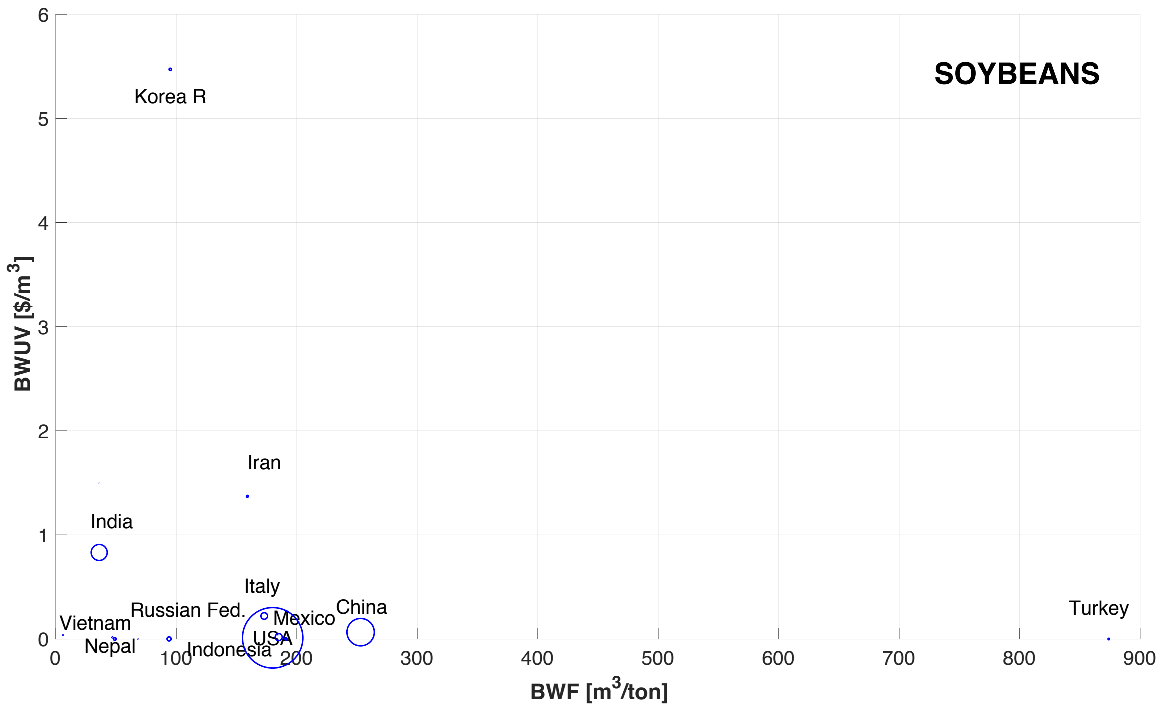

Figure 44 Blue Water Unit Value VS Blue Water Footprint in 2000, SOYBEANS. Bubbles represent the total production of soybeans (tons) in 2000 within the country.

5 Results of Blue Water Valuation in The Global Food Trade

This chapter will illustrate the results of the analysis in the global food trade context.
The spatial distribution of Blue Water Unit Value calculated with trade prices of each exchange will be depicted and the global trend of the flow of USD resulting from the blue virtual water trade will be analyzed. Due to the structure of the estimation method of this study values and flows will be illustrated just for those country that grow both rainfed and irrigated crops, namely wheat, rice, maize and soybeans. Furthermore, the scope of this chapter will be the the global trade of the main four staple crops in the year 2000, that is the only year with the full availability of data for the estimation of the blue water value at the country scale.

5.1 Blue Water Value Spatial Distribution

In this section Blue Water Unit Value numbers have been accounted in the scope of the global food commodities trade. Therefore, in Table 4 minimum, maximum, weighted average and weighted standard deviation of $BWUV$ in the trade have been illustrated.
Those parameters have been calculated at first for each exchange between exporters and importers, starting from the same Blue Water Productivity illustrated in the previous chapter multiplied by the peculiar trade price of the commodity in the exchange. Thus, for each trade link and for each crop (wheat, rice, maize and soybeans) the value of a cubic meter of blue water have been illustrated. In the light of this the matrix $BWUV\_TR$ (Blue Water Unit Value in the Trade) has been obtained where the rows represent the exporting countries and the columns the importing countries. Each cell is the particular unit price of blue water of the link. In order to aggregate the $BWUV$ at the country scale, weighted averages for each country have been calculated, where the weight of each link is the blue water amount exchanged in it. Finally, a further weighted average between countries (a global average) has been

calculated, in which the weight of each country is its total export of blue water in the year considered (2000).

Hence, Table 6 shows that the global averages of each staple crop, namely wheat, rice, maize and soybeans, which varies from 0.014 USD/m^3 to 0.116 USD/m^3. These values seem to be comparable to the ones estimated in the production context. In fact, in the trade the value for wheat is 0.116 instead of 0.068 (USD/m^3), for maize is 0.107 instead of 0.190 (USD/m^3), for rice 0.058 instead of 0.061 (USD/m^3) and 0.014 instead of 0.036 (USD/m^3). This means that the value of blue water for rice remains almost the same, the value for wheat is higher (one order of magnitude more), while maize and soy are slightly lower. Wheat in the trade has the highest standard deviation (weighted) among the crops considered. Indeed, this case also presents the biggest range, thus it is really variable. Rice is the only one with a significantly small range so it is the least spread crop compared to the others. Eventually, the weighted standard deviation of soybeans is the smallest one but the range is considerably wide, which means that extremes values have a little weight due to the size of the blue water trade link.

Parameter	Crop	Minimum Value	Maximum Value	Global Weighted Average	Global Weighted St. Dev.
BWUV_TR [USD/m^3]	Wheat	$4.50 \cdot 10^{-6}$	8.47	0.12	0.24
	Maize	$1.33 \cdot 10^{-5}$	4.97	0.11	0.15
	Rice	0.01	0.24	0.06	0.07
	Soybeans	$1.32 \cdot 10^{-4}$	3.27	0.01	0.03

Table 6: Minimum, maximum, global weighted average and global weighted standard deviation for Blue Water Unit Value calculated for wheat, maize, rice and soybeans in 2000.

Furthermore, Figure 45 shows distributions of *BWUV_TR*, i.e. the Blue Water Value in the trade. Wheat and maize diagrams have the same shape, and they seem to be well approximated by an exponential distribution. In both cases the majority of values are close to the average but there are some isolated cases significantly far away from the average. The abscissa for the diagram corresponding to rice is the least wide, and even if the tails seem to be fat there is the important consideration of the smaller standard deviation compared to wheat and maize. The rice distribution is the only one that could be approximated by a normal distribution even if it is still be substantially asymmetric. The soybeans case shows a situation where the majority of the countries have a value close to the average, but there are other probable events far from the average. But the weight of them seems not to be significant due to the low value of weighted standard deviation accounted for in Table 6.

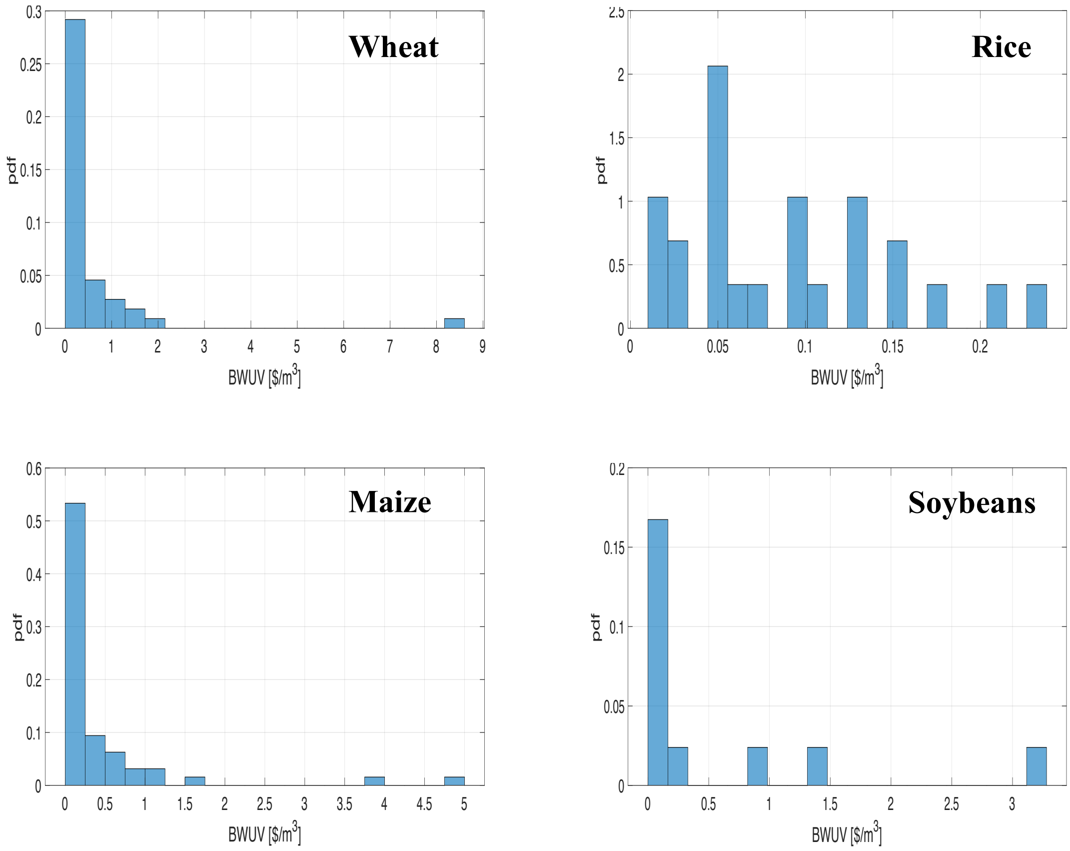

Figure 45: Probability Distribution Functions of Blue Water Unit Value for Wheat, Rice, Maize and Soybeans in 2000.

In order to better investigate how the Blue Water Unit Value is globally distributed in the trade Figure 46, Figure 47, Figure 48 and Figure 49 show bar diagrams of *BWUV* in weighted terms for each country, where the weight of each export is the amount of blue water traded. The bubble size is proportional to the total amount of blue water traded by the country calculated as the sum of all the links from that country to the importers. Not significant values in terms of weight have been omitted, namely Bulgaria in the wheat case (8.5 USD/m^3), Hungary (4.9 USD/m^3) and Vietnam (3.7 USD/m^3) in the maize case and Slovenia (3.3 USD/m^3) in the soybeans case.

In the wheat case it is possible to observe that big exporters of blue water, namely USA, India and Mexico, tend to have low *BWUV_TR*. This situation is replicated in maize and soybeans cases where big exporters, respectively USA, China and France for maize and USA for soybeans, have low *BWUV_TR*. However, in the rice case instead there are some big exporters of blue water, namely Pakistan and China, with *BWUV_TR* less or equal to the weighted average, and other big exporters of blue water, India and Thailand, with *BWUV_TR* relatively greater.

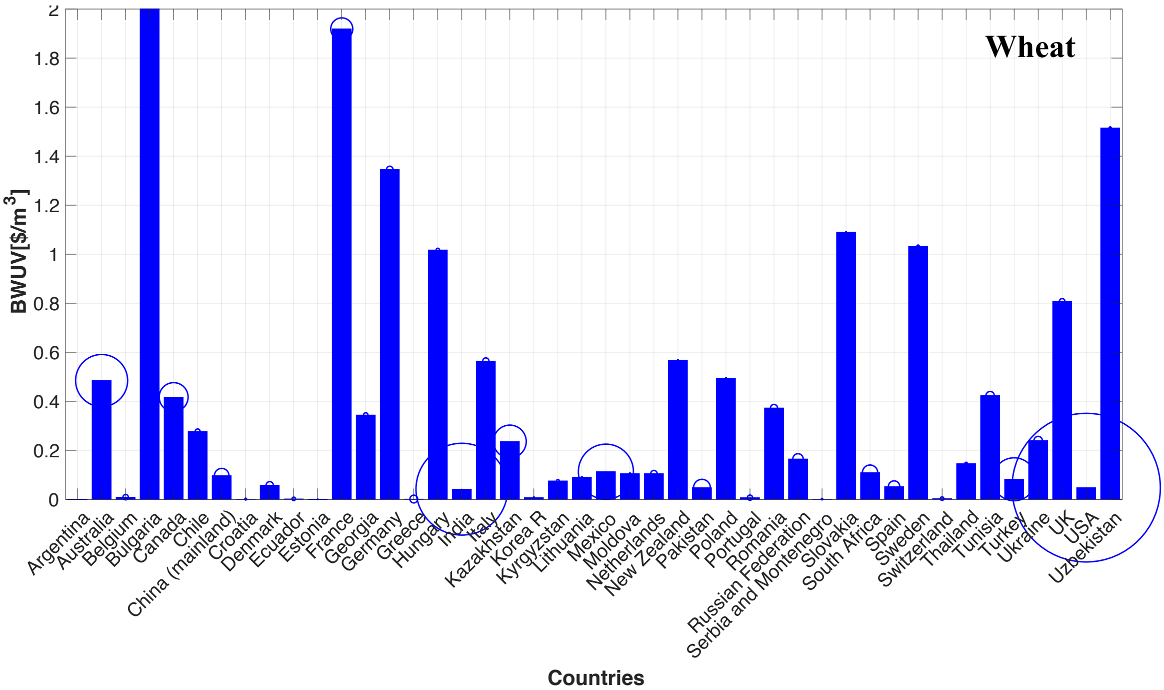

Figure 46: Bar diagram of National Average of Blue Water Unit Value in the Trade, WHEAT (2000). Bubble size proportional to the total export of Blue Water of the country in 2000.

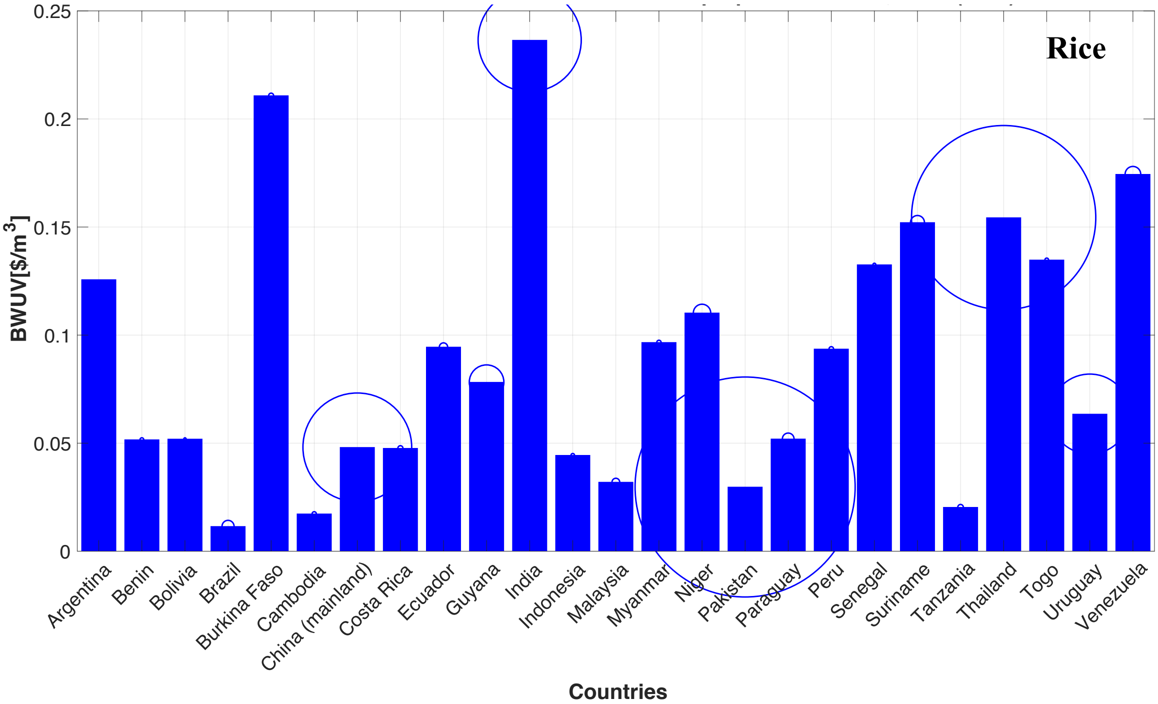

Figure 47: Bar diagram of National Average of Blue Water Unit Value in the Trade, RICE (2000). Bubble size proportional to the total export of Blue Water of the country in 2000.

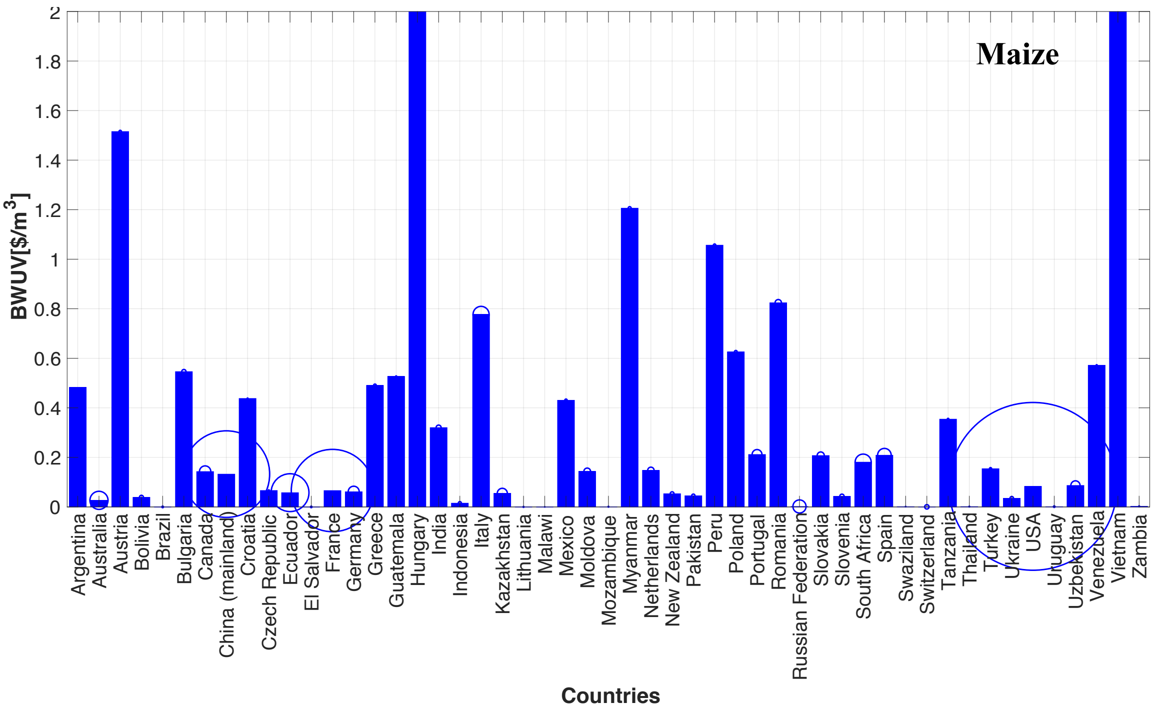

Figure 48: : Bar diagram of National Average of Blue Water Unit Value in the Trade, MAIZE (2000). Bubble size proportional to the total export of Blue Water of the country in 2000.

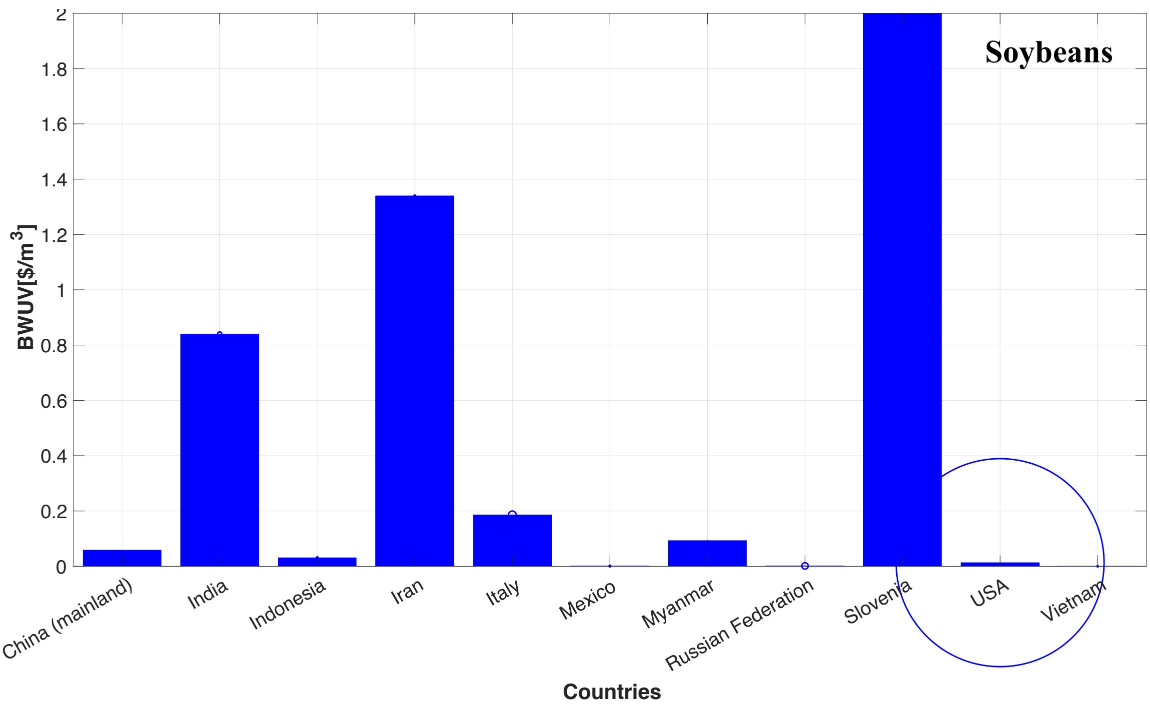

Figure 49: Bar diagram of National Average of Blue Water Unit Value in the Trade, SOYBEANS (2000). Bubble size proportional to the total export of Blue Water of the country in 2000.

Thus, the distributions of *BWUV_TR* in the global food commodities trade pattern seem to be comparable to the ones in the global crop production scope. In both contexts, rice is the crop that presents more homogeneity in the distribution of Blue Water Value. The fact that it makes an exception seem to be more reasonable than others because, among the four staple crops it is the one that stands out for the higher intensity of water, especially blue water. Furthermore, it is useful to recall that countries taken into account in this study are the ones that grow both irrigated and rainfed crops. The case of rice is interesting because countries that grow rainfed rice are the ones with same climatic zones, because it requires a huge amount of precipitation. It could be possible that countries with this climatic pattern have a similar behavior and this could be the reason for the homogeneity in the *BWUV_TR* spatial distribution in the rice case.

Subsequently, Figure 50 shows the world maps of the distribution of national averages of Blue Water Unit Value in the global trade of blue water. As said before, the map for rice is the most homogeneous map with values less than 0.4 USD/m^3 with the majority of countries concentrate in Southern America and Asia, especially in wide countries with different climatic zones.

In the wheat case, Canada, Australia and the European countries, together with Uzbekistan, show highest *BWUV_TR*, greater than 0.4 USD/m^3.

Highest values in the maize case are present in Central and Southern America, in Europe and Asia (Vietnam).
Eventually, the estimation of Blue Water Unit Value in the Blue Water trade for soybeans case, has been possible mainly for the Asian continent together with USA, Mexico, Italy and Slovenia. The highest values are presented by Slovenia, Iran and India, greater than 0.6 USD/m^3.
As opposed to the global crop production scope, in trade, generally, there is the absence of the majority of Africans countries, especially the Northern Africans. Indeed, there is no *BWUV_TR* as there is no blue water export accounted for in these countries where, furthermore, even the production is not significant due too climatic factors and water scarcity conditions. This seems to be coherent, contrary to the Middle Eastern Countries, that even if often are in water scarce conditions (as already said in the first chapter) tend to have blue water export.
Figure 51 exhibits the world map of scarcity according to the Falkenmark water scarcity indicator.

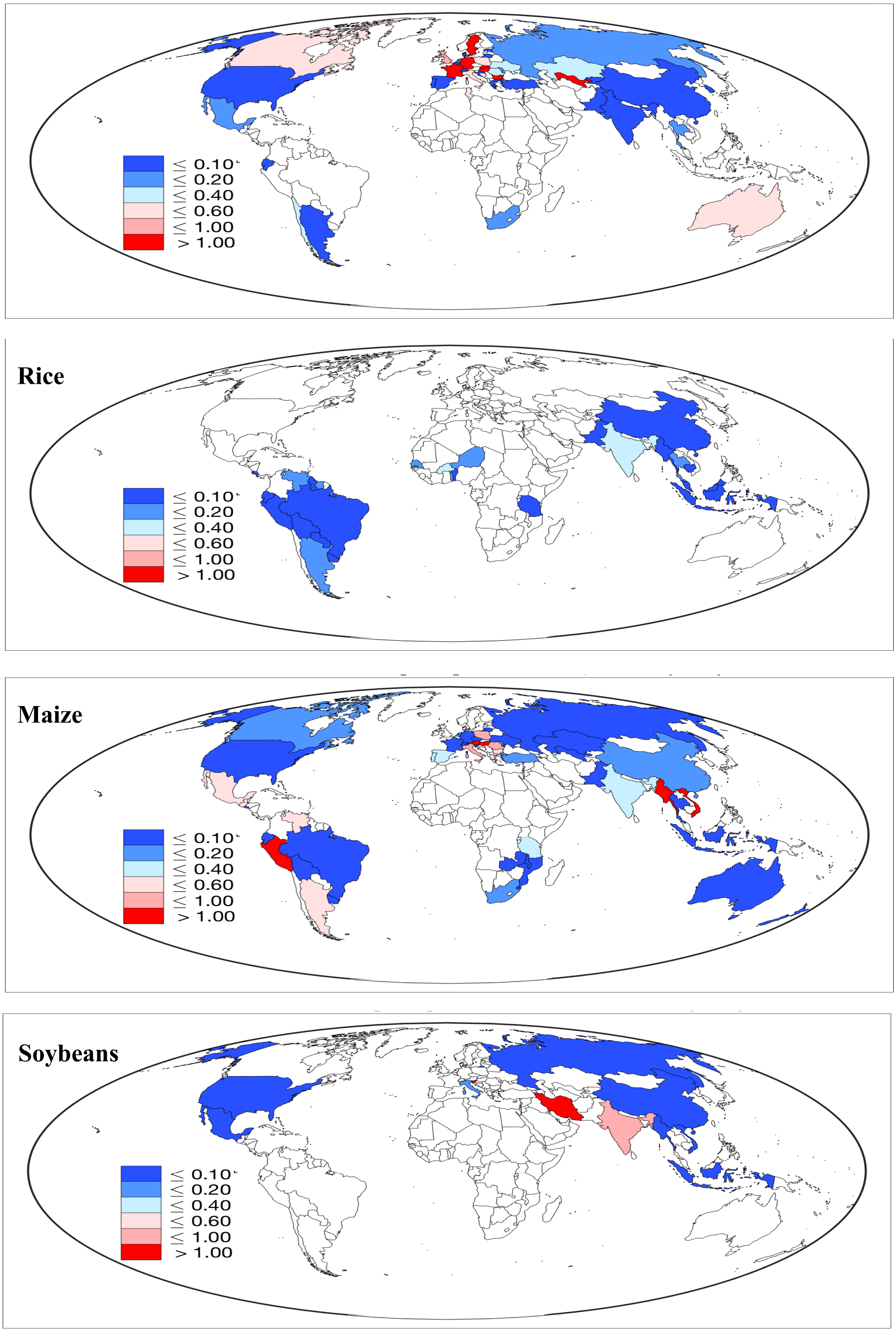

Figure 50: World Maps of Blue Water Unit Value in the Trade, respectively for wheat, rice, maize and soybeans (2000).

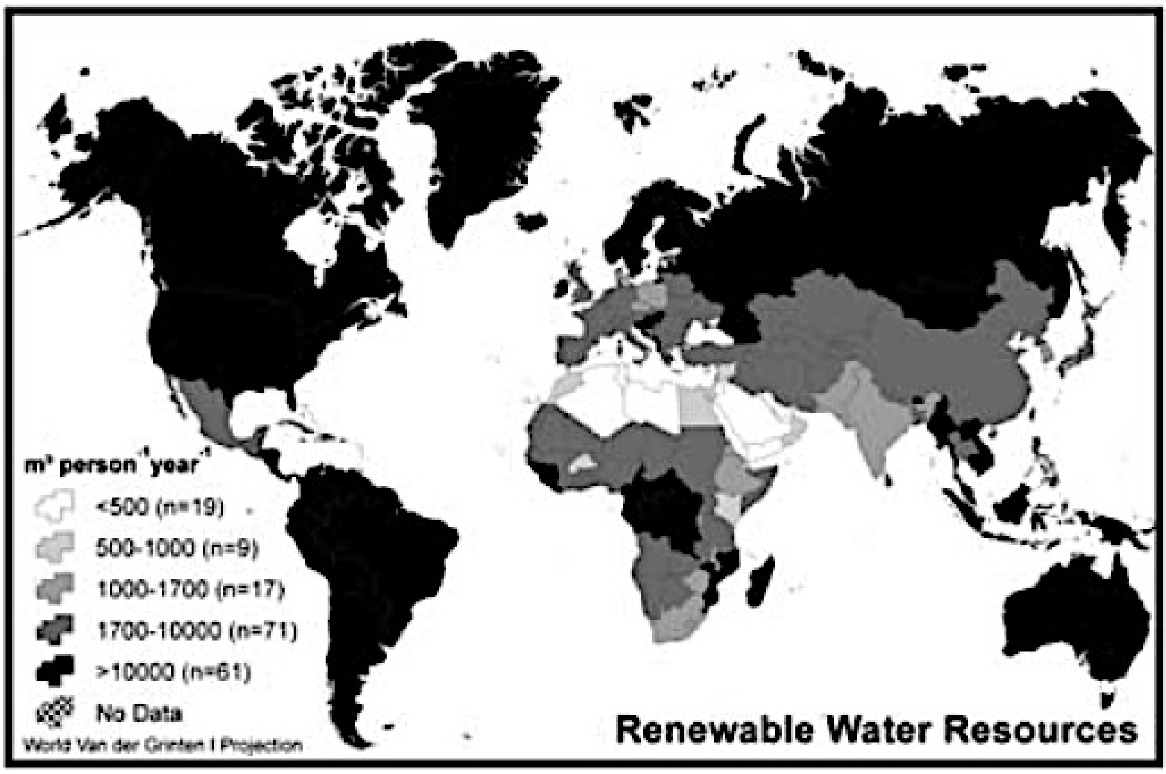

Figure 51: Map of annual per capita water availability, i.e. Falkenmark water scarcity indicator). Lower levels represent higher scarcity. Data source: AQUASTAT 2009. Map produced by Stacey Maples, Yale University.

5.2 Economic Flows of Blue Water

In this section the dynamics of the blue water trade in economics terms have been considered. Indeed, blue water flows in the global trade of wheat, rice, maize and soybeans, have been separated from the green water flows and they have been considered in the economic point of view thanks to the estimation of blue water value of each link, through Blue Water Unit Value.

For the sake of understanding the order of magnitude of the blue water trade pattern (in the trade of the 4 main staple crops) Table 7 shows the global aggregate values (as the global sum of all the countries) of blue water trade in terms of cubic meters (*BW_TR*) and in terms of USD *(BWV_TR*). As expected the biggest amount of blue water traded arises from the rice trade between nations. In fact, around 20 billion cubic meters of blue water have been traded in the rice global trade, while, overall an amount equal to 35.2 billions of cubic meters of blue water have been traded in 2000. The corresponding value has been estimated equal to 2.3 billions of USDs resulting from the blue water trade arising from wheat, rice, maize and soybeans trade.

Parameter	Crop	Global Aggregate
	Wheat	$4.89 \cdot 10^9$
BW_TR	Maize	$5.08 \cdot 10^9$
[m³]	Rice	$20.10 \cdot 10^9$
	Soybeans	$5.09 \cdot 10^9$
	Wheat	$5.65 \cdot 10^8$
BWV_TR	Maize	$5.43 \cdot 10^8$
[USD]	Rice	$11.58 \cdot 10^8$
	Soybeans	$0.70 \cdot 10^8$

Table 7: Global Aggregate Value of Blue Water Trade both in cubic meters and USD in 2000.

As a result of blue water trade, there is an increment of income of dollars resulting from the use of water for irrigation in agriculture. Each link between two nations represents the blue water exchanged along with a flow of USD in the opposite direction, from the importer to the exporter of blue water.

Therefore, for the sake of showing the global dynamics of the Blue Water Trade in terms of USD, oriented graphs have been plotted for each of the four staple crops (respectively Figure 52, Figure 53, Figure 54 and Figure 55), where the nodes are exporters and importers of blue water located in their geographical position on the world map. The oriented edges between nodes represent the income in terms of 'blue water dollars' resulting from net flows of blue water among the 2 nodes. The arrows indicate the direction of the income, from the buyer to the seller. In order to make the diagrams readable just edges greater that 1 million dollars have been depicted for the wheat, rice and maize cases and greater than 0.1 million dollars for the soybeans case (in fact the global amount of blue water dollars exchanged in the soybeans case is 1 order of magnitude with respect to wheat and maize and 2 orders of magnitude less than rice).

In the case of wheat trade (Figure 52), it is possible to notice that the main countries that gain blue water dollars, i.e. the USD deriving from the blue water trade, are Australia, Canada, France, Germany, India, Kazakhstan, Mexico, Pakistan, Russian Federation, South Africa, Tunisia, Turkey and USA as written in bold in the graph.

Thus, flows greater than 10 million dollars for the wheat case are the followings:

- from Indonesia, Iran, Japan and Korea Republic to Australia;
- from Belgium, Italy and Netherlands to France;
- from Bangladesh, Korea Republic to India;
- from Russian Federation to Kazakhstan;
- from Switzerland and Turkey to Mexico;
- from Egypt and Japan to USA.

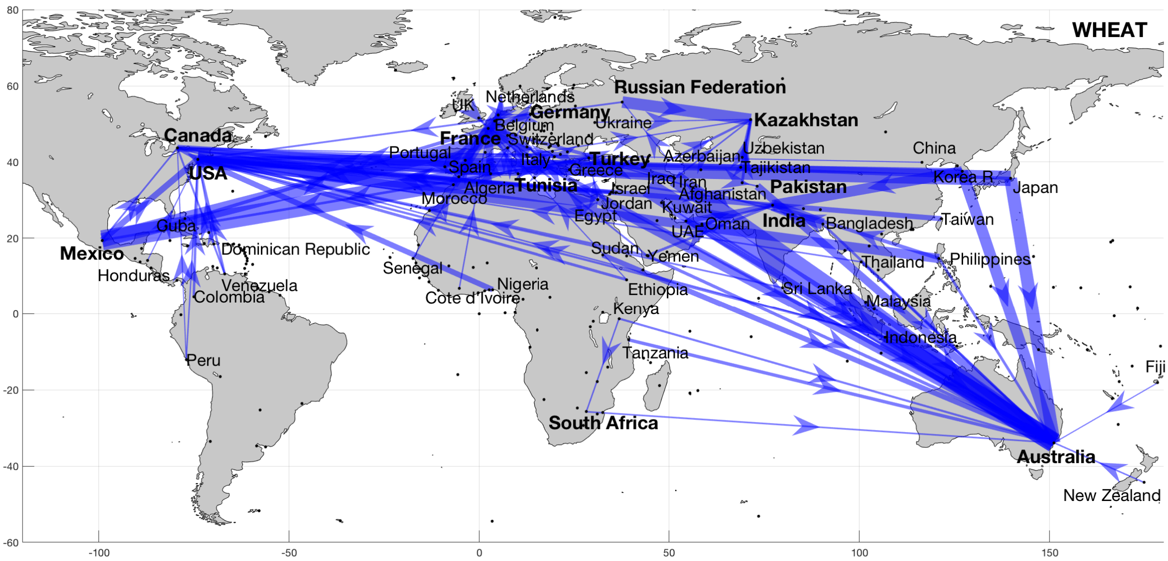

Figure 52: Main flows (greater or equal to 1 million dollars) of USDs deriving from the virtual blue water trade, WHEAT (2000). The nodes represent countries that export or import blue water value in their geographical position. The edges represent the flow of USDs. Arrows indicate the direction of the income, from the importer (buyer) of blue water to the exporter (seller) of blue water. Flows converge in countries in bold.

In the rice case (Figure 53), the number of significant links seem to be greater than wheat (and also greater than maize and soybeans), indeed the number of edges greater than 1 million dollars is 127 with respect to 103 for the wheat case. Countries with bigger incomes of blue water dollars in this case are Argentina, China, Guyana, India, Pakistan, Suriname, Thailand, Uruguay and Venezuela. The exchanges greater than 10 million dollars are the followings:

- from Brazil and Iran to Argentina;
- from Cote d'Ivoire to China;
- from Bangladesh, Kuwait, Saudi Arabia, United Arab Emirates, UK and USA to India;
- from Afghanistan, Saudi Arabia and United Arab Emirates to Pakistan;
- from China (82 million dollars), Indonesia, Iran, Iraq, Korea DPR, Malaysia, Nigeria, Senegal, Singapore, South Africa, United Arab Emirates, USA and Yemen to Thailand;
- from Brazil to Uruguay.

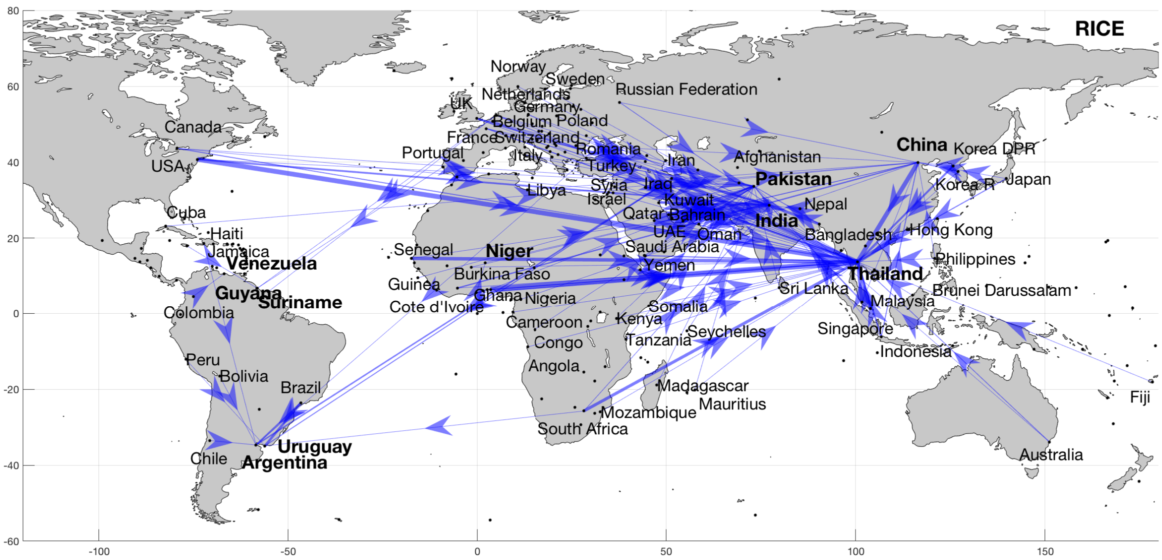

Figure 53: Main flows (greater or equal to 1 million dollars) of USDs deriving from the virtual blue water trade, RICE (2000). The nodes represent countries that export or import blue water value in their geographical position. The edges represent the flow of USDs. Arrows indicate the direction of the income, from the importer (buyer) of blue water to the exporter (seller) of blue water. Flows converge in countries in bold.

Meanwhile, maize case (Figure 54) accounts 79 significant links (greater than 1 million dollars). The major flow that stands out is the blue water dollars' transfer from Asian countries to USA. Indeed, the main incomes of Blue Water Value are for Argentina, China, Ecuador, France, Hungary, Italy, South Africa and USA.

Hence, exchanges greater than 10 million dollars are the following:

- from Korea Republic and Malaysia to China;
- from Taiwan, Egypt, Japan, Korea Republic and Mexico to USA.

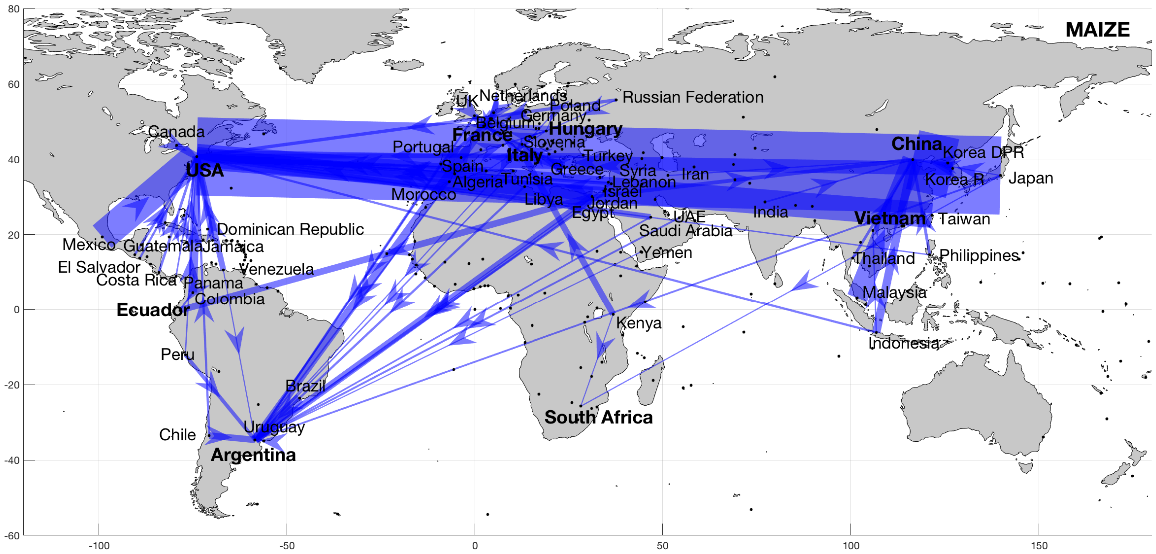

Figure 54: Main flows (greater or equal to 1 million dollars) of USDs deriving from the virtual blue water trade, MAIZE (2000). The nodes represent countries that export or import blue water value in their geographical position. The edges represent the flow of USDs. Arrows indicate the direction of the income, from the importer (buyer) of blue water to the exporter (seller) of blue water. Flows converge in countries in bold.

Lastly, in the soybeans case (Figure 55) the value of the trade in terms of USDs resulting from blue water (virtually) exchanged is less than the other cases as already described.

In fact, the 44 main links have been illustrated in Figure 55, but in this case they are greater than 0.1 million dollars, while the ones greater than 1 million are just 13 and they are mainly from USA.

Nevertheless, there is just one exchange with a value greater than 10 million dollars, namely the one from China to USA (12.2 million USDs).

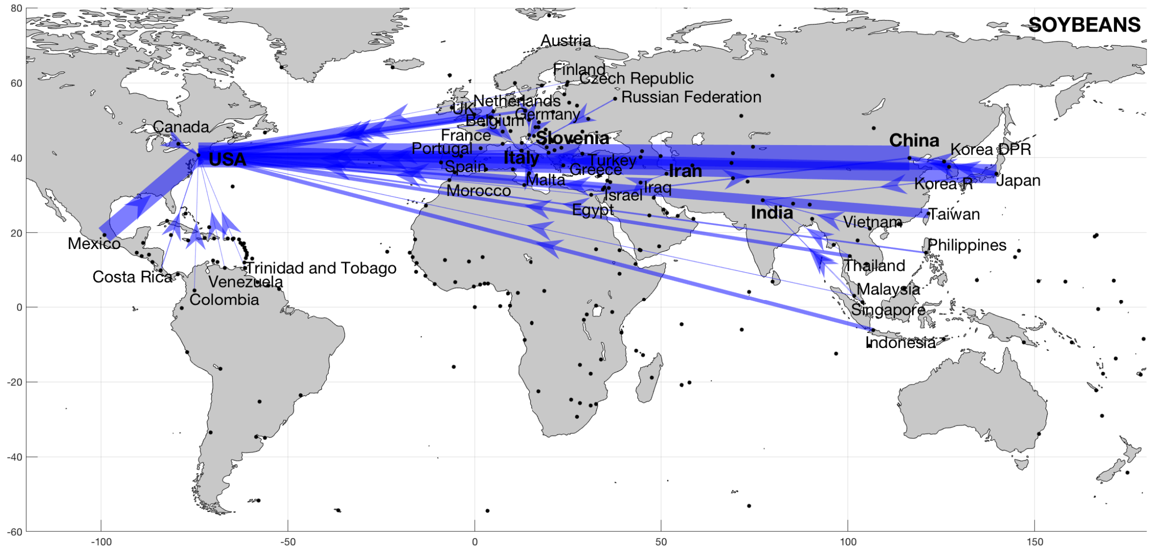

Figure 55: Main flows (greater or equal to 0.1 million dollars) of USDs deriving from the virtual blue water trade, SOYBEANS (2000). The nodes represent countries that export or import blue water value in their geographical position. The edges represent the flow of USDs. Arrows indicate the direction of the income, from the importer (buyer) of blue water to the exporter (seller) of blue water. Flows converge in countries in bold.

Eventually, for the sake of summarizing the information from the graphs, total amounts of Blue Water Value income for each country have been mapped in Figure 56, for all the four staple crops.

The biggest Blue Water Value incomes are the ones in red in maps. It is possible to observe that USA has an intake in terms of blue water dollar greater than 50 million USDs in the wheat, maize and soybeans cases. Still in the wheat case, also Australia and France have a significant income greater than 50 million USDs. India and Canada also show relatively high values of income of Blue Water Value.

In the rice case Asian countries, namely China, India, Pakistan and Thailand are the countries with greater incomes. Since the income of USDs have a correspondence of blue water cubic meters, these countries also have biggest exports of Blue Water. India and Pakistan that have big transfers of blue water are also countries in a relatively water stress situation. While India is exporting blue water with a Blue Water Unit Value of almost 0.25 USD/m^3, thus above the global weighted average (0.06 USD/m^3), Pakistan has a BWUV less than 0.05, which is below the average.

Along with USA, in the maize case, China and Argentina have a virtual income of Blue Water greater than 50 million dollars.

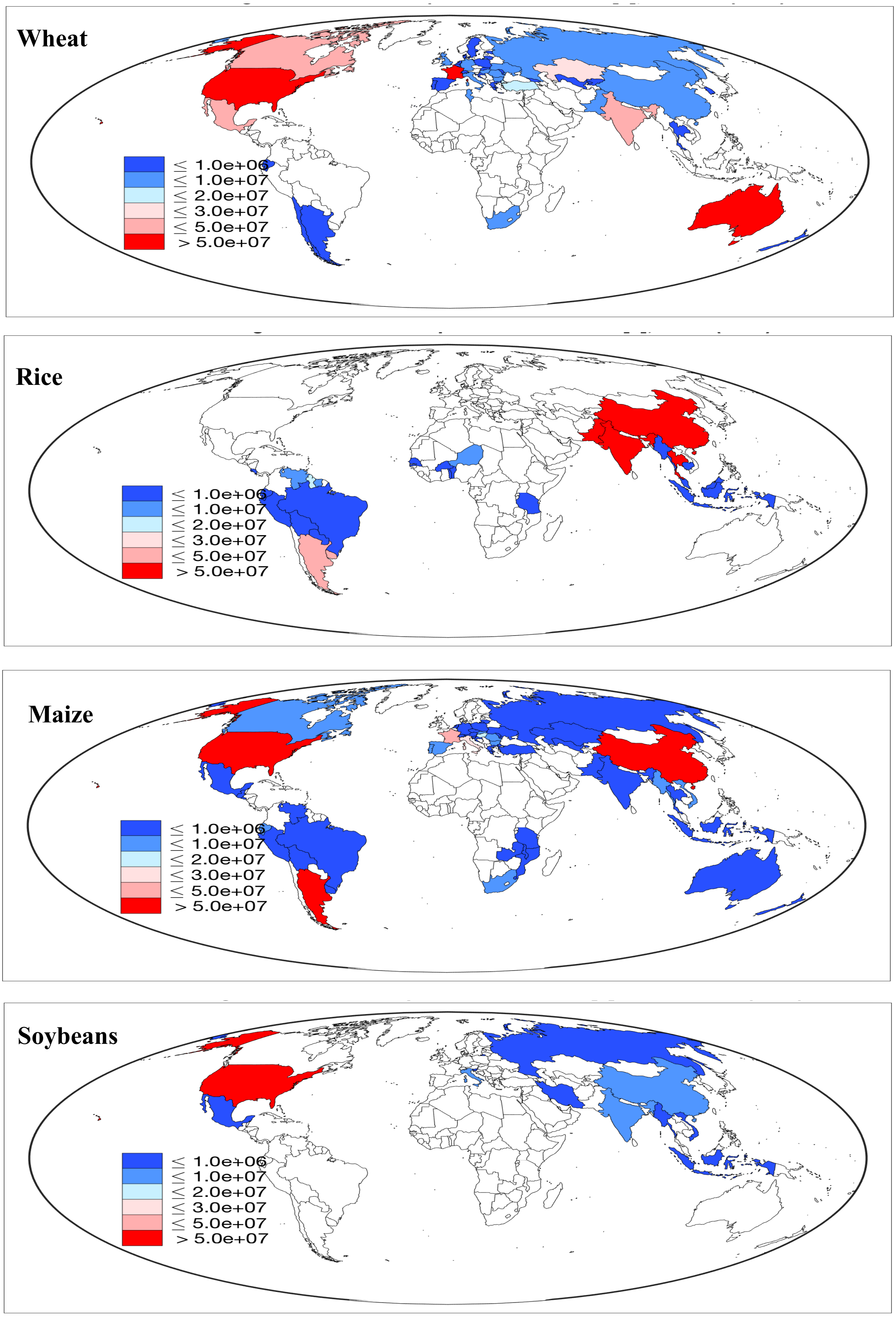

Figure 56: World map of the total virtual income of USDs resulting from blue water, respectively in the wheat, rice, maize and soybeans in 2000. Countries that do not produce both rainfed and irrigated crops have been depicted in white in the maps.

6 Conclusion and Future Studies

The method developed in this study leads to the estimation of the value in USDs of a cubic meter of Blue Water in the agriculture context. This value can be seen as a virtual cap price of blue water since it will be the actual economic yield of water used in the crop production. By using the farm-gate prices in the production stage of wheat, rice, maize and soybeans, we obtained global average values respectively equal to 0.07, 0.06, 0.19 and 0.04 USD/m^3 for the year 2000. These numbers seem to be reasonable in fact, we expected these virtual prices less than desalination cost that, in the case of reverse osmosis, is equal to 0.68-0.92 USD/m^3. This cost can be seen as a benchmark, indeed if the economic yield of blue water had been greater than desalination cost, farmers could have used treated sea water as an alternative of blue water (not considering logistic issues).

Nevertheless, the Blue Water Unit Value, i.e. the economic yield of blue water is more or less equal to the Green Water Unit Value in terms of global average for each crop (wheat, rice, maize and soybeans). This underline the fact that the world in aggregate does not seem to associate a greater value to blue water with respect to green water. In fact, water is not a significant driver of cost when farmers set the farm-gate price of a crop and moreover they do not divide the two different water components.

Moreover, the analysis of the crop production underlines that the *BWUV* has a high disperse spatial distribution, in fact countries, in all the four cases, show a heterogeneous behavior.

Also, big producers of crops, that are also big consumers of blue water, generally do not have high values of Blue Water Unit Value with a significant exception of France in the wheat case, which is a really blue water efficient country.

In some cases, highest values of *BWUV* have been determined by high productivity increase or great blue water efficiency (low Blue Water Footprint).

We expected a general positive trend between Blue Water Unit Value and the percentage increase of production yield but the pattern is not always well delineated, but it is often confused.

The hyperbolic relationship between *BWUV* and Blue Water Footprint is the most relevant trend observed. Indeed, the relationship of inverse proportionality between them is the main driver of blue water value. Therefore, the water efficiency is the matter of greatest importance.

As expected, dry countries show great percentage increase in yield production since the gap between rainfed lands and irrigated lands is the widest among nations. This relative increase does not always lead to a great Blue Water Unit Value because, as just said, the main factor is the Blue Water Footprint.

The estimation of Blue Water Unit Value in the trade (*BWUV_TR*) leaded to global average values for wheat, rice, maize and soybeans equal to 0.12, 0.06, 0.11, 0.01 USD/m^3. These numbers are essentially more or less equal to the values in the crop production. In fact, the only difference between them is the price, farm-gate price VS trade price, and we already described in the second chapter that in weighted average terms there are not significant discrepancies between them. Also, the staples crops are food commodities and we do not expect high trade prices with respect to the farm-gate prices.

Moreover, there is heterogeneity among countries also in the case of Blue Water Unit Value in the trade for all the staple crops.

In the year 2000 more than 35 billion cubic meters of blue water have been virtually transferred due to the trade of the four staple crops with a corresponding opposite transfer of more than 2 billion dollars.

The country with the greatest incomes of USDs resulting from the transfer of blue water is USA that overall (in wheat, maize and soybeans cases together) have an income greater than 150 million dollars. France and Australia account more than 50 million dollars of income resulting from irrigation in the wheat case. Eastern countries, namely China, India, Pakistan and Thailand also have incomes greater than 50 million dollars, together with Argentina.

Two of the biggest exporter of blue water resulting from rice trade, namely India and Pakistan seem to be in a relatively water stress situation. Moreover, Pakistan have a high Blue Water Footprint of rice underlining that it is not an efficient country in terms of blue water use.

Eventually, this study shows that an increment in irrigation turns into an additional crop production that can be traded between nations in the global context having as a result an additional income of USDs. This economic return of blue water transfer can represent the basis for a future study in order to estimate and understand the environmental and social cost behind it.

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