WATER

TO

FOOD

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ACKNOWLEDGEMENTS

There are way too many people we should thank, and this single page is surely not enough space to successfully complete this task.

Water to Food represents a multidimensional effort to communicate the research conducted under the CWASI (Coping With Water Scarcity In A Globalized World) project, financed by the ERC (European Research Council), which has shaped our research activity and our lives for the last five years. When you think about it, five years is a long time, and many colleagues, mentors, and friends constantly inspired and influenced us throughout all this period. We like to believe that every single one of them is somehow part of this handbook and, for this reason, part of who we became ourselves. We would like to thank you all for everything, whether we know you or not, for helping us achieve this result.

First of all, special acknowledgments are dedicated to Tony Allan and Arjen Hoekstra. Thank you for believing and showing us that water can be studied, taught, and told to make the world a better place.

Secondly, although we, Benedetta, Carla, Elena, and Marta, as researchers and friends, found in this project a way to escape from the closure of lockdown, we found support and collaboration in those who have always been our scientific mentors, Francesco and Luca. They made CWASI a reality and supported us and many others during their academic journey. Thank you for believing in us and in the whole Water To Food communication project. Thank you for giving us the freedom to explore, create and build something as a group, and for trusting our collective vision from start to finish.

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Thanks to Marco Maria Pedrazzi, who first believed in the graphical potential of our research results. Some of the figures we have shown here were the by-product of his creative intelligence and guided us in the creation of the whole communication project.

Thanks to our team: Antonio Curedda, Stefano De Marco, Luca Di Giovanni, Niccolò Falsetti, Morena Faverin, David Fregoli, and in particular our graphics designers, Donato Loforese and Roberto Memoli, who found a way to provide visual coherence for our research outputs, transforming our vision into reality.

Thanks to Politecnico di Torino for providing us with an environment where to work, grow, think and imagine together. Thanks to our Department of Environment, Land and Infrastructure Engineering, and all the staff who supported our project, especially Silvia Antonietti and Elisa Vanin.

And our final thanks go directly to you, our reader. Thanks for your curiosity and trust. Your willingness to access our distant world inspired us to create tools for everybody with the Water To Food communication project. We do believe that together will find a way to take care of water resources in the global food system.

FOREWARD

Francesco Laio

“When I ask for a watercress sandwich, I do not mean a loaf with a field in the middle of it.”, Oscar Wilde reportedly said to a waiter who was serving his order. Wilde’s interest in the environmental impact of the food we consume is dubitable, but still “a loaf with a field in the middle of it” is the perfect image to remind us that there might be something hidden in what we eat and that while eating, we humans also feed on natural resources. As a hydrologist, my entry point to the problem has been the pioneering work on the water-food nexus introduced by Tony Allan and Arjen Hoekstra, who formalized the concepts of virtual water and water footprint as means to quantify the water resources virtually embedded in the food we produce, trade, and consume.

The project Coping with water scarcity in a globalized world, funded by the European Research Council, has expanded these concepts, and explored the environmental and socio-economic consequences of the globalization of water resources, which derives from the globalization of the food system. It has been a 5-years long trip, accompanied by a wonderful group of colleagues with very diverse expertise and a common intent: to tackle the challenges posed by the water-food nexus with data-based approaches bridging the gap between different disciplines, including, among others, hydrology, complex-network physics, agricultural sciences, and trade economics.

With this publication, we would like to share some of the most relevant results we have found, trying to balance scientific accuracy and readability, still without forgetting that (again, borrowing the words of Oscar Wilde) “the pure and simple truth is rarely pure and never simple”.

INTRODUCTION

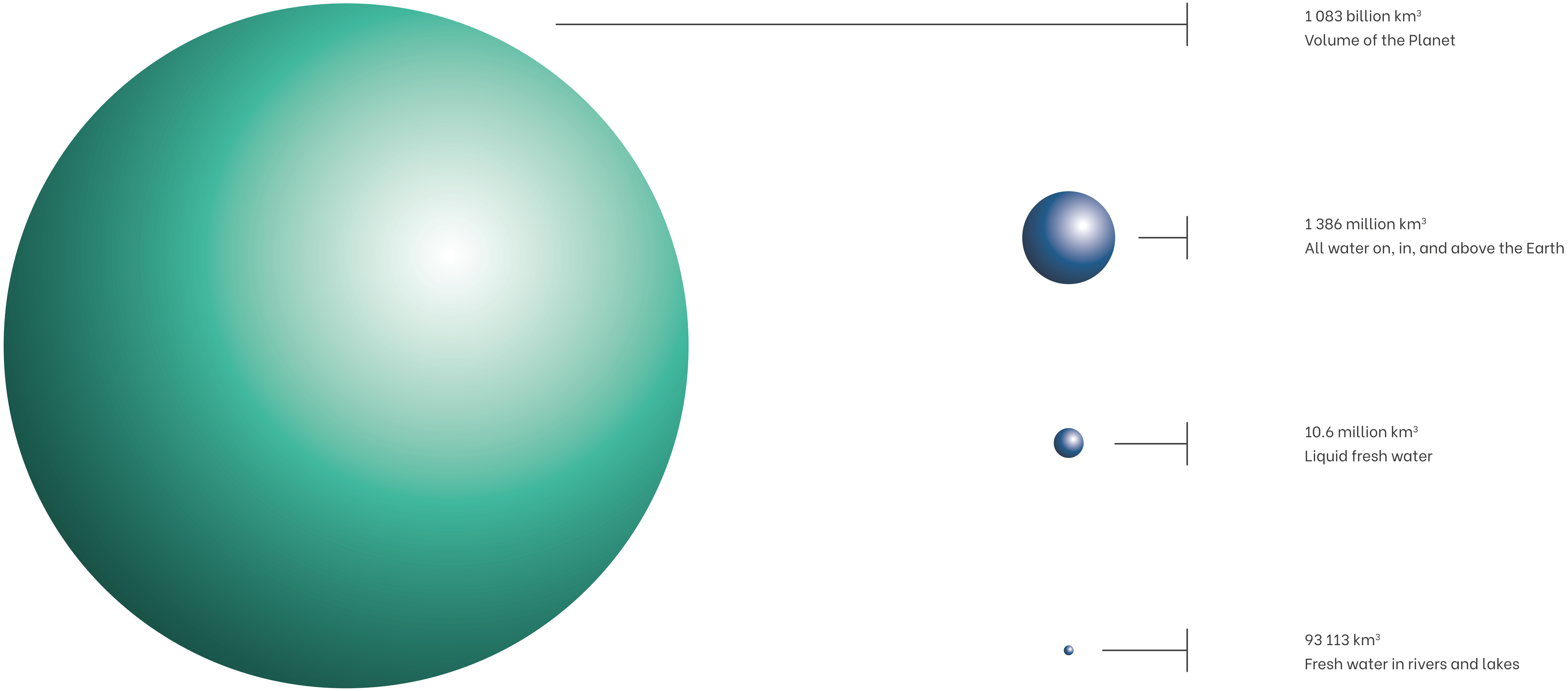
This handbook is one of the many different parts that compose the Water To Food communication project. Water To Food was born as a common and multidimensional hub to communicate, outside of the academic world, the results of the European Research Council known as CWASI (Coping With Water Scarcity In A Globalized World).

The CWASI project, which started in 2015 and ended in 2020, addressed and tackled the globalization of water resources consumed and used for food production, using quantitative methods to study the effects of water shifts on food security and conflicts related to its use. During the 2020 lockdown for the COVID-19 emergency, a clearer idea of how to communicate the results of this project outside the scientific world arose within our group. From this idea, the WaterToFood project was born to make information about the water footprint in the food chain accessible through user-friendly communication tools and platforms.

The key to the WaterToFood project is the belief that society as a whole should be involved in protecting and managing water resources, but that is hard to make informed decisions if the results of scientific research are not presented in a comprehensible way. Therefore, with this piece of work, we attempt to bridge science and society, raise awareness of the problem, and provide effective tools to cope with it, to preserve water resources together.

All the other resources created in the context of the Water To Food communication project, such as videos and databases, are available for you to consult at www.watertofood.org.

The Blue Planet



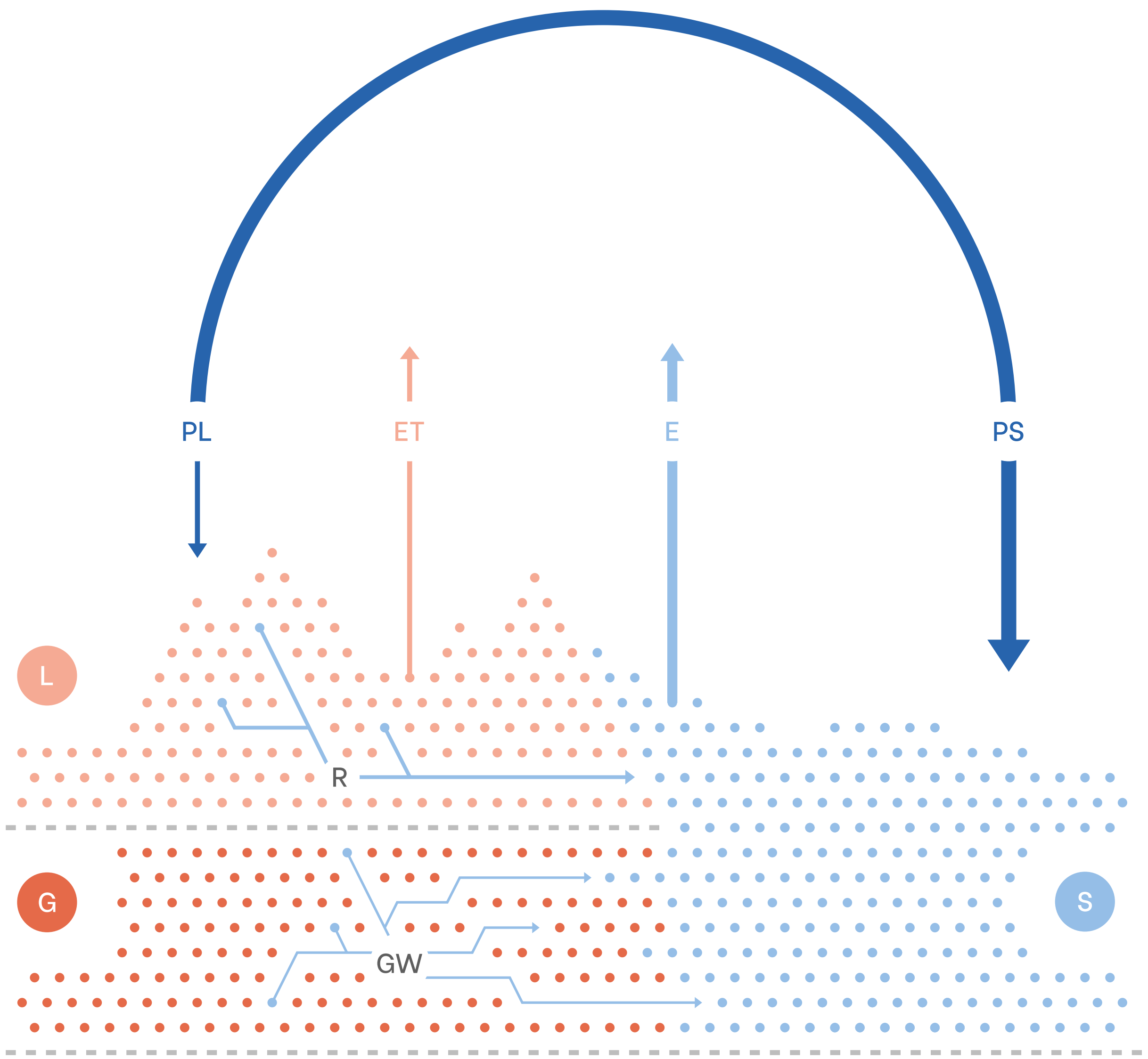
INTRODUCTION

The hydrological cycle

Water has many forms and shapes, and it flows through the Earth's ecospheres following the hydrological cycle. Water evaporates from the oceans, evapotranspires from lands due to soil moisture evaporation and plant respiration. Once formed, water vapor lifts in the atmosphere until it condenses for precipitating onto seas and lands. Precipitated water can either be intercepted by vegetation or become overland flow. It can discharge into rivers or infiltrate into the soil. In this latter case, water may percolate deeper and recharge groundwater reservoirs. As defined, the cycle has no beginning nor end.

At the global scale, neglecting possible variation due to climate change effects, the water fluxes involved in the hydrological cycle are in equilibrium. On average, 577 000 km³ of water precipitates every year over land and seawater bodies. This exact amount of water evaporates from oceans, rivers, lakes and transpires from plants. Nevertheless, the global equilibrium of the cycle is not granted on a local scale due to the atmospheric dynamics and the interactions with soils, plants, and water bodies, even without considering the anthropic pressure. That is why we can enjoy the wonderfulness of the changing landscapes across the latitudes: glaciers, forests, grasslands, savannas, and deserts.

Where does water for human uses come from? The dynamics of the hydrological cycle.



PL : Precipitation on land
P = 119 000 km³

ET : Evaporation and evapotranspiration from lands · ET = 72 000 km³

E : Evaporation of seawater
E = 505 000 km³

PS : Precipitation on seawater
P = 458 000 km³

R : Runoff from rivers to seawater
R = 44 700 km³

GW : Groundwater reservoirs
GW = 2 200 km³

L : Land

G : Ground

S : Sea

Water consumption in the modern society

Water is said to be the ultimate commodity: it is essential for the sustainment of all living beings and of particular value for humankind due to its role in the provision of services. In particular, freshwater resources are more precious to humanity: water can be withdrawn from rivers and lakes or retrieved by exploiting technological advancements providing non-conventional sources.

SOURCES OF FRESHWATER

NATURAL

- Surface Water (rivers, lakes)
- Renewable Groundwater
- Fossil or Non-Renewable Groundwater

NON-CONVENTIONAL

- Desalinated Water
- Treated Wastewater
- Agricultural Drainage Water

Water withdrawal has three main anthropic uses: agricultural (including irrigation, livestock, and aquaculture), municipal (including domestic services), and industrial. In most regions of the world, over 70 percent of freshwater is used for agriculture.

11% MUNICIPALITIES

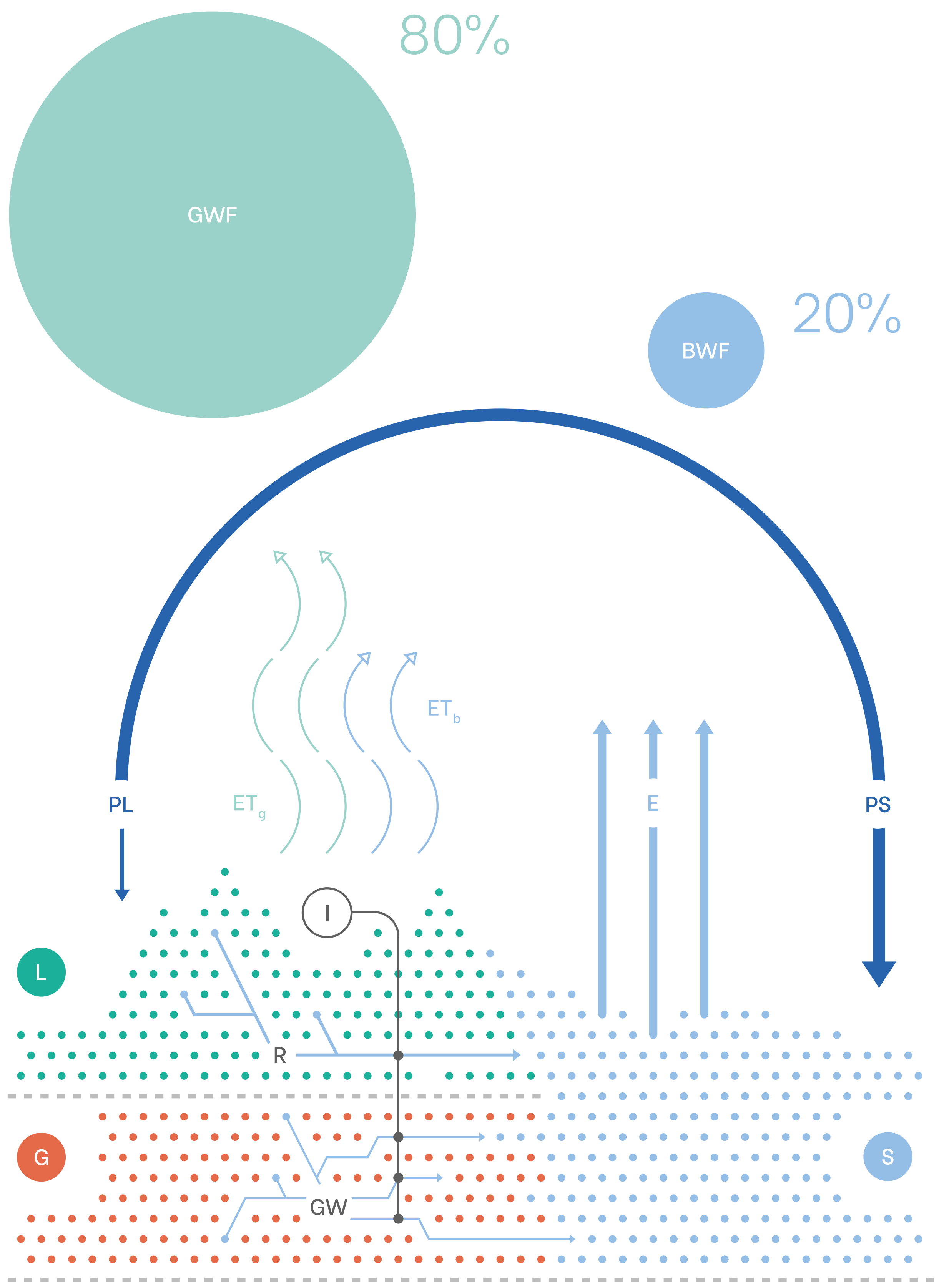
19% INDUSTRIES

70% AGRICULTURE

- Irrigation (also accounting for fodder and pasture for livestock)
- Livestock watering and cleaning
- Aquaculture

The structuring of the concepts

Crop production dominates the use of global freshwater in agriculture, which accounts for nearly 70% of the total water withdrawal. Worldwide, freshwater use has increased by 6-8 times during the past century due to rising food demand and changing living standards (promoting high-calories and protein-intense diets, *(see pages 140-141)*. Simultaneously, the areas equipped for irrigation have doubled, with proven consequences for aquifers, lakes, and river ecosystems *(see pages 170-187)*.
The awareness of the essential role of water for the sustainment of human activities, and preservation of ecosystems, led to the structuring of the concepts of *virtual water and the water footprint*.
In the early '90s, Tony Allan first introduced *the idea of virtual water* to investigate how, in water-scarce countries, the provision of food, clothing, and other water-intensive goods could be granted to the population. The term virtual – or *embedded* – water aims to measure the water quantity associated with producing a single unit of goods or a single service. Following the idea of virtual water, to explore the nexus between production, consumption, and water use, Arjen Hoekstra introduced in 2002 the novel notion of *water footprint*: a water assessment to assess and communicate humans' water use, and measuring the total *footprint* that this virtual water use leaves on *water resources*.
The concepts of virtual water and water footprint are intrinsically related. While the term virtual water refers to the water requirements for a single produced or served unit, the Water Footprint (WF) tool can be applied to quantify the freshwater needs of different processes together, thus extending the virtual water analysis to a broader framework. One can be interested in assessing the WF associated with producing a good, either along its entire supply chain or just during a process step. Eventually, one can determine the water footprint of a group of consumers, a river basin, or a nation. The spatial and time scales of analysis of the Water Footprint assessment depend on the context of analysis.
As we will further discuss, the differences between the two concepts clearly arise when introducing the globalization of resources through the international trade of goods and services *(see pages 96-101)*: on a commercial route, the water footprint of any commodity (or service) moves with it in the form of virtual water. Therefore, trade allows one to relate the water footprint of production to the water footprint of consumption, wherever it occurs *(see page 88 - 89)*.
The Water Footprint methodology also distinguishes two water sources being used during the process at hand. In particular, in the agricultural sector, the *Green Water Footprint* refers to the use of Green Water resources, namely rainfall that infiltrates into the upper soil layer, which is thus available for roots water uptake. Instead, the *Blue Water Footprint* refers to the use of Blue Water resources, namely, water withdrawn from rivers, lakes, and aquifers. The concept of Blue Water Footprint is not limited to the agricultural sector, though, but it extends to the domestic and industrial ones. Eventually, the *Grey Water Footprint* considers the amount of wastewater produced, and it can be measured for all processes in the three sectors of production.
As we consider water as an essential input for any process, our results focus on the Green and Blue Water Footprints, thus neglecting the wastewater output.



L : Land
G : Ground
S : Sea

R : Runoff from rivers to seawater
GW : Groundwater reservoirs
I : Irrigation
GWF : Green Water Footprint
BWF : Blue Water Footprint

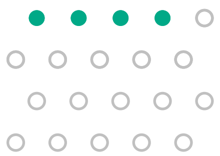
E : Evaporation of seawater
ET$_b$: Blue evapotranspiration
ET$_g$: Green evapotranspiration
PL : Precipitation on land
PS : Precipitation on seawater

DECOMPOSING AND TRACKING THE WATER USE THROUGH EACH STEP OF THE SUPPLY CHAIN

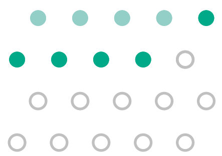
Many products contain ingredients from agriculture or forestry. Crops are used for (but not limited to) the production of food, feed, fibers, fuel, oils, soaps, and cosmetics. During the production and supply chain, the most extensive use of water occurs during the growing process of the crop or tree, i.e., from seeding to harvesting. Other steps, such as transformation, packaging, and transportation, generally require a smaller amount of water. That is why most of our analyses focus on the production side, assessing the water that is used at the very origin of the supply chain.

WATER REQUIREMENTS DURING THE CROPS PRODUCTION AND SUPPLY CHAIN of a 100g of apple

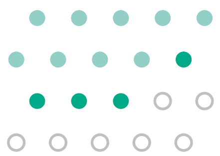
SEEDING
14 liters



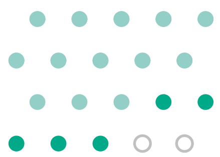
GROWTH
31.5 liters



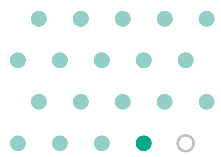
HARVEST
45.5 liters



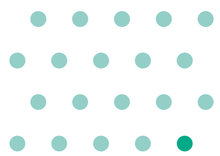
TRASFORMATION
59.5 liters



PACKAGING
66.5 liters



TRANSPORTATION
70 liters

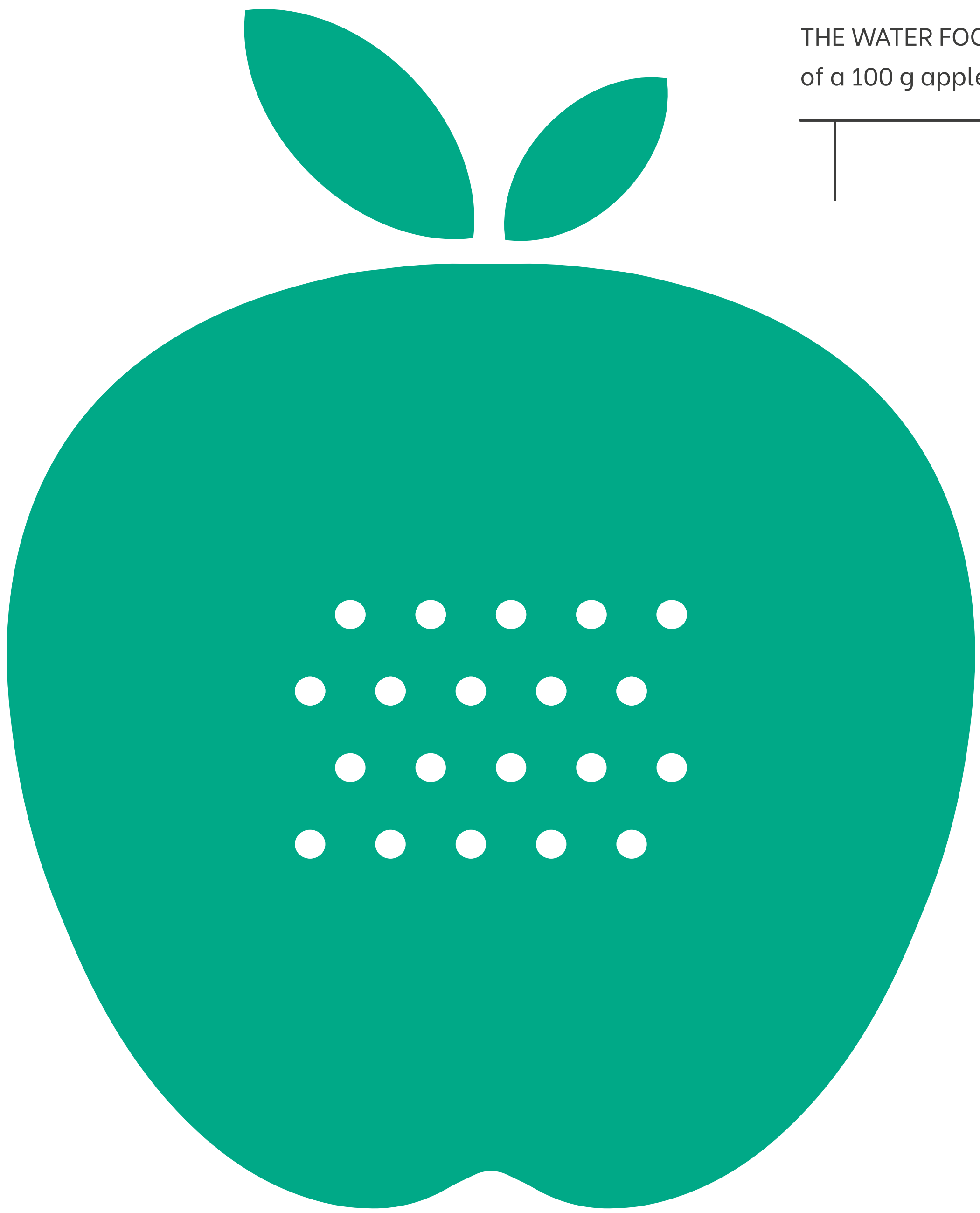


○ : A single point is equivalent to 3.5 liters
● : The woter footprint of the specific step along the supply chain
● : The water footprint of the previous step along the supply chain

70 liters quantifies the total amount of water embedded in the production process of an apple.

70L

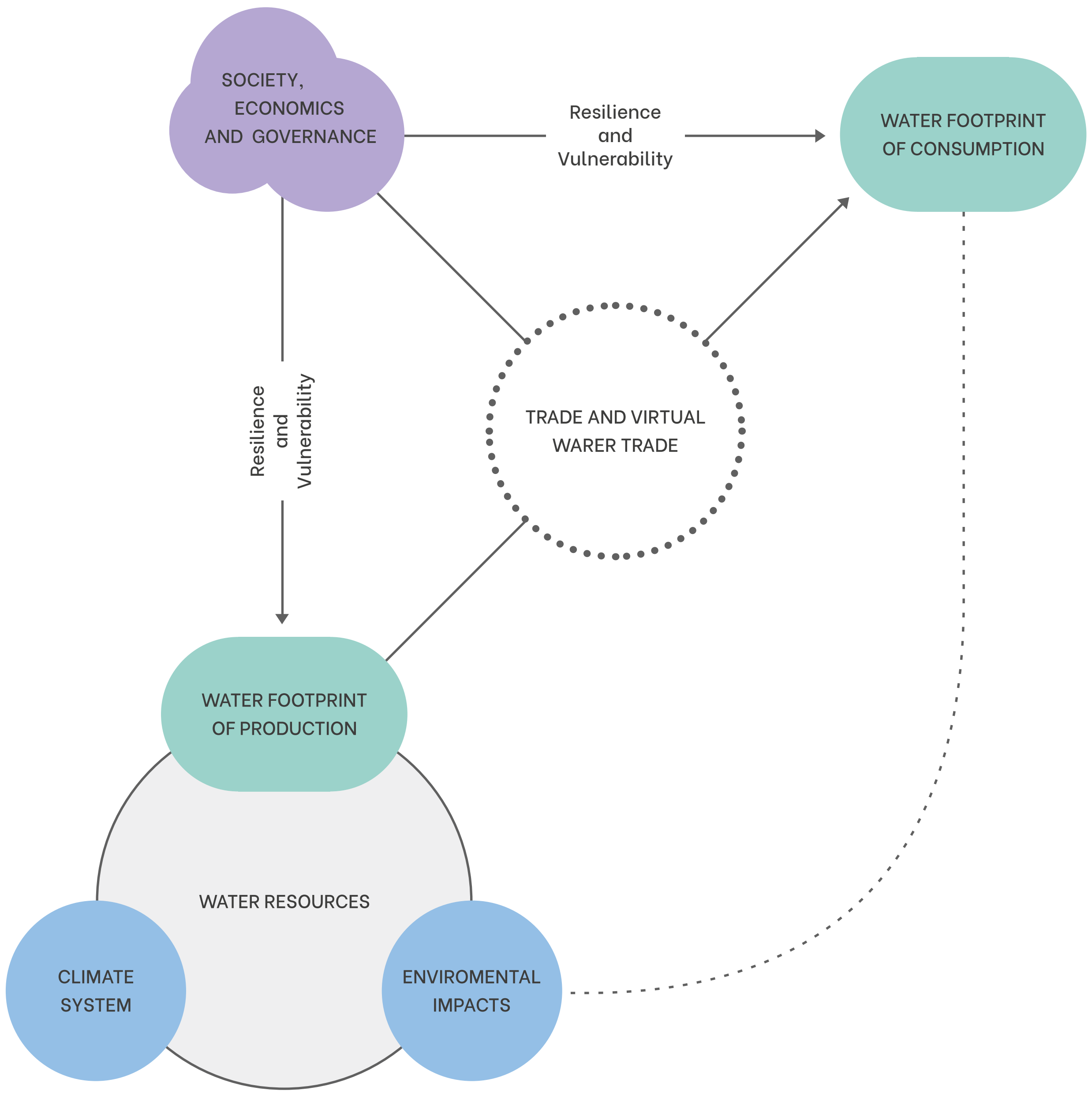
THE WATER FOOTPRINT
of a 100 g apple



The complexity around virtual water and water footprints

Over the last decades, the concepts of water footprint and virtual water have allowed scholars and policymakers to study how water moves around the globe due to production and trading processes.
On a national scale, one can calculate a country's water footprint from a production or consumption point of view. On the one hand, the WF of production represents the total amount of water used along the whole supply chain within the country. On the other hand, the WF of consumption is measured for all products consumed within the given country. Therefore, consumption also considers possible imports of goods and so the import of virtual water.
In fact, the water used in producing (or exporting) areas is virtually transferred to consumption (or importing) areas. This set of interchanges creates what is called the virtual water trade network.
Factors concerning society, economy, and governance affect the production, consumption, and trade of water at both local and global scales. These factors include population dynamics, possibly increasing the food demand with increasing population size, and the Gross Domestic Product, which can determine changes in goods demand and production. (Increased wellness is associated with increased requests for more sophisticated and water-intensive products such as meat).
Moreover, governments have their role in deciding and implementing policies, including international market agreements, that influence the food market through trade and global dynamics of food demand.
The globalization of food products has pros and cons, especially in terms of water and food security. As pros, it contributes to improving food availability and feeding the population, reducing the dependence of production on local resources. In contrast, globalization favors the propagation of crises, as it leads to complex, interconnected production-consumption systems that are vulnerable to failures. Local food-production crises, which may have a social, economic, or environmental origin, propagate in the trade network, thus modifying the virtual water trade and perturbing local and global food availability. Defining the resilience and vulnerabilities of countries to food crises helps monitor the dynamics and effects of shocks' propagation. Moreover, food production has an environmental impact. Unsustainable use of water resources defines situations of water stress *(see pag. 180-181)*. It can be quantitative when water withdrawals exceed the natural capacity of water regeneration, or qualitative when the resource is altered in biological or chemical terms, with damaging effects on the ecosystems. Beyond threats to the ecosystems, water stress possibly enhances phenomena of water insecurity.

In light of such considerations, the water footprint and virtual water concepts – the ones we framed within the DIMENSION 0 – are intrinsically related to the complexity of the dynamics of the society, economy, and environment. To fully catch the shape of the dimension 0, other dimensions pertaining to these dynamics must be considered. We identify in the virtual water trade, socio-economic and governance issues, resilience and vulnerability, and environmental impact, these other dimensions. We will detail these in the following pages, also describing their relationship and influence on the water footprint and virtual water definition. Notice that, despite the categorization, these further dimensions shall not be considered in isolation but overlapped for a complete comprehension of the drivers defining the world's water footprint and virtual water fluxes. The charts in the following three pages spotlight such overlapping and interconnections between these four dimensions.



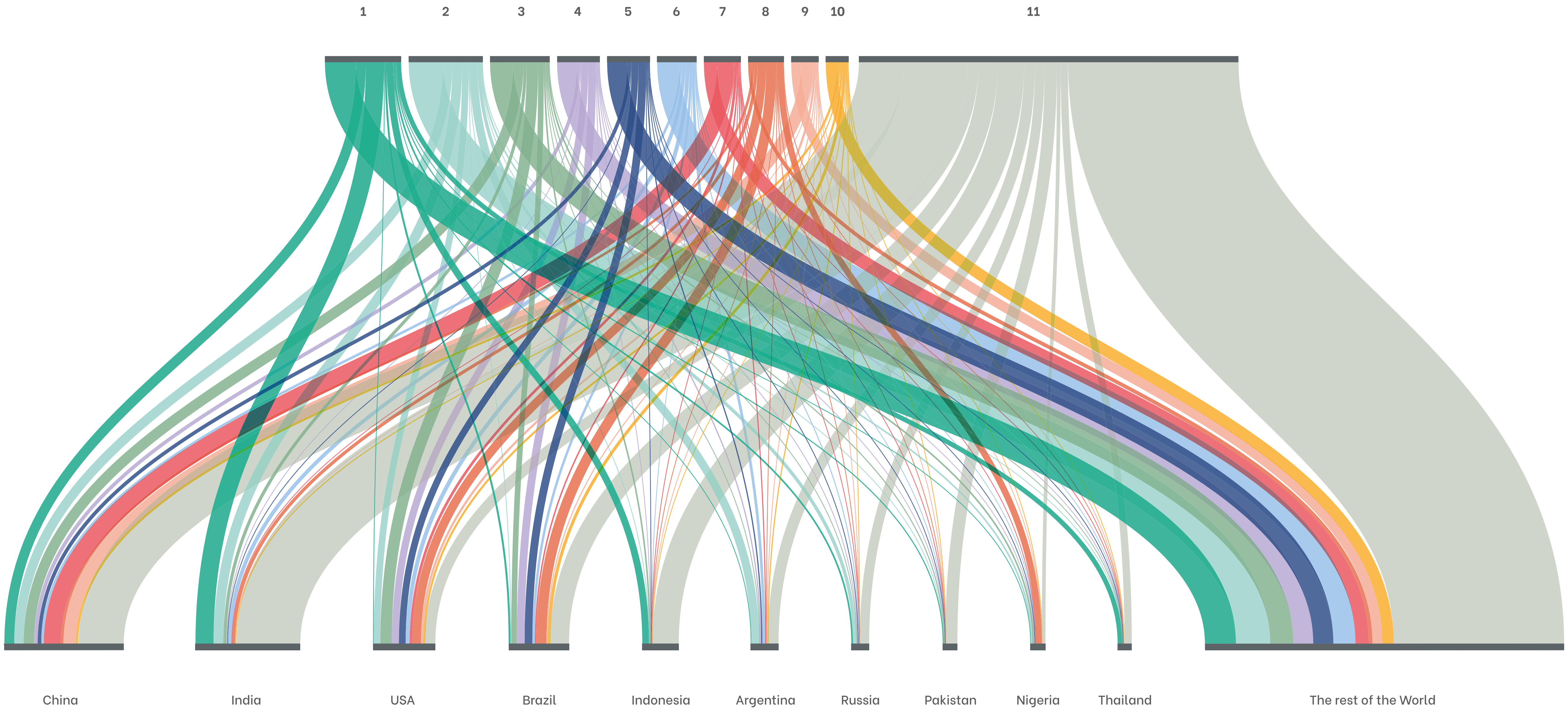
WATER FOOTPRINT OF PRODUCTION

The items listed here are the top ten goods responsible for nearly 60% of the total WF of agricultural production and livestock in the year 2011. Each item-specific bar represents its total WF around the world, evaluated as the sum of all the country-specific WF.
From each product, flows depart and connect to the ten top countries in terms of the water footprint of production. The country-specific bar represents the WF of production measured in each country, given as the sum of WFs over all the food production. For instance, these ten selected products contribute to 60% of the Chinese Water Footprint.

PRODUCTS :

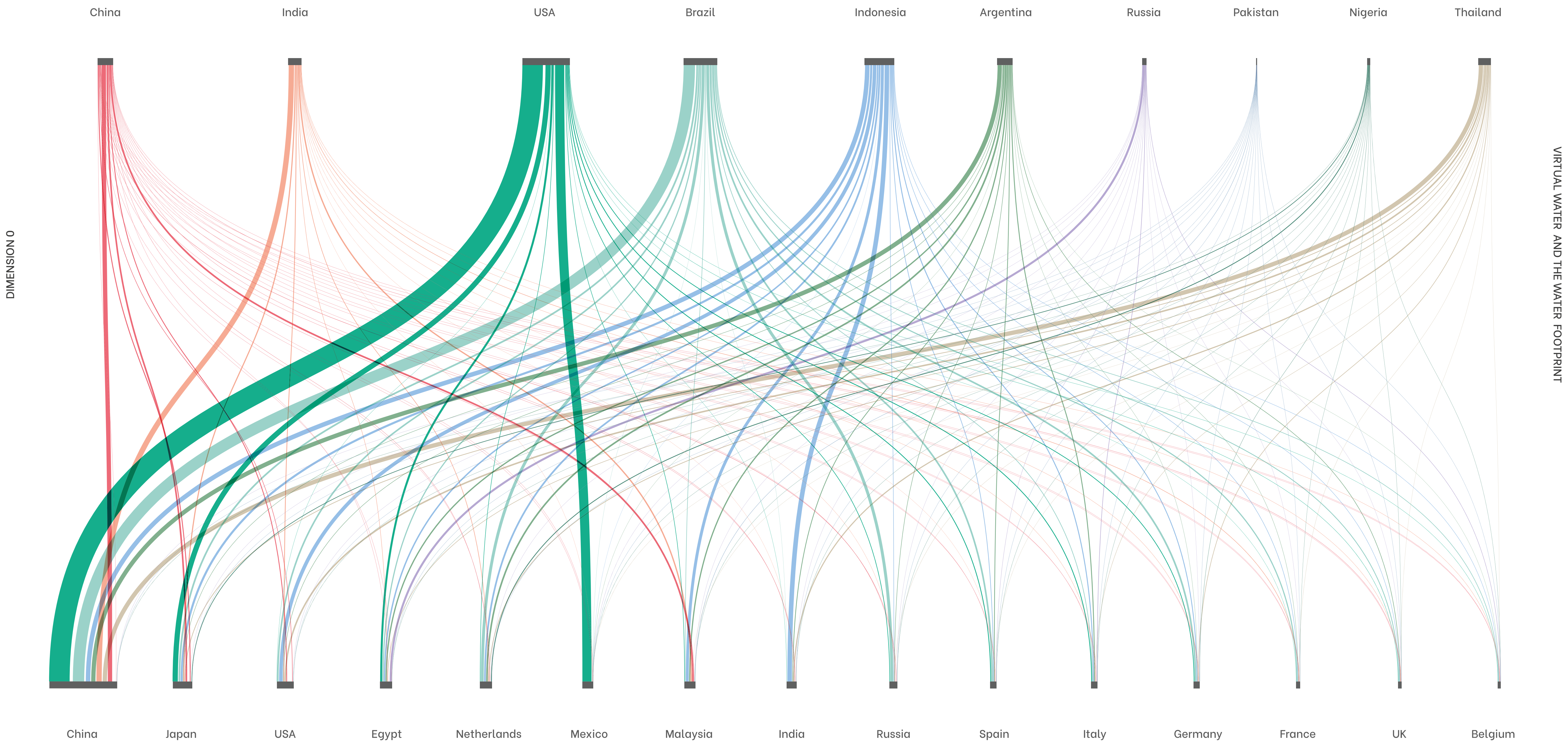
1	RICE PADDY
2	WHEAT
3	MAIZE
4	CATTLE MEAT
5	INDIGENOUS CATTLE MEAT
6	COW MILK
7	INDIGENOUS PIG MEAT
8	SOYBEANS
9	PIG MEAT
10	CHICKEN MEAT
11	Other Products

The nomenclature Rice paddy identifies the rice grains after threshing and winnowing. This product is destined for human consumption. Indigenous meat identifies meat products of autochthonous origin.



VIRTUAL WATER TRADE

These flows are the most intense international flows of virtual water in 2011, flowing from the top ten exporters to the top fifteen importers. Each flow is proportional to the water volume embedded in the traded goods. This volume results from the traded quantity of a given good multiplied by its unit WF in the country of production.



ENVIRONMENTAL IMPACT

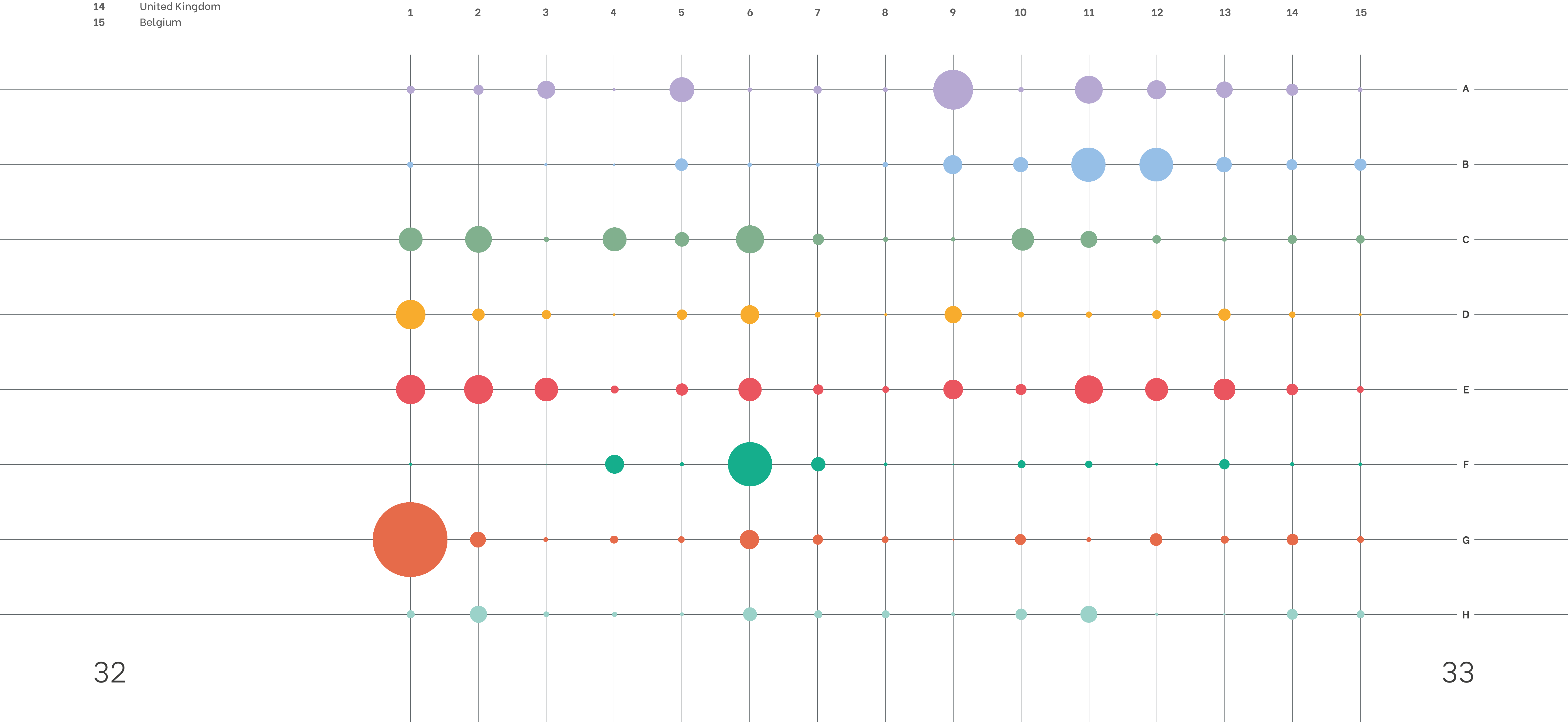
Importing countries have an environmental impact on the world's water resources, particularly on the surface water resources. The bubbles' size qualitatively defines the environmental impact of each importing country due to the production of these items.

COUNTRY :

1	China
2	Japan
3	USA
4	Egypt
5	Netherlands
6	Mexico
7	Malaysia
8	India
9	Russia
10	Spain
11	Italy
12	Germany
13	France
14	United Kingdom
15	Belgium

PRODUCTS :

A	Cattle Meat
B	Cow Milk
C	Maize
D	Chicken
E	Pig Meat
F	Rice
G	Soybeans
H	Wheat



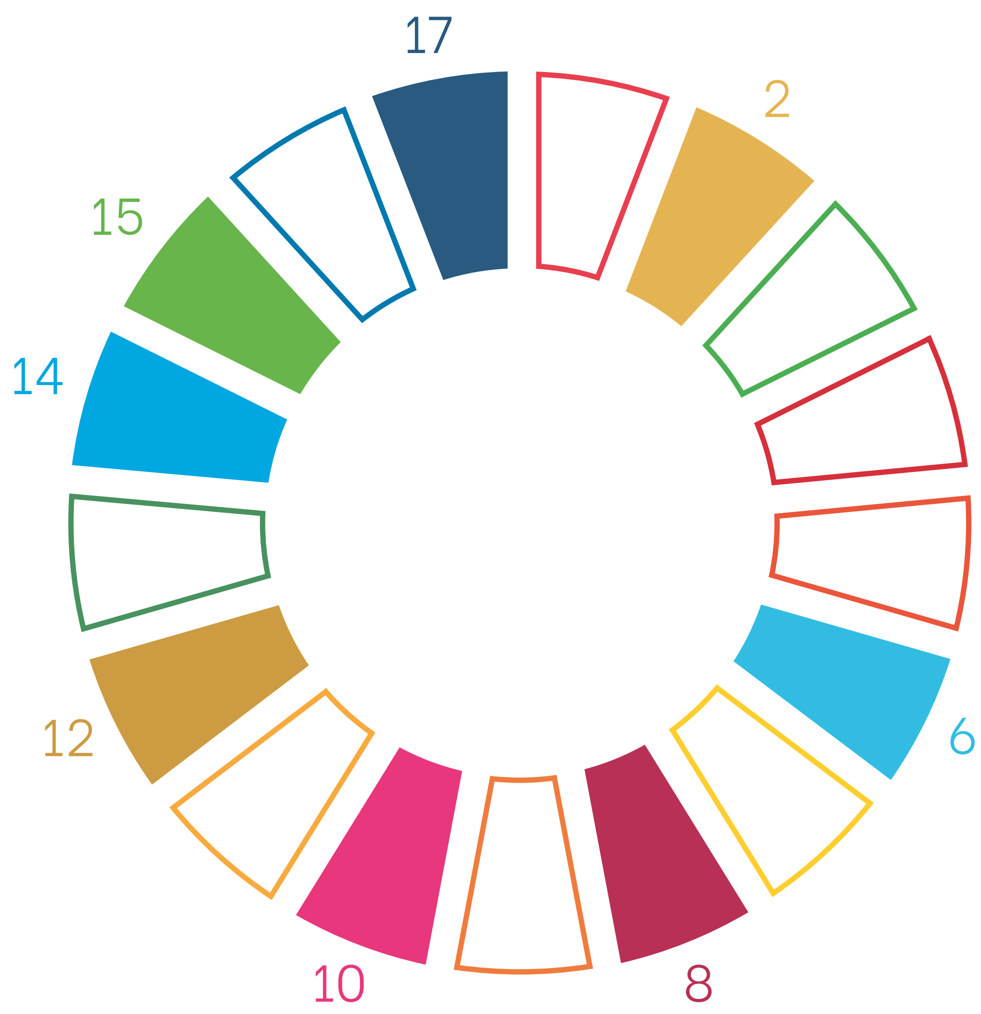
The Agenda 2030

The United Nations "call for actions" defined by the global 2030 Agenda aims at facing and tackling the world's challenges, including food and water security. The 2030 Agenda introduces the so-called Sustainable Development Goals, a set of 17 macro-objectives that aim to promote economic growth while preserving the environment and fostering inclusive development.

Our research intends to offer data-based support to countries to develop their strategies toward sustainability. In particular, due to the synergies and trade-offs across the goals, our support is not limited to one objective, but it stands beyond many Goals. Our research strictly addresses the monitoring of the following SDGs: 2 - Zero Hunger, SDG3 - Clean Water and Sanitation, 8 - Decent Work and Economic Growth, 10 - Reduced Inequalities, 12 - Responsible Consumption and Production, 14 - Life below Water, 15 - Life on Land, 17 - Partnerships for the Goals.

THE 17 SUSTAINABLE DEVELOPMENT GOALS

GOAL 1: No Poverty
GOAL 2: Zero Hunger
GOAL 3: Good Health and Well-Being
GOAL 4: Quality Education
GOAL 5: Gender Equality
GOAL 6: Clean Water and Sanitation
GOAL 7: Affordable and Clean Energy
GOAL 8: Decent Work and Economic Growth
GOAL 9: Industry, Innovation and Infrastructure
GOAL 10: Reduced Inequalities
GOAL 11: Sustainable Cities and Communities
GOAL 12: Responsible Consumption and Production
GOAL 13: Climate Action
GOAL 14: Life below Water
GOAL 15: Life on Land
GOAL 16: Peace, Justice and Strong Institutions
GOAL 17: Partnerships for the Goals



Coping with water scarcity in a globalized world

The quality and quantity of water resources define the development of anthropic and ecological systems.
A water stress condition occurs when water withdrawals exceed the natural capacity of water regeneration, (quantitative water stress) or when the resource is altered in biological or chemical terms (qualitative water stress).
Nowadays, more than two billion people live in highly water-stressed areas, and two-thirds of the global population live under severe water-stress conditions for at least one month a year. Moreover, the intensification of surface and groundwater use in the last decades, especially for irrigation purposes, has led to staggering water depletion levels in important aquifers and river systems worldwide, with consequent threats for natural ecosystems. Hence, balancing water demand with availability is a tremendous challenge for humankind and for the preservation of the environment.
Agriculture stands as the primary driver of water resources consumption worldwide, and the dynamics of food production may lead to water scarcity conditions. According to the United Nations Food and Agriculture Organization, a state of water scarcity occurs in the contexts of:

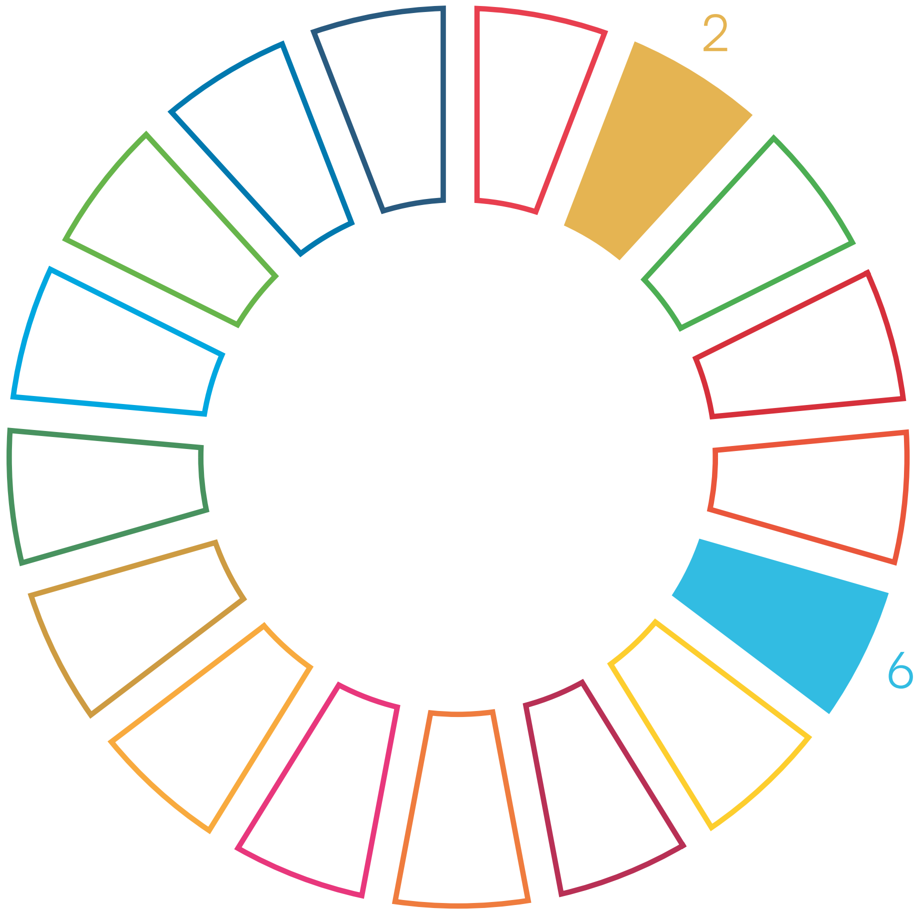
- *Scarcity of freshwater availability in quantity and quality (physical water scarcity).*
- *Scarcity of access to water services due to lack of correct regulations needed to guarantee an extended supply.*
- *Scarcity of suitable infrastructures and economic resources (economic water scarcity).*

Although water consumption for agricultural use is locally confined, the international trade of food production complexes the exploitation of water resources.
Analyzing the socio-economic and environmental factors influencing food production and trade improves our capacity to define water scarcity characteristics of a country and comprehend how the global food system impacts the anthropic and ecological systems.

INTRODUCTION

DIMENSION 0

GOAL 2: Zero Hunger
GOAL 6: Clean Water and Sanitation



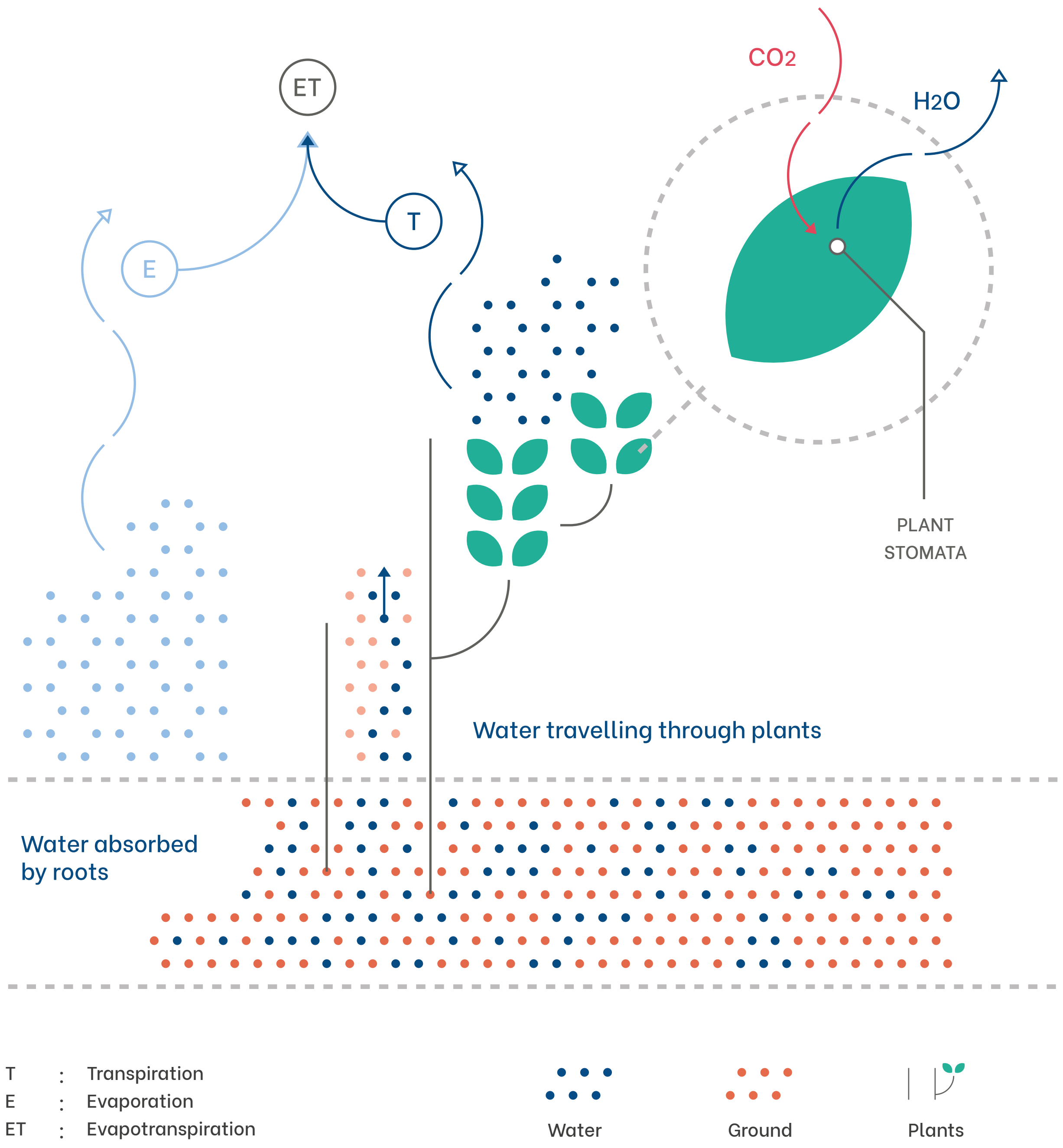
VIRTUAL WATER AND THE WATER FOOTPRINT

Water Footprint: How To Bake An Indicator

The unit Water Footprint (uWF) of growing a crop is calculated as the ratio between the crop water use (expressed in millimeters) along the growing season, multiplied by a factor of 10, and the crop yield (expressed in tonnes per hectare). uWF is, thus, measured in cubic meters per tonne or, equivalently, in liters per kilogram. The crop water use is quantified as a function of the crop evapotranspiration *(see pages 50-51)*, and it can be green and (or) blue depending on the water source that is available for feeding the crop *(see pages 52-53)*.
The unit WF is often interpreted as a measure of water use efficiency in agriculture. Indeed, by employing this indicator, one can compare different products or locations to understand which one is more efficient in terms of water use.
The unit WF of a product is also referred to as its virtual water content *(see page 22)*.
The total WF of the production of a specific good is the product between its total production and its corresponding unit WF. The total WF is measured in cubic meters or liters.
An example makes the understanding of the Water Footprint indicator easier. Let us consider the production of apples. On a global average, the unit WF of one kg of apples is 700 liters. This number comes from the evaluation along the entire supply chain of apples' production *(see page 24-25)*, albeit the plant's water use along the growing season stands as the most significant water contribution. Hence, the Water Footprint of a 100g apple (or its virtual water content) is 70 liters *(see page 30-31)*. The total water footprint of apples' production worldwide is 61 000 000 000 cubic meters (corresponding to 87.2 million tonnes of apples in 2019).
The water footprint of food production varies across different countries of production. This variability also explains the difference between the WF of production and the WF of consumption. Again, a case scenario can help for better understanding. Imagine your food basket is filled with two bags of flour, one produced in Italy and the other made in the United States, each weighing half a kilo. The Water Footprint of the 'Italian' flour is 480 l per package, while the one of the 'American' flour is 760 l per package. Eventually, assuming that you will consume both packages of flour for baking a loaf of bread, your WF of consumption will be 1 240 liters.
As you will see in the following pages, the WF of production depends on local climatic conditions, soil properties, crop yield, and irrigation practices. That is why there is such a significant difference between the water embedded in the two bags of flour or any other products. Instead, the Water Footprint of consumption depends on international trade, dietary habits *(see page 144-145)*, and socio-economic factors.

FIRST INGREDIENT: CROP EVAPOTRANSPIRATION

Evaporation from soil (E) and transpiration from a plant's tissues (T) co-occur, and there is no easy way of distinguishing between the two processes. When the crop is small, evaporation from soil dominates, but transpiration becomes the primary process once the crop is well developed and completely covers the soil. The combination of evaporation and transpiration is called evapotranspiration (ET).



THE KEY FACTORS OF CROP EVAPOTRANSPIRATION

Evapotranspiration of crops depends on three key factors:

1. The climate: sun radiation, temperature, wind speed, and air humidity.

By using only climatological data, it is possible to estimate the evapotranspiration, ET_0, from a reference surface that closely resembles a well-watered piece of grasses of uniform height (imagine the grass of a lush English garden).

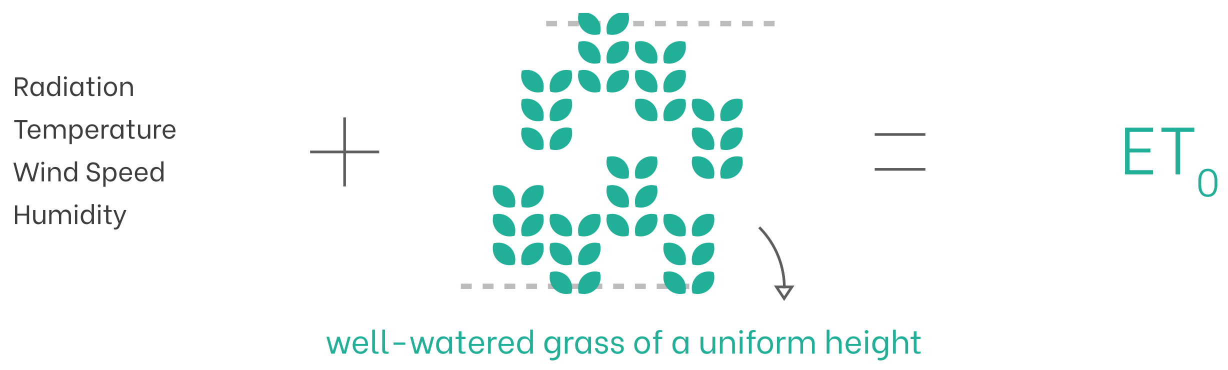
2. The crop characteristics: the canopy, height, and rooting depth.

These properties concur to determine the crop coefficient (Kc). The product of ET_0 and the crop coefficient is the crop potential evapotranspiration (ET_c). It is called 'potential' because it refers to a crop ideally grown in a large field under excellent agronomic and water conditions.

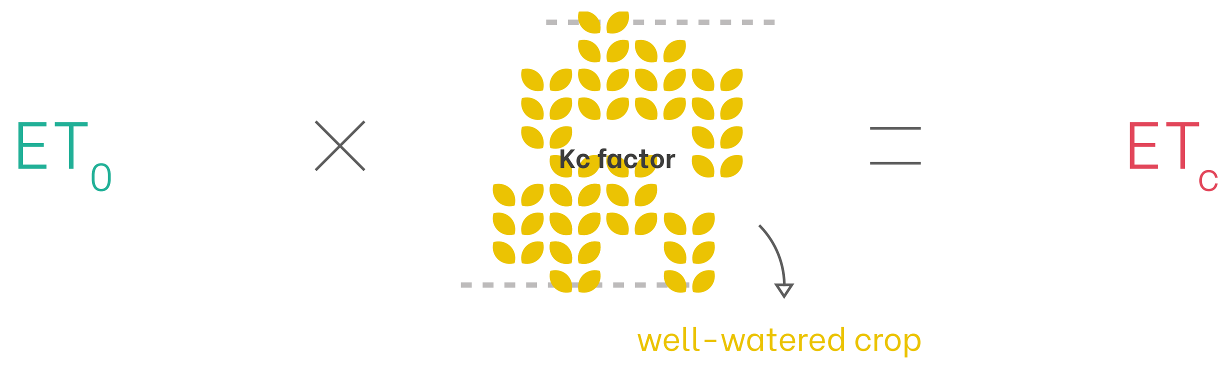
3. The water content in the root zone determining whether the crop can transpire at the potential rate.

The daily amount of water available in the root zone may change due to rainfall rates and soil water losses. When there is insufficient water for the root uptake, the crop undergoes a water-stress condition measured by the water-stress coefficient (Ks). In this case, the actual evapotranspiration (ET_a) is lower than the potential one. That is why the dynamics of crop's water stress and evapotranspiration change between rainfed and irrigated agriculture.

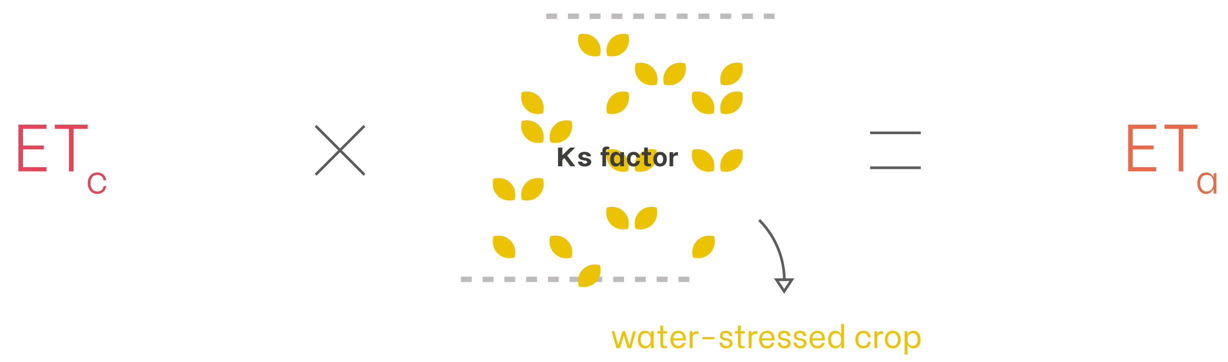
1. Reference evapotranspiration



2. Crop potential evapotranspiration



3. Actual evapotranspiration



Kc : Crop coefficient
Ks : Water stress coefficient
ET : Evapotranspiration

ET_0 : Reference evapotranspiration
ET_c : Crop potential evapotranspiration
ET_a : Actual evapotranspiration

RAINFED AGRICULTURE

1. The crop coefficient (Kc) changes along the growing season depending on the crop's evolution and growth. For each crop species, the most used model requires three values to plot the evolution of Kc along the growing season: the initial value (e.g., Kc = 0.7 for wheat), the middle-season value (Kc = 1.15), and the final value (Kc = 0.3).

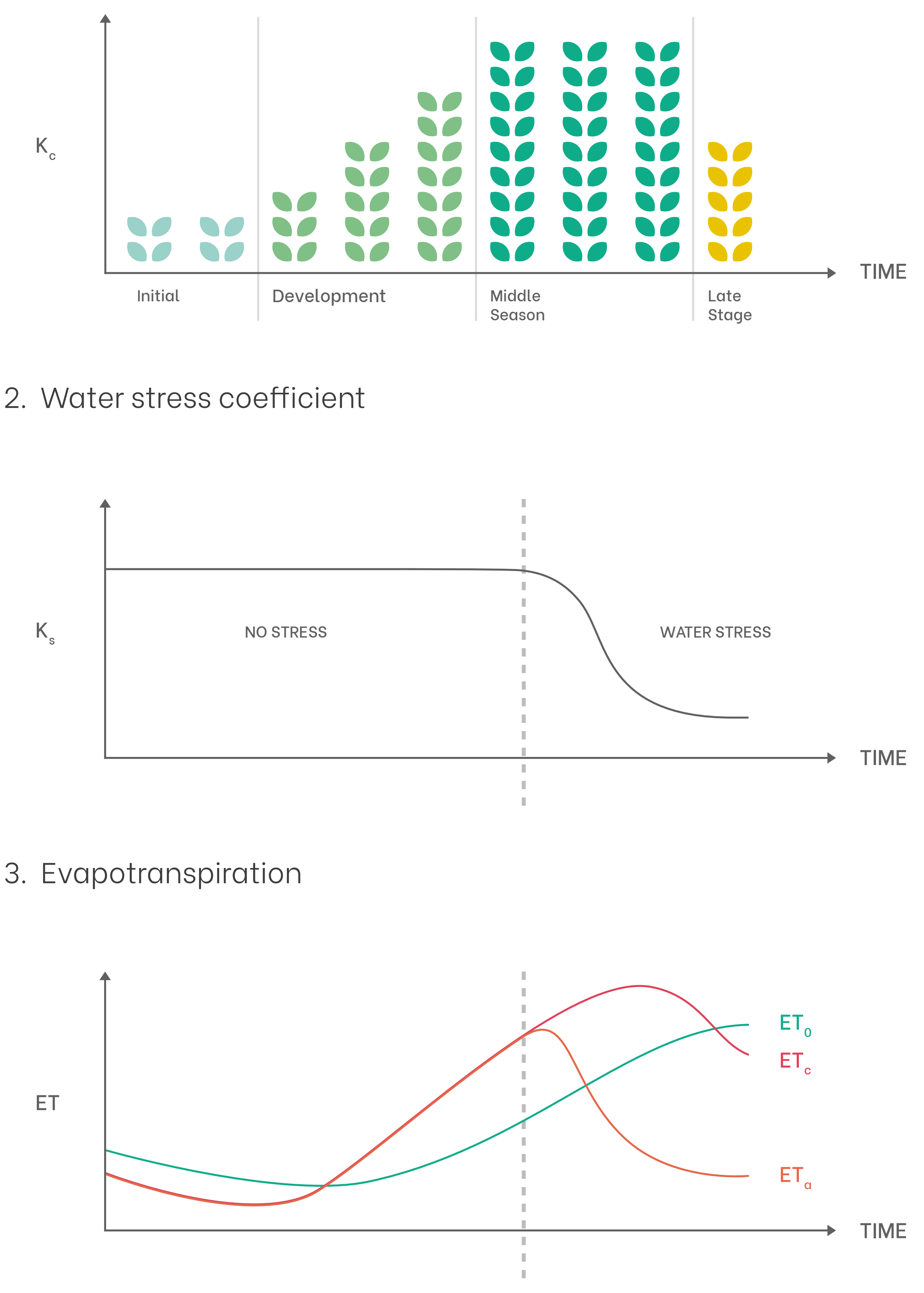
2. The water stress coefficient (Ks) changes during the growing season depending on the amount of water available in the soil for the root uptake. This content depends on the amount of rainfall that infiltrates into the ground and becomes available for plants. In addition, the capability of soil water retention depends on the soil texture and porosity.

3. An example of the ET dynamics follows:
During the initial stage of the growing season, the crop is under the soil layer for most of the time. Hence, its ET is lower than that of a grass surface (ET_0). As the crop grows, ET increases up to a maximum value during the middle of the season. At this moment, some water stress may occur under rainfed conditions, and the crop cannot evapotranspire at the potential rate (ET_C). When ET_a is lower than ET_C, the crop evapotranspires at a lower rate than its potential one. This phenomenon may have implications for the crop's growth, thus impacting its final yield.

1. Crop coefficient

2. Water stress coefficient

3. Evapotranspiration



K_c : Crop coefficient
K_s : Water stress coefficient
ET : Evapotranspiration

ET_0 : Reference evapotranspiration
ET_c : Crop potential evapotranspiration
ET_a : Actual evapotranspiration

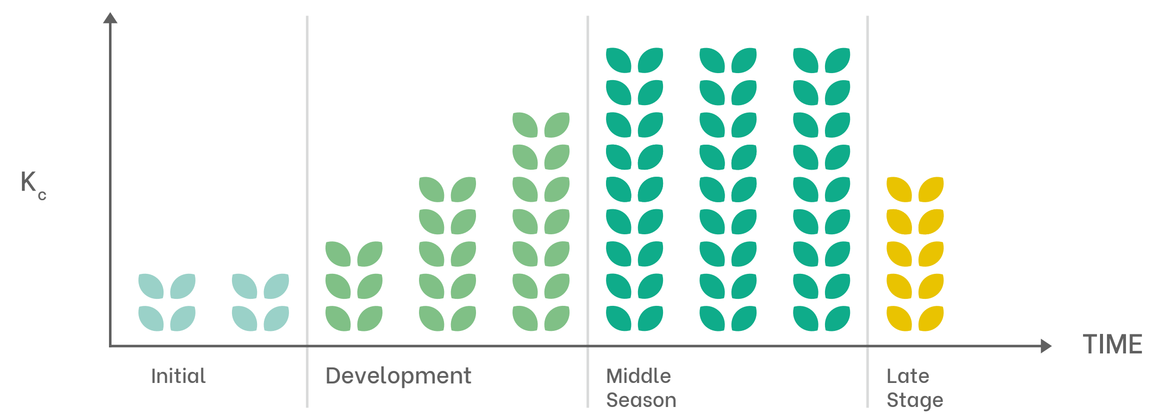
IRRIGATED AGRICULTURE

1. The crop coefficient (Kc) under irrigated agriculture has the same shape as that under rainfed agriculture. Indeed, its dynamics are only determined by the crop's characteristics.

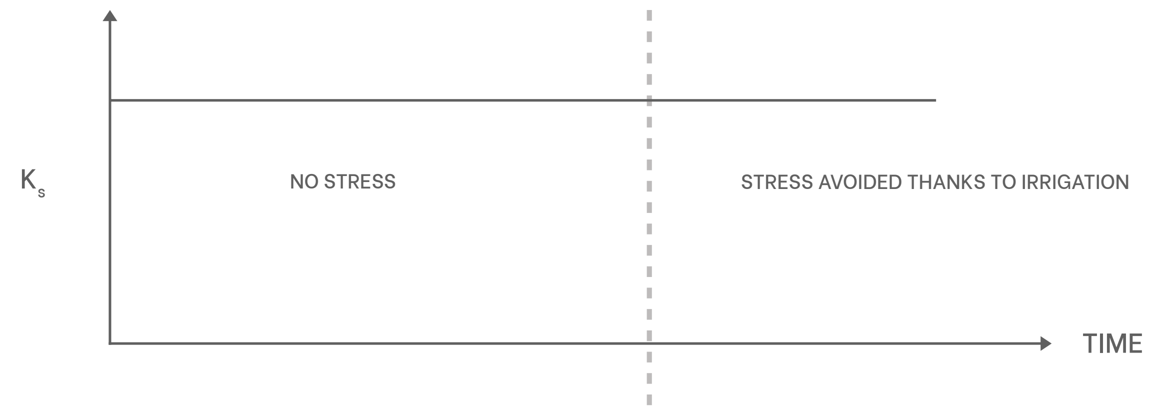
2. The water stress coefficient (Ks) under irrigated agriculture stays nearly constant throughout the whole growing season. Indeed, as the crop approaches a water stress condition, irrigation is provided to fill the impending water shortage in the soil.

3. Thanks to irrigation, there is enough water in the root zone. Accordingly, the crop can evapotranspire at its potential rate. Therefore, ET_a equals ET_c for the whole duration of the growing season. Even under irrigated agriculture, water stress might happen due to failures in irrigation techniques or water shortages, or when specific irrigation-deficit practices are adopted.

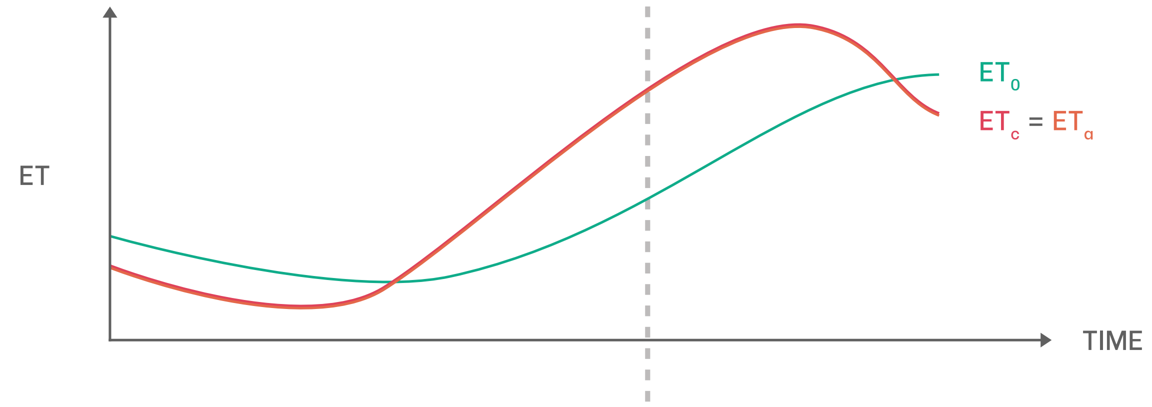
1. Crop coefficient



2. Water stress coefficient



3. Evapotranspiration

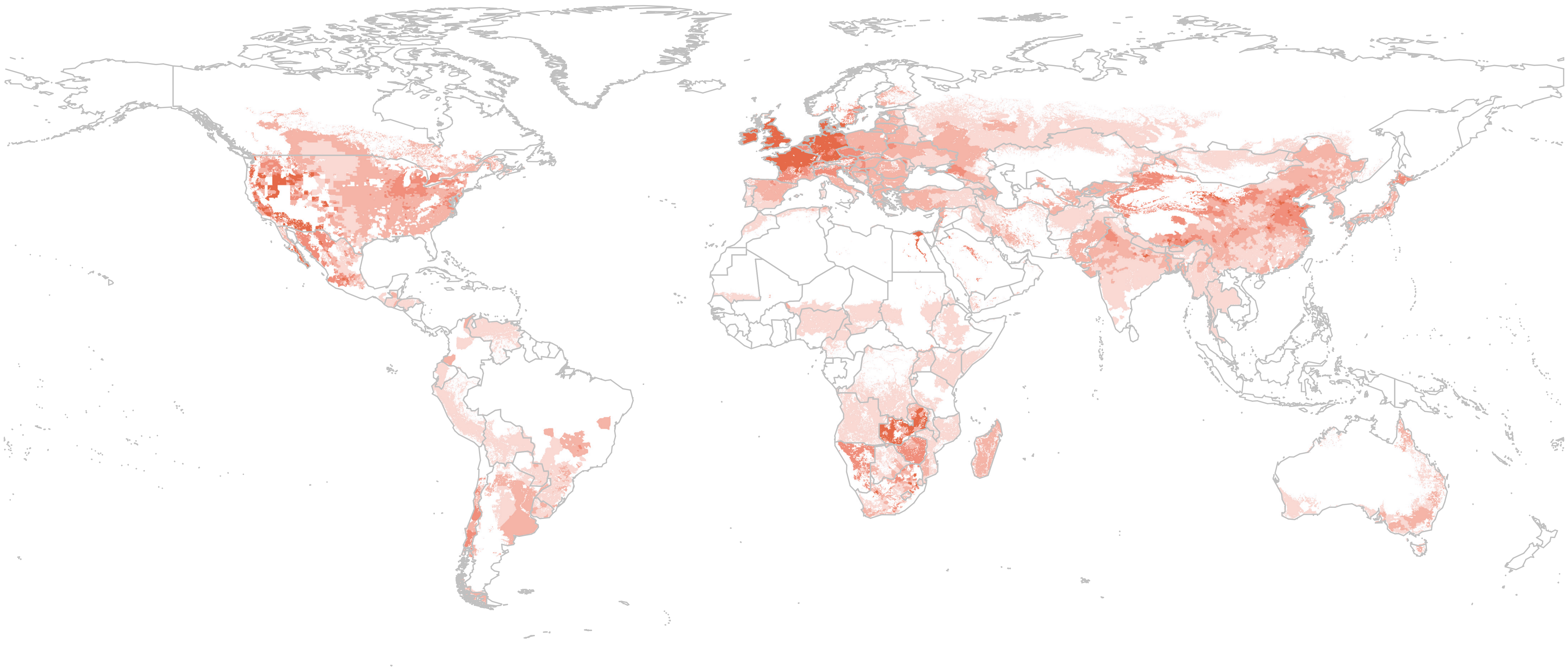


K_c : Crop coefficient
K_s : Water stress coefficient
ET : Evapotranspiration

ET_0 : Reference evapotranspiration
ET_c : Crop potential evapotranspiration
ET_a : Actual evapotranspiration

SECOND INGREDIENT: CROP YIELD

The photosynthesis process determines the growth of the plant and its fruits. Crop yield measures how much of the plant and its fruits can be harvested within a unit of land. The yield has a spatial variability of its own, depending on the soil's properties and moisture, climate conditions, and the nutrients available in the root zone. Yield is measured by matching agricultural data from censuses, surveys, and statistics reporting the tonnes produced per year and the harvested area (ha).
This map shows the spatial variability of the wheat yield in year 2000. Maximum yield occur in the North European countries, such as Germany (7.2 tonnes per hectare, ton/ha), and parts of the Southern African continent, as Zambia (6.2 ton/ha). The Middle Eastern planes of the United States of America, known for being areas of intensive cultivations, are less productive than other areas such as California.



The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

Wheat Yield (ton/ha) ≤ 2 | 2 - 4 | 4 - 6 | > 6

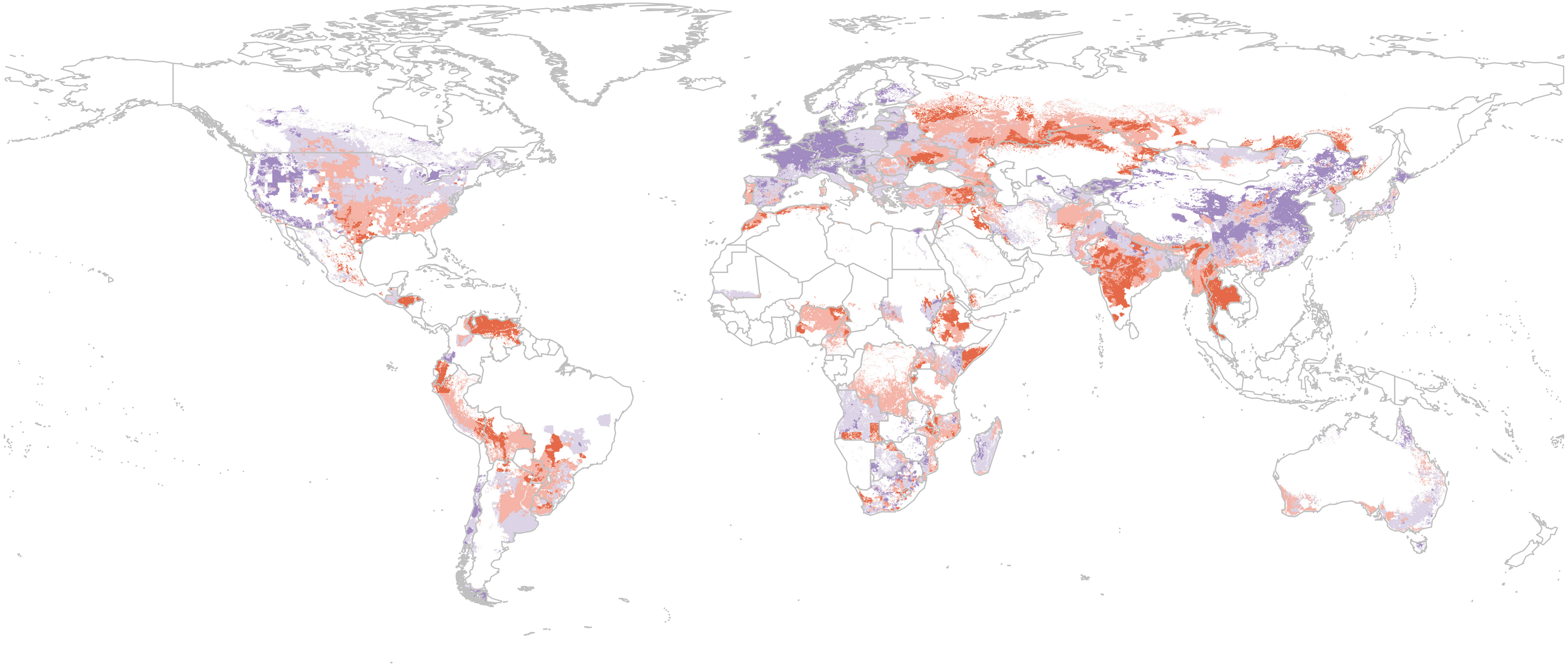
BAKE IT: THE WATER FOOTPRINT OF WHEAT IN THE GLOBAL CONTEXT

The global average water footprint of wheat is 1500 liters per kg, but it shows great spatial variability.

Crop yield and evapotranspiration determine the crop water footprint. Yield patterns mainly drive the observed spatial variability of WF: generally, the lower the yield, the higher the water footprint. This map shows the spatial distribution of the water footprint of wheat per unit of production (uWF, in liters per kg) in the year 2000. Areas such as India below the Indo-Gangetic plain and most of the Andes have lower crop yields in wheat production, determining a high water footprint value.

The opposite happens in the North European regions and the Western USA. Thanks to the fertility of the Nile Valley, Egypt can achieve wheat yields like those of Europe, where wheat production has the highest water efficiency.

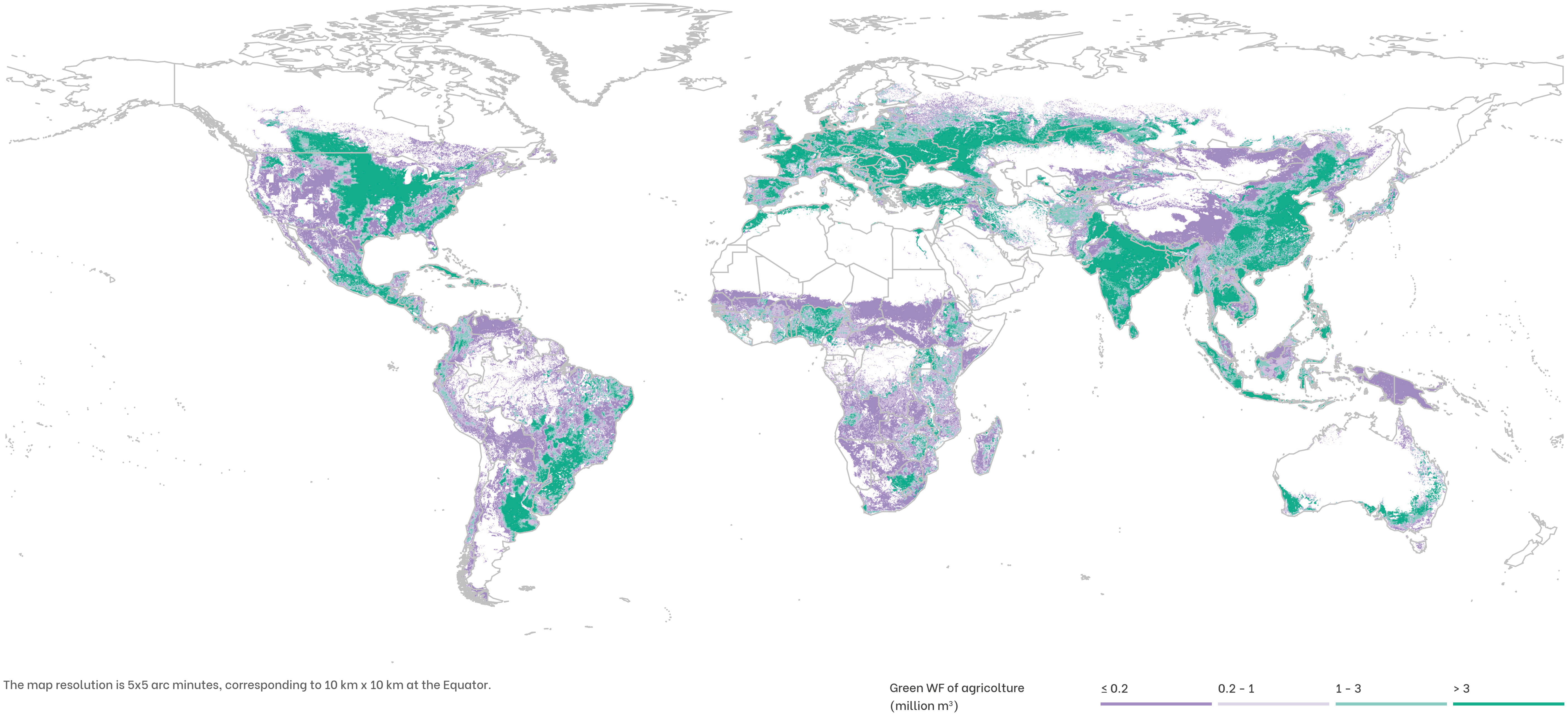
The world's top producers of wheat are found in the Asiatic region (China and India were the top-two in 2019). Here, nearly 20% of the water is provided through irrigation, with important implications for the water ecosystems.



The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

The green water footprint of agricultural production

The world's population is fed for 70% (in terms of calories) through 8 principal crops: wheat, rice, maize, soybean, barley, potatoes, sugar cane, and sugar beet. If one also accounts for the production of cotton for the textile sector, the water requirement of these nine plants together amounts to 3 313 km³ per year. Eighty percent of this water requirement relies on green water resources (2 716 km³). Clearly, the green water footprint varies with the latitude, climate, thus local biomes, and – no less – with production volumes. In fact, taking the USA as an example, due to its role as a relevant producer of maize and soybean, it has its largest green water footprints at the production sites of the crops. Also, Brazil and Argentina show high green water use at the production sites of soybean and sugarcane, crops of relevant economic significance for these countries. In fact, sugarcane production – as well as sugar beet one – is not limited to human and animal consumption, but it also interests the energy sector to process biofuels. Large green water footprints are also found in India and China for wheat, maize, and rice production. The map on pages 44-45 defines the geography of such dominant green water footprints.

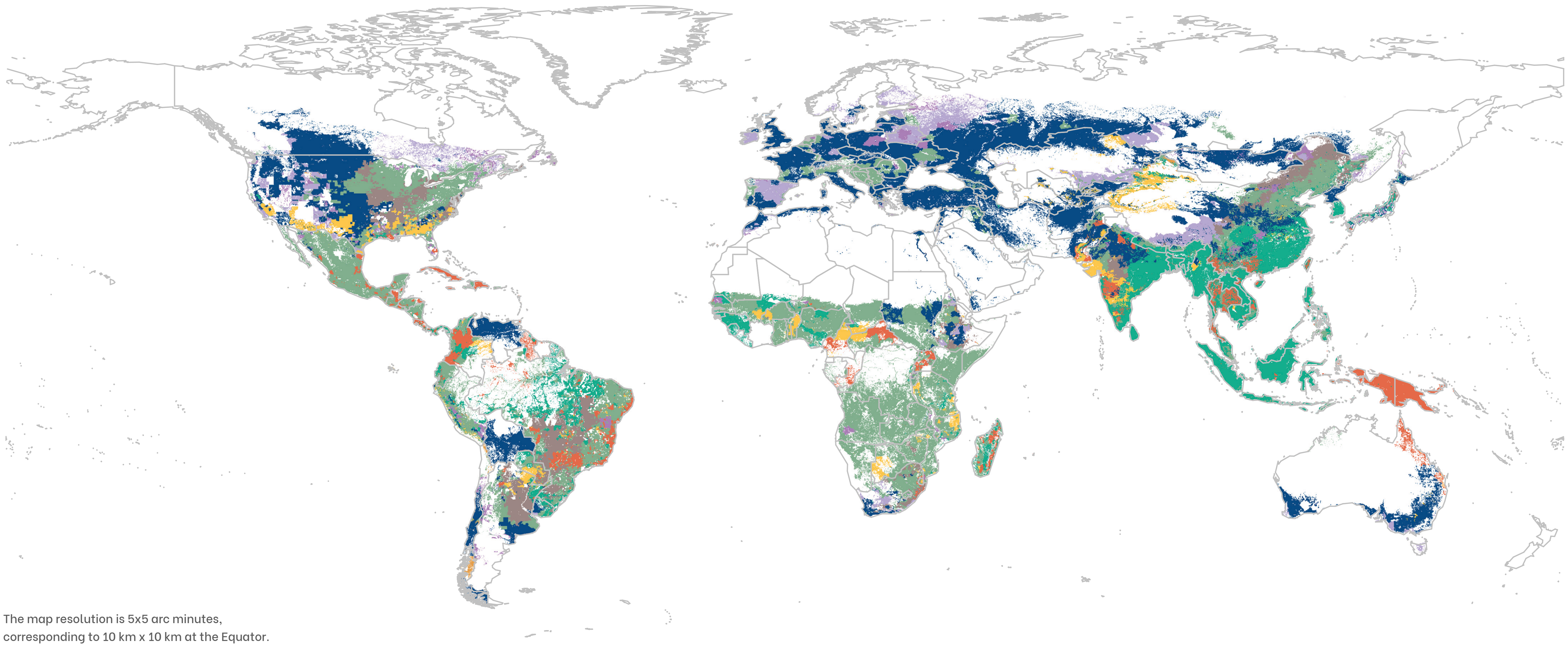


The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

THE CROP-GEOGRAPHY OF THE GREEN WATER FOOTPRINT OF AGRICULTURAL PRODUCTION

The colors define the dominant crop in terms of green water footprint: worldwide, wheat and maize dominate the green water footprint scene. Rice is relevant in South-East Asia, along with sugarcane. North and South America and Asia stand out for being the most diversified areas of production based on green water exploitation. Wheat, maize, barley, and potatoes primarily constitute Europe's footprint of green water.

The green water footprint of Africa is mainly contributed by maize production, and the continent stands as the only example of nearly non-irrigated terrains *(see pages 60-61)*. Australia's green water footprint is relevantly determined by wheat and sugarcane.



The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

PRODUCT

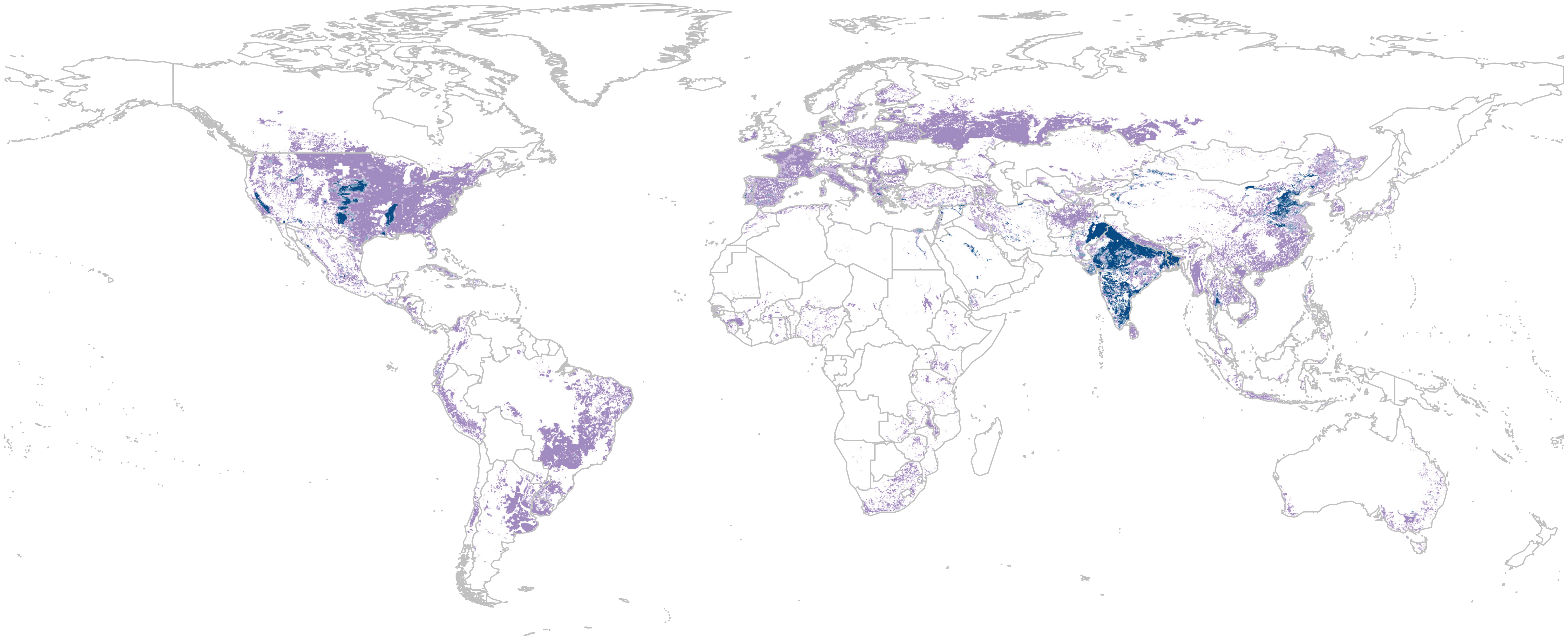
Wheat | Rice | Maize | Soybean | Barley | Potatoes | Sugarcane | Sugar beet | Cotton

The blue water footprint of agricultural production: water withdrawal from groundwater sources

In places where precipitations are insufficient to cope with the water requirements of crop production, irrigation water is supplied to the agricultural system. Such water is withdrawn from groundwater and surface water sources.

Around 265 km^3/yr of irrigation water is withdrawn from aquifers to sustain agricultural production. One-half of the groundwater used worldwide originates from just four significant aquifers, namely the Indo-Gangetic Plain (41%), US High Plain (8%), North China Plain (5%), and the California Central Valley (1.6%) aquifers.

The highest groundwater use is found in the Indo-Gangetic plain (100 km^3/yr), where 64% of the Indian and Pakistan crop production is located. The Indo-Gangetic plain is the most iconic example of water overexploitation in both green and blue water resources. Here, depletion of the groundwater reservoirs happens due to the intensification of agriculture to cope with the increasing population and consequent food demand.



The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

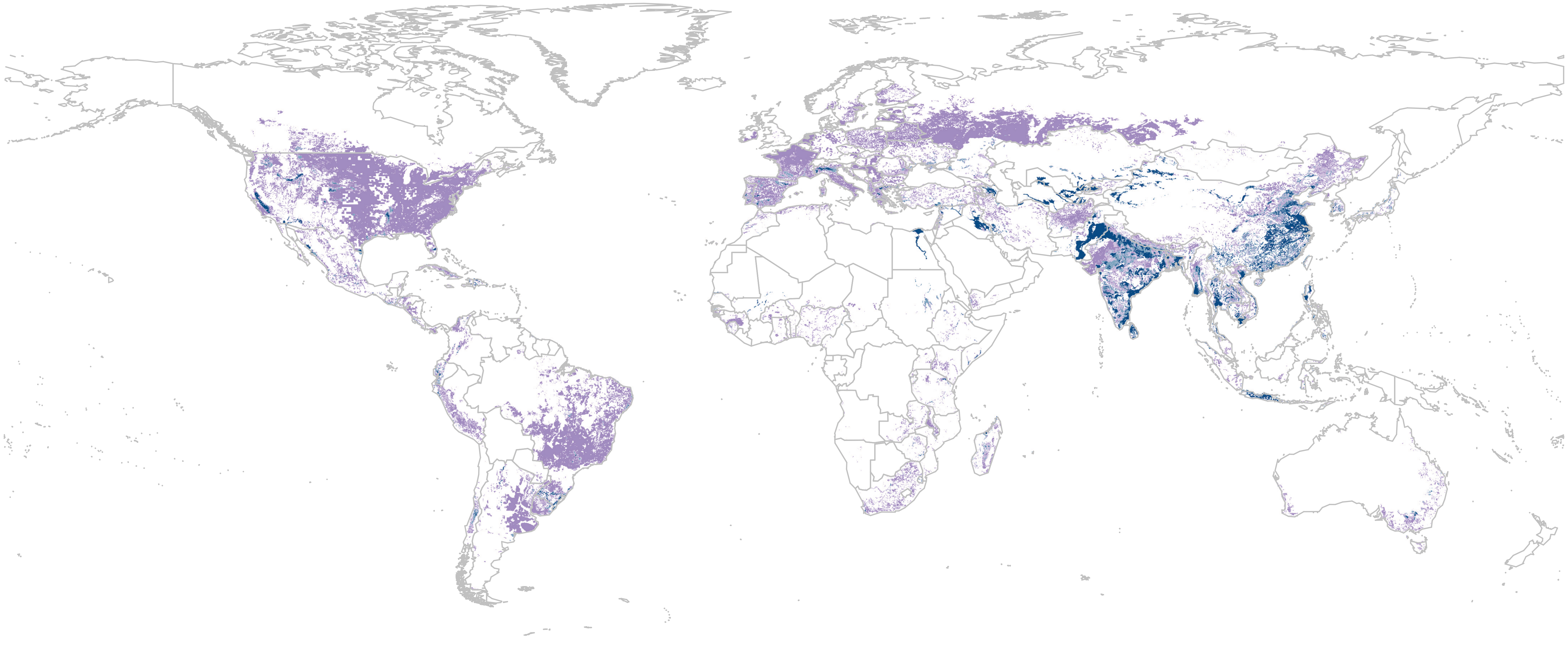
Total blue WF from groundwater ($million\ m^3$)

≤ 0.2 | 0.2 - 1 | 1 - 3 | > 3

THE BLUE WATER FOOTPRINT OF PRODUCTION: WATER WITHDRAWAL FROM SURFACE WATER BODIES

Around 400 km³/yr of irrigation water is withdrawn from surface water bodies. The largest blue Water Footprints are found along the major river basins (e.g., the Nile River and the Indus River basins).

Large blue water footprints are also found along the Amu Darya River that has been transformed into an irrigation channel for watering the cotton cultivations in Uzbekistan. In this same area, the *Aral Lake* stands as the worst case of water exploitation due to the intensification of agricultural practices, which led the lake to almost completely disappear. The Yellow River mostly sustains rice and maize production; the Tarim River feeds rice.



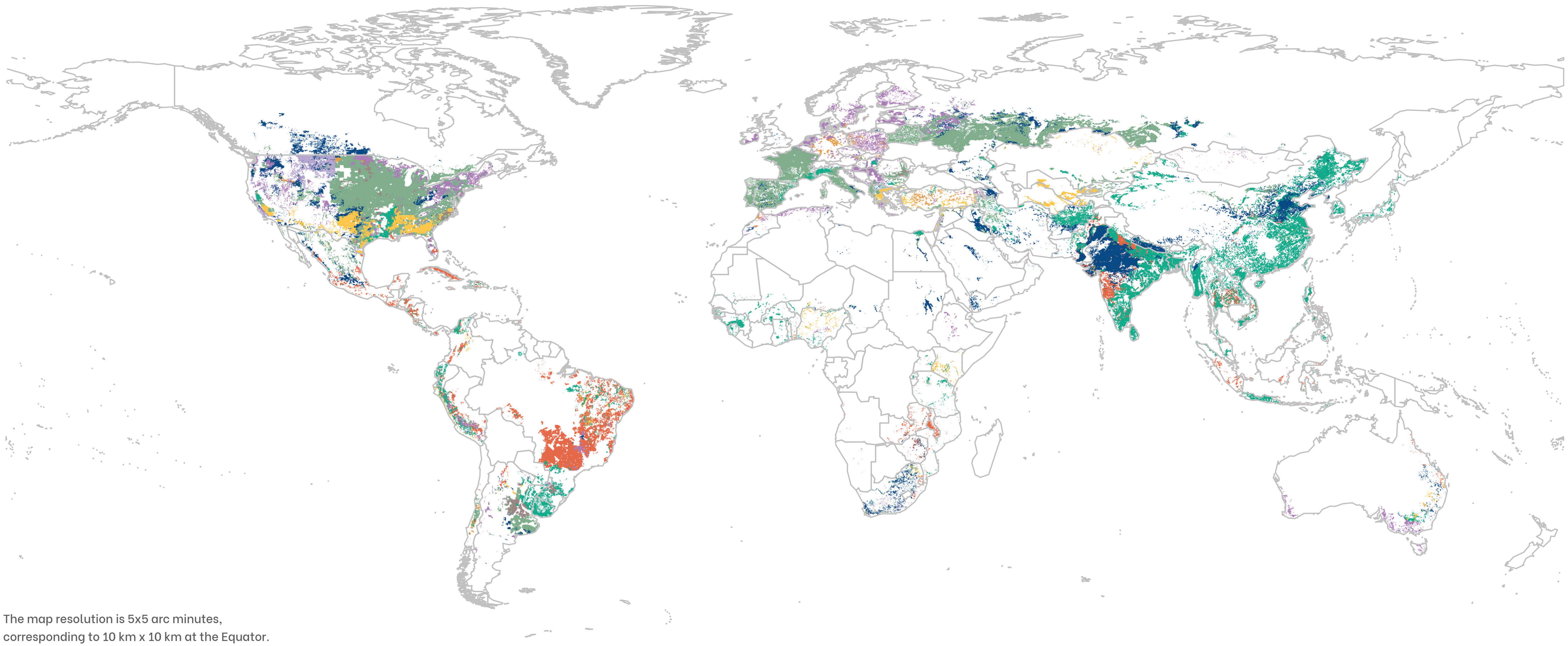
The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

Total blue WF ofrom surface water (million m³)

≤ 0.2 | 0.2 - 1 | 1 - 3 | > 3

THE CROP-GEOGRAPHY OF THE BLUE WATER FOOTPRINT OF AGRICULTURAL PRODUCTION

The colors define the dominant crop in terms of blue water footprint. India, East China, and Thailand predominantly use irrigation for rice, wheat, and sugarcane production. In Egypt, the Nile delta is among the relevant examples of irrigation in Africa, with water mainly destined for rice production. Other examples include the production of sugarcane and sugar beet in South-East Africa. Also, Brazil invests its irrigation resources to produce sugarcane.
As for the green water footprint, North America shows significant crop variability contributing to its blue water footprint. The most irrigated crop in Europe is maize, followed by potatoes and sugar beet. Although sugar beet and cotton boom in the Anatolian peninsula, cotton dominates the water use in the river basins tributing the Aral and Caspian seas.



The map resolution is 5x5 arc minutes, corresponding to 10 km x 10 km at the Equator.

PRODUCT

Wheat | Rice | Maize | Soybean | Barley | Potatoes | Sugarcane | Sugar beet | Cotton

From roots to national borders

The high-resolution estimates of the water requirements for crop cultivation, obtained from the mathematical approach just introduced, constitute the first building block for valuing the water footprint of production at the national and global scale.

In fact, these values can be aggregated for several crops and spatial scales, providing an outlook regarding the impact of agriculture at the national and international levels. Such analysis permits evaluating the spatial and temporal distribution of the water use for food production, unfolding the spatial heterogeneity of agricultural efficiencies and production, and the key actors (countries and food products).

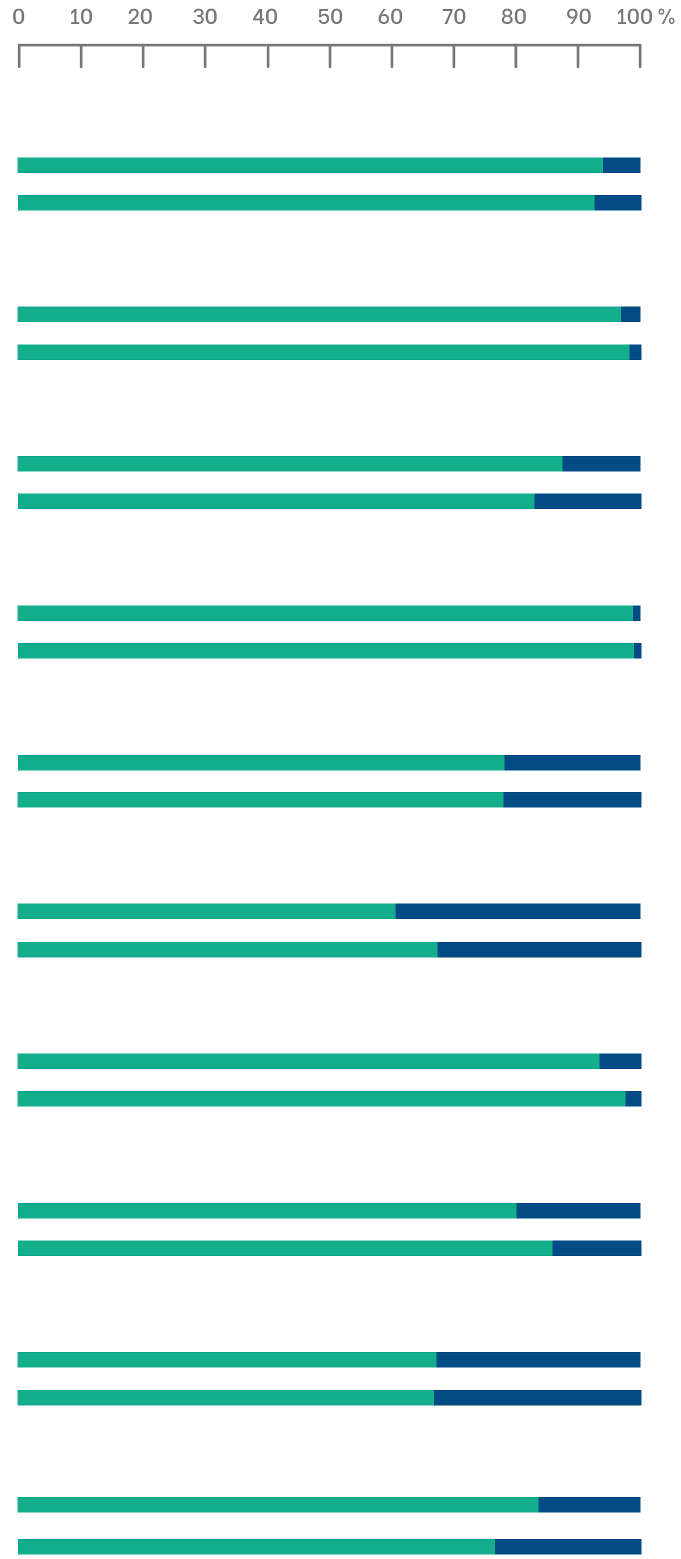
The following pages are dedicated to this outlook, evidencing how the food production of the world and its consequent water footprint changed during the past sixty years. The following maps, plots, and values pave the way for unraveling the complexity around the concepts of water footprint and virtual water *(see page 28)*.

Are today's crops more water-efficient than yesterday's ones?

The average values of global water footprint of these trending item in our food basket changed from 1961 to 2016.

Product (year)	Green uWF (l/kg)	Blue uWF (l/kg)
ALMONDS		
1961	5 436	1 185
2016	3 384	1 475
APPLES		
1961	600	213
2016	357	120
AVOCADOS		
1961	1 300	210
2016	744	212
COCOA BEANS		
1961	35 394	49
2016	23 311	46
COFFEE BEANS		
1961	22 417	372
2016	12 418	197
EGGS		
1961	10 846	673
2016	2 976	222
LENTILS		
1961	7 575	1 359
2016	3 016	1 051
MAIZE		
1961	600	213
2016	357	120
CATTLE MEAT		
1961	23 405	964
2016	16 911	356
PIG MEAT		
1961	20 851	1 318
2016	5 734	502

Product (year)	Green uWF (l/kg)	Blue uWF (l/kg)
POULTRY MEAT		
1961	6 672	428
2016	2 106	172
COW MILK		
1961	2 725	89
2016	1 515	29
POTATOES		
1961	260	37
2016	156	32
QUINOA		
1961	5 026	64
2016	4 112	45
RICE		
1961	3 854	1 073
2016	1 595	452
COTTON		
1961	4 547	2 937
2016	2 033	984
SOYBEANS		
1961	3 778	274
2016	1 715	42
TEA		
1961	15 732	3 908
2016	6 672	1 109
VANILLA		
1961	116 725	56 834
2016	119 567	59 391
WHEAT		
1961	3 376	665
2016	1 014	311



Italy in the global context of water footprint efficiency

How much water does Italy use to produce a kilogram of these agricultural products compared to the rest of the world?*

*Per each item, the unitary water footprint of production (in liters per kilogram or, equivalently, cubic meters per tonne) of top-producing countries (from largest to smaller production volumes) and Italy are compared.
The world values specify each item's mean unit Water Footprint as the weighted average of the country-specific production and unit water footprint volumes. When a ★ accompanies the item-specific datum, Italy figures among the top 10 worldwide producers. When a \ is present instead, the Italian climatic conditions (plus other factors) do not allow for the item's production, and the national consumption is only fulfilled through imports.

Product	Italy (l/kg)	Country	(l/kg)
APPLE	**163** ★	**WORLD**	**476**
		China	394
		USA	293
		Poland	258
		Turkey	262
		Iran	1 319
		France	188
AVOCADO	/	**WORLD**	**937**
		Peru	736
		Chile	1 832
		Colombia	1 115
		Israel	962
		Spain	776
		Indonesia	910
		South Africa	2 087
BANANA	/	**WORLD**	**615**
		China	339
		India	413
		Brazil	790
		Ecuador	261
		Costa Rica	275
		Colombia	534
		Indonesia	1 081
		Spain	255

Product	Italy (l/kg)	Country	(l/kg)
BUTTER COW MILK	**5 094**	**WORLD**	**4 478**
		USA	6 603
		New Zealand	3 085
		Germany	3 104
		France	3 437
		Russia	7 282
		Turkey	5 587
		Poland	4 237
		Ireland	2 530
CARROT	**79**	**WORLD**	**87**
		China	60
		Uzbekistan	53
		USA	83
		Russia	57
		Ukraine	86
CATTLE MEAT	**7 522**	**WORLD**	**11 018**
		USA	9 553
		Brazil	13 776
		China	9 434
		Argentina	4 093
		Australia	10 734
		France	5 370
		Germany	4 835
		Ireland	4 034

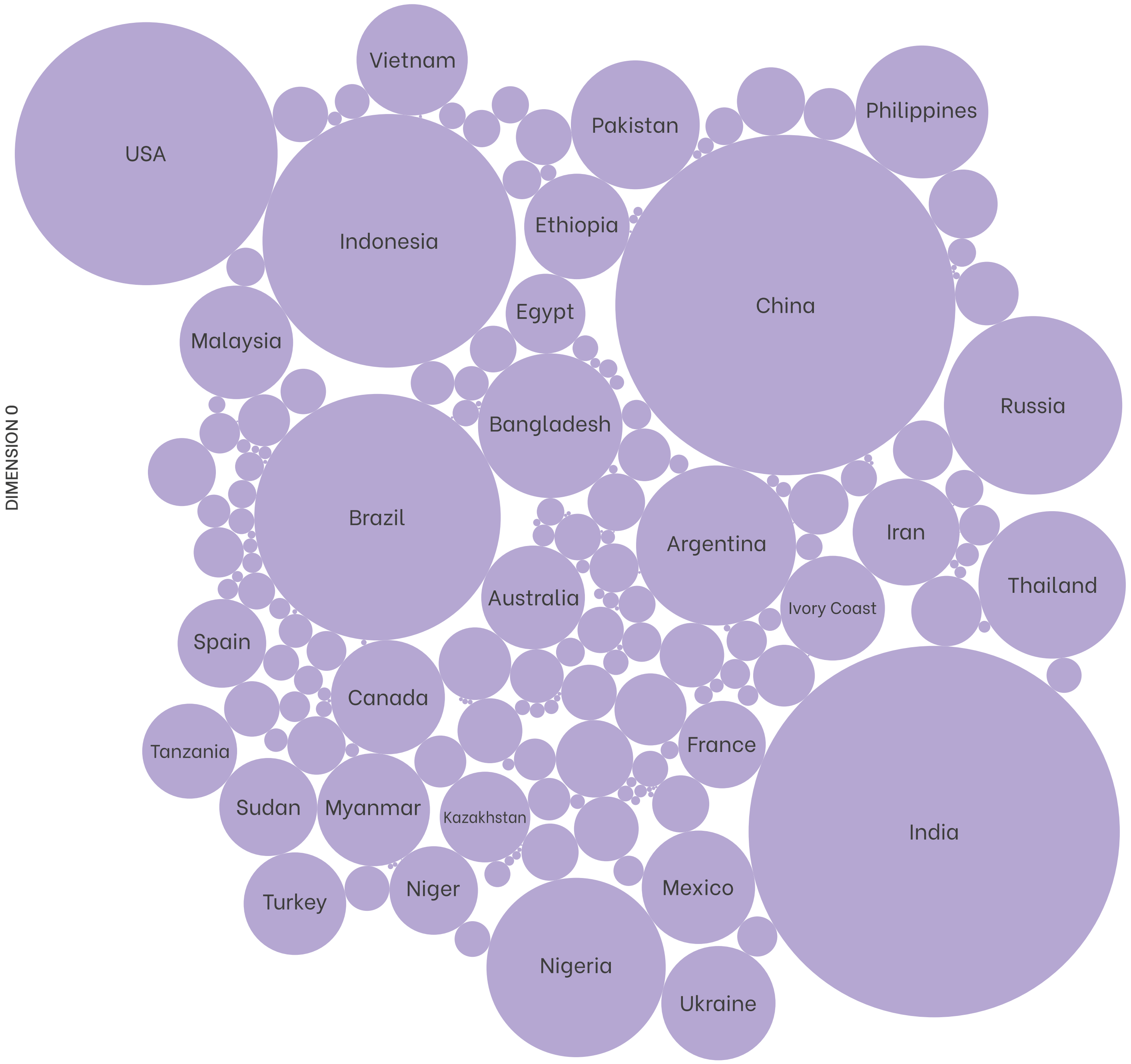
Product	Italy (l/kg)	Country	(l/kg)
COCOA	**/**	**WORLD**	**23 204**
		Ivory Coast	17 653
		Ghana	17 134
		Indonesia	36 660
		Nigeria	37 800
		Cameroon	23 376
		Brazil	33 386
		Ecuador	19 655
COFFEE	**/**	**WORLD**	**12 450**
		Brazil	6 113
		Vietnam	4 550
		Colombia	13 151
		Indonesia	27 113
		Ethiopia	11 432
		Honduras	11 297
COW MILK	**703**	**WORLD**	**1 108**
		India	1 049
		USA	730
		Pakistan	1 200
		Brazil	1 221
		China	1 107
		Russia	1 383
		Germany	466
		Turkey	1 061
EGGPLANT	**137** ★	**WORLD**	**163**
		China	107
		India	262
		Egypt	301
		Turkey	130
		Indonesia	416
		Iraq	675
		Spain	98
GOAT MILK	**703**	**WORLD**	**1 479**
		India	1 049

Product	Italy (l/kg)	Country	(l/kg)
		Bangladesh	1 073
		Sudan	1 555
		Pakistan	1 200
		France	524
		Spain	1 607
		Turkey	1 061
		Somalia	2 054
GROUNDNUTS	**2 994**	**WORLD**	**2 764**
		China	1 157
		India	2 867
		Nigeria	7 852
		Sudan	5 201
		Argentina	1 803
HAZELNUTS	**4 646** ★	**WORLD**	**6 179**
		Turkey	6 672
		USA	4 616
		Azerbaijan	5 989
		Chile	365
		China	3 907
		Georgia	4 545
		Spain	7 062
		France	3 598
KIWI	**340** ★	**WORLD**	**485**
		Chile	432
		China	503
		New Zealand	271
		Greece	256
		France	374
		Turkey	1 254
MAIZE	**462**	**WORLD**	**804**
		USA	462
		China	717
		Brazil	1 137
		India	1 679

Product	Italy (l/kg)	Country	(l/kg)
		Argentina	809
		Mexico	1 319
		South Africa	1 144
ORANGE	**311** ★	**WORLD**	**453**
		Brazil	319
		USA	415
		China	339
		India	576
		Mexico	612
		Spain	369
		Egypt	468
		Turkey	174
PIG MEAT	**3 932**	**WORLD**	**3 956**
		China	3 972
		Thailand	4 811
		USA	3 455
		Brazil	4 975
		South Korea	5 930
		France	3 349
		Spain	4 643
		Germany	2 518
		India	4 291
		Uzbekistan	10 994
PINEAPPLE	**/**	**WORLD**	**194**
		Costa Rica	90
		Brazil	127
		Philippines	130
		Mexico	103
		Colombia	120
		Nigeria	282
RICE	**932**	**WORLD**	**1 361**
		China	717
		India	2 933
		Indonesia	1 365

Product	Italy (l/kg)	Country	(l/kg)
		Bangladesh	2 582
		Vietnam	921
		Thailand	2 034
		USA	1 108
TOMATO	**79**	**WORLD**	**125**
		China	101
		India	343
		Turkey	75
		USA	81
		Spain	41
TEA	**/**	**WORLD**	**7 500**
		China	7 397
		India	4 963
		Kenya	4 183
		Sri Lanka	101 056
		Vietnam	6 803
		Turkey	2 013
WHEAT	**922**	**WORLD**	**1 295**
		China	930
		India	1 542
		Russia	1 546
		USA	1 521
		France	777
		Australia	1 861
		Canada	948
		Ukraine	1 303
WHOLE COW MILK	**3 380** ★	**WORLD**	**3 715**
		USA	3 507
		Germany	2 243
		France	2 524
		Netherlands	2 502
		Poland	3 897
		Egypt	5 925

The biggest water footprints of production: who are the key actors?



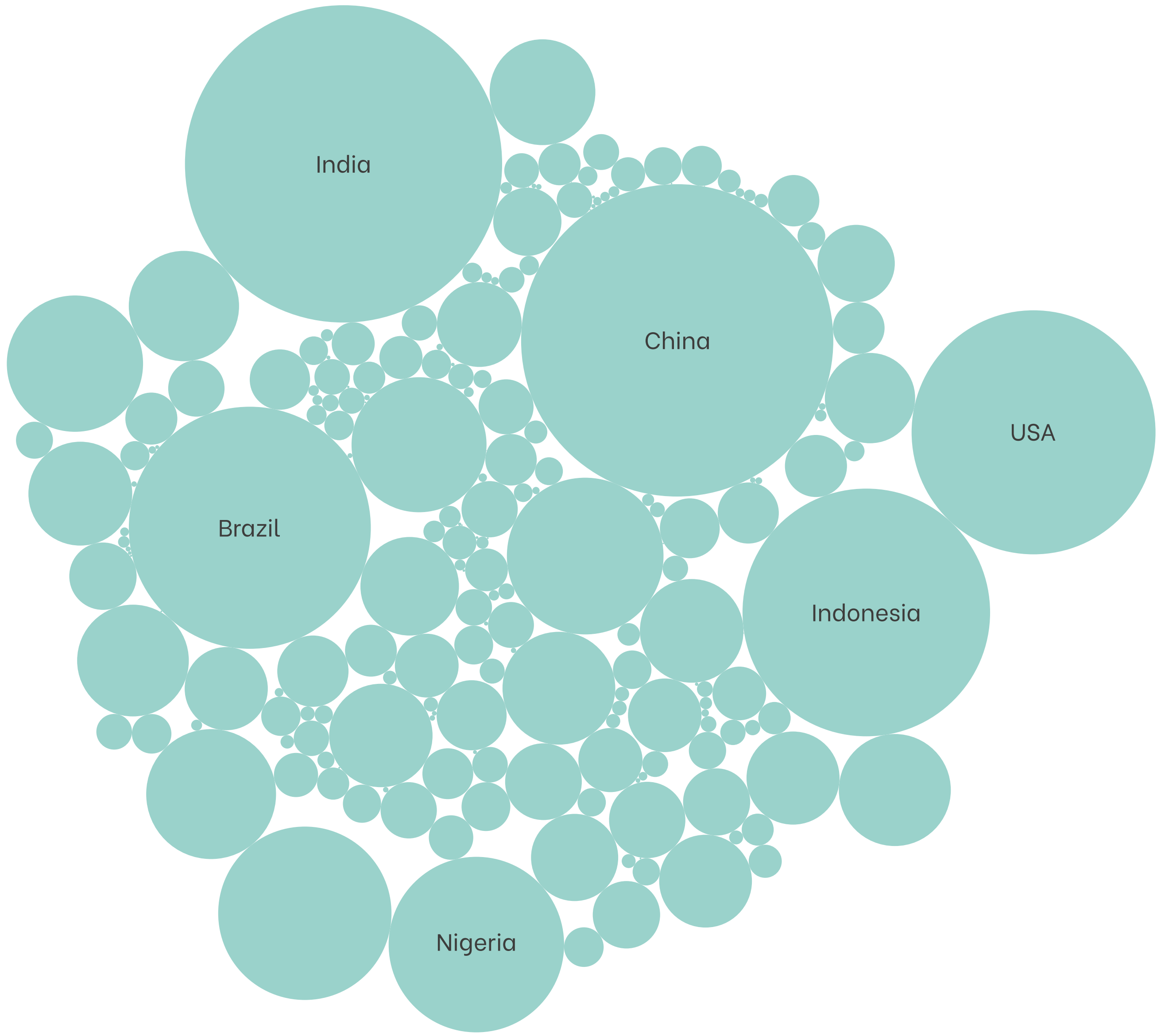
Data refer to the year 2016.

The total water footprint measures the two contributions of green and blue WFs of agricultural production, including 167 crops cultivated to sustain both human and animal diets, and fibers productions. The table sorts the top 30 countries in order of water footprint of their production. These countries account for more than 80% of the total water footprint worldwide.

Country	Total WF (km³)	Cumulative WF over the global total WF (%)
India	1 030	14%
China	865	26%
USA	517	33%
Indonesia	480	39%
Brazil	454	46%
Nigeria	240	49%
Russia	238	52%
Argentina	191	55%
Thailand	162	57%
Bangladesh	156	59%
Philippines	132	61%
Pakistan	124	62%
Ukraine	98	64%
Canada	97	65%
Malaysia	96	66%
Mexico	96	68%
Myanmar	95	69%
Vietnam	93	70%
Iran	86	71%
Ethiopia	83	73%
Ivory Coast	82	74%
Australia	80	75%
Turkey	79	76%
Sudan	72	77%
Tanzania	67	78%
Kazakhstan	61	79%
Spain	59	79%
Niger	59	80%
France	57	81%
Egypt	48	82%

THE BIGGER GREEN WATER FOOTPRINTS OF PRODUCTION

The first 6 countries cover 48% of the total green water footprint.



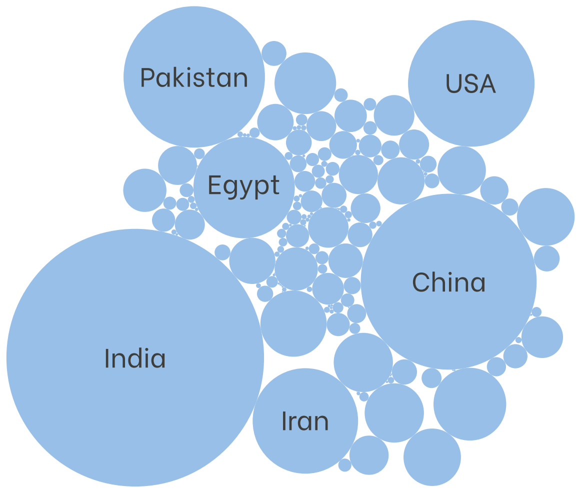
Data refer to the year 2016.

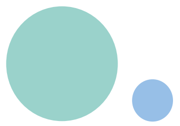
The Table sorts the top 30 countries in order of green water footprint of their production. These countries account for more than 80% of the green water footprint worldwide. India, China, and Insonesia account for one third the total green water footprint.

Country	Green WF (km³)	Cumulative GWF over the global GWF (%)
India	765	12%
China	742	23%
Indonesia	466	31%
USA	453	38%
Brazil	445	45%
Nigeria	234	48%
Russia	228	52%
Argentina	187	55%
Thailand	141	57%
Bangladesh	139	59%
Philippines	128	61%
Canada	97	63%
Ukraine	95	64%
Malaysia	95	66%
Myanmar	92	67%
Vietnam	85	68%
Mexico	82	70%
Ivory Coast	82	71%
Ethiopia	81	72%
Australia	74	73%
Tanzania	66	74%
Turkey	65	75%
Sudan	62	76%
Niger	58	77%
France	55	78%
Kazakhstan	53	79%
Spain	45	80%
Ghana	45	80%
Pakistan	44	81%
Iran	41	82%

THE BIGGER BLUE WATER FOOTPRINTS OF PRODUCTION

The first 6 countries cover 67% of the total blue water footprint.





The proportion between the Blue and the Green Water Footprint is 1 to 7.

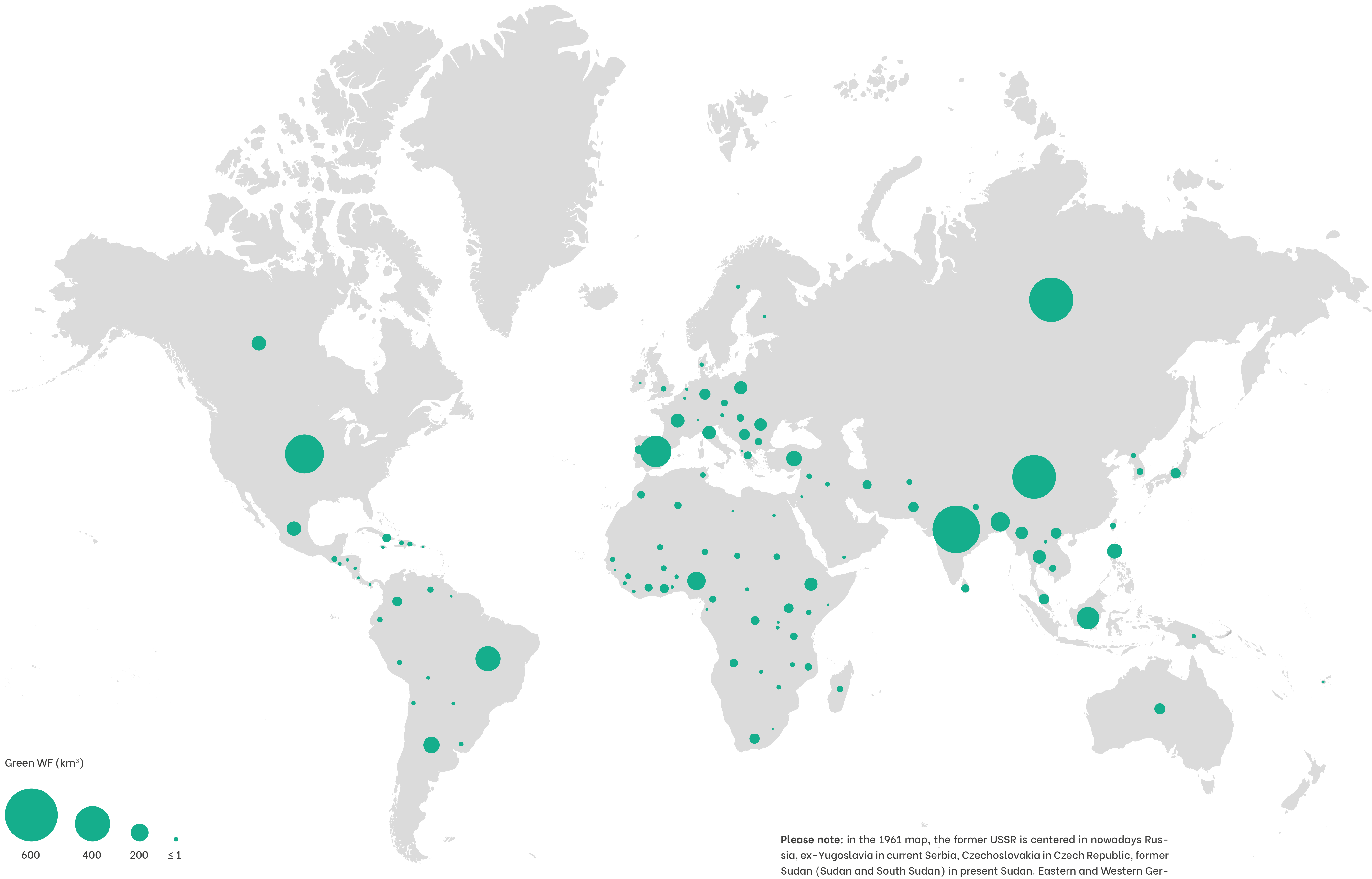
Data refer to the year 2016.

The Table sorts the top 30 countries in order of blue water footprint of their production. These countries account for more than 90% of the blue water footprint worldwide. Asian countries have high blue water footprints, and this is particularly true for the most arid ones as Iran, Uzbekistan, Kazakhstan, and Syria.

Country	Blue WF (km³)	Cumulative BWF over the global BWF (%)
India	265	29%
China	124	42%
Pakistan	80	51%
USA	64	58%
Iran	44	63%
Egypt	41	67%
Thailand	21	70%
Bangladesh	18	71%
Uzbekistan	15	73%
Mexico	14	75%
Indonesia	14	76%
Spain	13	78%
Turkey	13	79%
Sudan	10	80%
Russia	9	81%
Kazakhstan	9	82%
Brazil	9	83%
Vietnam	7	84%
Afghanistan	7	85%
Syria	7	85%
Turkmenistan	7	86%
Australia	7	87%
Morocco	6	87%
Iraq	6	88%
Nigeria	6	89%
Peru	5	89%
Argentina	5	90%
Saudi Arabia	4	90%
Algeria	4	91%
Philippines	4	91%

KEY ACTORS OF THE GREEN WATER FOOTPRINT IN TIME

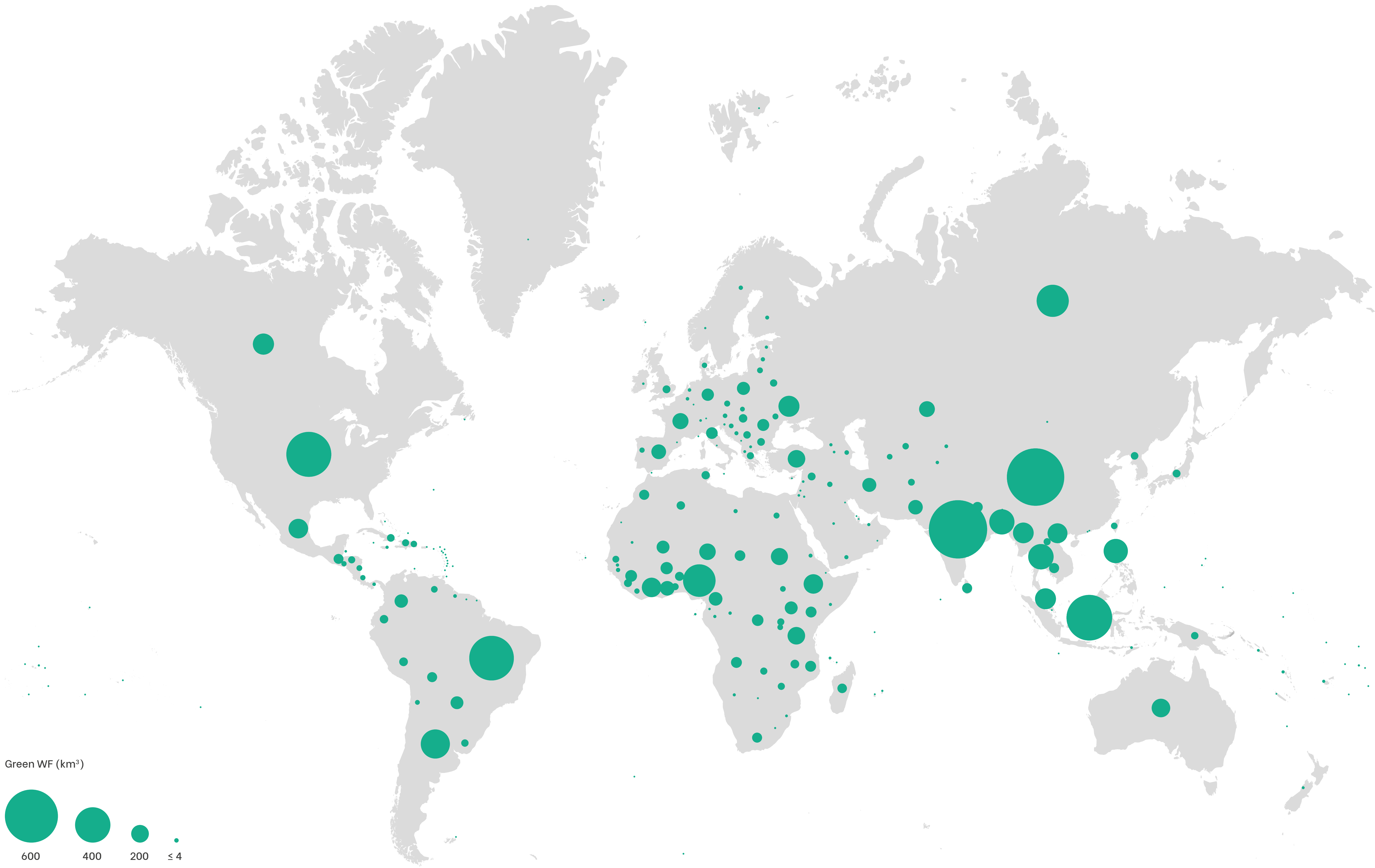
1961



Please note: in the 1961 map, the former USSR is centered in nowadays Russia, ex-Yugoslavia in current Serbia, Czechoslovakia in Czech Republic, former Sudan (Sudan and South Sudan) in present Sudan. Eastern and Western Germany are considered as a whole, consistently to FAO dataset (see page 193).

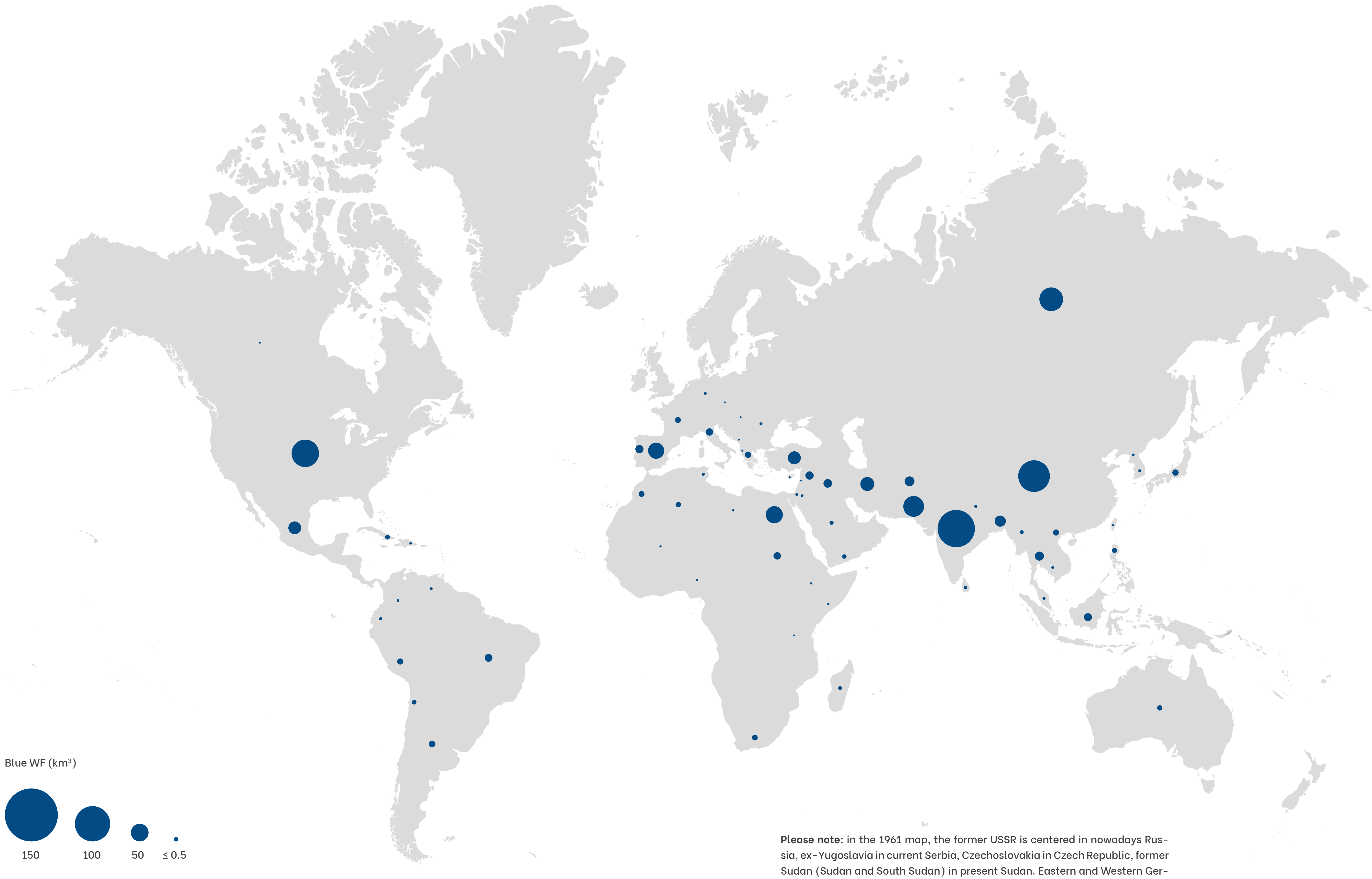
KEY ACTORS OF THE GREEN WATER FOOTPRINT IN TIME

2016



KEY ACTORS OF THE BLUE WATER FOOTPRINT IN TIME

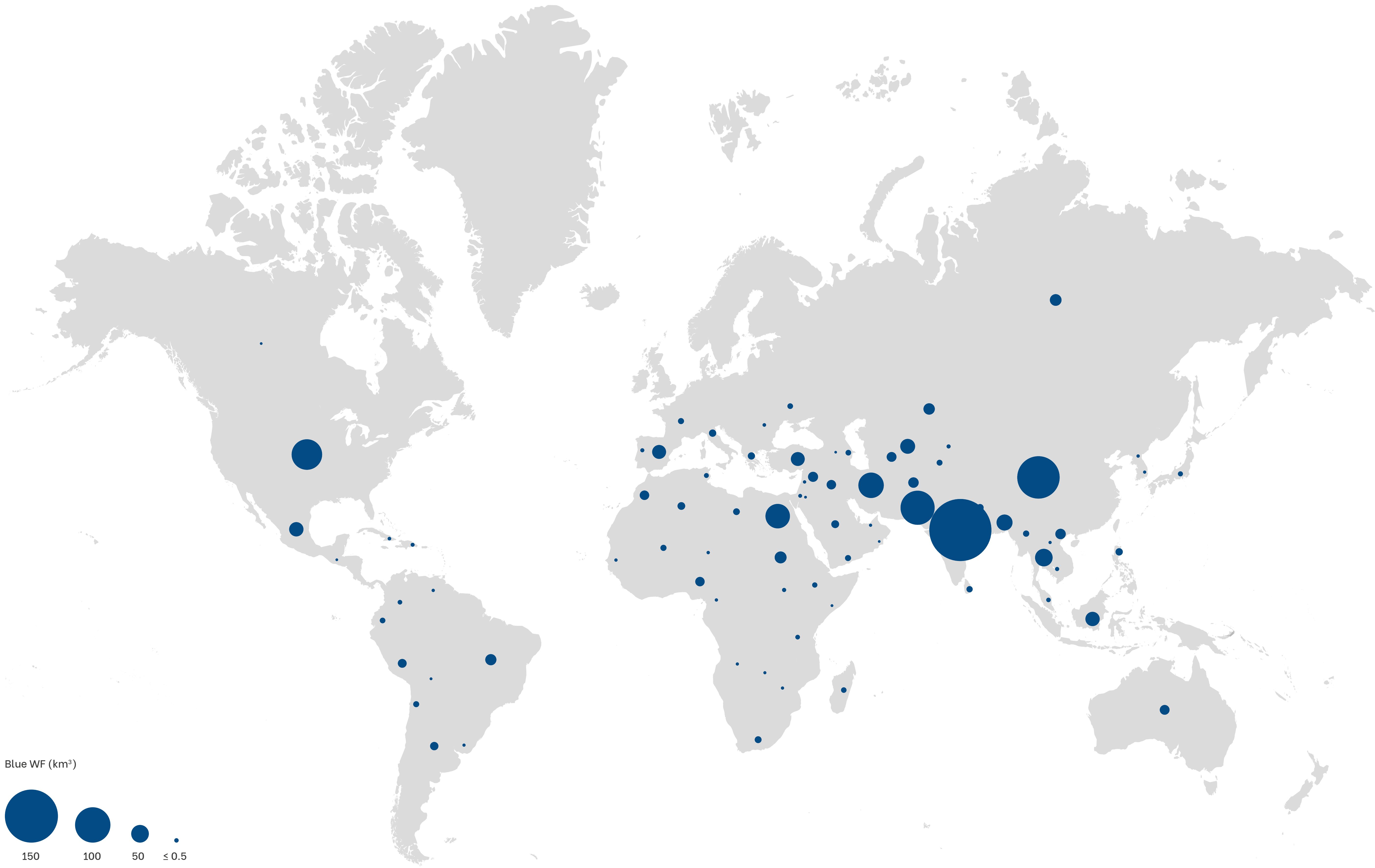
1961



Please note: in the 1961 map, the former USSR is centered in nowadays Russia, ex-Yugoslavia in current Serbia, Czechoslovakia in Czech Republic, former Sudan (Sudan and South Sudan) in present Sudan. Eastern and Western Germany are considered as a whole, consistently to FAO dataset *(see page 193)*.

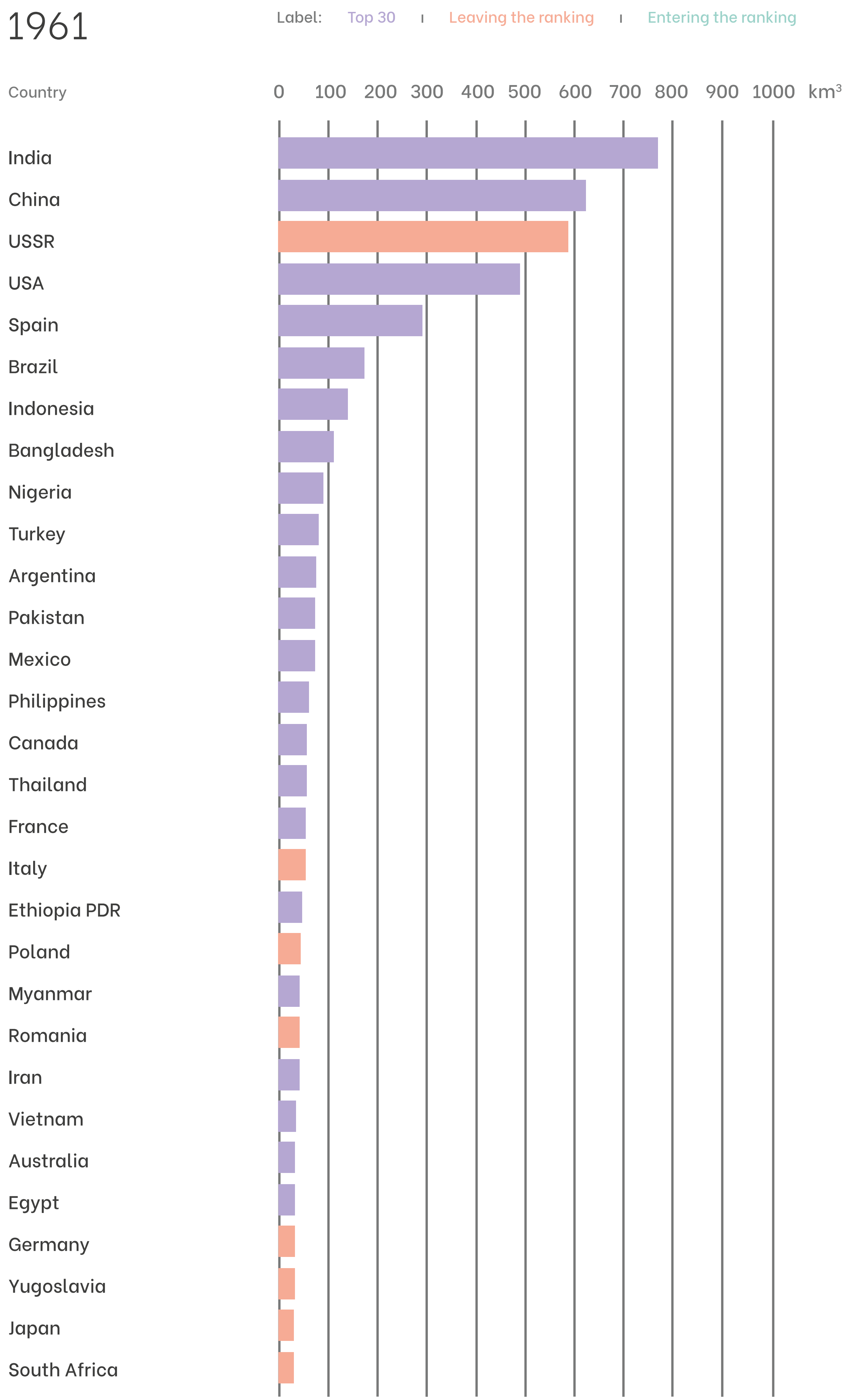
KEY ACTORS OF THE BLUE WATER FOOTPRINT
IN TIME

2016

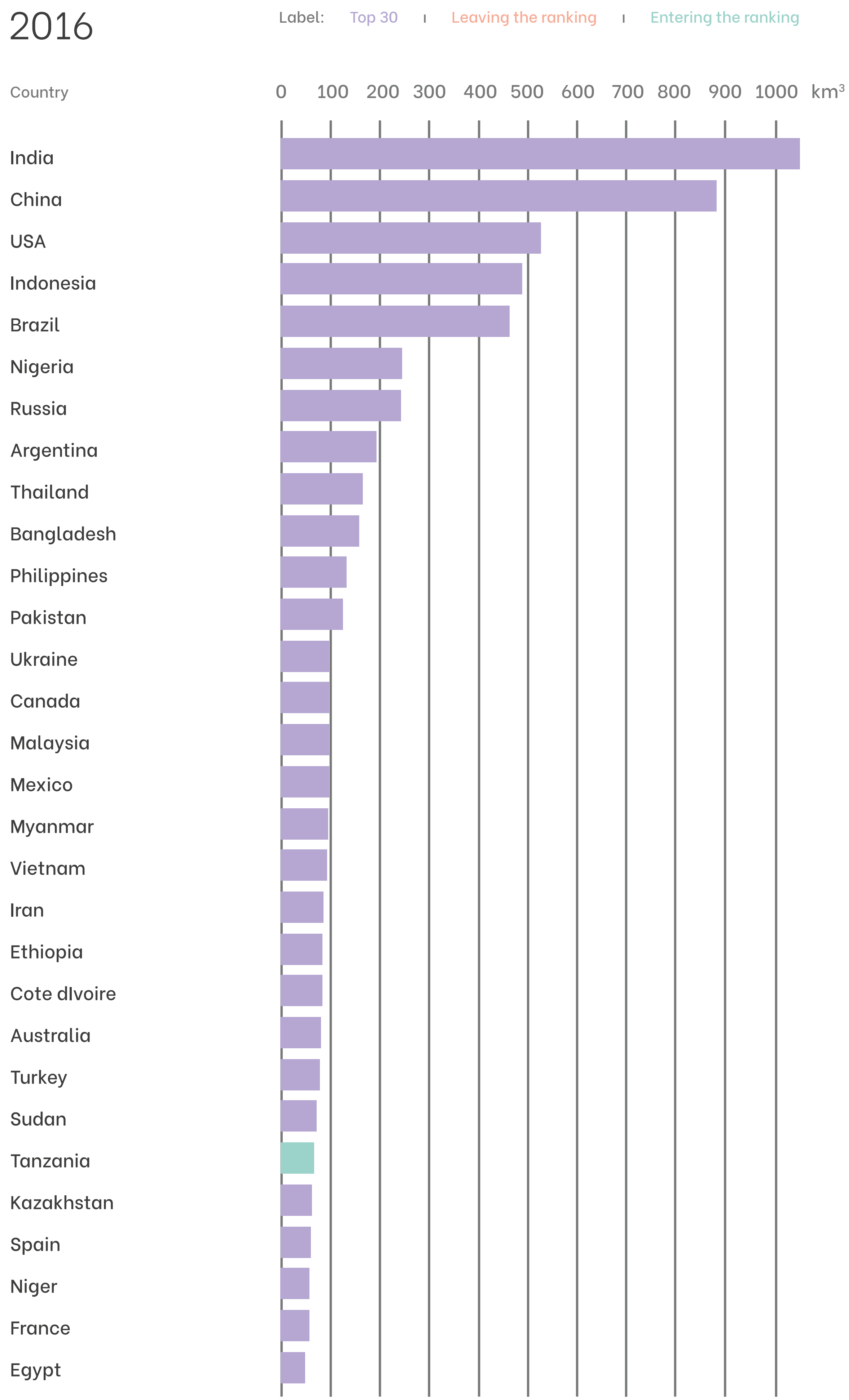


TOP 30 CONTRIBUTORS OF WATER FOOTPRINTS OVER TIME

Globally, the water footprint of production increased from 1961 to 2016. However, not all countries contributed equally to this increment. Since the dissolution of the USSR, the top three contributors of water footprint are India, China, and the USA. Over time, the Water Footprints of Latin American countries, such as Mexico, Brazil, and Argentina, as well as the ones of Central African countries, such as Ethiopia, Ivory Coast, and Sudan, significantly increased. Australia also stands out as a relevant increasing contributor to global water footprint.
Instead, European countries slowly decreased their overall contribution to the global WFs of production over time: Spain has lost 16 positions in its ranking, while Italy disappeared from the top 30 contributors. This could happen thanks to the increased role of food imports from the global market.

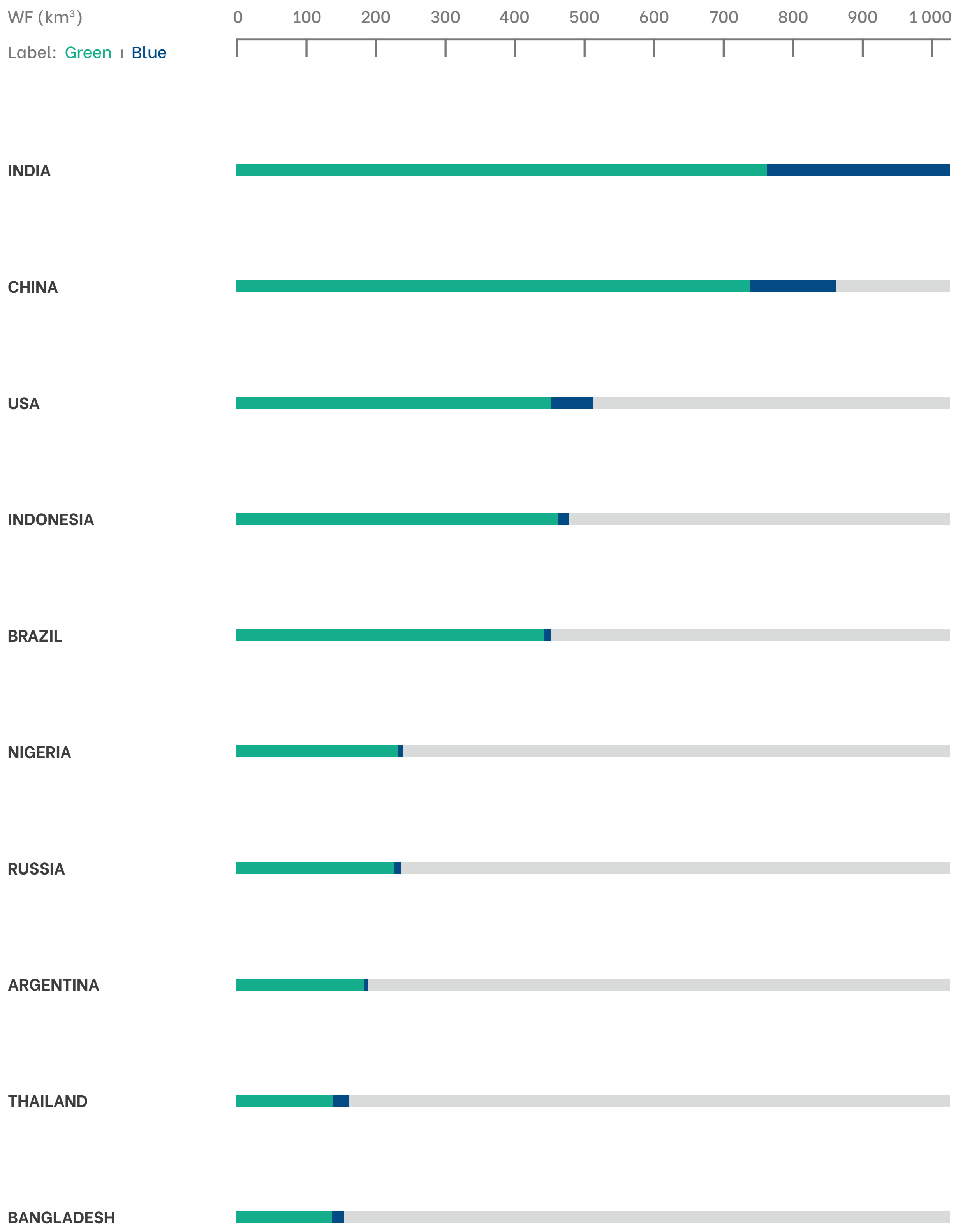



2000
Label: Top 30 | Leaving the ranking | Entering the ranking
Country
0 100 200 300 400 500 600 700 800 900 1000 km³
India
China
USA
Indonesia
Brazil
Russia
Nigeria
Bangladesh
Thailand
Argentina
Pakistan
Malaysia
Philippines
Turkey
Mexico
Australia
Canada
Myanmar
Iran
Vietnam
Ukraine
Spain
France
Ethiopia
Ivory Coast
Kazakhstan
Poland
Sudan (former)
Egypt
Niger

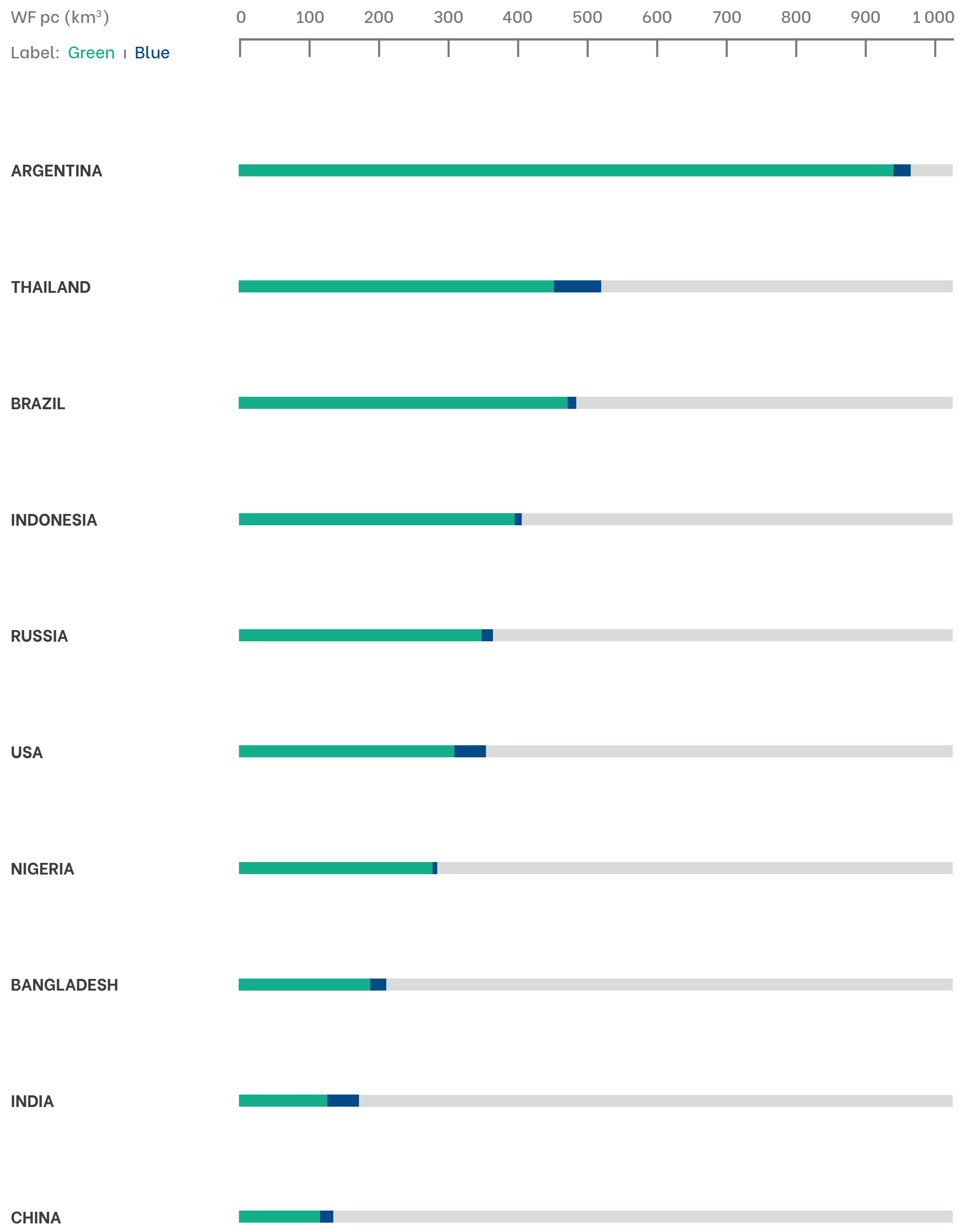

2016
Label: Top 30 | Leaving the ranking | Entering the ranking
Country
0 100 200 300 400 500 600 700 800 900 1000 km³
India
China
USA
Indonesia
Brazil
Nigeria
Russia
Argentina
Thailand
Bangladesh
Philippines
Pakistan
Ukraine
Canada
Malaysia
Mexico
Myanmar
Vietnam
Iran
Ethiopia
Cote dIvoire
Australia
Turkey
Sudan
Tanzania
Kazakhstan
Spain
Niger
France
Egypt

HOW DOES POPULATION SIZE CHANGE THE NATIONAL WATER FOOTPRINT OF PRODUCTION?

The water footprints of production, in green and blue water resources (measured in cubic meters), change if framed within the perspective of the countries' population size, thus creating worldwide variability in the water footprints per number of inhabitants (cubic meters per capita). The chart of the top ten countries changes from the absolute values in water footprint (diagram on the left) to the per capita values (diagram on the right).



Data refer to the year 2016.



Data refer to the year 2016.

DIMENSION 1

GOAL 2: Zero Hunger
GOAL 10: Reduced Inequalities
GOAL 17: Partnerships for the Goals

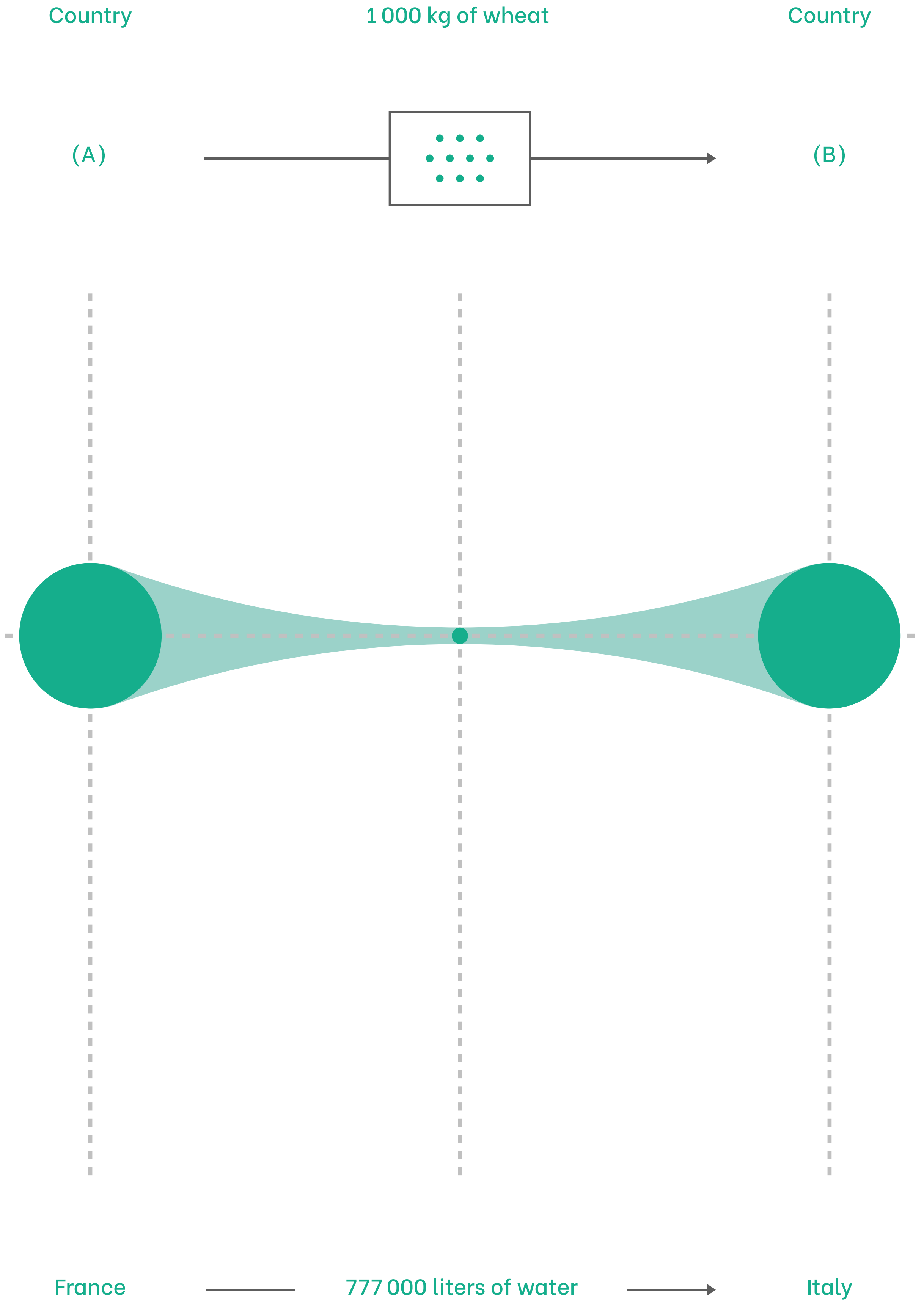
THE VIRTUAL WATER TRADE

The virtual water trade

The global value of agricultural products involved in the international trade of commodities has increased by six times over the last 40 years. Due to trade, the water used for food production virtually moves around the world. This phenomenon creates a virtual connection of water flowing from exporting (i.e., producing) to importing (i.e., consuming) countries, defined as virtual water (VW) trade.
Let's make a case scenario. Suppose Italy imports 1 000 kg of wheat from France. Through this trade flow, Italy also virtually imports 777 000 liters of water, i.e., the water required to produce a tonne of wheat in France. This volume of virtual water flow depends on the amount of good that is traded (as in this case, 1 000 kg) and the unit Water Footprint of the producing countries (777 m^3/ton or, equivalently 777 l/kg, as it is the case of producing wheat in France).
Clearly, the virtual water imports-exports fluxes are in balance with the water footprint of production and consumption, according to this water balance:

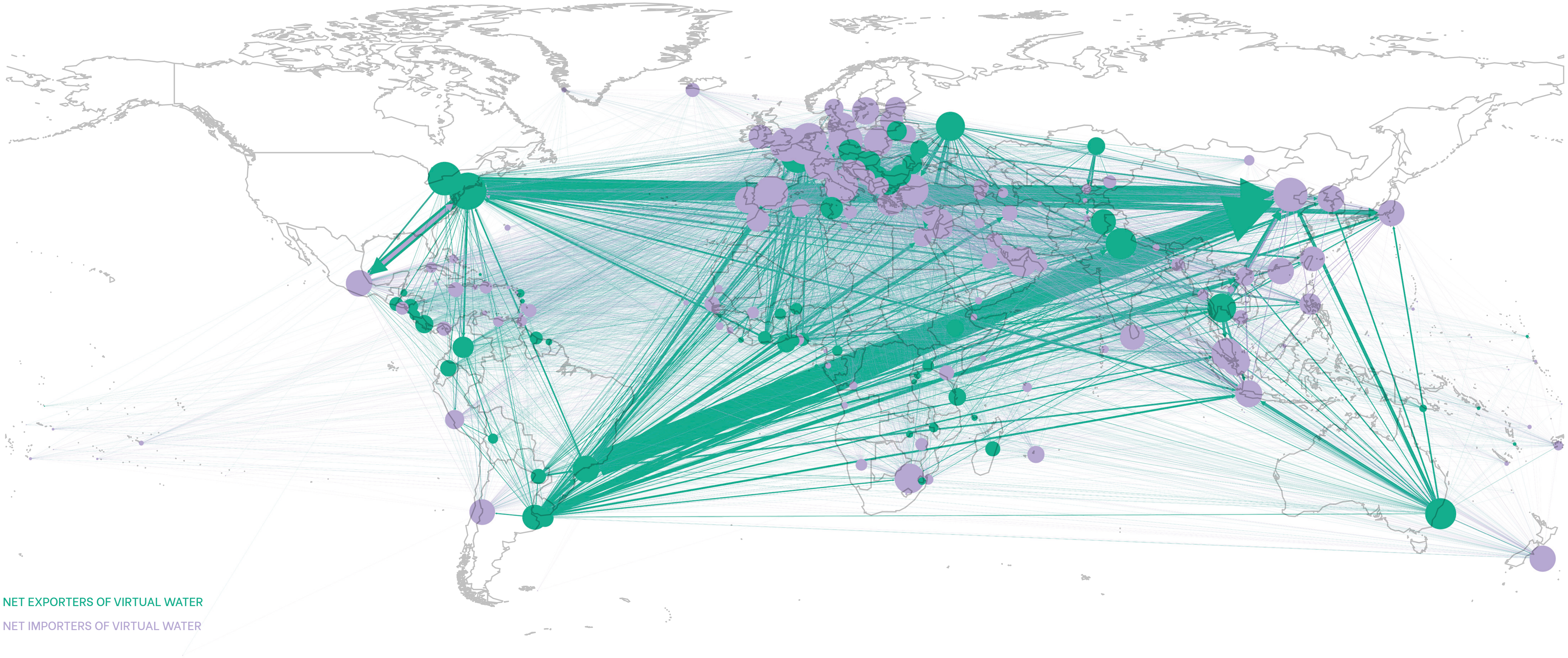
Water Footprint Production + Virtual Water Import =
Water Footprint Consumption + Virtual Water Export

This balance equation can be defined for each country and at the world level.
A country is defined as a net importer of virtual water when imported water is more significant than the exported one. In this case, the country relies on the water resources of other countries for the consumption of agricultural goods. Viceversa, a net exporter is a country that exports more virtual water than it imports.
This chapter is dedicated to the identification of the most significant dynamics characterizing the virtual water trade. Being our home, we chose to use Italy as a paradigmatic case for describing these characteristics.



VIRTUAL WATER TRADE OF CROPS AT THE GLOBAL SCALE IN THE YEAR 2016

The virtual water trade can be represented as a network in which countries are the nodes, and the VW flows are the links, exporters pointing to importers. In 2016, this network counted 14 501 links connecting all countries, totaling 1 784 km^3 of virtual water exchanged in the form of crops. The size of the arrows is proportional to the VW flow it represents. Nodes are color-coded on the basis of their net virtual water trade: green for net-exporters and purple for net-importers. Connections (or links) are color-coded according to exporting countries: fluxes originating from net importers of virtual water are in purple, from net exporters in green. European countries and China are relevant examples of net importers.
Instead, the USA, Canada, Russia, Brazil, and Australia are the most important net exporters.



NET EXPORTERS OF VIRTUAL WATER

NET IMPORTERS OF VIRTUAL WATER

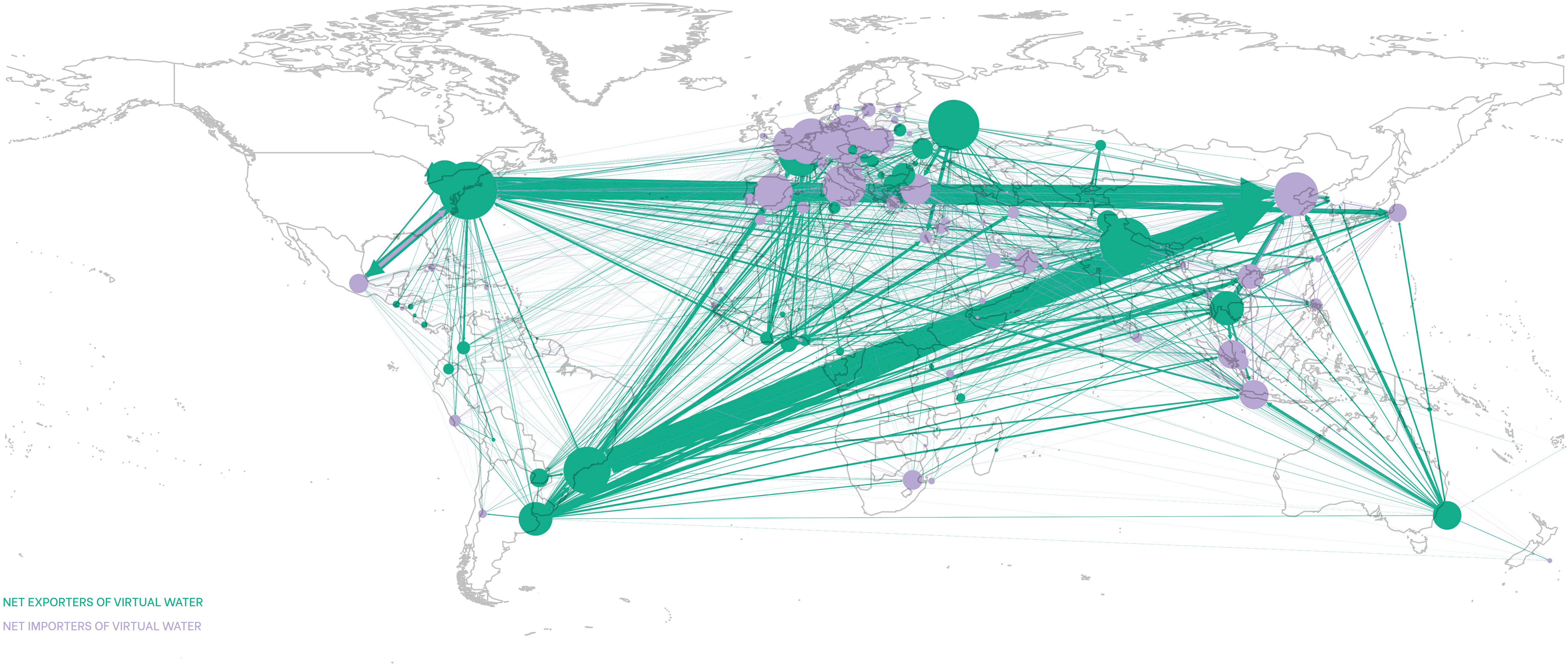
Number of active links: 14 501

Total virtual water volume: 1 784 km^3

* The geographic barycenters are placed according to the most populated city in each country.

THE KEY FLOWS OF VIRTUAL WATER TRADE

Among all these links, just about 10% define 94% of the global virtual water flows in crop trading, totaling 1 753 links (and 1 676 km³). Each connection in this market weighs at least 100 million m³ of virtual water. China is the top recipient of virtual water, mainly coming from Brazil and the USA. Yearly, these two commercial relations make 7% of the global water trade, thus suggesting the strong dependence of China on external water resources.



NET EXPORTERS OF VIRTUAL WATER

NET IMPORTERS OF VIRTUAL WATER

Number of active links: 1 753

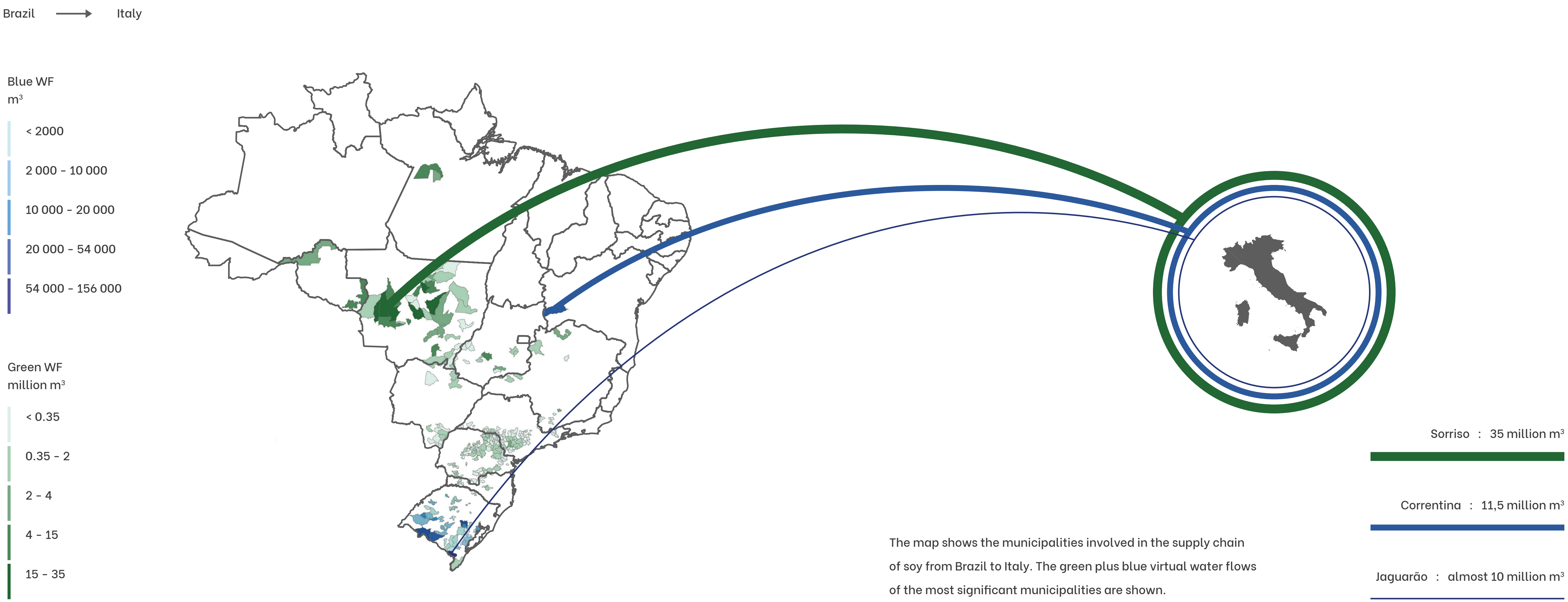
* The geographic barycenters are placed according to the most populated city in each country.

Enhancing the spatial resolution of the virtual water trade

Water footprint shows uneven spatial distribution at the subnational scale due to climate, soil properties, irrigation techniques, and fertilizer inputs *(see pages 50-51)*.
This variability is generally lost in trade analyses since most data are only available at the country scale *(data details are given on page 193)*.
Instead, mapping the supply chain from producers to consumers, back and forth, allows one to unfold the granularity of the supply chain and to define additional tools to build sustainable water management strategies.

In particular, tracing back the supply chain from the consumers to the producers allows businesses, governments, non-profit organizations, communities, and individuals to make more conscious choices, engage in the sustainability transition, and find integrated solutions and policies.

An iconic example is the soybean market from Brazil to Italy. The high-resolution map – detailing where the Brazilian soybean actually originates – helps define the water consumption and the socio-economic and environmental sustainability of its use. In particular, the high-resolution enables one to discern the green and blue water footprint, and the overlapping of the two provides insights into the sustainability of the supply chain. Due to soy imports, some of the most significant virtual water flows from Brazil to Italy depart from the municipalities of Sorriso, Correntina, and Jaguarão. Sorriso's production relies on green water resources and the magnitude of this virtual flows strongly depend on the production's quantity, being the largest producer in the country. Instead, the soy production of Correntina and Jaguarão also derives from blue water resources, despite green water providing the larger contribution.



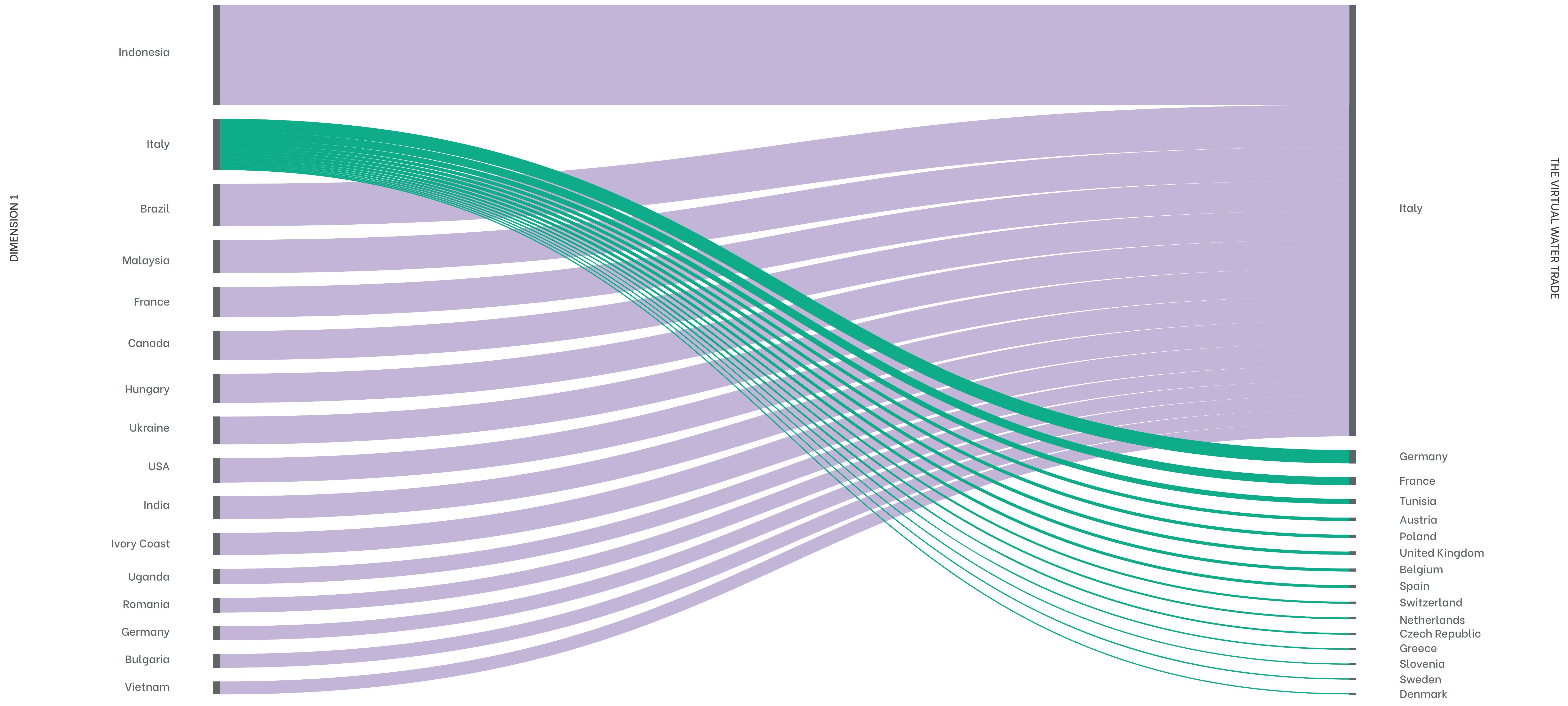
The map shows the municipalities involved in the supply chain of soy from Brazil to Italy. The green plus blue virtual water flows of the most significant municipalities are shown.

The italian case of import-export flows of virtual water

Italy is a net importer of virtual water. In 2016, imports accounted for 30 billion cubic meters of water, while exports only account for 3.3 billion cubic meters. This chart processing the data for the year 2016, shows the top 15 trading partners of the import-export fluxes to and from Italy are in bold. Actual trends confirm the analysis from 2016, with Italy importing more water than it exports.

LARGEST VIRTUAL WATER FLOWS FROM ITALY

LARGEST VIRTUAL WATER FLOWS TO ITALY

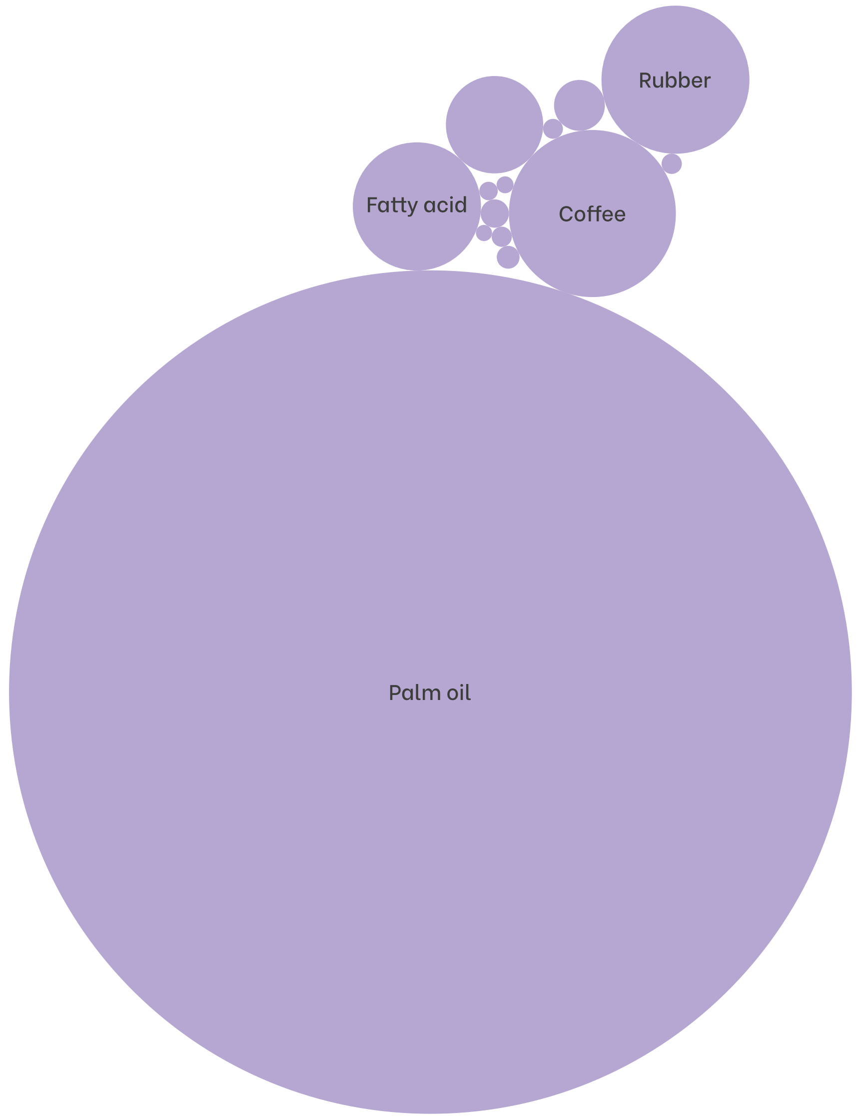


WHERE DOES THE IMPORTED VIRTUAL WATER OF ITALY HIDE AND COME FROM?

For imports, in 2016, the top five trading partners were Indonesia, Brazil, Malaysia, France, and Canada. Import baskets from these countries vary in items and quantities. Imported items include palm oil, soybean (mainly addressed to animal feed industry), fatty acids, wheat, maize, and coffee. The import basket from France also includes cattle, barley, and refined sugar.
The bubbles unveil the items and corresponding traded quantities (in tonnes) responsible for the virtual water entering Italy. The size of the bubbles is country-specific, and the minimum and maximum sizes are specified.

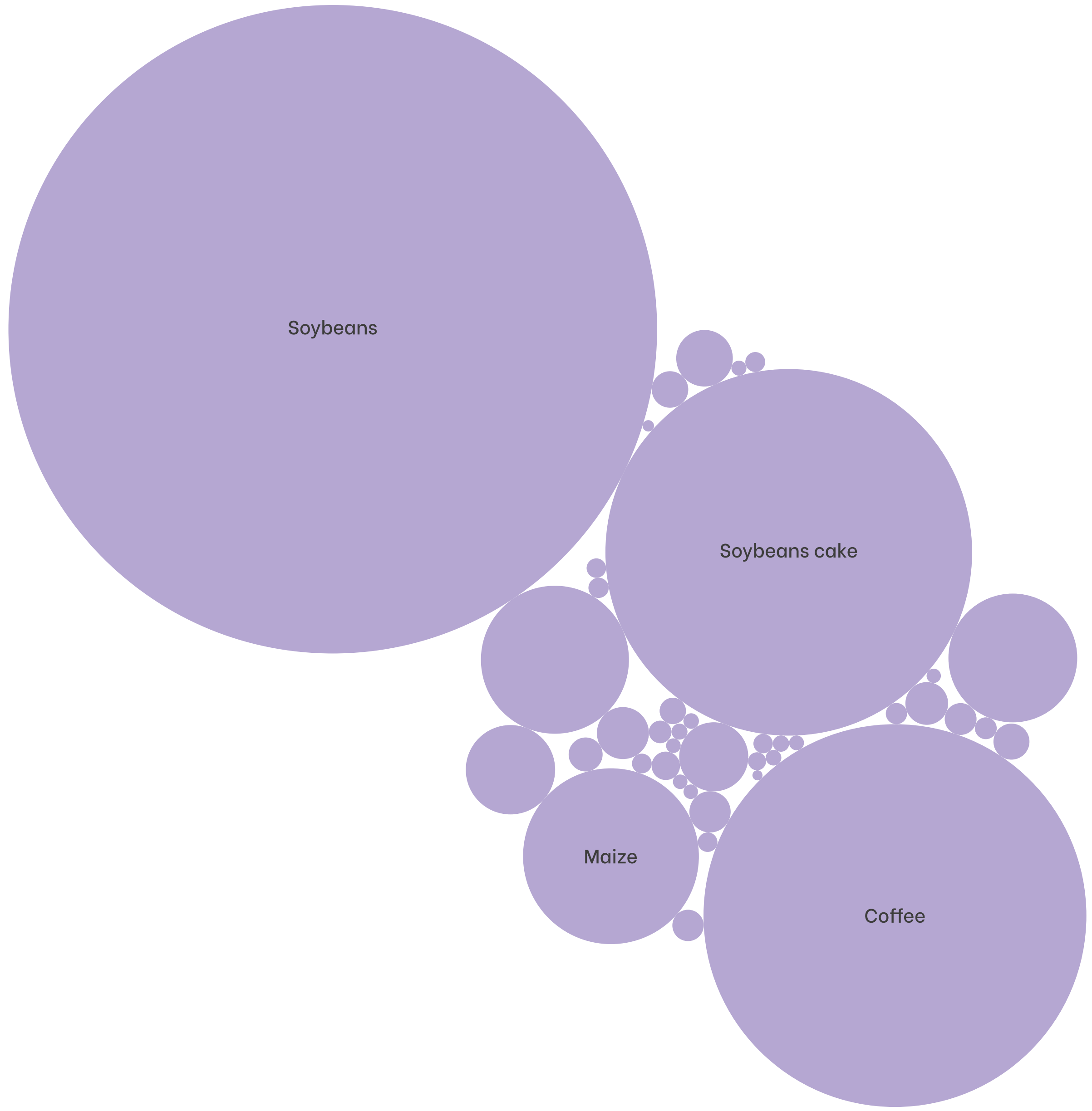
INDONESIA

MAX : Palm oil , 912 943 tons
MIN : Fats, 336 tons



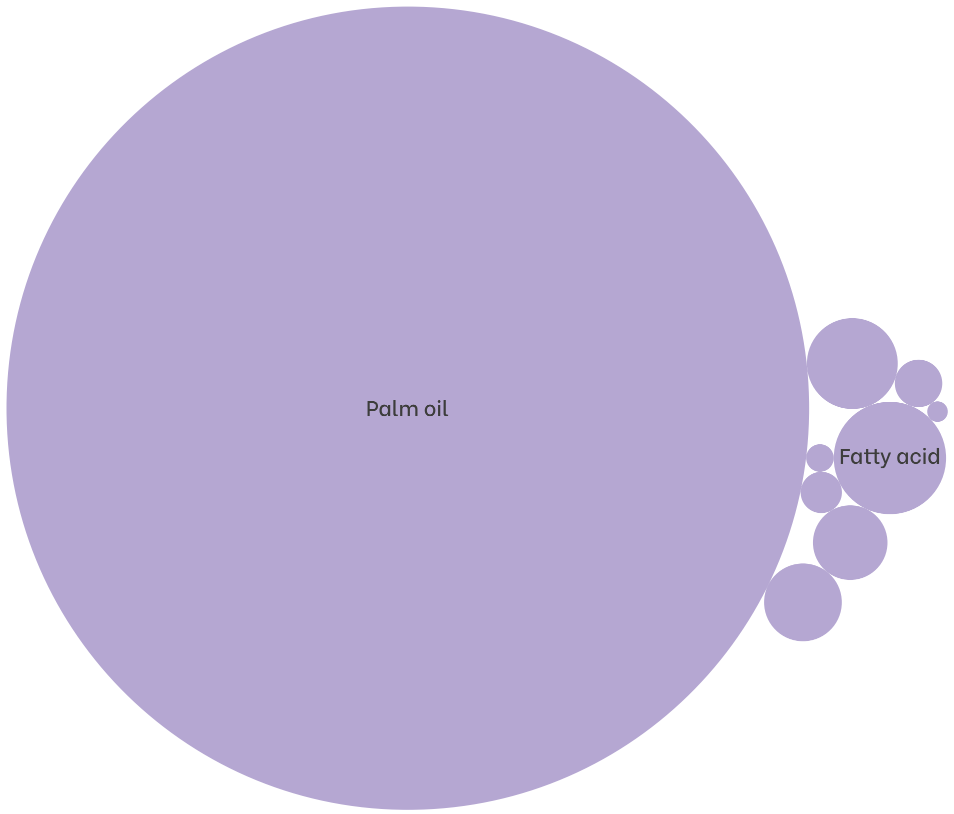
BRAZIL

MAX : Soybeans, 494 207 tons
MIN : Plums and Sloes, 119 tons



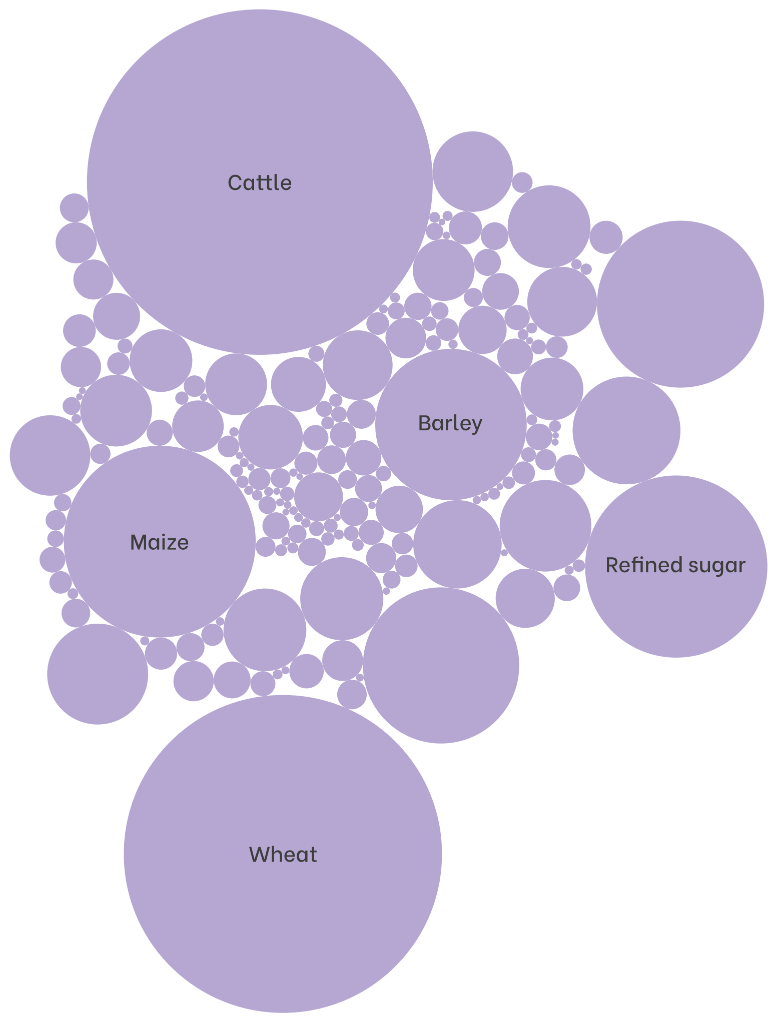
MALAYSA

MAX : Palm oil, 410 371 tons
MIN : Degreased wool, 269 tons



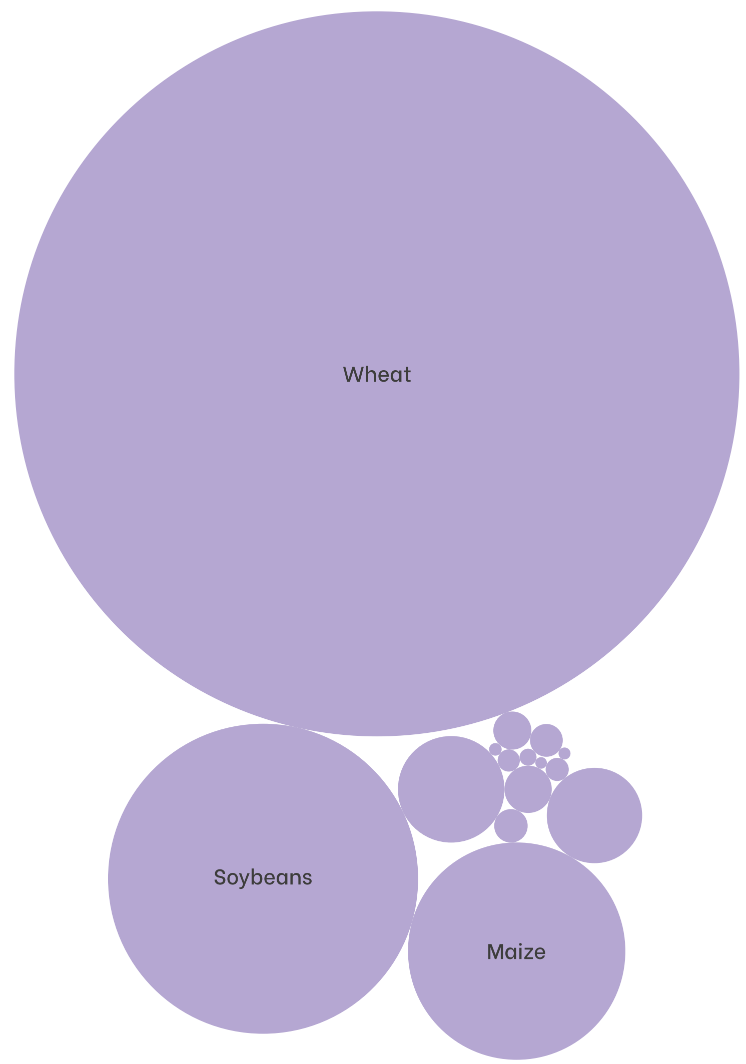
FRANCE

MAX : Wheat, 1 080 240 tons
MIN : Plums and Sloes, 460 tons



CANADA

MAX : Wheat, 1 092 870 tons
MIN : Hide and Skins, 278 tons



WHERE DOES THE EXPORTED VIRTUAL WATER OF ITALY HIDE AND GO TO?

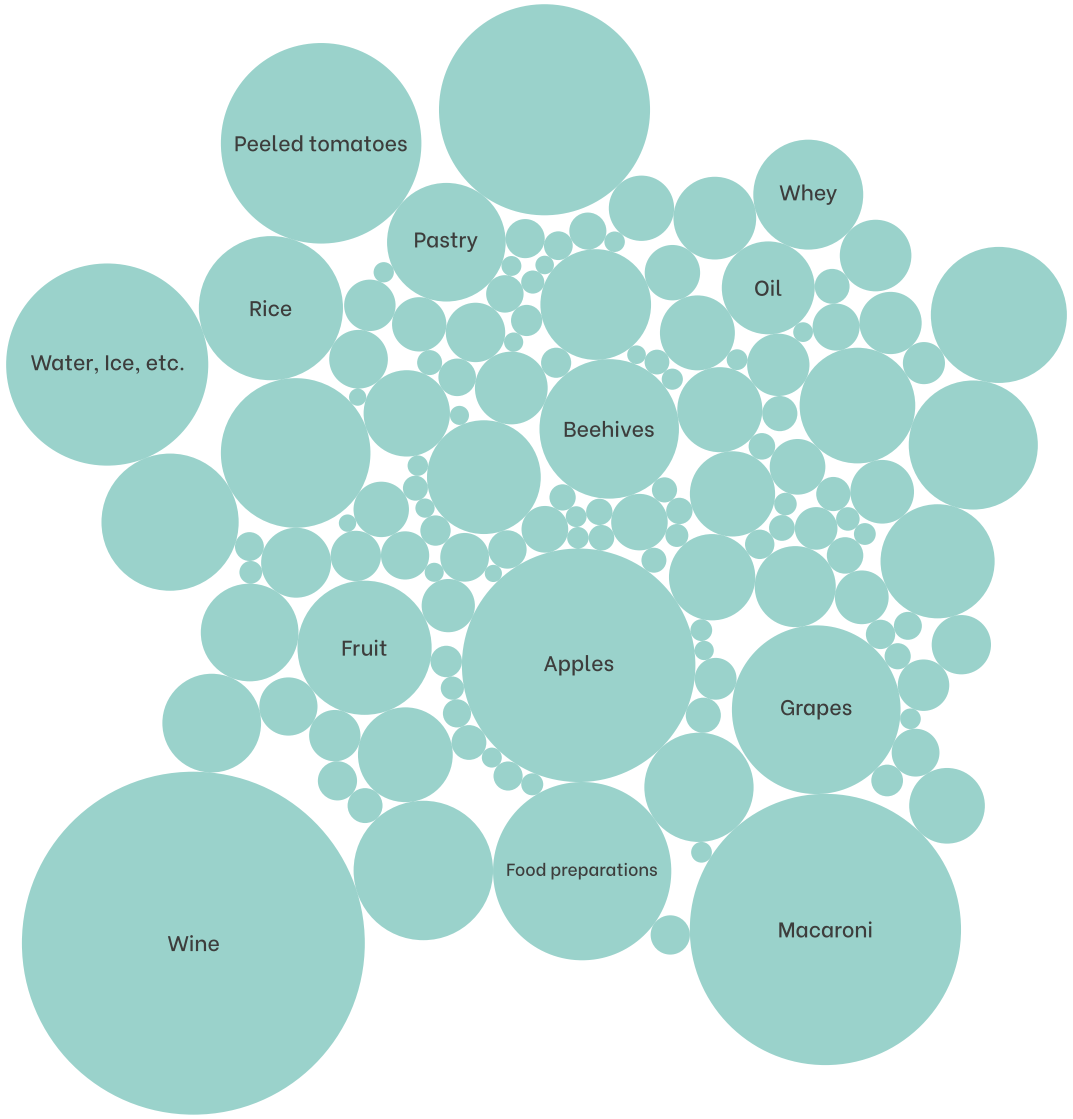
For exports, in 2016, the top five trading partners were Germany, France, Indonesia, Austria, and Poland. Italy virtually exports water through a greater variety of commodities: vegetables, fruit, cheese and milk, macaroni, rice, flour and wheat, wine, and beverages (alcoholic and non-alcoholic). In addition, Italy relevantly exports virtual water for the feed industry through oil and cake soybean and other animal feed (alfalfa meal and pellets).

Italy uses part of the imported wheat (e.g., from Canada) to process products like pasta and pastries exported to other countries, such as Germany and the UK, thus re-exporting the imported virtual water. Italy also re-exports (in virtual water terms) parts of the considerable amount of the imported soybeans (e.g., from Brazil) as processed cake for animal feed (e.g., to Austria). Of interest is stands the significant amount of virtual water that Italy exports as bottled mineral water.

The bubbles unveil the items and corresponding trade quantities (in tonnes) responsible for the virtual water departing from Italy. The size of the bubbles is country-specific, and the minimum and maximum sizes are specified.

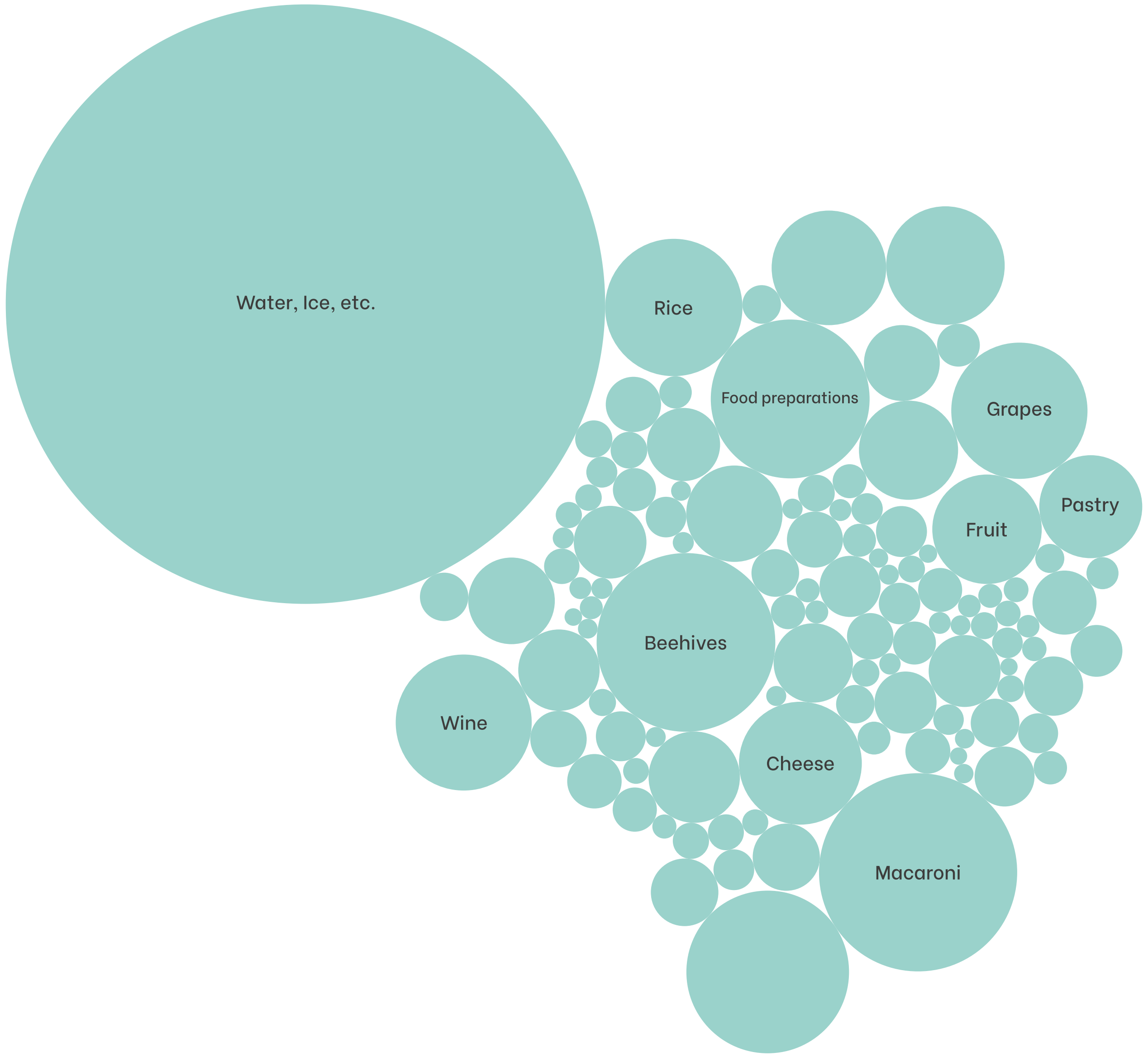
GERMANY

MAX : Wine, 554 337 tons
MIN : Pig meat, 1 392 tons



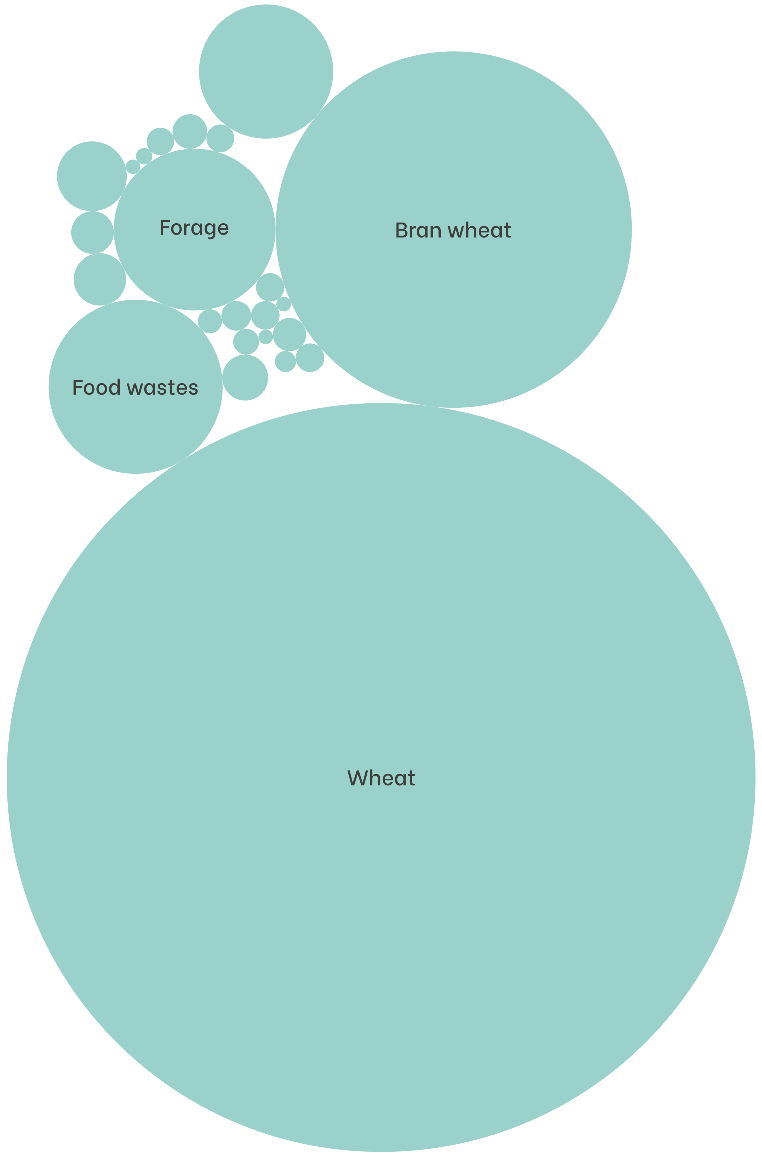
FRANCE

MAX : Waters and Ice, 1 952 536 tons
MIN : Yeasts, 1 616 tons



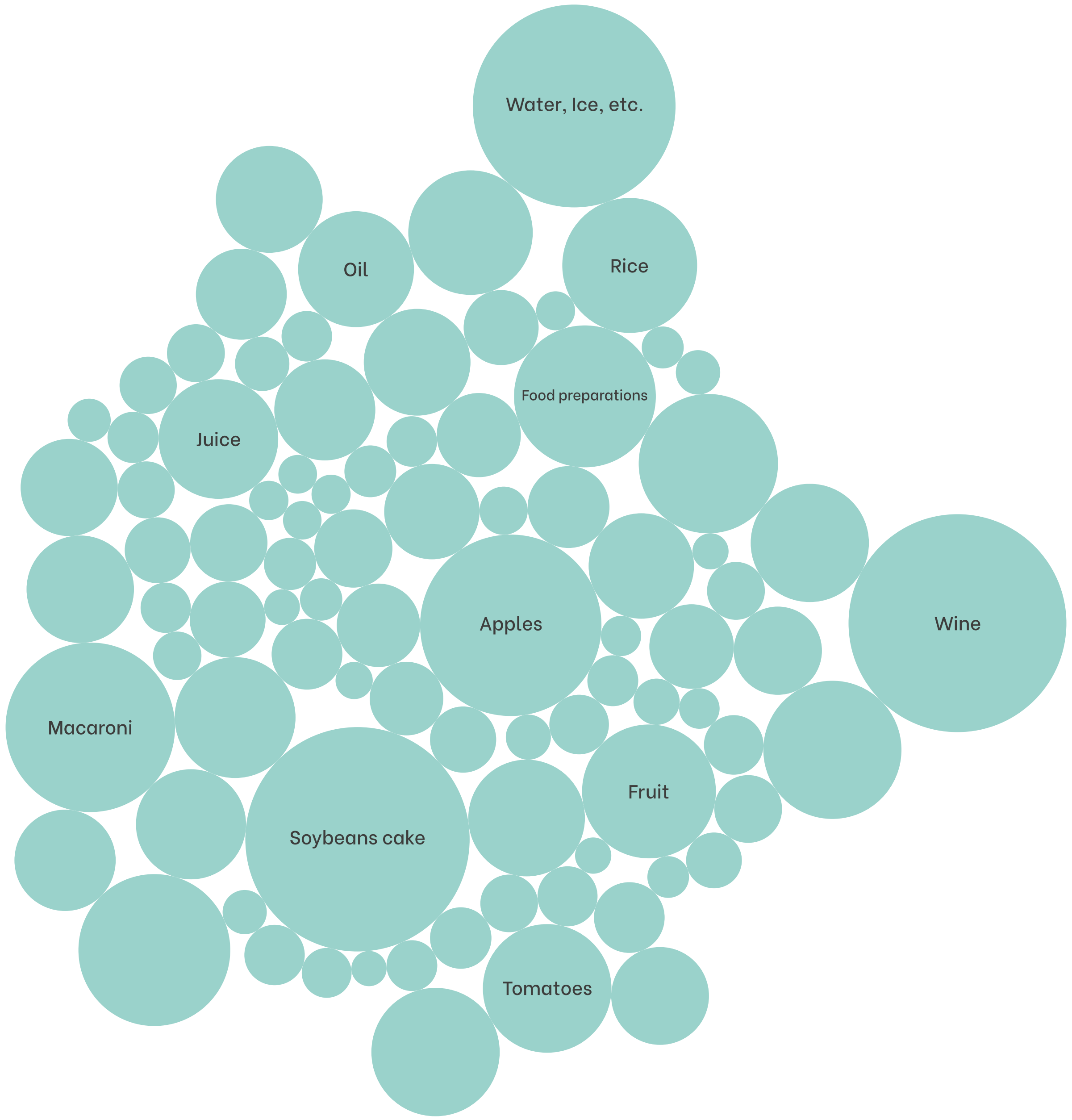
TUNISIA

MAX : Wheat, 376 720 tons
MIN : Lactose, 140 tons



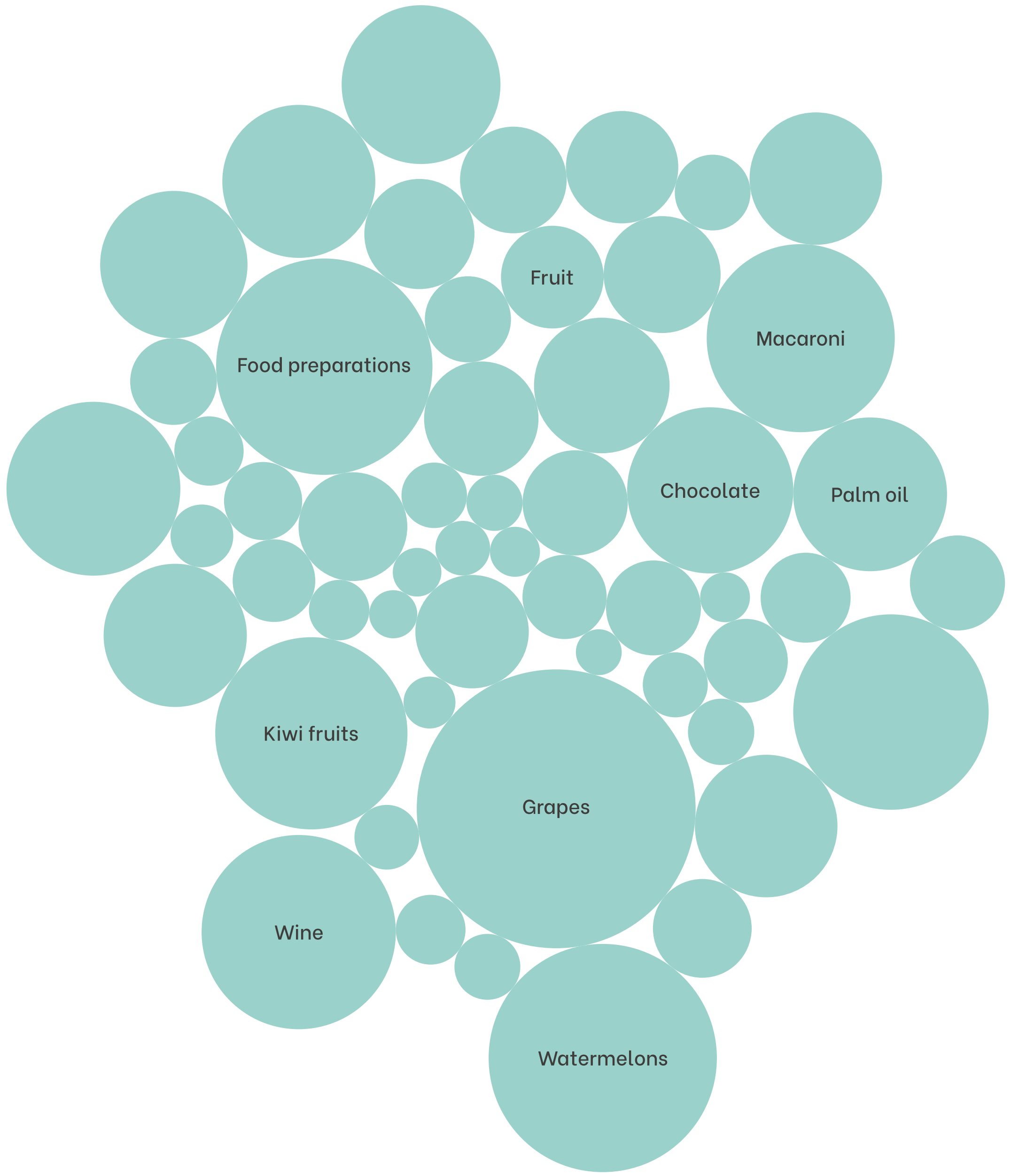
AUSTRIA

MAX : Soybeans cake, 53 328 tons
MIN : Preparation of Pig meat, 1 315 tons



POLAND

MAX : Grapes, 47 238 tons
MIN : Glucose and Dextrose, 1 275 tons



DIMENSION 2

GOAL 6: Clean Water and Sanitation
GOAL 8: Decent Work and Economic Growth
GOAL 17: Partnerships for the Goals

SOCIETY, ECONOMICS AND GOVERNANCE

Society, Economics and Governance

Many socio-economic and governance factors define the virtual water flows and water footprints of production, consumption, and trade at both local and global scales. In determining such factors, one should also consider their synergies and trade-offs for understanding their influence on water resources.

Society

• Population dynamics is one of the major drivers because it determines the demand for food in time and space. The grounding reasoning is simple: the more the population to be fed, the higher the demand. Nevertheless, considering the scale of population dynamics is also relevant: migratory fluxes can determine changes in food demand at the local level.

• Population culture plays an essential role in defining food preferences and diet habits, thus the food demand.

Economics

• The Gross Domestic Product may determine changes in dietary habits: in fact, increased prosperity is associated with an increase in demand for more sophisticated - and water-intensive - products, such as meat. In fact, a higher level of wealth also corresponds to a higher purchasing power. Since animal food products have generally high prices than crop-based ones, the change in the purchasing power associates with switching habits to more water-intensive products.

• International market competition dynamics, usually aimed to improve the national Gross Domestic Product, can determine the national Water Footprint of food production. According to the law of comparative advantage in economics, countries tend to produce more of a good for which they can gain from trade, thus assigning production to export rather than to local consumption.

Governance

• Governments play a crucial role at the policy level by establishing international agreements, thus defining the global market. The presence - or the entry into force - of trade agreements between two or more countries can impact the food market, influencing prices, food demand, water footprint, and virtual water trade. These factors are unavoidably linked to the already mentioned economic drivers.

• Beyond international market dynamics, governance is crucial for water resources management. Despite their water availability, many countries still face severe difficulties in using water resources for human activities because of economic and infrastructural obstacles. The feature of water resources management at the national level is crucial for understanding the socio-environmental impact of the water footprints of food production.

The following pages will show crucial results that put under the spotlight how these factors are intrinsically entangled and how they drive the exploitation of water resources at the local and global levels. Some principles of economics and demography are detailed to help understand the dynamics of some phenomena.

Hiding in plain sight

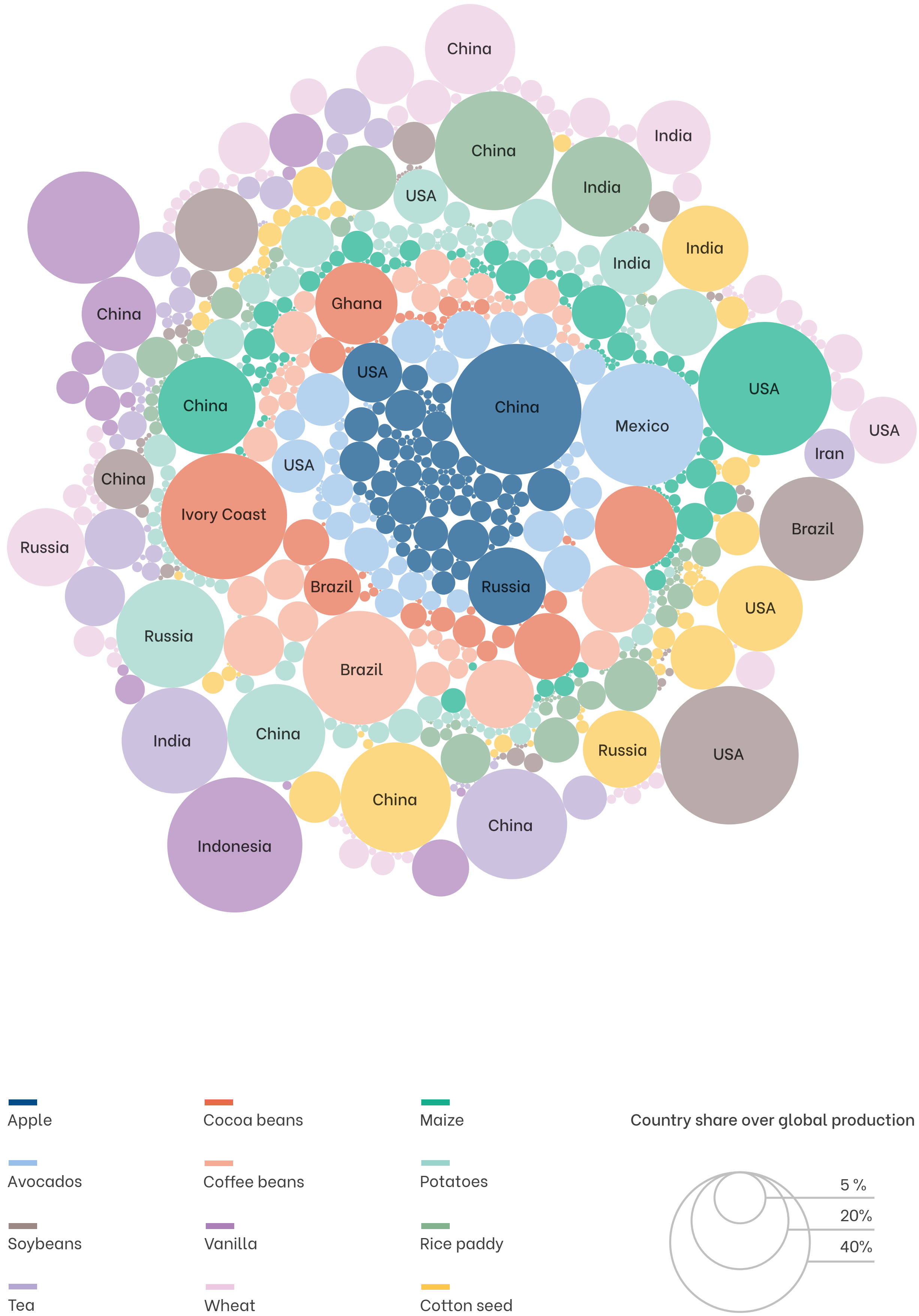
How do market dynamics influence countries' production, export, and pricing choices?

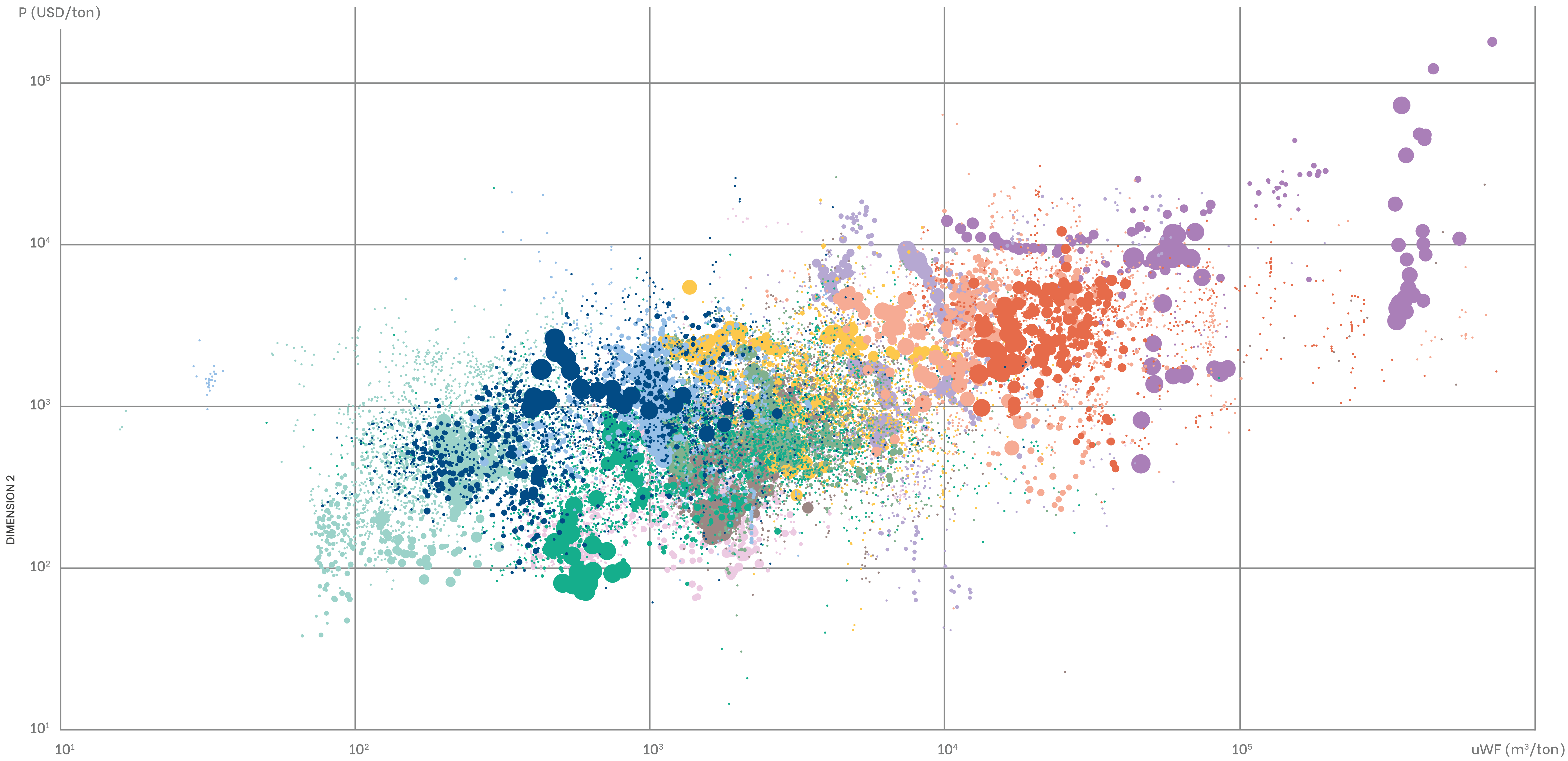
Competition, demand, and input costs are known to determine the market prices of food. What about the water footprint, instead? Do prices reflect the amount of water used for crop cultivation?

A heterogeneous set of agricultural commodities can reveal different patterns of water use on price definition. Let's consider wheat, maize, rice, potatoes, and soybeans, to start. These crops are defined as staple crops and account for about 60% of global calorie intake. Products such as cocoa and coffee beans, cottonseed, tea, and vanilla are defined as cash products, instead, since their cultivation is mainly export-oriented. Eventually, fruits as apples and avocados belong to the cash products market due to the climate requirements for their production.
As explained, the water footprint of an item changes according to the production areas, resulting in heterogeneity in the geographical distribution of its production and in its price variability. The crop-specific bubble graph here shows the world's major producing countries of 12 iconic staple and cash crops to understand the heterogeneous geography of production. The size of each crop-specific circle represents the average percentage over time (1991-2016) of each country's production compared to the total crop production worldwide.

Paradoxically, among these products, only the prices of the relatively less water-intensive products reflect the water footprint of production, an observation that arises from the plot on the following two pages. An increase in the price of staple crops (e.g., maize and wheat) is associated with a high water footprint. Therefore, their prices reflect the amount of water used to grow them *(as shown in the scatter plot on pages 126-127)*. Staple crops are often produced in markets with relatively more competition. This trend may be explained by the fact that, in order to maximize profits, producers tend to include more input values in the final price, thus also considering the value of water.

Instead, cash crops are often produced in oligopoly situations, and large producers and traders mainly determine prices. Producers can detach price creation from the cost dynamics of specific inputs, such as water. This detachment can lead to water overexploitation and the exclusion of its value from the price.





P : Country and crop-specific deflated unit price (at purchasing power parity, PPP*) (USD/ton)
uWF : Country and crop-specific unit WF (m^3/ton)

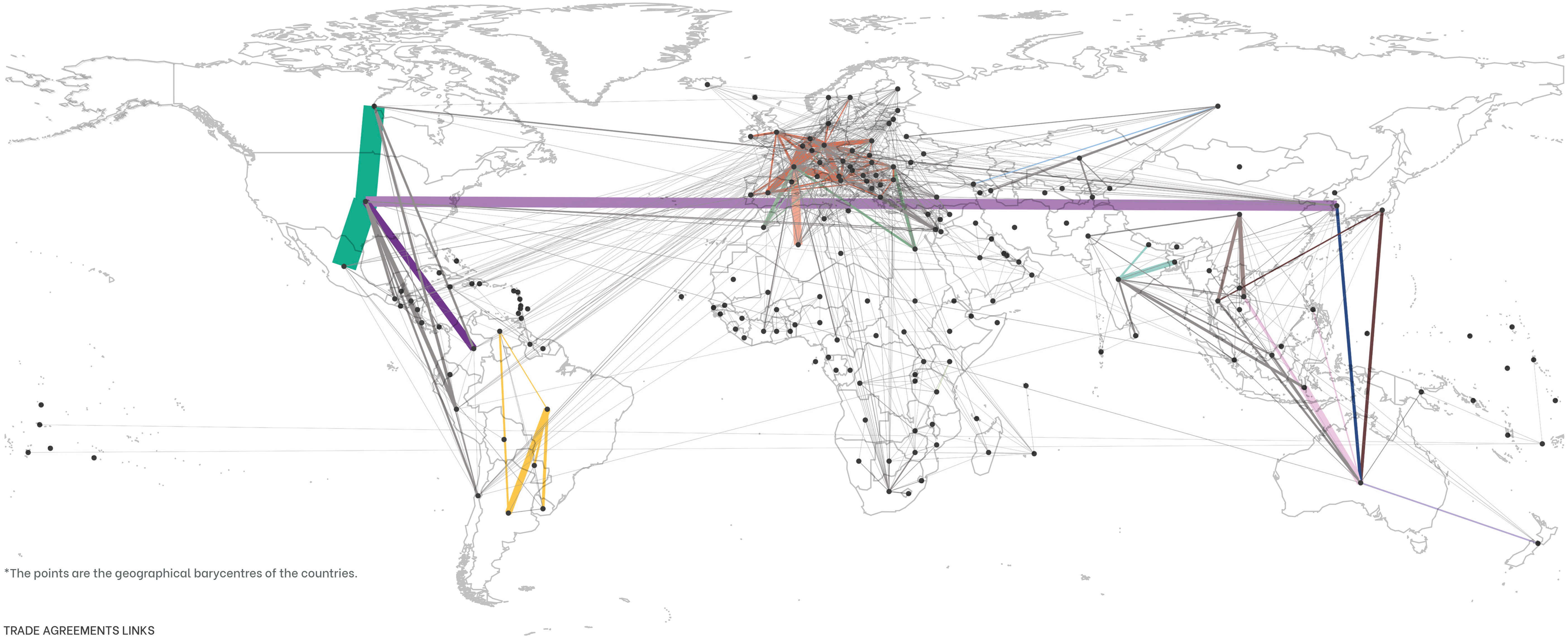
Country share over global production [%]: 10, 20, 30, 40, 50

Apple
Cocoa beans
Maize
Avocados
Coffee beans
Potatoes
Soybeans
Vanilla
Rice paddy
Tea
Wheat
Cotton seed

The influence of trade agreements

Staple crops as cereals represent the most traded items globally due to their role in diets and sustainment, thus assigning them a considerable economic value in which the water input is considered. The establishment of a trade agreement among countries favors commercial relationships that can enhance the exchange of virtual water embedded in the cereal market, thus increasing the water footprint of production in the exporting countries. In particular, among the currently present major market treaties, fourteen of them (e.g., NAFTA and USA-Rep. of Korea) catalyze 80% of the cereal flows, and more than 150 treaties regulate the remaining portion of the flow, instead. This trade can be represented as a network in which the nodes are the countries, and the links are the cereal volumes (in USD) exchanged under the establishments of trade agreements. Notice that the fact of considering only the fluxes under trade agreements entails isolating – in this network – some of the countries involved in the cereals market. In particular, among the most relevant cereals fluxes globally, the commercial relationship between the USA and China does not appear in the network because any trade agreements does not regulate it. In general, establishing a trade agreement induces an six fold increase in the probability of activating a new commercial relationship in the world cereals market.

1 • ANZCERTA: Australia New Zealand Closer Economic Agreement (Australia, and New Zeland)
2 • ASEAN: Association of Southeast Asian Nations (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam)
3 • EAEU: Eurasian Economic Union (Belarus, Kazakhstan, and Russia)
4 • EC: European Community
5 • MERCOSUR: Southern Common Market (Argentina, Brazil, Paraguay, Uruguay, Venezuela, and Bolivia)
6 • NAFTA: North American Free Trade Agreement (Canada, Mexico, and the United States)
7 • SAFTA: South Asian Free Trade Area Agreement (Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka)



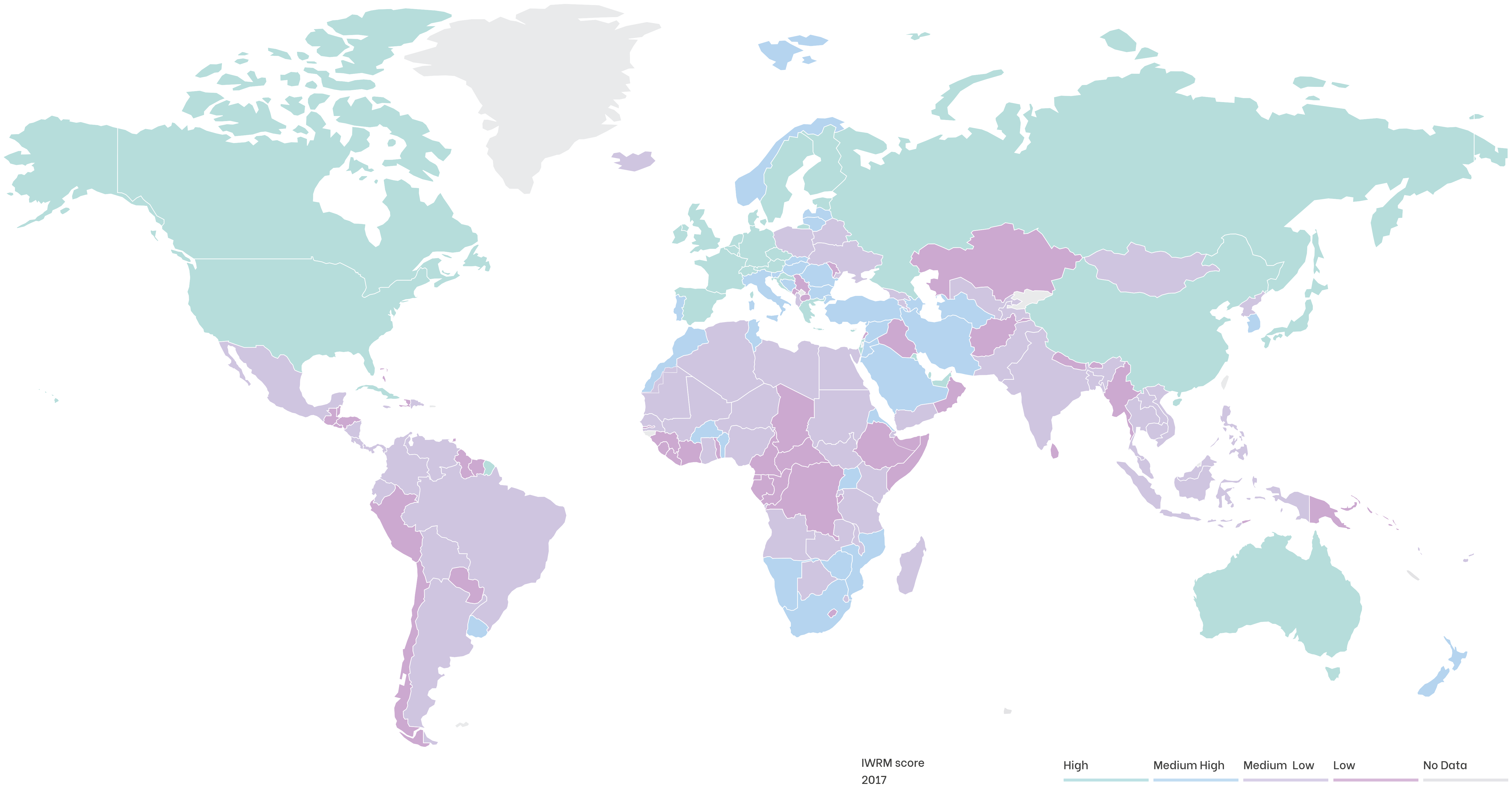
*The points are the geographical barycentres of the countries.

TRADE AGREEMENTS LINKS

NAFTA[6] | US-COLOMBIA | MERCOSUR[5] | US-Rep. of Korea | EC[4]-TREATY | EC[4]-Algeria | EC[4]-Egypt | SAFTA[7] | EAEU[3] | China-ASEAN[2] | Rep. of Korea -Australia | Japan-Australia | ASEAN-Australia New Zealand | ANZCERTA[1]

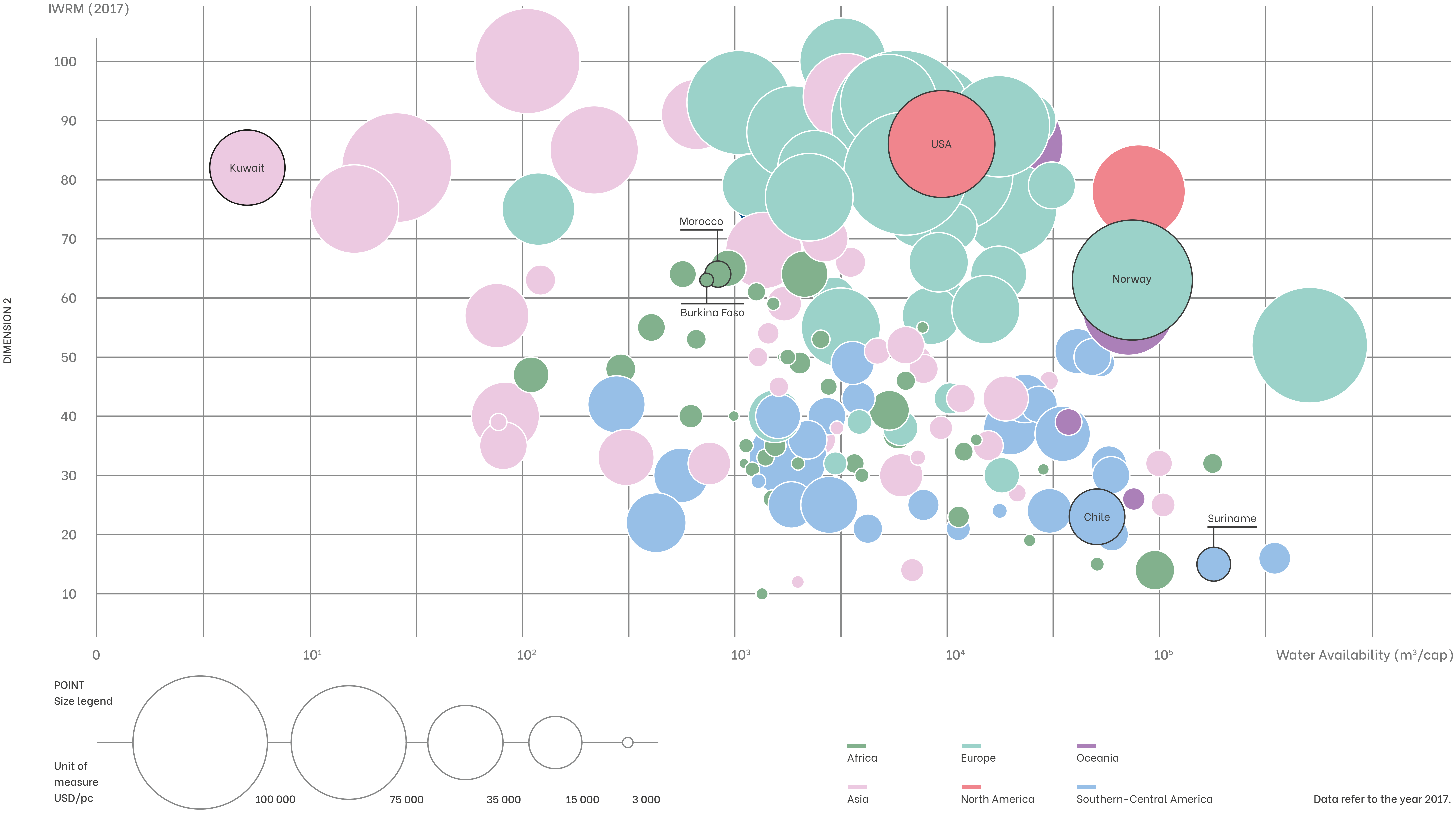
Economic and Physical water scarcity

Economic water scarcity occurs when water is available, but it is impossible to use it due to a lack of infrastructure or to socio-economic obstacles. A possible measure of economic water scarcity is the degree of implementation of Integrated Water Resource Management (IWRM). This indicator assesses whether water resources are developed, managed, and used in an equitable, sustainable, and efficient manner. The map here shows the heterogeneity of the world in managing the water resources. Large values of the index indicate low economic water scarcity. Instead, physical water scarcity can be measured as water availability during a year, and such availability might be affected by human water exploitation. Several indicators of physical water scarcity exist *(see page 180-181)*.



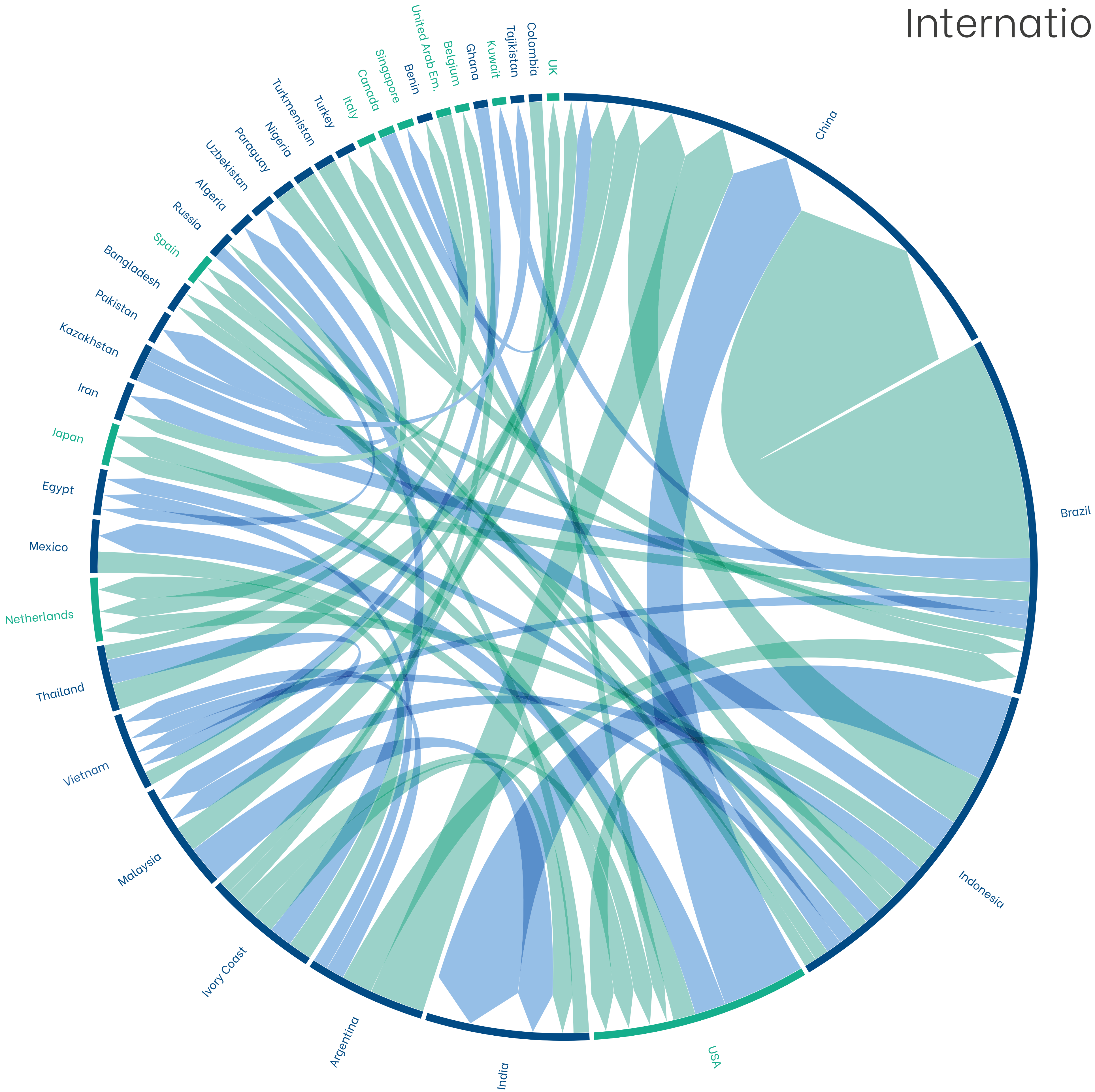
Generally, decreasing water availability is associated with increasing water management abilities necessary to cope with the scarcity of resources, and this relationship relates to the economic size of the countries. Relevant examples of this phenomenon are Kuwait, with the lowest water availability worldwide but good management skills, and Suriname, with the lowest IWRM index but high water availability.

Nevertheless, the inverse relationship between physical and economic scarcity does not hold for most high-income and water-abundant countries, such as the USA or Norway, wich have good water management skills. Some other high-income countries only show a medium level of IWRM (as Chile and Italy). Instead, low-to-middle income countries have, in general, more difficulties in boosting their IWRM. Burkina Faso and Morocco stand as relevant exceptions, recording good levels of IWRM despite their low-income situation.



Data refer to the year 2017.

SOCIETY, ECONOMICS AND GOVERNANCE



International trade of scarce water

In many cases, exports enhance water scarcity by favoring the exploitation of water resources and infrastructures. The introduction of a composite water scarcity index, merging the physical and economic water scarcity indicators, unveils the uneven redistribution of water resources through virtual water trade.

This diagram shows the top 50 largest fluxes of virtual water weighted through the composite water scarcity index. The fluxes follow the direction of the arrows, moving from exporting to importing countries. The thickness of the arrows is proportional to the exchanged virtual water volume. 39% of the virtual water traded through primary crops trade are 'unfair': they have origin in a country with higher economic and physical water scarcity than the recipient country. Often, these large unfair fluxes flow also from low to high-income countries. An iconic example is the virtual water flux from Ivory Coast to Italy, with water flowing from a more to a less water-scarce country.

Data refer to the year 2016.

HIGH-INCOME COUNTRY

LOW-TO-MIDDLE INCOME COUNTRY

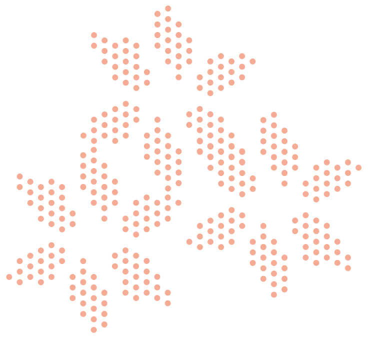
UNFAIR FLUX : The exporter suffers more from composite water scarcity than the importer.

FAIR FLUX : The exporter suffers less from composite water scarcity than the importer.

TWO PRODUCTS UNDER THE SPOTLIGHT

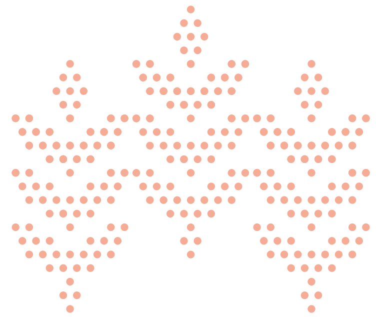
Summarizing, trade plays a crucial role in the definition of the water footprint of production in one country. Even without establishing trade agreements, or considering the environmental impact of exports, countries try to gain economic advantage from becoming relevant exportes of particular items.
Following the law of comparative advantage to explain trade dynamics, the Revealed Comparative Advantage (RCA) is an analytical tool to measure the market advantage a country gains from trading an item. The Revealed Comparative Advantage assigns a value of significance to the item-specific share of a country's export at the global level. The RCA value is defined as the ratio between two terms. The first term is the amount of dollars exported by a country through a given item compared to the worldwide value traded for that same item. The second term is the share of a country's monetary value relative to the total monetary flux of all products traded worldwide during a given year (also including non-agricultural products). Countries are considered relevant exporters of a given product if their RCA value is greater than 1, considered as the standard threshold value for revealing market advantage. From the 'water' point of view, these competition dynamics drive the trade of economically relevant products, often the more water-demanding ones.
The RCA analysis helps revealing the difference between stable and cash products, like wheat and vanilla we describe below. Per each item, and corresponding major country of production, we highlight the RCA value, the quantity of production and trade, the price per unit of the good, and the water footprint of production. For example, China invests a lot of its water resources in producing and exporting both wheat and vanilla, despite gaining a slight market advantage. The significance of vanilla as a cash crop clearly arises from Madagascar production and export's water footprint, price, and advantage.

VANILLA



Producers	**China**	**Madagascar**	**Indonesia**
Water footprint (m³/ton)	64 478	339 868	90 783
Price per unit (USD/ton)	16 912	3 412	1 708
Volume of production (tonnes)	57	292	200
Export share (% global amount of export)	0.13%	62.20%	5.19%
Revealed Comparative Advantage (RCA > 1)	0.009	3 641	4.6

WHEAT

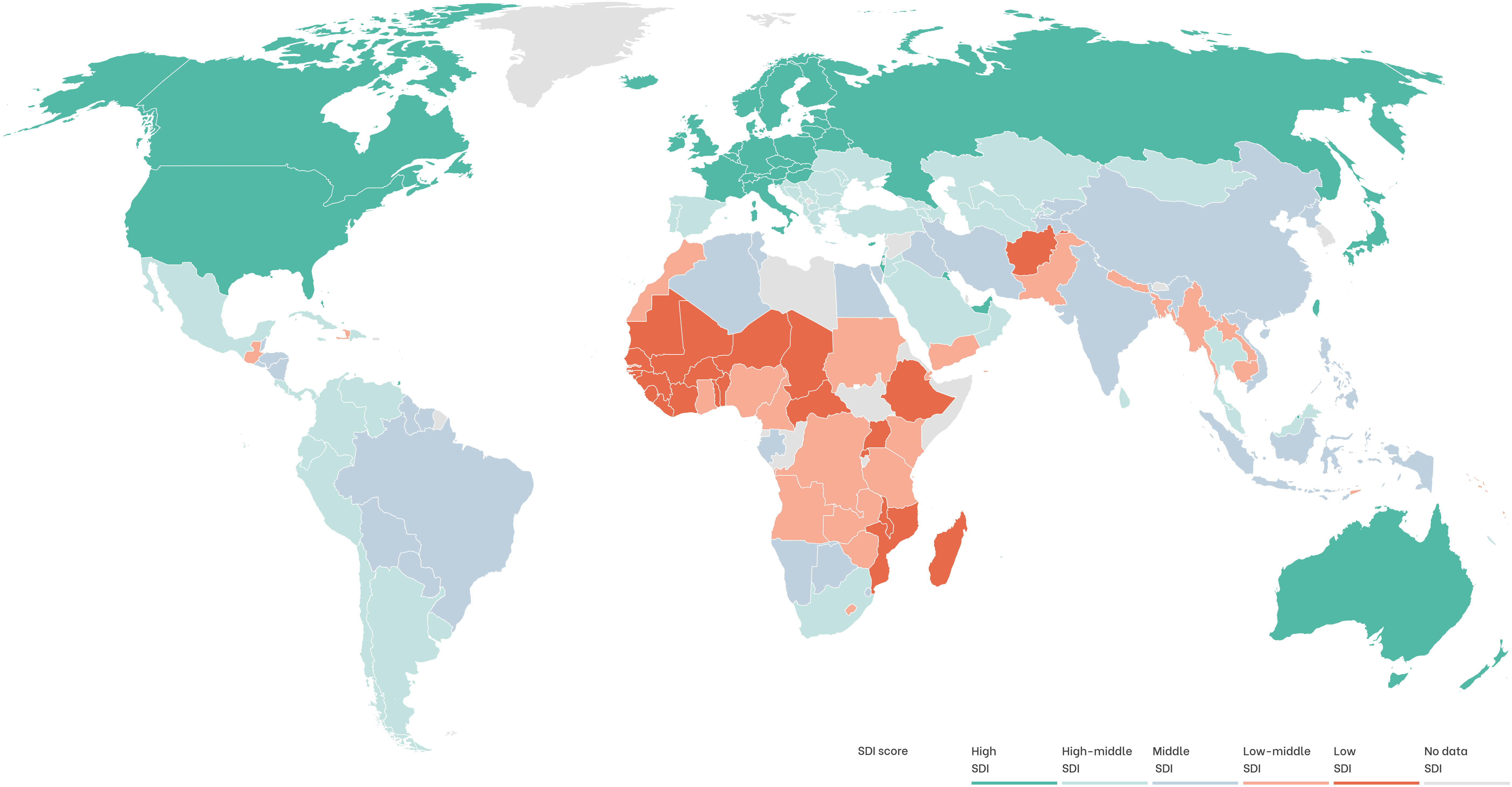


Producers	**USA**	**Brazil**	**China**
Water footprint (m³/ton)	479	881	723
Price per unit (USD/ton)	130	227	602
Volume of production (tonnes)	34 548 634	8 528 307	26 499 200
Export share (% global amount of export)	30.60%	17.50%	0.03%
Revealed Comparative Advantage (RCA > 1)	3.42	13.62	0.0017

Mapping the drivers of food habits

Socio-economic dynamics such as education, fertility rate, population dynamics, and per capita income have helped shape dietary habits worldwide. The availability of a food item in a country thanks to the international trade

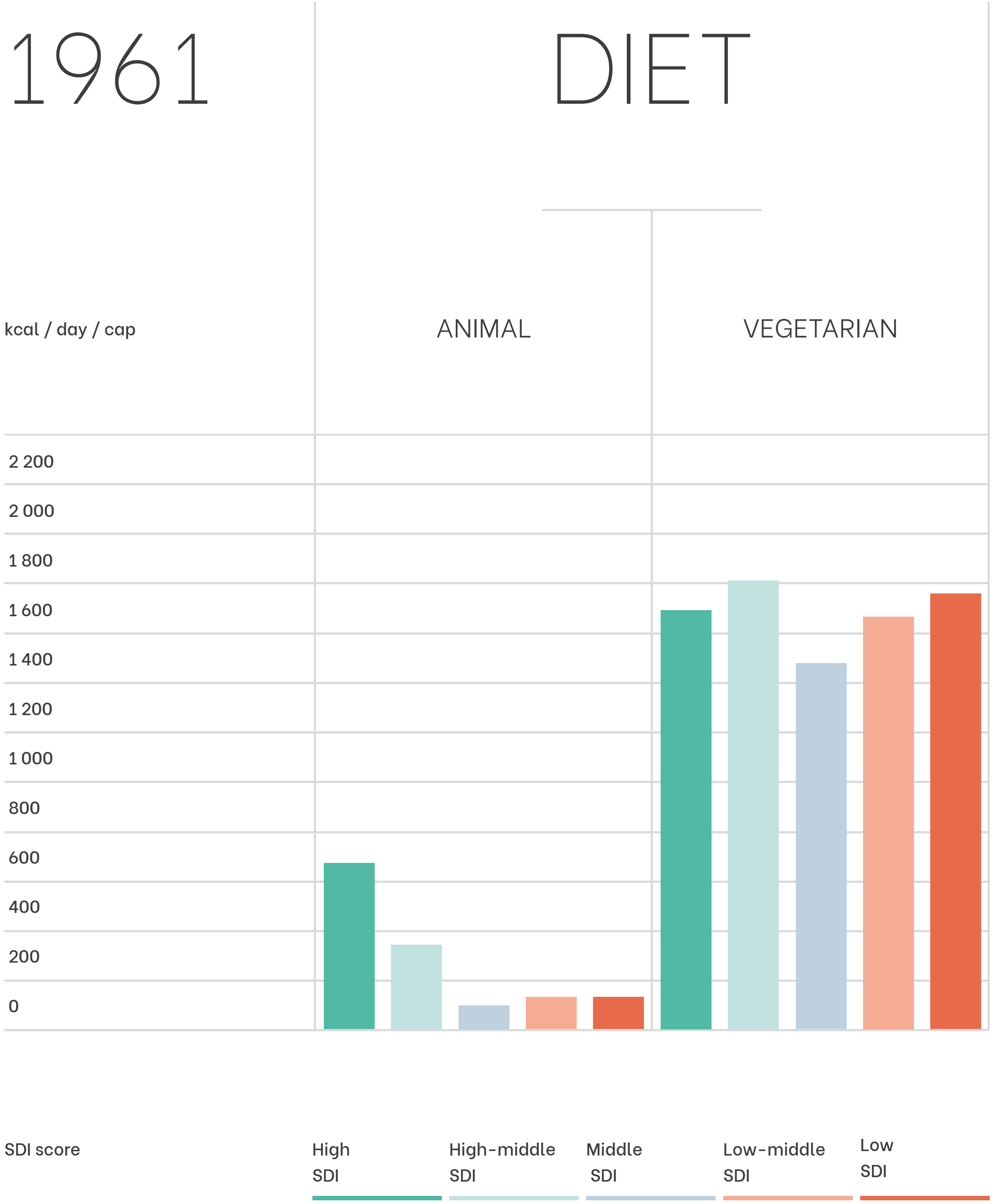
The Socio-Demographic Index, SDI, combines all those socio-economic variables to identify clusters of countries set in similar contexts, grouping countries in 5 classes of development, from high to low SDI. These groups can help illustrate common changes in diets across the world.

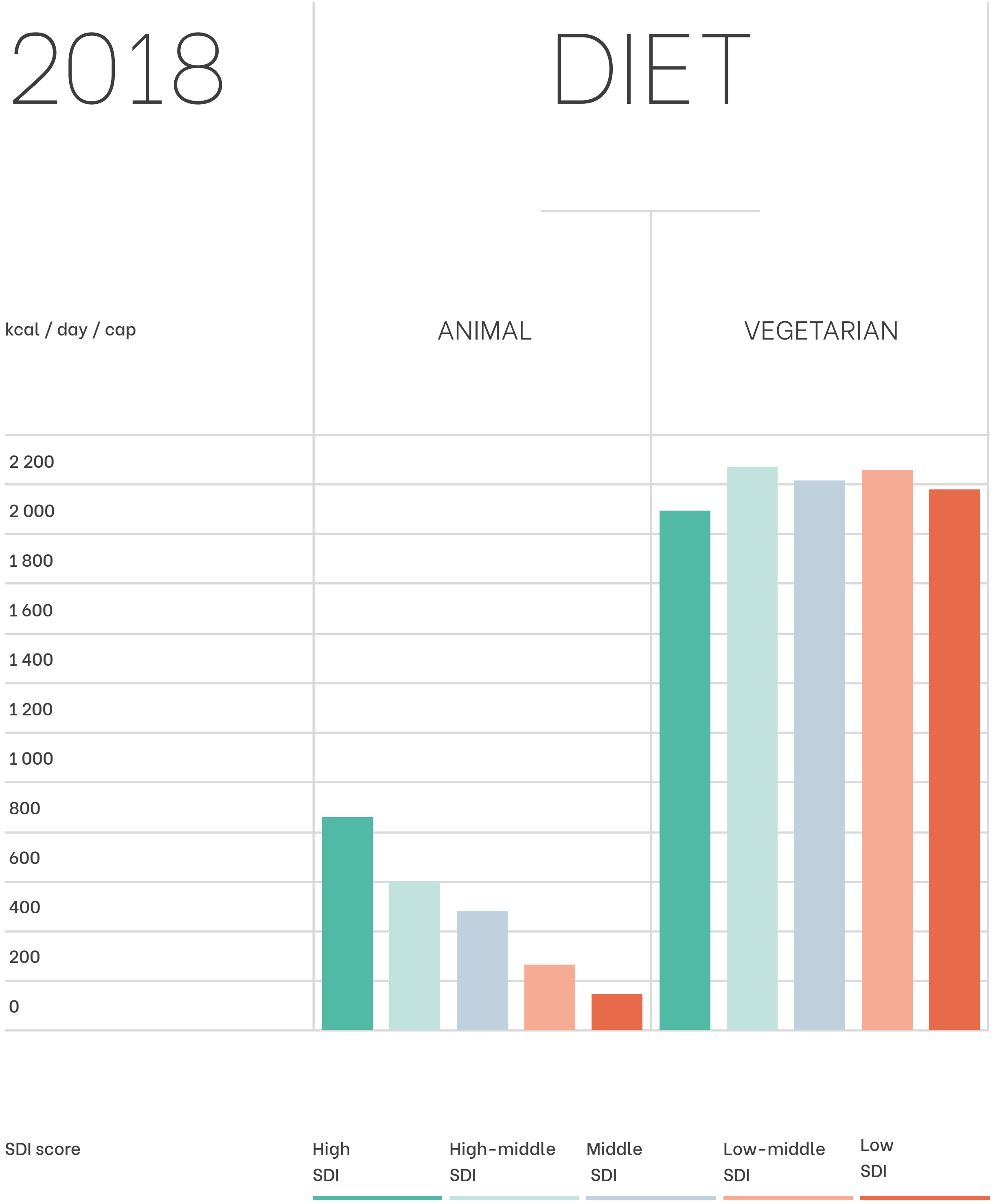


The food we ate yesterday, The food we eat today

From 1961 to 2018, the world has seen an increasing consumption of crop products. In the last 60 years, the consumption of animal products has nearly doubled in high-middle SDI countries (from 250 kcal/day to 500 kcal/day), and it has seen an eightfold increase in middle SDI countries (from 50 kcal/day to 400 kcal/day).

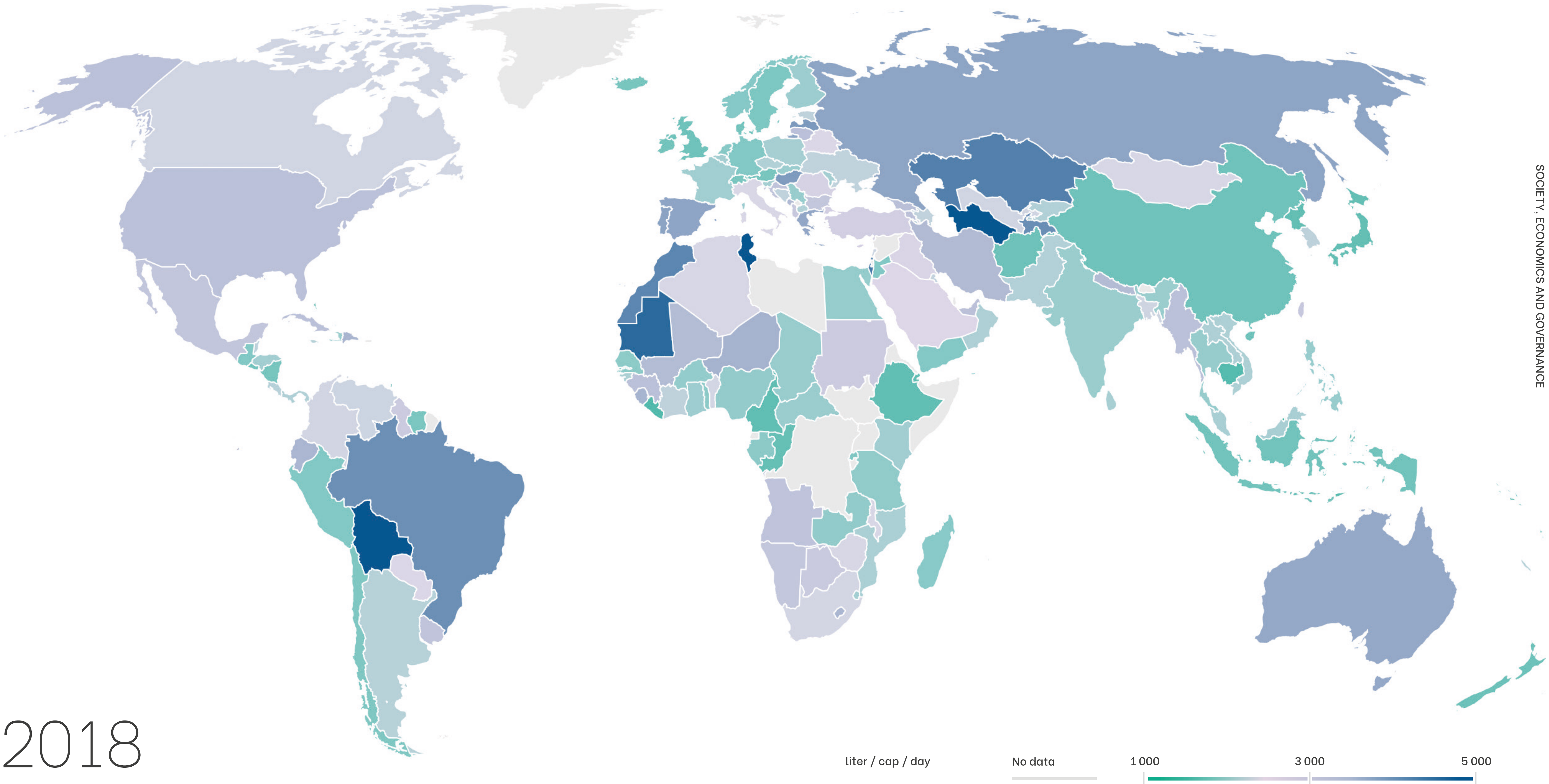
Conversely, across low SDI countries, the consumption of animal-based products has not changed, on average. For the consumption of vegetarian products, a significant increase can be observed for all the SDI groups. This growth can relate to two significant changes in food habits. The first factor is the increased caloric intake that occurred in the past decades, with proven health consequences in some high-income countries. The second factor pertains to increased food waste at the household level.





HOW DO OUR DIETS SHAPE OUR DAILY WATER FOOTPRINT?

Throughout the past 50 years, our food habits have changed, and so did the water footprint of our consumption. Most of the world shifted from a low to a high water-intensive diet due to increased consumption of animal products. Nevertheless, the daily water footprint of an average citizen of the countries in this map is the synthesis of the complexity of the food system. These values depend on the citizen's dietary habits, and the water-use efficiency of domestic and foreign production, which are related through trade dynamics.



2018

The eat-lancet diet for human health and sustainable production

Diets define an inextricable link between human health and environmental sustainability. In light of this relation, the Eat-Lancet commission provided guidelines on the specific daily intake of main dietary food groups targeting the preservation of the environment and human health (other similar guidelines include the Mediterranean and New-Nordic diets). The ranges of the group-specific calories intake are wide enough to consider the world's cultural, religious, and social heterogeneity driving food consumption.

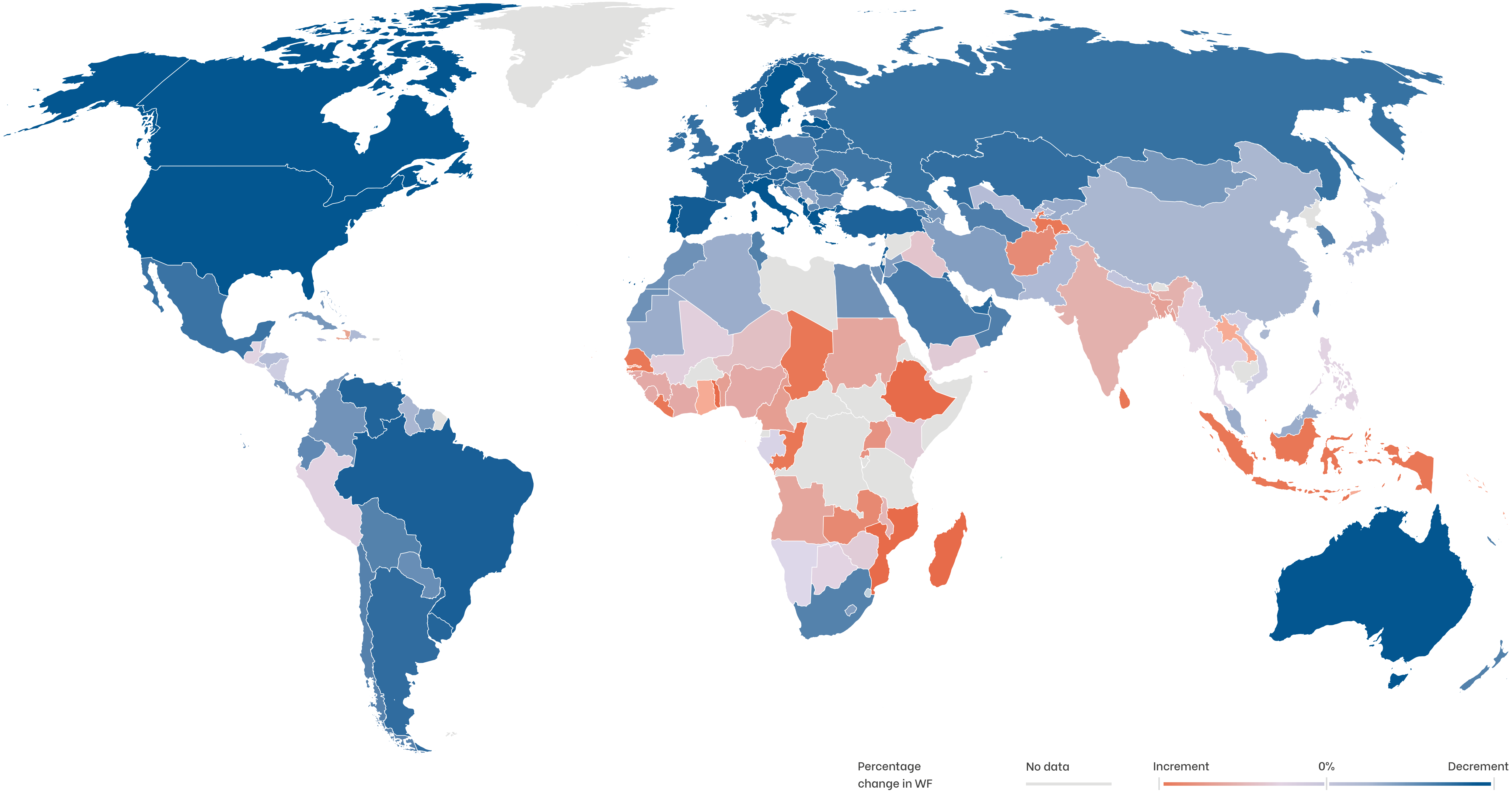
Food group	Food subgroup	Reference diet (g/day)	Possible ranges (g/day)
Whole Grains	All grains	232	0 to 60% of energy*
Tubers/Starchy Vegetables	Potatoes, cassava	50	0 to 100
Vegetables	All vegetables	300	200 to 600
Fruits	All Fruits	200	100 to 300
Dairy Foods	Dairy Foods	250	0 to 500
	Beef, lamb, pork	14	0 to 28
Protein Sources	Chicken, other poultry	29	0 to 58
	Eggs	13	0 to 25
	Fish	28	0 to 100
	Dry beans, lentils, peas	50	0 to 100
	Soy	25	0 to 50
	Nuts	50	0 to 75
Added fats	Unsaturated oils	40	20 to 80
Added sugars	All sweeteners	31	0 to 31

*Mix and amount of grains can vary to maintain isocaloric intake.

WHAT IF THE WORLD ADOPTS THE EAT-LANCET DIET?

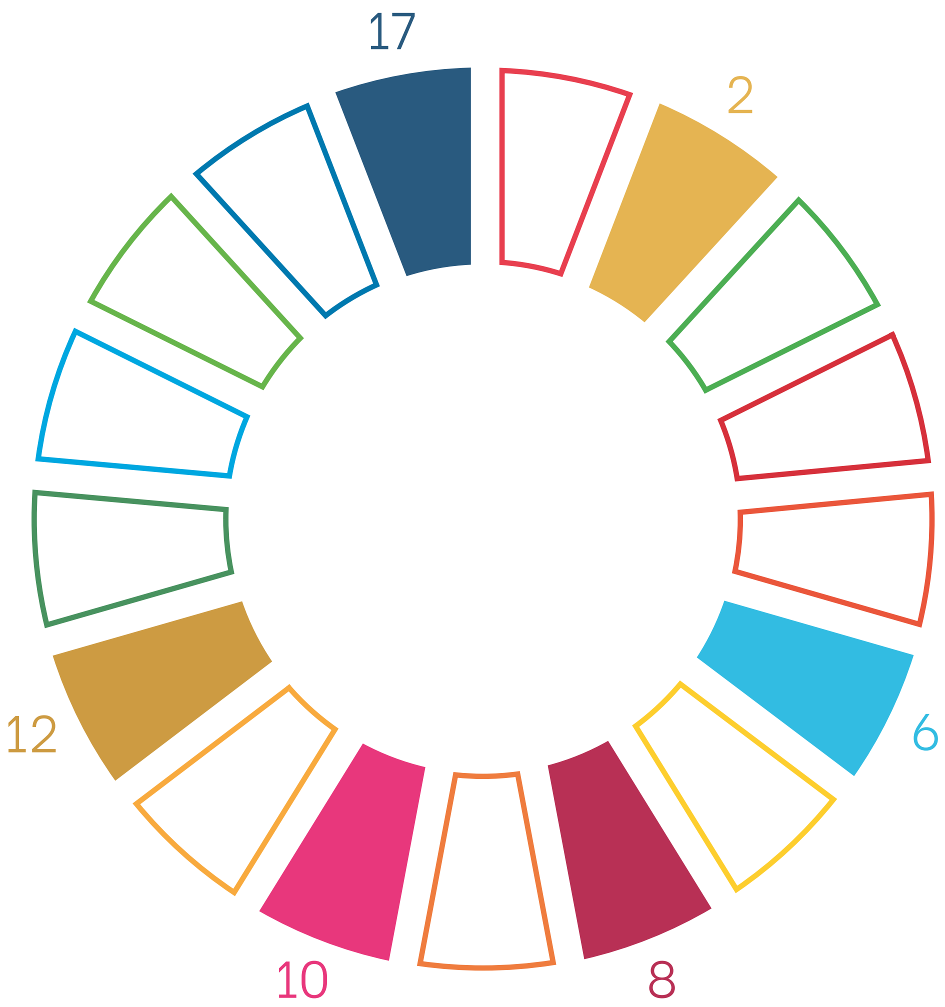
If all countries would adopt the healthy reference diet from the EAT-Lancet commission, the global water footprint could be cut by 12% compared to the current value. The most significant per-capita reductions (>50%) would happen in Israel, Hong Kong, the USA, Greece, and Australia, thanks to the decrease in consumption of the most water-intensive foods *(see pages 54-55 and 60-61)*.

In 55 countries (nearly 40% of the global population), the transition would increase dietary WF, mainly in Sub-Saharan Africa and South Asia. The largest gains in WF volumes (per-capita changes shown in the figure multiplied by the country population) would happen in India, Indonesia, and Nigeria. In per capita terms, each inhabitant would increase its dietary WF by 430-844 liter a day. In Tajikistan, Sri Lanka, and Chad, the daily per capita dietary WF would double. Globally, the heterogeneous patterns across countries demonstrate the critical role that food trade may have in the future in redistributing water resources from the bluish to the reddish countries.



DIMENSION 3

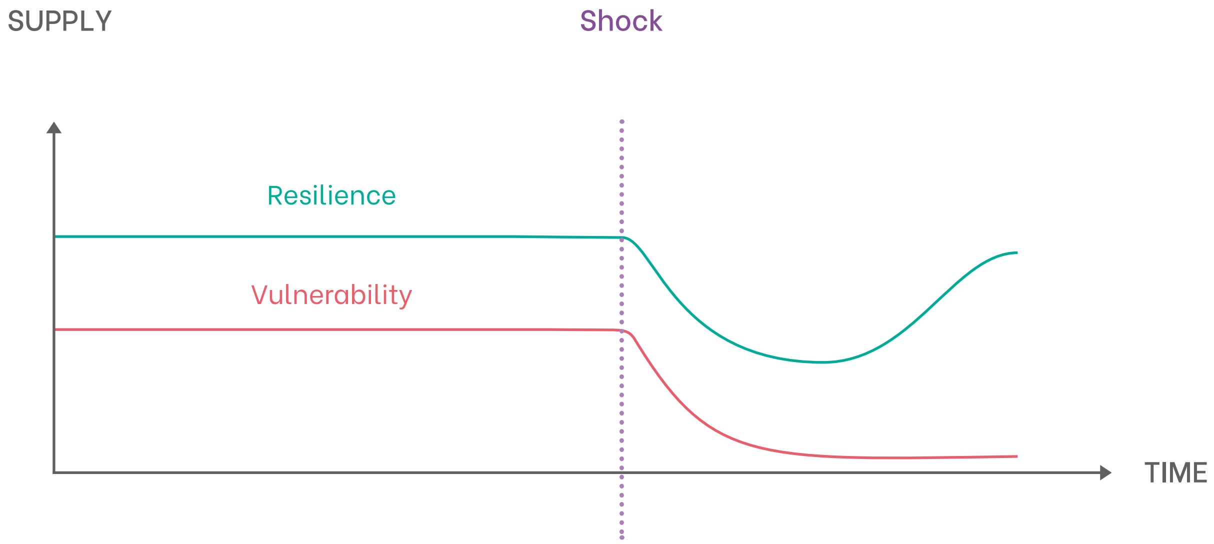
GOAL 2: Zero Hunger
GOAL 6: Clean Water and Sanitation
GOAL 8: Decent Work and Economic Growth
GOAL 10: Reduced Inequalities
GOAL 12: Responsible Consumption and Production
GOAL 17: Partnerships for the Goals



RESILIENCE AND VULNERABILITY

Resilience and vulnerability

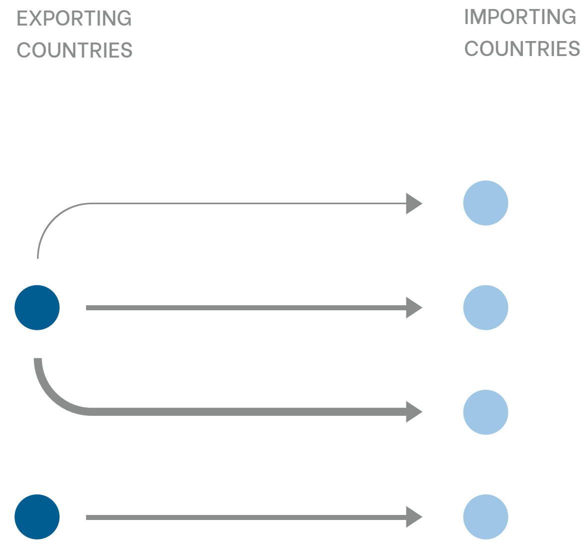
Due to the globalization of resources as governed by trade, the dynamics of countries are highly entangled and interconnected. Many countries rely on imports for meeting their local demand for food, thus ensuring national food security. Nevertheless, this is just one side of the coin: when a crisis occurs in one part of the globe, its effects are spread worldwide due to the commercial relationships. This fact also determines the vulnerability of countries to induced shocks, which is proportional to their dependency on import resources. Nevertheless, not all countries have the same abilities to recover from a crisis, and their resilience depends on several factors (e.g., income and Gross Domestic Product, volumes of imports). Two case scenarios can be used to exemplify the effects of trade-induced shocks. In case A, countries have similar economic conditions (same size of nodes), and a given shock creates an impact proportional to countries' dependency on import volumes: the larger the volume imported, the larger the shock. Instead, in case B the differences in countries' economy sizes are considered (nodes' size is proportional to GDP per capita): the larger of the country's economy, the higher the country's resilience to the crisis.
Studying the resilience and vulnerability of crisis helps define support mechanisms for guaranteeing food security in case of changes in supply.



INITIAL SITUATION

Trade shocks have larger impact on bigger importers: these countries are more vulnerable.

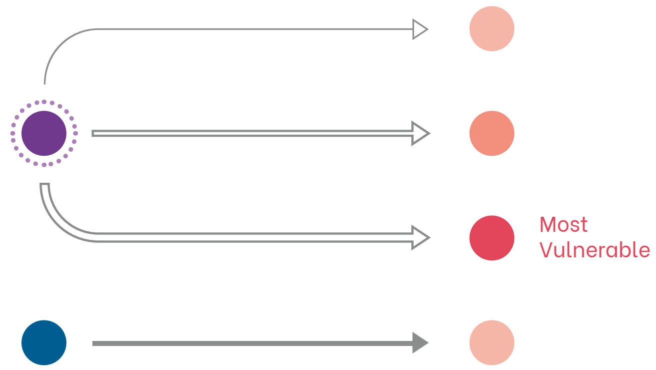
Trade shocks have larger impact on smaller economies (GDP per capita): these countries are less resilient.



CASE A

All import coutries have the same economic size.

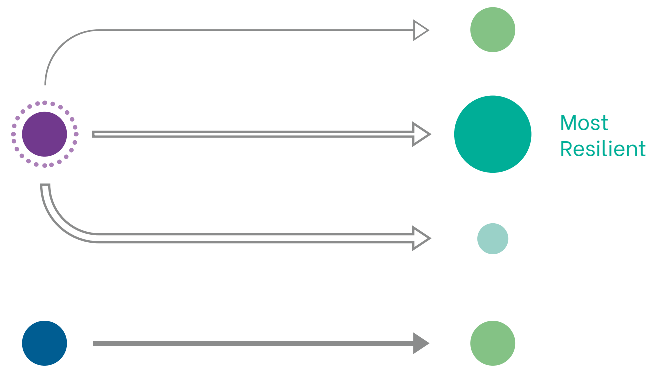
- Countries
- Trade shock
- Vulnerable country



CASE B

Import coutries have different economic size.

- Countries
- Trade shock
- Resilient country



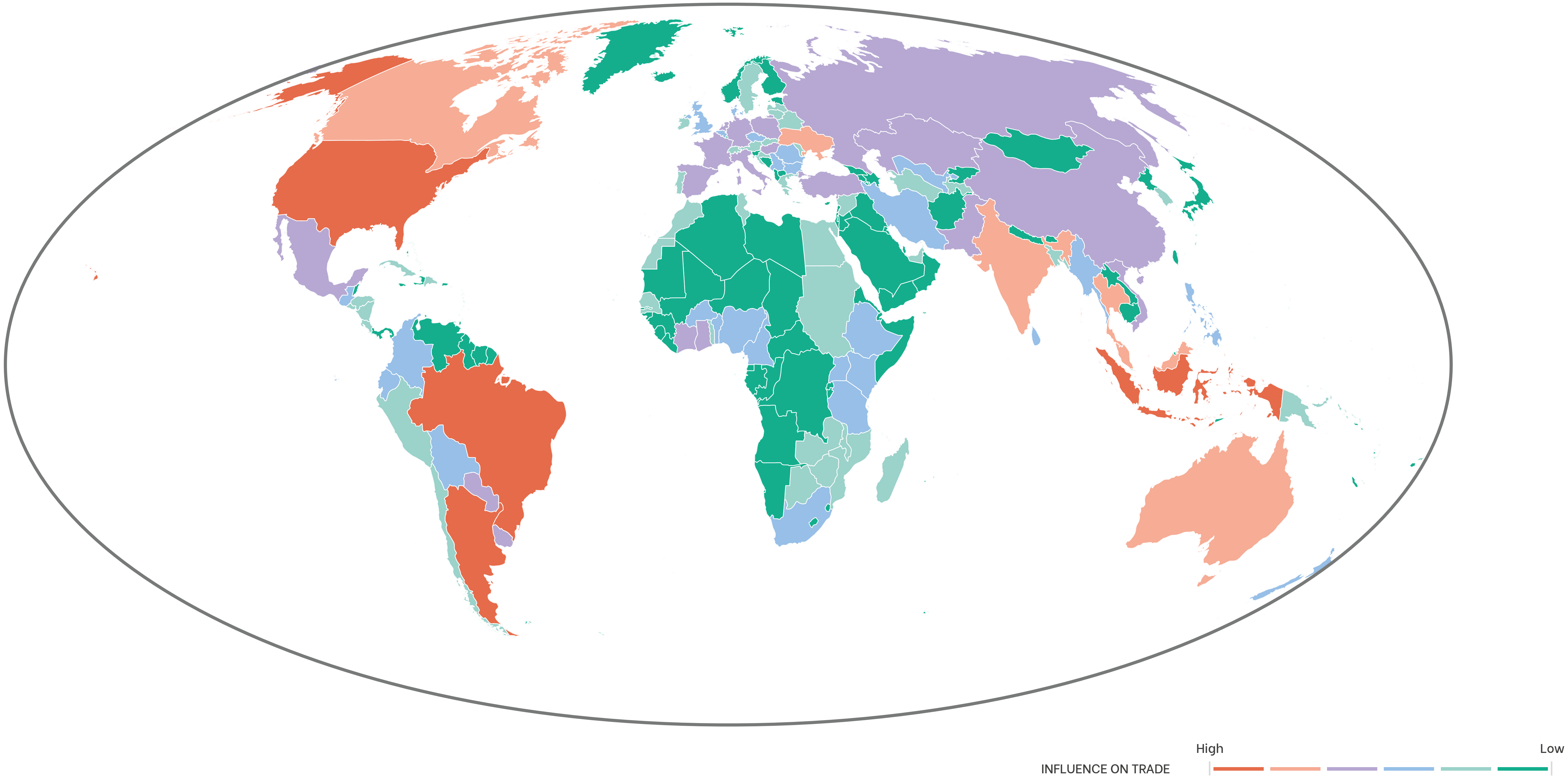
Your trade partners matter: impact

Local food-production crises, generating from social, economic, or environmental conditions, may propagate in the international trade network. The propagation determines changes in the virtual water trade and it perturbs the local and global food availability (again measurable in terms of virtual water).

Due to political and commercial reasons, crises generate different propagation dynamics over the trade network according to the country of origin. In fact, the propagation dynamics depend on the trade partners and the amount of supply it supports. Therefore, any country hit by a crisis generates a diverse impact on the food-water availability of its trading partners. This impact is measurable considering the percentage of reduction in virtual water volumes embedded in aviable food induced in the whole trade network system.

The heterogeneity of these impacts and propagation dynamics can be shown by assuming, per each country, the same crisis, thus considering that all countries could be hit by the same percentage of decrease in virtual water and food production.

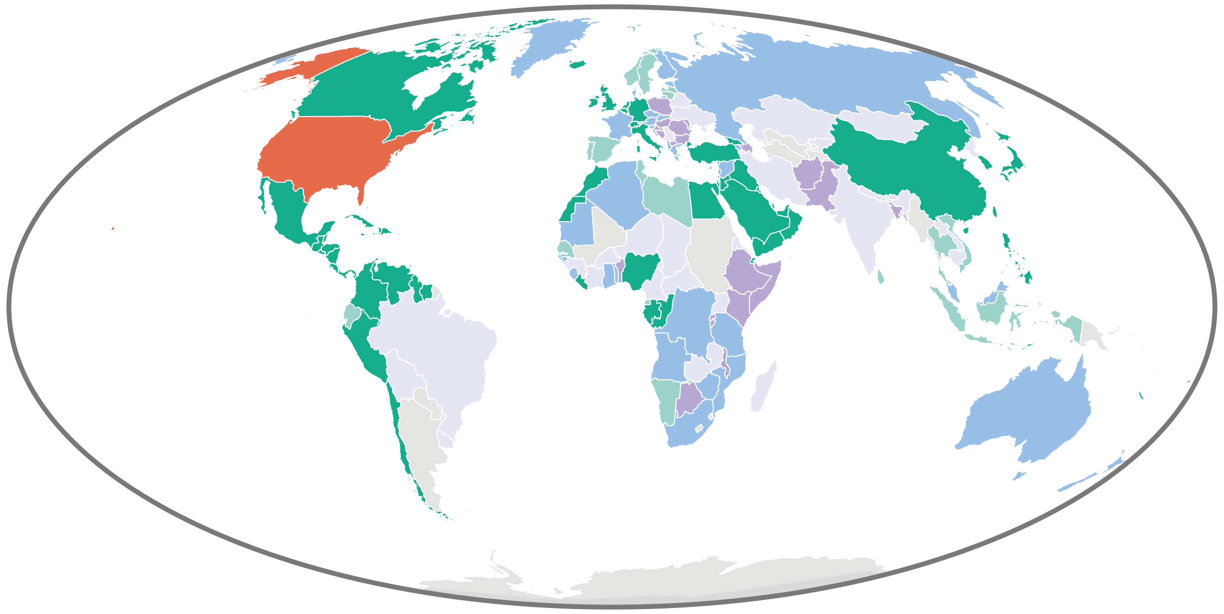
This map shows the most and least influential countries in terms of the impact they generate in the trade networks assuming a crisis of 30% reduction in production. Due to its leading role in the virtual water trade, a crisis hitting the USA determines an import reduction almost everywhere (high influence). The same spillover effects would happen if a shock hits Brazil due to its role as a relevant food (and virtual water) exporter. European countries would have a relatively lower influence on the rest of the world, while African and Middle Eastern countries would have the smallest one.



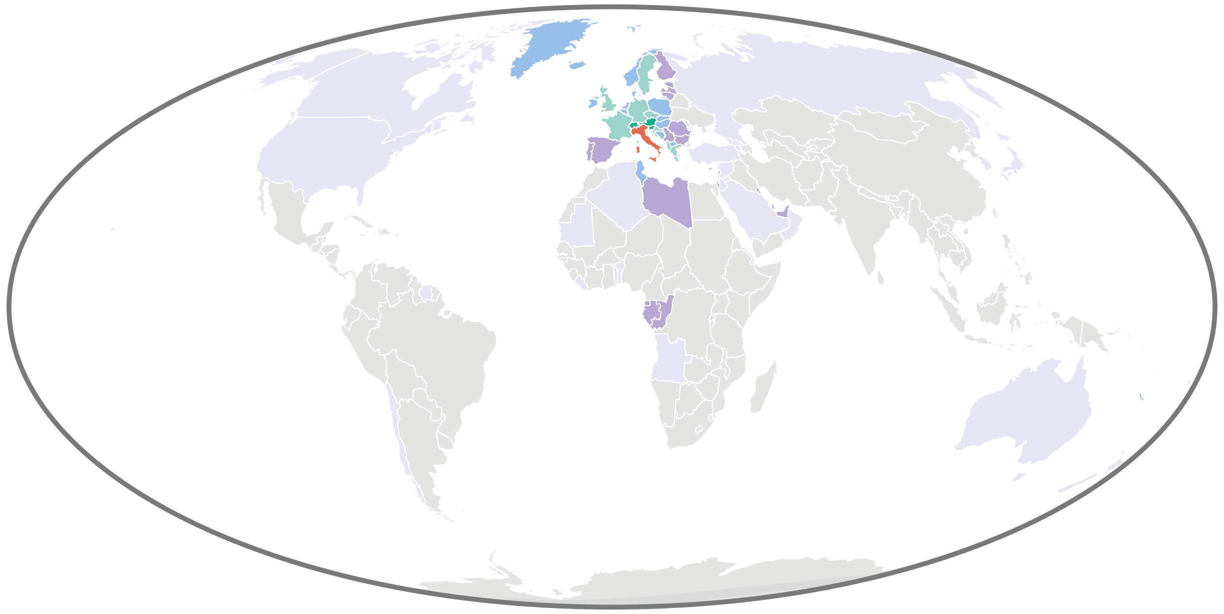
COUNTRY-SPECIFIC IMPACTS

From left to right, top to bottom, these four case scenarios assume different origins for a 30% reduction crisis: the USA, Italy, South Africa, and Japan. A crisis in the USA spreads more than one from Japan due to the structure of their commercial relationships (trade network structure).

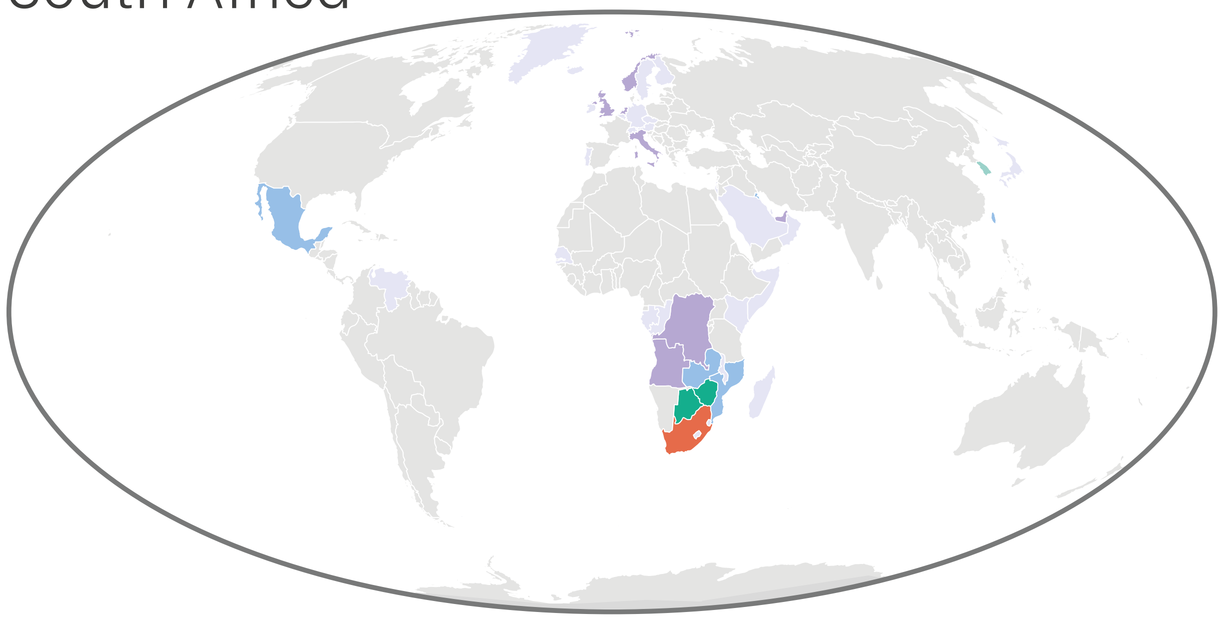
USA



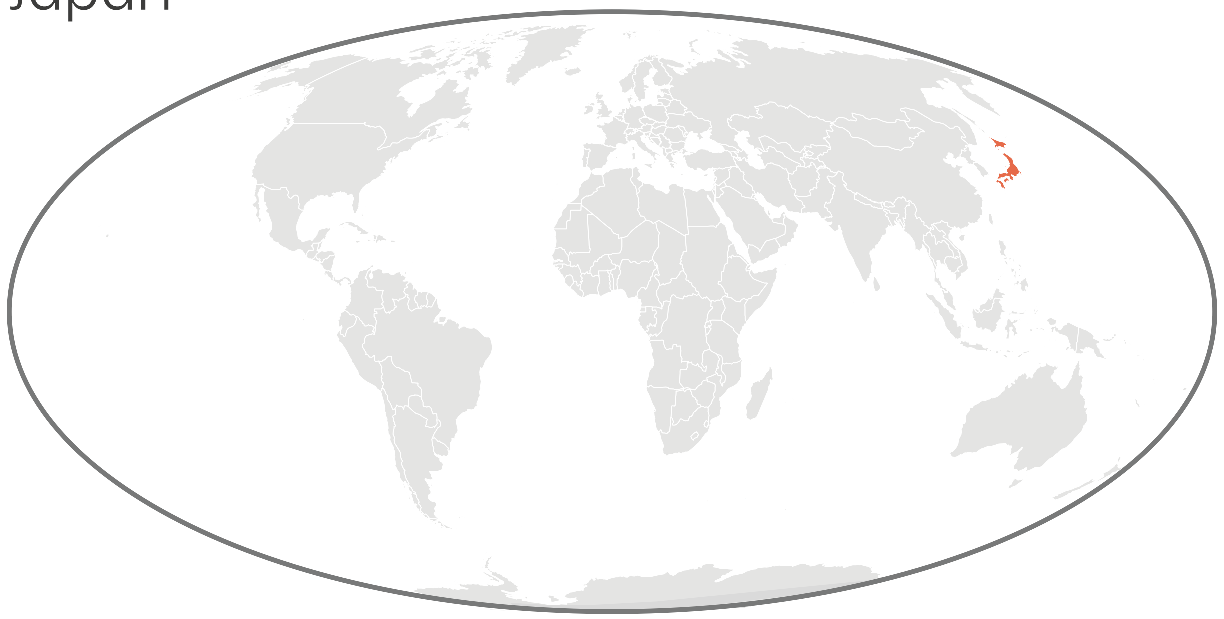
Italy



South Africa



Japan



Country where the crisis originated from ●

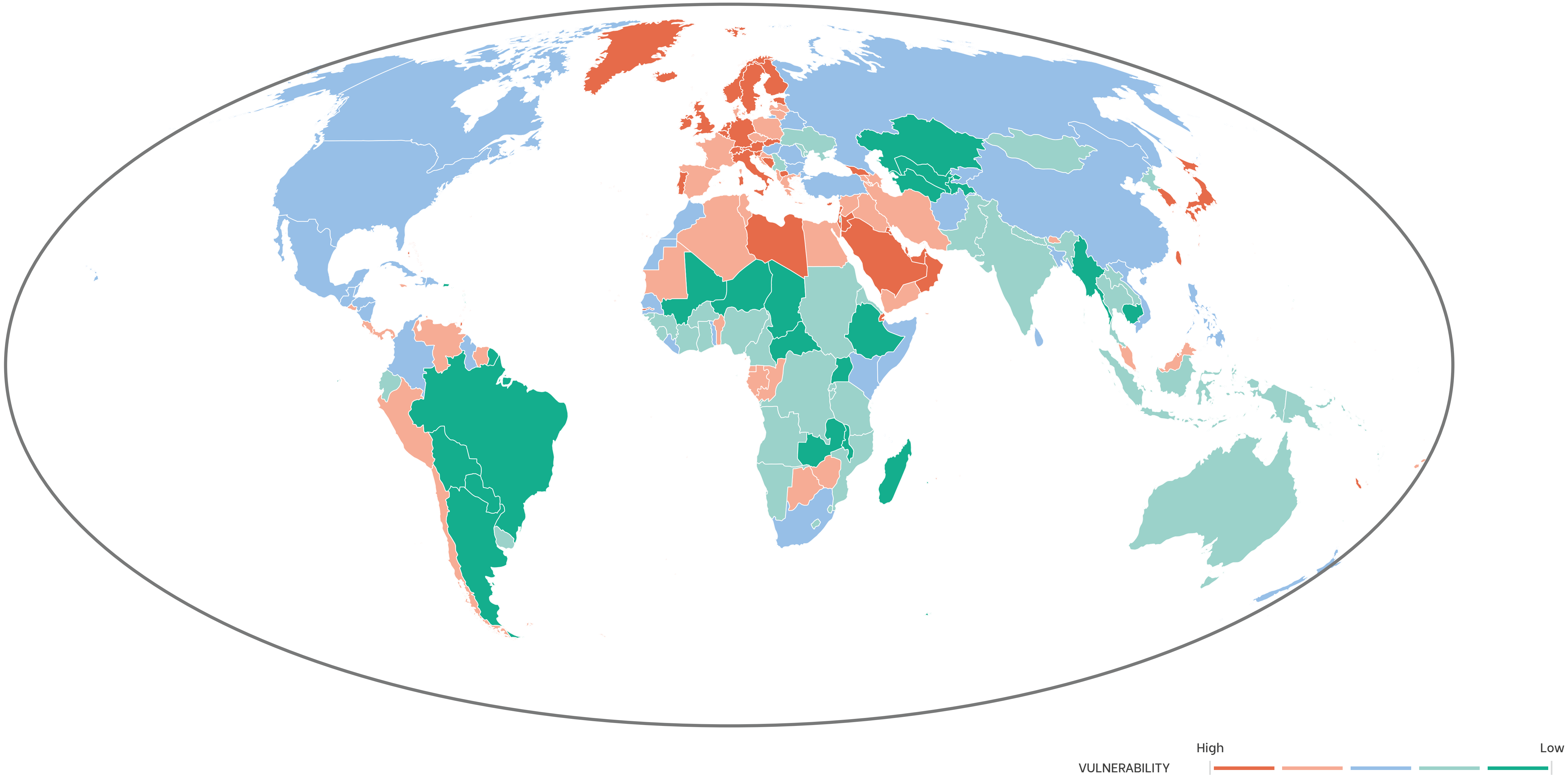
IMPACTS High — Low

Your trade partners matter: vulnerability

While, on the one hand, the impact measures how a crisis of a country influences the food-water availability of its trading partners, on the other hand, the vulnerability measures the country's exposure to food-production crises happening elsewhere and propagating in the global trade network.

The more a country relies on the international food trade network to ensure national food security (also corresponding to dependency on external water resources), the larger its vulnerability to crises occurring elsewhere.

A country's vulnerability is measurable considering the total percentage of reduction in its virtual water flows as induced by assuming that all its trading partners undergo a trade shock. A country's vulnerability depends on its capability to cope with the reduction of imports through internal production and the number and characteristics of its trading partners (due to their capacities to generate trade shocks and induced impacts).

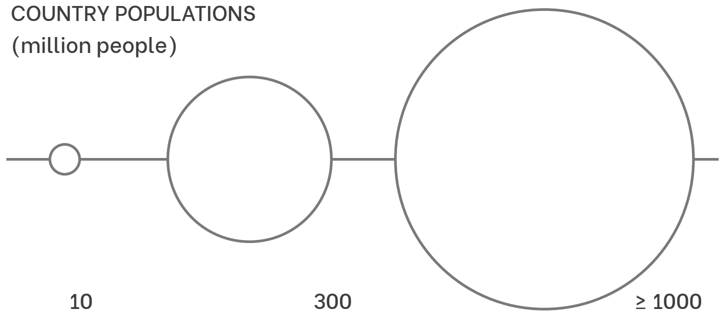


COUNTERBALANCING IMPACT AND VULNERABILITY

The two facets of countries' roles in the trade system, namely their vulnerability and generated impacts, are scattered and compared in this bubble chart. For a more extensive outlook on these two characteristics, countries' socio-economic size is considered. In fact, crises-related impacts and vulnerability of countries also change according to population and Gross Domestic Product (GDP) in a non-trivial way.

Generally, less populated countries have a small impact and higher vulnerability. From a country's wealth perspective, wealthier countries are more vulnerable to external crises. Conversely, less wealthy countries are also generally characterized by lower stability, thus showing a higher propensity to originate socio-economic crises. Therefore, low-wealth countries may generate more significant impacts on the trade. Examples are India, Pakistan, Vietnam, and Nigeria (to mention the largest ones).

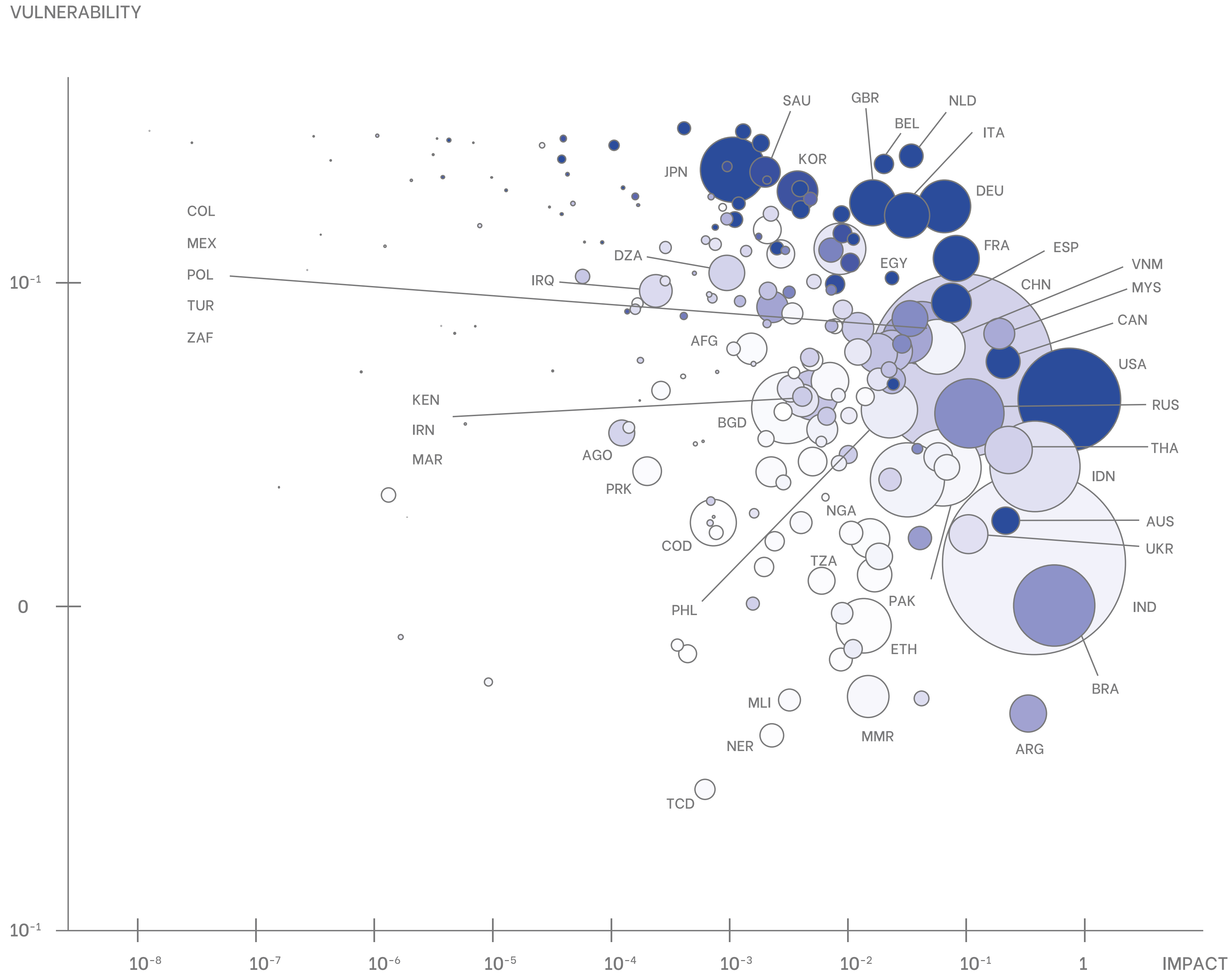
COUNTRY POPULATIONS
(million people)



Colors scale according to the per-capita Gross Domestic Products of countries (USD/cap/year)

0 3000

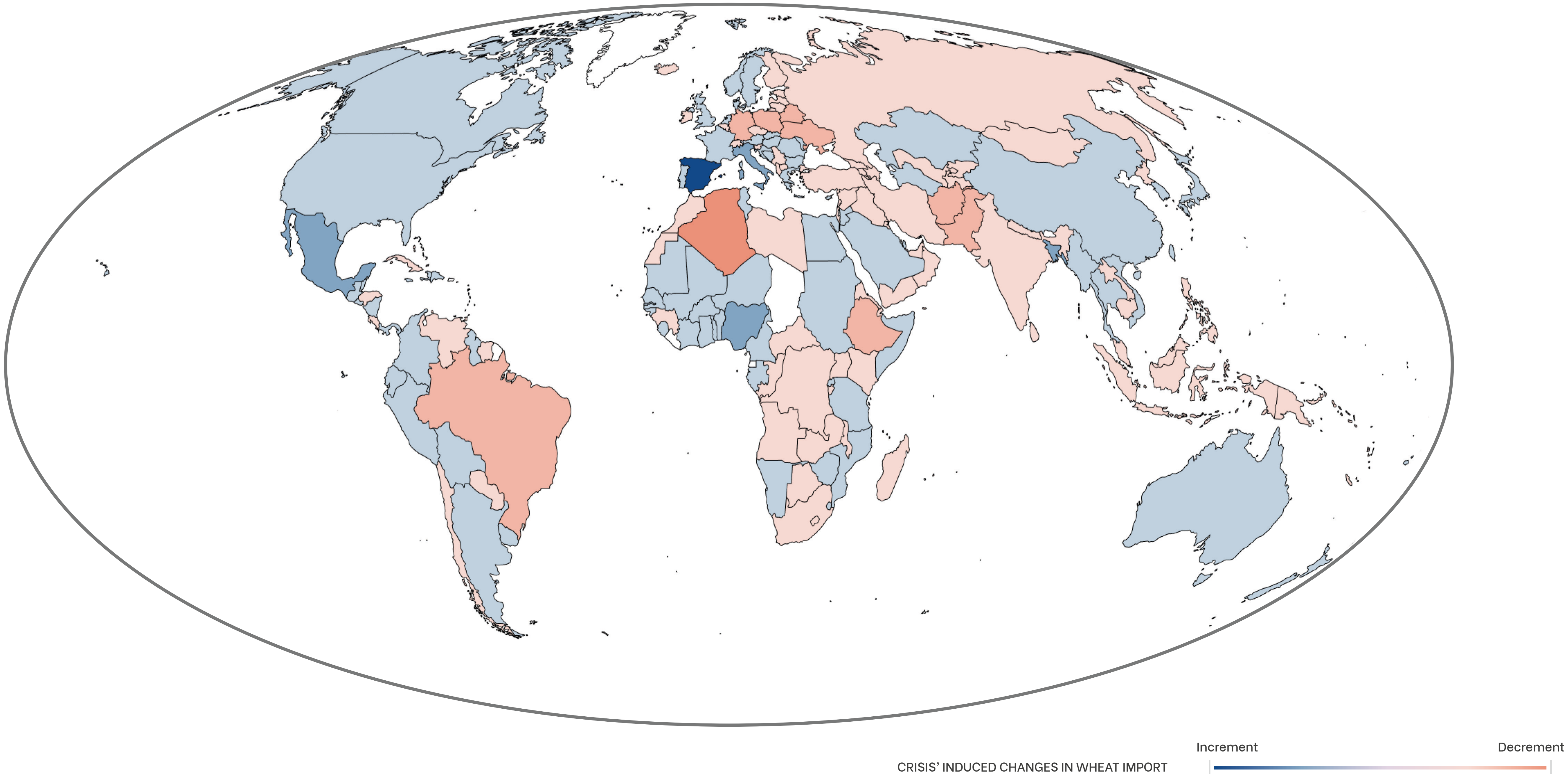
Generally, less populated countries have a small impact and higher vulnerability. From a country's wealth perspective, wealthier countries are more vulnerable to external crises. Conversely, less wealthy countries are also generally characterized by lower stability, thus showing a higher propensity to originate socio-economic crises. Therefore, low-wealth countries may generate more significant impacts on the trade. Examples are India, Pakistan, Vietnam, and Nigeria (to mention the largest ones).



Your trade partners matter: The effects of the 2000–2001 global crisis on food security

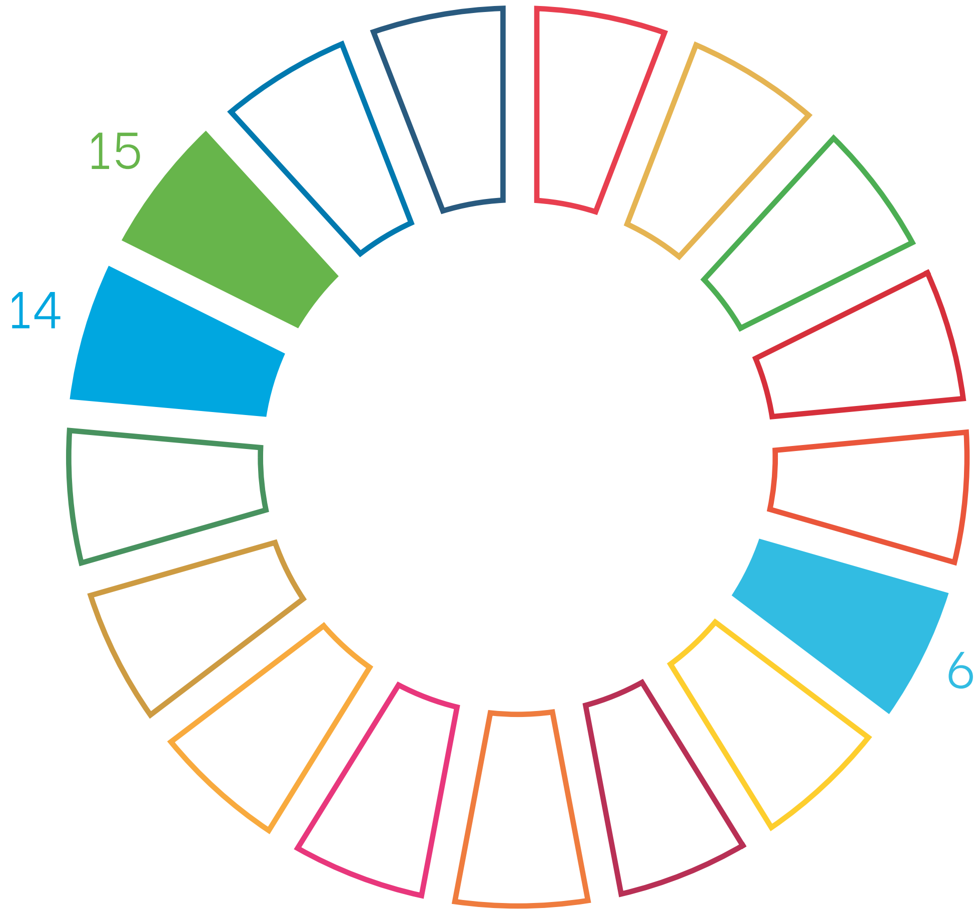
A decrement in food supply because of a shock mines a country's food security, especially in emerging countries, thus harshening already challenging socio-economics conditions. In particular, the per-capita income of importing countries is relevant in shock propagation since income levels determine the food purchasing power of citizens. At the same time, the economic size of a country is also relevant in determining the commercial relationship, as driven by trade agreements and competition dynamics.

The map shows the changes in wheat supply as triggered by the 2000 economic global crisis. Most African countries, like Ethiopia, saw a dramatic decrease in the import of wheat, thus determining a reduction in food security.



DIMENSION 4

GOAL 6: Clean Water and Sanitation
GOAL 14: Life below Water
GOAL 15: Life on Land



ENVIRONMENTAL IMPACT

Environmental impact

Until this point, we have told the story from the human perspective, highlighting the role of water resources in food production and food security. However, as already briefly introduced, the Water Footprint of food production aims to measure how the exploitation of resources impacts the environment and, thus, other living beings beyond humankind.

Considering all the freshwater available at the global level, freshwater use amounts to 10% of the maximum available renewable freshwater resources and 30% of the rainfall stored in soil and vegetation. Instead, at the local scale, agricultural production can lead to overexploitation of available water resources, possibly generating situations of water stress and scarcity *(see page 130 –131)*, and compromising the natural flow of water resources required for the sustainment of the ecosystems.

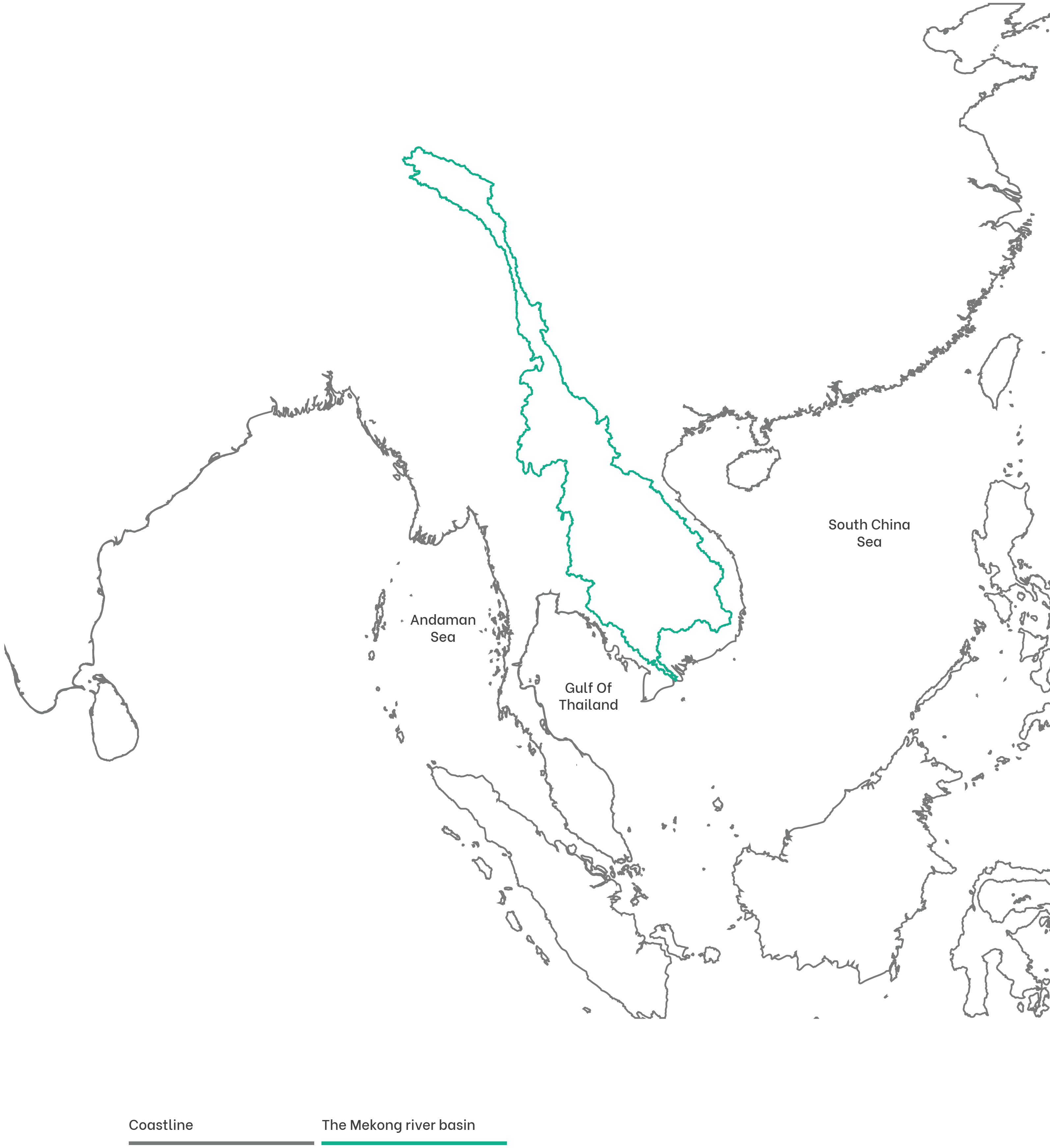
The impact on the environmental systems induced by food production can be measured by either quantifying the rate of withdrawal with respect to the natural abilities of the water system to replenish; or quantifying the loss in water flows necessary for the sustainment of the ecosystems.

The results in this chapter show iconic examples of water use for crop production and their impacts on local and global water resources.

Lost lives in the Mekong river basin

The Millennium Ecosystem Assessment (published in the year 2005) stated that freshwater ecosystems have been deteriorating consistently and faster than other ecosystems. In fact, the freshwater species declined on average by 50% between 1970 and 2000, compared to an average decline of 30% for both terrestrial and marine species over the same period. Moreover, aquatic habitats, associated with 65% of global river discharge, were classified as under moderate to high threat.
Rising water withdrawals have been pointed out as the principal cause of increasing water stress on many river basins worldwide. In several regions, the growing water withdrawals are expected to have more consequences on fluvial ecosystems than climate change. A relevant example of surface water exploitation is the one happening in East Asia, in the Mekong River Basin.

THE MEKONG RIVER BASIN



SHARED RESPONSIBILITIES

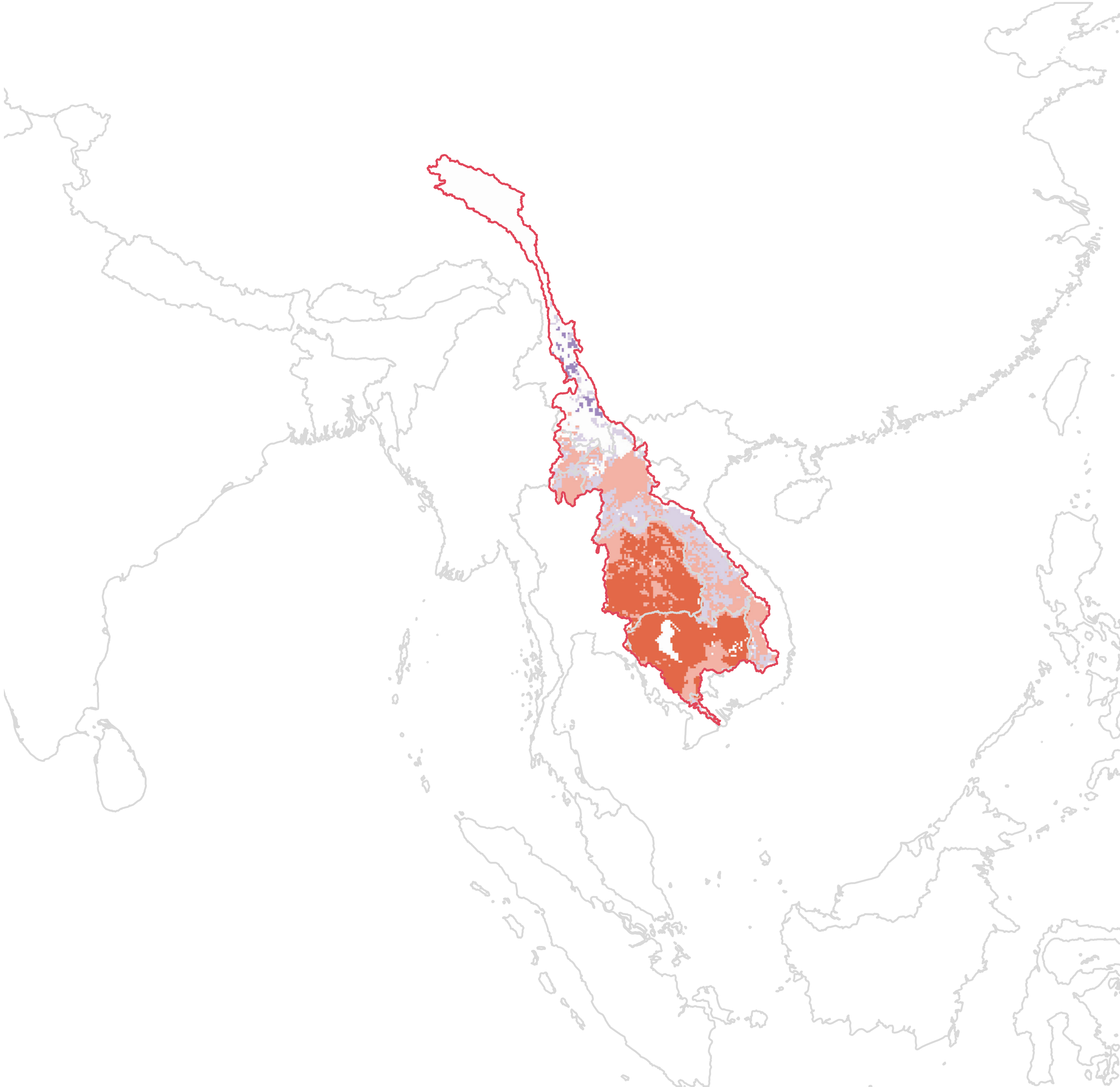
The Mekong River flows from China to Vietnam, through Myanmar, Laos, Thailand, and Cambogia, totaling 4350 km of river length and 800 000 km² of river basin. Each of the six countries the river wets has its own responsibility in creating an environmental cost of water withdrawal, namely the impacts on the river flows and its ecosystem. This environmental cost depends on the geographical position of the withdrawal point (whether it is closer to the river's source or to its mouth) and on the magnitude of the withdrawal.

COUNTRY	Area (km^2)
China	213 043
Myanmar	25 145
Laos	230 635
Thailand	204 985
Cambodia	165 685
Vietnam	68 414

THE WATER FOOTPRINT OF RICE PRODUCTION IN THE MEKONG RIVER BASIN

In this area, the critical agricultural driver of water withdrawal is rice production. Depending on the local unit Water Footprint of production *(see pages 50-51 and 60-61)*, the irrigation withdrawal from the river differs across the states.

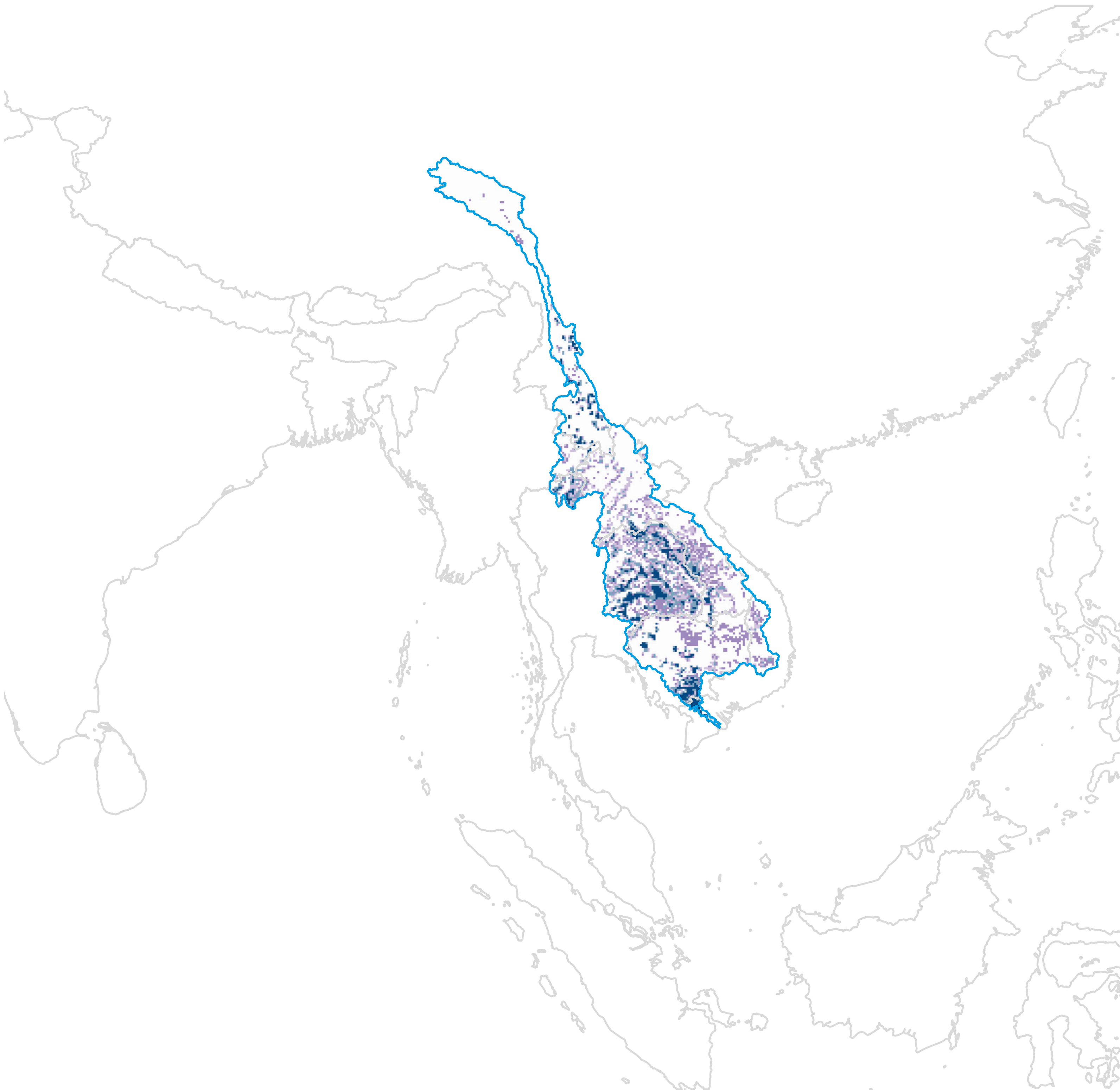
The unit Water Footprint of rice production across the Mekong River Basin ranges between 570 and 6275 liter/kg, as shown in the map. Thailand and Cambodia: the least water-efficient countries across the basin.



THE BLUE WATER FOOTPRINT OF RICE PRODUCTION IN THE MEKONG RIVER BASIN

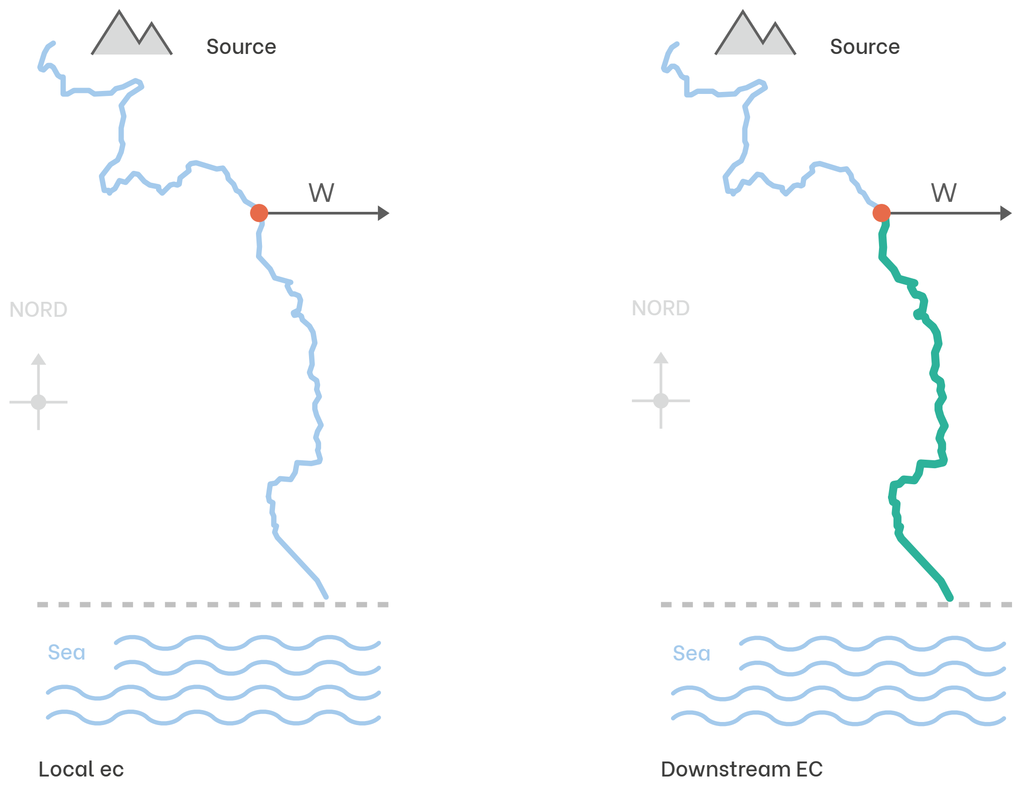
At the country level, the water withdrawals for irrigation are mainly localized in Thailand - the top producer of the basin - which annually with draws 2 km^3 of water. Vietnam and Cambodia follow with 1 km^3 of annual water withdrawal, each.

Instead, at the sub-national scale, the largest irrigation withdrawals are localized in the Mekong Delta (South-West Vietnam), which is also known as the "overflowing rice basket".

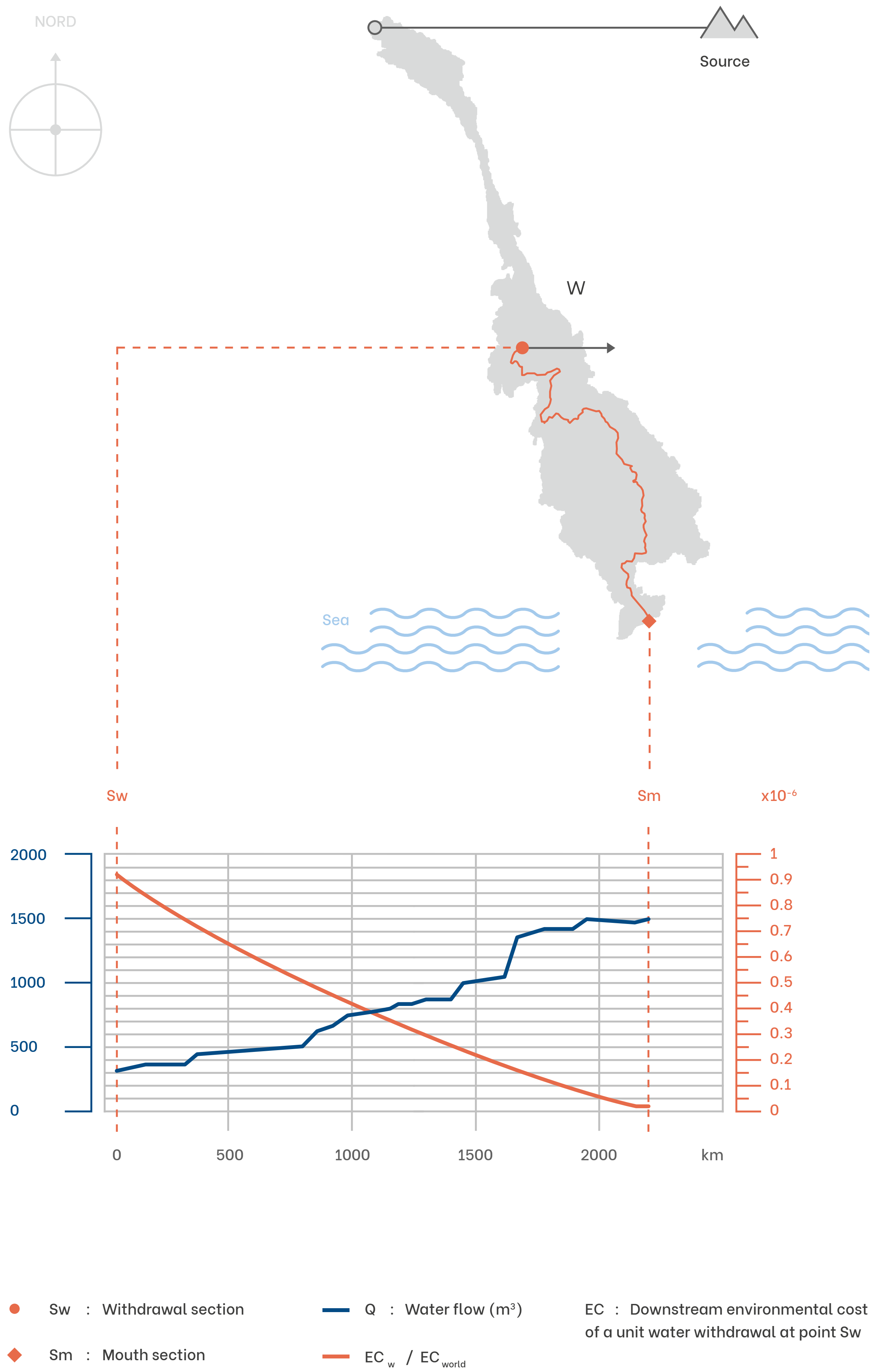


The environmental cost of a unit water withdrawal along the Mekong river

The water withdrawals to fulfill rice irrigation requirements come with consequences for the river ecosystems. In fact, the water withdrawal (W) for irrigation occurring in a specific river section impacts both the local portion of the river, the place where the withdrawal occurs, and the downstream fluvial area (see the green line in the figure representing the impact along the river). The environmental cost index measures the impact at the local (ec) and downstream river systems (EC), the latter being the local cumulated all along the river's curse.



A local water withdrawal (W) of one cubic meter in Myanmar for rice irrigation produces an environmental cost inversely proportional to the water flow (Q): as Q increases (from the source to the mouth of the river, as shows by the blue line in the chart), the environmental cost decreases (the purple line in the chart). The local withdrawal at the river section Sw impacts the downstream countries.. The impact of W goes as far as 2000 km (section Sm) along the river from the withdrawal point. For a fair comparison with other river basins, the environmental cost is better defined if normalized by a global indicator of impact. Here, the value EC_{world} is used, which measures the environmental cost if all the global surface water resources were consumed.



ARE WATER WITHDRAWALS SUSTAINABLE IN TIME AND SPACE?

At the world level, the total amount of water withdrawals throughout a year is almost negligible compared with the quantity of water available through the hydrological cycle. If considering the cultivation of primary crops, including wheat, rice, maize, soybean, cotton, barley, potatoes, sugarcane, and sugar beet *(in the maps at pages 60-61)*, the withdrawals are negligible if compared with the water flows available through the hydrological cycle. Every year, around 265 km^3 of water are withdrawn from groundwater sources, and nearly 400 km^3 from surface water bodies (i.e., rivers, lakes). The blue water footprint of these nine crops sums to 665 km^3 on average per year.

Instead, water withdrawals may overexploit water resources at the local level, thus determining an unsustainable water use, which may even lead to depleting the resource. Overexploitation of water occurs whenever the withdrawal rates are faster than those of the regeneration of the resources through the hydrological cycle. California Central Valley is an example of both surface and groundwater overexploitation.

The water debt indicator to monitor hotspots of unsustainable water use

In order to monitor a local water stress induced by water withdrawals, we introduce a new indicator that is called Water Debt.

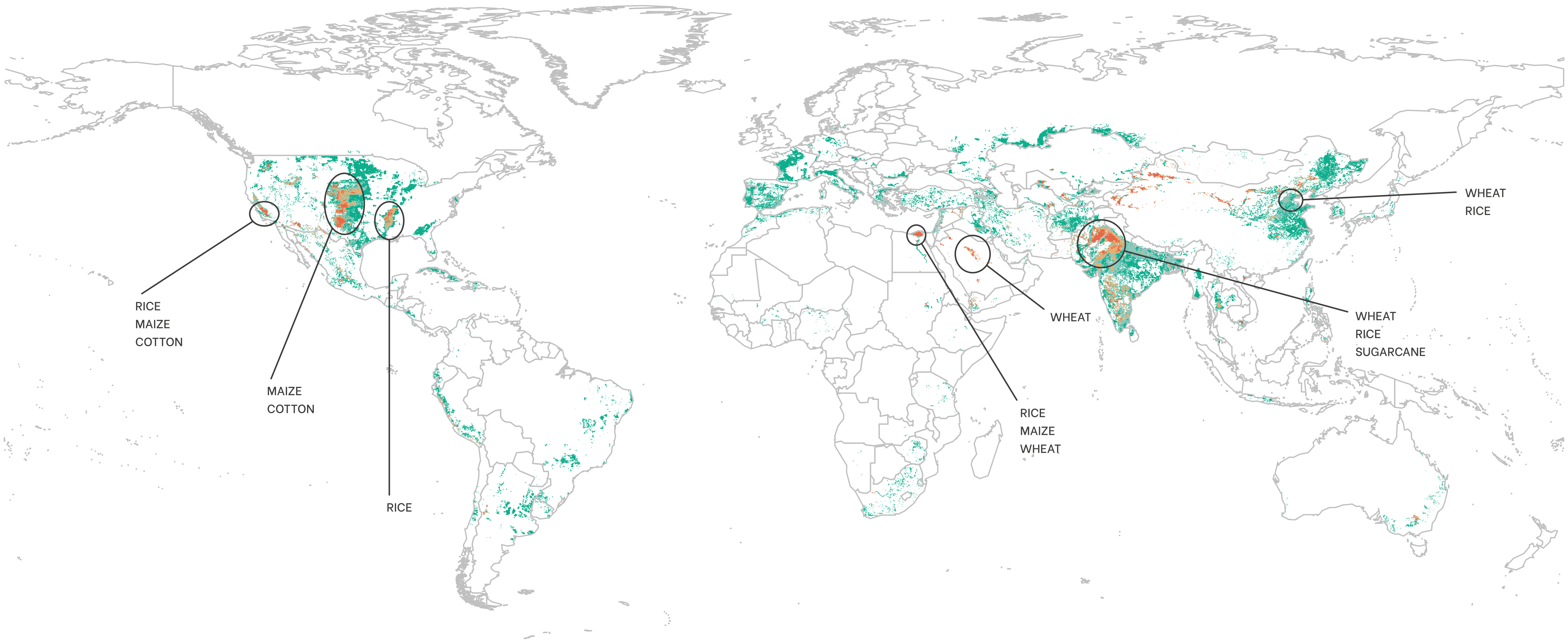
The Water Debt (WD) idea resembles the one of a bank loan: whenever the rate of water withdrawal is larger than the renewability rate of the water resource, the amount of water that is not sustainably available is temporarily borrowed from the resource's reserve. For groundwater resources, this reserve might be fossil water; instead, for surface waters, the reserve can be either the upstream water flow or the environmental flow that ensures the sustenance of the ecosystem. In these cases, the anthropic withdrawal generates a debt with the local water resource, which the hydrological cycle should naturally repay in a specific period. However, there could be cases in which this repayment might happen too late compared to the human-induced water debt, with irreversible damages for the environment *(see, the case of the Aral Sea, page 186-187)*.

The water debt indicator measures the amount of time nature spends in repaying this human-induced water loss and replenish the water resource. Suppose within a year rainfall naturally repays the debt caused by the anthropic water withdrawal. In that case, the withdrawal can be defined as sustainable, as it does not compromise the resource's natural equilibrium. Conversely, the water withdrawal is unsustainable if the one-year rainfall cannot replenish the source, and more time is needed. This happens, for instance, when groundwater is withdrawan at a rate faster than the natural recharge rate of the aquifer. Assessing the WD repayment time allows one to understand whether we are meeting the needs of the present generation without compromising the ability of future generations to meet their own. At the same time, the Water Debt stands as a further measure of the environmental damages induced by anthropic water use.

GROUNDWATER DEBT

The Water Debt highlights situations of groundwater depletion by analyzing the unsustainable local water withdrawal from aquifers. A water withdrawal from an aquifer is considered unsustainable when it exceeds the aquifers' recharge from rainfall and rivers, with consequent depletion of the natural groundwater level. Around the world, over half of the global groundwater use originates from just four major aquifers, *(as shown on pages 56-57)*.

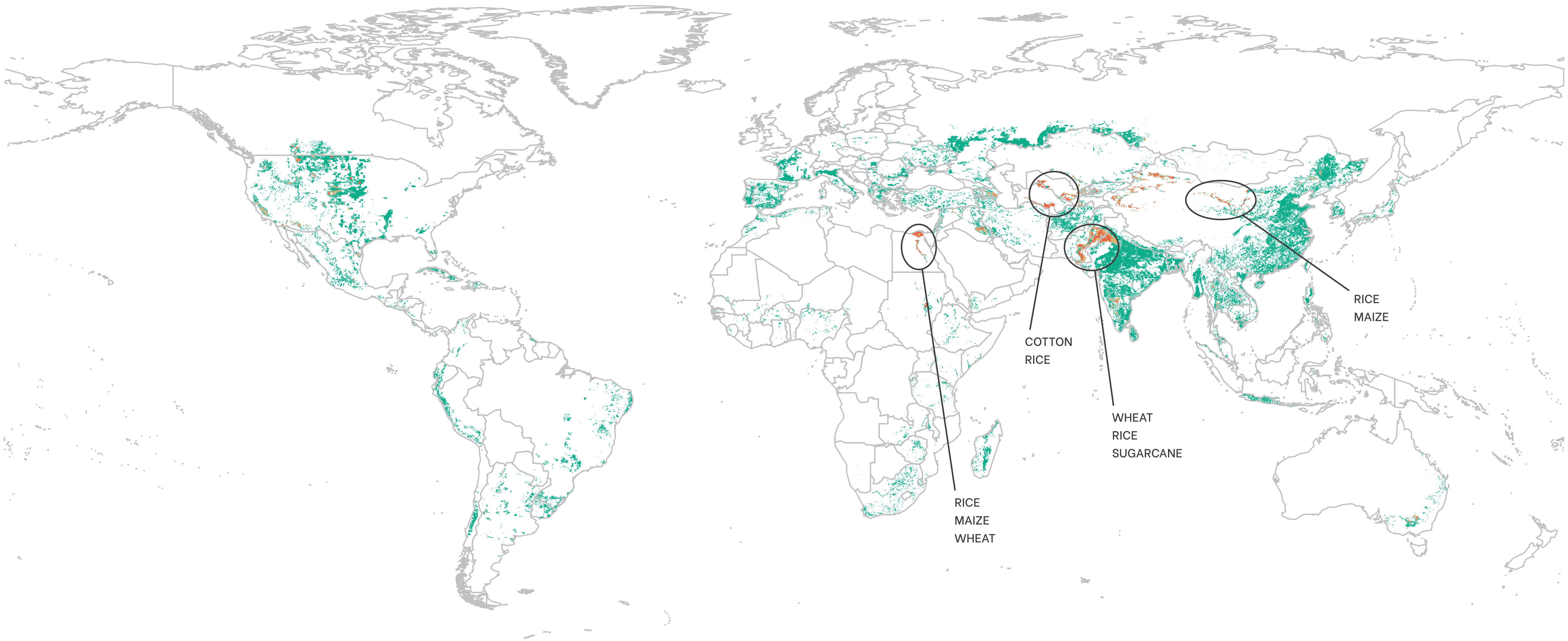
The WD varies from place to place depending on the blue Water Footprint of production and the amount of locally available water from aquifers, namely the aquifers' recharge.
Maize is among the main drivers of such depletion worldwide, particularly in the US High Plains. Other crops contributing to such overexploitation include rice in the California Central Valley, the Atlantic and Gulf Coastal Plains (USA); rice and wheat – the Nubian Aquifer system (Africa); wheat – Arabian Aquifer System (Asia); rice and wheat – the Indo-Gangetic Plain; rice and wheat – the North China Plain.



SURFACE WATER DEBT

Differently from the Environmental Cost - quantifying the environmental impacts of a withdrawal on the downstream countries *(see pages 178-179)* - the Water Debt (WD) measures the (un)sustainability of a local withdrawal from either a surface or a groundwater body. For surface water resources, considering only the local withdrawal (hence without including the downstream effect) in the computation of the water debt indicator may lead to overestimating the WD values (e.g., the Nile delta). Nevertheless, these values may spotlight possible dynamics of competition for water use across national borders and along the river basin. Downstream areas may be exposed to some water availability reduction if upstream areas overuse their water resources. This fact may have important implications for river water management.

Moreover, this share of transboundary resources might be furtherly complicated by the heterogeneity in economic and policy power of countries. These dynamics may even lead to conflicts for water uses, e.g., in the Nile basin among Ethiopia, Sudan, and Egypt; in the Indo basin between India and Pakistan; in the Tigris-Euphrates basin, among Turkey and Syria and Iraq.
The world map here is colored according to the surface water debt caused by irrigation demand for crop production. Circles identify areas getting into debts with some of the major surface water bodies worldwide for crop irrigation. Cotton and rice cultivations drive the overexploitation of the Amu Darya and Syr Darya rivers - thus affecting the natural recharge of the Aral Sea. Rice, maize, and wheat are responsible for the Nile River local overexploitation; wheat, rice, and sugar cane for the Indo and Gange basins. In lakes, overexploitation for irrigation purposes may lead to the shrink of the lake itself or even to its disappearance. For example, rice and maize cultivations are responsible for the depletion of Qinghai Lake in Tibet.



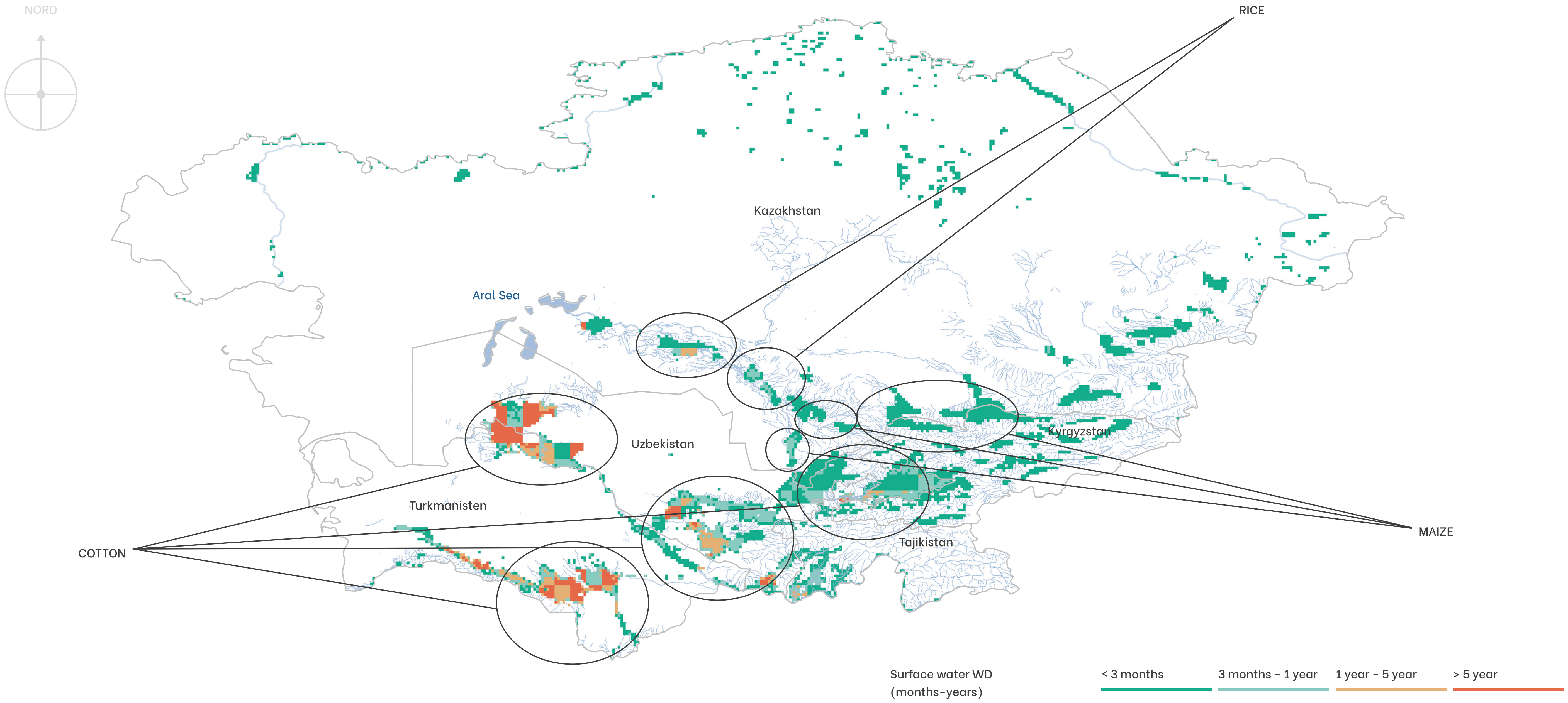
Surface water WD (months-years)

≤ 3 months | 3 months - 1 year | 1 year - 5 year | > 5 year

A striking case: the shrinking Aral Sea

The shrinking of the Aral Sea is among the worst cases of overexploitation of surface water bodies around the world. The SEVERITY of this overexploitation finds its reasons in the amount of water resource spilled for irrigation. The canals, which started to source from the Aral tributaries in the '60s, caused during the years the loss of 75% of the Sea original volume, which depleted from an initial volume of around 1040 km³ to a volume of around 105 km³ in 2010.

The water debt identifies cotton, rice, and maize as the critical cultivations responsible for such overexploitation. Nevertheless, cotton cultivations are the most significant water debt creators in this area. The withdrawal of water for irrigation has led to water debts as high as 20 years for the Amu Darya basin in Uzbekistan and for the Syr Darya basin in Kazakhstan.



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“WHAT CAN I DO TO LET THE WATER KEEP FLOWING?”

We have opened this piece of work by framing our research within the 17 Sustainable Development Goals, focusing on how some scientific results can help monitor the progress of countries with respect to the 2030 Agenda.

However, water is crucial for addressing all SDGs, as its presence empowers people, preserves lives and the environment, and reduces inequalities. Thus, water shall be a central issue for development.

In light of the results we have illustrated, we want to conclude with a call for collective actions, from citizens to governments and producers to consumers, to take care of water resources in the global food system.
Every single drop counts, and so does every single action.

I am a consumer

1. Take care of the water use efficiency of foods. The lower the water footprint per calorie and nutrient intake, the lower is the impact you generate on production sites. When creating your food basket, you may choose goods based on their water footprint, also considering that the same product can have a different water footprint depending on its supply chain.

2. Take care of the color of your water footprint. Preferably, choose products derived from agricultural techniques which maximize the occurence of precipitation within the growing season of plants to minimize the blue water requirements.

3. Take care of the blue water resources. In choosing irrigation-based products, choose those ones that minimize the impacts on the natural water resources, thus sustainably relying on the natural recharge of precipitation.

4. Take care of the origin of your food basket. Choose products that originate in production sites where the physical water scarcity is absent or limited.

5. Take care of the ID of your food. Claim for transparent supply chains and water-oriented labeling unveiling the impacts of food production. *

6. Take care of your daily diet. Balance your diet to eat nutrient and sustainable foods. The Eat-Lancet commission proposes a reference diet and some recipes that principally consist of vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils. Still, they also include a low to moderate amount of seafood and poultry. *

7. Take care of your bin: it hides a lot of virtual water. Reduce food waste by efficiently planning your grocery, organizing the fridge, and taking advantage of local initiatives against food waste. *

8. Take care of up-to-date scientific research. Chase information shared by scientific researchers, reports from recognized organizations, and journals to gain awareness and get data about the food systems facts and figures.

* **If you need ideas, here there are some projects that might help you:**

Recipes in line with the Eat-Lancet guidelines: https://eatforum.org/planetary-health-recipes/

Reducing food waste in groceries and restaurants: https://toogoodtogo.com/en-us

Reducing food waste in neighborhoods: https://olioex.com

I represent a firm

1. Take care of the water use efficiency of foods. The lower the water footprint, the lower is your impact on production sites. In growing and producing foods, try to optimize their water footprints. Consider all the climatic and agricultural parameters driving water footprints, such as rainfall regime and seasonality, temperature patterns, nutrients in the soil, optimized irrigation practices, and the crop calendar.

2. Take care of the color of your water footprint. Maximize the unexploited potential of rainwater available along the cropping period to avoid unnecessary additional irrigation.

3. Take care of the blue water resources. Whether rainfall is insufficient for production, reduce water exploitation by using drip irrigation to improve water use efficiency. Also, consider exploiting the potential of aquaponics, hydroponics, and agroecology.

4. Take care of the origin of your food basket. Enhance and increase production in places and timing where and when natural resources can support it.

5. Take care of the ID of your food. Inform consumers through transparent labels about the sustainability of food production by unfolding the granularity of the supply chains. *

6. Take care of the daily diet of your consumers. Improve communication of the healthiness and sustainability of the food you sell. Diminish the confusion around food labeling and expiration dates.

7. Take care of your bin: it hides a lot of virtual water. Reduce waste and losses along each step of the supply chain. Improve harvest management on production sites (e.g., cope with pre-mature or delayed harvesting due to weather conditions, improve farmers' access to the market through proper infrastructures). Consider joining local (and non) initiatives against food waste. *

8. Take care of up-to-date scientific research. Joint forces of the private and public sectors can help to improve productivity while reducing water use and waste. For example, only 0.7% of 1.7 million farms rely on consultancy in Italy to improve their green and blue water resources management. According to the Italian National Bureau of Statistics (ISTAT), these businesses show a reduction of their water footprint by 500 m^3 per cultivated hectare of land. Encourage constructive synergies between scientific research and agri-businesses.

* **If you need ideas, here there are some projects that might help you:**

Reducing food waste along the supply chain: https://www.imperfectfoods.com/

Tracing products' supply chains: https://www.trase.earth/

I am a policy and decision-maker

ACTIONS ARE NEEDED FOR...

FOOD AND WATER SECURITY

1. Support trade agreements: international efforts as trade negotiations, beyond market mechanisms, are required to ensure safe trade connections for emerging countries, especially during economic crises, when they are more vulnerable to global market dynamics.

2. Coordinate actions to tackle food insecurity, required to sustain a more equitable food distribution, thus guaranteeing trade and production entitlements.

3. Promote economic compensations for countries using scarce water to produce export-oriented agricultural goods.

WATER SCARCITY

1. Intensify international cooperation across all countries, from the major recipient countries of scarce water to the origin countries with the largest gap in terms of water availability and access. Water scarcity is a global challenge.

2. Promote agricultural practices that can maximize yield and reduce water withdrawals.

3. Improve the comprehension of the multidimensionality of water scarcity (physical and socio-economic dimensions).

4. Understand water use and water scarcity along the whole value chain of a product.

RESEARCH

1. Promote interdisciplinary research on water and environmental issues.

2. Promote dialogue between scientists and policy/decision-makers.

3. Support data collection and sharing, communication, and dissemination of research results.

TAXES AND INVESTMENTS

1. Establish environment-friendly policies for the definition of food prices. Consider introducing taxations on the least sustainable food types and companies overexploiting water resources.

2. Promote good water governance, water infrastructure, and equity in water access.

3. Support firms in applying sustainable agriculture to face increasing food demand.

AWARENESS

1. Invest in campaigns for environmental awareness of food-water consumption and waste reduction, starting from the education system.

2. Set high environmental standards based on water footprint to prioritize the consumption of less water-demanding foods during meals at public events and in schools and offices canteens.

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