POLITECNICO DI TORINO

MASTER's Degree in MATHEMATICAL ENGINEERING

Water footprint of waste and losses in cereal-related food: an analysis at the global scale

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Summary

In this thesis, our primary objective is to assess the water usage associated with the losses and waste in the production and consumption of staple crops (raw and processed food commodities), specifically focusing on identifying the link between producing countries, whose waters are employed to produce food and feed that is eventually lost or wasted throughout the food value chain and consuming countries, whose food and feed demand is associated with such food loss and waste (FLW).

Chapter 1 serves as an introductory exploration of the intricate relationship between food and water. Within this chapter, we highlight the critical importance of minimizing water wastage in agri-food systems and provide a comprehensive understanding of the concept of water footprint. Furthermore, we delve into an in-depth examination of the relevance of food loss and waste, elucidating the contributing factors and the far-reaching consequences of these phenomena, in terms of both social implications (wasting food while there are people experiencing malnutrition or hunger) and environmental considerations (misusing water and resources).

In Chapter 2, we present the data and the sources of our study. We then explain the reason for incorporating staple crops into our analysis, delineating the specific crops under consideration. We evaluate data coverage with respect to the global production of raw crops and their derivatives. Additionally, we expound on the concept of the unit water footprint, elucidating the origin of this data. Furthermore, within the same chapter, we delve into the intricacies of food loss and waste, emphasizing the regional variations in the distribution of losses at different stages of the value chain.

In Chapter 3, we explain the methodology employed for modeling food loss and waste along the value chain, as outlined in Semeria et al. 2024, providing insights into the complexities of food loss and waste dynamics at different stages. Furthermore, we clarify the tracing of food loss and waste along supply networks, leveraging the methodology proposed by T. Kastner, M. Kastner, et al. 2011, allowing us to delineate the impact of losses occurring in any given country on

both domestic water resources and resources employed in other nations.

Chapter 4 presents the results of our analysis and it is divided into two main sections. In the first segment, we concentrate on the emblematic case of wheat and its derived products. Subsequently, the second part of the chapter broadens its scope to encompass other staple crops. Within each section, our examination unfolds three distinct perspectives: crop production, food consumption, and feed usage. By adopting this tripartite approach, we aim to comprehensively capture the dynamics and impact that the FLW of these crops have on the use of freshwater resources across different dimensions of the supply chain.

In Chapter 5, we delve into the challenges and obstacles encountered throughout our analysis, from data constraints to methodological intricacies. This exploration of limitations lays the groundwork for the conclusions of Chapter 6, where we synthesize our findings and we present prospective avenues for future research, addressing the identified limitations and suggesting potential strategies for overcoming them.

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Chapter 1

Food - Water nexus

Water is considered the ultimate commodity due to its indispensable role in sustaining all forms of life on Earth. Food production heavily relies on adequate and accessible water resources, primarily for agriculture, that globally consumes 70% of freshwater resources (FAO 2021). Hence, it has become necessary to take a comprehensive approach to connect water and agriculture products: the nexus concept. It has gained recognition and is now regarded in scientific literature as the food-water nexus, emphasizing that water resources' availability, distribution and management are intricately linked to food production, and vice versa. Meeting the demand for food can depend either directly or indirectly on the local availability of water. Directly, in terrestrial ecosystems, all primary production, such as the one coming from crop plants, relies on water. Indirectly, all secondary production, i.e. the ones originated by animals, ultimately depends on water to cultivate grass, fodder, or feed. Thus, a profound connection exists between food production and the availability of water (D'Odorico et al. 2018).

The food-water nexus offers a conceptual approach to work toward more coordinated management and use of natural resources across sectors and scales. This can help people identify and manage trade-offs and build synergies through responses, allowing for more integrated and cost-effective planning, decision-making, implementation, monitoring, and evaluation. Adopting a nexus approach in the management of water and food resources leads to a wiser use of the limited resources (Biggs et al. 2015). By anticipating potential trade-offs and synergies, it is possible to design, appraise and prioritize response options that are viable across different sectors (FAO 2014).

Over the past century, freshwater consumption has significantly increased, as shown in Figure 1.1, due to rising food demands and shifts toward diets high in calories and protein. The growing demand for water resources is creating challenges, particularly in regions facing water stress. Nowadays, more than two billion people live in highly water-stressed areas, with two-thirds of the global population experiencing severe water stress for at least one month per year (Mekonnen et al. 2016). The intensified utilization of surface and groundwater resources, particularly for irrigation, has led to alarming levels of water depletion in various aquifers and river systems around the world. This poses a substantial threat to natural ecosystems. Striking a balance between the growing demand for water and its limited availability stands as a monumental challenge for humanity. This balance is not only crucial for meeting the basic needs of people, but also indispensable for preserving our environment and maintaining the fragile ecological equilibrium that sustains all life on Earth. Addressing water scarcity and implementing responsible water management are vital steps toward a more sustainable use of natural resources.

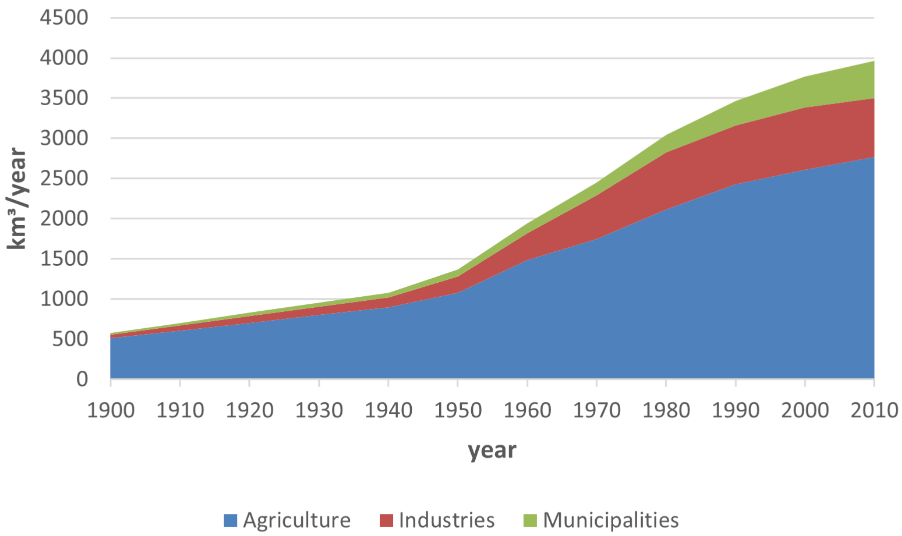

Figure 1.1: Global water withdrawal from 1900 to 2010. In 2010, proportions among types of withdrawal were 70% agricultural, 18% industrial, and 12% municipal (Shiklomanov 2000; FAO 2020a).

Moreover, climate change is altering precipitation patterns and increasing the frequency and severity of droughts and floods, making water availability and management even more unpredictable (Tabari 2020). Pollution from agricultural runoff and industrial activities can contaminate water sources, further compounding the problem (Mateo-Sagasta et al. 2017). This complex interdependence also has geopolitical dimensions, as disputes over water resources can have far-reaching consequences for regions and nations (Basumatary 2021). Constraints on water can challenge the reliability of existing agricultural operations and the viability of future farming projects (FAO 2020b). Water constraints can occur due to droughts, increased competition among users, or regulatory limitations on water access.

Water and food are also critical for achieving most of the Millenium Development Goals (United Nations 2005) and the majority of the Sustainable Development Goals, that commit subscribing countries to new action targets aimed at achieving sustainable water use and agricultural practices, as well as promoting more inclusive economic development (United Nations 2014), with the purpose of eradicating malnutrition in one billion undernourished people, ensuring safe and consistent water supply to 1.2 billion individuals facing water shortages, and providing access to clean water to 1.3 billion people.

Understanding and addressing the food-water nexus is essential, as integrated water and agricultural management practices will always be more necessary in the immediate future. This involves optimizing irrigation techniques, promoting water-efficient crop varieties, and reducing food waste throughout the supply chain. Sustainable farming practices, such as agroforestry and precision agriculture, can mitigate the environmental impacts of food production. Furthermore, international cooperation and policy frameworks are essential for the equitable and sustainable management of shared water resources.

1.1 Virtual water and water footprint

The need for quantifying the impacts that the production of goods, especially food commodities, on water resources has led to the development of concepts like virtual water and the water footprint. These concepts aim to quantify the hidden water costs associated with the production and trade of goods.

In the early '90s, Tony Allan first introduced the concept of virtual water (VW) to explore how countries facing water scarcity could ensure the supply of essential goods such as food and clothing for their populations. The term virtual water was coined to quantify the amount of water needed to produce a unit of goods or offer a specific service. It offers insights into the hidden costs of water embedded within individual items (Allan 1993; Allan 1994).

In 2002, Arjen Hoekstra presented the notion of the water footprint (WF) as a means to delve deeper into the intricate relationship between production, consumption, and water utilization. This innovative water assessment tool serves the dual purpose of evaluating and conveying the extent of human water consumption while measuring the cumulative impact this virtual water usage exerts on our planet's water resources (Hoekstra and Hung 2002).

For instance, to emphasize the significance of the water-food relationship, we could ask ourselves how much water is needed in the production of a loaf of bread. The global average water footprint of wheat stands at 1827 liters per kilogram, as reported by Mekonnen et al. 2011. Approximately 80% of this water footprint is attributed to the production of wheat flour. With 1 kilogram of wheat yielding roughly 790 grams of flour, the water footprint of wheat flour amounts to about 1850 liters per kilogram. When we consider that 1 kilogram of flour typically produces around 1.15 kilograms of bread, one can calculate that the water footprint of bread is approximately 1608 liters per kilogram. Hence, it's worth noting that, on a global average, the production of a 100-gram loaf of bread requires nearly 161 liters of water. However, it's important to acknowledge that the precise water footprint of bread can vary depending on factors such as the origin of the wheat and the methods used in its cultivation.

The concepts of virtual water and water footprint are fundamentally interconnected. While virtual water pertains to the water requirements of individual units produced or served, the water footprint tool offers a more comprehensive approach by quantifying the freshwater necessities of various processes collectively. This extension of the VW analysis provides a broader framework for understanding and addressing our global water challenges.

Assessing the water footprint can take various forms of focus and scope, depending on one's specific interests and objectives. It can entail a rigorous examination of the WF associated with the production of a particular good, either tracing it across its entire supply chain or focusing on a specific process step. Furthermore, it can be quantified the WF of a collective of consumers, a given river basin, or even an entire nation. The spatial and temporal scales applied in the water footprint assessment are contingent upon the context of the analysis and its intended purposes.

The most profound distinctions between virtual water and water footprint arise when we introduce the global dimension of resources through international trade of goods and services. On a commercial route, the water footprint of any commodity or service effectively migrates with it, assuming the form of virtual water. This dynamic nature of trade allows us to establish a connection between the water footprint of production and the water footprint of consumption, regardless of where it takes place geographically.

1.1.1 Water footprint of production and supply

The unit water footprint is a parameter based on quantifying crop evapotranspiration that serves as an essential indicator of water use efficiency in agriculture. It enables comparisons between different products or geographical locations, allowing us to identify which ones are more efficient in terms of water utilization. The WF associated with food production varies considerably among different countries as shown in Figure 1.2, and this variability contributes to the distinction between the water footprint of production and the water footprint of supply. (Hoekstra, Chapagain, et al. 2011).

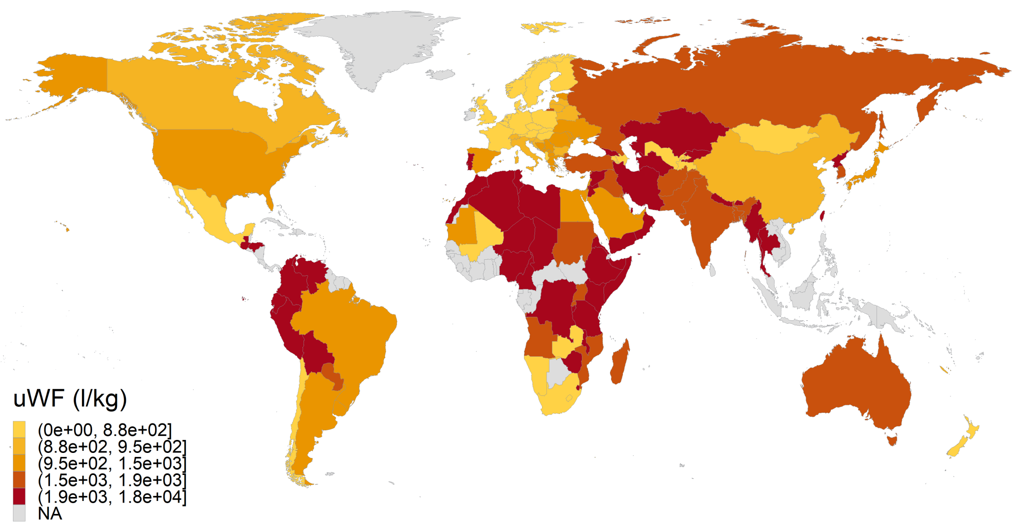

Figure 1.2: Spatial distribution of the water footprint of wheat per unit of production (uWF, in liters per kg) in the year 2016. The classes of this map are defined by the quintiles of the distribution of the uWF.

We can imagine having two bags of flour in our food basket, one produced in Italy and the other in the United States, each weighing half a kilogram. The water footprint of the "Italian" flour is 480 liters per package, while the "U.S." flour has a WF of 760 liters per package. We refer to these quantities as WF of production for Italy and the U.S. If we intend to use both packages to bake a loaf of bread, our water footprint of supply will be 1,240 liters.

For primary crops, the uWF of production (uWFp) is influenced by local factors such as climatic conditions, soil characteristics, crop yield, and irrigation methods. These factors vary significantly from one region to another, leading to substantial differences in the amount of water required to produce goods like flour or any other product. Conversely, uWF of supply (uWFs) is influenced by factors related to international trade, dietary preferences, and socio-economic conditions. It reflects the water embedded in the products consumed, taking into account where they were produced. As a result, it's possible for the water footprint of supply to be quite different from the water footprint of production, particularly in a globalized world where goods are traded across borders.

Basically, the contrast between these two footprints underscores the complex interplay of local and global factors that influence the water resources associated with the production and consumption of food and other products. Understanding these dynamics is essential for promoting sustainable water management and making informed choices to reduce water-related impacts on a global scale.

1.1.2 Green, Blue and Grey Water Footprint

The water footprint methodology identifies three distinct water sources utilized in the given process (Mekonnen et al. 2011).

1. The green water footprint represents the volume of rainwater consumed during the growth of crops and vegetation used in the production process. It accounts for the natural precipitation that is stored in the soil and used by plants. It is predominantly associated with the agricultural sector.

2. The blue water footprint refers to the volume of surface water and groundwater used directly for irrigation or industrial processes. It includes water abstracted 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.

3. The grey water footprint considers the amount of wastewater produced. It accounts for the volume of freshwater needed to dilute pollutants and contaminants resulting from the production or consumption of a product. It measures the environmental impact of water pollution. It can be measured for all processes in the three sectors of production.

Recalling the previous example, of the total water footprint associated with the production of bread, on global average, 70% is attributed to green water usage, 19% to blue water, and 11% to grey water (Hoekstra and Water Footprint Network 2017).

Since we regard water as an essential input in any process, our study considers the sum of green and blue water footprints, excluding the consideration of wastewater output, explicitly stating that grey water is not within the scope of our analysis.

1.2 Food loss and waste

Food loss and food waste are distinct terms used to describe the reduction in edible food mass at different stages of the food supply chain (FSC). Food losses occur during production, post-harvest handling, and processing, affecting the quantity of edible food available for human consumption. Conversely, food waste occurs primarily at the final stages of the food chain, such as in retail or by consumers, and it is driven by their behaviours, leading to the disposal of edible food (Gustavsson et al. 2011).

In the quantification of food losses or waste, the definition encompasses products initially intended for various purposes, including human consumption, animal feed, bio-energy, or other uses. It's crucial to note that if food originally designated for human consumption ends up being repurposed for non-food uses due to unforeseen circumstances, it is still categorized as "human" food loss or waste. This distinction is important in differentiating between planned non-food uses and unplanned non-food uses, providing a more accurate representation of the dynamics within the food supply chain.

We now use distinct categories for food loss and waste (FLW), specifically focusing on vegetable commodities and products. This is due to the fact that our analysis excludes discussions related to animal derivatives, as these are not within the scope of this thesis. To better understand these stages that form the so called value chain, we adopt five distinct system boundaries within the FSC, as defined by Gustavsson et al. 2011 in Table 1.1.

1.2.1 Drivers of food loss and waste

Food loss and waste is a pervasive issue that affect the entire food supply chain, from its initial production to the final consumption. The reasons for the generation of food waste differ based on the economic status of the country.

In low-income countries, the primary point of food loss is typically during the early stages of production and processing. Challenges such as inadequate infrastructure and technology contribute to this loss. In emerging economies, and occasionally in more advanced ones, food can be lost due to early harvesting

Table 1.1: Types of loss and waste as delineated by Gustavsson et al. 2011.

Type of loss and waste	Description
Agricultural production	Losses due to mechanical damage and/or spillage during harvest operation (e.g. threshing or fruit picking), crops sorted out post-harvest, etc.
Post-harvest handling and storage	Including losses due to spillage and degradation during handling, storage and transportation between farm and distribution.
Processing	Including losses due to spillage and degradation during industrial or domestic processing, e.g. juice production, canning and bread baking. Losses may occur when crops are sorted out if not suitable to process or during washing, peeling, slicing and boiling or during process interruptions and accidental spillage.
Distribution	Including losses and waste in the market system, at e.g. wholesale markets, supermarkets, retailers and wet markets.
Consumption	Including losses and waste during consumption at the household level.

practices. Impoverished farmers may harvest their crops prematurely due to reasons like immediate food shortages or urgent cash requirements during the latter part of the agricultural season. This premature harvesting not only diminishes the nutritional and economic value of the food, but can also lead to waste if the harvested produce is unsuitable for consumption. In developing countries, the problem of post-harvest food losses is aggravated by insufficient storage facilities and inadequate infrastructure. Specifically, fresh produce such as fruits and vegetables is highly vulnerable to spoilage in hot climates due to the absence of proper transportation, storage, cooling, and market infrastructure. Another significant factor contributing to these losses is the absence of adequate processing facilities. In many cases, the food processing industry lacks the capacity to efficiently process and preserve fresh farm produce to meet market demand. This challenge is further compounded by the seasonal nature of production and the high costs associated with investing in processing facilities that may remain unused for a significant part of the year. Furthermore, inadequate market systems play a substantial role in driving food losses. To mitigate these losses, it is crucial that agricultural products from farmers effectively reach consumers. Unfortunately, there is often a scarcity of wholesale, supermarket, and retail facilities equipped with suitable storage and sales conditions for food products. Wholesale and retail markets in developing countries are frequently characterized by their small size, overcrowding, unhygienic conditions, and a lack of essential cooling equipment. Food that is unsafe for human consumption is inevitably wasted. Neglecting to meet the minimum food safety standards can result in food losses and, in severe instances, even affect a country's food security status. Numerous factors can render food unsafe, including naturally occurring toxins in the food, contamination from unclean water, improper use of pesticides, and the presence of veterinary drug residues. Additionally, unsanitary handling and storage conditions, as well as inadequate temperature control, can also contribute to food becoming unsafe (Magalhães et al. 2021; Gustavsson et al. 2011).

In industrialized nations, surplus production can lead to food losses when there is an excess supply compared to demand. To hedge against unpredictable factors like adverse weather or pest outbreaks, farmers may overproduce. In the case of having produced more than required, some surplus crops are sold to processors or as animal feed. However, this is often not financially profitable considering lower prices in these sectors compared to those from retailers. Moreover, in developed countries, a prevailing mindset that favors disposal over reuse or re-purposing significantly contributes to the problem of food waste. Within the context of industrial food processing, a common practice is trimming to ensure that the final product meets specific size and shape requirements. Unfortunately, these trimmings, which in some cases could be perfectly suitable for human consumption, are regularly discarded. Furthermore, food losses occur during processing due to spoilage along the production line, and mistakes during the processing phase can lead to final products that deviate from the intended weight, shape, or appearance, or may have damaged packaging. It's worth noting that these deviations do not affect the safety, taste, or nutritional value of the food. Nevertheless, within standardized production lines, such products are often needlessly discarded. Stringent appearance quality standards imposed by supermarkets for fresh products contribute to food waste. Supermarkets tend to reject certain produce at the farm gate because they do not meet strict criteria related to weight, size, shape, and overall appearance. Consequently, substantial portions of crops remain on the farms, never making it to market shelves. Another contributor to food waste is the retail industry's practice of displaying vast quantities of various products and brands in stores. Retailers frequently order a wide range of food types and brands from the same manufacturer to secure favorable prices. Consumer demand for diverse product offerings also drives this practice. However, this diversity increases the likelihood of some products reaching their sell-by dates before being sold, leading to unnecessary wastage. While well-stocked shelves are visually appealing and contribute to sales, constantly replenishing supplies can lead to neglecting food products nearing their expiration dates, which poses a particular challenge for smaller retail stores. Lastly, the issue of high food waste is influenced by abundance and consumer attitudes. One of the primary reasons for significant food waste at the consumer level in wealthy nations is the financial capability of people to dispose of food without thought. Over recent decades, the quantity of food available per person in retail stores and restaurants has notably increased in both the USA and the EU. Many restaurants offer all-you-can-eat buffets at fixed prices, encouraging customers to overfill their plates with more food than they can consume. Retailers frequently promote large package sizes and "buy one, get one free" deals, while food manufacturers produce oversized ready-to-eat meals. This combination of factors fosters a culture of abundance and a casual approach to food waste among consumers in industrialized nations, leading people to discard food that is still perfectly edible due to factors like over-purchasing, improper storage, and aesthetic preferences (Magalhães et al. 2021; Gustavsson et al. 2011).

1.2.2 Impacts of food loss and waste

Food loss and waste have numerous consequences that span various domains and sectors.

1. Environmental impacts (Cattaneo et al. 2021; Kummu et al. 2012)

   1.1 FLW contribute significantly to greenhouse gas emissions. When food is discarded in landfills, it decomposes and produces methane, a potent greenhouse gas. Additionally, the energy and resources used in food production, transportation, and storage are wasted when food is not consumed.

   1.2 Food production requires large amounts of water. When food is lost or wasted, the water used in growing, processing, and transporting it is also wasted: 24% of freshwater resources used in food crop production (27 cubic meters per capita per year) result in wasted and discarded food.

   1.3 Agriculture covers vast amounts of land. Food that is lost or wasted represents a loss of 23% of global cropland area (31×10^{-3} hectares per capita per year). In particular, if we focus on the United States, the total production of wheat is 7.33×10^7 tonnes and US wheat yield in 2016 is 3.54 $[t/ha]$. Hence, the land used for wheat cultivation is 2.07×10^7 $[ha]$, i.e. nearly half of California extension (4.23×10^7 $[ha]$). The total FLW of US wheat production is 1.13×10^7 $[t]$, this means that wheat cropland in the US employed to produce food that is either lost or wasted amounts to 3.18×10^6 $[ha]$ an extension bigger than the size of the state of Hawaii (2.83×10^6 $[ha]$). Additionally, deforestation and habitat destruction may occur as a result of expanding agricultural activities to compensate for food losses. Lastly, land use changes driven by agriculture can lead to the loss of biodiversity and the disruption of ecosystems. This can have cascading effects on local flora and fauna.

2. Economic impacts (De Gorter et al. 2021)

   2.1 Farmers and producers bear the costs of food that is lost before it reaches the market. This includes costs associated with planting, harvesting, and transportation, all of which contribute to the overall financial burden on producers. Food manufacturers, distributors, and retailers incur financial losses when products expire or are damaged and cannot be sold. This results in lower profits and increased operational costs. Waste within the supply chain necessitates that both producers and intermediaries, including processors and retailers, must increase the unit price to regain expenses incurred across all units, including those lost as waste. Consequently, reducing waste rates leads to elevated sales while maintaining lower prices for every producer and intermediary. This, in a domino effect, can stimulate heightened sales, potentially resulting in increased waste across various stages of the supply chain. Nonetheless, it typically results in an overall reduction in waste within the food supply chain.

   2.2 Food waste also affects consumers economically. When people throw away food, they are essentially wasting the money they spent on groceries, which can strain the finances of individuals and households. Reducing consumer food waste can potentially increase overall consumption, although the extent of the decrease in purchases depends on the elasticity of demand. Decreasing food waste has a dual impact on the quantity of food available: a direct effect on the amount of purchased food that can be consumed and an indirect effect through changes in demand elasticity. Lower food waste rates lead to a reduction in the effective unit price of the food that is actually consumed.

3. Social impacts (Kummu et al. 2012; Statista 2023a)

   3.1 Reducing food loss and waste is recognized as one of the most effective measures to enhance food security in the future. Approximately 25% of the food supply (equivalent to 614 kilocalories per capita per day) is lost at various stages of the food supply chain. If we were able to achieve the lowest levels of FLW across each stage of the FSC on a global scale, food supply losses could be reduced by half. This reduction would result in an adequate food supply for approximately one billion additional people.

3.2 Nowadays, 11% of the global population experiences severe food insecurity and inadequate nutrition, even as vast amounts of food go to waste. Reducing FLW offers a solution by redirecting surplus food to those in need, including food banks, shelters, and charitable organizations. This approach not only helps address hunger and malnutrition but also optimizes the use of available resources, providing food security for vulnerable populations.

3.3 The resources wasted on food that is ultimately discarded could be redirected to other societal needs, such as education, healthcare, or infrastructure development. Reducing food waste can free up resources for other critical purposes.

Chapter 2

Data

2.1 Food production and trade

We decided to include the products in our analysis with the purpose of a comprehensive understanding of staple crops. Typically, staple foods are well adapted to the growth conditions in their source areas and they form the basis of a regular diet. Of more than 50000 edible plant species in the world, only a few hundred contribute significantly to food supplies, with just 15 crop plants providing 90% of the world's food energy intake (FAO 1995). Utilizing FAOSTAT 2023, the statistical database of the Food and Agriculture Organization (FAO), we gathered comprehensive data on on the supply and utilization 38 food commodities, divided into 12 commodity trees, that can be referenced in Appendix A. In particular, we included cereals (wheat, rice, maize, millets, sorghum, barley, oats, and rye), oil seeds (specifically soybeans) and starchy roots (such as cassava, potatoes, and sweet potatoes) along with their various derived products.

The dataset is sourced from national accounting records and, for each reporting country, contains the following information: opening stocks, production, import quantity, stock variation, export quantity, quantities used for feed and seed, losses, quantities directed to processing and residuals (FAO 1997). Trade matrices for each food commodity ($\mathbf{Z}$) were taken from Tamea et al. 2021: elements z_{ij} quantify quantities in tonnes traded to country i from country j in a given year. These matrices reconciliate FAO-reported bilateral trade fluxes of agricultural goods, correcting inconsistencies in the original records. For each food commodity considered, one trade matrix for every year of the period 1986-2016 is available, reporting 255 countries as its dimensions. For the scope of this analysis, data relative to year 2016 were employed. The inclusion of specific products in our analysis was contingent upon both the availability of data on FAOSTAT and the existence of pertinent trade matrices.

When examining cereals, as outlined in Table 2.1, our research encompasses an extensive 98.96% of the global production of primary products. It is noteworthy that we intentionally omitted the category labeled as "other cereals" (buckwheat, quinoa, fonio, triticale, canary seed, mixed grains, cereals n.e.c., cereal preparations), which collectively represents 1.04% of the overall production, because it was not possible to connect it with a unique trade matrix. This allows us to focus our analysis on the predominant cereals, ensuring a comprehensive understanding of the vast majority of global cereal production.

Table 2.1: World production of cereals in tonnes in the year 2016

Cereal	**Production (t)**	**Percentage (%)**	**Cumulative percentage (%)**
Maize	1.12×10^9	38.64	38.64
Wheat	7.48×10^8	25.74	64.39
Rice	7.33×10^8	25.21	89.60
Barley	1.46×10^8	5.01	94.61
Sorghum	6.26×10^7	2.15	96.77
Millets	2.75×10^7	0.95	97.71
Oats	2.33×10^7	0.80	98.51
Rye	1.30×10^7	0.45	98.96
Other Cereals	3.03×10^7	1.04	100

In the sunburst graph of Figure 2.1, the first layer illustrates the primary products of cereals. Moving through the subsequent layers, one can discern the derived products emanating from the three major cereals that dominate the production quantity: maize, wheat and rice. These three are the staples of over 4 billion people (FAO 1995).

To better comprehend Figure 2.1, we now focus on wheat and its derivatives. The first layer represents wheat global production, accounting for 7.48×10^8 tonnes in 2016, constituting 25.74% of the total cereal output. In the second layer, we distinguish between processed and unprocessed wheat. Unprocessed wheat, totaling 2.29×10^8 tonnes, undergoes diverse pathways. Notably, 51.37% of it, equivalent to 1.18×10^8 tonnes, is allocated for animal feed. The remaining portion, depicted in white in Figure 2.1, finds applications such as seed production, direct consumption, and inevitable losses. Processed wheat, on the other hand, transforms into essential products: the majority manifests as flour, 79.51%, or bran 16.84%, as shown in

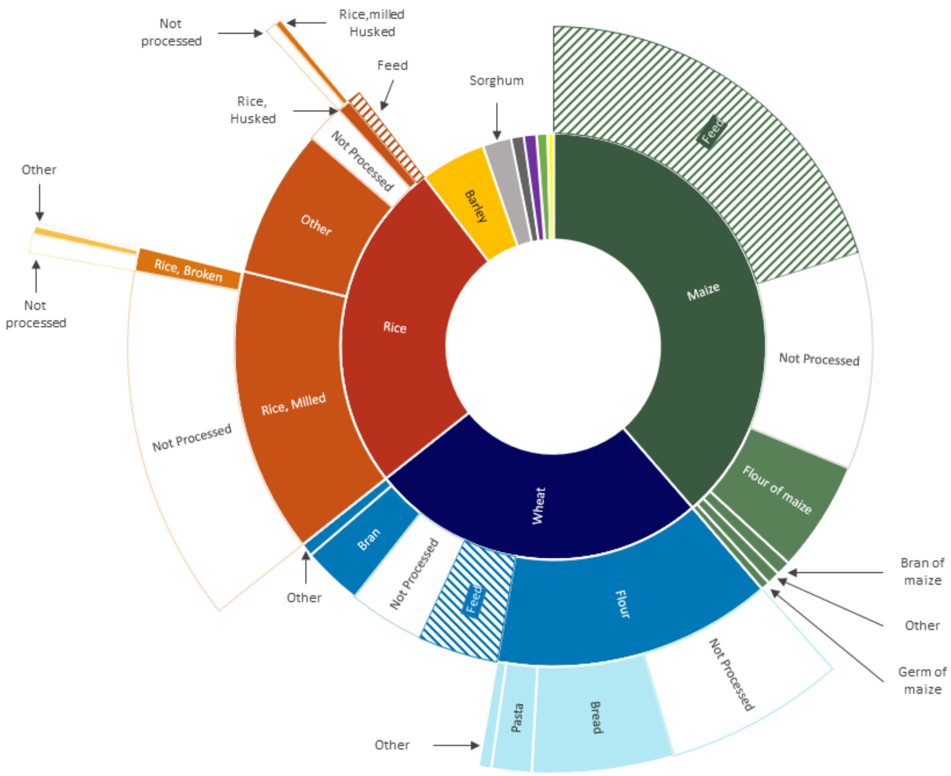

Figure 2.1: Sunburst graph representing the productions in tonnes of cereals and their derivatives in year 2016.

Figure 2.2; while the residual 3.65%, labeled as "other" in Figure 2.1, represents diverse wheat derivatives beyond our current focus, such as wheat germ, bulgur, and other specialized products detailed by FAO 2023. Advancing to the third layer, we encounter flour derivatives, denoting the second level of wheat derivatives. Here, we again distinguish between processed and unprocessed flour, with the latter depicted in white in the third layer of Figure 2.1. Processed flour undergoes further transformation into bread, 72.45%, and pasta, 21.06%, while the remaining 6.49%, labeled once more as "other," represents additional derivatives (always detailed in FAO 2023) like pastry that fall outside the purview of our current analysis. It is due to specify that, to address inaccuracies identified in the FAOSTAT database, the information pertaining to the supply and utilization of bread and pasta has been complemented with external data coming from from Statista 2023b.

Roots and tubers are important staples for over one billion people in the developing world. They account for roughly 40% of the food eaten by half the population

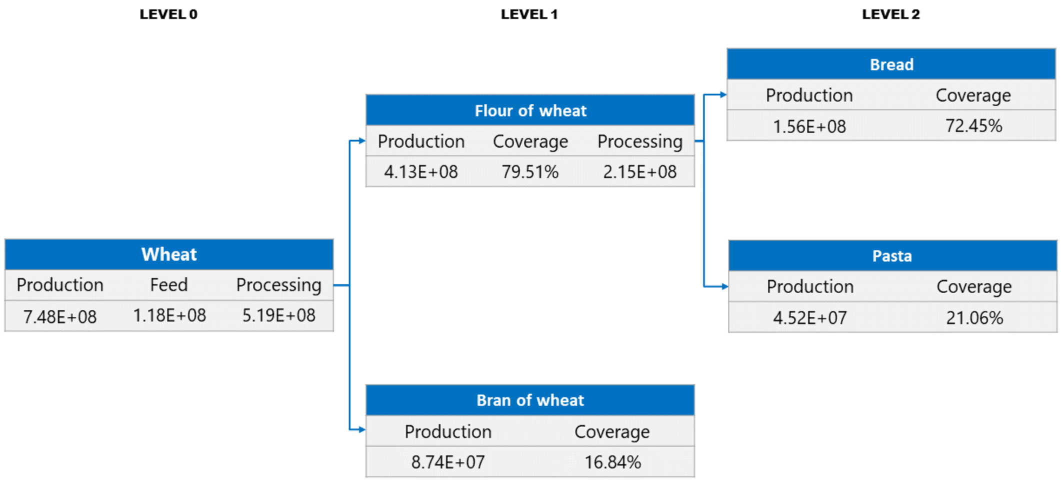

Figure 2.2: Wheat commodity tree. Production in tonnes of each item and percentage with respect to the processing part in tonnes of the parent item.

of sub-Saharan Africa. They are high in carbohydrates, calcium and vitamin C, but low in protein (FAO 1995). In our investigation of starchy roots, as detailed in Table 2.2, our research covers 88.65% of the worldwide primary product production. Cassava, once regarded as a minor crop in the early twentieth century, has evolved into a vital staple for approximately 500 million people in the developing world (FAO 1995). It's important to note that our analysis excludes yams due to the absence of a trade matrix. Additionally, we deliberately omitted the "other roots" category (comprising yautia, taro, and other roots and tubers with high starch or inulin content), which collectively makes up 2.37% of the overall production.

Table 2.2: World production of starchy roots in tonnes in the year 2016

Root	Production (t)	Percentage (%)	Cumulative percentage (%)
Potatoes	3.55×10^8	42.97	42.97
Cassava	2.87×10^8	34.72	77.69
Sweet potatoes	9.05×10^7	10.96	88.65
Yams	7.41×10^7	8.98	97.63
Other roots	8.26×10^7	2.37	100

Turning our attention to oil seeds our research encompasses only soybean, which accounts for 33.92% of the total global primary product production, as outilined in Table 2.3. This specific focus stems from a deliberate choice, considering that while oil palm fruits and other oil seeds boast significant global production, they fall outside the conventional categorization of standard staple crops (FAO 1995; Ribeiro-Duthie et al. 2021).

Table 2.3: World production of oil seeds in tonnes in the year 2016

Oil seed	**Production (t)**	**Percentage (%)**	**Cumulative percentage (%)**
Soya beans	3.36×10^8	33.92	33.92
Oil palm fruit	3.31×10^8	33.44	67.36
Groundnuts	6.96×10^7	7.03	74.39
Rape or colza seed	6.82×10^7	6.89	81.28
Coconuts	5.85×10^7	5.91	87.19
Sunflower seed	4.75×10^7	4.80	91.99
Cotton seed	4.14×10^7	4.18	96.17
Olives	2.00×10^7	2.02	98.18
Sesame seed	5.35×10^6	0.54	98.72
Mustard seed	6.85×10^5	0.07	98.79
Other oilseeds	1.19×10^7	1.21	100

2.2 Agricultural water footprint

The unit water footprint (uWF) for evaluating crop cultivation is determined by dividing the crop's water consumption during the growing season (measured in millimeters) by the crop yield (expressed in tonnes per hectare) and then multiplying the result by 10. This yields the uWF, which is expressed in cubic meters per tonne or equivalently in liters per kilogram. We recall that the calculation of uWF relies on quantifying crop evapotranspiration, which can be categorized as either green or blue depending on the water source used for irrigation; however, the present work considers the sum of green and blue water footprint (Tamea et al. 2021).

To compute the total water footprint of a particular product, it is sufficient to multiply its total production quantity by its corresponding unit WF. The total WF is measured in cubic meters or liters, providing a comprehensive assessment of the water resources consumed throughout the production process. Reference unit WF values for every commodity and country, for year 2016, are taken from CWASI 2021.

2.3 Food loss and waste

We now recall the five categories of food loss and waste depicted in Section 1.2: agricultural losses, post-harvest losses, processing losses, distribution waste and consumption waste.

Tables 2.4, 2.5 and 2.6 provide insights into the distribution of losses and waste across the five stages of the food value chain, specifically for cereals, roots and oil seeds. The categorization of countries follows the segmentation proposed by Gustavsson et al. 2011, grouping them into seven world regions not solely based on geographical boundaries, but rather by endeavoring to cluster them according to economic and industrial similarities (e.g., Oceania is grouped with North America). The reported shares correspond to the fraction of the input quantities at each stage that are lost or wasted. Distinctions between milling and baking processes are made for cereals, when applicable.

In general, high-income countries tend to exhibit lower proportions of agricultural, post-harvest, and processing losses compared to their low-income counterparts. On the flip side, consumption waste tends to be considerably higher in high-income countries. For instance, regarding cereals, Europe demonstrates agricultural losses of merely 2%, coupled with a substantial consumption waste of 25%. In contrast, Sub-Saharan Africa experiences agricultural losses three times higher (6%), yet the consumption waste remains minimal at 1%.

The disparity between high and low-income countries becomes less apparent when examining roots and oil seeds, as industrialized nations continue to waste more in the final stages of the supply chain, but the losses in the first stages are similar to developing economies.

Table 2.4: Shares of loss and waste for the 5 stages of the food value chain in the case of cereals. In the processing column, the first number corresponds to milling, while the second number pertains to baking.

Region	Shares of loss and waste (%) for each stage				
	Agricultural	Post-harvest	Processing	Distribution	Consumption
Europe (incl. Russia)	2	4	0.5, 10	2	25
North America and Oceania	2	2	0.5, 10	2	27
Industrialized Asia	2	10	0.5, 10	2	20
Sub-Saharan Africa	6	8	3.5	2	1
N. Africa; West & Centr. Asia	6	8	2, 7	4	12
South and Southeast Asia	6	7	3.5	2	3
Latin America	6	4	2, 7	4	10

Table 2.5: Shares of loss and waste for the 5 stages of the food value chain in the case of roots and tubers.

Region	Shares of loss and waste (%) for each stage				
	Agricultural	Post-harvest	Processing	Distribution	Consumption
Europe (incl. Russia)	20	9	15	7	17
North America and Oceania	20	10	15	7	30
Industrialized Asia	20	7	15	9	10
Sub-Saharan Africa	14	18	15	5	2
N. Africa; West & Centr. Asia	6	10	12	4	6
South and Southeast Asia	6	19	10	11	3
Latin America	14	14	12	3	4

Table 2.6: Shares of loss and waste for the 5 stages of the food value chain in the case of oil seeds and pulses.

Region	Shares of loss and waste (%) for each stage				
	Agricultural	Post-harvest	Processing	Distribution	Consumption
Europe (incl. Russia)	10	1	5	1	4
North America and Oceania	12	0	5	1	4
Industrialized Asia	6	3	5	1	4
Sub-Saharan Africa	12	8	8	2	1
N. Africa; West & Centr. Asia	15	6	8	2	2
South and Southeast Asia	7	12	8	2	1
Latin America	6	3	8	2	2

Chapter 3

Methods

3.1 Modelling food loss and waste along the supply chain

Loss and waste in the global food supply chain exhibit significant disparities based on various factors, with distinct patterns emerging at different phases. The geographical location plays a crucial role in shaping these variations, and we can identify three key stages where this influence is prominent:

1. the country of production, for agricultural and post-harvest stages;
2. the country of processing, for processing stage;
3. the country of consumption, for distribution and consumption stages.

Processing activities play a pivotal role in yielding various food commodities from a given primary crop or processed product (e.g., milling transforms wheat into wheat flour, while baking turns flour into bread). Despite the fact that derived products are traded separately, it is imperative to meticulously track loss and waste flows across products to reconstruct the entire intricate and interconnected food supply network. To achieve this, we conceptualized commodities as interrelated variables linked through processing, categorizing them into:

1. primary products, harvested from the field (level 0);
2. derived products, produced after primary products (level 1) or from other derived products (level 2 and following).

Furthermore, all products in this network may undergo processing or be consumed in their raw form, emphasizing the need to track and understand the entire supply chain. In the case of the wheat commodity tree, as depicted in Figure 2.2, the corresponding products were classified in the following way:

1. wheat is the primary product;

2. flour of wheat and bran are derived products of level 1;

3. bread and pasta are derived products of level 2.

In the following paragraphs, the level of the product which variables refer to will be marked as a superscript. For example L^0_{S1} is defined as agricultural losses of the primary product (wheat), while D^2 represents the domestic supply of a derived product of level 2 (e.g., bread). This hierarchical organization allows us to attribute specific stages of food loss and waste to specific products and to define flow relations between food commodities, improving from previous methodologies that lumped together primary products and derived ones.

A schematic representation of the proposed methodology, following Semeria et al. 2024, is presented in Figure 3.1, illustrating the supply chain of a generic food commodity from production to consumption. While we use the case of wheat and its derived products in Italy as an illustrative example to enhance comprehension, it's important to note that the procedure is adaptable to any crop product or its transformed derivatives. For primary products, the top layer in Figure 3.1, we calculate agricultural losses (L^0_{S1}) after net domestic production as in Gustavsson et al. 2011:

$$L^0_{S1} = \frac{l^0_{s1}}{1 - l^0_{S1}} \cdot P^0_N \tag{3.1}$$

where l^0_{s1} indicates the specific share of agricultural losses of the region to which the country belongs. Gross domestic primary production (P^0_G) is the sum of net domestic production and agricultural losses (i.e., $P^0_G = P^0_N + L^0_{S1}$). For example, as net wheat production amounts to 8.04×10^6 tonnes and agricultural losses share (l^0_{s1}) is 2% for Italy, gross wheat production is 8.20×10^6 tonnes and agricultural losses 1.64×10^5 tonnes. Post-harvest losses (L^0_{S2}) are then subtracted to net primary local production as a share of net primary production.

$$L^0_{S2} = l^0_{S2} \cdot P^0_N \tag{3.2}$$

In our example, given a post-harvest losses share l^0_{S2} of 4% for Italy, post-harvest losses amount to 3.22×10^5 tonnes and post-harvest wheat output ($H^0 = P^0 - L^0_{S2}$) is 7.72×10^6 tonnes.

The first two losses of the supply chain (L^0_{S1} and L^0_{S2}) occur in the country of primary production and therefore only impact domestic water resources. The following three stages of loss and waste (processing, distribution, consumption) instead, impact countries' domestic supply (D^0), which is constituted by post-harvest quantities originating from domestic production ($H^0 = P^0_N - L^0_{S2}$) and

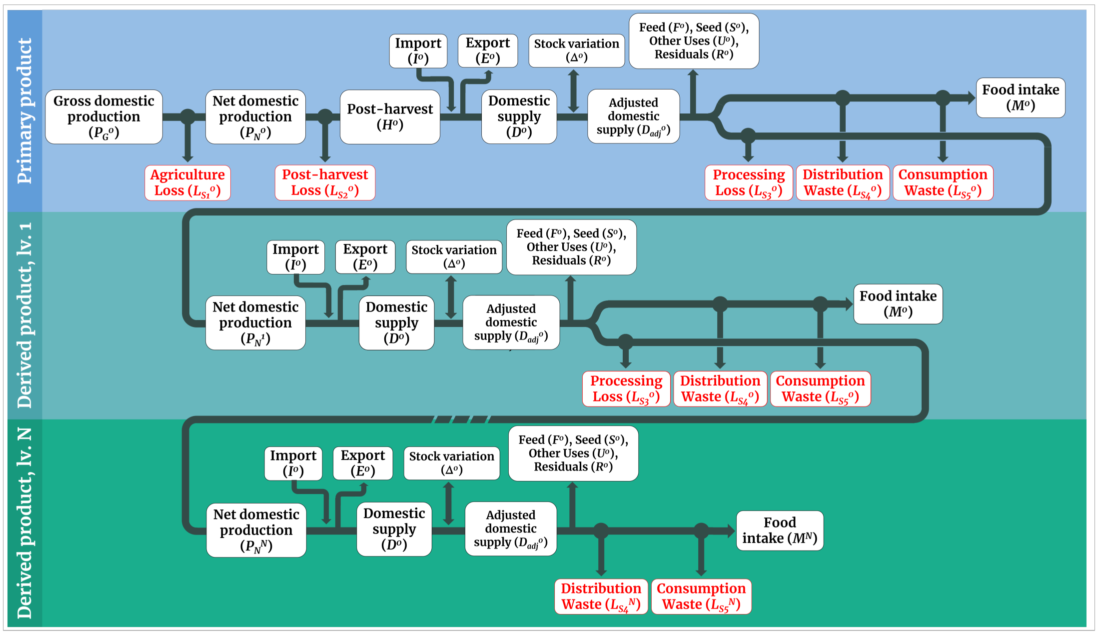

Figure 3.1: Scheme of flow of a generic food supply chain, as modelled in this work. From gross food production of primary products, food wastes and losses (in red) occur along the chain, reducing the quantity to the one being consumed as food intake. Import, export and other outflows also need to be considered, after domestic agricultural and post-harvest losses are accounted for.

imports from the international trade network (I^0), while exports (E^0) are to be subtracted:

$$D^0 = H^0 + I^0 - E^0 \tag{3.3}$$

We now have to consider potential stock variations in the domestic supply (Δ^0), hence we define the adjusted domestic supply ($D^0_{adj} = D^0 - \Delta^0$). The quantity in the adjusted domestic supply can be destined to different purposes as shown in Equation 3.4: quantities of primary products directed to food consumption (C^0); quantities of primary products which are directed to processing (T^0), to be transformed into a derived product of level 1; quantities destined to non-food uses (U^0); feed (F^0); seed (S^0) and residuals (R^0).

$$D^0_{adj} = C^0 + T^0 + U^0 + F^0 + S^0 + R^0 \tag{3.4}$$

As depicted in Figure 3.1, the absence of detailed information on the specific uses of domestic and imported products at a global scale precludes the ability to distinguish between their origins without making assumptions. In our illustrative example, Italy imports 7.65×10^6 tonnes of wheat and exports 4.54×10^5 tonnes, while feed and seed quantities are respectively 1.72×10^6 tonnes and 3.58×10^5 tonnes. Residuals are negligible and stock variation is 1.0×10^6 tonnes. The adjusted domestic supply results in 1.18×10^7 tonnes.

For the first outflow (C^0) of Equation 3.4, which bypasses processing, no specific processing losses are attributed; instead, it is subject to distribution (L^0_{S4}) and consumption losses (L^0_{S5}). Distribution waste (L^0_{S4}) is computed as a share of the food consumption quantity C^0:

$$L^0_{S4} = l^0_{S4} \cdot C^0 \tag{3.5}$$

The output quantity A^0, derived by reducing C^0 by the quantity of L^0_{S4}, represents primary crops that are brought to the consumer as food, and it is subject to the last stage of food waste (L^0_{S5}), related to consumption waste:

$$L^0_{S5} = l^0_{S5} \cdot A^0 \tag{3.6}$$

where l^0_{S5} is the share of consumption waste. Conversely, the second set of quantities (T^0) necessitates the consideration of specific processing losses (L^0_{S3}), calculated as percentage shares of quantities of primary product that undergo processing (l^0_{S3}):

$$L^0_{S3} = l^0_{S3} \cdot T^0 \tag{3.7}$$

Processing losses (L^0_{S3}) for wheat are intricately tied to milling operations, with a set rate of 0.5% in Italy. Consequently, the computed processing losses stand at 5.9×10^4 tonnes.

To link level-1 derived food commodities to primary ones, we assume that the processed quantity $B^0 = (T^0 - L^0_{S3})$ is equivalent to the cumulative production quantity of the level-1 derived products, since FAOSTAT data are already adjusted for extraction rates:

$$B^0 = \sum_i P^1_i \tag{3.8}$$

For wheat, it equals the production of wheat's derived products of level 1: flour of wheat and bran of wheat. Considering one generic derived product, losses are defined in a similar way as they were for primary ones. However, no agricultural and post-harvest losses (L^1_{S1} and L^1_{S2}) occur, as they are specific of primary products. Domestic supply for level 1 derived products is then computed as follows:

$$D^1 = P^1 + I^1 - E^1 \tag{3.9}$$

where P^1 is defined as the domestic production of the derived product of level 1 and all the other terms of the equation indicate the same variables as in Equation 3.3, but referred to the derived product of level 1 instead of the primary one. Taking flour of wheat as an example of derived product of level 1, its production is 8.71×10^6 tonnes. Multiple outflows can be present also in the case of derived products, when a fraction of the commodity is consumed raw another one is processed and all the other ones described earlier. For flour, 7.22×10^6 tonnes are directed to processing and 1.26×10^6 tonnes to food consumption. Losses L^1_{S3} and waste L^1_{S4} and L^1_{S5} are computed in the same way as the ones relative to primary products. For flour, they amount respectively to 7.22×10^5 tonnes (10% losses associated with baking), 2.52×10^4 tonnes (2% distribution waste rate) and 3.09×10^5 tonnes (25% consumer waste rate).

As figure 3.1 shows, many different levels of derived products can be present in a single supply chain. Eventually, at the last level (level N) of the chain, only products which are not processed further are present. Then, at level N, no processing losses (L^N_{S3}) are present, and only distribution- and consumer-level waste need to be considered. Taking bread as an example of level N derived product ($N = 2$), its production is 2.89×10^6 tonnes, and the quantity directed to domestic food consumption is 2.87×10^3 tonnes. Waste L^2_{S4} and L^2_{S5} are respectively 5.75×10^4 tonnes (2% distribution waste rate) and 7.04×10^5 tonnes (25% consumer waste rate).

3.2 Tracing food loss and waste along supply networks

As detailed in the preceding section, losses occurring in any country can have repercussions on both domestic water resources and resources belonging to other countries. The extent of this impact is contingent upon the specific loss stage and the supply network of the food commodity in the country where the loss occurs. Figure 3.2 illustrates the intricate nature of one layer (wheat) within such a network, involving numerous countries.

Notably, bilateral trade matrices ($\mathbf{Z}$) quantify the exchange of food commodities between countries. However, countries frequently re-export food that they have previously imported, leading to feedback loops within the network. This dynamic complexity complicates the understanding of the origin of exports. Furthermore, the network may encompass multiple layers of trade, one for the primary product (Figure 3.2) and additional layers for each of its derived products, as better shown in Appendix B. These layers are nested and interconnected through processing, as depicted earlier in Figure 3.1.

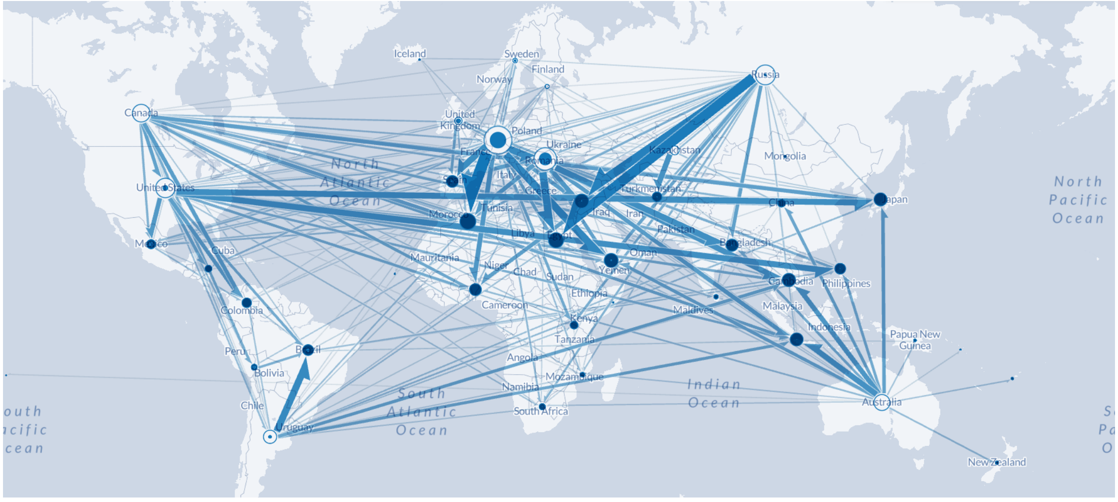

Figure 3.2: Complexity of the wheat trade network: flows of wheat (layer 0) around the World.

3.2.1 Kastner's algorithm

Within the network of a specific food commodity, domestic supply in a given country is reconnected to its production origin by means of the algorithm applied in T. Kastner, M. Kastner, et al. 2011. When aiming to determine the origin of materials in consumed products, a fundamental assumption regarding the distribution of domestically produced and imported products between consumption and exports becomes essential. As shown in Figure 3.3, due to the absence of detailed information at the national level, it is common to adopt a proportional distribution assumption (Erb 2004; Oel et al. 2009; T. Kastner and Nonhebel 2010), i.e. the same proportions are allocated to consumption and exports. Consequently, a country's consumption is presumed to originate from proportional shares of its own production and imports. The origin of the latter can be further specified by utilizing bilateral trade data.

To conceptualize and develop the method, we present a simplified example setting, containing only four trading partners, handled in this study. In the context of agricultural products, the aim of our calculation is to determine where the crops contained in products consumed in a given nation were actually cultivated.

The following data are required to perform the calculation:

1. production data giving the amount of the primary product domestically produced for all trading partners (in tonnes);

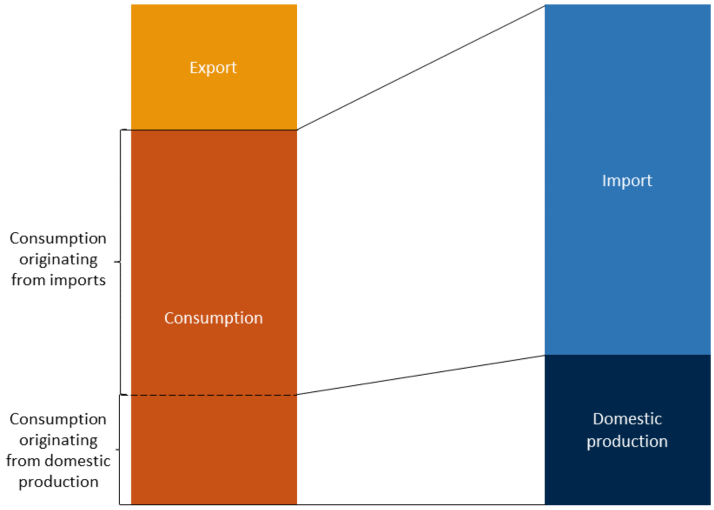

Figure 3.3: The products consumed in a given country originate in proportional shares from the country's imports and own domestic production; this implies the same composition for the country's exports.

2. bilateral trade data for the primary product and secondary products derived from it (in tonnes);

3. conversion factors to convert secondary products into primary equivalents;

4. factors for the assessed environmental impact per unit primary product (in impact/tonne).

It is crucial to emphasize that, for both production and trade considerations, the calculations rely on data pertaining to the physical quantities of the flows. In this specific example, the environmental impact being assessed is the land required for cultivation. The process involves utilizing data on the average environmental impact per unit of the product, which must be available for all trading partners involved. Tables 3.1 and 3.2 offer a comprehensive overview of the input data employed in these calculations.

The input data include information on domestic production and bilateral trade across all partners. While the assumption presented in Figure 3.3 provides a starting point, it introduces challenges addressed by the proposed approach. For instance, if country A imports substantial quantities of a good from country B, and country B either does not produce this good or does so in minimal quantities,

Table 3.1: Country with relative production and environmental impact.

Country	**Production (t)**	**Environmental impact (ha/t)**
A	200	1/6
B	1000	1/3
C	100	1/9
D	10	1/12
Total	1310	/

Table 3.2: Bilateral trade data **Z** in tonnes between units, the rows represent the importers, the columns represent the exporters.

Export/Import (t)	A	B	C	D	Total Import
A	0	0	100	200	300
B	0	0	0	0	0
C	50	350	0	50	450
D	50	200	200	0	450
Total Export	100	550	300	250	/

the assumption that the product originates from country B becomes untenable. Clearly, country B must have imported the product from elsewhere. The proposed approach addresses this limitation by incorporating information on the proportional composition of the supply from trading partners, enabling a more accurate tracing of the origin of the product.

To discern the origins of the crops contained in products consumed in a specific nation, it is necessary to delve into the sources of crop products constituting a country's total domestic material input (DMI, i.e., domestic production plus imports, presented in primary equivalents). To facilitate this analysis, we introduce a matrix $\mathbf{R}$, where each element r_{ij} represents the portion of the DMI x_i of the country i that is produced in country j. The vector of DMIs can be calculated from production and trade data as:

$$\mathbf{x} = \mathbf{p} + \mathbf{Z} \cdot \mathbf{i} \tag{3.10}$$

where $\mathbf{p}$ is the production vector (p_i elements are produced in country i), $\mathbf{Z}$ is the matrix of bilateral trade data (z_{ij} are the exports of country j to country i) and i is a vector of ones (i.e. a summation vector). Our first approximation for $\mathbf{R}$, purely based on reported trade flows, is

$$\mathbf{R}^A = \hat{\mathbf{p}} + \mathbf{Z} \tag{3.11}$$

The matrix $\hat{\mathbf{p}}$ is a diagonal matrix containing the elements of the vector p. This approximation is commonly used in studies on land and water footprints (Hoekstra and Hung 2005; Kissinger et al. 2010) and introduces a challenge that the described methodology seeks to address: the case where the exporting country sources the materials for its exports not from its own production but through imports.

If we define a matrix of export shares,

$$\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \tag{3.12}$$

where a_{ij} is the share of exports from country j to country i in country j's DMI, we can rewrite Equation 3.11 as

$$\mathbf{R}^A = \hat{\mathbf{p}} + \mathbf{A} \cdot \hat{\mathbf{p}} + \mathbf{A} \cdot (\hat{\mathbf{x}} - \hat{\mathbf{p}}). \tag{3.13}$$

The term $\hat{\mathbf{x}}^{-1}$ in Equation 3.12 denotes a diagonal matrix built up by the reciprocal elements of $\mathbf{x}$. In Equation 3.13 we split the trade data, containing the reported imports $\mathbf{Z}$, proportionally in a part that originates directly from the sending countries' production (second term) and a part that is imported by the sending countries (third term). To refine the first estimate, we now relocate these second order inputs using the original trade matrix to

$$\mathbf{R}^B = \hat{\mathbf{p}} + \mathbf{A} \cdot \hat{\mathbf{p}} + \mathbf{A} \cdot \mathbf{Z} \tag{3.14}$$

and again split $\mathbf{Z}$ into two parts, resulting in

$$\mathbf{R}^B = \hat{\mathbf{p}} + \mathbf{A} \cdot \hat{\mathbf{p}} + \mathbf{A} \cdot \mathbf{A} \cdot \hat{\mathbf{p}} + \mathbf{A} \cdot \mathbf{A} \cdot (\hat{\mathbf{x}} - \hat{\mathbf{p}}). \tag{3.15}$$

As the input data $\mathbf{Z}$ and $\mathbf{p}$ contain only non-negative elements, for Miller et al. 2009; Hubbard et al. 2015 it follows

$$\mathbf{R} = \underset{s\to\infty}{lim}\left(\sum_{n=0}^{s}(\mathbf{A}^n)\right) \cdot \hat{\mathbf{p}} + \underset{s\to\infty}{lim}(\mathbf{A}^s) \cdot \mathbf{Z} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \hat{\mathbf{p}}, \tag{3.16}$$

where $\mathbf{I}$ is an identity matrix with the same dimensions as $\mathbf{A}$.

From matrix $\mathbf{R}$ we now know where the DMI of each considered country originates from. Assuming equal distribution between consumption and exports, this can be easily extended to derive a matrix

$$\bar{\mathbf{R}} = \hat{\mathbf{c}} \cdot \mathbf{R} \tag{3.17}$$

where r_{ij} is the part of the apparent consumption of country i originating from country j. $\mathbf{c}$ is the vector of consumption shares, where

$$c_i = \frac{1}{x_i}\left(x_i - \sum_k z_{kj}\right) \tag{3.18}$$

is the share of material consumed in country i in its DMI. And $\hat{\mathbf{c}}$ is the corresponding diagonal matrix. Assuming the same distribution of origin $\mathbf{c}$ can be replaced by other units of consumption for which the impacts at the places of origin/crop cultivation are to be analyzed.

The results of this simple example, applying the proposed method are shown in Table 3.3, where we understand that we obtain different values in the matrices $\mathbf{R}^A$ and $\bar{\mathbf{R}}$. For example, A imports from D an amount equal to 160 tonnes; however, only 4t are actually produced by D.

Table 3.3: Consumption in tonnes according to origin, calculated with the reported trade data $\mathbf{R}^A$ compared to values obtained with the suggested calculation procedure $\bar{\mathbf{R}}$.

Place of consumption	**c**	$\mathbf{R}^A$				$\bar{\mathbf{R}}$			
		A	B	C	D	A	B	C	D
A	400	160	0	80	160	174	191	31	4
B	450	0	450	0	0	0	450	0	0
C	250	23	159	45	23	11	188	49	1
D	210	23	91	91	5	14	171	20	5

3.2.2 Integration of Kastner's algorithm in the modelling framework

We now apply the algorithm explained in the previous section in order to map water resources used in agricultural production.

By normalizing the rows of $\mathbf{R}$ to 1, resulting in the matrix $\mathbf{R}^n_{norm}$, we can observe the relative contributions of all producing countries to the DMI of country i. Then, knowing the vector of overall quantities of food loss and waste at the generic stage s, and for the generic product level n (l^n_s) occurring in country i, we can use this matrix to estimate the amount of such losses originating in each country j within network n ($\mathbf{L}_s^{n,n}$). This approach allows to trace the origin within the network of the single commodity.

$$\mathbf{L}_s^{n,n} = l_s^n \mathbf{R}_{norm}^n \tag{3.19}$$

As an illustration, we can measure the quantity of wheat lost at the processing stage in Italy, sourced from Canada, amounting to 4.44×10^3 tonnes. Similarly, we can assess the amount of flour wasted at the consumption stage in France, which has been milled in Germany, totaling 1.64×10^3 tonnes.

A nested application of the algorithm allows instead to trace the origin across the networks of the commodities (e.g., 1.91×10^4 tonnes is the amount wheat grown in the U.S. that has been wasted as bread at the distribution stage in Germany), by applying the $\mathbf{R}_{norm}$ matrices relative to the products of the supply chain (from level n to the primary product of level 0).

$$\mathbf{L}_s^{n,0} = l_s^n \mathbf{R}_{norm}^n \cdot \mathbf{R}_{norm}^{n-1} \cdot \ldots \cdot \mathbf{R}_{norm}^0 \tag{3.20}$$

Taking again the bread consumed in Italy as an example for a derived product of level N (N = 2), consumption waste (L_{S5}^2) gets subdivided between all countries belonging to the upstream trade networks (bread, flour, wheat), resulting in 3.55×10^5 tonnes of wheat cultivated in Italy, 5.06×10^4 tonnes in France and 5.21×10^4 tonnes in Canada.

In previous studies, the application of this algorithm involved transforming derived products into primary equivalents in both production vectors and trade matrices. This was necessitated by the lack of more detailed datasets about derived products, imposing a significant limitation on analyses. Consequently, a single, non-product-specific trade network was artificially constructed, leading to unclear bilateral relations between countries, as no information about the specific food commodities could be derived. In contrast, the proposed methodology empowers us to distinctly define various trade networks and their interconnections.

Once the relationship between countries of food production and those experiencing food loss is established, we can quantify virtual water trade between them. This involves multiplying the quantities of food commodities produced by each country by the value of their specific unit water footprints of production (uWFp). While uWFp remains unchanged, as it depends only on local production, the application of the proposed methodology may introduce changes in the assessment of the unit water footprints of supply (uWFs). This shift arises from the underlying assumption of the methodology, which implies a change in the supply network of the countries involved.

The model assesses FLW, along with the associated wasted water, by reconstructing a network for each analysed food commodity. This approach offers a dual perspective on the geographical distribution of each stage of FLW.

1. Farm to fork perspective: it traces FLW associated with the cultivation of a primary crop in each country or region, connecting it forward to the countries where the FLW is generated.

2. Fork to farm perspective: it traces FLW linked to the consumption of food in a specific country or region, reconnecting it back to the countries of production.

Additionally, this approach is extended to include the feed side.

1. Farm to feeder perspective: it traces FLW associated with the cultivation of a primary crop in each country or region, connecting it forward to the countries where the FLW is generated. However, it is equal to the farm to fork perspective up to the processing level, as distribution and consumption waste for feed are not considered in the model. Hence, it won't be part of our analysis.

2. Feeder to farm perspective: it traces FLW linked to the feed in a specific country or region, reconnecting it back to the countries of production.

Chapter 4

Results

4.1 Wheat

In this chapter, we unveil the outcomes derived from our comprehensive analysis with an initial emphasis on wheat. Wheat cultivation covers an estimated 2.17×10^8 hectares globally, establishing it as the most extensively grown crop worldwide (Erenstein, Jaleta, Mottaleb, et al. 2022). This deliberate focus allows us to gain an expansive perspective on the water footprint associated with the food loss and waste of wheat and its derivatives, from the complementary perspective of production, food consumption and feed consumption. By delving into the intricate details of this essential crop, we aim to provide a solid understanding of its environmental impact, shedding light on the complex interplay between water usage and agricultural practices across various regions.

From a consumption-side perspective, considering food and feed intake joint, the water footprint relative to the losses and waste of wheat amounts to $3.77 \times 10^{11}\ m^3$, more than three times the volume of the waters in the Dead Sea ($1.14 \times 10^{11}\ m^3$). In Figure 4.1, we present a chord diagram illustrating the top 100 virtual water fluxes attributed to losses and waste in the food and feed intake of wheat and its derivatives. Notably, self-fluxes (such as those involving wheat produced in a specific country and consumed as bread within the same country) have been deliberately excluded from this figure. By focusing exclusively on external virtual water fluxes associated with FLW, this diagram provides a clear and insightful visualization of the significant contributors to the global interconnections of the water footprint. It's worth mentioning that the colors of the fluxes in the diagram are coded based on the region of the country, following Gustavsson et al. 2011, adding an additional layer of information to the visualization. This regional distinction enhances our understanding of the geographical distribution of virtual water fluxes, providing a more complete perspective on the global impact of the FLW of wheat and its derivatives on water resources. Specifically, the North America & Oceania region predominantly acts as an exporter in terms of water fluxes. This implies that the region expends water resources in producing goods that are ultimately consumed in other regions. On the other hand, Industrialized Asia, Sub-Saharan Africa, and South & Southeast Asia operate as importers, indicating that they consume products whose water footprint belongs to other regions. In contrast, Europe, Latin America, and North Africa, West & Central Asia exhibit a more complex pattern with numerous inbound and outbound fluxes. This signifies a substantial amount of water exchanges both towards other regions and within countries of the same region. Notably, the highest fluxes of water are: from Russia to Egypt 1.76×10^9 m^3, from Kazakhstan to Uzbekistan 1.71×10^9 m^3 and from Argentina to Brazil 1.33×10^9 m^3.

Figure 4.1: Chord diagram depicting the top 100 virtual water fluxes attributed to the FLW of food and feed intake of wheat and its derivatives. Self-fluxes have been excluded for clarity.

4.1.1 Farm to fork perspective

To illustrate the production-side perspective, we examine the global water resources lost due to FLW associated with the utilization of wheat-based commodities, whether for food, feed, or other purposes. We can observe that the total water footprint amounts to 2.00×10^{11} m^3, as shown in Table 4.1. Focusing on specific items, raw wheat emerges as the most significant contributor to FLW-related virtual water, accounting for 1.08×10^{11} m^3 (54.08% of the total). Other notable contributors include flour (26.65%) and bread (13.41%). A detailed analysis of the value chain reveals that consumption and post-harvest stages are the primary sources of water wastage, with 6.14×10^{10} m^3 (30.74% of the total) and 5.60×10^{10} m^3 (28.02%) of water lost, respectively. In comparison, agricultural practices contribute 19.01%, processing 15.90%, and distribution 6.34%, playing comparatively less significant roles in the overall water wastage.

Table 4.1: Global water footprint disaggregated per each item of the wheat tree, divided by stage.

Item	**Water footprint (m^3), divided by stage**					**Total**	
	Agricultural	Post-harvest	Processing	Distribution	Consumption	m^3	%
Wheat	3.80×10^{10}	5.60×10^{10}	1.40×10^{10}	1.55×10^{7}	3.72×10^{7}	1.08×10^{11}	54.08%
Flour of wheat	0	0	1.77×10^{10}	6.07×10^{9}	2.95×10^{10}	5.33×10^{10}	26.65%
Bran of wheat	0	0	4.70×10^{7}	3.44×10^{8}	3.36×10^{9}	3.75×10^{9}	1.88%
Pasta	0	0	0	1.37×10^{9}	6.60×10^{9}	7.97×10^{9}	3.99%
Bread	0	0	0	4.87×10^{9}	2.19×10^{10}	2.68×10^{10}	13.41%
Total	3.80×10^{10}	5.60×10^{10}	3.18×10^{10}	1.27×10^{10}	6.14×10^{10}	2.00×10^{11}	100.00%

Now, our aim is to address the question: where does the waste generated from wheat produced in a specific country occur, and what is the corresponding water usage in those locations? This analysis involves identifying the countries that contribute to the waste of wheat produced in a given nation. For our examination of wheat producers, we adopt a methodical approach by selecting one country from each of the seven regions delineated by Gustavsson et al. 2011, as shown in Table 4.2. This selection is based on the criterion of highest wheat production, measured in tonnes. By strategically choosing leading producers from diverse regions, we aim to capture a representative snapshot of global wheat cultivation patterns. This method not only ensures a geographically balanced representation but also allows for a meaningful analysis of the varying dynamics influencing wheat production on a regional scale.

Table 4.2: Countries chosen for the analysis from a production-side perspective, with the corresponding region of belonging and production quantity of wheat.

Country	Region	Production (t)
China	Industrialized Asia	1.33×10^8
India	South & Southeast Asia	9.23×10^7
Russia	Europe	7.33×10^7
United States	North America & Oceania	6.28×10^7
Turkey	North Africa, West & Central Asia	2.06×10^7
Argentina	Latin America	1.13×10^7
Ethiopia	Sub-Saharan Africa	4.54×10^6

To enhance our understanding of the types of losses and waste, we have categorized them into the five distinct stages outlined in Table 1.1. Figure 4.2 visually presents the proportional utilization of freshwater resources across the stages for FLW. This depiction shows both the global scenario and the seven countries under consideration. While this initial comparison with the world average already offers valuable insights, such as the variations between industrialized and developing economies, it's important to note that these losses and waste, particularly from the processing stage, also occur in countries different from those where wheat is produced. Therefore, more detailed considerations will be made for each country individually.

To provide a comprehensive overview of the water volumes involved, Table 4.3 details the water footprint associated to the wheat crops of each analyzed country, segmented by stages. The global data is also incorporated for reference. Notably, distribution waste emerges as consistently low in comparison to other stages across all producers. Additionally, a noteworthy observation is that the combined water usage associated to FLW of wheat produced in China, India, Russia, and the United States accounts for more than 50% of the global water footprint.

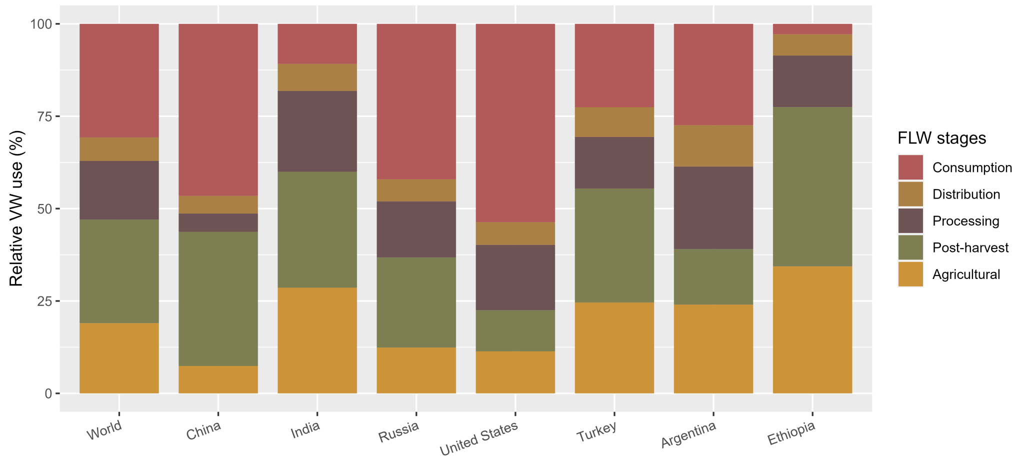

Figure 4.2: Relative use of freshwater resources for FLW of the wheat produced globally and in each specific country, by stage (%).

Table 4.3: Global and per country water footprint, divided by stage.

Country	**Total water footprint (m^3), divided by stage**					
	Agricultural	Post-harvest	Processing	Distribution	Consumption	Total
World	3.80×10^{10}	5.60×10^{10}	3.18×10^{10}	1.27×10^{10}	6.14×10^{10}	2.00×10^{11}
China	2.53×10^{9}	1.24×10^{10}	1.69×10^{9}	1.63×10^{9}	1.59×10^{10}	3.42×10^{10}
India	9.08×10^{9}	9.96×10^{9}	6.94×10^{9}	2.32×10^{9}	3.44×10^{9}	3.17×10^{10}
Russia	2.31×10^{9}	4.54×10^{9}	2.83×10^{9}	1.11×10^{9}	7.84×10^{9}	1.86×10^{10}
United States	1.95×10^{9}	1.91×10^{9}	3.03×10^{9}	1.05×10^{9}	9.20×10^{9}	1.71×10^{10}
Turkey	2.29×10^{9}	2.87×10^{9}	1.30×10^{9}	7.50×10^{8}	2.10×10^{9}	9.31×10^{9}
Argentina	9.20×10^{8}	5.76×10^{8}	8.55×10^{8}	4.29×10^{8}	1.05×10^{9}	3.83×10^{9}
Ethiopia	6.14×10^{8}	7.70×10^{8}	2.49×10^{8}	1.03×10^{8}	5.04×10^{7}	1.79×10^{9}

United States

Our analysis successfully identifies the countries where the losses and waste and their relative impact on freshwater resources of wheat produced in the U.S. occur. In Figure 4.2, we observe that the majority of the water waste is concentrated in the final stage of consumption (53.80%). Notably, both the agricultural and post-harvest stages are exclusively confined within the borders of the United States. Given this geographical limitation, the need for visualizing the losses' WF on a map becomes unnecessary for these stages. However, it's noteworthy to highlight that agricultural losses contribute to a water footprint of 6.04 m^3 per person, while post-harvest losses account for 5.92 m^3 of water per person. The significance of mapping becomes apparent when examining the processing stage, as depicted in Figure 4.3.

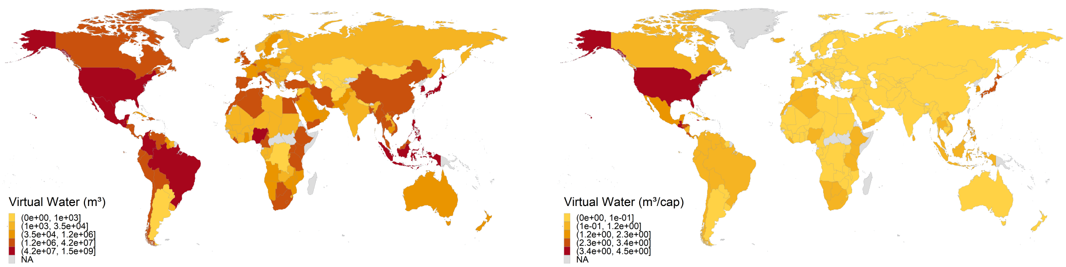

Figure 4.3: Water footprint relative to the processing losses of wheat produced in the U.S., both for total population (left) and per capita (right).

It is crucial to note that in the figure two types of maps are presented. On the left side, the map illustrates the distribution between the countries of the water footprint concerning the processing losses of wheat produced in the United States, considering the total population of the different countries. In the context of total population, the classification depicted on these maps, as well as subsequent ones in this chapter, is determined through the application of a logarithmic scale with base 10 to the values of the virtual water. Additionally, a minimum threshold, set at 1×10^3 m^3, is employed, below which all values are uniformly categorized into the same class. Meanwhile, on the right side, the same map is presented on a per capita basis. The concept of "per capita" is applied by dividing the total volumes by the number of inhabitants of the country where the loss or waste is occurring. In the case of per capita data, the classes are determined applying a linear scale with a threshold set at 0.1 m^3/cap.

Examining Figure 4.3, it becomes apparent that the United States exports wheat that undergoes further processing in various parts of the world. This observation aligns with the fact that the United States is the second-largest wheat exporter globally. Going into more detail, from a total population perspective, the countries with the highest water footprint of food loss and waste in the processing stage of wheat produced in the United States, excluding the U.S. itself (which accounts for

1.47×10^9 m^3 of water), are as follows: Japan with 3.10×10^8 m^3, Mexico with 1.66×10^8 m^3, and the Philippines with 1.36×10^8 m^3. On a per capita basis, the United States takes the lead with a substantial water footprint of 4.54 m^3 per person. Following closely are El Salvador with 4.36 m^3 per capita, Jamaica with 4.24 m^3/cap, and Guatemala with 3.44 m^3/cap.

Transitioning to the distribution stage, the outcomes of our analysis are depicted in Figure 4.4. When considering the total population, the United States consistently leads with the highest water footprint at 5.51×10^8 m^3, followed by Mexico at 5.77×10^7 m^3, Japan at 5.49×10^7 m^3, and Brazil at 4.06×10^7 m^3. Shifting to a per capita perspective we find one peculiarity: Jamaica emerges as the frontrunner with a water footprint of 2.80 m^3 per person, followed by Belize at 2.64 m^3/cap, the United States are only third at 1.71 m^3/cap, and El Salvador at 1.44 m^3/cap.

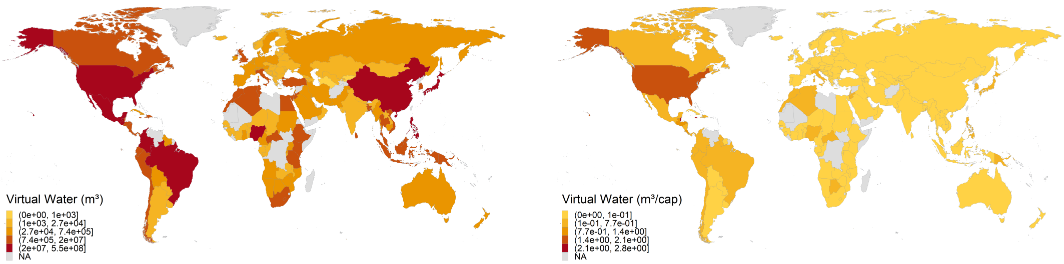

Figure 4.4: Water footprint relative to distribution waste of wheat produced in the U.S., both for total population (left) and per capita (right).

Concluding with the consumption stage, the findings are illustrated in Figure 4.5. When considering the total population, the United States leads in water wastage with 7.29×10^9 m^3, followed by Japan with 5.38×10^8 m^3, China with 1.99×10^8 m^3, and the Republic of Korea (South Korea) with 1.44×10^8 m^3. From a per capita standpoint, the United States again holds the top position with a water wastage of 22.56 m^3 per person, followed by Jamaica wasting 6.71 m^3/cap, Belize with 6.34 m^3/cap, and Japan wasting 4.23 m^3/cap. On the contrary China falls behind with only 0.14 m^3/cap.

To offer a comprehensive view of the total water footprint of FLW associated with wheat produced in the U.S., Figure 4.6 presents an integrated depiction of all stages of losses and waste. From a total population perspective the United States wastes 1.32×10^{10} m^3 of freshwater resources, followed by Japan 9.03×10^8 m^3, Mexico 3.62×10^8 m^3 and China 2.40×10^8 m^3. While considering the volumes

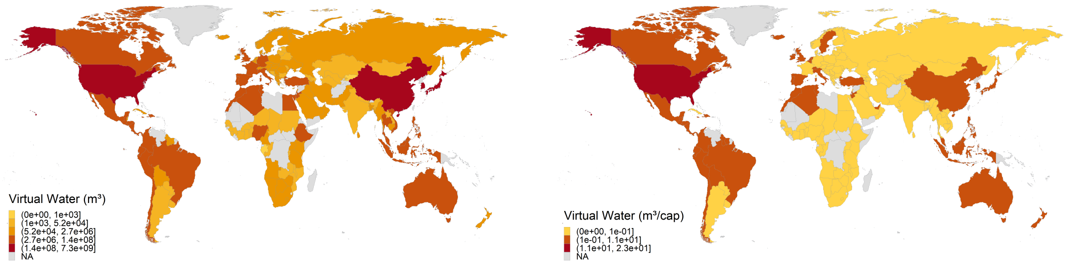

Figure 4.5: Water footprint relative to the consumption waste of wheat produced in the U.S., both for total population (left) and per capita (right).

per person, the United States waste 40.75 m^3/cap of water, Jamaica 13.74 m^3/cap and Belize 10.72 m^3/cap. Japan is still consistent with 7.10 m^3/cap, while Mexico (2.98 m^3/cap) and China (0.17 m^3/cap) are far behind.

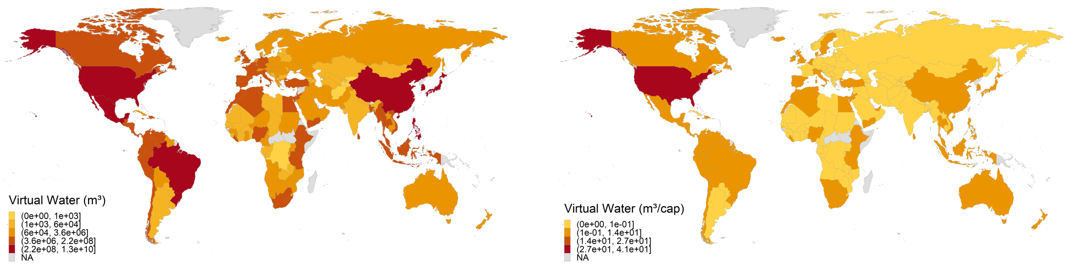

Figure 4.6: Water footprint relative to the FLW of wheat produced in the U.S., both for total population (left) and per capita (right).

China

China holds the position of the world's largest wheat producer. As discerned from Figure 4.2, it becomes evident that the most substantial volumes of water associated with food loss and waste of wheat produced in China are attributed to post-harvest losses (36.29%) and consumption waste (46.61%).

Particularly, post-harvest losses are entirely localized within China, but it is still impressive to note that these losses account to 8.94 m^3 per capita in terms of water usage. However, the visualization of the map for the consumption stage, shown in Figure 4.7, proves particularly insightful. Additional maps can be referenced in

Appendix C.1.1 for a comprehensive examination of other stages (the same applies to the maps of other countries in this subsection that are not displayed in the text).

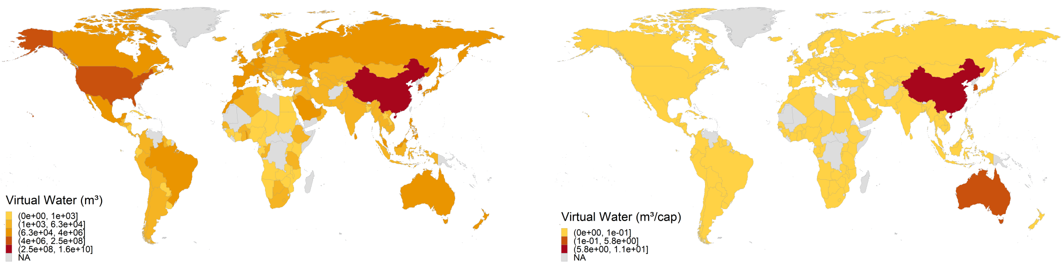

Figure 4.7: Water footprint relative to the consumption stage of wheat produced in China, both for total population (left) and per capita (right).

From a total population perspective, it becomes evident that a significant portion of the wheat produced in China is consumed domestically. Specifically, the water footprint associated with the consumption waste is substantial within China with 1.59×10^{10} m^3. The other countries with the next highest water footprints are the Republic of Korea at 1.33×10^7 m^3, the United States at 9.46×10^6 m^3, and Japan at 3.02×10^6 m^3. Significantly, a mere 0.23% of the water footprint associated with the FLW in the consumption stage of wheat produced in China occurs outside the borders of China itself. This pattern is also apparent when considering per capita figures, where China dominates with a WF amounting to 11.45 m^3 per capita. The subsequent countries are less relevant, with the highest water usage per capita being in the Republic of Korea at 0.26 m^3/cap, in Australia at 0.11 m^3/cap, and in Canada at 0.06 m^3/cap.

India

India holds a prominent position as the major wheat producer in the South & Southeast Asia region. An intriguing observation can be made from the barstack presented in Figure 4.2. In contrast to the previous countries discussed, the water footprint associated with the consumption stage in India is notably lower (10.84%) compared to the agricultural (28.61%), post-harvest (31.38%), and processing stages (21.86%). This suggests that India, as an emerging economy, is still navigating challenges and inefficiencies in managing losses and waste in the first stages of wheat value chain.

Specifically, the water footprint for agricultural losses amounts to 6.79 m^3 per capita, while the freshwater resources used for post-harvest losses are 7.44 m^3 per capita. For a comprehensive understanding of processing losses, Figure 4.8 provides an informative overview of countries with the highest water footprints in this stage. In particular, the water footprint associated with the processing stage is predominantly internal, amounting to 5.17 m^3 per capita. The subsequent countries, even if not very relevant, are the United Arab Emirates at 0.42 m^3 per capita, Nepal at 0.32 m^3 per capita, and Oman at 0.08 m^3 per capita. Confirming this observation from a total population perspective, India accounts for 6.92×10^9 m^3 of water, followed by Nepal at 8.78×10^6 m^3, the United Arab Emirates at 3.75×10^6 m^3, and the United States at 2.83×10^6 m^3. Remarkably, 99.71% of the water footprint associated with the processing stage remains within the borders of India.

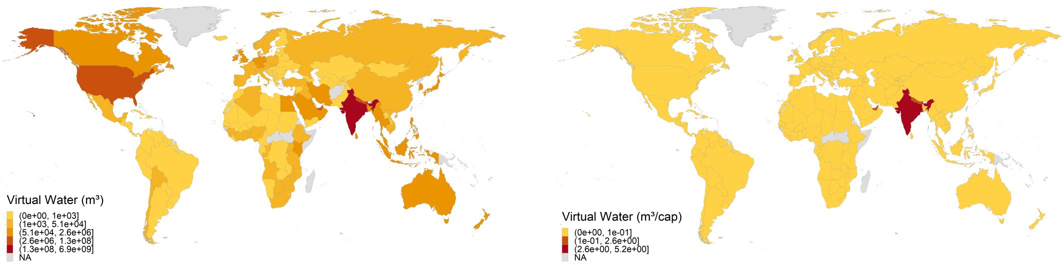

Figure 4.8: Water footprint relative to the processing losses of wheat produced in India, both for total population (left) and per capita (right).

Russia

Russia plays a pivotal role as the primary wheat producer in the European region. A notable observation can be made from Figure 4.2, similar to the trend seen in the United States. In both cases, a significant portion of the water footprint is associated with the consumption stage, in this case accounting to 42.08% of the total.

As it can be seen in the map of Figure 4.9, other than Russia itself, who is the cause of 5.98×10^9 m^3 of water used for wheat derivatives wasted in the consumption stage (or 42.40 m^3 per person), the countries with the highest volume of water are Egypt (5.88×10^8 m^3), Azerbaijan (2.22×10^8 m^3) and Turkey (2.17×10^8 m^3). Or considering the volume per person: Georgia (31.55 m^3/cap), Azerbaijan (22.72 m^3/cap) and Armenia (17.31 m^3/cap).

However, for a more in-depth examination, it's important to note that Russia is the top global exporter of unprocessed wheat. As such, we can delve deeper into

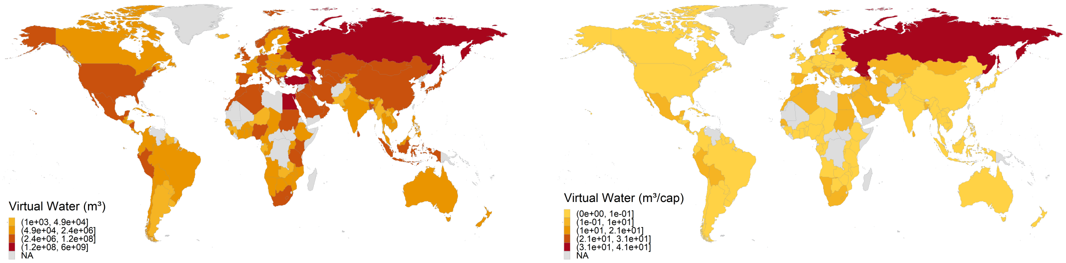

Figure 4.9: Water footprint relative to the consumption waste of wheat produced in Russia, both for total population (left) and per capita (right).

the water footprint associated with losses specifically occurring in the processing stage (milling) of wheat produced in Russia in order to make flour. This focused analysis excludes subsequent stages like the baking of flour to produce bread and pasta. Figure 4.10 visually presents the results of this analysis. Russia leads with 4.07×10^8 m^3 of water usage, however, it is remarkable that 72.22% of the water footprint considered lies beyond Russian borders. The other countries contributing the most to this footprint are Egypt (1.89×10^8 m^3), Nigeria (1.27×10^7 m^3), and Turkey (1.06×10^7 m^3), underlying the significant role of the African continent and the Middle East in the processing of wheat produced in Russia.

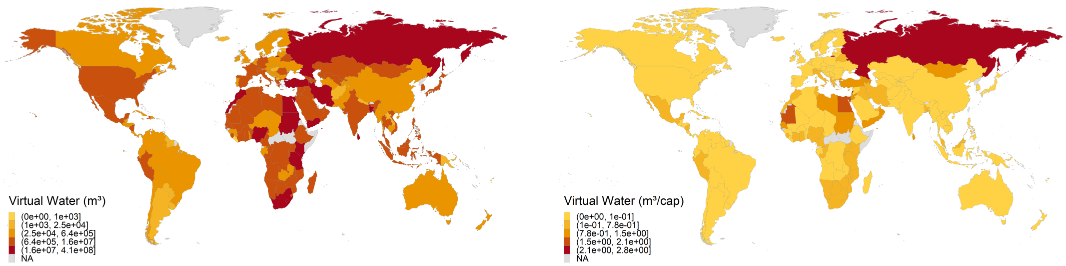

Figure 4.10: Water footprint relative to the processing losses of wheat produced in Russia, with consideration only given to milling into flour, both for total population (left) and per capita (right).

Turkey

Turkey stands out as the primary wheat producer in a vast region encompassing North Africa, West & Central Asia. Figure 4.2 illustrates that Turkey exhibits agricultural and post-harvest losses (24.57% and 30.79% respectively) that are higher in absolute terms than the respective ones of the United States, as shown in Table 4.3. This is noteworthy, considering the United States has a wheat production three times higher than that of Turkey, as indicated in Table 4.2.

Offering an alternative perspective, it's remarkable that Turkey holds the distinction of being the largest global exporter of flour. Additionally, Turkey ranks as the second-largest exporter of pasta on a global scale, exporting 7.97×10^5 t. This quantity exceeds that of the United States by over sevenfold, though it falls short of Italy's export volume, which is more than twice that of Turkey. Given its role as exporter of wheat derivatives, it is interesting to analyze the dispersion of the water usage across the countries for the distribution waste, as depicted in Figure 4.11. Turkey itself contributes significantly with 6.04×10^8 m^3. Other countries prominently involved, considering their total population, include Iraq (8.58×10^7 m^3), Sudan (1.65×10^7 m^3), and Angola (6.37×10^6 m^3). Particularly, even when excluding Turkey, the water usage associated with distribution waste accounts for 88.19% in countries from the regions of North Africa, West & Central Asia, and Sub-Saharan Africa. Since the last two stages of the value chain usually go hand in hand, these exports to developing countries could also motivate the fact that the consumption waste is relatively low (22.56%) compared to other countries analyzed from a production side. This underscores that the efficiency and sustainability of water use in the consumption phase may differ significantly based on where the products are effectively consumed.

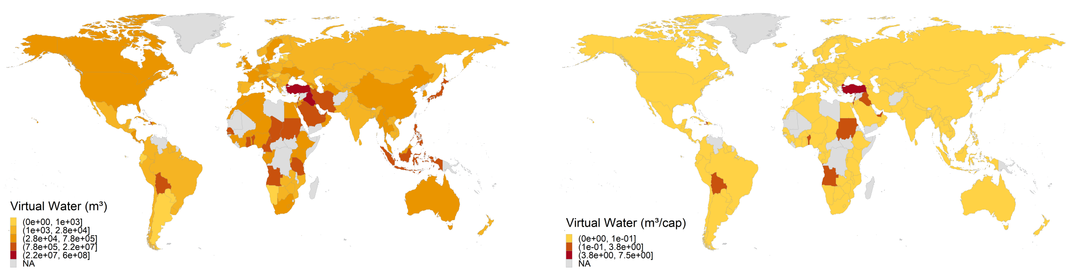

Figure 4.11: Water footprint relative to the distribution waste of wheat produced in Turkey, both for total population (left) and per capita (right).

Argentina

Argentina assumes the role of the primary wheat producer in South America; however, its production output is notably lower compared to the top producers in the regions analyzed thus far. Consequently, the water footprint associated with FLW is comparatively lower, as shown in Table 4.3. A distinctive feature is evident when scrutinizing the water distribution across the five stages of the value chain. In contrast to other countries, Argentina displays a more equitable proportion of water usage among these stages. In fact, the percentage associated with the distribution waste, 11.20%, is the highest among the countries analyzed, while the post-harvest losses are one of the lowest with 15.05%. None of the stages reaches 30% of the total, and this marks a significant departure from the usual pattern observed in other nations, where one or two stages typically dominate with a substantially higher volume of water footprint compared to the others. Therefore, in this scenario, a more comprehensive analysis of all stages together becomes imperative, as depicted in Figure 4.12.

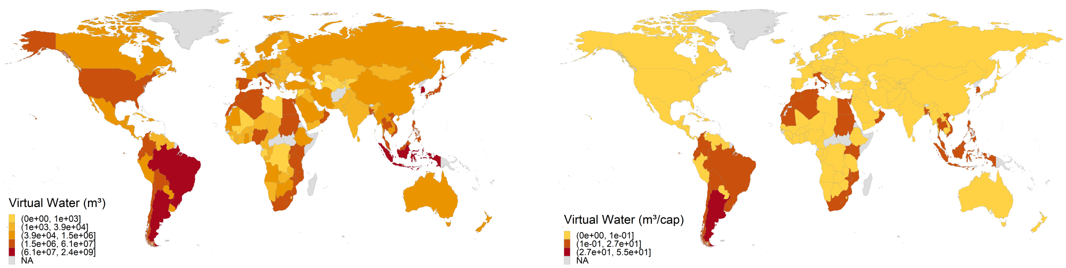

Figure 4.12: Water footprint relative to the FLW of wheat produced in Argentina, both for total population (left) and per capita (right).

The water footprint attributed to FLW related to wheat production is predominantly influenced by Argentina itself, accounting for 2.38×10^9 m^3, when considering the data relative to the total population. Other notable contributors include Brazil (7.58×10^8 m^3), Indonesia (1.73×10^8 m^3), and the Republic of Korea (8.52×10^7 m^3). In a per capita perspective, Argentina (54.70 m^3/cap) and Brazil (3.66 m^3/cap) occupy again the first two positions, while Bolivia (3.17 m^3/cap) and Chile (2.09 m^3/cap) trail behind. This emphasizes Argentina's pivotal position in sustaining wheat-related food needs within the region, underscoring its significant role played in providing wheat to the broader Latin American population.

Ethiopia

Ethiopia, as the final country under analysis for wheat production, represents a noteworthy case study within the context of Sub-Saharan Africa. Despite its wheat production being less than half of Argentina's output, valuable insights can be gleaned from its examination. Figure 4.2 sheds light on the water footprint distribution across different stages of the wheat production chain. Interestingly, the highest water footprint in Ethiopia is primarily associated with the initial stages of the production chain, with a significant emphasis on the first two stages, accounting to 77.32% of the total, if combined. In contrast, the water footprints linked to processing, distribution, and consumption are notably low. This trend aligns with the patterns explained in Section 1.2.1 for developing economies, highlighting a characteristic feature where the earlier stages of production exert a more substantial impact on the water footprint compared to the later stages.

In Ethiopia, the water footprint associated with agricultural losses amounts to 6.14×10^8 m^3, translating to 5.83 m^3 per capita. Additionally, the water usage linked to post-harvest losses is 7.70×10^8 m^3, corresponding to 7.31 m^3 per capita. It's crucial to remember that these values are entirely specific to Ethiopia, as subsequent import and export activities occur after these stages in the production chain. In Figure 4.13 we consider all the stages together, and the result is very clear. In fact, we comprehend that the water footprint associated to the FLW of the wheat produced by Ethiopia is most entirely (more than 99.99% even without considering the first two stages) due to Ethiopia with 1.79×10^9 m^3 while the second highest volume is Kuwait with 7.23×10^3 m^3 followed by United Kingdom (1.57×10^3 m^3) and Australia (8.36×10^2 m^3). The same result is obtained with a per capita perspective where Ethiopia wastes 16.96 m^3/cap, while the other countries values are negligible.

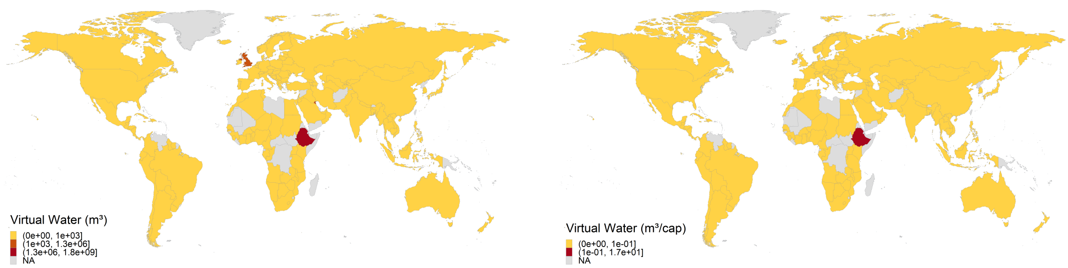

Figure 4.13: Water footprint relative to FLW of wheat produced in Ethiopia, both for total population (left) and per capita (right).

4.1.2 Fork to farm perspective

In exploring the fork-to-farm perspective, we delve into the global impact on water resources resulting from FLW associated with the annual consumption of wheat and its derivatives. The quantities under consideration can be regarded as the virtual water content of FLW linked to global consumption. We can observe that the total water footprint amounts to 1.63×10^{11} m^3 as shown in Table 4.4. Referencing the same table, we present an analysis of the estimated water resources impacted by FLW associated with the consumption of various products in the wheat commodity tree, disaggregated by stages in the value chain. Notably, within the different products, the largest share of virtual water (6.90×10^{10} m^3, constituting 42.22% of the total commodity tree) is linked to FLW generated within the value chain of flour. Other significant contributions come from FLW associated with bread (41.99%) and pasta (12.05%). Raw wheat and bran, based on our data sources, appear to have negligible food consumption and thus do not significantly contribute to the virtual water content of FLW. Examining the wheat chain, the consumption stage emerges as the primary driver of impact on water resources, accounting for 6.14×10^{10} m^3 (37.60% of the total virtual water of FLW). This underscores the importance of interventions aimed at reducing waste at the consumer level. The post-harvest stage follows closely with 21.43%, while processing and agricultural stages contribute 18.69% and 14.53%, respectively. Distribution stage has the lowest impact as expected, representing just 7.76%.

Table 4.4: Global water footprint disaggregated per each item of the wheat tree, divided by stage.

Item	**Water footprint (m^3), divided by stage**					**Total**	
	Agricultural	Post-harvest	Processing	Distribution	Consumption	m^3	%
Wheat	1.62×10^7	1.21×10^7	0	1.55×10^7	3.72×10^7	8.09×10^7	0.05
Flour of wheat	1.11×10^{10}	1.77×10^{10}	4.63×10^9	6.07×10^9	2.95×10^{10}	6.90×10^{10}	42.22
Bran of wheat	4.10×10^8	1.82×10^9	9.17×10^7	3.44×10^8	3.36×10^9	6.02×10^9	3.68
Pasta	2.59×10^9	3.34×10^9	5.78×10^9	1.37×10^9	6.60×10^9	1.97×10^{10}	12.05
Bread	9.60×10^9	1.22×10^{10}	2.00×10^{10}	4.87×10^9	2.19×10^{10}	6.86×10^{10}	41.99
Total	2.37×10^{10}	3.50×10^{10}	3.05×10^{10}	1.27×10^{10}	6.14×10^{10}	1.63×10^{11}	100

Now, our focus shifts on investigating the origins of losses and waste (along with the relative water footprint) associated with wheat and its derivatives (such as bran, flour, bread, pasta) consumed within a specific nation. In essence, we aim to determine the countries impacted by the losses and waste generated during the value chain of these wheat-based products consumed in the given nation. In relation to the countries of consumption, we follow a methodology similar to the one used for production, selecting one country per region based on the criterion of consuming the highest quantity of wheat, flour, bran, pasta, and bread combined, as shown in Table 4.5. To offer a larger sample of cases, we intentionally excluded countries already considered in the previous section, such as India, even if they exhibit the highest consumption levels. This approach ensures a diverse representation of consumption patterns across regions while considering the unique circumstances relevant to each country, thereby enriching the breadth and depth of our analytical insights.

Table 4.5: Countries chosen for the consumption analysis with the corresponding region of belonging and consumption of wheat and its derivatives in tonnes in the year 2016.

Country	**Region**	**Consumption (t)**					
		Wheat	Flour	Bran	Pasta	Bread	Total
Pakistan	South & Southeast Asia	0	1.10×10^{7}	0	1.62×10^{6}	6.24×10^{6}	1.89×10^{7}
Egypt	North Africa, West & Central Asia	0	5.53×10^{6}	0	6.92×10^{5}	3.31×10^{6}	9.53×10^{6}
Brazil	Latin America	0	0	0	1.95×10^{6}	4.94×10^{6}	6.90×10^{6}
Italy	Europe	0	9.23×10^{5}	0	1.68×10^{6}	2.11×10^{6}	4.71×10^{6}
Japan	Industrialized Asia	0	0	0	1.13×10^{6}	2.45×10^{6}	3.57×10^{6}
Nigeria	Sub-Saharan Africa	0	6.78×10^{-10}	0	7.79×10^{5}	2.44×10^{6}	3.22×10^{6}
Canada	North America & Oceania	0	3.49×10^{5}	0	2.49×10^{5}	8.58×10^{5}	1.46×10^{6}

Before delving into the water footprint characteristics of these countries associated with the consumption of wheat products, our primary goal is to compare them. This comparative analysis is presented in Figure 4.14, illustrating the relative use of freshwater resources for FLW across different stages for the selected countries and, more broadly, for the world. Additionally, Table 4.6 provides a per capita perspective of the data, offering insights into the water footprint associated with wheat derivatives FLW from a consumption-side perspective for each country, the global data is also incorporated for reference. It's important to note that, in the context of food intake analysis, the "per capita" concept is applied by dividing total volumes by the population of the country where wheat derivatives are consumed. This approach enhances our understanding of the countries and regions that contribute most significantly to water use.

To gain a more detailed understanding of the water footprint, our next step involves dividing this per capita volume by the kilograms of wheat products consumed in each country per capita. This calculation, shown in Table 4.7, aims to provide a value that signifies the volume of water wasted per kilogram of wheat derivatives consumed by an individual in a given country. This approach allows us to fully understand which countries exhibit more responsible water usage behaviors.

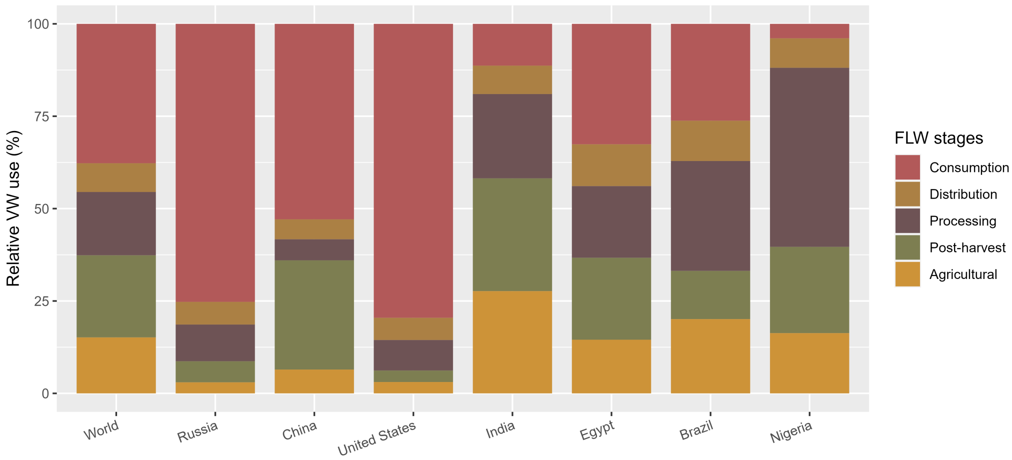

Figure 4.14: Relative use of freshwater resources for FLW, by stage (%)

Table 4.6: Water footprint per capita both globally and for the seven countries considered, categorized by stage.

Country	**Water footprint per capita (m^3/cap)**				
	Agricultural	Post-harvest	Processing	Distribution	Consumption
World	3.18	4.69	4.09	1.70	8.23
Pakistan	11.43	12.50	8.20	3.16	4.65
Egypt	4.31	7.19	7.31	5.48	15.73
Brazil	3.32	2.16	5.08	1.98	4.76
Italy	2.65	4.22	9.60	2.00	24.50
Japan	1.15	1.21	5.57	0.94	9.21
Nigeria	0.60	0.85	2.81	0.50	5.00
Canada	1.36	1.39	5.21	1.12	14.90

Table 4.7: Water footprint relative to the FLW of wheat derivatives per kilogram consumed.

Country	WF per capita (m^3/cap)	Consumption per capita (kg/cap)	WF per kilogram (m^3/kg)
World	21.89	56.53	0.39
Pakistan	39.94	88.51	0.45
Egypt	40.02	95.51	0.42
Brazil	17.30	33.36	0.52
Italy	42.97	77.69	0.55
Japan	18.08	28.09	0.64
Nigeria	9.76	17.07	0.57
Canada	23.98	40.43	0.59

Italy

Italy ranks as the second-highest consumer of wheat derivatives in Europe, trailing only behind Russia. Notably, Italy stands out for having the highest per-person consumption of pasta in the World, averaging 27.7 kilograms per person in the year 2016. This emphasizes the cultural significance and widespread popularity of pasta within the Italian diet. While, it's noteworthy that the Balkans region boasts the highest per-person consumption of bread globally. Specifically, Albania leads with 55.8 kilograms, closely followed by Bulgaria at 55.7 kilograms, and Romania at 55.6 kilograms.

Our analysis successfully identifies the countries impacting the losses and waste and their relative water footprint related to wheat derivatives' food intake in Italy. In Figure 4.14, we observe that 57.09% of the water usage associated to losses and waste is concentrated in the final stage of consumption.

A notable difference between fork-to-farm and farm-to-fork perspective analysis stems from the allocation of virtual water associated with agricultural and post-harvest losses in the former, which is not confined to a single country. Consequently, maps illustrating these aspects become crucial for comprehending the global distribution and repercussions of water use inefficiencies linked to food consumption. Additionally, since the "per capita" concept is applied by dividing total volumes by the population of the country where wheat derivatives are consumed, unlike production analysis, there is no need to present maps on a per capita basis as they would essentially replicate the total population maps, merely adjusted in scale.

In the case of the virtual water associated with FLW of wheat derivatives consumed in Italy, it's notable that the countries involved remain consistent across different stages. Therefore, we present the comprehensive map combining all stages together. For a detailed view of each stage, the additional maps can be found in Appendix C.1.2. In the presented Figure 4.15, Italy emerges as the major actor, accounting for a water footprint of 9.94×10^8 m^3. Following Italy, other significant contributors include Canada with 2.18×10^8 m^3, France with 1.85×10^8 m^3, and the United States with 1.59×10^8 m^3. From a regional perspective, Europe is accountable for 77.88% of the total water usage related to FLW, and North America & Oceania to 16.80%.

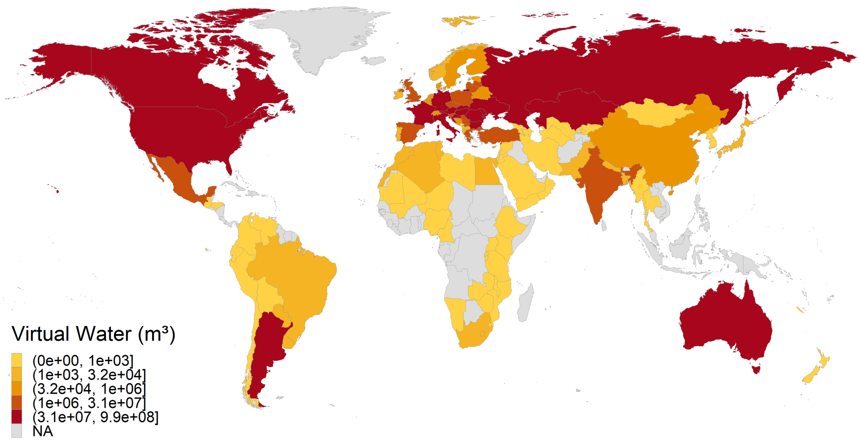

Figure 4.15: Water footprint relative to the FLW of wheat products consumed in Italy.

Pakistan

It's notable that Pakistan holds the position of being the third-largest consumer of wheat derivatives globally, securing the second position in the South & Southeast Asia region after India. This high consumption is particularly evident in the significant portion of raw flour consumption (1.10×10^7 t), as outlined in Table 4.5. The prevalence of homemade wheat-based products such as roti, naans, and other forms of bread, produced within families, contributes to the absence of data on waste and water footprint associated with these products.

In contrast to Italy, the major part of water footprint in Pakistan is distributed across the initial stages, with 80.42% accounting to agricultural, post-harvest and processing losses combined, as illustrated in Figure 4.14. This pattern is attributed to the predominant reliance on internal production for wheat derivatives consumed in Pakistan. Notably, Pakistan, being a developing country, exhibits higher losses than waste, underscoring the challenges associated with efficiency in the wheat production chain.

Given this distinctive pattern, a comprehensive analysis is achieved by examining the overall map, presented in Figure 4.16, which combines all stages. The water footprint attributed to Pakistan is substantial at 8.52×10^9 m^3, with significant gaps separating it from its closest counterparts, including the United States (2.23×10^6 m^3), Turkey (2.67×10^5 m^3), and Iran (2.50×10^5 m^3).

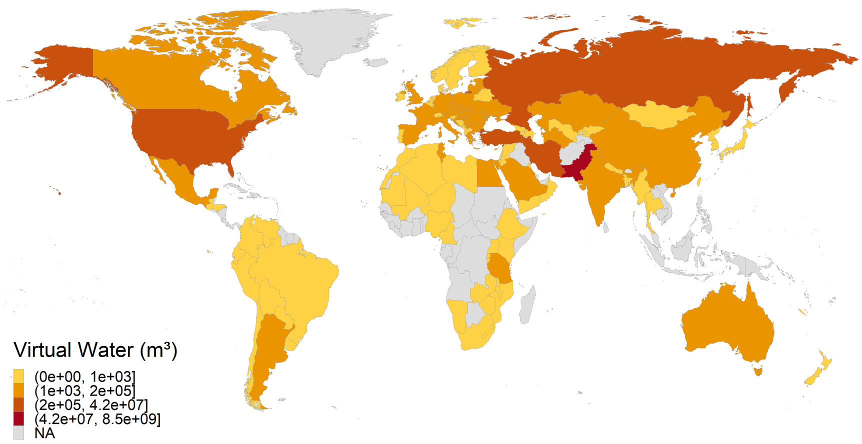

Figure 4.16: Water footprint relative to the FLW of wheat products consumed in Pakistan.

Egypt

Egypt emerges as the foremost consumer of wheat derivatives in the North Africa, West & Central Asia region, securing the seventh position globally. Notably, Egypt shares a similar consumption trend with Pakistan, characterized by a significant intake of raw flour. This pattern is prevalent in several countries within this region, exemplified by Tunisia with 119.34 kg and Morocco with 106.85 kg of raw flour consumption per person. Despite ranking twelfth in this specific category, Egypt maintains a noteworthy average of 55.40 kg of raw flour consumed per person in the year 2016. Once again, the prevalence of homemade wheat-based products, such as couscous and chapati, crafted within families, contributes to the lack of available data on waste and water footprint associated with these products. This homemade production, deeply rooted in cultural and culinary practices, poses challenges in quantifying waste and environmental impact on a broader scale.

In Egypt, Figure 4.14 highlights that the most substantial water footprint levels are linked to consumption waste (39.39%). This trend is likely attributable to the primary producers of wheat and its derivatives imported into the country, namely Russia and Ukraine. The Russian case presents a noteworthy aspect, particularly in the first three types of losses. The water footprint associated with FLW of wheat derivatives consumed in Egypt is higher in the European country than in the North African one. This distinction is also depicted in the map shown in Figure 4.17, where all stages are amalgamated. Here, Russia's water usage stands at 1.67×10^9 m^3, exceeding Egypt's use of freshwater resources at 1.19×10^9 m^3.

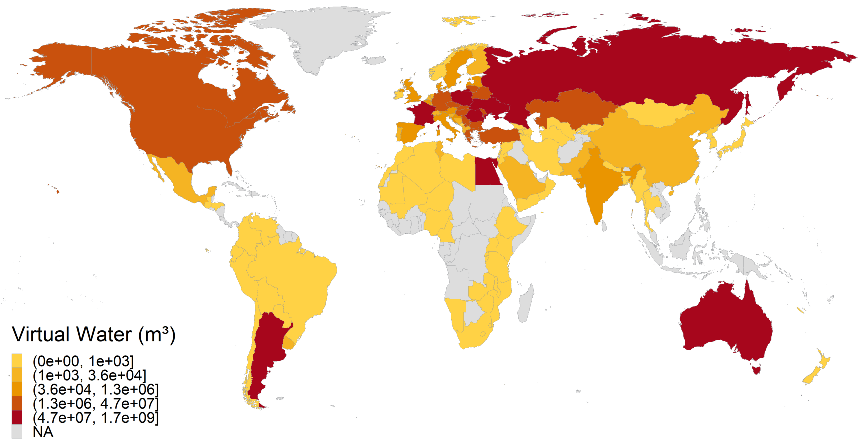

Figure 4.17: Water footprint relative to the FLW of wheat products consumed in Egypt.

Brazil

In Latin America, Brazil stands out as the highest consumer of wheat derivatives. The consumption pattern in Brazil reflects a unique situation, combining characteristics of both industrialized and developing countries. While Table 4.5 reports that no quantities of flour are consumed raw, a trait commonly observed in developed economies, Figure 4.14 presents a contrasting scenario. The figure unveils high losses during the processing stage, challenges akin to those faced by low-income countries.

It's important to clarify that the water footprint depicted in the figure doesn't solely pertain to Brazil; rather, it includes contributions from other countries that export wheat products to Brazil. Nevertheless, a significant 88.17% of this water footprint is attributed to South America, indicating a common trend throughout the region. In particular, as noted earlier in the case of Egypt, the water footprint associated with the first three types of losses is higher in Argentina than in Brazil. As illustrated in Figure 4.18, Argentina consumes 1.58×10^9 m^3 of water in wheat derivatives FLW that come from the Brazilian food intake, while Brazil's usage is 8.94×10^8 m^3, and Paraguay's is 4.75×10^8 m^3.

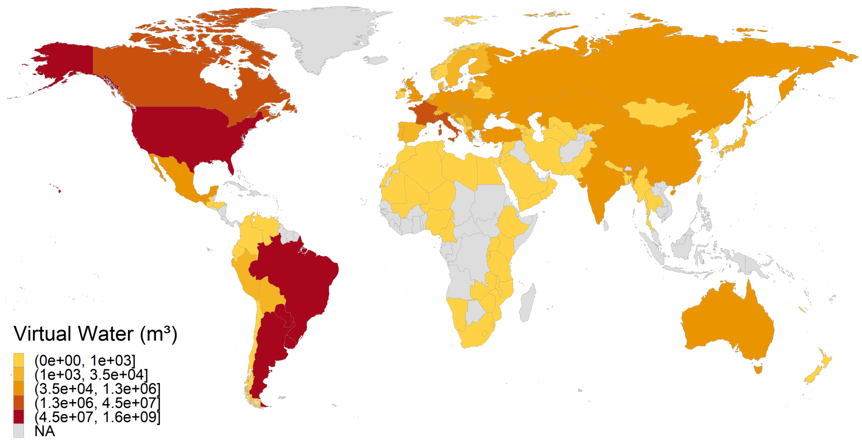

Figure 4.18: Water footprint relative to the FLW of wheat products consumed in Brazil.

Japan

Japan stands out as a significant importer of wheat and its derivatives, given its relatively low internal production of 7.91×10^5 t compared to its substantial consumption of 3.57×10^6 t, which is nearly five times higher. The primary source countries for its imports include the North America & Oceania region. The water footprint associated with various stages of the supply chain, depicted in Figure 4.14, effectively reflects the losses and waste incurred by these suppliers and the corresponding unit water footprint. In particular, the analysis reveals very low agricultural and post-harvest losses, consistent processing losses, minimal distribution waste, and notably high consumption waste.

Figure 4.19 aligns with the considerations outlined above, illustrating the singular presence of the countries in the North America & Oceania region in the dark red class. This class represents the set of countries with the highest water footprint associated with FLW of wheat derivatives consumed in Japan. Specifically, the water footprint associated with the U.S. amounts to 1.08×10^9 m^3, leading the list. Following the U.S., other significant contributors include Canada with 5.15×10^8 m^3, Australia with 4.20×10^8 m^3, and finally Japan itself with 1.21×10^8 m^3.

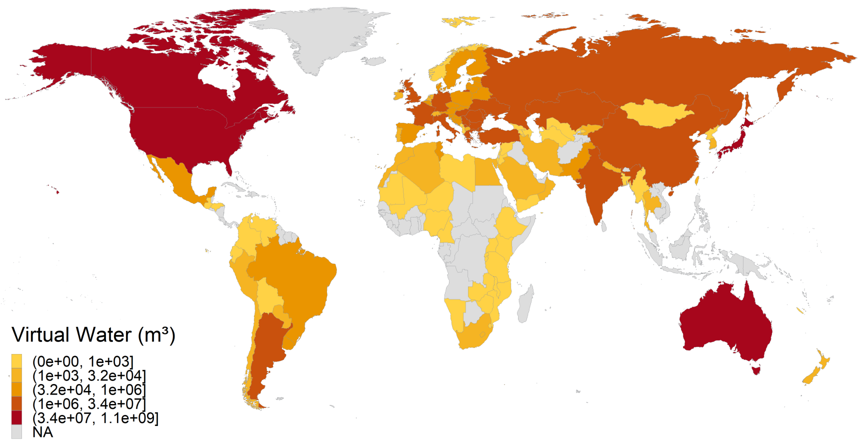

Figure 4.19: Water footprint relative to the FLW of wheat products consumed in Japan.

Nigeria

Nigeria holds the position as the second most significant consumer of wheat derivatives in Sub-Saharan Africa. Similar to Japan, Nigeria is an importing country, producing only 6.00×10^5 t of wheat for a consumption of 3.22×10^6 t of derivatives, which is more than five times higher. The primary import sources include Europe, as well as the North America & Oceania. This importing pattern is reflected in the low amounts of water footprint associated with agricultural and post-harvest losses, as depicted in Figure 4.14. However, the water footprint pattern changes from the processing stage onward, resembling that of a developing country. High processing losses are observed, likely due to a lack of machinery or infrastructure, while waste in distribution and consumption stages is relatively low.

Figure 4.20 provides further insight into Nigeria's status as a net importer. The water footprint of FLW associated with the food intake of wheat derivatives in Nigeria is particularly pronounced in Russia (3.61×10^8 m^3), the United States (2.31×10^8 m^3), Australia (1.26×10^8 m^3) and Canada (9.90×10^7 m^3), depicted in dark red in the picture. In contrast, Nigeria is twelfth in the ranking with only 4.84×10^6 m^3.

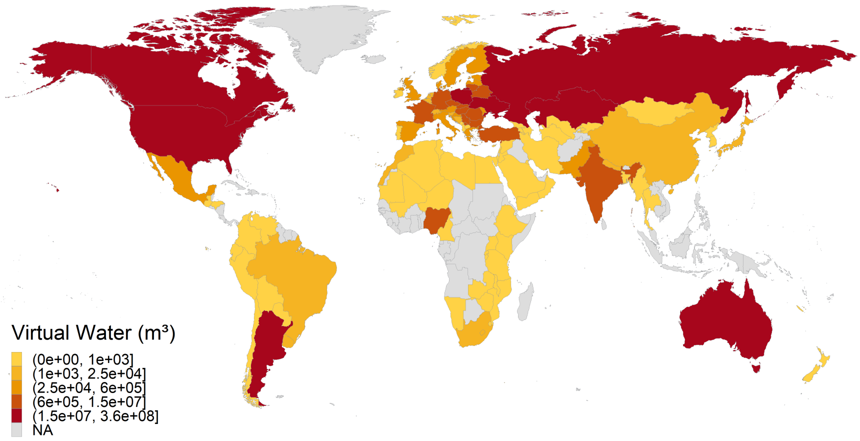

Figure 4.20: Water footprint relative to the FLW of wheat products consumed in Nigeria.

Canada

The final analysis from a food intake perspective pertains to Canada, which, beside being a significant producer and exporter, is also a large consumer of wheat based products. Canada consumes 1.46×10^6 t of wheat derivatives, in contrast to its substantial production quantity of 3.21×10^7 t and export quantity of 1.97×10^7 t of wheat. Although Canada's total consumption is nearly ten times lower than the United States in total, we chose to include it in the analysis anyway on a per capita perspective, where both countries have similar per person consumption (42.9 kg/cap per U.S. citizen compared to 40.3 kg/cap per Canadian in the year 2016). This choice aligns with the initial decision to use different countries in the production-side and consumption-side analyses while ensuring a meaningful comparison.

Given its significant role as a producer, Canada's losses and waste related to wheat derivatives' food intake are predominantly internal. Consequently, the breakdown of stages reflects that of industrialized countries, with the highest water footprint associated with the consumption stage, as depicted in Figure 4.14.

This observation is consistent with the findings depicted in Figure 4.21, where Canada and U.S. stand alone in the darkest class. Specifically, Canada, with a water footprint of 7.08×10^8 m^3, accounts for more than 81% of the total water footprint. When combined with the neighbouring United States (1.11×10^8 m^3), these two nations contribute to nearly 95% of the total water footprint.

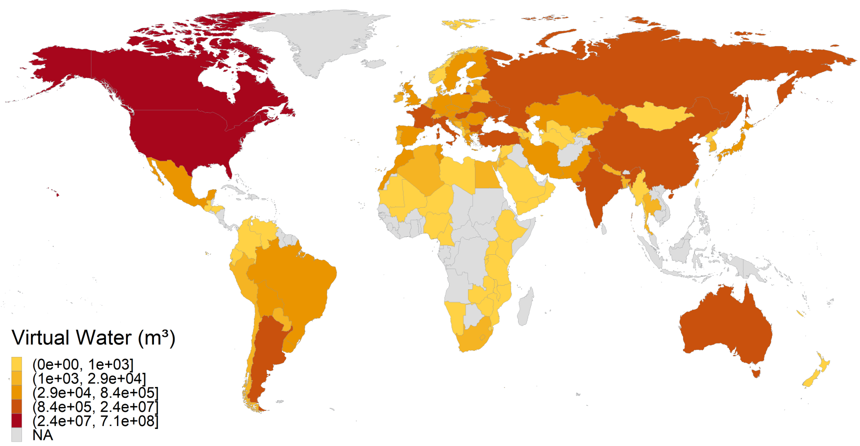

Figure 4.21: Water footprint relative to the FLW of wheat products consumed in Canada.

4.1.3 Feeder to farm perspective

In adopting a feeder-to-farm perspective, we explore the global impact on water resources resulting from FLW associated with the use of wheat and its derivatives as feed. In Table 4.8 we present an analysis of the estimated water resources impacted by FLW associated with the feed of the various disaggregated wheat products, divided by stage. The first observation is that the total water footprint amounts to 2.14×10^{10} m^3. Remarkably, almost all of the virtual water is linked to FLW generated within the value chain of raw wheat (53.22%) and bran (46.78%). The water footprint associated with pasta FLW is negligible, while the ones linked to flour and bread losses are null. It is noteworthy that we don't consider distribution and consumption stages. This exclusion is a deliberate aspect of our analytical framework, given that the feed value chain lacks these two stages, unlike human food intake value chain. The post-harvest stage emerges as the primary driver of the impact on water resources, accounting for 1.17×10^{10} m^3 (54.67% of the total virtual water of FLW). The agricultural stage closely follows with 37.67%, while the processing stage contributes with 7.57%.

Table 4.8: Global water footprint relative to the FLW, disaggregated per each item of the wheat tree, divided by stage, from a feeder-to-farm perspective.

Item	**Total water footprint (m^3), divided by stage**			**Total**	
	Agricultural	Post-harvest	Processing	m^3	%
Wheat	4.37×10^9	7.03×10^9	0	1.14×10^{10}	53.22
Flour of wheat	0	0	0	0	0
Bran of wheat	3.69×10^9	4.70×10^9	1.62×10^9	1.00×10^{10}	46.78
Pasta	4.47×10^4	4.93×10^4	2.30×10^4	1.17×10^5	0
Bread	0	0	0	0	0
Total	8.06×10^9	1.17×10^{10}	1.62×10^9	2.14×10^{10}	100

Our attention now shifts to a comprehensive investigation into the origins of FLW, along with their relative water footprint, associated with wheat and its derivatives used as feed within a specific nation. The purpose is to identify the source countries contributing to losses generated throughout the value chain of these wheat-based products in the given nation. We adopt a methodology akin to the one employed in the consumption-side analysis. Specifically, we select one country per region based on the criterion of consuming the highest quantity of wheat, flour, bran, pasta, and bread combined, as showed in Table 4.9. In contrast to the fork-to-farm perspective, we opt not to exclude countries already considered because of the lower relevance of the remaining countries. This approach ensures the inclusion of countries with the highest utilization of wheat products as feed, providing a comprehensive perspective on the global impact of feed intake.

Before delving into the water footprint characteristics of these countries linked to FLW of the utilization of wheat products as feed, our foremost objective is to conduct a comparative analysis of the stages of the value chain. This comparative assessment is depicted in Figure 4.22, showcasing the relative freshwater resource utilization for FLW across various stages for the selected countries and, more expansively, on a global scale. To provide a comprehensive overview of the water

Table 4.9: Countries chosen for the feed analysis with the corresponding region of belonging and the value of feed of wheat and its derivatives in tonnes.

Country	**Region**	**Feed (t)**			
		Wheat	Bran	Pasta	Total
Russia	Europe	1.09×10^7	3.55×10^6	0	1.45×10^7
China	Industrialized Asia	9.75×10^6	3.46×10^6	0	1.32×10^7
United States	North America & Oceania	5.17×10^6	5.62×10^6	0	1.08×10^7
India	South & Southeast Asia	2.19×10^6	7.92×10^6	4.00×10^2	1.01×10^7
Egypt	North Africa, West & Central Asia	4.67×10^6	2.57×10^6	0	7.24×10^6
Brazil	Latin America	8.00×10^5	2.66×10^6	0	3.46×10^6
Nigeria	Sub-Saharan Africa	6.69×10^3	1.03×10^6	0	1.04×10^6

volumes involved, Table 4.10 details the water footprint associated to the wheat and its derivatives destined to feed intake for each analyzed country, segmented by stages. The global data is also shown for reference. Notably, processing losses emerge as consistently low in comparison to the other stages across all the countries analyzed.

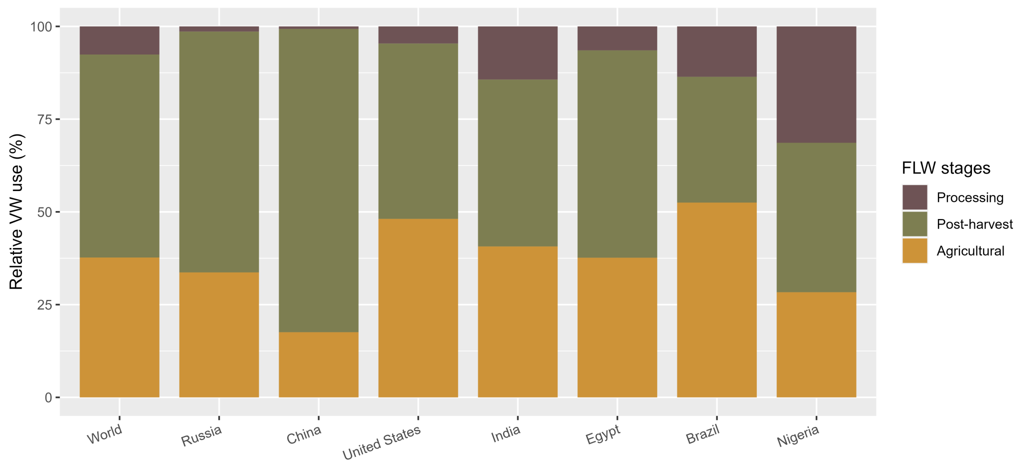

Figure 4.22: Relative use of freshwater resources for FLW (%), divided by stage, from a feeder-to-farm perspective.

Table 4.10: Water footprint relative to the FLW of wheat and its derivatives both global and for the selected countries, divided by stage, from a feeder-to-farm perspective.

Country	**Water footprint (m^3) by stage**			
	Agricultural	Post-harvest	Processing	Total
World	8.06×10^9	1.17×10^{10}	1.62×10^9	2.14×10^{10}
Russia	4.27×10^8	8.23×10^8	1.75×10^7	1.27×10^9
China	3.46×10^8	1.61×10^9	1.34×10^7	1.97×10^9
United States	2.82×10^8	2.77×10^8	2.70×10^7	5.86×10^8
India	1.23×10^9	1.36×10^9	4.33×10^8	3.02×10^9
Egypt	3.94×10^8	5.85×10^8	6.75×10^7	1.05×10^9
Brazil	2.88×10^8	1.86×10^8	7.45×10^7	5.49×10^8
Nigeria	5.06×10^7	7.19×10^7	5.60×10^7	1.78×10^8

Russia

Our analysis firstly focus on the impact on freshwater resources of the FLW related to the wheat products used as feed in Russia. Figure 4.22 shows that the major part of the water footprint is associated to the post-harvest stage (64.94%), followed by the agricultural stage (33.68%), while the processing stage is not so impactful (1.38%).

Figure 4.23 represents the distribution across the world of the water wasted across all the stages of the value chain. It is immediately visible that the country most impacted is Russia itself. In fact, Russia wastes 1.22×10^9 m^3 of water, followed by Kazakhstan with 4.80×10^7 m^3, Belarus with 1.24×10^6 m^3, and Ukraine with 9.30×10^5 m^3. Considering only the water wasted outside Russian borders, it is notable that 95.44% belongs to Kazakhstan, while 42 countries in Europe contribute to the remaining 4.56%.

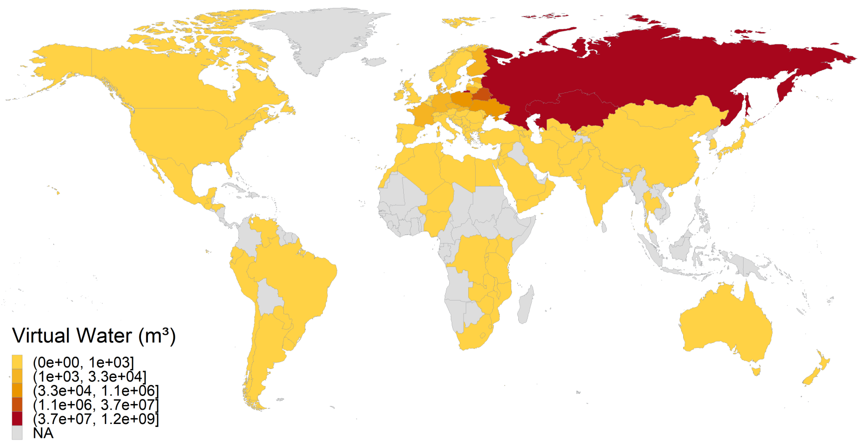

Figure 4.23: Water footprint relative to the FLW of wheat products used as feed in Russia.

China

If we analyze the distribution across the stages of the value chain of the water usage relative to the FLW of wheat products used as feed in China, Figure 4.22 is very clear. 81.77% of the water resources used are attributable to post-harvest losses (the largest percentage among the countries considered), 17.55% to agricultural losses and only 0.68% to processing losses.

In Figure 4.24 we can observe which countries are the most affected in terms of water wasted. China uses 1.93×10^9 m^3 of water for FLW, followed by Kazakhstan 1.69×10^7 m^3, Australia 1.57×10^7 m^3 and the United States 8.42×10^6 m^3. If we don't consider the internal water footprint, the region of North America & Oceania is accountable for 61.48% of the total, followed by North Africa, West & Central Asia with 37.75%. On the contrary, other countries in Industrialized Asia contribute merely 0.11% to the water footprint.

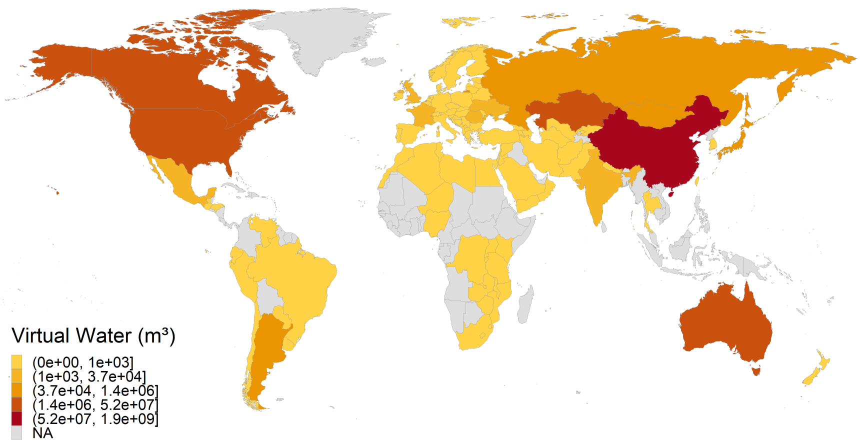

Figure 4.24: Water footprint relative to the FLW of wheat products used as feed in China.

United States

In comparison to the previous countries examined, the United States displays a more balanced water footprint distribution in the first two stages of the value chain for the FLW of wheat products used as feed. As depicted in Figure 4.22, the agricultural stage constitutes 48.13%, the post-harvest stage 47.27%, and the processing stage, though increasing, remains low at 4.61%.

The distribution of water usage across countries is shown in Figure 4.25. The United States wastes 5.66×10^8 m^3 of water, followed by Canada with 1.26×10^7 m^3, Argentina with 2.60×10^6 m^3, and Russia with 1.51×10^6 m^3. Considering the FLW that occurs outside of the U.S. borders, the region of North America & Oceania wastes 1.29×10^7 m^3 of water (64.15%), followed by Europe with 3.60×10^6 m^3 (17.83%) and Latin America with 2.96×10^6 m^3 (14.67%).

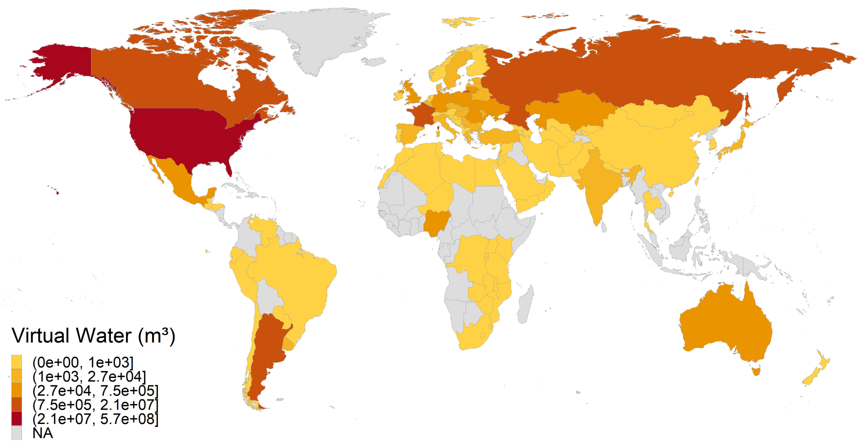

Figure 4.25: Water footprint relative to the FLW of wheat products used as feed in the United States.

India

The use of freshwater resources for the losses and waste of wheat used as feed in India is distributed across the various stages, with a significant portion in the processing stage at 14.35%, as we can see in Figure 4.22. However, agricultural (40.74%) and post-harvest (44.92%) stages are still predominant.

In Figure 4.26, the distribution of the water footprint across countries for the losses and waste of wheat used as feed in India is presented. India contributes to this water footprint with 2.97×10^9 m^3, followed by Ukraine (2.79×10^7 m^3), Australia (1.60×10^7 m^3), and Russia (1.18×10^6 m^3). If we consider losses and waste happening outside Indian borders, the region with the highest water footprint is Europe with 65.44% of the total, followed by North Africa & Oceania with 33.78%. While countries in South & Southeast Asia other than India contribute with a mere 0.70%.

When considering only the processing stage (Figure C.65 in the Appendix), the top countries remain mostly the same: India (4.20×10^8 m^3), representing 14.12% of total Indian water footprint, Ukraine (6.86×10^6 m^3) at 24.60%, Australia (5.55×10^6 m^3) at 34.64%, and France (2.73×10^9 m^3) at 23.02%

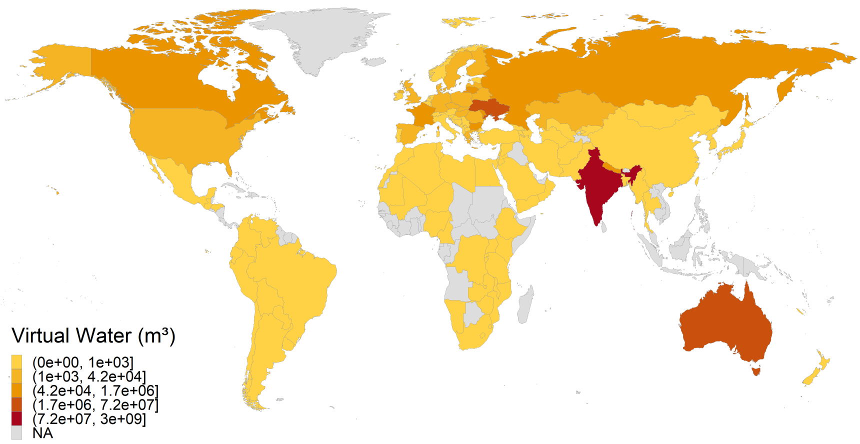

Figure 4.26: Water footprint relative to the FLW of wheat products used as feed in India.

Egypt

Losses and waste associated with wheat products used as feed in Egypt predominantly impact the water footprint during the post-harvest stage, constituting 55.91% of the total, as depicted in Figure 4.22. The agricultural stage follows closely, contributing 37.65%, while the processing stage remains comparatively low at 6.45%.

In Figure 4.27, we present the global distribution of the water footprint, with Egypt leading at 5.71×10^8 m^3. However, unlike other countries examined, Egypt's contribution accounts for only 54.35% of the total water footprint. Other significant contributors include Russia with 2.89×10^8 m^3, Ukraine with 8.16×10^7 m^3, and Romania with 3.82×10^7 m^3. When considering only the water wasted outside of Egypt's borders, Europe emerges as the most affected, accounting for 93.84%.

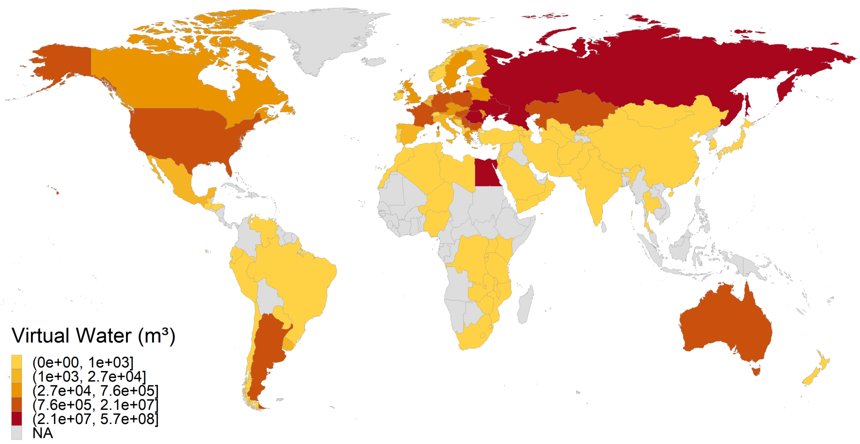

Figure 4.27: Water footprint relative to the FLW of wheat products used as feed in Egypt.

Brazil

The water footprint related to the food loss and waste of wheat products used as feed in Brazil is primarily attributed to the agricultural stage, comprising 52.50% of the total. The post-harvest losses are relatively lower compared to other countries in this analysis, accounting for 33.91%, while processing losses remain consistent at 13.59%, as illustrated in Figure 4.22.

As noted previously for Egypt, Brazil, despite being the country most impacted in terms of water waste with 2.43×10^8 m^3, contributes only 44.23% to the overall water footprint. Other noteworthy participants include Argentina with 1.88×10^8 m^3, Paraguay with 5.30×10^7 m^3, and the United States with 3.61×10^7 m^3. Taking a regional perspective, even without considering the water usage related to the FLW occurring within Brazil's borders, Latin America is the most affected, accounting for 87.11% of the total.

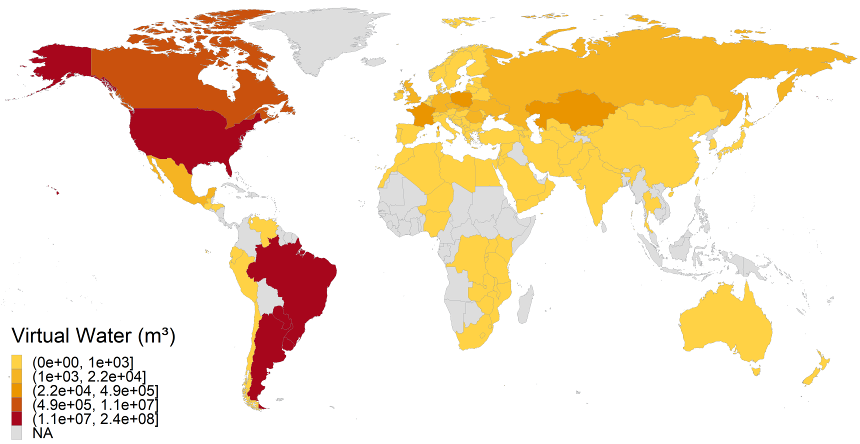

Figure 4.28: Water footprint relative to the FLW of wheat products used as feed in Brazil.

Nigeria

Nigeria, representing the Sub-Saharan Africa region, exhibits a unique aspect in its water footprint related to the FLW of wheat products used as feed. Notably, the processing stage accounts for an outstanding 31.36%, surpassing even the agricultural stage at 28.35%. Additionally, the post-harvest stage has the lowest percentage among the countries analyzed, standing at 40.29%. This distinctive feature could be attributed to Nigeria's predominantly importing status. Consequently, the water footprint associated with the first two stages of the value chain is significantly influenced by the countries from which the wheat products are sourced.

From Figure 4.29, it is evident that Russia and the United States have the highest water footprints, amounting to 7.36×10^7 m^3 and 4.08×10^7 m^3, respectively. Following closely are Australia (1.78×10^7 m^3) and Canada (1.39×10^7 m^3), with Nigeria ranking fifth in this assessment at 9.84×10^6 m^3. Regarding the regional analysis, even when considering losses and waste within the borders of Nigeria, the water footprint is highest in Europe at 50.69%, followed by North America & Oceania at 40.63%, while Sub-Saharan Africa accounts for only 5.51%.

In terms of processing losses (Figure C.74), the pattern is similar to the overall water footprint, with Russia leading at 2.02×10^7 m^3, representing 27.46% of the overall Russian water footprint. The United States follows with 1.48×10^7 m^3

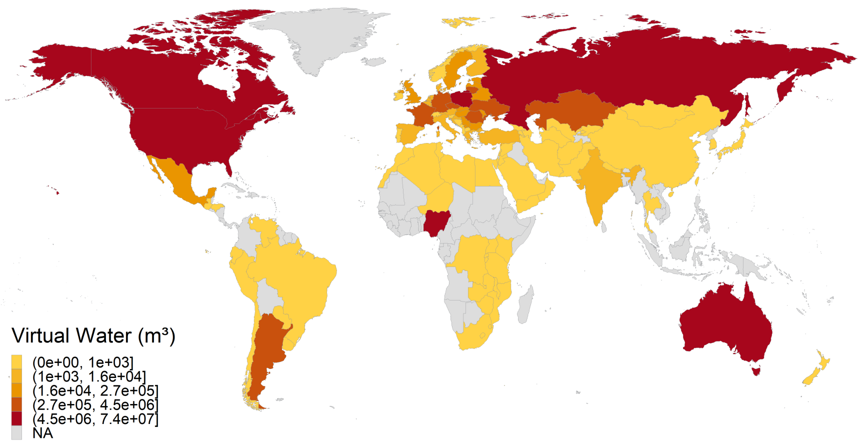

Figure 4.29: Water footprint relative to the FLW of wheat products used as feed in Nigeria.

(36.32%), Australia with 7.55×10^6 m^3 (42.33%), and Canada with 5.80×10^6 m^3 (41.88%). Nigeria is still fifth in the rankings with 1.79×10^6 m^3 (18.20%).

4.2 Staple crops

After conducting a thorough analysis of wheat, we expanded the scope of our study to encompass staple crops. This expansion is driven by the recognition that staple crops play a fundamental role in global food consumption patterns, representing major sources of nutrition for populations around the world. By transitioning from the specific examination of wheat to a broader investigation of staple crops, we aim to provide a more comprehensive understanding of the water footprint associated with the losses and waste of essential food sources. Staple crops, being dietary mainstays, have far-reaching implications for both regional and global food security. By delving into the complexities of water usage and cultivation practices associated with FLW of various staple crops, we can uncover patterns and insights that contribute to the broader discourse on sustainable agriculture and resource management. This expansion allows us to explore similarities and differences in the environmental impact of different staple crops, facilitating a more robust analysis of the challenges and opportunities associated with their production and consumption, both human and animal.

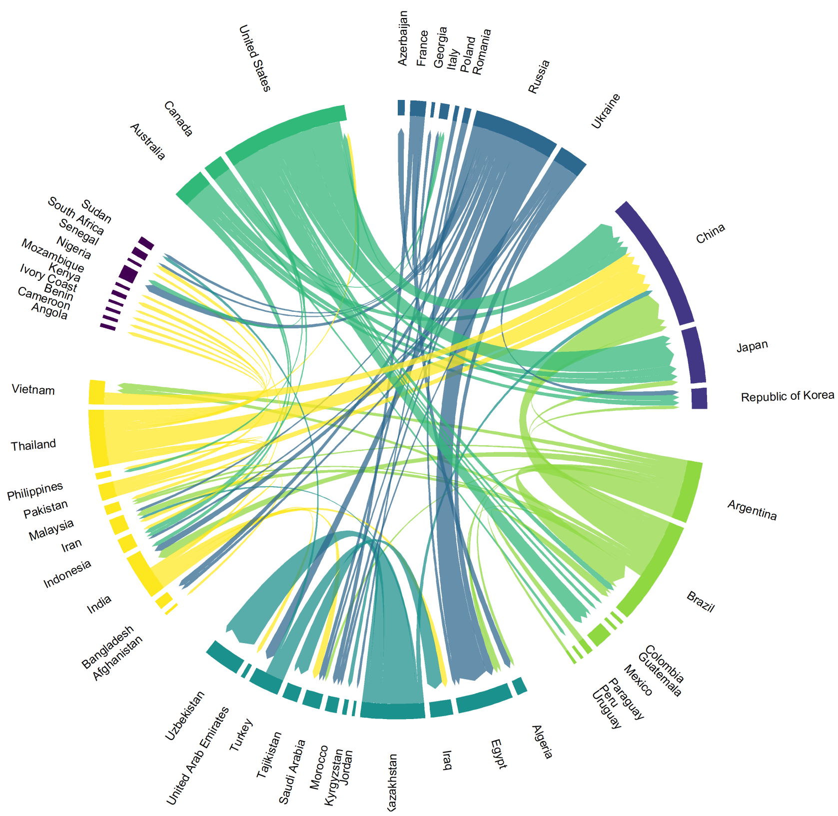

Figure 4.30: Chord diagram depicting the top 100 virtual water fluxes attributed to the FLW of food and feed intake of all staple crops and their derivatives. Self-fluxes have been excluded for clarity.

From a consumption standpoint, when evaluating food and feed intake, the water footprint in relation to losses and waste across staple crops amounts to a volume equal to $5.32 \times 10^{11}\ m^3$. Notably, this surpasses more than half of the water volume in Lake Titicaca, totaling $8.96 \times 10^{11}\ m^3$. In Figure 4.30, we present a chord diagram that visually captures the top 100 virtual water fluxes attributed to losses and waste in the food and feed intake of all staple crops and their derivatives. It is important to note that self-fluxes, involving the same country at both ends of the flow, have been intentionally excluded from this analysis. An additional layer of information is given by the colors representing the regions of the countries involved. We can grasp that the regions of Europe and North America & Oceania predominantly act as exporters in terms of water fluxes. In contrast, Industrialized Asia and Sub-Saharan Africa are primarily importers. Additionally, Latin America, South & Southeast Asia, and North Africa, West & Central Asia exhibit a hybrid pattern with substantial inbound and outbound fluxes. Beside the fluxes already mentioned in the wheat section, the highest amount of water traded is for the soybean crop losses from Brazil to China, amounting to $1.64 \times 10^9\ m^3$.

4.2.1 Farm to fork perspective

Initially, we examine all staple crops collectively from a production-side perspective. In Figure 4.31, we depict the global and regional distribution of water resource usage for FLW across all staple crops, including wheat, segmented by stage. Globally, the post-harvest stage emerges as the most impactful on virtual water, accounting for 35.21% of the total, closely followed by the agricultural stage at 32.20%. In contrast, the distribution stage has the least impact, representing only 4.78% of wasted water. Regions such as the North America & Oceania (42.23%) and Latin America (41.28%) exhibit the highest percentages of virtual water associated with agricultural losses. Conversely, South & Southeast Asia, along with Sub-Saharan Africa and Industrialized Asia, lead in water usage linked to post-harvest losses at 40.60%, 43.56% and 43.21% respectively. Additionally, Europe with 30.19% and Industrialized Asia with 31.66% are notable for the highest percentages of water usage in consumption waste.

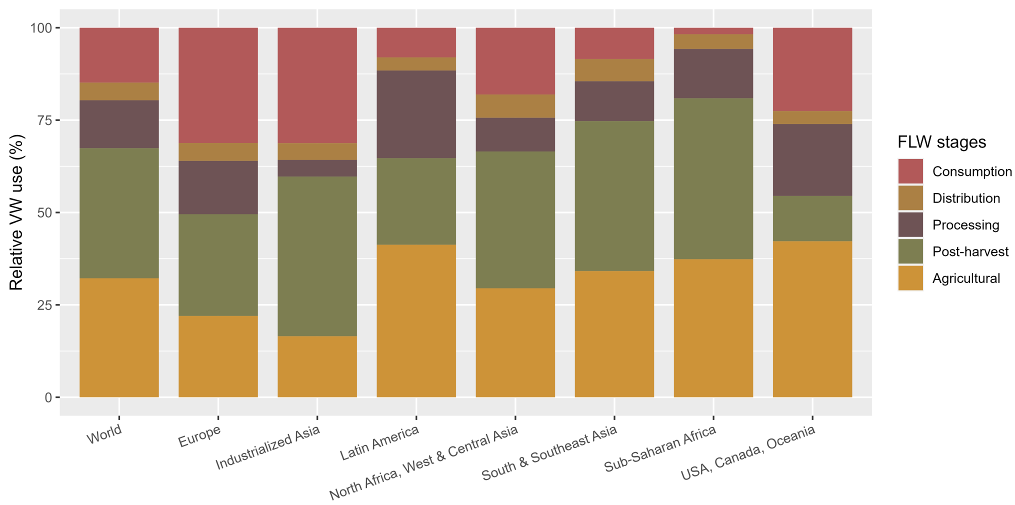

Figure 4.31: Relative use of freshwater resources for FLW of the staple crops (wheat included) produced globally and in each specific region, by stage (%).

Table 4.11 provides a comprehensive overview of the water footprint associated with each region, categorized by stage, along with global data for comparison. Remarkably, the cumulative global water footprint for the food loss and waste of combined staple crops amounts to 7.60×10^{11} m^3. The region that is affected by the highest water waste is South & Southeast Asia with 2.27×10^{11} m^3, while the least affected is North Africa, West & Central Asia with 4.13×10^{10} m^3.

Table 4.11: Water footprint relative to the FLW of the staple crops combined (wheat included) global and per region, divided by stage.

Region	Water footprint (m^3), divided by stage					
	Agricultural	Post-harvest	Processing	Distribution	Consumption	Total
World	2.45×10^{11}	2.68×10^{11}	9.85×10^{10}	3.63×10^{10}	1.13×10^{11}	7.60×10^{11}
Europe	1.60×10^{10}	2.00×10^{10}	1.05×10^{10}	3.50×10^{9}	2.26×10^{10}	7.25×10^{10}
Industrialized Asia	1.97×10^{10}	5.15×10^{10}	5.37×10^{9}	5.43×10^{9}	3.72×10^{10}	1.19×10^{11}
Latin America	4.01×10^{10}	2.28×10^{10}	2.30×10^{10}	3.46×10^{9}	7.78×10^{9}	9.71×10^{10}
North Africa, West & Central Asia	1.22×10^{10}	1.53×10^{10}	3.77×10^{9}	2.60×10^{9}	7.46×10^{9}	4.13×10^{10}
South & Southeast Asia	7.75×10^{10}	9.21×10^{10}	2.44×10^{10}	1.36×10^{10}	1.92×10^{10}	2.27×10^{11}
Sub-Saharan Africa	4.90×10^{10}	5.71×10^{10}	1.75×10^{10}	5.23×10^{9}	2.29×10^{9}	1.31×10^{11}
North America & Oceania	3.03×10^{10}	8.79×10^{9}	1.39×10^{10}	2.53×10^{9}	1.62×10^{10}	7.17×10^{10}

Our exposition now shifts to the analysis of each staple crop, taken separately, always from a production-side perspective. To accomplish this, we select the countries with the highest production for each staple crop, as indicated in Table 4.12. This decision stems from several considerations. By choosing the leading producer, we aim to access the widest impact on water of staple crop cultivation. Our choice enables us to scrutinize how the selected nations manage water resources in cultivating the specific staple crop, providing insights into resource allocation strategies and potential environmental consequences. Given that the largest producers often play a central role in global supply chains, our analysis offers a glimpse into how staple crops are integrated into international trade networks, emphasizing the interconnectedness of different regions in terms of FLW from a production point of view. Given that wheat has been comprehensively addressed in the previous subsection, it will be omitted from the subsequent analysis.

Figure 4.32 illustrates the distribution of water resources usage associated to the FLW of each staple crop. The data is segmented by stage, considering the country with the highest production for each staple crop, as outlined in Table 4.12. This visualization offers a clear view of which crops are predominantly used for human consumption and which are more directed towards animal feed. However, a more in-depth analysis will be conducted subsequently for each crop. To support the presented figure, we provide the corresponding data in Table 4.13, offering a

Table 4.12: Countries chosen for the analysis from a production-side perspective of each one of the staple crops with the corresponding production in tonnes in the year 2016.

Staple crop	**Country**	**Production (t)**
Rice	China	2.13×10^8
Barley	Russia	1.80×10^7
Maize	United States	4.12×10^8
Rye	Germany	3.17×10^6
Oats	Russia	4.77×10^6
Millets	India	1.03×10^7
Sorghum	United States	1.22×10^7
Potatoes	China	8.50×10^7
Sweet Potatoes	China	5.16×10^7
Cassava	Nigeria	5.96×10^7
Soybeans	United States	1.17×10^8

comprehensive overview of the virtual water footprint associated with the FLW of each staple crop in the respective countries, from a production perspective, further enriching the analysis.

Table 4.13: Water footprint (m^3) per each staple crop, considering the countries selected, divided by stage.

Staple crop (Country)	**Total water footprint (m^3), divided by stage**					
	Agricultural	Post-harvest	Processing	Distribution	Consumption	Total
Rice (China)	3.09×10^9	1.51×10^{10}	1.65×10^9	1.65×10^9	1.62×10^{10}	3.77×10^{10}
Barley (Russia)	6.41×10^8	1.26×10^9	2.18×10^8	5.36×10^5	2.86×10^6	2.12×10^9
Maize (U.S.)	3.89×10^9	3.81×10^9	3.74×10^8	2.03×10^8	8.18×10^8	9.09×10^9
Rye (Germany)	2.30×10^7	4.51×10^7	1.68×10^6	4.29×10^2	1.22×10^3	6.98×10^7
Oats (Russia)	2.21×10^8	4.33×10^8	3.79×10^6	9.00×10^6	9.40×10^7	7.60×10^8
Millets (India)	1.80×10^9	1.97×10^9	9.49×10^8	8.23×10^4	2.69×10^5	4.71×10^9
Sorghum (U.S.)	2.30×10^8	2.25×10^8	3.60×10^7	3.60×10^6	4.71×10^7	5.42×10^8
Potatoes (China)	4.03×10^9	1.13×10^9	2.15×10^8	1.06×10^9	1.07×10^9	7.51×10^9
Sweet Potatoes (China)	3.01×10^9	8.43×10^8	2.09×10^7	6.26×10^8	6.33×10^8	5.13×10^9
Cassava (Nigeria)	5.75×10^9	6.35×10^9	3.76×10^9	2.94×10^8	1.12×10^8	1.63×10^{10}
Soybeans (U.S.)	1.96×10^{10}	0	6.56×10^9	2.04×10^8	5.74×10^8	2.69×10^{10}

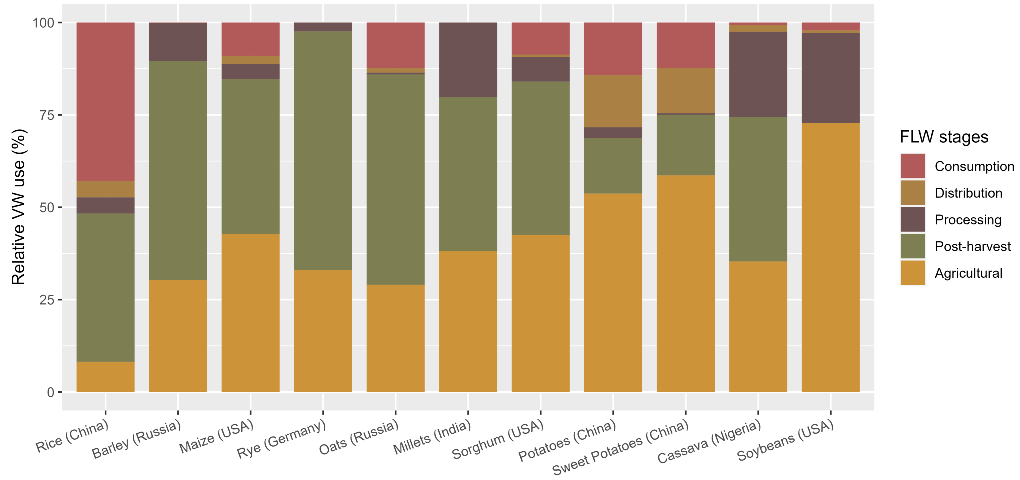

Figure 4.32: Relative use of freshwater resources for FLW of each staple crop produced globally in the country chosen for the analysis, by stage (%).

Rice

Rice is the staple food of an estimated 3.5 billion people worldwide. It is also the primary source of income and employment for more than 200 million households across countries in the developing world (Muthayya et al. 2014). The use of freshwater resources impacted by the FLW of rice produced globally amounts to 1.86×10^{11} m^3, i.e. 24.47% of the one relative to the FLW of all staple crops joint.

From Figure 4.32 we understand that the water usage associated to the post-harvest losses and consumption waste are the highest, with the former accounting for 40.13% of the total while the latter is 42.92% of the total. In Figure 4.33, the distribution of water wastage related to the consumption waste of rice produced in China is depicted. From a total population perspective, it is evident that this water usage is primarily internal, with China accounting for 1.62×10^{10} m^3, while Republic of Korea (2.52×10^7 m^3), Japan (2.20×10^6 m^3), and Canada (7.18×10^5 m^3) exhibit significantly lower contributions. This distinction becomes even more pronounced from a per capita perspective, with China registering 11.64 m^3/cap, Republic of Korea 0.49 m^3/cap, Mongolia 0.05 m^3/cap, and Liberia 0.05 m^3/cap. For a comprehensive map encompassing all stages of the value chain linked together, please refer to Appendix C.2.

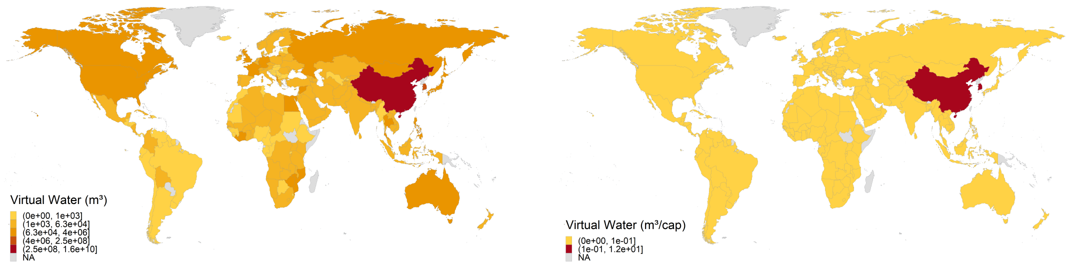

Figure 4.33: Water footprint relative to the consumption waste of rice produced in China, both for total population (left) and per capita (right).

Barley

Barley, among the earliest domesticated crops, initially played a crucial role in human consumption. However, with the growing prominence of wheat in human diets, it has evolved into a significant feed source, with an impressive 62.20% of global production dedicated to this purpose. Despite its transition, barley remains a staple for certain cultures (Lukinac et al. 2022). The WF relative to the losses and waste of barley produced globally amounts to 1.55×10^{10} m^3, i.e. 2.04% of the one relative to the FLW of all staple crops joint.

A closer look at Figure 4.32 suggests the predominant use of Russian barley for animal feed. In fact, agricultural (30.26%) and post-harvest (59.30%) losses together constitute a substantial part of the water footprint, with processing losses at 10.28%. In contrast, distribution and consumption waste contribute a mere 0.16% combined. This feature is reflected in Figure 4.34 in which the water footprint relative to the FLW of barley produced in Russia for all the stages together is depicted. In fact, Russia contributes with 2.10×10^9 m^3 of water, while Kazakhstan with 1.60×10^6 m^3, Egypt with 1.32×10^6 m^3 and Morocco with 1.32×10^6 m^3, underlying a substantial use of this crop in the North African region. In terms of per capita water usage, Russia takes the lead with a steady rate of 14.57 m^3/cap, establishing a notable margin over the subsequent countries. Cyprus follows with a mere 0.93 m^3/cap, trailed by Latvia at 0.48 m^3/cap, and Lebanon with 0.11 m^3/cap.

However, it is interesting to note that the water footprint of Cyprus and Latvia is mostly associated to the consumption waste (Figure C.80) with the former accounting to 0.81 m^3/cap and the latter to 0.21 m^3/cap. While Russia, Egypt and Morocco have 0 m^3/cap of water wasted in this stage and Lebanon a mere 0.02 m^3/cap.

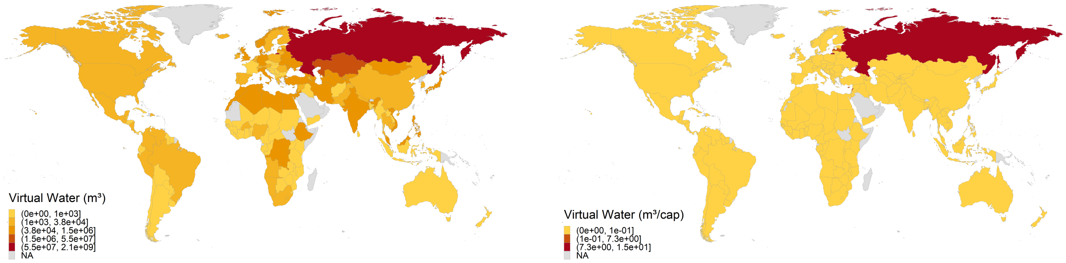

Figure 4.34: Water footprint relative to the FLW of barley produced in Russia, both for total population (left) and per capita (right).

Maize

Maize, also commonly known as corn, was domesticated more than 9000 years ago in southern Mexico and Mesoamerica. Today, it has become the leading global staple cereal in terms of annual production, being the only cereal exceeding 1×10^9 tonnes (Erenstein, Jaleta, Sonder, et al. 2022). The WF relative to the losses and waste of maize produced globally amounts to 1.08×10^{11} m^3, i.e. 14.26% of the one relative to the FLW of all staple crops joint.

Observing Figure 4.32 we can understand that water usage associated to agricultural and post-harvest losses are substantial in the production of maize from the United States, but processing (4.11%), distribution (2.24%) and consumption (9.00%) stages are not negligible. In particular, from Table 4.13 we understand that distribution and consumption waste account to more than 10^9 m^3 of water combined. The water footprint associated to the FLW of maize produced in the U.S. is related to the United States for 8.33×10^9 m^3, but a major part is also due to Latin America, in fact the following countries with the most water usage are Mexico 3.26×10^8 m^3, Colombia 7.52×10^7 m^3 and Guatemala 3.78×10^7 m^3. From a per capita point of view, as we can see in Figure 4.35, this trend is confirmed with United States 25.78 m^3/cap, Honduras 2.69 m^3/cap, Mexico 2.69 m^3/cap and Guatemala 2.39 m^3/cap. If we consider water usage related to consumption waste (Figure C.83) we understand that the central and south American countries import maize from the U.S. for human food intake, in fact averagely 60% of the water footprint associated to the countries in this region are related to the consumption stage. Conversely, the United States virtual water associated to the consumption waste of the maize produced inside its borders is less than 0.05%.

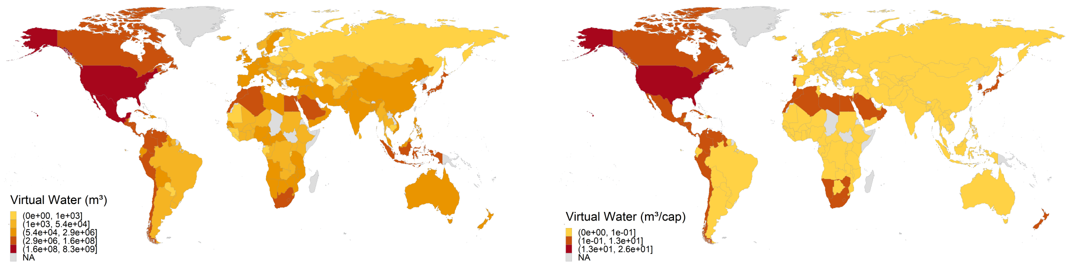

Figure 4.35: Water footprint relative to the FLW of maize produced in the United States, both for total population (left) and per capita (right).

Rye

Rye is a widely cultivated cereal, particularly in regions of Europe and North America where soil and temperature conditions may be unfavorable for other cereal crops. Rye grains stand out for having one of the highest levels of fiber content compared to other commonly consumed cereals (Ikram et al. 2023). The WF relative to the losses and waste of rye produced globally amounts to 8.84×10^8 m^3, i.e. just 0.12% of the one relative to the FLW of all staple crops joint.

The analysis of the water footprint associated with FLW of rye produced in Germany reveals clear patterns. Figure 4.32 distinctly illustrates that a staggering 97.60% of the water utilized is attributed to agriculture and post-harvest losses. This emphatically suggests that rye in Germany is predominantly directed towards uses other than human consumption. In this context, the water footprint is primarily internal, with Germany being accountable for 6.97×10^8 m^3 of water, constituting 99.86% of the total (Figure C.86).

It's important to clarify that the absence of data on rye derivatives, such as flour, bran and bread, may impact the complete understanding of the situation. However, insights into the rye derivatives can be gleaned from the processing stage, as depicted in Figure 4.36. The water footprint related to processing losses is localized in Germany (1.58×10^6 m^3), the Netherlands (5.73×10^4 m^3), the United States (1.04×10^4 m^3), and Sweden (5.36×10^3 m^3).

Notably, only three countries contribute to water wastage during the consumption stage of raw rye (Figure C.85): the United Arab Emirates with 1.22×10^3 m^3, Niger with 2.86 m^3, and Lesotho with 0.09 m^3.

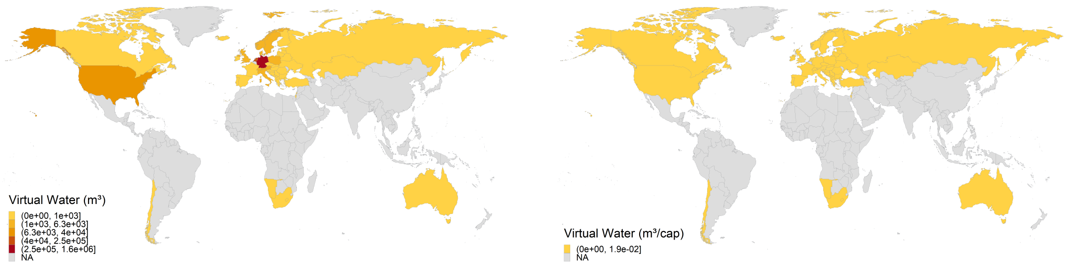

Figure 4.36: Water footprint relative to the processing losses of rye produced in Germany, both for total population (left) and per capita (right).

Oats

Oats are commonly regarded as a minor cereal crop in terms of annual grain production or cultivated areas. Additionally, they have traditionally been utilized predominantly as animal feed. However, oats have gained recognition as a healthful and nutritious cereal due to their high concentration of soluble fiber and dense nutrient content. (Wani et al. 2014). The WF attributed to losses and waste in globally produced oats stands at 2.96×10^9 m^3, constituting a mere 0.39% of the cumulative water footprint associated with the FLW of all staple crops combined.

Virtual water relative to losses and waste of oats produced in Russia is mostly associated to post-harvest (56.91%) and agriculture (29.04%) stages, as it can be observed from Figure 4.32. However, consumption waste is consistent with 12.37% of the total. As depicted in Figure 4.37, Russia is responsible for 7.34×10^8 m^3 of water wasted along all the stages of the value chain, followed by United States 8.15×10^6 m^3, United Kingdom 3.11×10^6 m^3 and Kazakhstan 2.94×10^6 m^3.

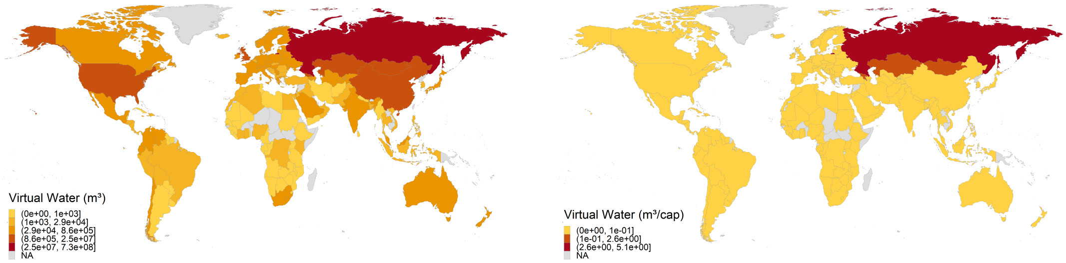

Figure 4.37: Water footprint relative to the FLW of oats produced in Russia, both for total population (left) and per capita (right).

While if we focus on the consumption waste (Figure C.89), Russia uses 0.50 m^3/cap of water, followed by Mongolia 0.35 m^3/cap, Georgia 0.33 m^3/cap, and Armenia 0.27 m^3/cap.

Millets

Millets are renowned for their resilience to various abiotic stresses associated with climate change. Notably water-efficient, millets demand 70% less water than rice and exhibit remarkable tolerance to high temperatures, enduring conditions as extreme as 42°C. This unique set of attributes positions millets as an ideal choice for tropical countries grappling with the challenges of climate-induced drought, offering a drought-resilient and sustainable food solution (Kheya et al. 2023). The WF attributed to losses and waste in globally produced millets stands at 1.84×10^{10} m^3, constituting 2.42% of the cumulative water footprint associated with the FLW of all staple crops combined.

Regrettably, similar to rye, the scarcity of data on millets derivatives significantly hampers our analysis. Presently, we only possess data on raw millets and millets bran, with the absence of information on millets flour limiting a more comprehensive understanding of the water footprint in the later stages of the value chain. The insights derived from Figure 4.32, illustrating the relative water usage of FLW of millets produced in India, underscore this limitation. Agricultural and post-harvest losses account for a substantial 79.86% of the total water footprint, while processing losses still contribute significantly at 20.13%, leaving a mere 0.01% for the last two stages.

In Figure 4.38, a notable observation is the almost complete exclusion of the American continent from the water usage. Furthermore, India, the most significant player, wastes a substantial 4.71×10^9 m^3 of water throughout the entire supply chain, with only 9.46×10^8 m^3 (20.08%) attributed to processing losses. In contrast, the followers Namibia 7.01×10^5 m^3, Nepal 6.57×10^5 m^3 and Saudi Arabia 6.36×10^5 m^3 waste 100% of their water in the processing stage. This means that all the imported millet from India in these countries is destined to the production of bran, used as feed, since there isn't distribution and consumption waste.

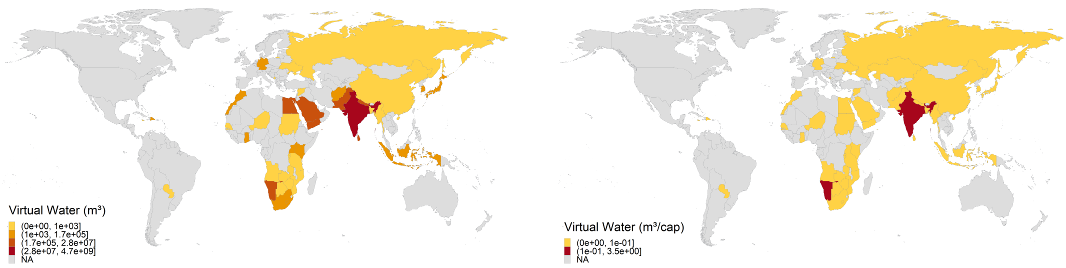

Figure 4.38: Water footprint relative to the FLW of millets produced in India, both for total population (left) and per capita (right).

Sorghum

Sorghum exhibits adaptability to higher average temperatures compared to many other cereal crops. This resilient crop holds notable importance in Africa, standing as the second most crucial staple grain for millions of people, following maize. Its primary mode of consumption is in the form of grains, emphasizing its significance as a dietary staple in the region (Mundia et al. 2019). The WF attributed to losses and waste in globally produced sorghum amounts to 2.54×10^{10} m^3, constituting 3.34% of the cumulative water footprint associated with the FLW of all staple crops combined.

In Figure 4.32, the relative distribution of the water footprint along the FLW stages of sorghum produced in the United States is depicted. While agricultural and post-harvest stages still dominate at 84.01% of the total, the processing (6.63%) and consumption (8.69%) stages are also noteworthy. When considering all stages combined, as shown in Figure 4.39, the United States wastes 5.14×10^8 m^3 of water, followed by China (1.45×10^7 m^3), Pakistan (4.51×10^6 m^3), and South Africa (2.36×10^6 m^3). From a per capita perspective, South Africa takes the lead with 46.78 m^3/cap, followed by Kenya (27.23 m^3/cap), the U.S. (14.85 m^3/cap), and China (5.05 m^3/cap), while Pakistan falls behind at 0.11 m^3/cap. Notably, the water footprint of China, Pakistan, and South Africa is related to processing

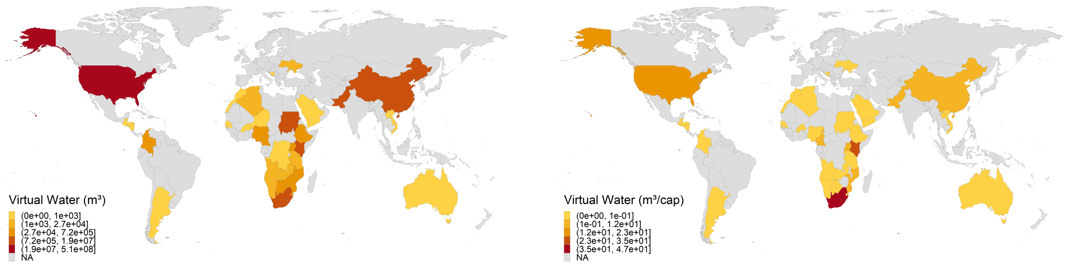

Figure 4.39: Water footprint relative to the FLW of sorghum produced in the United States, both for total population (left) and per capita (right).

losses, while only 1.64% of the U.S.'s water footprint pertains to this stage. In the consumption stage (Figure C.95), the United States is accountable for 4.70×10^7 m^3 of water, representing more than 99% of the total for this stage. Other countries included are Colombia (1.09×10^5 m^3), Sudan (3.54×10^2 m^3), and Laos (5.58×10^1 m^3).

Potatoes

Potato is currently grown on an estimated 20 million hectares of farmland globally, and the potato production worldwide stands for 3.55×10^8 tonnes, as showed in Table 2.2. Consumption of fresh potatoes accounts for approximately two-thirds of the harvest and around 1.3 billion people eat potatoes as a staple food (Devaux et al. 2021). The water use attributed to losses and waste in globally produced potatoes amounts to 2.74×10^{10} m^3, constituting 3.61% of the cumulative water footprint associated with the FLW of all staple crops combined.

In Figure 4.32, we can examine the distribution of virtual water related to the FLW of potatoes produced in China across all stages of the value chain. The WF related to agricultural losses is predominant with 53.72% of the total, while the post-harvest stage, unlike previous staple crops, accounts for a smaller portion at 15.04%. The processing stage is notably low at 2.87%, while distribution (14.12%) and consumption (14.25%) waste contribute significantly to the overall water usage. When considering all stages together, China overwhelmingly dominates water usage related to the FLW, representing 99.85% of the total. However, a nuanced exploration of the distribution stage becomes interesting, as depicted in Figure 4.40, while the map of the stages linked together is accessible in Appendix C.2. China maintains its position as the country with the highest water footprint, amounting to 1.06×10^9 m^3. Malaysia follows with 1.58×10^6 m^3, Vietnam with 1.44×10^6 m^3, and Sri Lanka with 7.18×10^5 m^3.

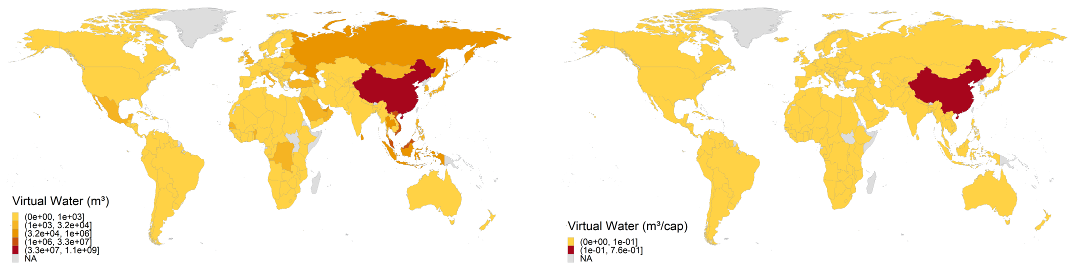

Figure 4.40: Water footprint relative to the distribution waste of potatoes produced in China, both for total population (left) and per capita (right).

Sweet Potatoes

Sweet potato is recognized as one of the world's most important, versatile, and under-exploited food crops. Its significance extends to playing a crucial role in addressing food shortages during times of crisis, such as natural disasters or wars, in many countries (Alam 2021). The use of freshwater resources attributed to losses and waste in globally produced sweet potatoes amounts to 1.34×10^{10} m^3, constituting 1.76% of the cumulative water footprint associated with the FLW of all staple crops combined.

Examining the water footprint associated with losses and waste of sweet potatoes produced in China reveals a distribution along the stages that is reminiscent of the one observed in the production of potatoes, highlighting similarities for these root crops. The breakdown across the stages is as follows: agricultural 58.64%, post-harvest 16.42%, processing 0.41%, distribution 12.20%, and consumption 12.34%. In Figure 4.41, it's evident that China holds the highest water usage throughout the entire value chain for sweet potatoes, wasting a substantial 5.13×10^9 m^3. Following China are Japan (3.85×10^5 m^3), the United States (6.89×10^4 m^3), and Canada (3.68×10^9 m^3). From a per capita perspective, the water wastage in China is comparatively moderate, amounting to 3.70 m^3 per person. In contrast, other countries exhibit minimal water wastage per person, such as New Zealand (4.06×10^{-3} m^3/cap), Japan (3.03×10^{-3} m^3/cap), and the Netherlands (1.89×10^{-3} m^3/cap). Canada and the United States contribute even less with values of 1.02×10^{-3} m^3/cap and 2.13×10^{-4} m^3/cap, respectively.

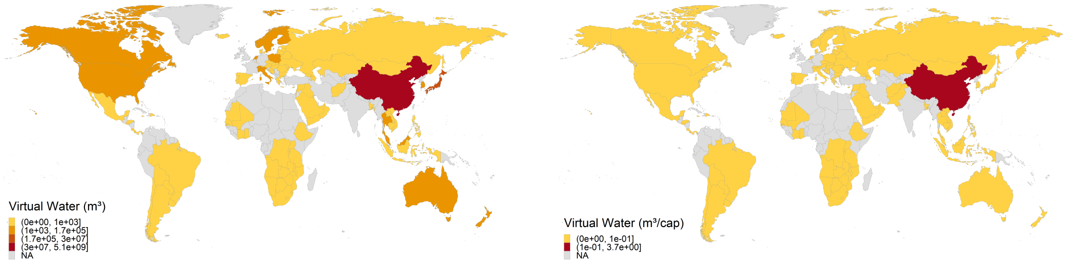

Figure 4.41: Water footprint relative to the FLW of sweet potatoes produced in China, both for total population (left) and per capita (right).

Cassava

Cassava, during its growth, produces multiple tuberous roots, serving as reserves and containing up to 35% starch. It offers significant advantages for food security due to its stable and high yields, even when cultivated in marginal soils and under conditions of uncertain rainfall. Moreover, the crop requires minimal labor and production costs. The unique characteristic of cassava leaves closing in on themselves allows the plants to be left undisturbed, optimizing labor efficiency without compromising cassava production (Kouakou et al. 2016). The WF attributed to losses and waste in globally produced cassava amounts to 5.90×10^{10} m^3, constituting 7.76% of the cumulative water footprint associated with the FLW of all staple crops combined.

Observing Figure 4.32, representing the WF related to losses and waste of Cassava produced in Nigeria, we can recognize the trend typical of developing countries, where the highest losses pertain to agricultural (35.34%), post-harvest (39.07%) and processing (23.10%) stages. This is even further notable since only 16.48% of the production is destined to feed purposes. An intriguing observation is that raw cassava is exclusively processed within the country of its production and is not exported in its raw form. This is a departure from the typical pattern where only the first two stages of the value chain are localized in the country of production, however we have to acknowledge that trades not reported in the data could be present. In the context of Table 4.13, it becomes evident that the considerable water wastage of 3.76×10^9 m^3 of FLW during the processing phase is entirely localized to Nigeria. This underscores the unique situation where inefficiencies in water use during cassava processing impact the water resources within the country itself.

Given this pattern, as we can see from Figure 4.42, the most of the water footprint along all the stages pertains to Nigeria itself, with 1.63×10^{10} m^3. While other contributors are Niger 2.62×10^4 m^3, Mozambique 4.86×10^3 m^3 and Namibia 3.71×10^{10} m^3, highlighting the regional importance of this crop.

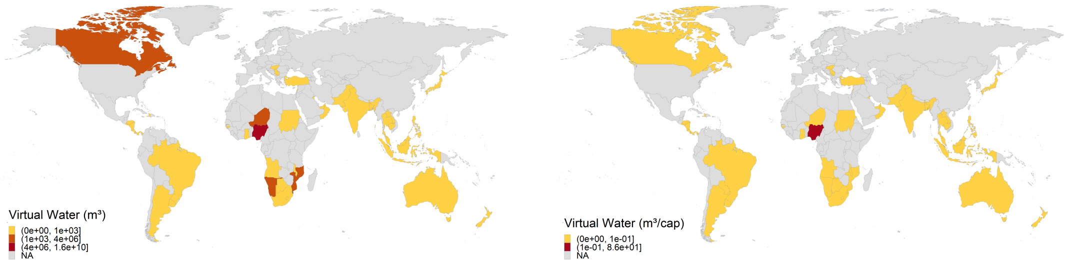

Figure 4.42: Water footprint relative to the FLW of cassava produced in Nigeria, both for total population (left) and per capita (right).

Soybeans

Soybean stands out as one of the most valuable, versatile, and nutritionally significant legumes worldwide. The importance of soybean meal extends to both direct human consumption and indirect consumption as a major source of livestock feed. In recent times, the growing demand for plant-based protein in diets positions soy foods as a globally viable alternative to animal protein (Shea et al. 2020). The water usage attributed to losses and waste in globally produced soybeans amounts to 1.03×10^{11} m^3, constituting 13.51% of the cumulative water footprint associated with the FLW of all staple crops combined.

From Figure 4.32, significant insights emerge regarding soybeans produced in the United States. Notably, agricultural losses dominate the water footprint, constituting a substantial 72.76%. However, what sets soybeans apart is the absence of water usage associated with post-harvest losses, standing at 0.00%. This anomaly can be attributed to the fact that oil seeds in the region of North America & Oceania exhibit a post-harvest loss share of 0%, as it can be observed in Table 2.3. Moving to other stages, WF linked to processing losses accounts for 24.35%, while distribution and consumption waste jointly contribute 2.89%.

In Figure 4.43, a visualization of the countries involved in water usage for processing losses of soybeans produced in the United States is presented. While the map presenting all the stages combined is suitable in Appendix C.2. The United States takes a prominent role, with an involvement of 3.41×10^9 m^3. Other significant contributors include China (1.73×10^9 m^3), Mexico (2.46×10^8 m^3), and Indonesia (1.93×10^8 m^3). The proportion of water wastage in this stage for the U.S. is 52.02%, comparatively low when contrasted with other staple crops. Examining the per capita perspective, the United States leads with 10.56 m^3/cap, followed by the Netherlands (5.87 m^3/cap), Costa Rica (5.80 m^3/cap), and Tunisia (3.21 m^3/cap), providing additional insights into the distribution of water usage across different nations.

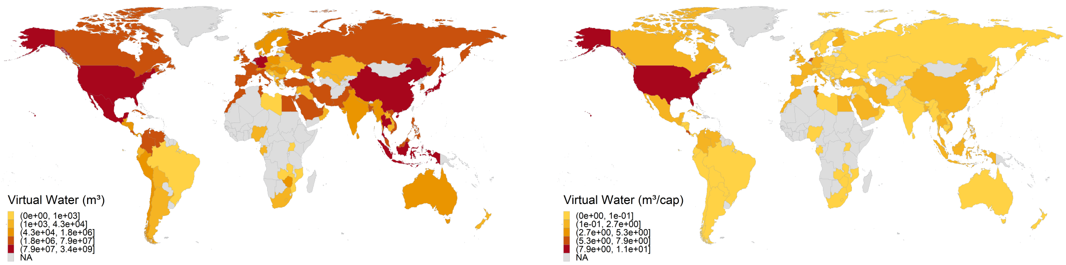

Figure 4.43: Water footprint of the processing losses of soybeans produced in the United States, both for total population (left) and per capita (right).

4.2.2 Fork to farm perspective

We now turn our focus to the analysis of FLW, and its impact on freshwater resources, relative to staple crop trees from the perspective of human consumption. Figure 4.44 provides a global and regional distribution of the water footprint, considering all the staple crops and their derivatives joint, including wheat, segmented by stage. Globally, the post-harvest stage emerges as the most impactful on virtual water, accounting for 27.36% of the total, closely followed by the consumption stage at 27.09%. The agricultural stage is not far behind, contributing 23.03%. In contrast, the processing and distribution stages have the least impact, representing only 13.78% and 8.73% of wasted water, respectively. Regional variations are notable, with regions such as the North America & Oceania (62.73%), and Europe (54.39%) exhibiting the highest percentages of virtual water associated with consumption waste. On the other hand, South & Southeast Asia, along with Sub-Saharan Africa, lead in water usage linked to agricultural and post-harvest losses combined, accounting for 60.86% and 73.81%, respectively.

Table 4.14 provides a comprehensive overview of the total water footprint associated with these regions, categorized by stage, along with global data for comparison.

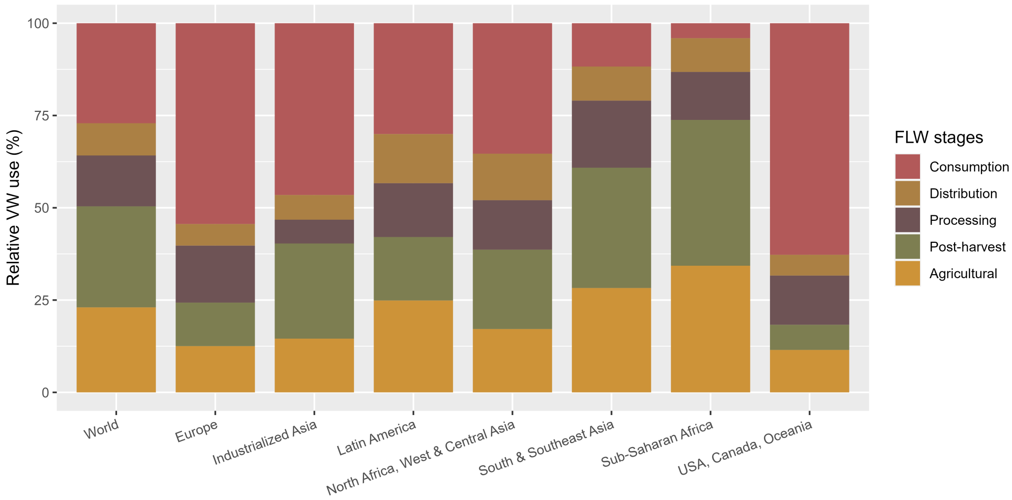

Figure 4.44: Relative use of freshwater resources for FLW of the staple crops and their derivatives (wheat included) consumed globally and in each specific region, by stage (%).

Remarkably, the cumulative global water footprint relative to the FLW associated with the food intake of these staple crops and their derivatives amounts to 4.16×10^{11} m^3. The region that is affected by the highest water waste is South & Southeast Asia with 1.47×10^{11} m^3, while the least affected is North America & Oceania with 1.84×10^{10} m^3.

Table 4.14: Water footprint of the staple crops and their derivatives combined (wheat included) consumed globally and per region, divided by stage.

Region	**Water footprint (m^3), divided by stage**					
	Agricultural	Post-harvest	Processing	Distribution	Consumption	Total
World	9.59×10^{10}	1.14×10^{11}	5.74×10^{10}	3.63×10^{10}	1.13×10^{11}	4.16×10^{11}
Europe	4.66×10^{9}	4.39×10^{9}	5.75×10^{9}	2.18×10^{9}	2.02×10^{10}	3.72×10^{10}
Industrialized Asia	1.30×10^{10}	2.31×10^{10}	5.77×10^{9}	6.00×10^{9}	4.17×10^{10}	8.95×10^{10}
Latin America	6.51×10^{9}	4.50×10^{9}	3.82×10^{9}	3.48×10^{9}	7.86×10^{9}	2.62×10^{10}
North Africa, West & Central Asia	5.60×10^{9}	7.01×10^{9}	4.37×10^{9}	4.11×10^{9}	1.15×10^{10}	3.26×10^{10}
South & Southeast Asia	4.16×10^{10}	4.80×10^{10}	2.68×10^{10}	1.36×10^{10}	1.73×10^{10}	1.47×10^{11}
Sub-Saharan Africa	2.23×10^{10}	2.57×10^{10}	8.45×10^{9}	5.95×10^{9}	2.63×10^{9}	6.50×10^{10}
North America & Oceania	2.12×10^{9}	1.26×10^{9}	2.45×10^{9}	1.04×10^{9}	1.16×10^{10}	1.84×10^{10}

We seek to understand the staple crop trees that wield the most significant influence on the water footprint relative to FLW, both globally and in specific regions. Figure 4.45 presents this information in terms of percentages. Globally, wheat products showcase the highest water usage for FLW at 39.25%. When combined with rice (33.55%) and maize (9.83%) products, they collectively contribute to over 82.64% of the total water footprint. In contrast, the water usage for FLW of globally consumed rye is minimal and can be considered negligible. However, regional disparities are evident. For instance, in Sub-Saharan Africa, maize (32.07%) and cassava (30.21%) products emerge as the most impactful in terms of water footprint. Additionally, sweet potatoes play a relevant role, accounting for 8.87% of the total. In Europe, wheat products dominate with 74.50%, followed by potato products, contributing 14.26% to the total water footprint related to FLW.

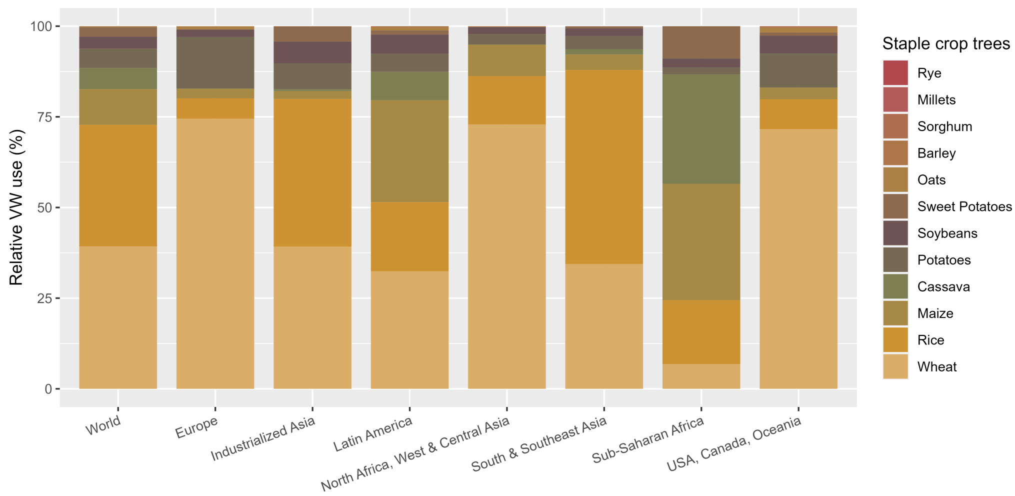

Figure 4.45: Relative use of freshwater resources for the FLW of the staple crops products consumed globally and in each specific region, divided by staple crop tree (%).

Our discussion now shifts towards the analysis of each staple crop individually, always with a fork-to-farm perspective. To achieve this, we identify the countries with the highest consumption of each staple crop and its derivatives, as outlined in Table 4.15. Recognizing that wheat has been extensively covered in the previous subsection, it is omitted from the subsequent analysis.

Table 4.15: Countries chosen for the analysis from a consumption-side perspective of each one of the staple crops with the corresponding consumption of its products in tonnes.

Staple crop tree	**Country**	**Food intake (t)**
Rice	China	1.22×10^8
Barley	Iraq	1.4×10^5
Maize	Mexico	1.25×10^7
Rye	Iran	3.13×10^2
Oats	Tanzania	6.00×10^5
Millets	Indonesia	1.59×10^4
Sorghum	United States	2.07×10^5
Potatoes	China	6.08×10^7
Sweet Potatoes	China	2.60×10^7
Cassava	Congo (Democratic Republic of the)	3.27×10^7
Soybeans	China	1.19×10^7

In Figure 4.46, the distribution of water resource usage for FLW associated with each staple crop is depicted. The data is segmented by stage, taking into account the country with the highest consumption for each staple crop and its derivatives, as detailed in Table 4.15. While this visualization provides valuable insights, such as that sorghum has a massive consumption waste corresponding to 81.40% of the total, a more thorough analysis for each crop will be conducted subsequently to delve deeper into the specific dynamics of water resource usage at different stages.

To complement the presented figure, we offer the corresponding data in Table 4.16. This table provides a comprehensive overview of the water footprint associated with the FLW of each staple crop in the respective countries, offering a detailed analysis from a consumption-side perspective.

Additionally, Table 4.17 provides a per capita perspective. It's important to remember that, in the context of food intake analysis, the "per capita" concept is applied by dividing total volumes by the population of the country where wheat derivatives are consumed. This approach enhances our understanding of the countries and regions that contribute most significantly to water use.

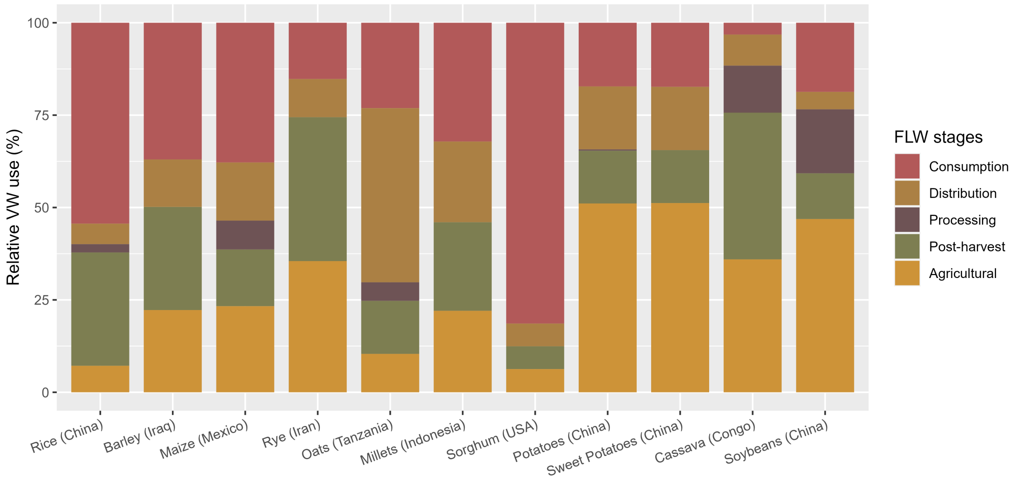

Figure 4.46: Relative use of freshwater resources for FLW of each staple crop and its derivatives consumed in the country chosen for the analysis, by stage (%).

Table 4.16: Water footprint relative to the FLW of each staple crop tree, from a consumption-side perspective, considering the countries selected, divided by stage.

Staple crop tree (Country)	**Total water footprint (m^3), divided by stage**					
	Agricultural	Post-harvest	Processing	Distribution	Consumption	Total
Rice (China)	2.25×10^9	9.64×10^9	7.05×10^8	1.74×10^9	1.71×10^{10}	3.14×10^{10}
Barley (Iraq)	9.00×10^6	1.13×10^7	4.18×10^2	5.19×10^6	1.50×10^7	4.04×10^7
Maize (Mexico)	7.57×10^8	4.98×10^8	2.53×10^8	5.11×10^8	1.23×10^9	3.25×10^9
Rye (Iran)	1.56×10^4	1.71×10^4	0	4.55×10^3	6.68×10^3	4.39×10^4
Oats (Tanzania)	2.54×10^2	3.51×10^2	1.22×10^2	1.15×10^3	5.64×10^2	2.44×10^3
Millets (Indonesia)	7.99×10^5	8.68×10^5	0	7.92×10^5	1.16×10^6	3.62×10^6
Sorghum (U.S.)	3.63×10^6	3.56×10^6	0	3.55×10^6	4.70×10^7	5.78×10^7
Potatoes (China)	3.17×10^9	8.87×10^8	2.19×10^7	1.06×10^9	1.07×10^9	6.20×10^9
Sweet Potatoes (China)	1.87×10^9	5.23×10^8	0	6.26×10^8	6.33×10^8	3.65×10^9
Cassava (Congo)	1.65×10^9	1.82×10^9	5.85×10^8	3.85×10^8	1.46×10^8	4.59×10^9
Soybeans (China)	1.90×10^9	5.01×10^8	7.02×10^8	1.91×10^8	7.58×10^8	4.05×10^9

To achieve a complete perspective on the water footprint, we delve deeper by dividing the per capita volume by the kilograms of each consumed staple crop product in each country, as we already did for wheat. This calculation, presented in Table 4.18, unveils a crucial metric per each staple crop tree: the volume of

Table 4.17: Water footprint per capita relative to the FLW of each staple crop tree, considering the countries selected, divided by stage.

Staple crop (Country)	**Water footprint per capita (m^3/cap), divided by stage**					
	Agricultural	Post-harvest	Processing	Distribution	Consumption	Total
Rice (China)	1.62	6.94	5.08×10^{-1}	1.26	1.23×10^{1}	2.26×10^{1}
Barley (Iraq)	2.33×10^{-1}	2.92×10^{-1}	1.08×10^{-5}	1.34×10^{-1}	3.87×10^{-1}	1.04×10^{0}
Maize (Mexico)	6.23×10^{0}	4.10×10^{0}	2.08×10^{0}	4.21×10^{0}	1.01×10^{1}	2.67×10^{1}
Rye (Iran)	1.87×10^{-4}	2.05×10^{-4}	0	5.46×10^{-5}	8.02×10^{-5}	5.27×10^{-4}
Oats (Tanzania)	4.67×10^{-6}	6.45×10^{-6}	2.25×10^{-6}	2.12×10^{-5}	1.04×10^{-5}	4.49×10^{-5}
Millets (Indonesia)	3.05×10^{-3}	3.31×10^{-3}	0	3.02×10^{-3}	4.44×10^{-3}	1.38×10^{-2}
Sorghum (United States)	1.12×10^{-2}	1.10×10^{-2}	0	1.10×10^{-2}	1.46×10^{-1}	1.79×10^{-1}
Potatoes (China)	2.28×10^{0}	6.39×10^{-1}	1.58×10^{-2}	7.62×10^{-1}	7.70×10^{-1}	4.47×10^{0}
Sweet Potatoes (China)	1.35×10^{0}	3.77×10^{-1}	0	4.51×10^{-1}	4.56×10^{-1}	2.63×10^{0}
Cassava (Congo)	2.03×10^{1}	2.24×10^{1}	7.18×10^{0}	4.73×10^{0}	1.80×10^{0}	5.63×10^{1}
Soybeans (China)	1.37×10^{0}	3.61×10^{-1}	5.05×10^{-1}	1.38×10^{-1}	5.46×10^{-1}	2.92×10^{0}

the water footprint relative to the FLW per kilogram of product consumed in a specific country. This method empowers us to discern and compare the water usage behaviors of different countries more comprehensively.

Table 4.18: Total WF of each staple crop and its derivatives FLW per kilogram consumed.

Staple crop (Country)	**Total per capita WF (m^3/cap)**	**Total per capita consumption (kg/cap)**	**WF per kilogram (m^3/kg)**
Rice (China)	2.26×10^{1}	8.84	2.56
Barley (Iraq)	1.04	0.36	2.89
Maize (Mexico)	2.67×10^{1}	10.29	2.60
Rye (Iran)	5.27×10^{-4}	3.76×10^{-4}	1.40
Oats (Tanzania)	4.49×10^{-5}	1.10	4.07×10^{-5}
Millets (Indonesia)	1.38×10^{-2}	6.07×10^{-3}	2.28
Sorghum (United States)	1.79×10^{-1}	6.41×10^{-2}	2.79
Potatoes (China)	4.47	4.38	1.02
Sweet Potatoes (China)	2.63	1.88	1.40
Cassava (Congo)	5.63×10^{1}	4.01×10^{1}	1.40
Soybeans (China)	2.92	8.56×10^{-1}	3.41

Rice

The insights gleaned from Figure 4.46 underscore that, in the context of rice products consumed in China, water usage for FLW is notably concentrated. Consumption waste accounts for 54.35% of the overall water usage, additionally, post-harvest losses represent 30.68% .

In Figure 4.47, the different contributions of countries to the water footprint related to FLW along the entire value chain are represented. China emerges as the most affected by this waste of freshwater resources, accounting for 2.94×10^{10} m^3, followed by Thailand (7.70×10^8 m^3), Vietnam (5.68×10^8 m^3), and Pakistan (5.23×10^8 m^3).

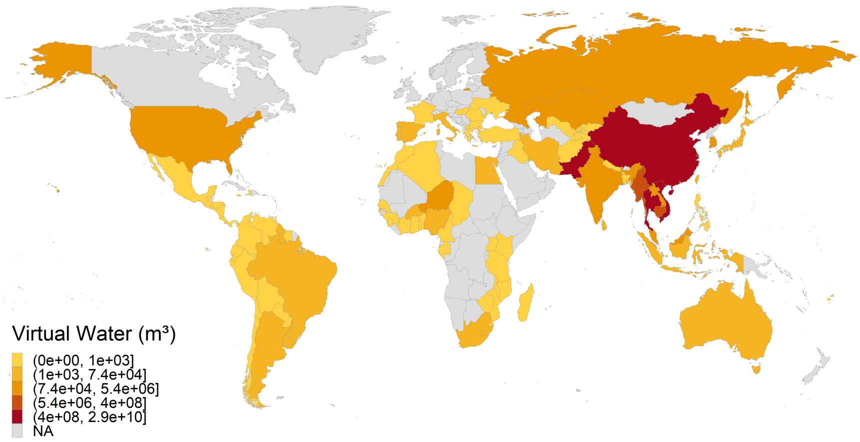

Figure 4.47: Water footprint relative to the FLW of rice products consumed in China.

If we narrow our focus to the consumption stage (Figure C.112), the pattern remains consistent, with China contributing significantly at 1.62×10^{10} m^3, followed by Thailand (3.30×10^8 m^3), Vietnam (2.68×10^8 m^3), and Pakistan (2.53×10^8 m^3).

Barley

Considering the use of freshwater resources for the FLW of barley and its derivatives consumed in Iraq, as shown in Figure 4.46, the consumption stage is the most impactful with 36.99%, followed by the post-harvest and agricultural stages with 27.91% and 22.26%, respectively. On the contrary, the processing stage, in which barley is transformed into malt, has a negligible impact on the water footprint.

Figure 4.48 represents the distribution across the countries of the water footprint associated to FLW of barley products consumed in Iraq, considering all the stages of the value chain. Iraq is responsible for 4.04×10^7 m^3 of water usage, while Bulgaria 1.77×10^4 m^3, Slovakia 1.93×10^3 m^3 and Serbia 5.64×10^2 m^3 stand far behind.

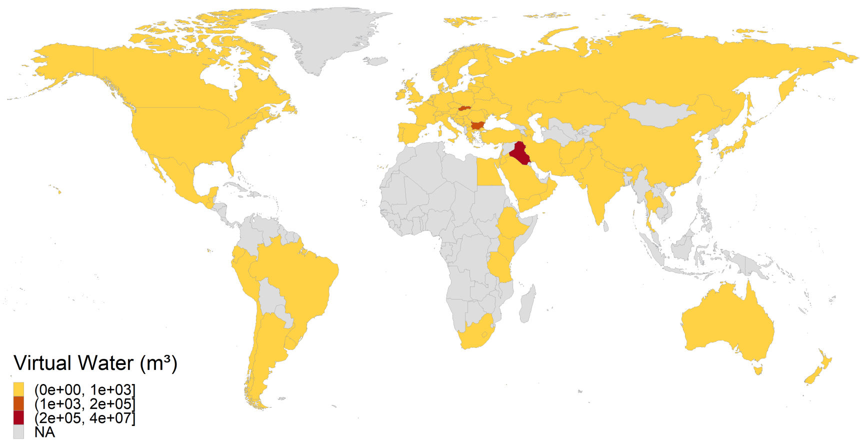

Figure 4.48: Water footprint relative to the FLW of barley products consumed in Iraq.

This trend is also valid if we consider the agricultural and post-harvest stages alone. In fact, Iraq contributes with 2.03×10^7 m^3 of water, Bulgaria with 4.52×10^3 m^3, Slovakia 4.98×10^2 m^3 and Serbia with 1.59×10^2 m^3. This indicates that the barley products consumed in Iraq mostly come from internal production.

Maize

The WF associated with FLW of maize products consumed in Mexico follows a trend similar to other cereals analyzed thus far, with the highest water usage related to the consumption waste, accounting for 37.80%. However, the post-harvest stage exhibits a relatively lower impact at 15.35%, while the processing and distribution stages are more impactful compared to the previous ones, representing 7.80% and 15.75%, respectively.

In figure 4.49 we can observe the WF associated to the FLW of each country for the maize products consumed in Mexico, considering all the stages. The water usage pertains almost exclusively to the American continent. In fact, Mexico contributes with 2.79×10^9 m^3 of water, the United States with 4.43×10^8 m^3, Argentina with 7.99×10^6 m^3 and Brazil 6.92×10^6 m^3.

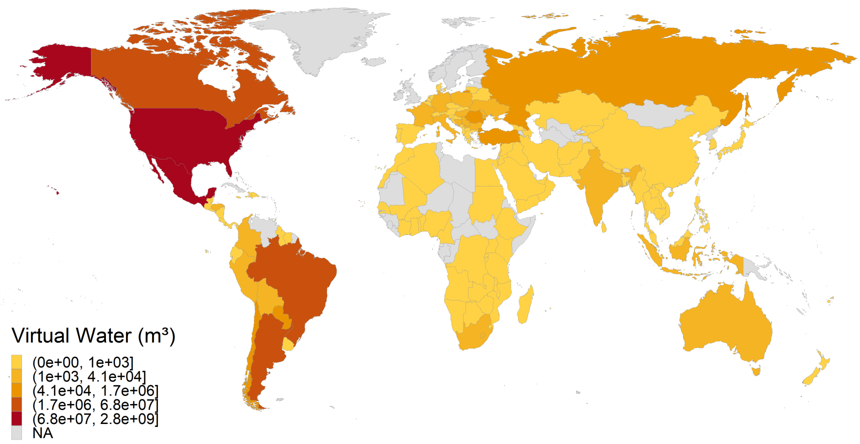

Figure 4.49: Water footprint relative to the FLW of maize products consumed in Mexico.

Rye

We now analyze the use of freshwater resources for the losses and waste of rye consumed in Iran. The first thing to consider is that in the rye tree there is data only on raw rye, as shown in Figure A.4, hence the processing stage doesn't contribute to the water waste. Agricultural and post-harvest losses are the predominant ones with 35.50% and 38.94%, respectively, while distribution (10.35%) and consumption (15.21%) waste stand behind. The water footprint pertains solely to Iran itself and amounts to 4.39×10^4 m^3, as it can be seen in Figure 4.50.

Expanding our analysis to a global perspective, we discover that only a few countries have a water footprint associated with the consumption of rye, including Iran. The additional countries are Uruguay (3.41×10^4 m^3), Lesotho (8.36×10^3 m^3), the United Arab Emirates (3.31×10^3 m^3), and Niger (2.60×10^3 m^3).

Oats

The analysis of the water footprint associated with oats products consumed in Tanzania poses a challenge. From Table 4.18, we observe that the total per capita consumption is consistent at 1.10 kg. However, the water usage per kilogram of product is negligible, measuring at 4.07×10^{-5} m^3. This minimal water usage per unit of product presents a unique scenario, making it challenging to discern significant water footprint patterns.

Figure 4.50: Water footprint relative to the FLW of rye products consumed in Iran.

An unusual pattern emerges from the analysis of Figure 4.46, where the highest share of water usage is associated with distribution waste, constituting 47.13%. Consumption waste also contributes significantly, representing 23.10% of the WF. Consequently, the last two stages, distribution waste and consumption waste, collectively account for an outstanding 70.23% of the total water footprint.

Upon analyzing the countries with the water footprint associated with FLW of oats and and rolled oats consumed in Tanzania across all stages of the value chain, a noteworthy insight emerges: the contribution of Tanzania to this water footprint is recorded as 0. This is due to the fact that, according to FAO data, Tanzania has no internal production of oats. Instead, the three countries that contribute the most, as shown in Figure 4.51, are Lithuania (8.35×10^2 m^3), Ukraine (4.32×10^2 m^3), and Brazil (2.31×10^2 m^3).

Given these challenges, we adopt also a global perspective, analyzing the countries most affected in terms of water usage by the FLW of oats products consumed worldwide, as presented in Figure 4.52. The United States tops the list, wasting 2.20×10^8 m^3 of water, followed by Brazil with 1.64×10^8 m^3, Russia with 9.83×10^7 m^3, and the United Kingdom with 8.42×10^7 m^3.

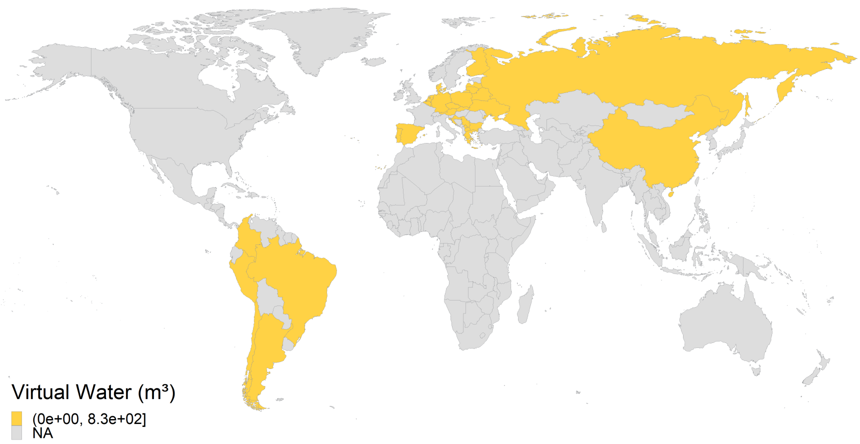

Figure 4.51: Water footprint relative to the FLW of oat products consumed in Tanzania.

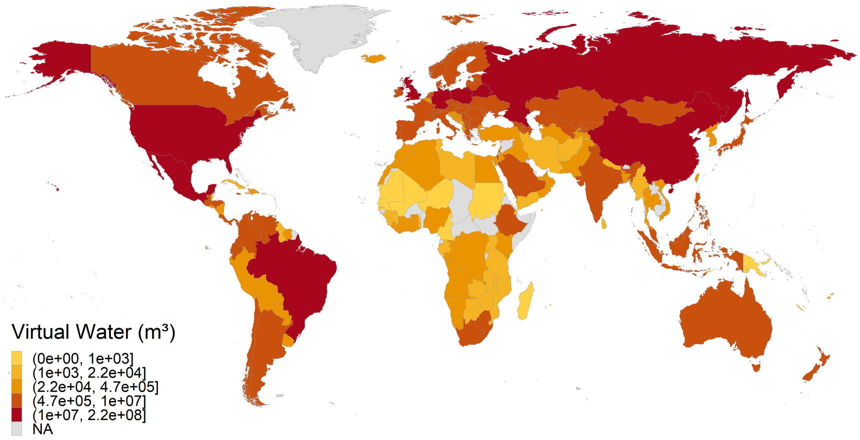

Figure 4.52: Water footprint relative to the FLW of oats products consumed in the World.

Millets

From Figure 4.46, we can analyze the distribution along the different stages of the value chain of water usage for FLW of millets and its derivatives consumed in Indonesia. Since the millets tree in our analysis contains only raw millets and bran of millets, as shown in Figure A.6, the latter not being suitable for human consumption, there are no processing losses in this analysis. The other stages are well-distributed with agricultural accounting for 22.06%, post-harvest for 23.96%, distribution for 21.86%, and consumption for 32.13%.

In Figure 4.53, it is apparent that Indonesia itself doesn't contribute to the water footprint, confirmed by the absence of internal production in the FAO data. Nevertheless, it is interesting to observe that the countries with the highest water usage for the FLW related to millets consumed in Indonesia are the United States with 3.28×10^6 m^3, Ukraine with 2.39×10^5 m^3, and China with 8.14×10^4 m^3.

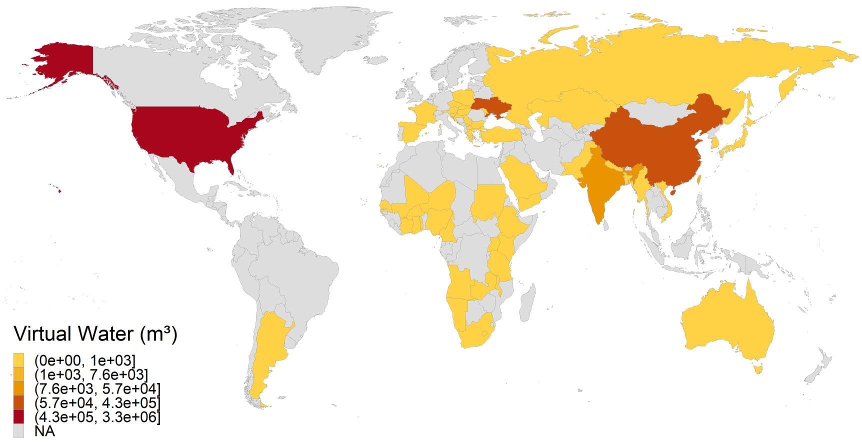

Figure 4.53: Water footprint relatives to the FLW of millets products consumed in Indonesia.

Sorghum

We now delve into the analysis of the water footprint associated with losses and waste of sorghum and bran of sorghum consumed in the United States. As depicted in Figure 4.46, the share attributed to the processing stage is null, given that bran of sorghum isn't consumed by humans. The predominant use of freshwater resources is associated with the consumption stage, accounting for 81.40%.

In Figure 4.54, the contribution of each country to the water footprint associated with the FLW of sorghum consumed in the U.S. is illustrated across all stages of the value chain. The United States itself wastes 5.77×10^5 m^3 of water, followed by India (3.64×10^4 m^3), Argentina (1.28×10^3 m^3), and Haiti (3.76×10^2 m^3). Notably, the consumption stage contributes to 81.41% of the water footprint in the U.S., 61.75% in India, 67.78% in Argentina, and 67.37% in Haiti. Meanwhile, the first two stages of the value chain combined contribute to 12.44% in the U.S., 33.59% in India, 27.10% in Argentina, and 27.54% in Haiti.

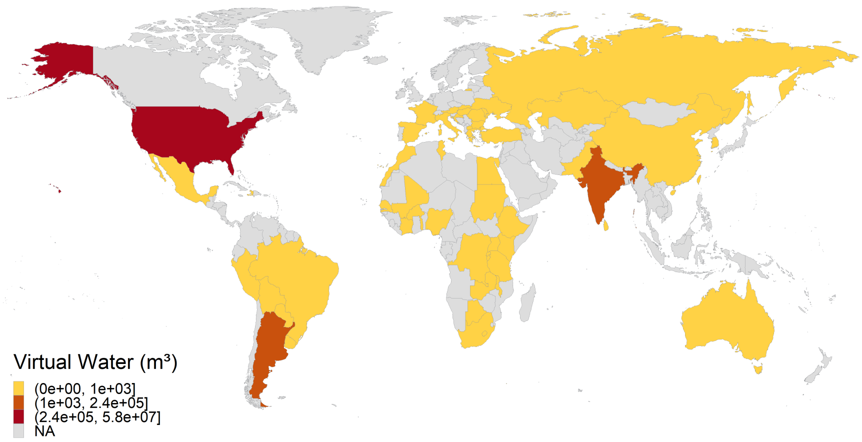

Figure 4.54: Water footprint relative to the FLW of sorghum products consumed in the United States.

Potatoes

The water footprint associated with FLW of potatoes and its derivatives consumed in China is predominantly attributed to the agricultural stage, accounting for 51.09%, as illustrated in Figure 4.46. The remaining water usage is evenly distributed among post-harvest losses (14.30%), distribution waste (17.03%), and consumption waste (17.22%). The processing stage contributes only 0.35%, indicating that the transformation of potatoes into flour and frozen potatoes is not very impactful. This aligns with the insights from Figure A.8, where it is observed that these two derivatives cover slightly more than 25% of the potatoes sent for processing.

Figure 4.55 illustrates the contribution of each country to the water footprint associated with the losses and waste of potato products consumed in China. Considering all stages together, China contributes 6.19×10^9 m^3 of water, followed by Canada with 6.66×10^6 m^3, the United States with 1.96×10^6 m^3, and the Netherlands with 6.69×10^5 m^3. Focusing specifically on the agricultural losses (Figure C.140), water usage in China accounts for 51.08% of the total, 40.29% in Canada, 40.88% in the United States, and 40.35% in the Netherlands.

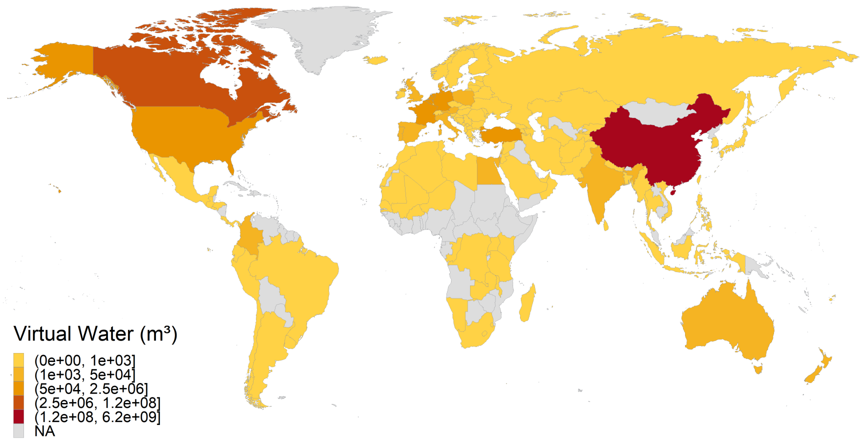

Figure 4.55: Water footprint relative to the FLW of potatoes products consumed in China.

Sweet Potatoes

Now, we can delve into the analysis of sweet potatoes consumed in China. From Figure 4.46, it is evident that the proportions of water usage relative to the losses and waste of the value chain are very similar to those observed for potatoes. The majority is attributed to the agricultural stage, accounting for 51.21%, while the remaining is evenly divided among post-harvest, distribution, and consumption stages. The processing contribution is null in our analysis, given the absence of sweet potato derivatives, as shown in Figure A.9.

Figure 4.56 depicts the countries contributing to water usage associated with the FLW of sweet potatoes consumption in China, and interestingly, there are only 11 countries with a water footprint higher than 1 m^3. China dominates the scenario, practically holding a monopoly, with a water waste of 3.65×10^9 m^3. Following China are Indonesia with 4.30×10^3 m^3, the United States with 1.69×10^3 m^3, and Taiwan with 2.03×10^2 m^3.

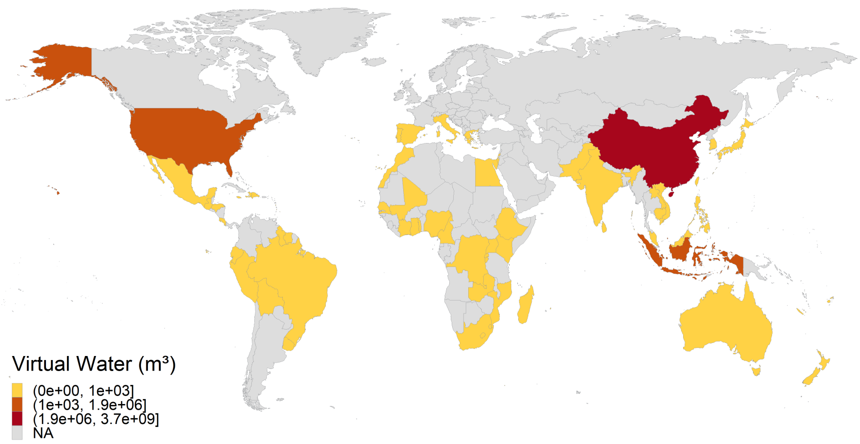

Figure 4.56: Water footprint relative to the FLW of sweet potato products consumed in China.

Cassava

Examining the use of freshwater resources for the losses and waste of cassava consumed in the Democratic Republic of Congo, Figure 4.46 reveals that the initial stages contribute the most: agricultural at 35.97%, post-harvest at 39.69%, and processing at 12.74%. Distribution and consumption waste are responsible for 8.40% and 3.19%, respectively.

Considering all the stages of the value chain together, as depicted in Figure, the Democratic Republic of Congo itself wastes 1.65×10^9 m^3 of water, followed by Uganda with 1.45×10^3 m^3 and Tanzania with 3.79×10^2 m^3. This limited number of contributors emphasizes the localized nature of the water footprint associated with this crop.

To gain a more comprehensive view of the water footprint related to cassava losses and waste on a global scale, we shift our perspective beyond individual countries. Among the nations contributing significantly to the freshwater usage for the FLW of cassava products consumed worldwide, Congo emerges as the leader, with a substantial water waste of 4.58×10^9 m^3. Nigeria closely follows with 3.36×10^9 m^3, while Uganda and Ivory Coast contribute significantly with 1.88×10^9 m^3 and 1.43×10^9 m^3, respectively. This global perspective highlights the crucial role of cassava in the African continent, as illustrated in Figure 4.58.

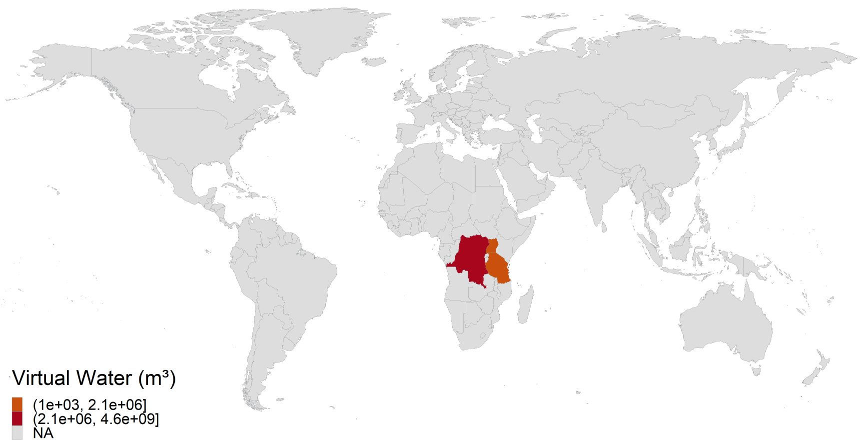

Figure 4.57: Water footprint relative to the FLW of cassava products consumed in Congo.

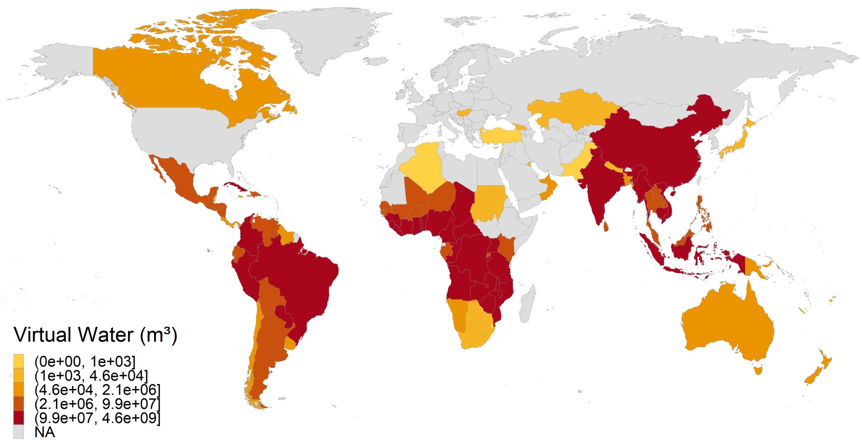

Figure 4.58: Water footprint relative to the FLW of cassava products consumed globally.

Soybeans

The analysis of the water footprint associated with the FLW of soybean products consumed in China reveals distinctive patterns. Figure 4.46 indicates that the major contributor is the agricultural stage, accounting for 46.89% of the total water usage. Notably, the processing stage assumes particular significance with a contribution of 17.31%. This is noteworthy, especially considering that soybean derivatives such as soybean oil, soy paste, and soy sauce, which fall under the processing stage, make up only slightly more than 20% of the processed soybeans, as shown in FigureA.11.

Figure 4.59 provides insightful information, revealing that, unlike other staple crop trees, soybean products stand out as the country with the highest water footprint associated with FLW not being China itself. This observation underscores the interconnectedness of the global soybean market, where multiple countries play crucial roles in the soybean supply chain. Brazil emerges as the top contributor to water waste in this context, accounting for 1.64×10^9 m^3. It is followed by the United States with 1.19×10^9 m^3, China is only third with 6.64×10^8 m^3, and Argentina follows with 3.47×10^9 m^3. From a regional point of view, Latin America contributes to 52.03% of the water footprint, North America & Oceania to 30.74% and Industrialized Asia to 16.41%.

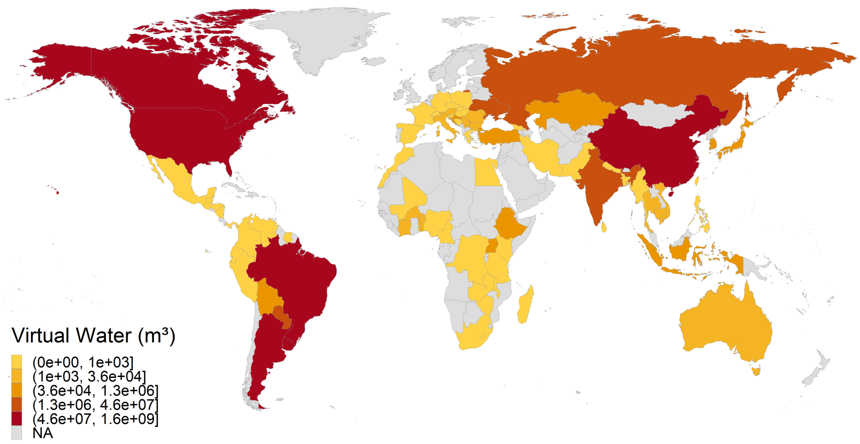

Figure 4.59: Water footprint relative to the FLW of soybean products consumed in China.

The processing stage (Figure C.156), crucial in soybean products, follows a similar trend, with Brazil contributing 3.23×10^8 m^3 (19.62% of the total water footprint associated with Brazil), the United States contributing 1.68×10^8 m^3 (14.12%), China contributing 1.00×10^8 m^3 (15.13%), and Argentina contributing

7.68×10^7 m^3 (22.11%).

4.2.3 Feeder to farm perspective

We now shift our attention to the analysis of food loss and waste and its impact on freshwater resources, relative to staple crop trees from a feed-side perspective. Figure 4.60 provides a global and regional distribution of the water footprint, considering all staple crops and their derivatives together, including wheat, segmented by stage. Globally, the post-harvest stage emerges as the most impactful on virtual water, accounting for 53.10% of the total, followed by the agricultural stage at 42.07%. In contrast, the processing stage has the least impact, representing only 4.83% of wasted water. Additionally, it's important to remember that distribution and consumption stages are not present in the feed-side perspective. Regional variations are not so accentuated; however, Industrialized Asia exhibits the highest percentages of virtual water associated with the post-harvest stage at 69.55%, while Latin America has the lowest at 38.57%. On the other hand, Latin America leads in water usage linked to agricultural losses, accounting for 59.86%, while Industrialized Asia only has 29.27%. Finally, Sub-Saharan Africa has the highest processing losses at 12.40%, while Europe has the lowest at 0.90%.

Table 4.19 provides a comprehensive overview of the total water footprint associated with these regions, categorized by stage, along with global data for comparison. Remarkably, the cumulative global water footprint relative to the FLW associated with the feed intake of these staple crops and their derivatives amounts to 1.15×10^{11} m^3. The region whose water resources are most affected by water waste is Industrialized Asia with 2.59×10^{10} m^3, while the least affected is North America & Oceania with 4.92×10^9 m^3.

We also want to understand which staple crop trees have the greatest impact on the water footprint relative to FLW, both globally and regionally. Figure 4.61 provides this information in terms of percentages. Globally, maize products present the highest water usage for feed FLW at 42.80%, and when combined with wheat and cassava products, they account for more than 70% of the total water footprint. However, regional differences exist; for example, cassava is the most impactful in Sub-Saharan Africa with 32.60%, barley in North Africa, West & Central Asia with 29.78%, and rice in South & Southeast Asia with 24.54% of the water footprint.

We now delve into the individual analysis of each staple crop, specifically from a feed-side perspective. For this examination, we concentrate on countries with the highest feed usage for each staple crop and its derivatives, as outlined in Table 4.12. Notably, since wheat has already undergone a comprehensive analysis in the

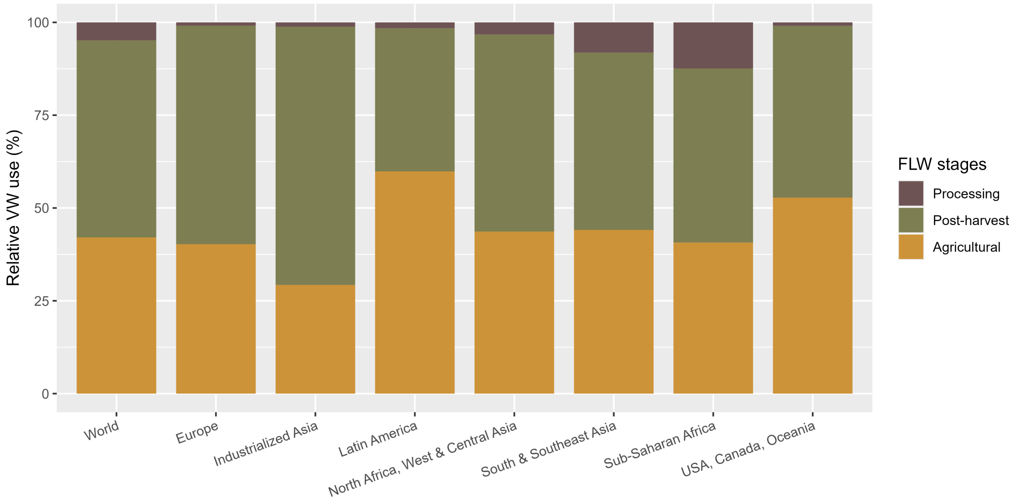

Figure 4.60: Relative use of freshwater resources for the FLW of the staple crops products combined (wheat included) used for feed globally and in each specific region, by stage (%).

Table 4.19: Water footprint (m^3) of the staple crops products combined (wheat included) used for feed globally and per region, divided by stage.

Region	**Total water footprint (m^3), divided by stage**			
	Agricultural	Post-harvest	Processing	Total
World	4.85×10^{10}	6.12×10^{10}	5.57×10^{9}	1.15×10^{11}
Europe	5.32×10^{9}	7.77×10^{9}	1.19×10^{8}	1.32×10^{10}
Industrialized Asia	7.57×10^{9}	1.80×10^{10}	3.07×10^{8}	2.59×10^{10}
Latin America	8.97×10^{9}	5.78×10^{9}	2.36×10^{8}	1.50×10^{10}
North Africa, West & Central Asia	5.62×10^{9}	6.83×10^{9}	4.17×10^{8}	1.29×10^{10}
South & Southeast Asia	9.70×10^{9}	1.05×10^{10}	1.79×10^{9}	2.20×10^{10}
Sub-Saharan Africa	8.72×10^{9}	1.00×10^{10}	2.66×10^{9}	2.14×10^{10}
North America & Oceania	2.60×10^{9}	2.28×10^{9}	4.61×10^{7}	4.92×10^{9}

previous section, we exclude it from the subsequent investigation. This approach enables a more focused exploration of the impact of feed-related food loss and waste for various staple crops.

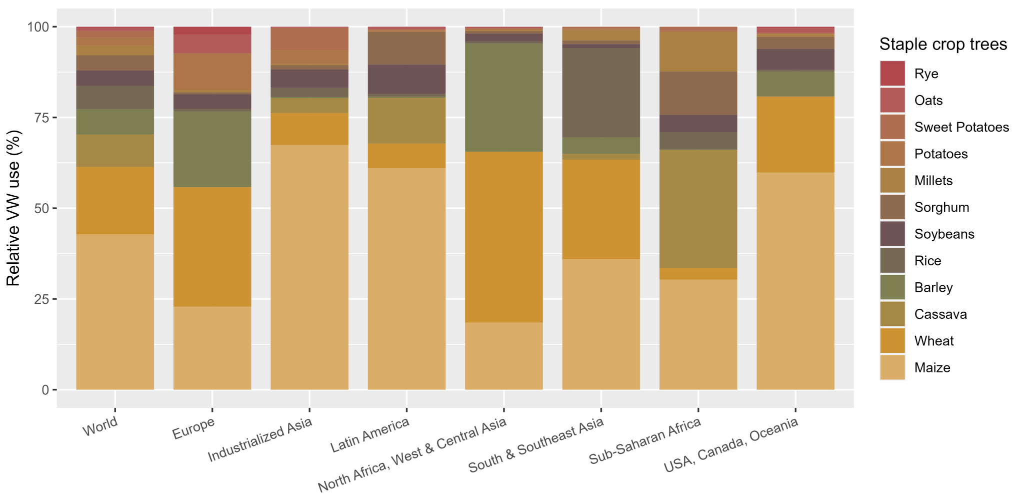

Figure 4.61: Relative use of freshwater resources for the FLW of the staple crops products used for feed globally and in each specific region, divided by staple crop tree (%).

In Figure 4.62, the distribution of water resource usage for FLW associated with each staple crop is depicted. The data is segmented by stage, taking into account the country with the highest feed intake for each staple crop and its derivatives, as detailed in Table 4.20. This initial analysis sheds light on key insights, for example in the case of China's four major crops. Maize stands out with the highest water usage attributed to post-harvest losses, accounting for a significant 82.87%. Meanwhile, for potatoes, sweet potatoes, and soybeans, over 78% of freshwater resource utilization is linked to agricultural losses. While this visualization provides valuable insights, a more granular analysis for each crop will be conducted subsequently to delve more profoundly into the specific dynamics of water resource usage at different stages.

To complement the presented figure, we offer the corresponding data in Table 4.21. This table provides a comprehensive overview of the water footprint associated with the FLW of each staple crop in the respective countries, offering a detailed analysis from a feed-side perspective.

Table 4.20: Countries chosen for the analysis from a feed-side perspective of each one of the staple crops with the corresponding feed of all its products.

Staple crop tree	**Country**	**Feed (t)**
Rice	Myanmar	5.79×10^6
Barley	Russia	9.88×10^6
Maize	China	1.77×10^8
Rye	Germany	1.87×10^6
Oats	Russia	3.15×10^6
Millets	Niger	9.26×10^5
Sorghum	Mexico	5.40×10^6
Potatoes	China	1.56×10^7
Sweet Potatoes	China	1.63×10^7
Cassava	Nigeria	1.24×10^7
Soybeans	China	7.02×10^6

Table 4.21: Water footprint relative to the FLW of each staple crop tree, from a feed-side perspective, considering the countries selected, divided by stage.

Staple crop tree (Country)	**Total water footprint (m^3), divided by stage**			
	Agricultural	Post-harvest	Processing	Total
Rice (Myanmar)	7.32×10^8	8.03×10^8	5.01×10^8	2.04×10^9
Barley (Russia)	3.58×10^8	6.98×10^8	0	1.06×10^9
Maize (China)	2.77×10^9	1.34×10^{10}	4.00×10^6	1.62×10^{10}
Rye (Germany)	1.82×10^7	3.57×10^7	0	5.38×10^7
Oats (Russia)	1.32×10^8	2.58×10^8	0	3.89×10^8
Millets (Niger)	5.30×10^8	6.64×10^8	1.05×10^8	1.30×10^9
Sorghum (Mexico)	3.93×10^8	2.51×10^8	0	6.44×10^8
Potatoes (China)	7.68×10^8	2.15×10^8	0	9.83×10^8
Sweet Potatoes (China)	1.23×10^9	3.44×10^8	0	1.57×10^9
Cassava (Nigeria)	1.72×10^9	1.90×10^9	1.30×10^9	4.91×10^9
Soybeans (China)	1.02×10^9	2.74×10^8	0	1.30×10^9

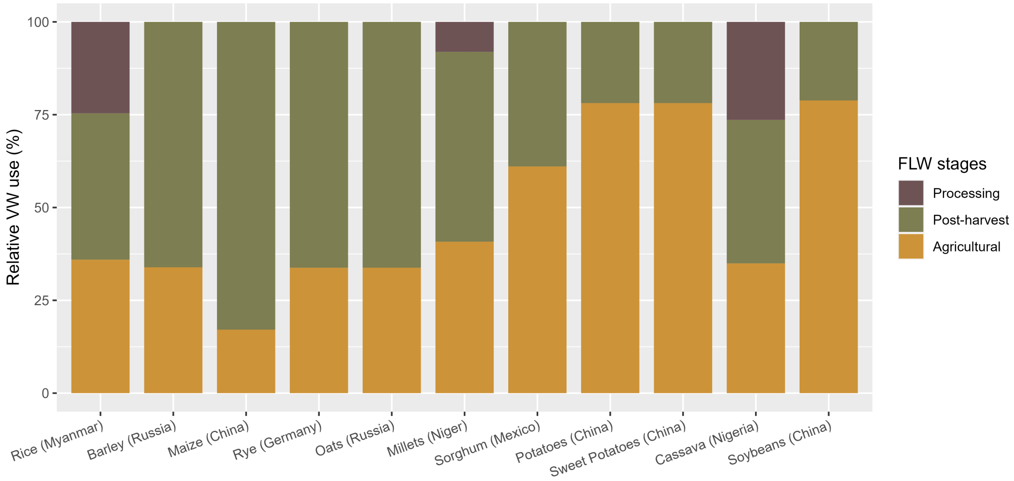

Figure 4.62: Relative use of freshwater resources for FLW of each staple crop and its derivatives used as feed in the country chosen for the analysis, by stage (%).

Rice

We begin our analysis by examining the impact on freshwater resources attributed to the losses and waste of rice used as feed in Myanmar (also known as Birmania). As depicted in Figure 4.62, the post-harvest stage holds the largest share of the water footprint at 39.43%, followed closely by the agricultural stage at 35.96%. Additionally, the water usage associated with processing losses is significant, comprising 24.61% of the total water footprint.

Figure 4.63 illustrates the global distribution of this water footprint. Myanmar leads in water usage with 2.03×10^9 m^3, followed by Thailand with 8.90×10^6 m^3, India with 8.89×10^3 m^3, and China with 8.04×10^3 m^3. This distribution pattern indicates that the losses and waste are predominantly internal to Myanmar.

Considering the processing stage alone (Figure C.161), Myanmar remains the top contributor to water waste with 4.99×10^8 m^3, followed by Thailand with 2.77×10^6 m^3, India with 2.69×10^3 m^3, and China with 2.27×10^3 m^3. This emphasizes that the overall pattern of the water footprint is mirrored in the processing stage as well.

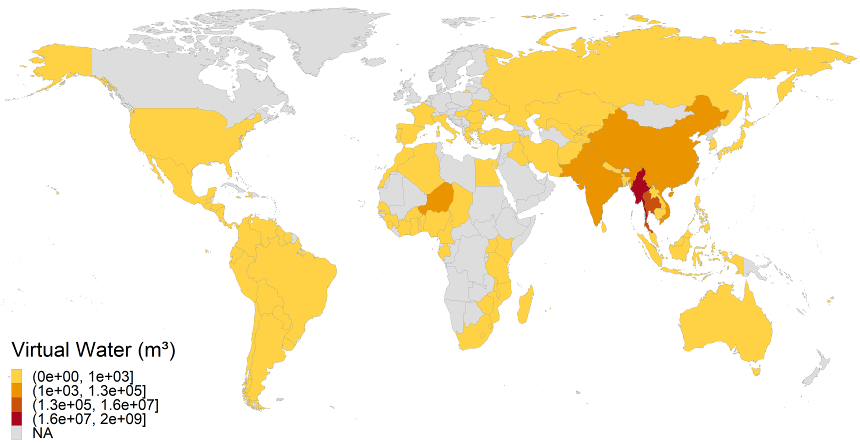

Figure 4.63: Water footprint relative to the FLW of rice products used as feed in Myanmar.

Barley

We then shift our focus to the water footprint associated with the FLW of barley products used as feed in Russia. It's important to note that in our data, the only barley derivative is malt, as illustrated in Figure A.2, and consequently, the processing stage has no impact on FLW, since it is not used as feed intake. The primary contributor is the post-harvest stage, accounting for 66.11%, followed by the agricultural stage with 33.89%, as depicted in Figure 4.62.

Figure 4.64 displays the distribution of water waste among countries, with Russia itself being the most affected at 1.04×10^9 m^3. Other notable contributors include Kazakhstan (1.04×10^7 m^3), Belarus (1.45×10^6 m^3), and Ukraine (4.66×10^5 m^3). From a regional perspective, excluding losses and waste within Russian borders, Kazakhstan accounts for 80.45% of the water footprint. While 38 countries in Europe are responsible for 19.54%.

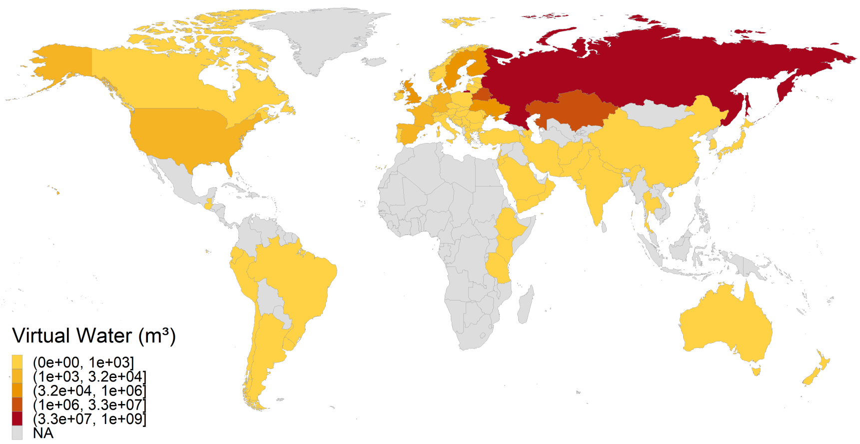

Figure 4.64: Water footprint relative to the FLW of barley products used as feed in Russia.

Maize

Maize products used as feed in China exhibit the highest proportion of water waste relative to post-harvest losses among the staple crops analyzed, amounting to 82.87%, as depicted in Figure 4.62. The agricultural stage, while low, is not negligible at 17.11%, whereas the processing stage accounts for a mere 0.02%.

From a spatial perspective, China has the highest water footprint associated with the FLW of maize products used as feed, amounting to 1.61×10^{10} m^3. This is followed at a considerable distance by Ukraine (7.19×10^7 m^3), Brazil (1.43×10^7 m^3), and Laos (1.05×10^7 m^3). When considering only the FLW outside China's borders, Europe has the highest water waste with 65.99%, followed by the region of South & Southeast Asia with 14.14%, and Latin America with 13.34%. Notably, the only country in Industrialized Asia other than China with a not null water usage is the Republic of Korea (South Korea), with a mere 8.07 m^3.

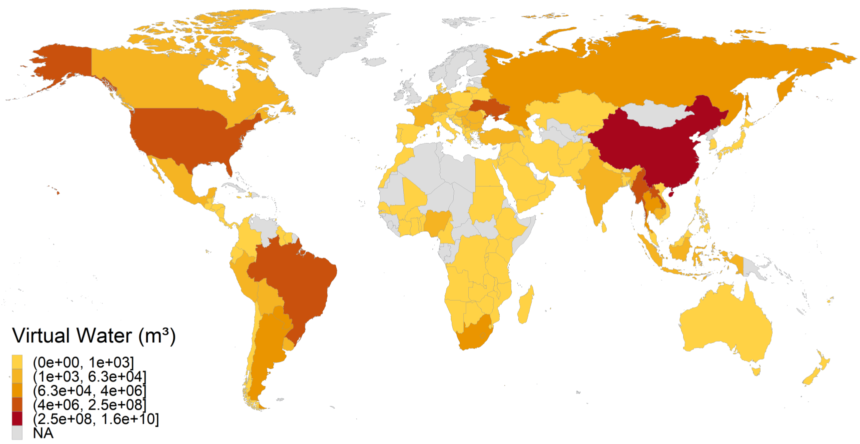

Figure 4.65: Water footprint relative to the FLW of maize products used as feed in China.

Rye

As depicted in Figure A.4, raw rye is the sole component in this staple crop tree. Therefore, when examining the water usage associated with the losses and waste of rye products used as feed in Germany, the processing stage doesn't contribute to any portion of it. The post-harvest stage is responsible for 66.22% of water waste, while the agricultural stage accounts for the remaining 33.78%.

Considering the spacial distribution, as shown in Figure 4.66, Germany stands out as the top contributor to the water footprint with 3.86×10^7 m^3, closely followed by Poland with 1.46×10^7 m^3. This is noteworthy because Germany is the leading producer of rye, as explained in Table 4.12, but Poland is also a significant producer, ranking third in this specialized category, with 2.24×10^6 t produced. Other notable contributors include the Czech Republic with 1.76×10^5 m^3 and France with 9.85×10^4 m^3. Particularly, all the countries with significant water waste are in Europe, while the countries in all the other regions have associated values so low they can be disregarded.

Expanding our analysis globally, the countries most affected in terms of the use of freshwater resources for the FLW of rye used as feed are Russia with 1.24×10^8 m^3, Germany with 5.38×10^7 m^3, China with 5.03×10^7 m^3, and Poland with 4.00×10^7 m^3. Europe leads in water wastage, accounting for 76.37% of the

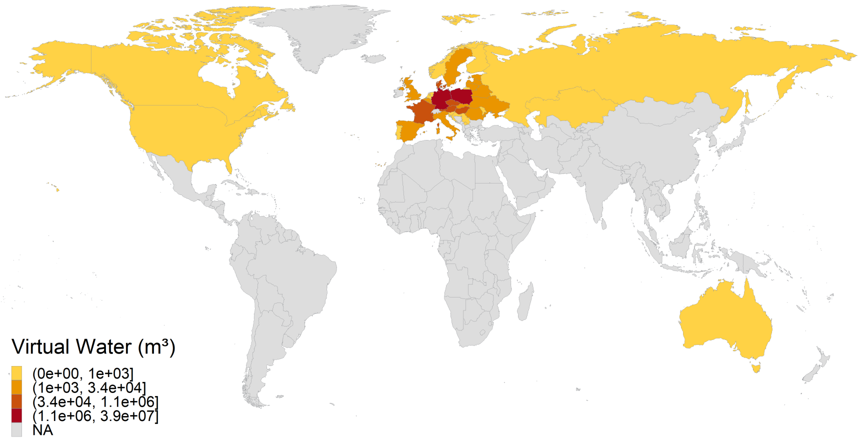

Figure 4.66: Water footprint relative to the FLW of rye products used as feed in Germany.

total, followed by Industrialized Asia with 13.62%, and North America & Oceania with 4.83%.

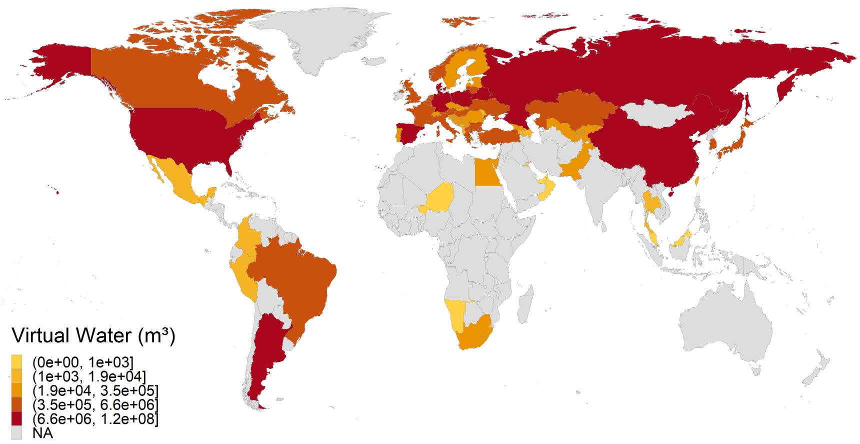

Figure 4.67: Water footprint relative to the FLW of rye products used as feed globally.

Oats

We now examine the use of freshwater resources for the FLW of oats products used as feed in Russia. Since the only oats derivative is rolled oats (as shown in Figure A.5) and is not used for feed intake, there is no contribution from the processing stage. The post-harvest stage contributes 66.22%, and the agricultural stage contributes 33.78%, as depicted in Figure 4.62.

From Figure 4.68 we can understand that the use of freshwater resources for the losses and waste of oats used as feed in Russia is mostly internal. Russia wastes 3.88×10^8 m^3 of water, followed at a distance by Belarus 7.33×10^5 m^3, Finland 3.10×10^5 m^3, and Ukraine 1.83×10^5 m^3.

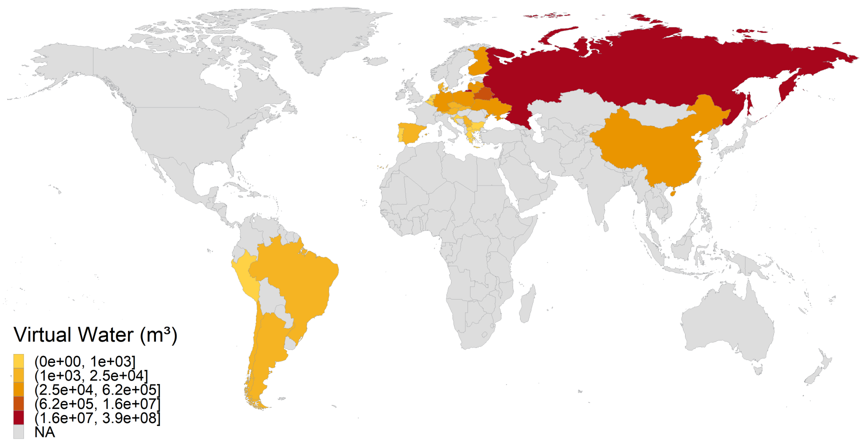

Figure 4.68: Water footprint relative to the FLW of oat products used as feed in Russia.

To gain a more comprehensive understanding of the water used for the FLW of oats used as feed, we now move to a global perspective. As seen in Figure 4.69, Russia remains the leader with 3.89×10^8 m^3, closely followed by Spain with 1.07×10^8 m^3. Other significant contributors include Poland, which wastes 4.58×10^7 m^3 of water, and Argentina with 4.33×10^7 m^3. From a regional perspective, the major contribution to the global water footprint comes from Europe with 72.86%. Other consistent contributors are Latin America (10.32%), North America & Oceania (7.21%), and North Africa, West & Central Asia (6.32%).

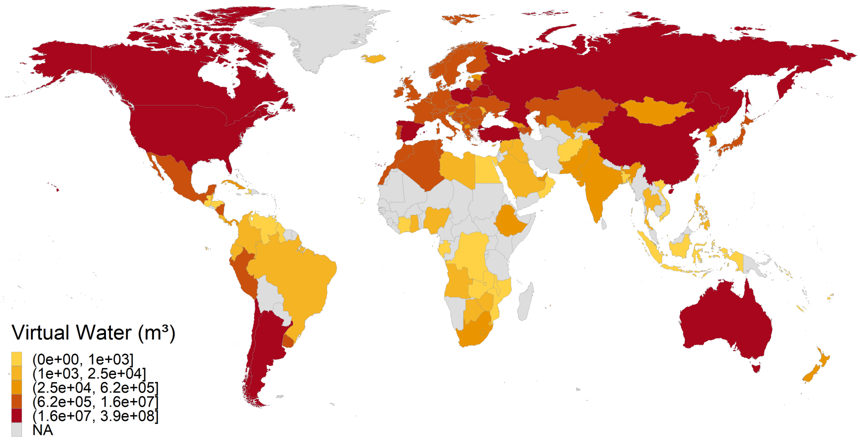

Figure 4.69: Water footprint relative to the FLW of oats products used as feed globally.

Millets

When considering millet products used as feed in Niger, the water footprint associated with FLW presents a notable portion of 8.08% in the processing stage, as shown in Figure 4.62. However, agricultural and post-harvest losses remain predominant, accounting for 40.79% and 51.13%, respectively.

As shown in Figure 4.70, nearly the entire water usage is attributed to Niger, accounting for 1.30×10^9 m^3 and Nigeria with 1.64×10^5 m^3. The subsequent countries in the ranking are China and Cameroon, each with a minimal contribution of 6.39×10^1 m^3 and 3.32×10^1 m^3, respectively.

Similarly, when accounting for processing losses impacting the freshwater resources used in bran production from millets used as feed (Figure C.173), the pattern remains consistent. Niger leads with a water waste of 1.05×10^8 m^3, followed by Nigeria with 1.84×10^4 m^3, China with 5.01 m^3, and Cameroon with 4.26 m^3.

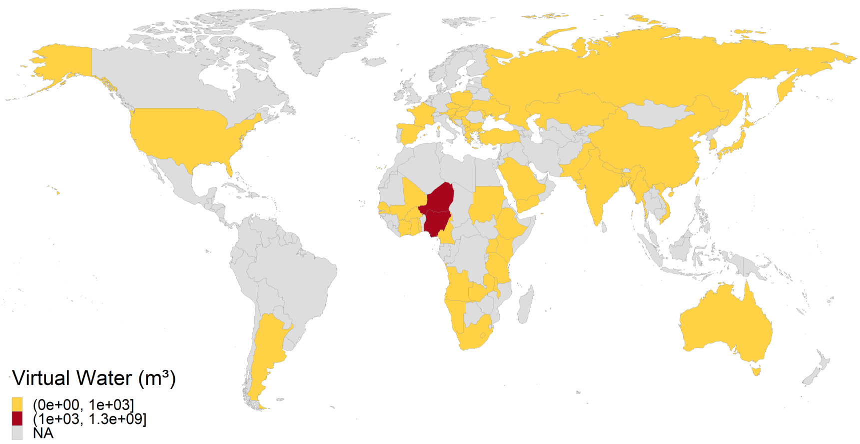

Figure 4.70: Water footprint relative to the FLW of millets products used as feed in Niger.

Sorghum

In the case of sorghum products used as feed in Mexico, the primary product is raw sorghum, and there is no water footprint designated for processing losses, indicating that sorghum bran is generally not utilized as feed intake. The agricultural losses have the most significant impact on freshwater resources, accounting for 61.05%, followed by post-harvest losses with 38.95%, as depicted in Figure 4.62.

Figure 4.71 displays the countries with the highest water footprint. Mexico leads with 6.19×10^8 m^3, followed by the United States with 2.47×10^7 m^3, India 4.19×10^4 m^3 and Argentina 3.67×10^3 m^3.

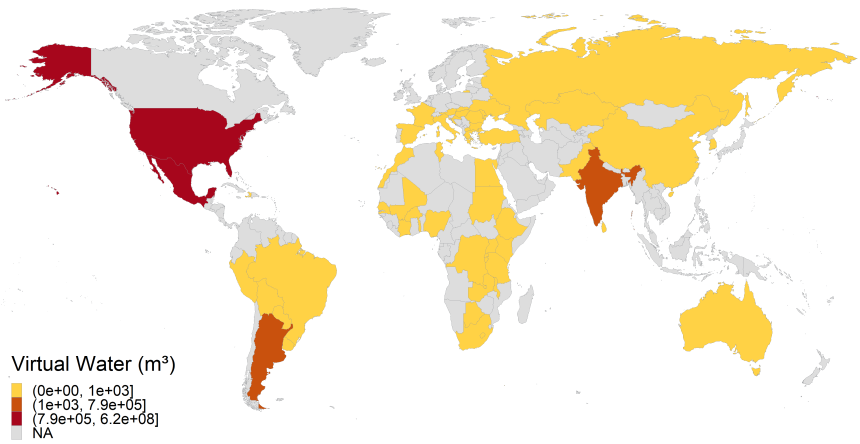

Figure 4.71: Water footprint relative to the FLW of sorghum products used as feed in Mexico.

Potatoes

Shifting our focus to the utilization of freshwater resources for the FLW associated with potatoes used as feed in China, we specifically consider raw potatoes, as the derivatives illustrated in Figure A.8 are not included in the feed intake. The predominant portion of the water footprint is attributed to agricultural losses, constituting 78.12%, while post-harvest losses account for the remaining 21.88%, as shown in Figure 4.62.

In Figure 4.72 we can see the distribution of the water usage across the countries. China is the leader by far with 9.83×10^8 m^3, followed by the United States with 5.69×10^3 m^3.

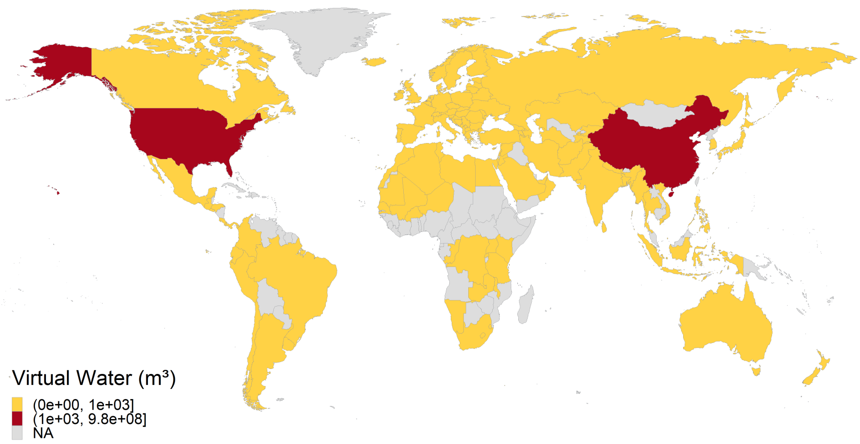

Figure 4.72: Water footprint relative to the FLW of potatoes products used as feed in China.

Sweet potatoes

We now examine the water footprint associated with the use of sweet potatoes as feed in China. Given that sweet potatoes, as depicted in Figure A.9, lack derivatives, there are no processing losses influencing the water footprint. The consumption of freshwater resources is influenced by agricultural losses, accounting for 78.12%, and post-harvest losses, constituting 21.88%, as depicted in Figure 4.62.

Examining the distribution among countries, the water usage is predominantly attributed to China, accounting for 1.57×10^9 m^3. Another minor contributor include Indonesia with 1.80×10^3 m^3 of water.

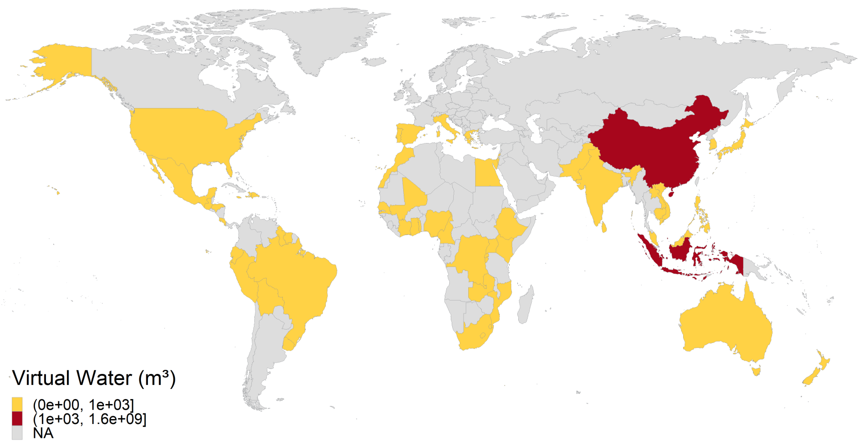

Figure 4.73: Water footprint relative to the FLW of sweet potatoes products used as feed in China.

Cassava

The water usage associated with processing losses of cassava used as feed in Nigeria is the highest in percentage among all the staple crops analyzed, including wheat, with 26.41%, as shown in Figure 4.62. In fact, cassava has derivatives, such as dried cassava (as shown in Figure A.10), that can be used as feed intake. The water footprint associated with agricultural losses accounts for 34.95% of the total, while post-harvest losses contribute to 38.64%. From Figure 4.74, we can see that the water footprint is solely internal, with Nigeria wasting 4.91×10^9 m^3 of water.

On the contrary, if we shift to a global perspective, as shown in Figure 4.75, after Nigeria, there are other countries with a considerable water footprint associated with losses and waste of cassava used as feed, such as Brazil with 1.32×10^9 m^3, China 1.05×10^9 m^3 and Ivory Coast 4.87×10^8 m^3. Considering the distribution among the regions: Sub-Saharan Africa is accountable for 67.60%, followed by Latin America 18.31%, and Industrialized Asia 10.33%.

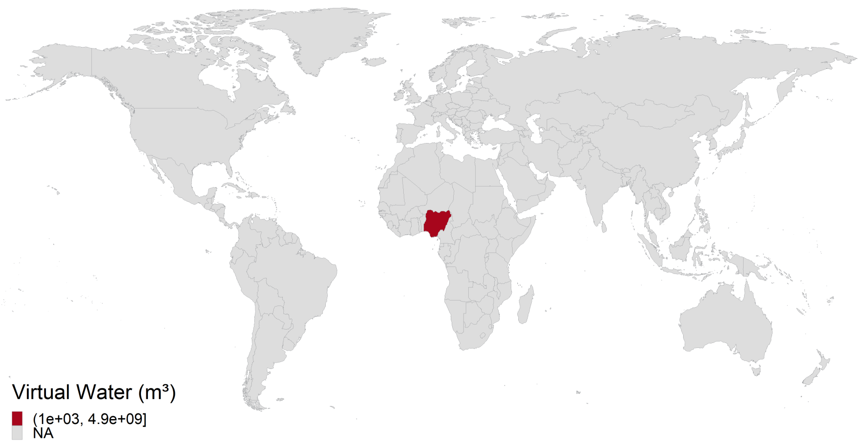

Figure 4.74: Water footprint relative to the FLW of cassava products used as feed in Nigeria.

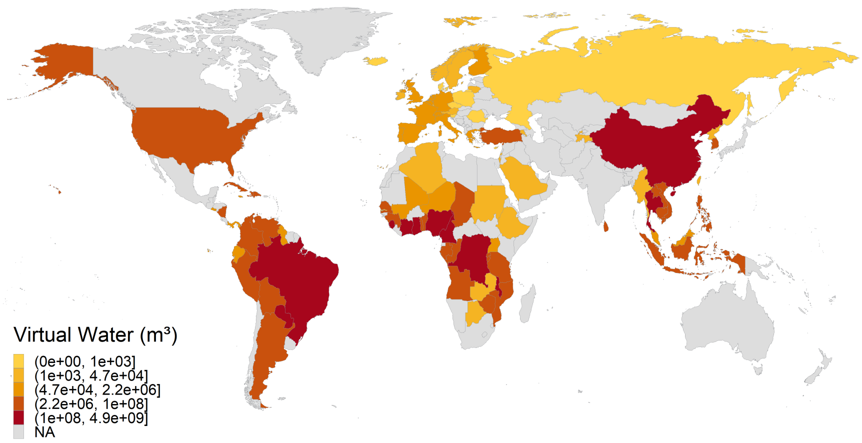

Figure 4.75: Water footprint relative to the FLW of cassava products used as feed globallt.

Soybeans

The water footprint associated with the losses and waste of soybean products used as feed in China is primarily attributed to the agricultural stage, accounting for

78.83%, as shown in Figure 4.62. The remaining portion is entirely related to the post-harvest stage with 21.17%, as none of the soybean derivatives shown in Figure A.11 are considered in the feed intake.

The distribution of the water footprint among countries for soybean products used as feed reveals a trend similar to the consumption-side perspective. Unlike other crops, China isn't the primary contributor, indicating its significant role as an importer of soybeans. As illustrated in Figure 4.76, the top contributors to the water footprint are: Brazil 4.90×10^8 m^3, United States 4.16×10^8 m^3, China 2.34×10^8 m^3 and Argentina 9.41×10^7 m^3. From a regional perspective, including both the FLW inside and outside Chinese borders, Latin America accounts for 47.74% of the water footprint, followed by North America & Oceania with 33.60%, and Industrialized Asia with 18.07%.

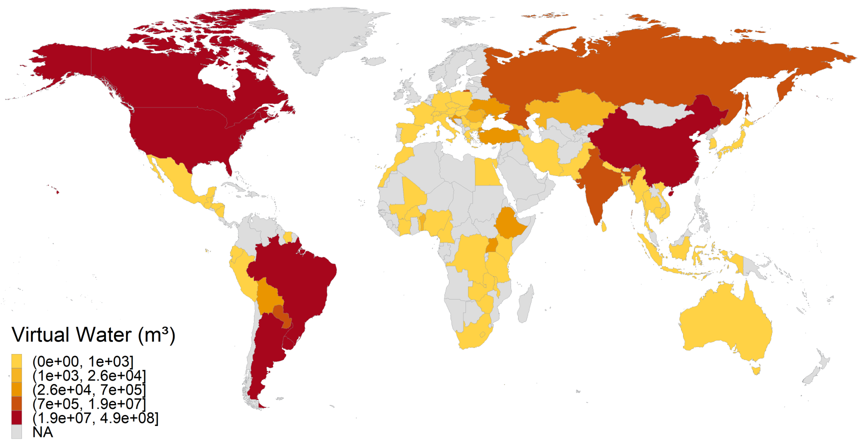

Figure 4.76: Water footprint relative to the FLW of soybeans products used as feed in China.

Chapter 5

Limitations

While we confidently assert that our analysis was successful, it is crucial to acknowledge certain limitations that have surfaced during our study.

Our reliance on loss and waste shares, as provided by Gustavsson et al. 2011, has been instrumental in our analysis. However, it's important to recognize a limitation in these shares: they are uniform across all countries within the same region. The challenge lies in the fact that, with only seven regions encompassing numerous countries, these shares offer a generalized average that could be more granular. For example, oil seeds (including soybeans), exhibit a post-harvest loss share of 0% in North America & Oceania according to the provided data. This particular case highlights the need for more precise and localized information, as regional averages may not accurately reflect the specific dynamics within individual countries. Furthermore, the uniformity extends to crop families, such as cereals, starch roots and oil seeds, where the provided shares are consistent across all crops within the same family. However, acknowledging the inherent variability among crops within a family, obtaining individualized loss and waste shares for each crop would undoubtedly enhance the precision and reliability of our analysis. Therefore, future iterations of our research would benefit significantly from accessing more detailed and specific data to better capture the intricacies of water resource usage in the context of agricultural losses and waste.

Additionally, it is essential to acknowledge that certain derivatives of each staple crop under consideration have not been incorporated into the analysis. This omission is typically attributed to various factors such as the unavailability of pertinent FAO data, the absence of corresponding trade matrices, or the complexity arising from a derivative being composed of more than one "parent." To illustrate the latter point, consider the case of breakfast cereals, which encompass a first-level wheat derivative, a second-level rice derivative (derived from milled rice), a second-level barley derivative (from pot barley), a first-level maize derivative, a first-level rye derivative, and a first-level oats derivative. Due to the lack of information regarding the proportions of processed parents involved in the preparation of breakfast cereals, it proved impractical to include them in our analysis. The comprehensive list of staple crop trees, encompassing all their derivatives, is accessible in FAO 2023.

In the maps presented in Chapter 4, it's important to note that we haven't made a visual distinction between NA values and 0 values. Both NA and 0 values are categorized under the same visual representation as NA. This decision is a direct consequence of the mathematical transformations applied during the modeling process, where, for the purpose of computing matrix operations, every NA value was transformed into 0.

Chapter 6

Conclusions

Our comprehensive analysis has assessed the water footprint associated with losses and waste in staple crops, exploring various dimensions. From a spatial standpoint, we meticulously examined the global, regional, and national scenarios, offering nuanced insights at each level. In addition to the spatial perspective, our investigation extended to the value chain analyis, encompassing a farm-to-fork, fork-to farm, and feeder-to-farm perspective. This exhaustive exploration aimed to uncover diverse results contingent upon the specific viewpoint adopted.

The farm-to-fork perspective offered insights into water use for the FLW of crops cultivated in a selected country or region. The freshwater resources used for the losses and waste of combined staple crops globally produced reach 7.60×10^{11} m^3. Wheat stands out as the most impactful crop, with 2.00×10^{11} m^3 of water wasted, representing 26.30% of the total, followed by rice at 1.86×10^{11} m^3 (24.49%), maize at 1.08×10^{11} m^3 (14.26%) and soybeans at 1.03×10^{11} m^3 (13.51%). The post-harvest stage emerges as the primary contributor to virtual water waste, totaling 2.68×10^{11} m^3. Moreover, South & Southeast Asia is the region most significantly impacted, accounting for 2.27×10^{11} m^3 of water.

The fork-to-farm perspective focused on the nations impacted by the losses and waste of a product consumed in a given country. The cumulative water footprint relative to the FLW associated with the global food intake of staple crops and their derivatives amounts to 4.16×10^{11} m^3. Wheat and rice products are the most impacting with 39.25% and 33.55% of the total, respectively. The post-harvest stage emerges again as the primary contributor to the water footprint with 1.14×10^{11} m^3, closely followed by the consumption stage with 1.13×10^{11} m^3. South & Southeast Asia is still the region most significantly impacted, accounting for 1.47×10^{11} m^3 of water.

The feeder-to-farm perspective took into account inputs and resources required for livestock feed. The freshwater resources used for the losses and waste of combined staple crops globally used as feed amount to 1.15×10^{11} m^3. Maize products are the most impactful accounting for 42.80% of the total, followed by wheat (18.57%) and cassava (8.96%). The post-harvest stage is always the primary contributor to the water footprint with 6.12×10^{10} m^3. The region most significantly impacted is Industrialized Asia with 2.59×10^{10} m^3 of water.

By adopting these varied lenses, we aimed not only to capture the geographical distribution and severity of water usage related to food loss and waste, but also to discern the intricate dynamics and interdependencies at play in different stages of the food value chain. Mapping these waste levels with such granularity across the value chain for various food commodities is the initial step to identify the most strategic areas for effective intervention in the battle against food waste.

In terms of future perspectives, an important stride would involve the incorporation of meat within our analytical framework, thereby enhancing the comprehensiveness of our model. By integrating meat production and consumption into our methods, we can create a more complete approach that considers the water footprint associated with both plant-based staple crops and animal products. This expansion would also capture the interconnections and dependencies between plant and animal agriculture. Including meat in our analysis would enable us to evaluate the water implications of the entire food system, addressing the complexities of resource usage in a more nuanced manner.

Appendix A

Staple crops trees

A.1 Cereals

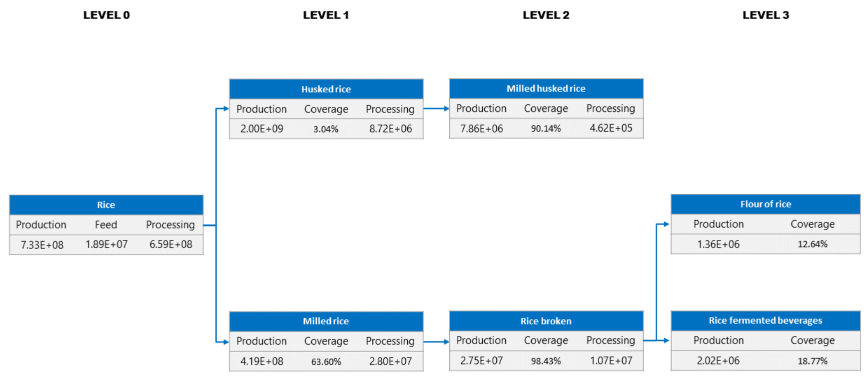

Figure A.1: Production in tonnes of each item of the rice tree and percentage with respect to the processing part in tonnes of the parent item.

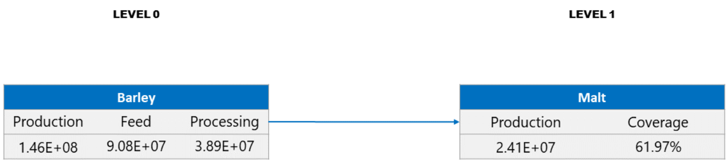

Figure A.2: Production in tonnes of each item of the barley tree and percentage with respect to the processing part in tonnes of the parent item.

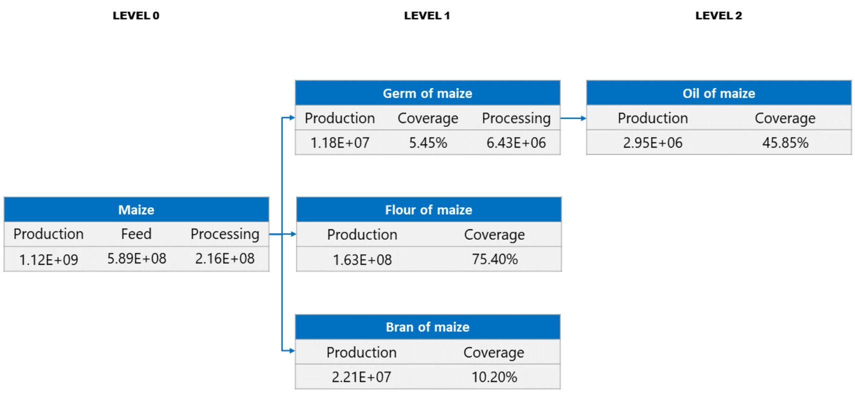

Figure A.3: Production in tonnes of each item of the maize tree and percentage with respect to the processing part in tonnes of the parent item.

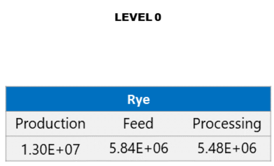

Figure A.4: Production in tonnes of each item of the rye tree and percentage with respect to the processing part in tonnes of the parent item.

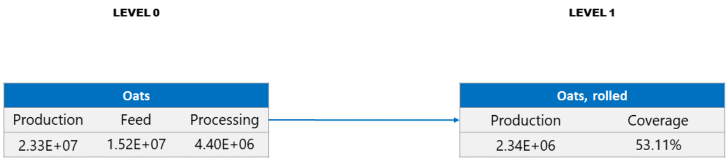

Figure A.5: Production in tonnes of each item of the oats tree and percentage with respect to the processing part in tonnes of the parent item.

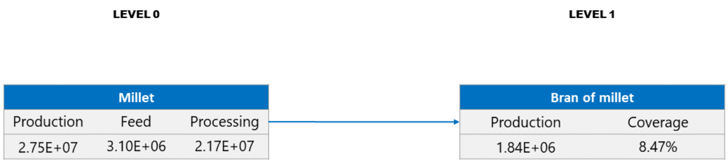

Figure A.6: Production in tonnes of each item of the millet tree and percentage with respect to the processing part in tonnes of the parent item.

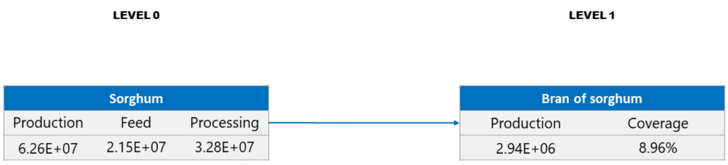

Figure A.7: Production in tonnes of each item of the sorghum tree and percentage with respect to the processing part in tonnes of the parent item.

A.2 Starchy roots

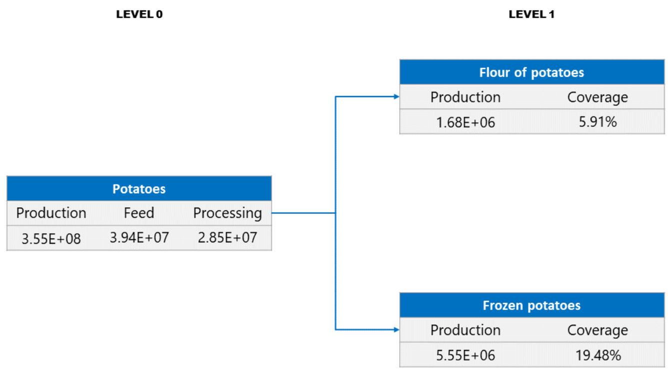

Figure A.8: Production in tonnes of each item of the potatoes tree and percentage with respect to the processing part in tonnes of the parent item.

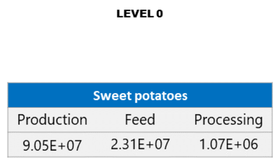

Figure A.9: Production in tonnes of each item of the sweet potatoes tree and percentage with respect to the processing part in tonnes of the parent item.

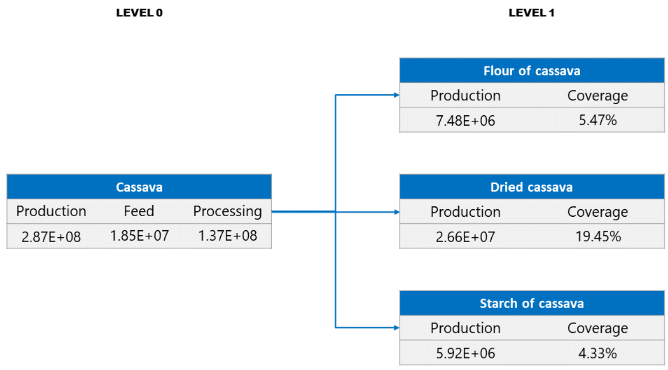

Figure A.10: Production in tonnes of each item of the cassava tree and percentage with respect to the processing part in tonnes of the parent item.

A.3 Oil seeds

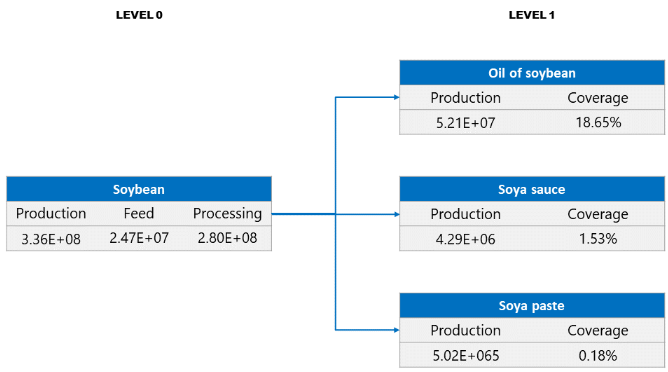

Figure A.11: Production in tonnes of each item of the soybean tree and percentage with respect to the processing part in tonnes of the parent item.

Appendix B

Complexity of wheat trade network

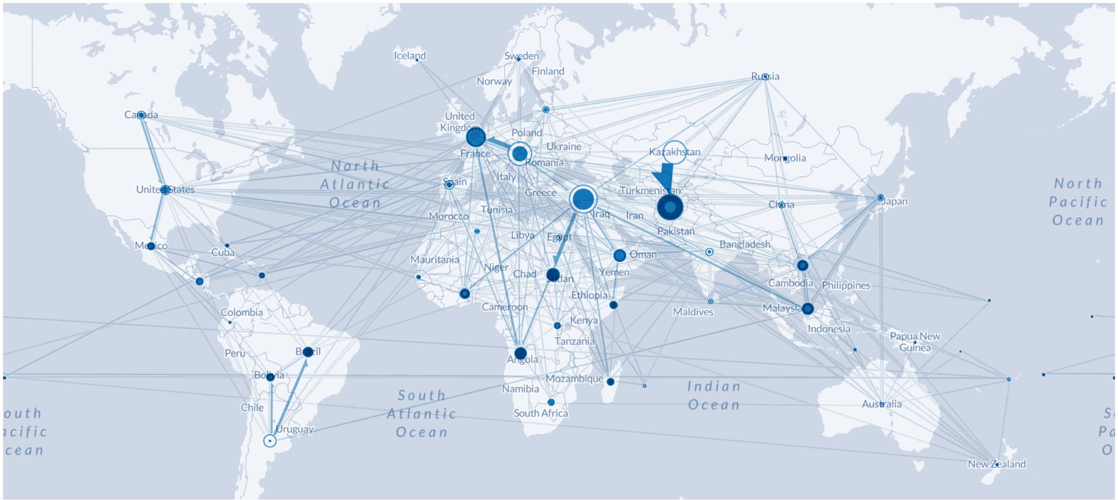

Figure B.1: Complexity of the wheat trade network: flows of flour (layer 1) around the World

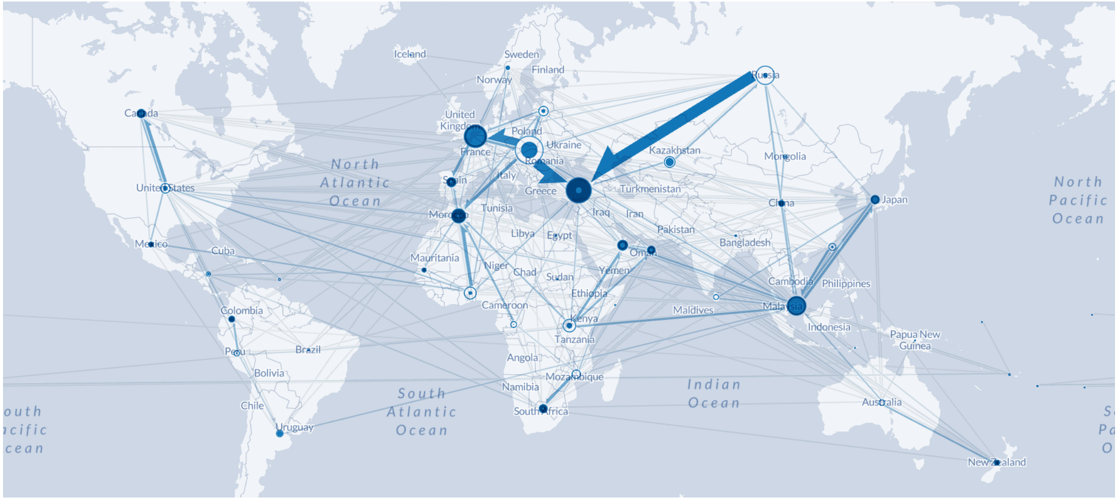

Figure B.2: Complexity of the wheat trade network: flows of bran (layer 1) around the World

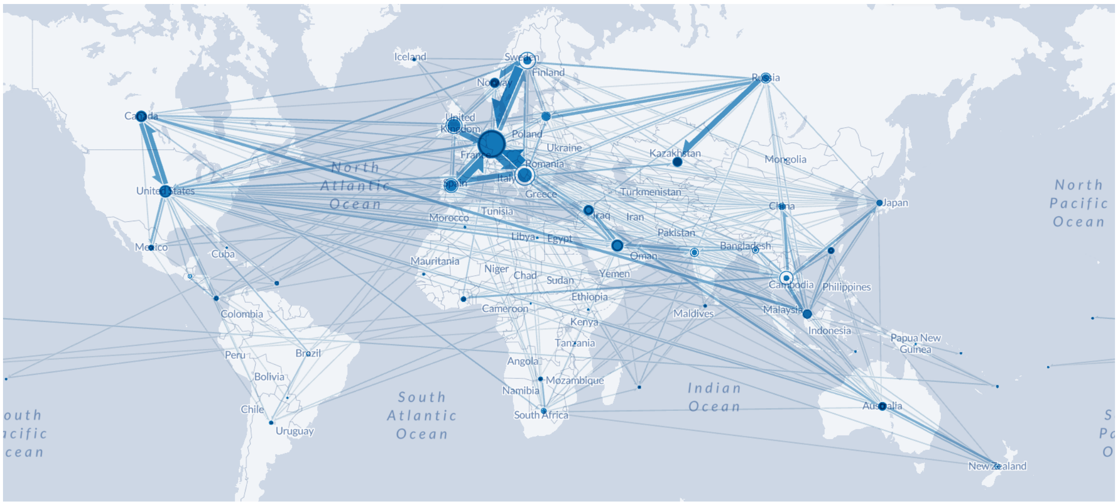

Figure B.3: Complexity of the wheat trade network: flows of bread (layer 2) around the World

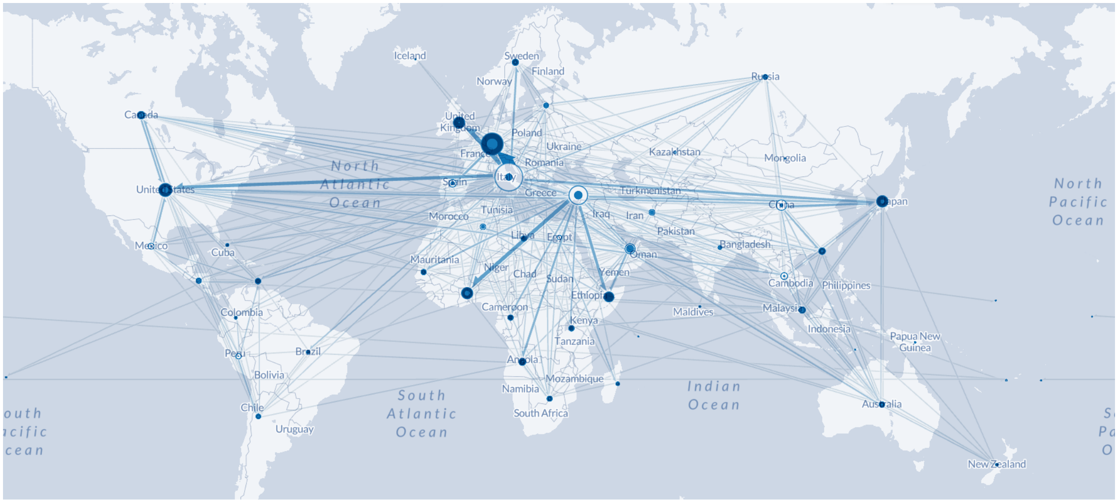

Figure B.4: Complexity of the wheat trade network: flows of pasta (layer 2) around the World

Appendix C

Water footprint distribution

C.1 Wheat

C.1.1 Farm to fork perspective

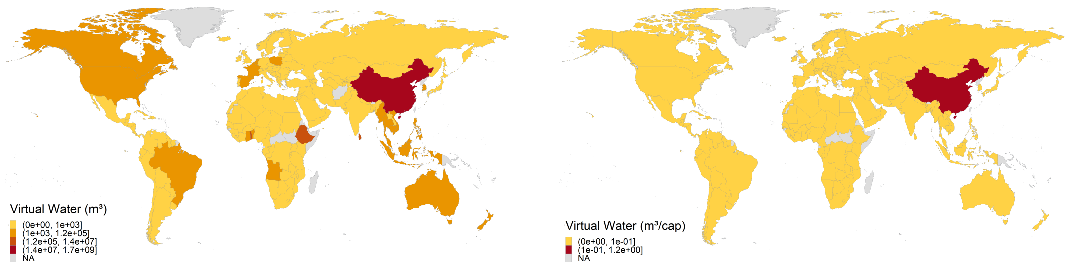

Figure C.1: Water footprint in m^3 relative to processing losses of wheat produced in China, both for total population (left) and per capita (right).

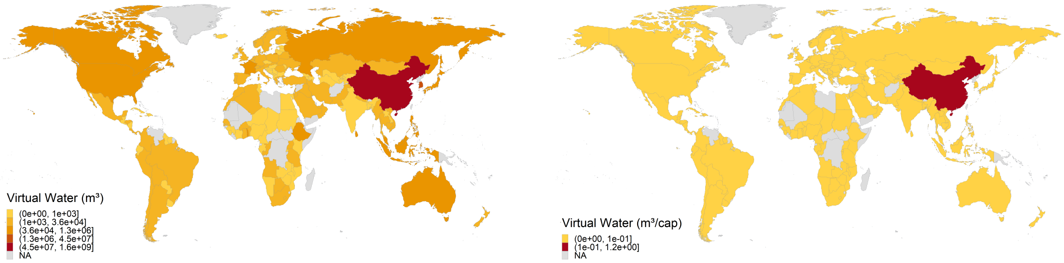

Figure C.2: Water footprint in m^3 relative to relative to distribution waste of wheat produced in China, both for total population (left) and per capita (right).

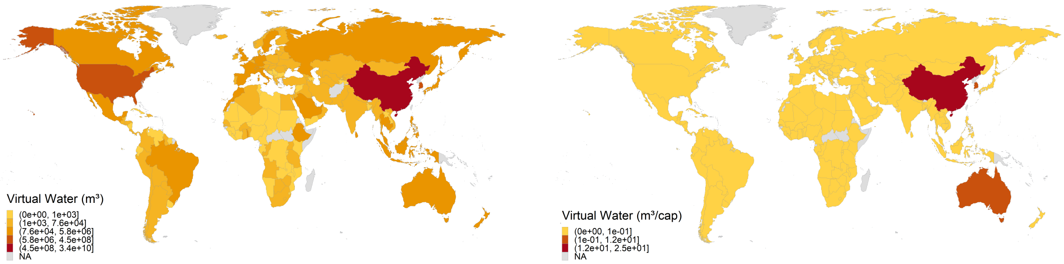

Figure C.3: Water footprint in m^3 relative to FLW of wheat produced in China, both for total population (left) and per capita (right).

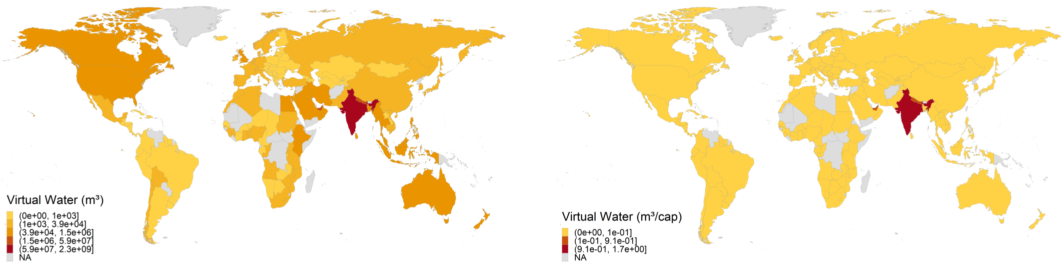

Figure C.4: Water footprint in m^3 relative to distribution waste of wheat produced in India, both for total population (left) and per capita (right).

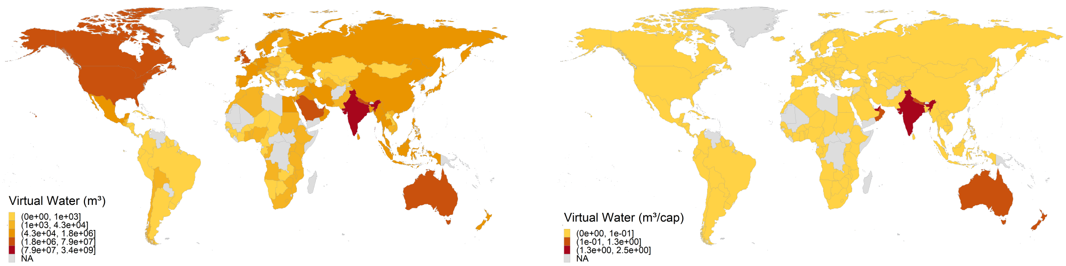

Figure C.5: Water footprint in m^3 relative to consumption waste of wheat produced in India, both for total population (left) and per capita (right).

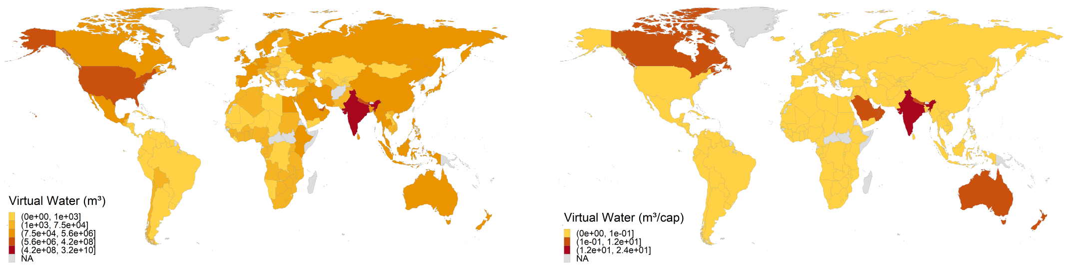

Figure C.6: Water footprint in m^3 relative to FLW of wheat produced in India, both for total population (left) and per capita (right).

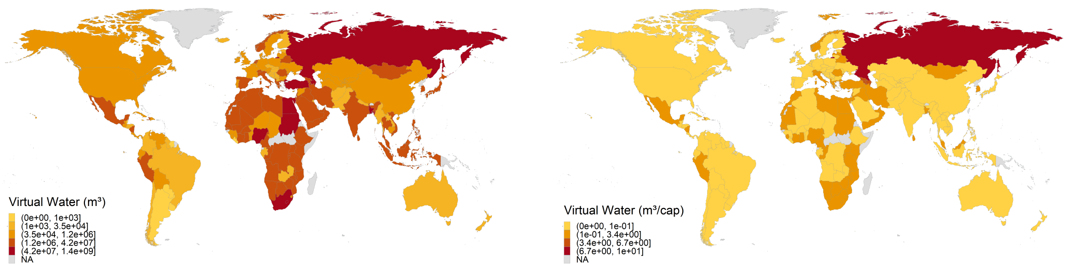

Figure C.7: Water footprint in m^3 relative to processing losses of wheat produced in Russia, both for total population (left) and per capita (right).

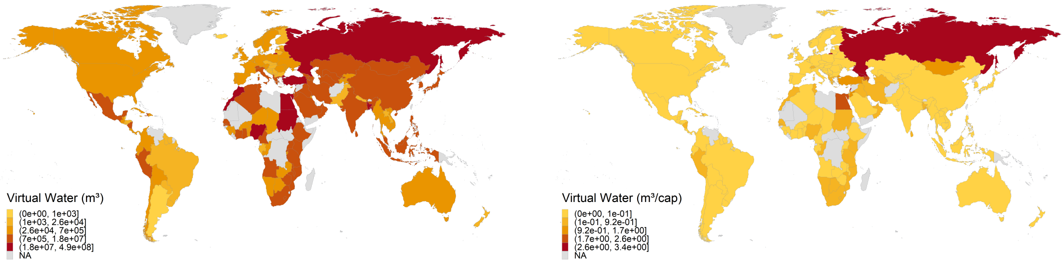

Figure C.8: Water footprint in m^3 relative to distribution waste of wheat produced in Russia, both for total population (left) and per capita (right).

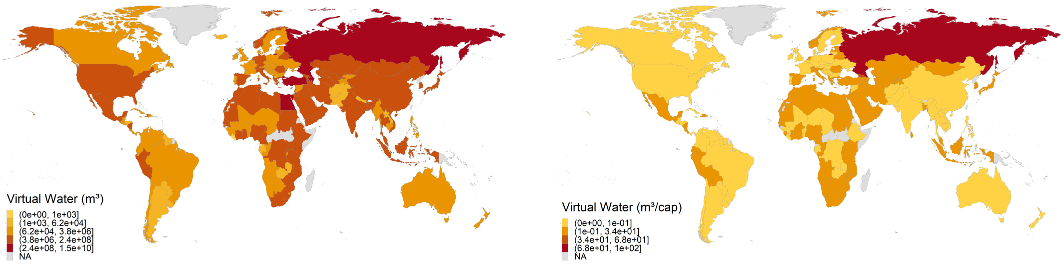

Figure C.9: Water footprint in m^3 relative to FLW of wheat produced in Russia, both for total population (left) and per capita (right).

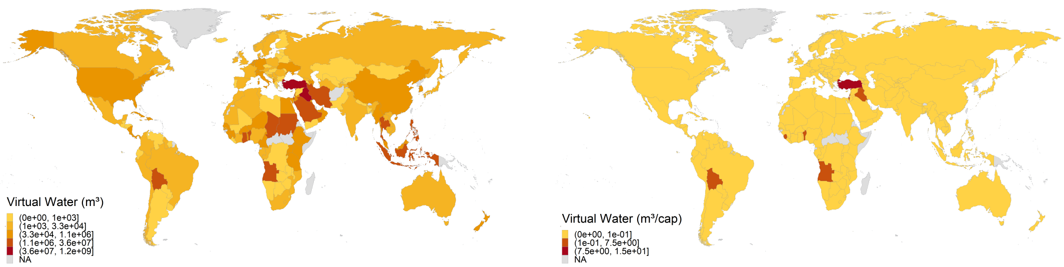

Figure C.10: Water footprint in m^3 relative to processing losses of wheat produced in Turkey, both for total population (left) and per capita (right).

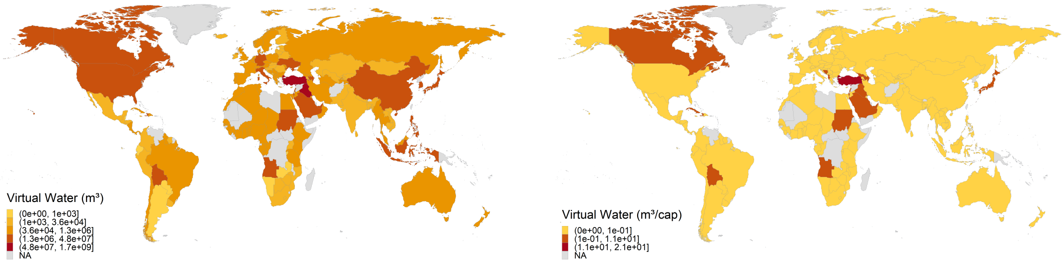

Figure C.11: Water footprint in m^3 relative to distribution waste of wheat produced in Turkey, both for total population (left) and per capita (right).

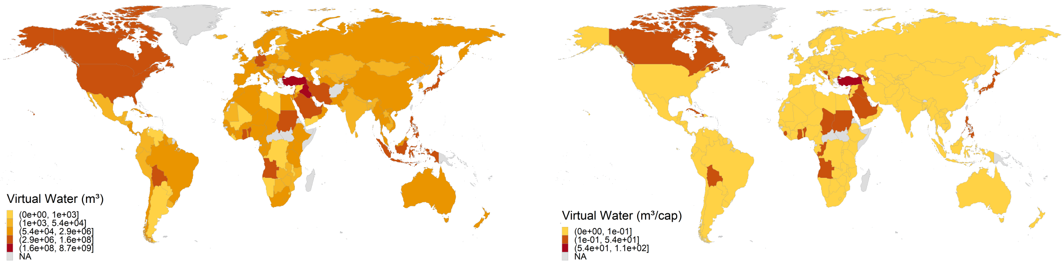

Figure C.12: Water footprint in m^3 relative to FLW of wheat produced in Turkey, both for total population (left) and per capita (right).

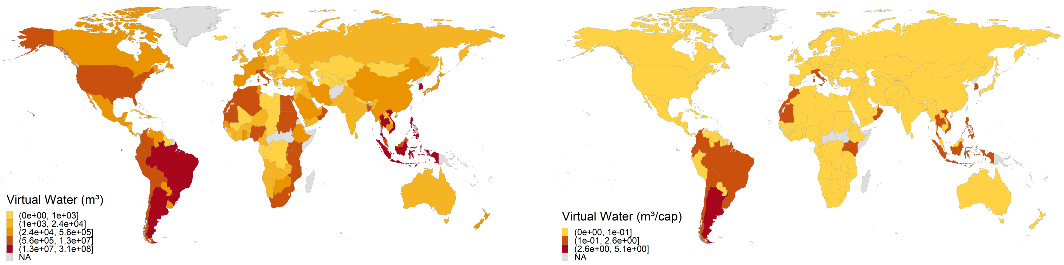

Figure C.13: Water footprint in m^3 relative to processing losses of wheat produced in Argentina, both for total population (left) and per capita (right).

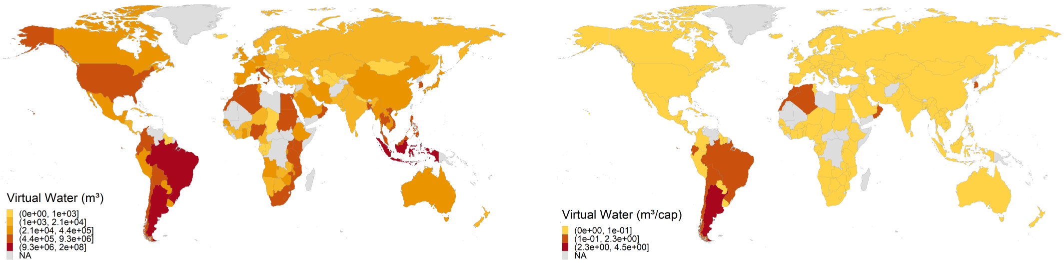

Figure C.14: Water footprint in m^3 relative to distribution waste of wheat produced in Argentina, both for total population (left) and per capita (right).

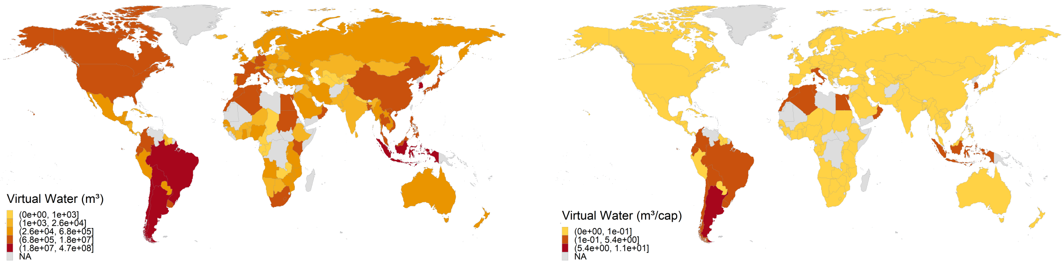

Figure C.15: Water footprint in m^3 relative to consumption waste of wheat produced in Argentina, both for total population (left) and per capita (right).

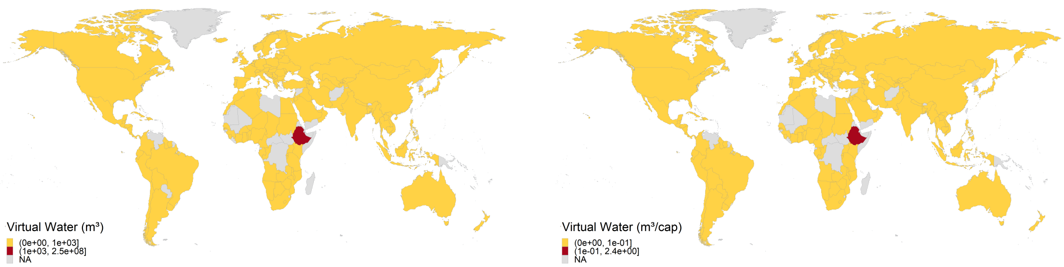

Figure C.16: Water footprint in m^3 relative to processing losses of wheat produced in Ethiopia, both for total population (left) and per capita (right).

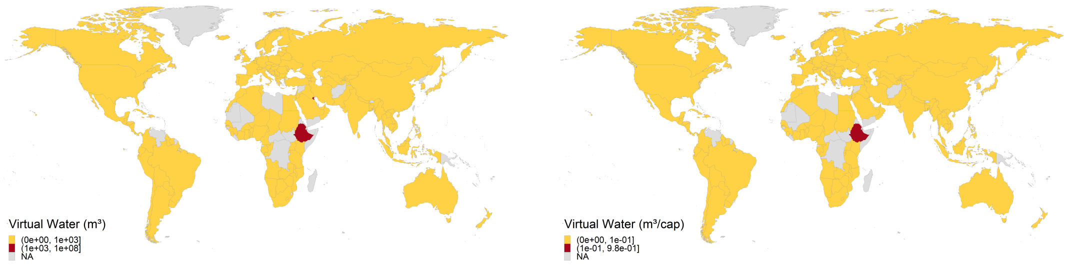

Figure C.17: Water footprint in m^3 relative to distribution waste of wheat produced in Ethiopia, both for total population (left) and per capita (right).

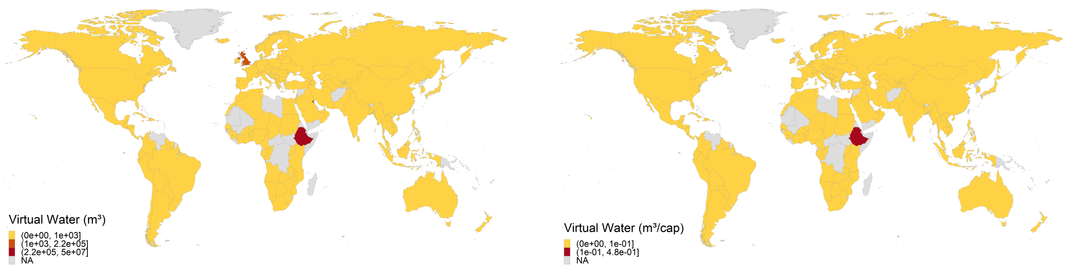

Figure C.18: Water footprint in m^3 relative to consumption waste of wheat produced in Ethiopia, both for total population (left) and per capita (right).

C.1.2 Fork to farm perspective

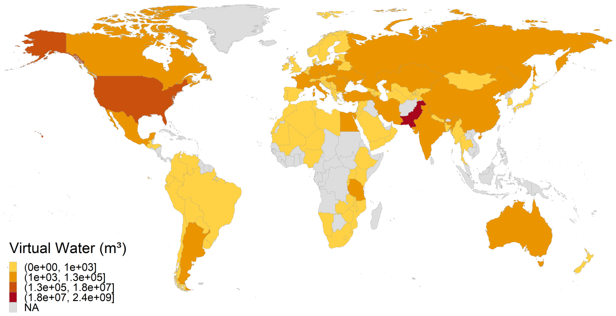

Figure C.19: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Pakistan.

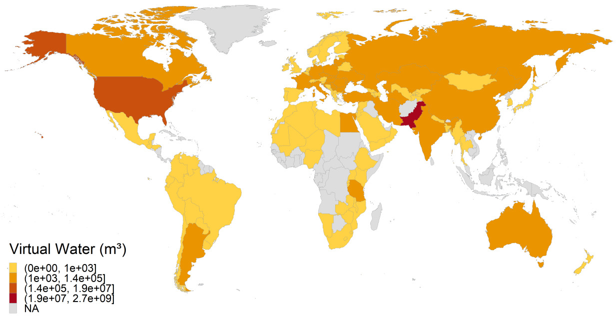

Figure C.20: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Pakistan.

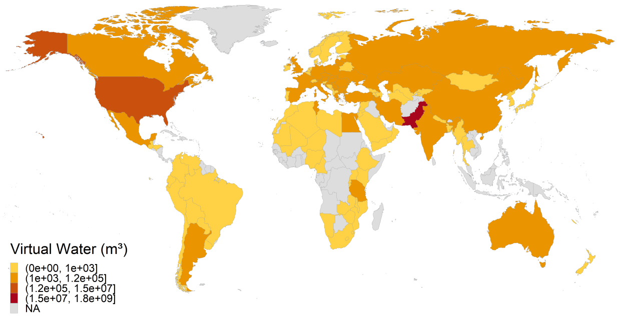

Figure C.21: Water footprint in m^3 associated with processing losses of wheat products consumed in Pakistan.

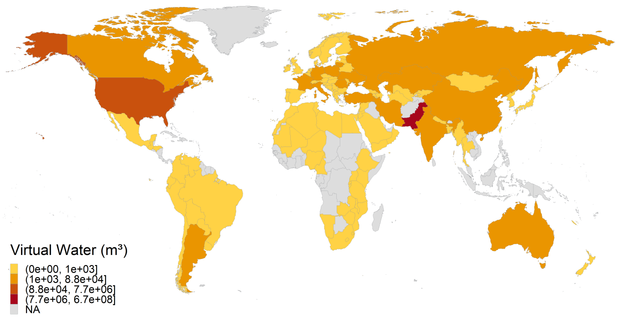

Figure C.22: Water footprint in m^3 associated with distribution waste of wheat products consumed in Pakistan.

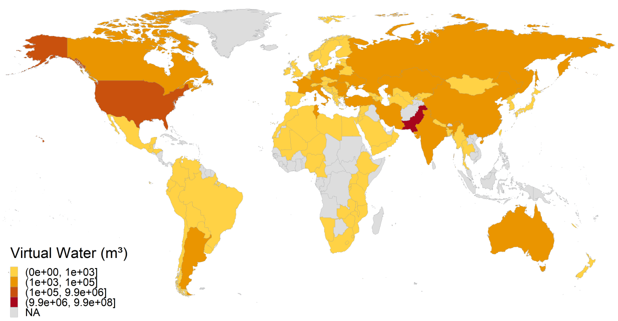

Figure C.23: Water footprint in m^3 associated with consumption waste of wheat products consumed in Pakistan.

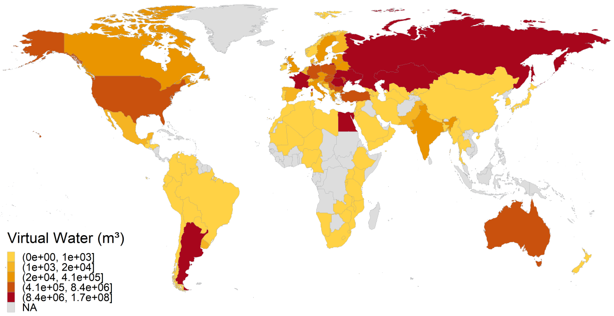

Figure C.24: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Egypt.

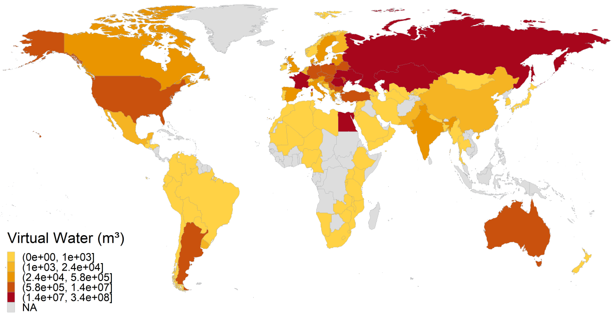

Figure C.25: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Egypt.

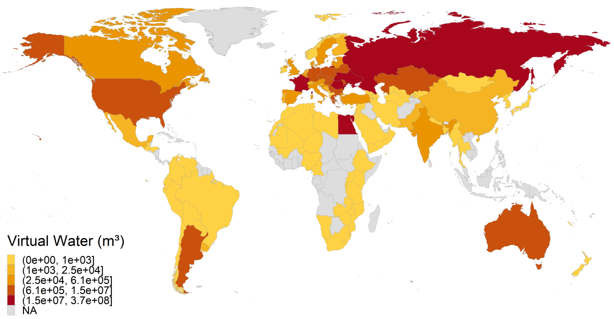

Figure C.26: Water footprint in m^3 associated with processing losses of wheat products consumed in Egypt.

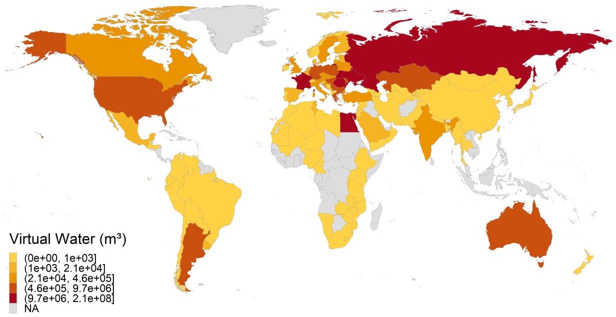

Figure C.27: Water footprint in m^3 associated with distribution waste of wheat products consumed in Egypt.

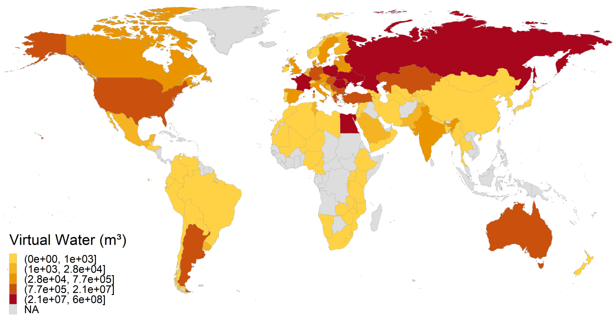

Figure C.28: Water footprint in m^3 associated with consumption waste of wheat products consumed in Egypt.

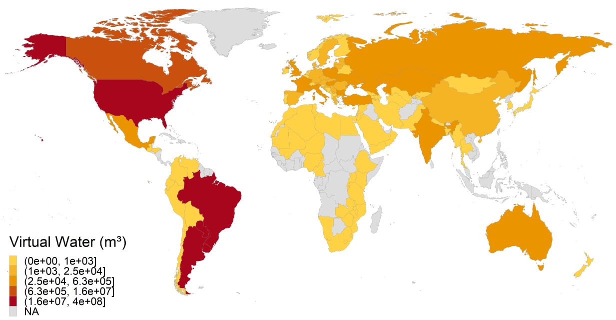

Figure C.29: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Brazil.

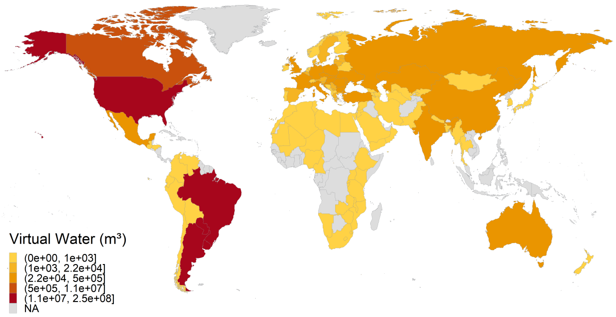

Figure C.30: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Brazil.

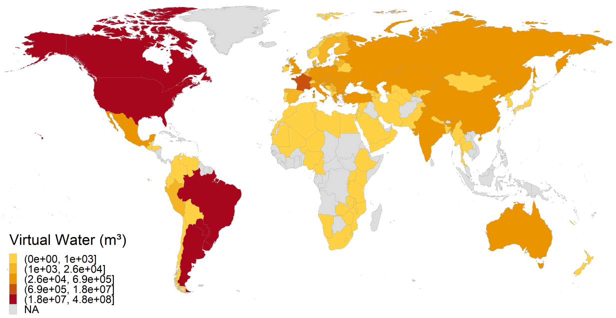

Figure C.31: Water footprint in m^3 associated with processing losses of wheat products consumed in Brazil.

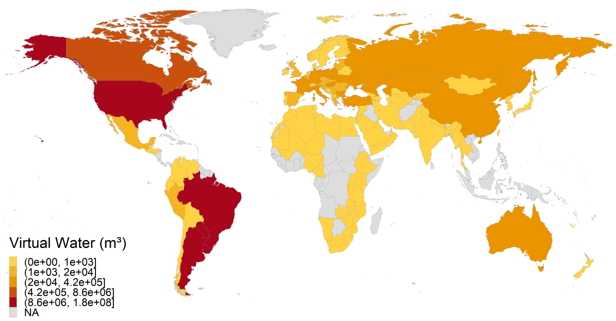

Figure C.32: Water footprint in m^3 associated with distribution waste of wheat products consumed in Brazil.

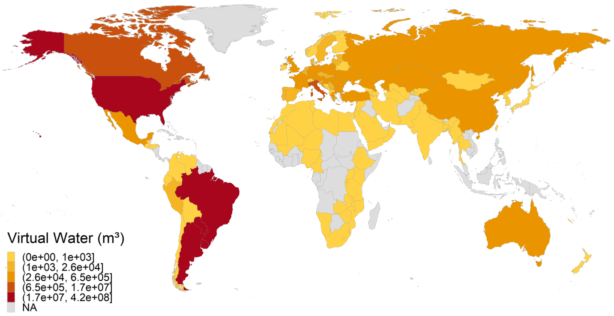

Figure C.33: Water footprint in m^3 associated with consumption waste of wheat products consumed in Brazil.

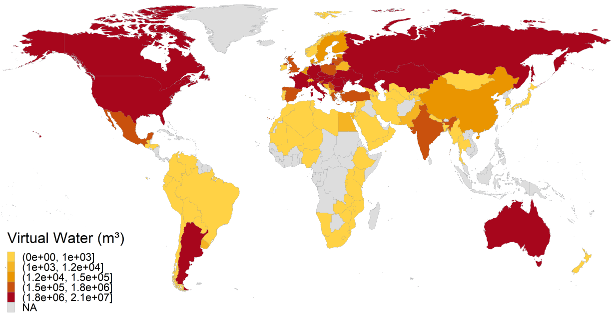

Figure C.34: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Italy.

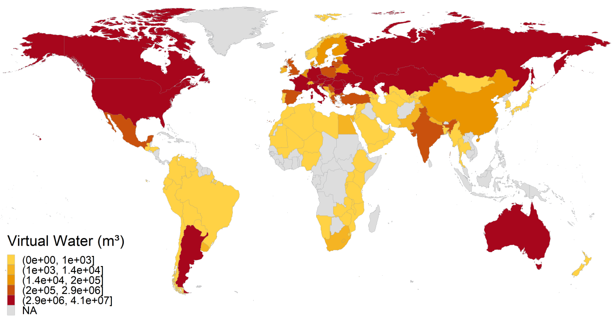

Figure C.35: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Italy.

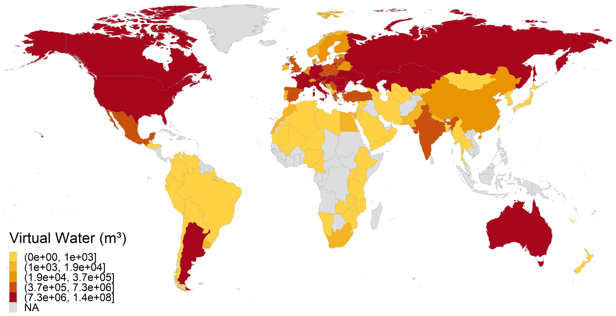

Figure C.36: Water footprint in m^3 associated with processing losses of wheat products consumed in Italy.

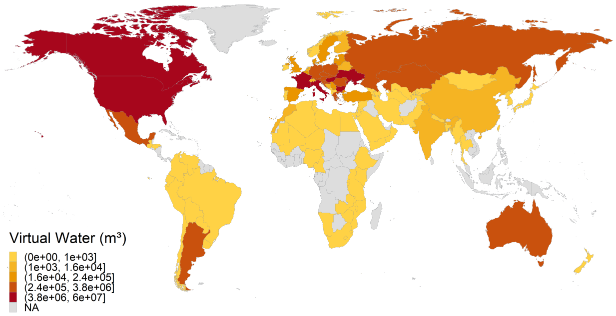

Figure C.37: Water footprint in m^3 associated with distribution waste of wheat products consumed in Italy.

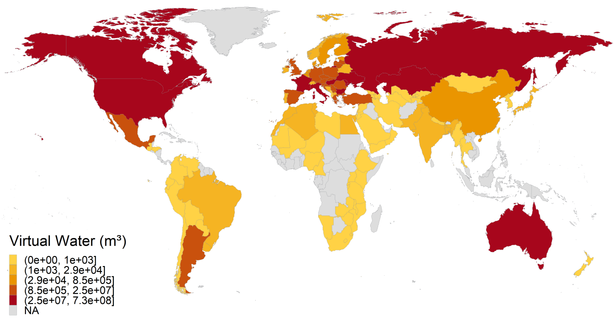

Figure C.38: Water footprint in m^3 associated with consumption waste of wheat products consumed in Italy.

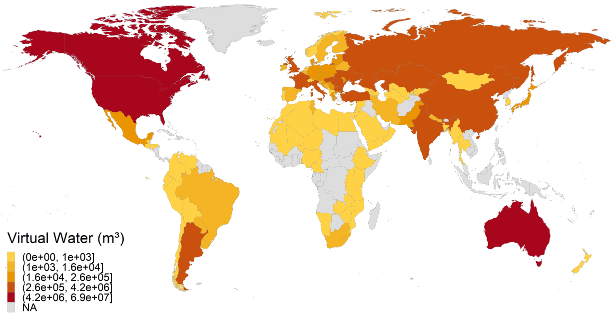

Figure C.39: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Japan.

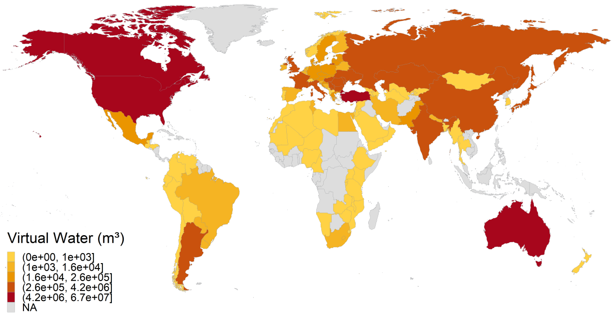

Figure C.40: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Japan.

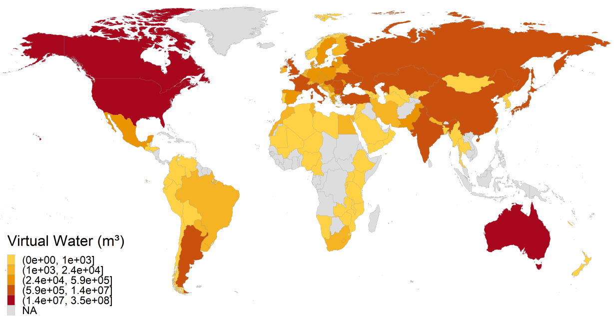

Figure C.41: Water footprint in m^3 associated with processing losses of wheat products consumed in Japan.

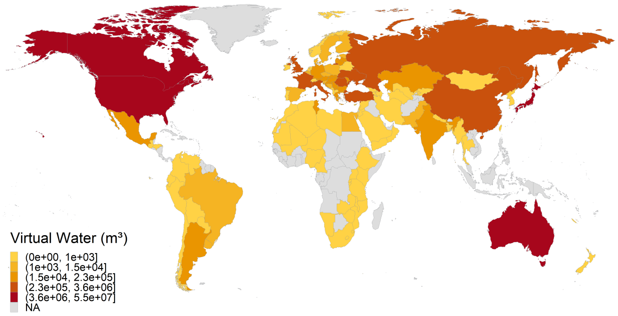

Figure C.42: Water footprint in m^3 associated with distribution waste of wheat products consumed in Japan.

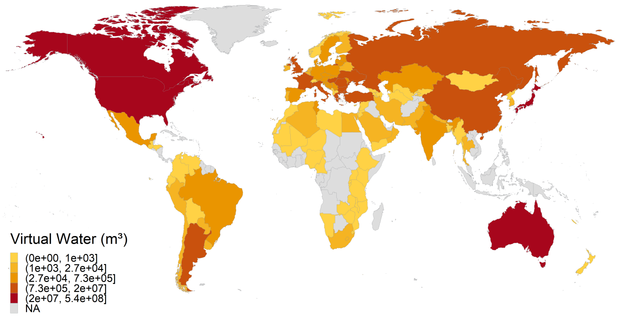

Figure C.43: Water footprint in m^3 associated with consumption waste of wheat products consumed in Japan.

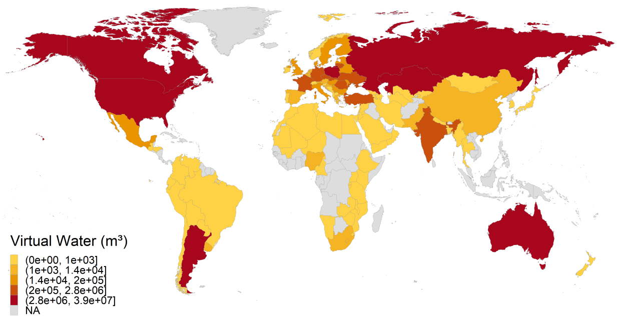

Figure C.44: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Nigeria.

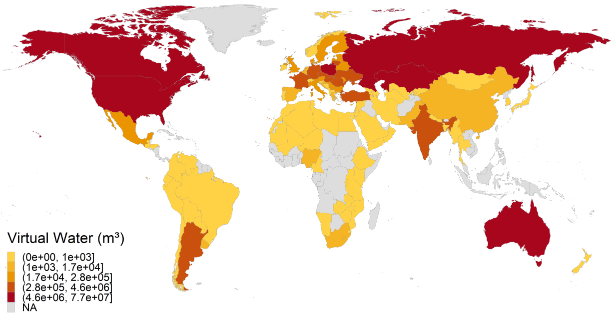

Figure C.45: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Nigeria.

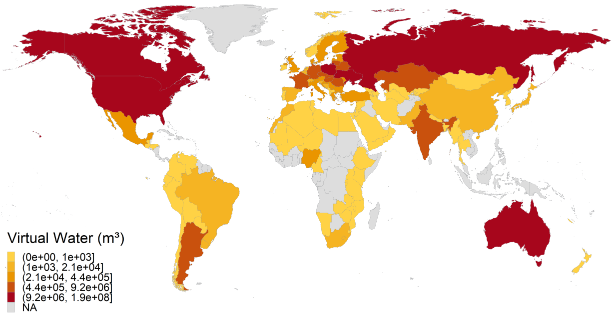

Figure C.46: Water footprint in m^3 associated with processing losses of wheat products consumed in Nigeria.

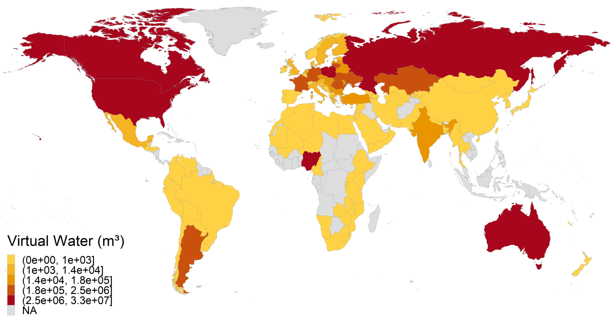

Figure C.47: Water footprint in m^3 associated with distribution waste of wheat products consumed in Nigeria.

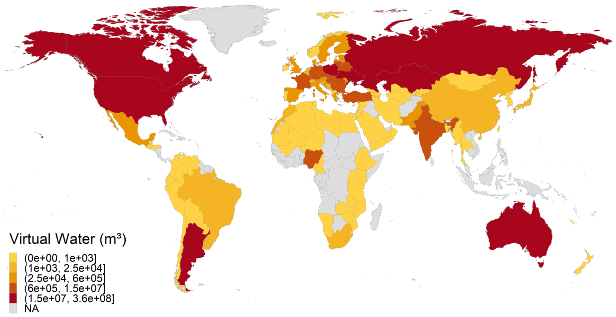

Figure C.48: Water footprint in m^3 associated with consumption waste of wheat products consumed in Nigeria.

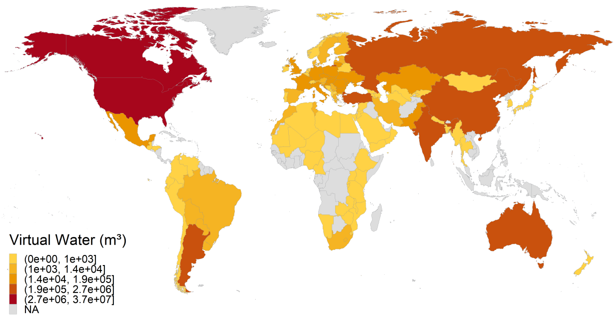

Figure C.49: Water footprint in m^3 associated with agricultural losses of wheat products consumed in Canada.

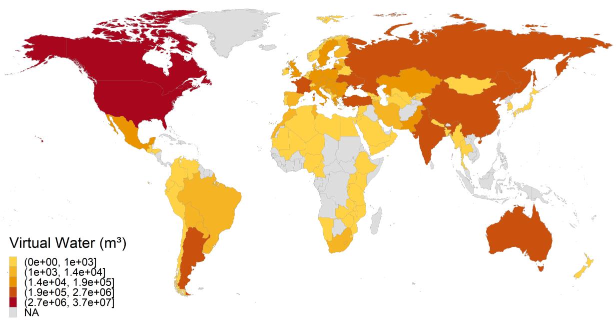

Figure C.50: Water footprint in m^3 associated with post-harvest losses of wheat products consumed in Canada.

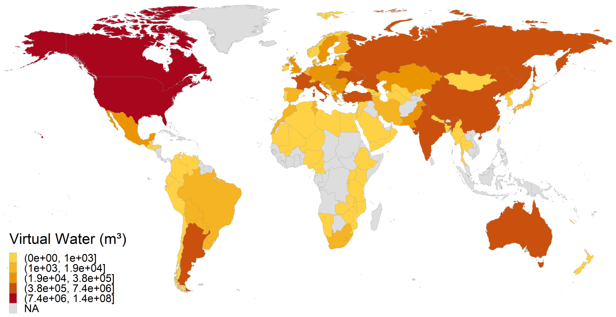

Figure C.51: Water footprint in m^3 associated with processing losses of wheat products consumed in Canada.

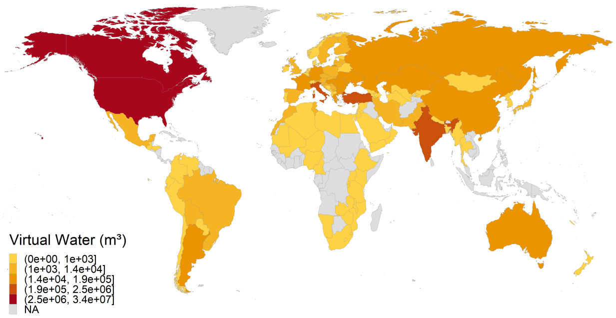

Figure C.52: Water footprint in m^3 associated with distribution waste of wheat products consumed in Canada.

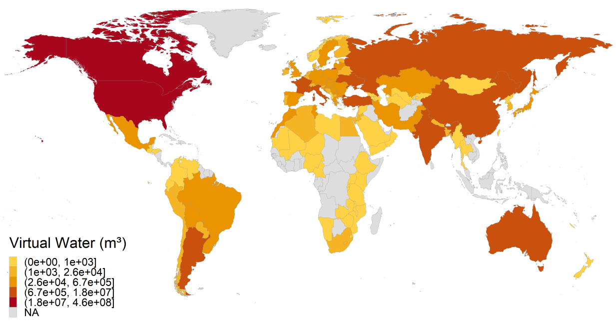

Figure C.53: Water footprint in m^3 associated with consumption waste of wheat products consumed in Canada.

C.1.3 Feeder to farm perspective

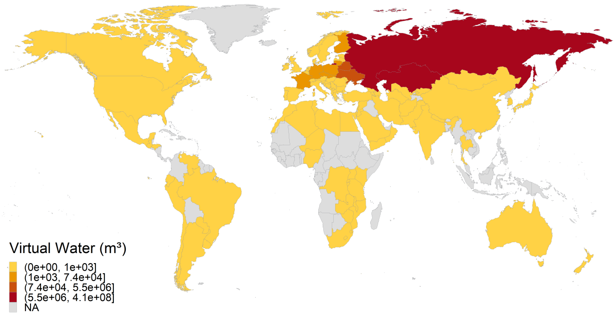

Figure C.54: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in Russia.

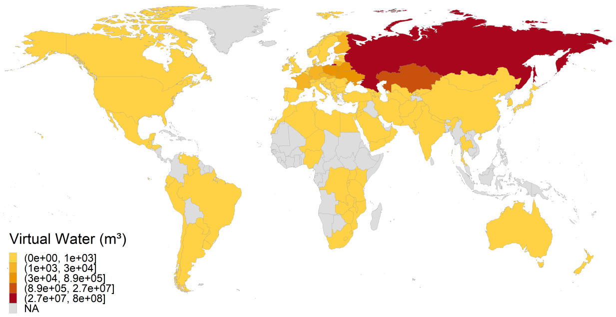

Figure C.55: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in Russia.

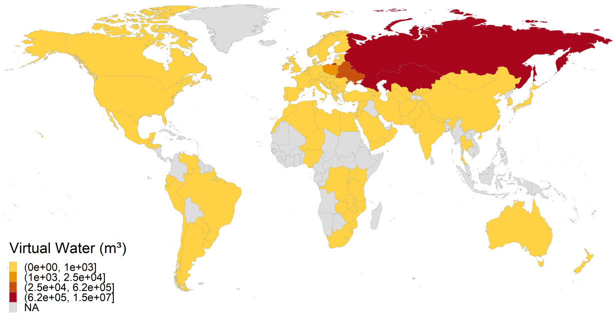

Figure C.56: Water footprint in m^3 associated with processing losses of wheat products used as feed in Russia.

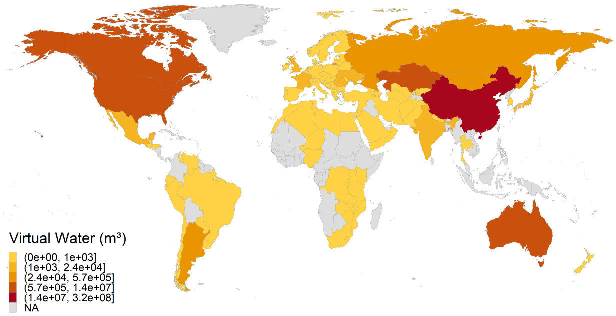

Figure C.57: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in China.

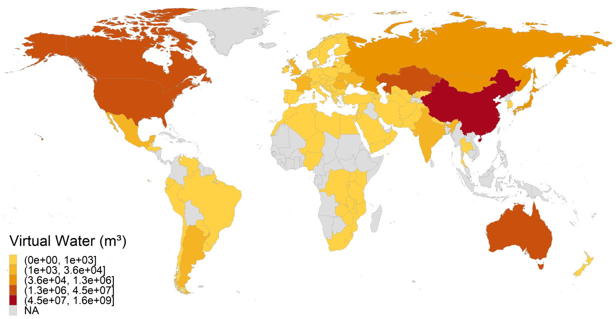

Figure C.58: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in China.

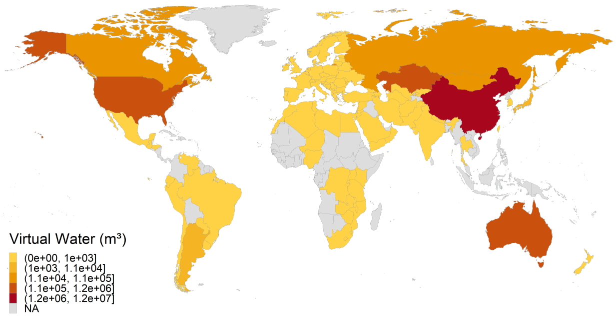

Figure C.59: Water footprint in m^3 associated with processing losses of wheat products used as feed in China.

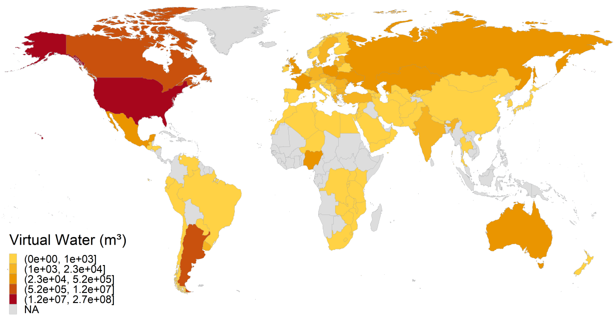

Figure C.60: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in the United States.

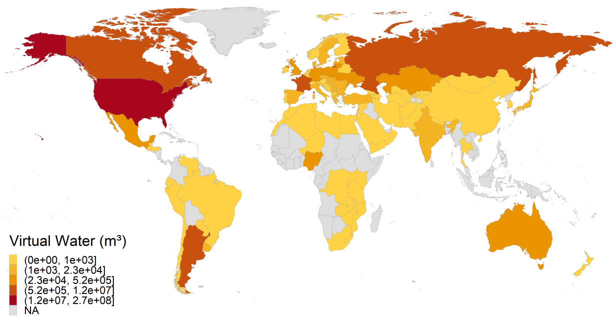

Figure C.61: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in the United States.

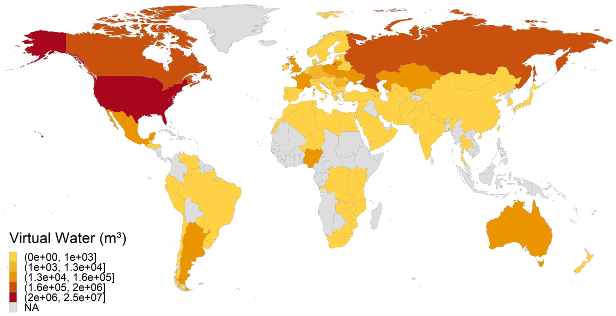

Figure C.62: Water footprint in m^3 associated with processing losses of wheat products used as feed in the United States.

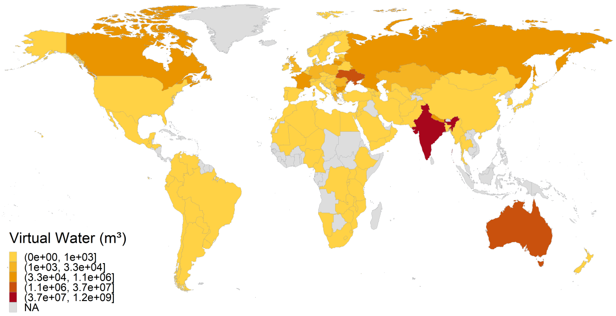

Figure C.63: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in India.

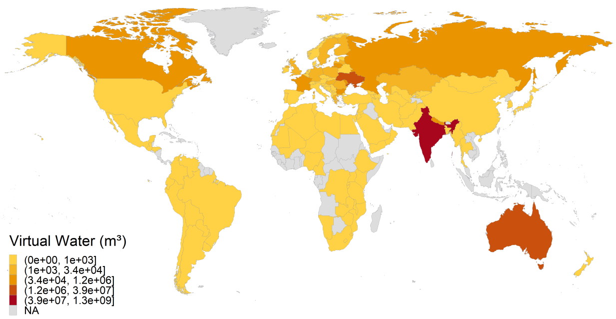

Figure C.64: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in India.

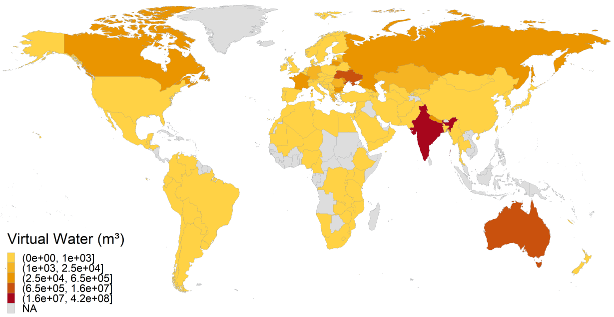

Figure C.65: Water footprint in m^3 associated with processing losses of wheat products used as feed in India.

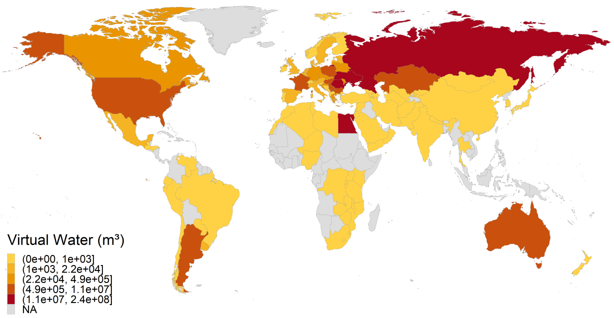

Figure C.66: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in Egypt.

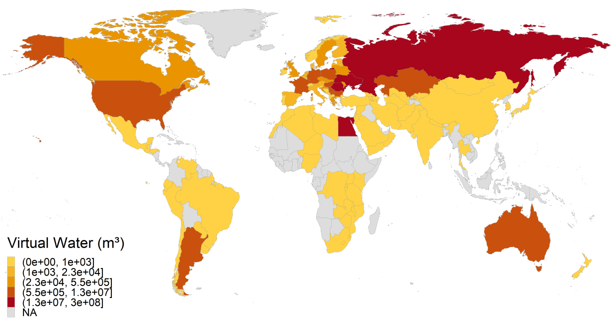

Figure C.67: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in Egypt.

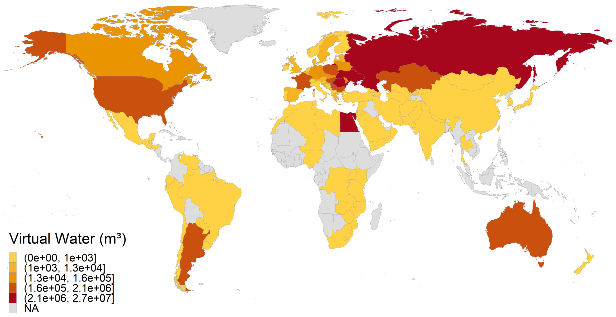

Figure C.68: Water footprint in m^3 associated with processing losses of wheat products used as feed in Egypt.

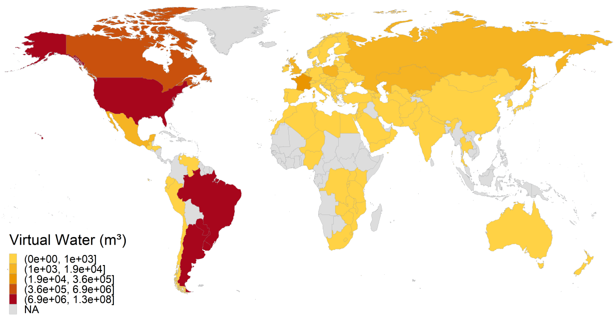

Figure C.69: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in Brazil.

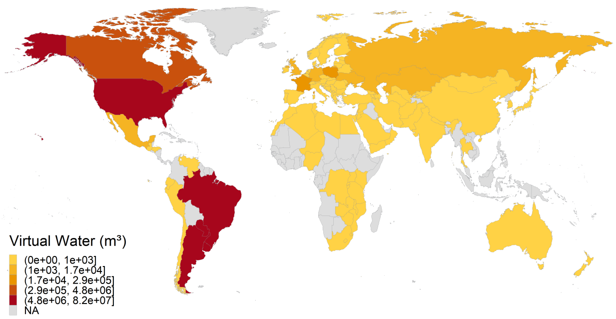

Figure C.70: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in Brazil.

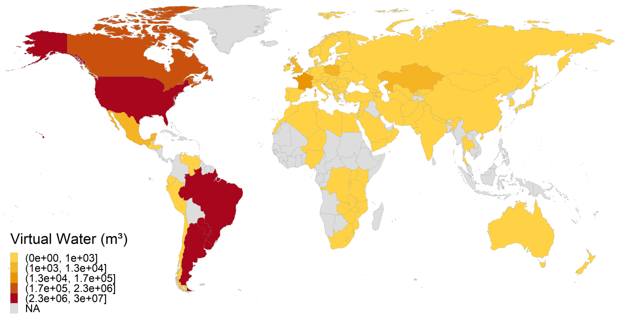

Figure C.71: Water footprint in m^3 associated with processing losses of wheat products used as feed in Brazil.

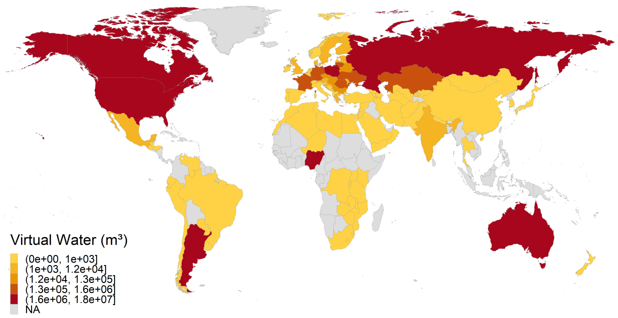

Figure C.72: Water footprint in m^3 associated with agricultural losses of wheat products used as feed in Nigeria.

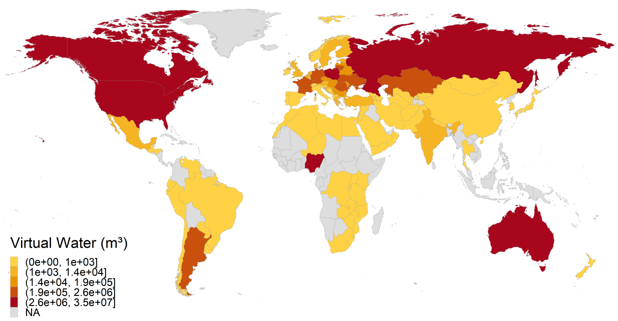

Figure C.73: Water footprint in m^3 associated with post-harvest losses of wheat products used as feed in Nigeria.

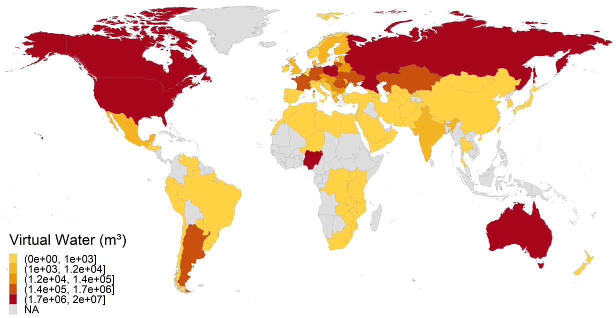

Figure C.74: Water footprint in m^3 associated with processing losses of wheat products used as feed in Nigeria.

C.2 Staple crops

C.2.1 Farm to fork perspective

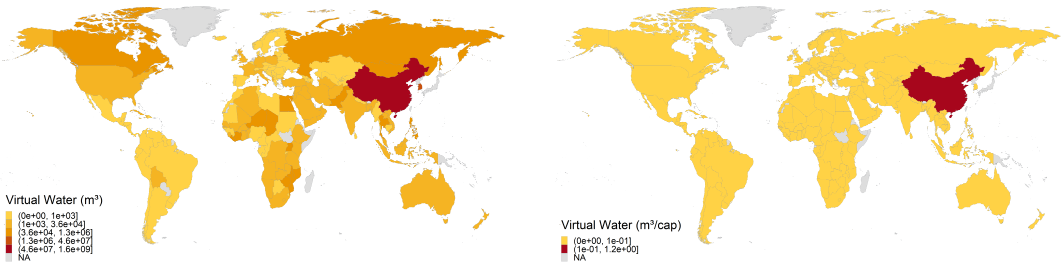

Figure C.75: Water footprint in m^3 relative to processing losses of rice produced in China, both for total population (left) and per capita (right).

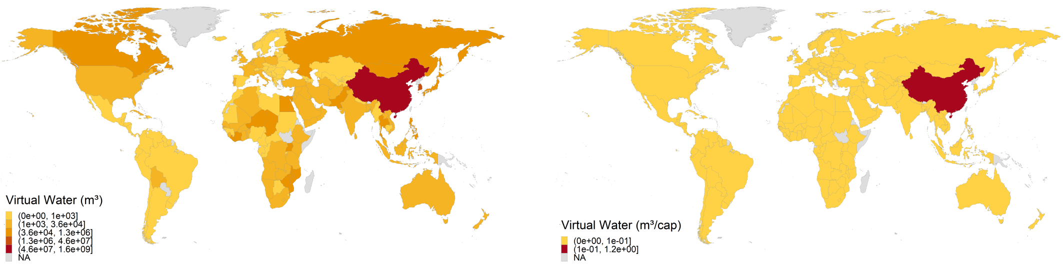

Figure C.76: Water footprint in m^3 relative to distribution waste of rice produced in China, both for total population (left) and per capita (right).

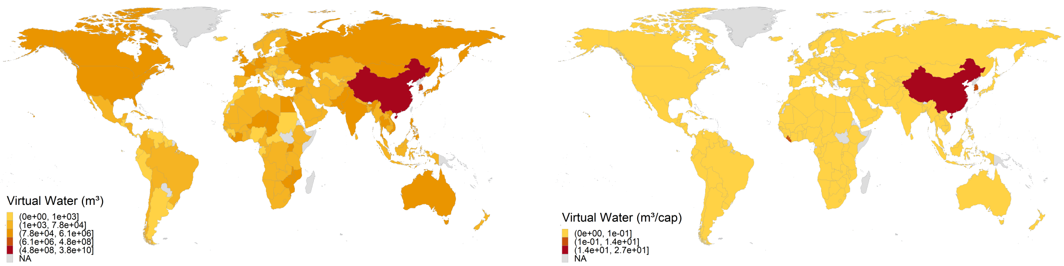

Figure C.77: Water footprint in m^3 relative to FLW of rice produced in China, both for total population (left) and per capita (right).

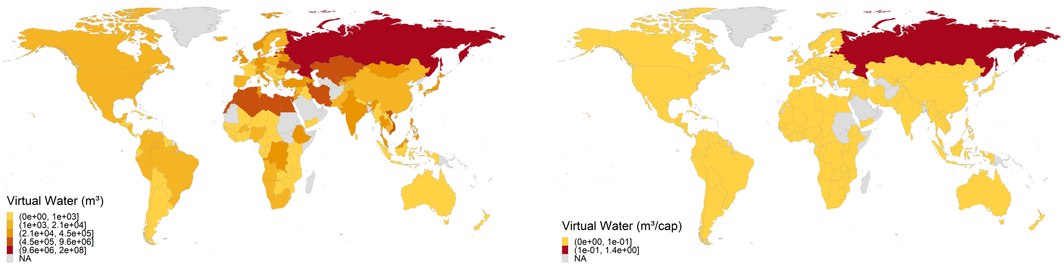

Figure C.78: Water footprint in m^3 relative to processing losses of barley produced in Russia, both for total population (left) and per capita (right).

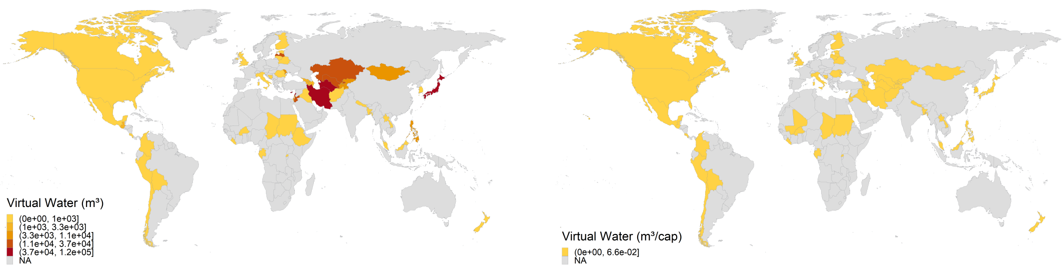

Figure C.79: Water footprint in m^3 relative to distribution waste of barley produced in Russia, both for total population (left) and per capita (right).

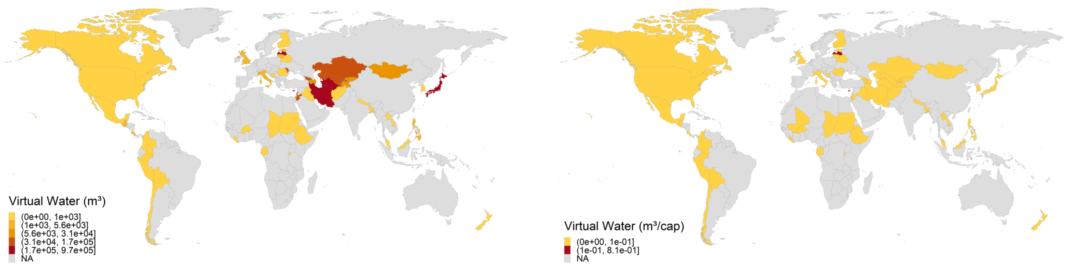

Figure C.80: Water footprint in m^3 relative to consumption waste of barley produced in Russia, both for total population (left) and per capita (right).

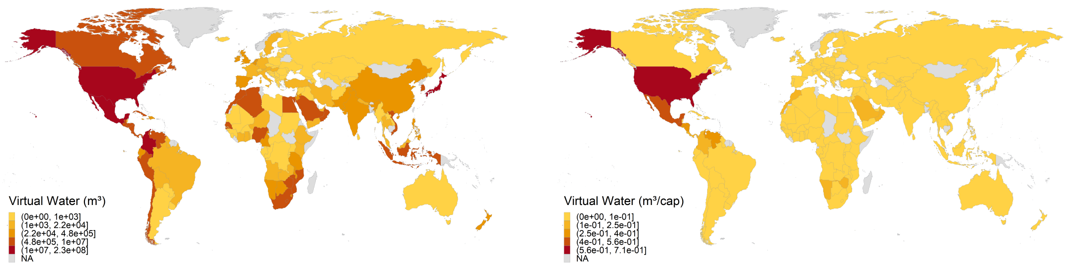

Figure C.81: Water footprint in m^3 relative to processing losses of maize produced in the United States, both for total population (left) and per capita (right).

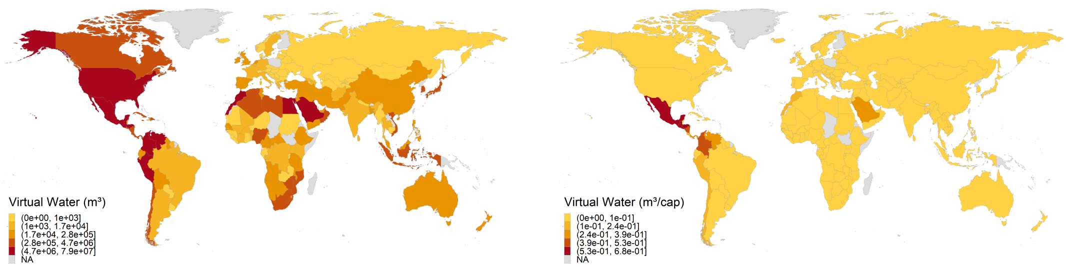

Figure C.82: Water footprint in m^3 relative to distribution waste of maize produced in the United States, both for total population (left) and per capita (right).

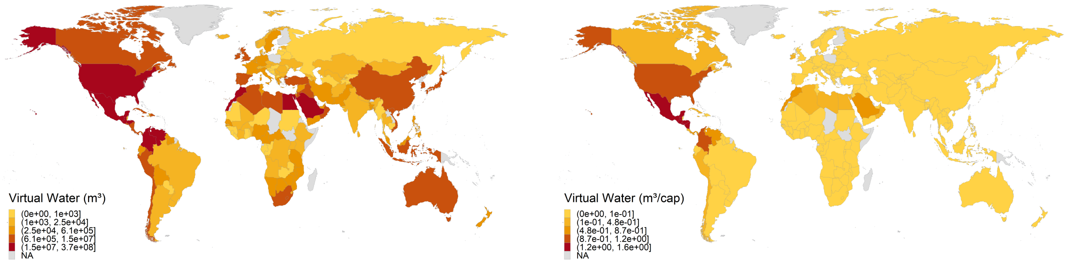

Figure C.83: Water footprint in m^3 relative to consumption waste of maize produced in the United States, both for total population (left) and per capita (right).

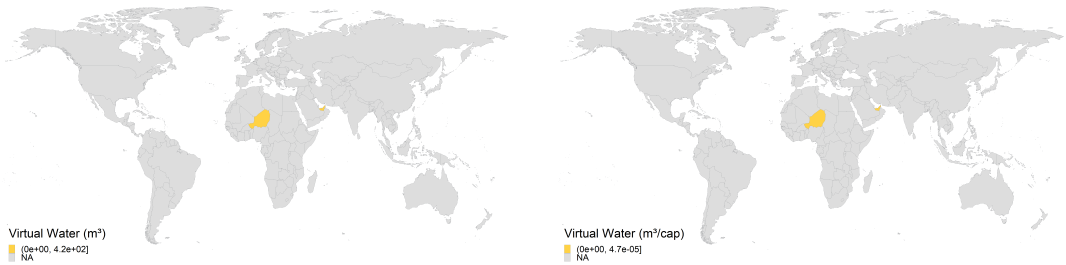

Figure C.84: Water footprint in m^3 relative to distribution waste of rye produced in Germany, both for total population (left) and per capita (right).

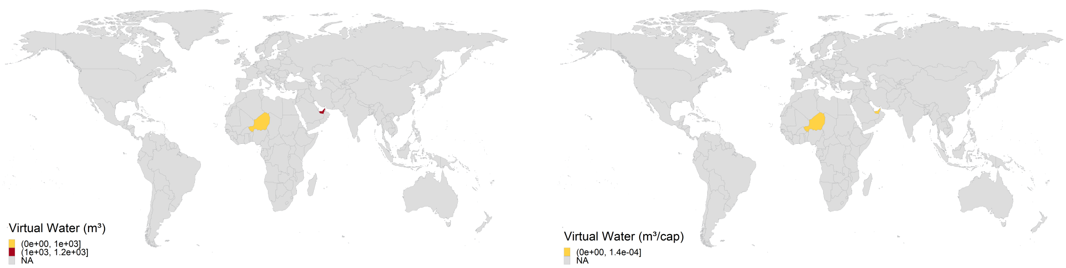

Figure C.85: Water footprint in m^3 relative to consumption waste of rye produced in Germany, both for total population (left) and per capita (right).

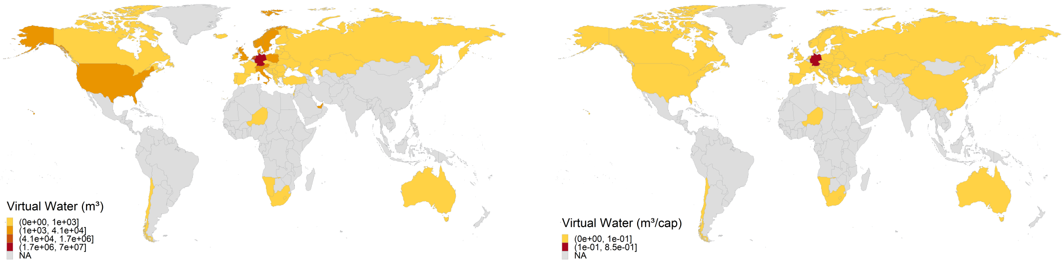

Figure C.86: Water footprint in m^3 relative to FLW of rye produced in Germany, both for total population (left) and per capita (right).

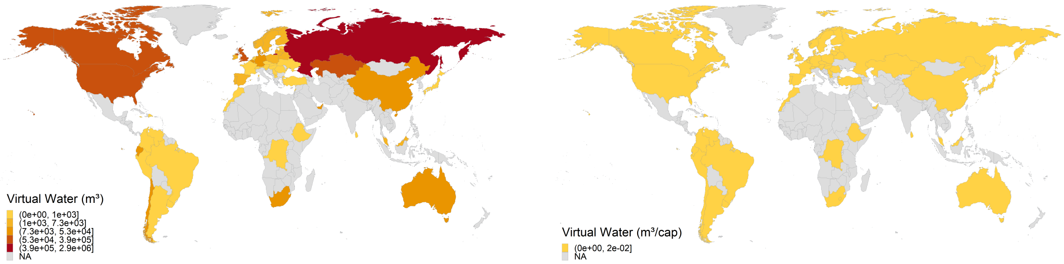

Figure C.87: Water footprint in m^3 relative to processing losses of oats produced in Russia, both for total population (left) and per capita (right).

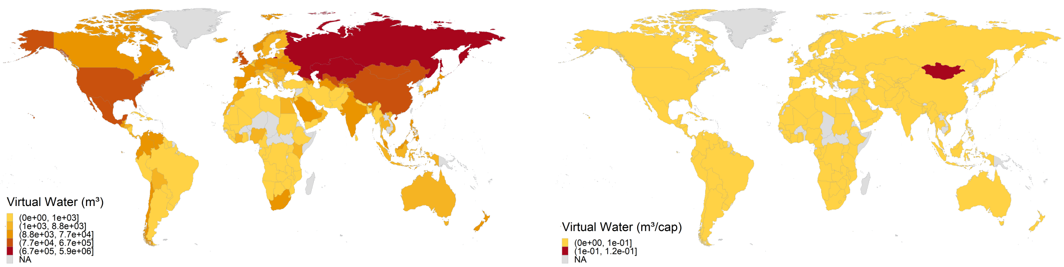

Figure C.88: Water footprint in m^3 relative to distribution waste of oats produced in Russia, both for total population (left) and per capita (right).

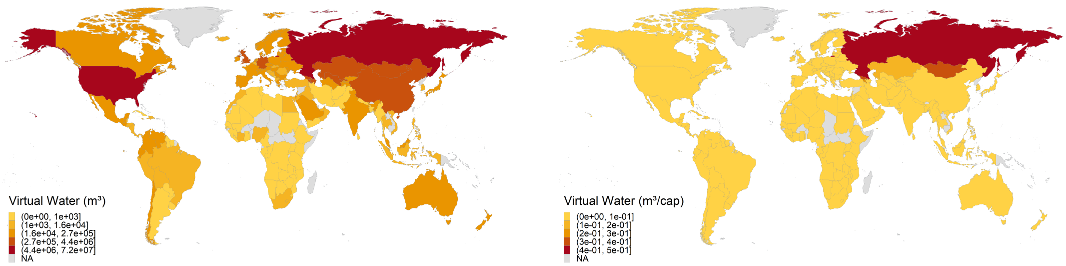

Figure C.89: Water footprint in m^3 relative to consumption waste of oats produced in Russia, both for total population (left) and per capita (right).

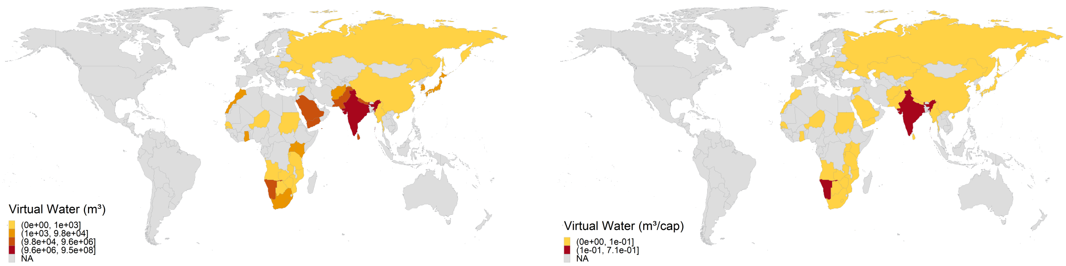

Figure C.90: Water footprint in m^3 relative to processing losses of millets produced in India, both for total population (left) and per capita (right).

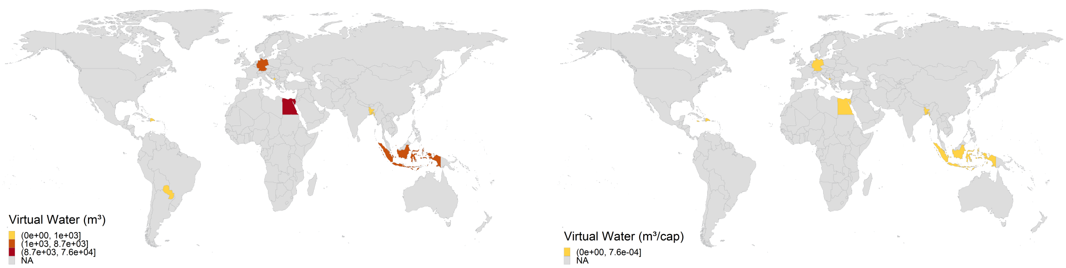

Figure C.91: Water footprint in m^3 relative to distribution waste of millets produced in India, both for total population (left) and per capita (right).

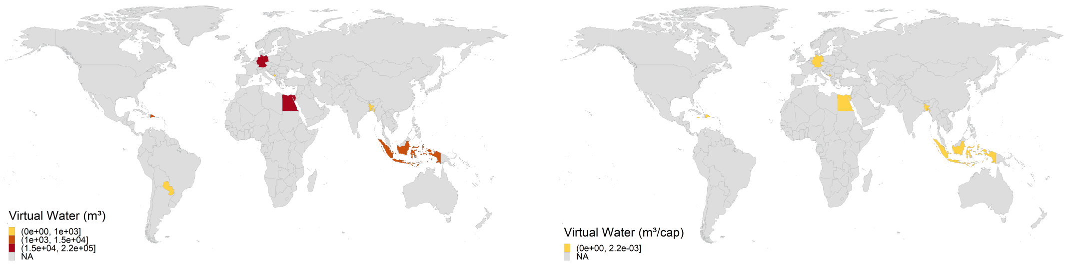

Figure C.92: Water footprint in m^3 relative to consumption waste of millets produced in India, both for total population (left) and per capita (right).

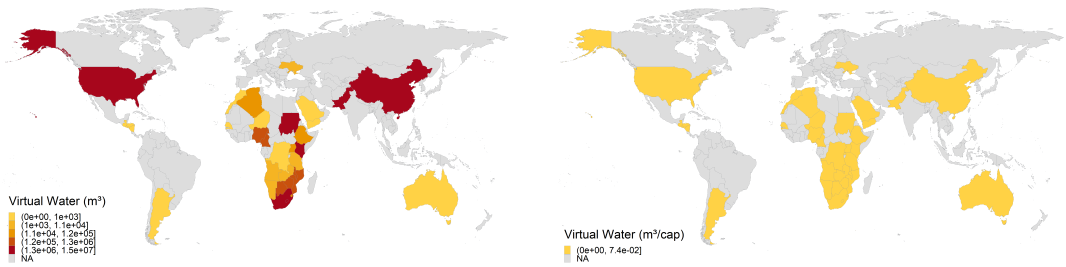

Figure C.93: Water footprint in m^3 relative to processing losses of sorghum produced in the United States, both for total population (left) and per capita (right).

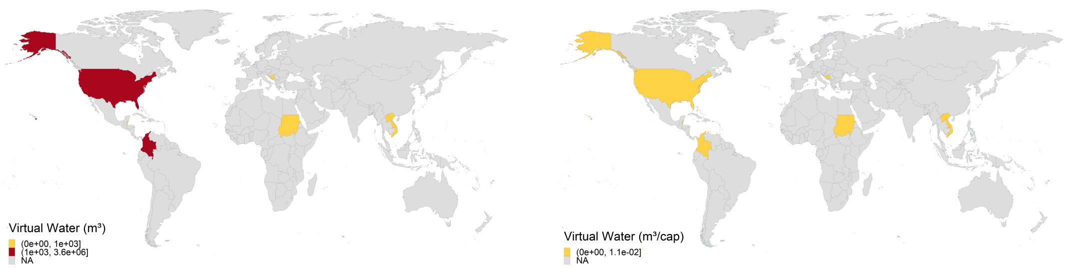

Figure C.94: Water footprint in m^3 relative to distribution waste of sorghum produced in the United States, both for total population (left) and per capita (right).

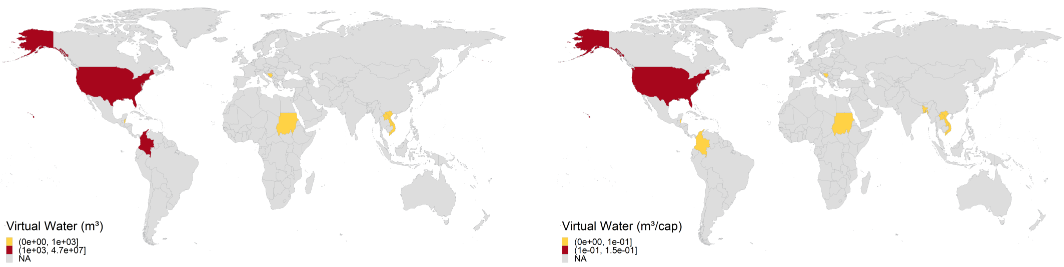

Figure C.95: Water footprint in m^3 relative to consumption waste of sorghum produced in the United States, both for total population (left) and per capita (right).

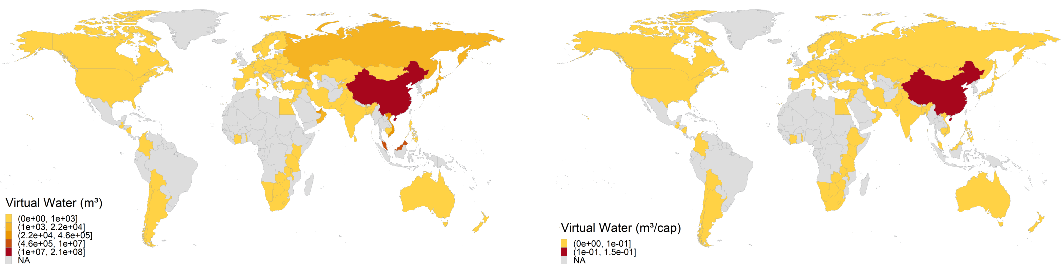

Figure C.96: Water footprint in m^3 relative to processing losses of potatoes produced in China, both for total population (left) and per capita (right).

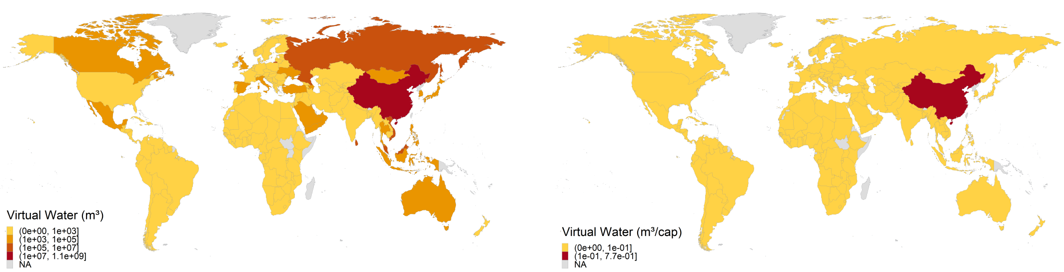

Figure C.97: Water footprint in m^3 relative to consumption waste of potatoes produced in China, both for total population (left) and per capita (right).

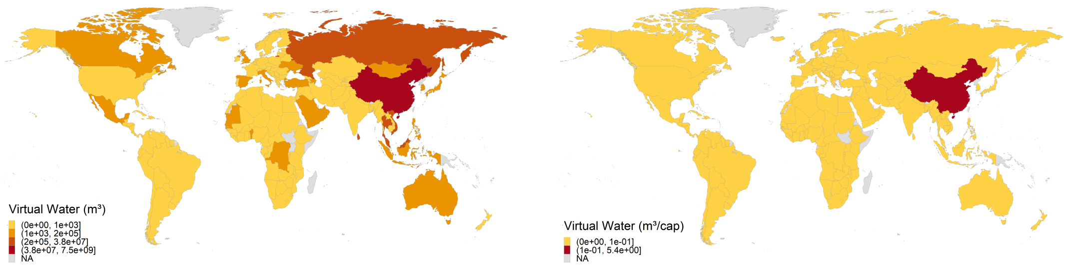

Figure C.98: Water footprint in m^3 relative to FLW of potatoes produced in China, both for total population (left) and per capita (right).

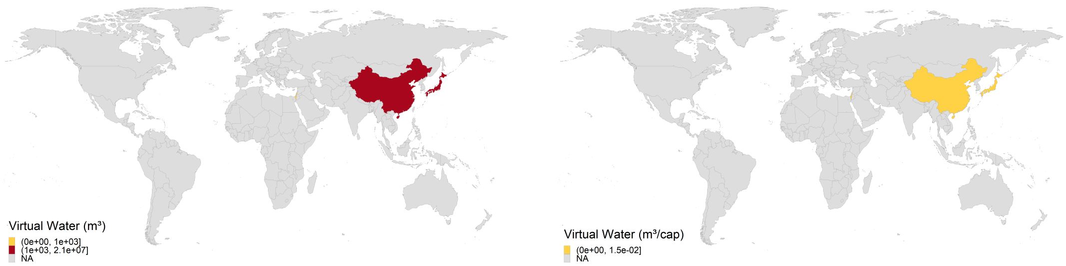

Figure C.99: Water footprint in m^3 relative to processing losses of sweet potatoes produced in China, both for total population (left) and per capita (right).

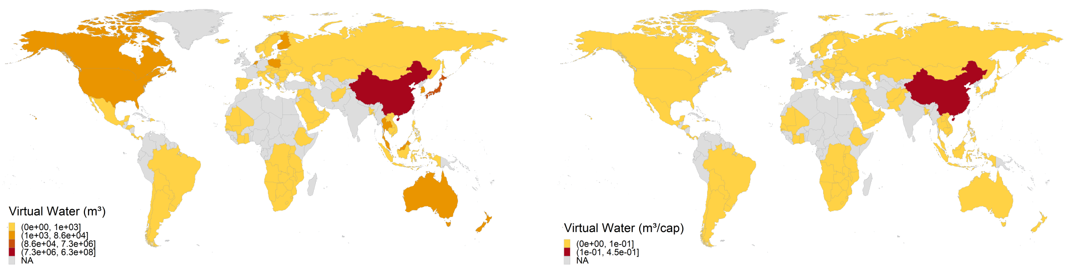

Figure C.100: Water footprint in m^3 relative to distribution waste of sweet potatoes produced in China, both for total population (left) and per capita (right).

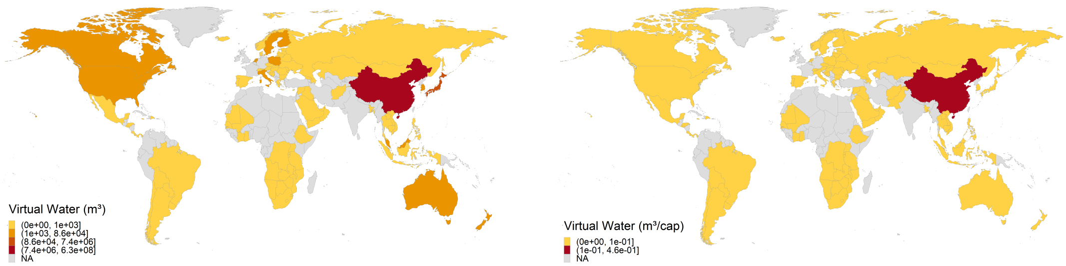

Figure C.101: Water footprint in m^3 relative to consumption waste of sweet potatoes produced in China, both for total population (left) and per capita (right).

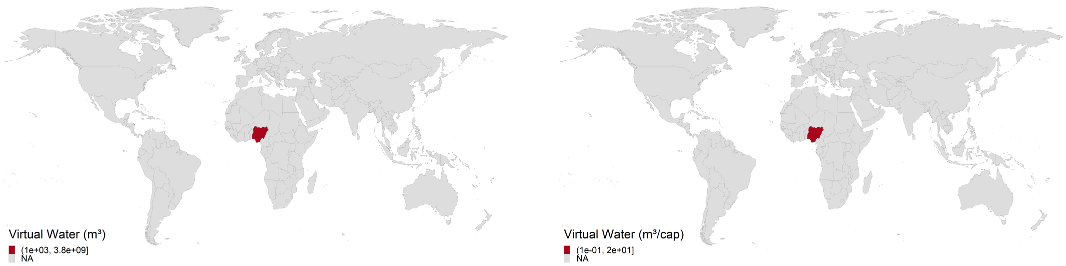

Figure C.102: Water footprint in m^3 relative to processing losses of cassava produced in Nigeria, both for total population (left) and per capita (right).

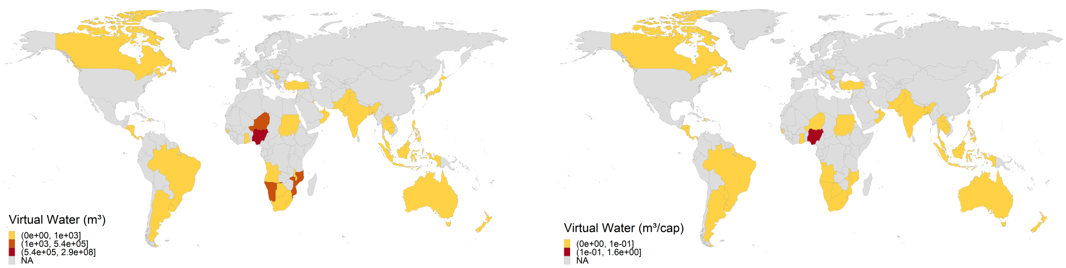

Figure C.103: Water footprint in m^3 relative to distribution waste of cassava produced in Nigeria, both for total population (left) and per capita (right).

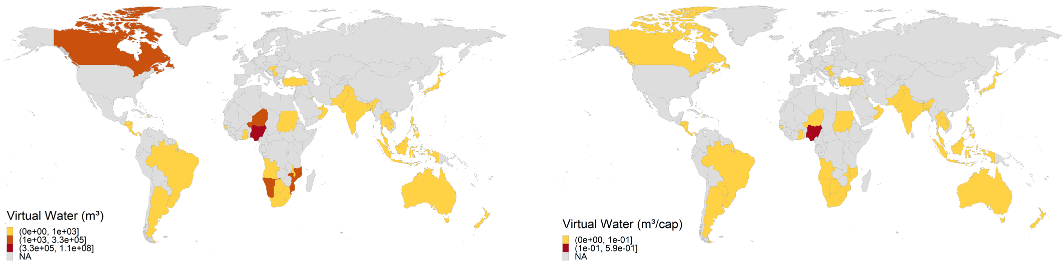

Figure C.104: Water footprint in m^3 relative to consumption waste of cassava produced in Nigeria, both for total population (left) and per capita (right).

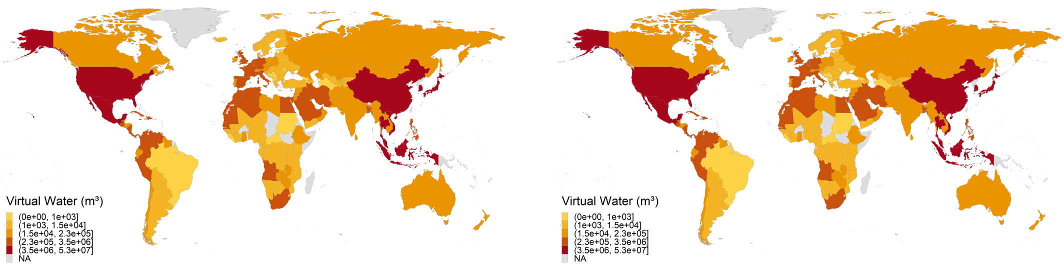

Figure C.105: Water footprint in m^3 relative to distribution waste of soybeans produced in the United States, both for total population (left) and per capita (right).

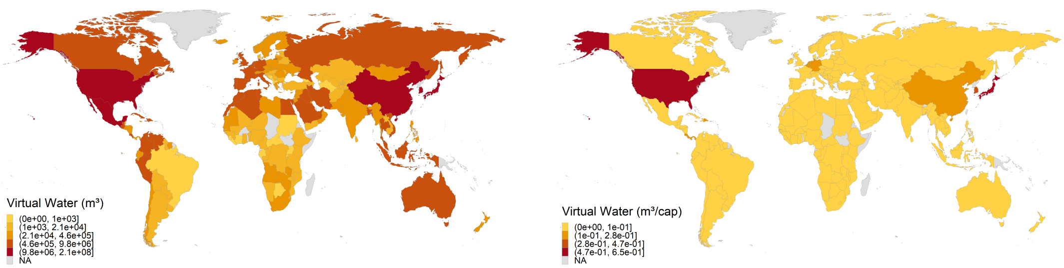

Figure C.106: Water footprint in m^3 relative to consumption waste of soybeans produced in the United States, both for total population (left) and per capita (right).

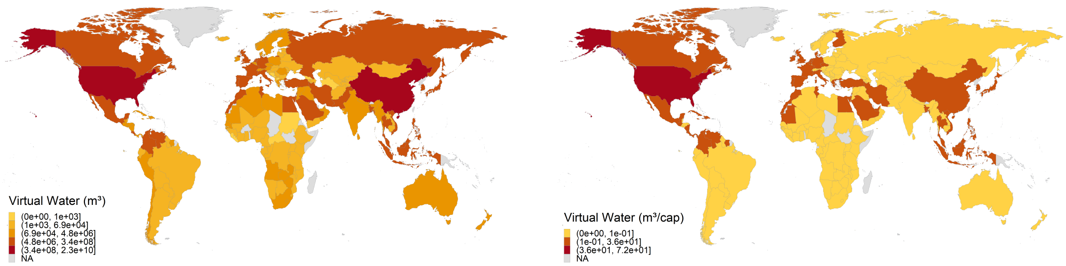

Figure C.107: Water footprint in m^3 relative to FLW of soybeans produced in the United States, both for total population (left) and per capita (right).

C.2.2 Fork to farm perspective

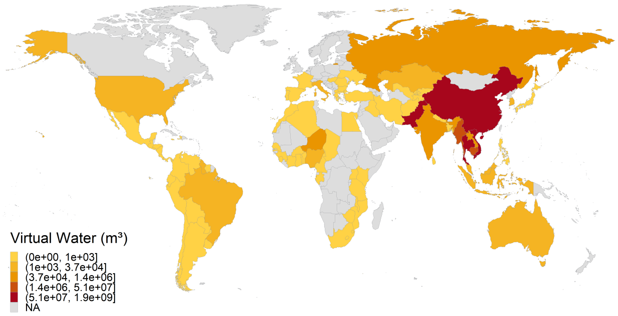

Figure C.108: Water footprint in m^3 associated with agricultural losses of rice products consumed in China.

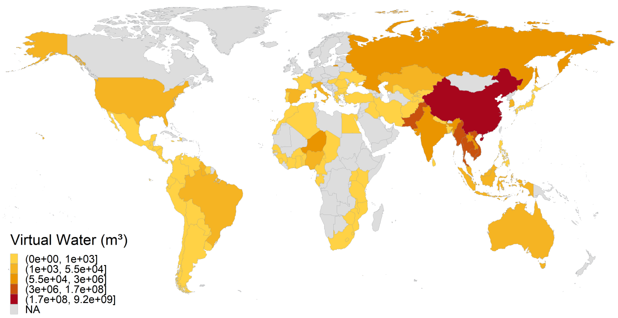

Figure C.109: Water footprint in m^3 associated with post-harvest losses of rice products consumed in China.

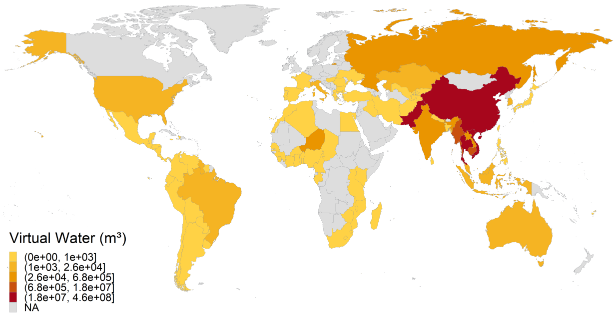

Figure C.110: Water footprint in m^3 associated with processing losses of rice products consumed in China.

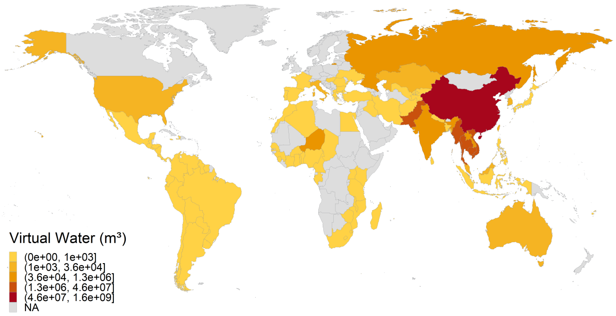

Figure C.111: Water footprint in m^3 associated with distribution waste of rice products consumed in China.

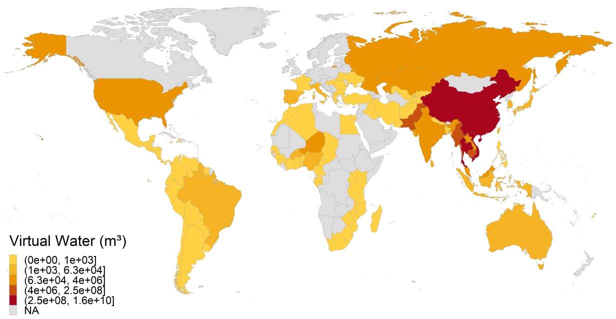

Figure C.112: Water footprint in m^3 associated with consumption waste of rice products consumed in China.

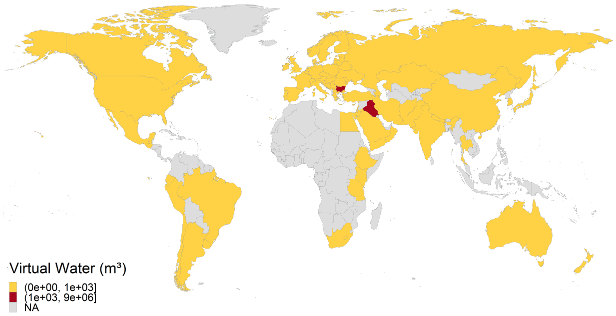

Figure C.113: Water footprint in m^3 associated with agricultural losses of barley products consumed in Iraq.

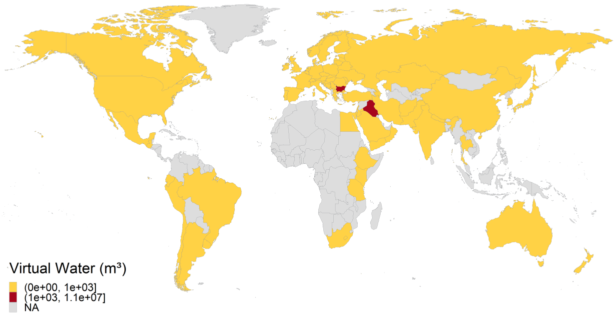

Figure C.114: Water footprint in m^3 associated with post-harvest losses of barley products consumed in Iraq.

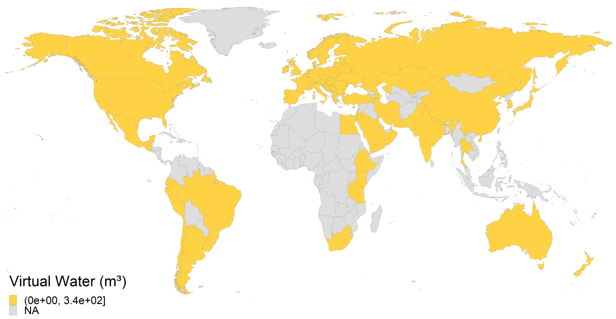

Figure C.115: Water footprint in m^3 associated with processing losses of barley products consumed in Iraq.

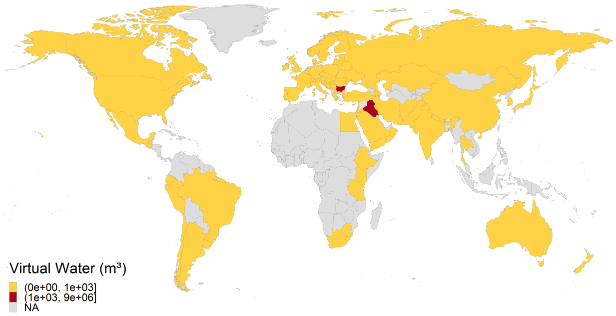

Figure C.116: Water footprint in m^3 associated with distribution waste of barley products consumed in Iraq.

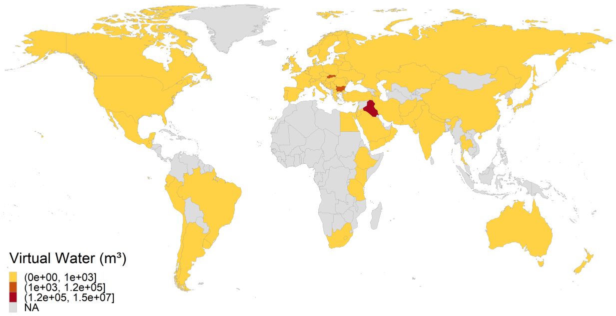

Figure C.117: Water footprint in m^3 associated with consumption waste of barley products consumed in Iraq.

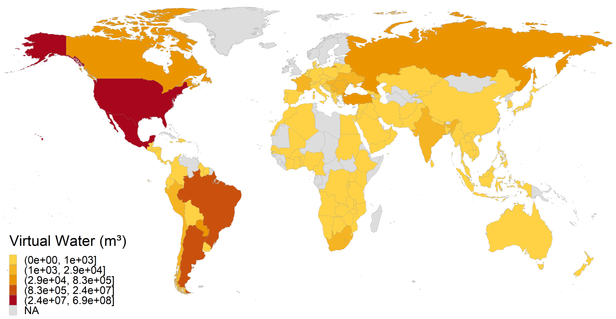

Figure C.118: Water footprint in m^3 associated with agricultural losses of maize products consumed in Mexico.

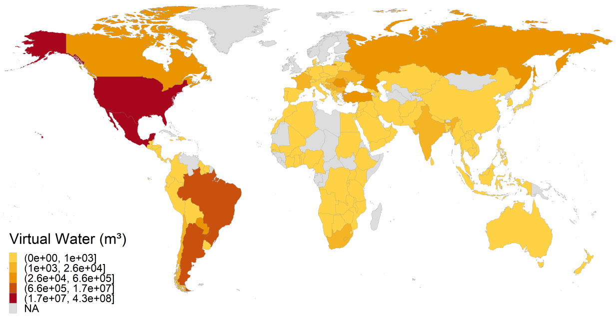

Figure C.119: Water footprint in m^3 associated with post-harvest losses of maize products consumed in Mexico.

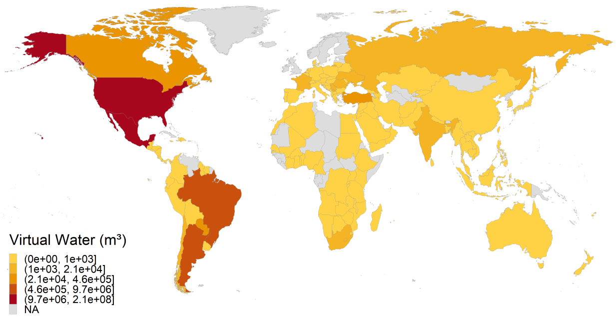

Figure C.120: Water footprint in m^3 associated with processing losses of maize products consumed in Mexico.

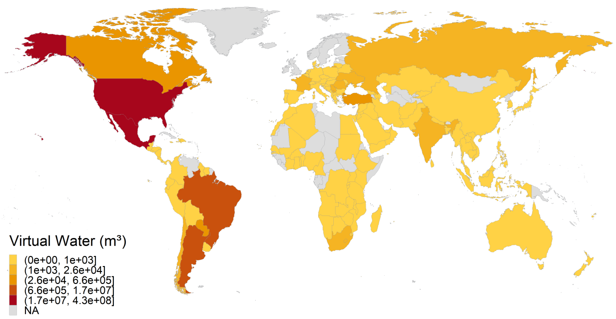

Figure C.121: Water footprint in m^3 associated with distribution waste of maize products consumed in Mexico.

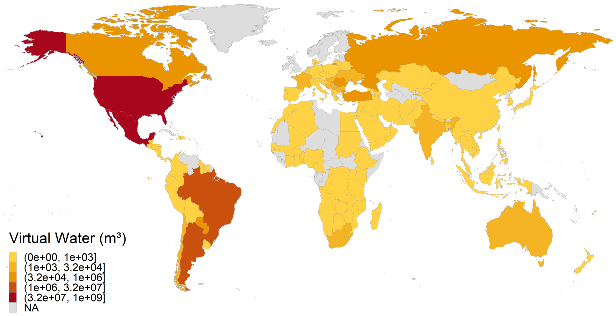

Figure C.122: Water footprint in m^3 associated with consumption waste of maize products consumed in Mexico.

Figure C.123: Water footprint in m^3 associated with agricultural losses of rye products consumed in Iran.

Figure C.124: Water footprint in m^3 associated with post-harvest losses of rye products consumed in Iran.

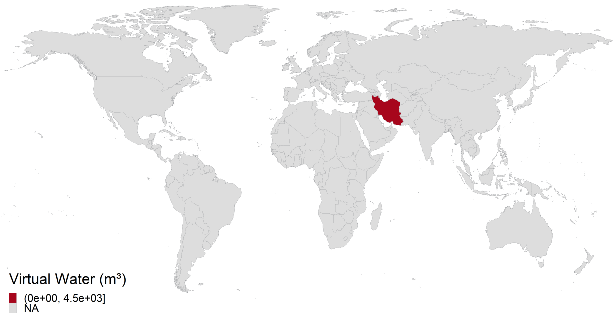

Figure C.125: Water footprint in m^3 associated with distribution waste of rye products consumed in Iran.

Figure C.126: Water footprint in m^3 associated with consumption waste of rye products consumed in Iran.

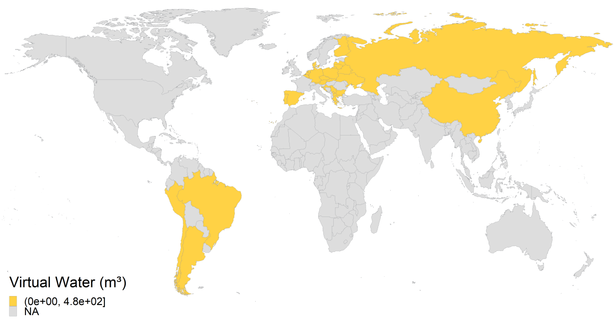

Figure C.127: Water footprint in m^3 associated with agricultural losses of oat products consumed in Tanzania.

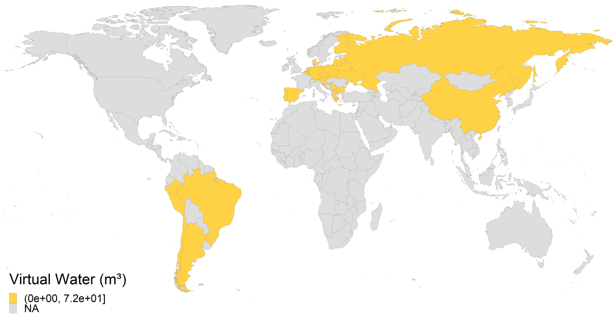

Figure C.128: Water footprint in m^3 associated with post-harvest losses of oat products consumed in Tanzania.

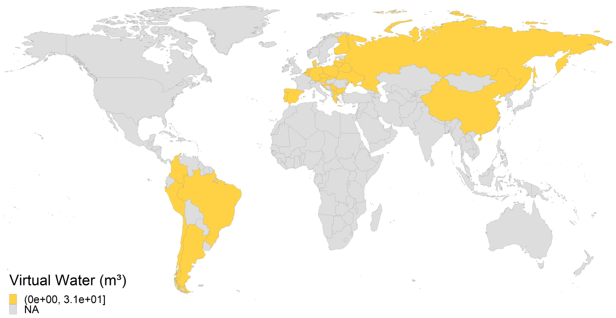

Figure C.129: Water footprint in m^3 associated with processing losses of oat products consumed in Tanzania.

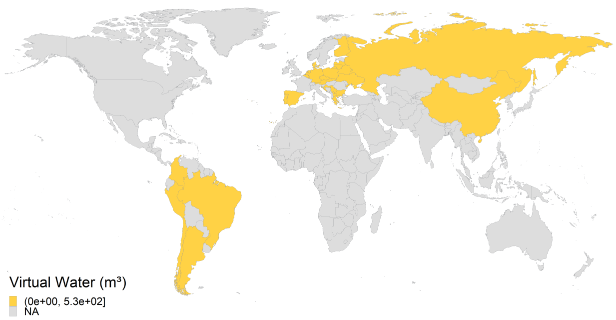

Figure C.130: Water footprint in m^3 associated with distribution waste of oat products consumed in Tanzania.

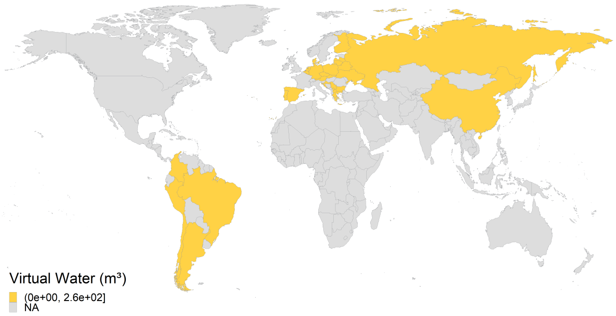

Figure C.131: Water footprint in m^3 associated with consumption waste of oat products consumed in Tanzania.

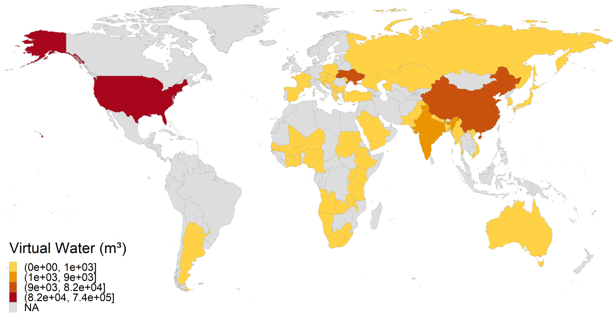

Figure C.132: Water footprint in m^3 associated with agricultural losses of millet products consumed in Indonesia.

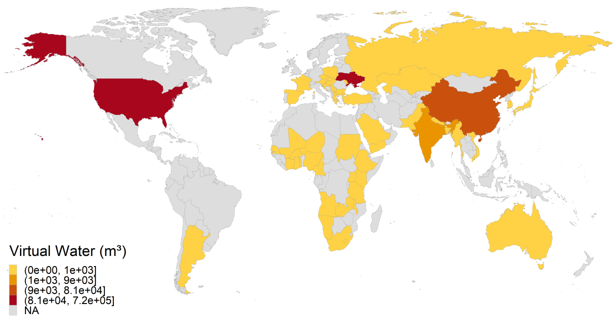

Figure C.133: Water footprint in m^3 associated with post-harvest losses of millet products consumed in Indonesia.

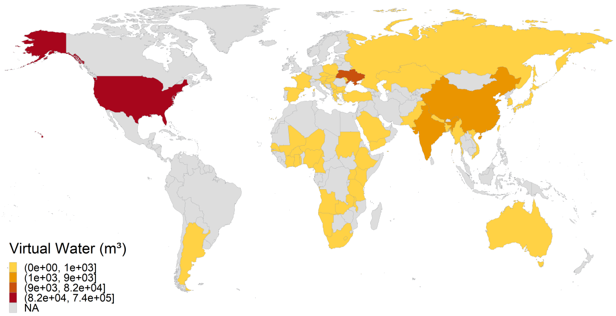

Figure C.134: Water footprint in m^3 associated with distribution waste of millet products consumed in Indonesia.

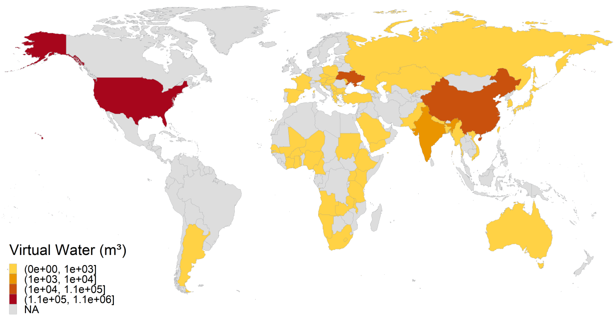

Figure C.135: Water footprint in m^3 associated with consumption waste of millet products consumed in Indonesia.

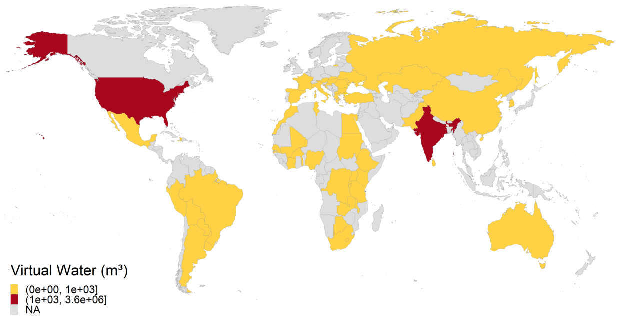

Figure C.136: Water footprint in m^3 associated with agricultural losses of sorghum products consumed in the United States.

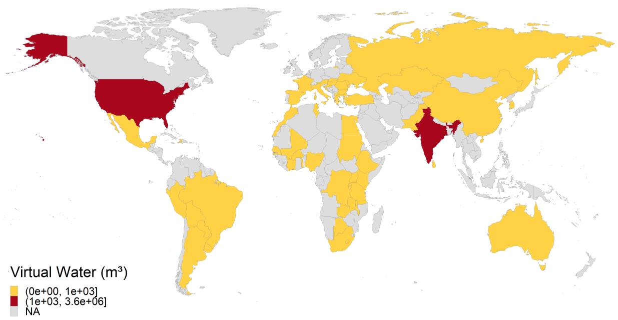

Figure C.137: Water footprint in m^3 associated with post-harvest losses of sorghum products consumed in the United States.

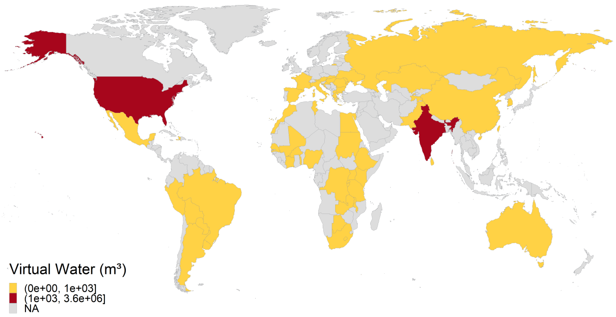

Figure C.138: Water footprint in m^3 associated with distribution waste of sorghum products consumed in the United States.

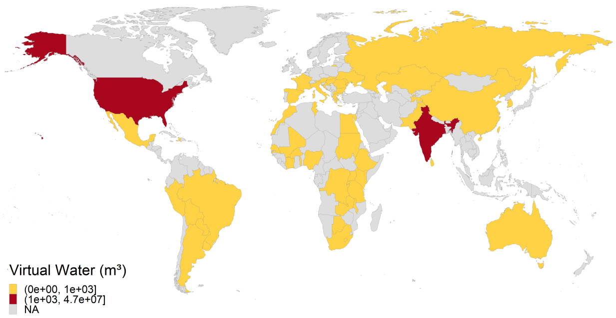

Figure C.139: Water footprint in m^3 associated with consumption waste of sorghum products consumed in the United States.

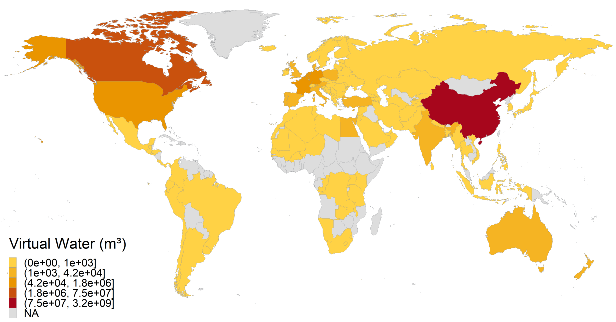

Figure C.140: Water footprint in m^3 associated with agricultural losses of potato products consumed in China.

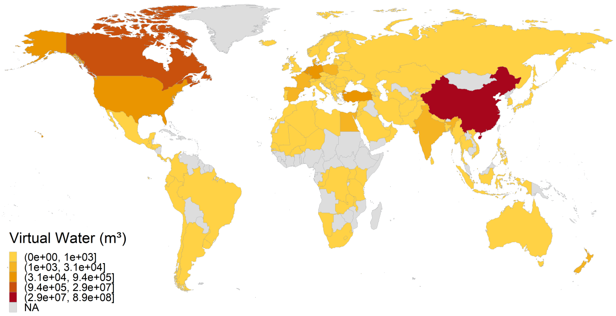

Figure C.141: Water footprint in m^3 associated with post-harvest losses of potato products consumed in China.

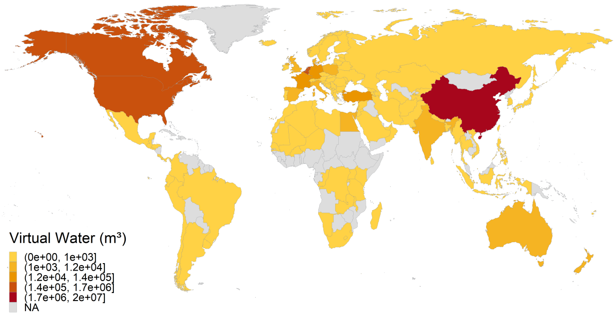

Figure C.142: Water footprint in m^3 associated with processing losses of potato products consumed in China.

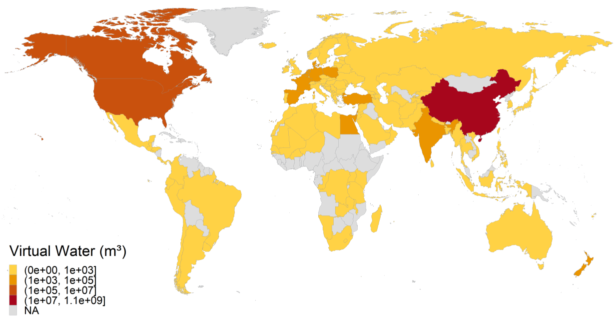

Figure C.143: Water footprint in m^3 associated with distribution waste of potato products consumed in China.

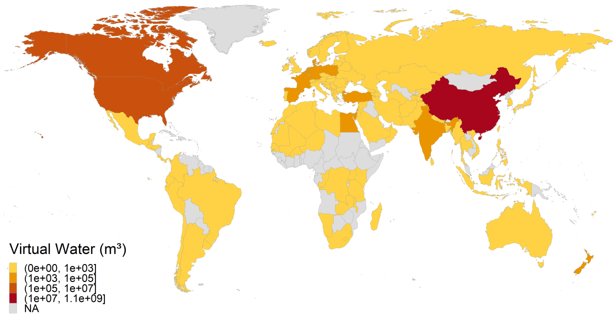

Figure C.144: Water footprint in m^3 associated with consumption waste of potato products consumed in China.

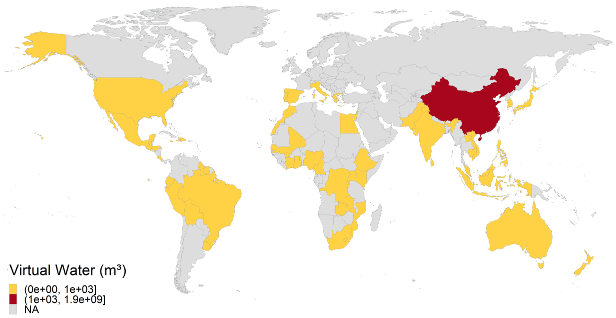

Figure C.145: Water footprint in m^3 associated with agricultural losses of sweet potato products consumed in China.

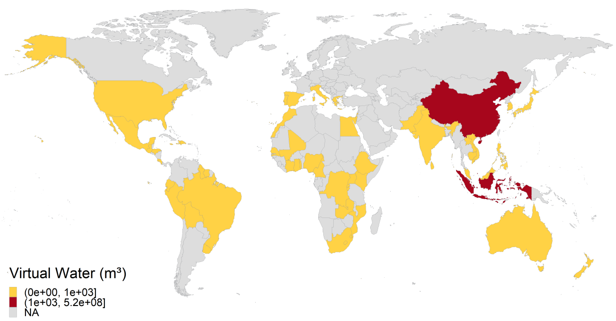

Figure C.146: Water footprint in m^3 associated with post-harvest losses of sweet potato products consumed in China.

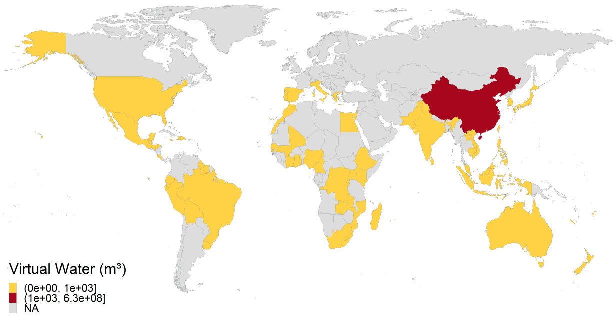

Figure C.147: Water footprint in m^3 associated with distribution waste of sweet potato products consumed in China.

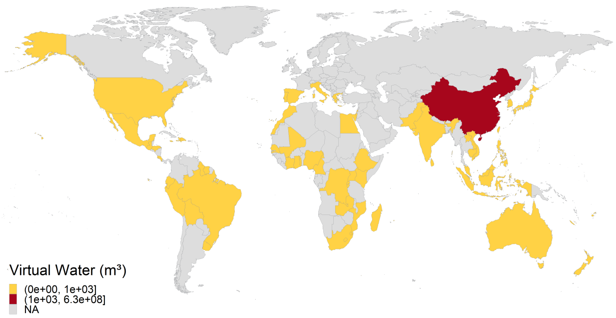

Figure C.148: Water footprint in m^3 associated with consumption waste of sweet potato products consumed in China.

Figure C.149: Water footprint in m^3 associated with agricultural losses of cassava products consumed in Congo.

Figure C.150: Water footprint in m^3 associated with post-harvest losses of cassava products consumed in Congo.

Figure C.151: Water footprint in m^3 associated with processing losses of cassava products consumed in Congo.

Figure C.152: Water footprint in m^3 associated with distribution waste of cassava products consumed in Congo.

Figure C.153: Water footprint in m^3 associated with consumption waste of cassava products consumed in Congo.

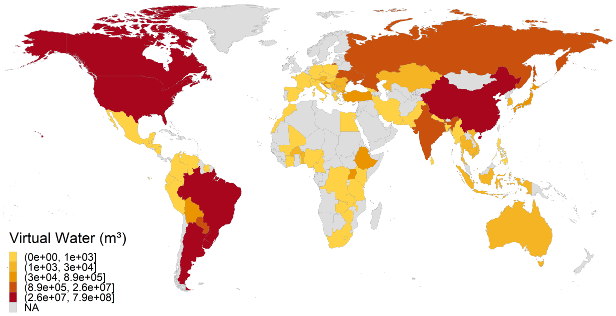

Figure C.154: Water footprint in m^3 associated with agricultural losses of soybean products consumed in China.

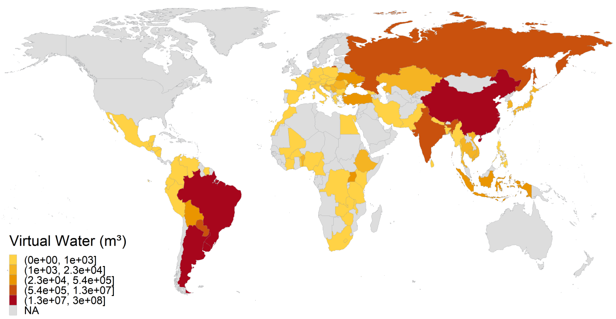

Figure C.155: Water footprint in m^3 associated with post-harvest losses of soybean products consumed in China.

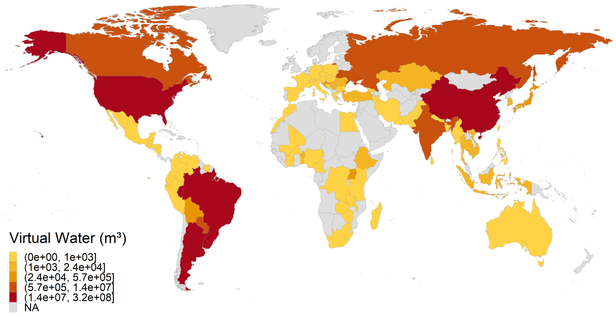

Figure C.156: Water footprint in m^3 associated with processing losses of soybean products consumed in China.

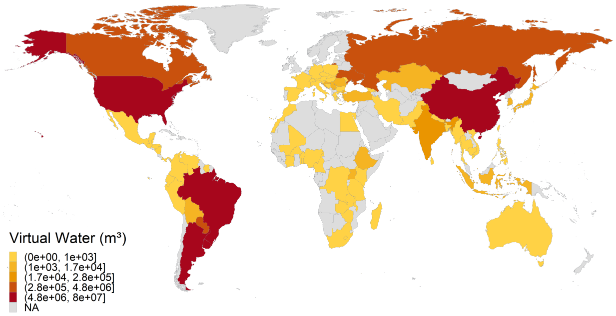

Figure C.157: Water footprint in m^3 associated with distribution waste of soybean products consumed in China.

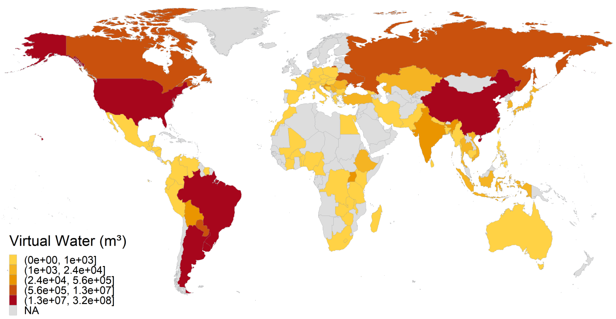

Figure C.158: Water footprint in m^3 associated with consumption waste of soybean products consumed in China.

C.2.3 Feeder to farm perspective

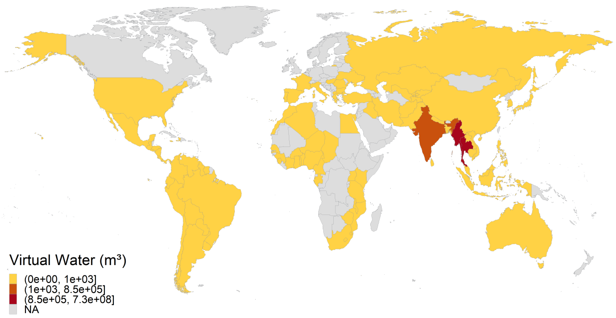

Figure C.159: Water footprint in m^3 associated with agricultural losses of rice products used as feed in Myanmar.

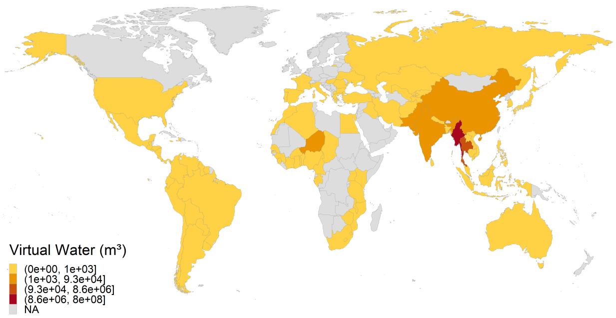

Figure C.160: Water footprint in m^3 associated with post-harvest losses of rice products used as feed in Myanmar.

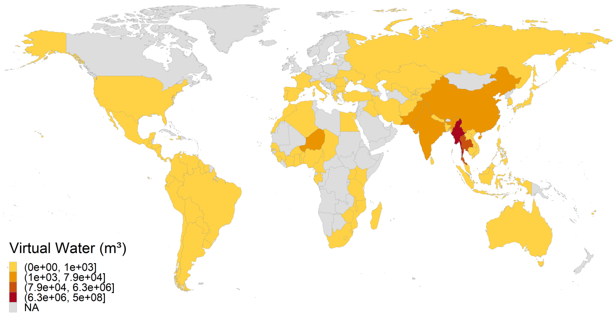

Figure C.161: Water footprint in m^3 associated with processing losses of rice products used as feed in Myanmar.

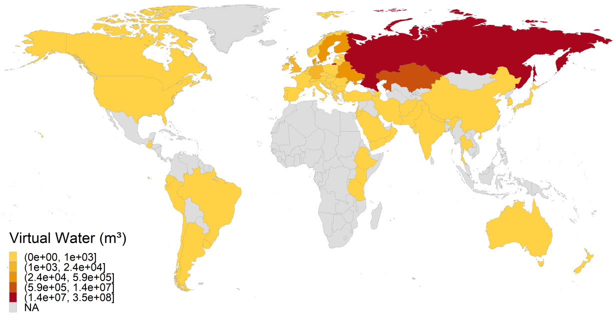

Figure C.162: Water footprint in m^3 associated with agricultural losses of barley products used as feed in Russia.

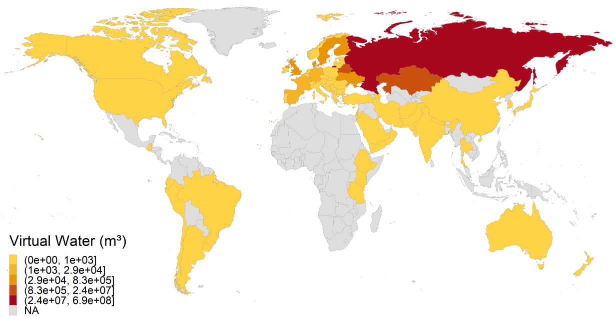

Figure C.163: Water footprint in m^3 associated with post-harvest losses of barley products used as feed in Russia.

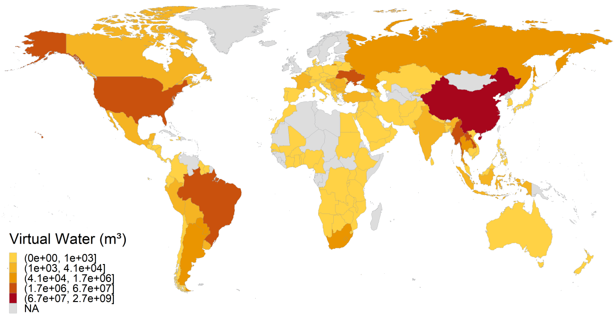

Figure C.164: Water footprint in m^3 associated with agricultural losses of maize products used as feed in China.

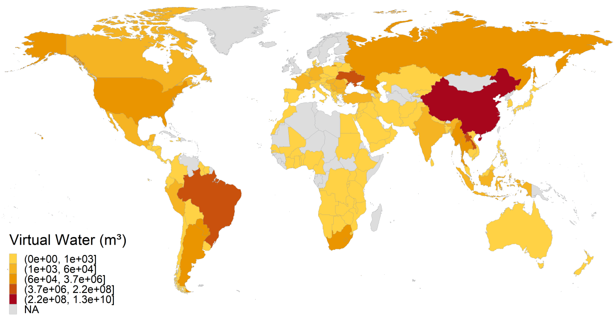

Figure C.165: Water footprint in m^3 associated with post-harvest losses of maize products used as feed in China.

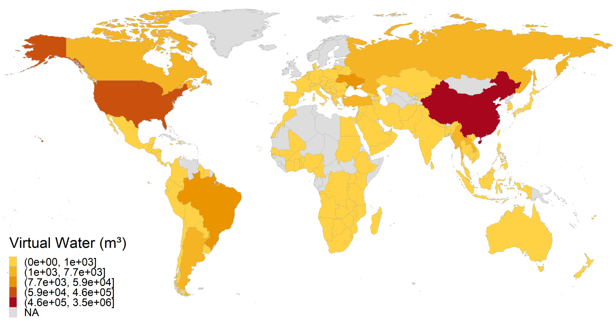

Figure C.166: Water footprint in m^3 associated with processing losses of maize products used as feed in China.

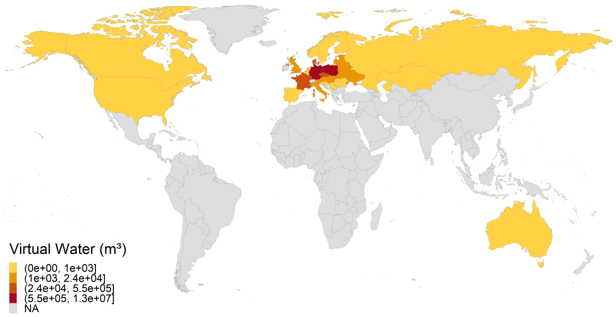

Figure C.167: Water footprint in m^3 associated with agricultural losses of rye products used as feed in Germany.

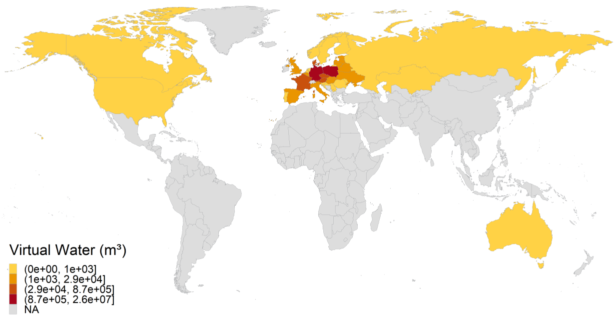

Figure C.168: Water footprint in m^3 associated with post-harvest losses of rye products used as feed in Germany.

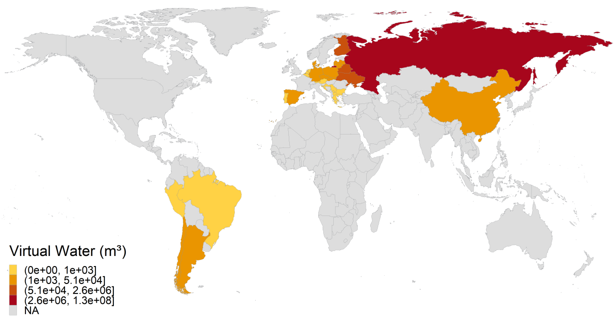

Figure C.169: Water footprint in m^3 associated with agricultural losses of oat products used as feed in Russia.

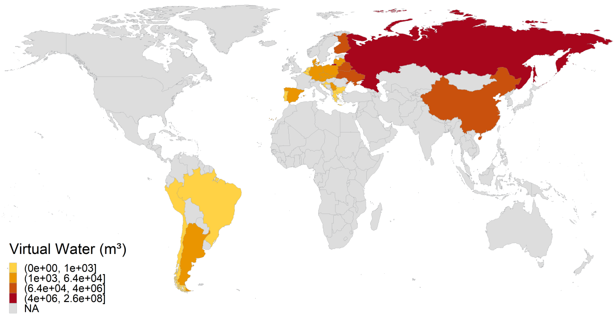

Figure C.170: Water footprint in m^3 associated with post-harvest losses of oat products used as feed in Russia.

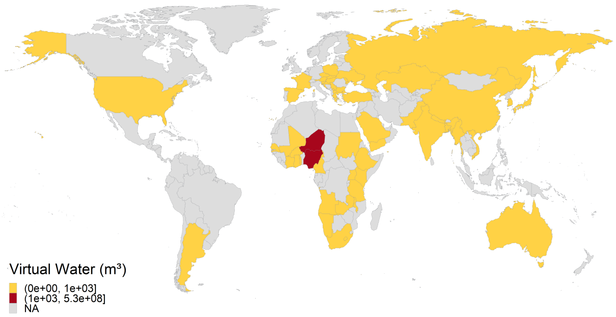

Figure C.171: Water footprint in m^3 associated with agricultural losses of millet products used as feed in Niger.

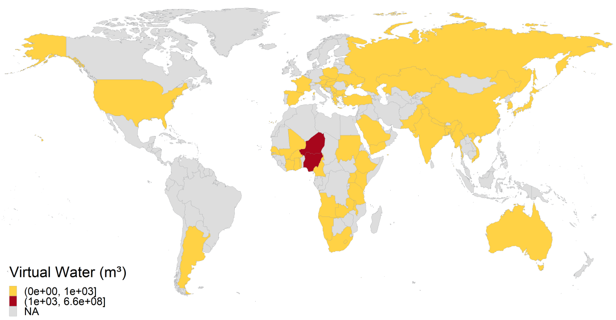

Figure C.172: Water footprint in m^3 associated with post-harvest losses of millet products used as feed in Niger.

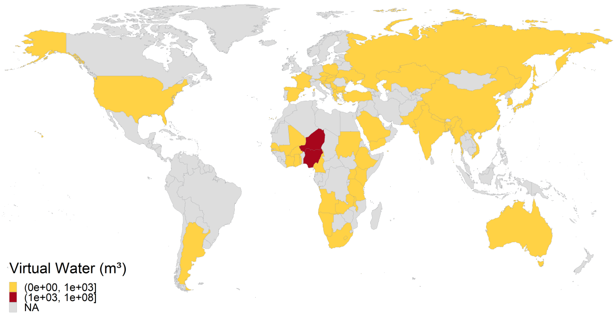

Figure C.173: Water footprint in m^3 associated with processing losses of millet products used as feed in Niger.

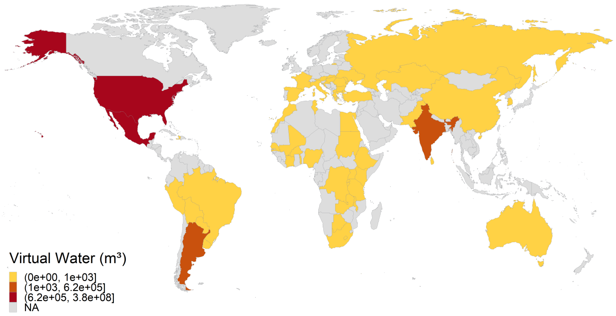

Figure C.174: Water footprint in m^3 associated with agricultural losses of sorghum products used as feed in Mexico.

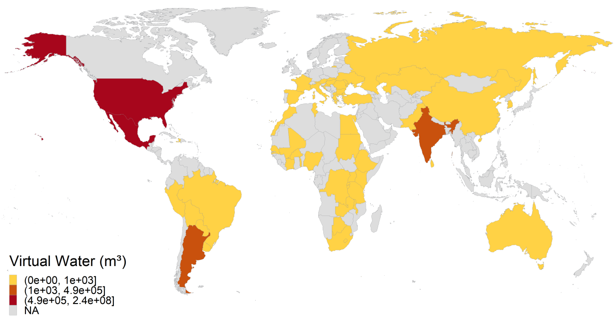

Figure C.175: Water footprint in m^3 associated with post-harvest losses of sorghum products used as feed in Mexico.

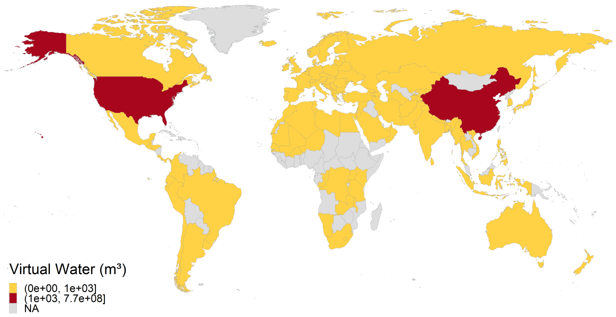

Figure C.176: Water footprint in m^3 associated with agricultural losses of potato products used as feed in China.

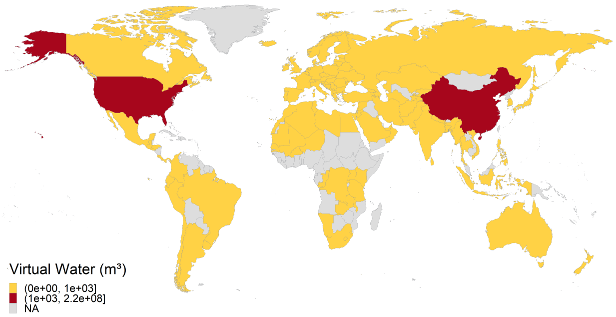

Figure C.177: Water footprint in m^3 associated with post-harvest losses of potato products used as feed in China.

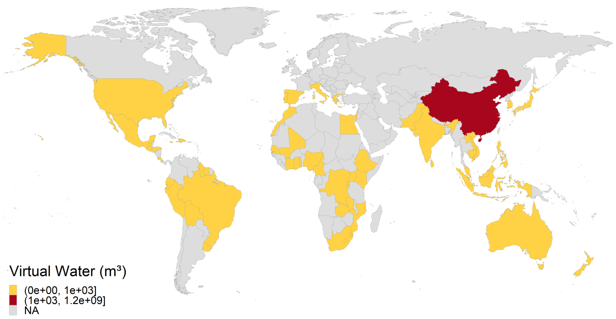

Figure C.178: Water footprint in m^3 associated with agricultural losses of sweet potato products used as feed in China.

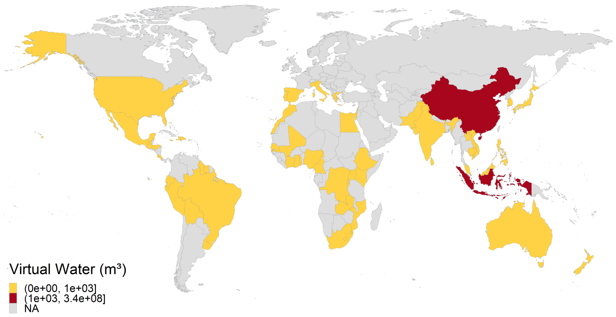

Figure C.179: Water footprint in m^3 associated with post-harvest losses of sweet potato products used as feed in China.

Figure C.180: Water footprint in m^3 associated with agricultural losses of cassava products used as feed in Nigeria.

Figure C.181: Water footprint in m^3 associated with post-harvest losses of cassava products used as feed in Nigeria.

Figure C.182: Water footprint in m^3 associated with agricultural losses of cassava products used as feed in Nigeria.

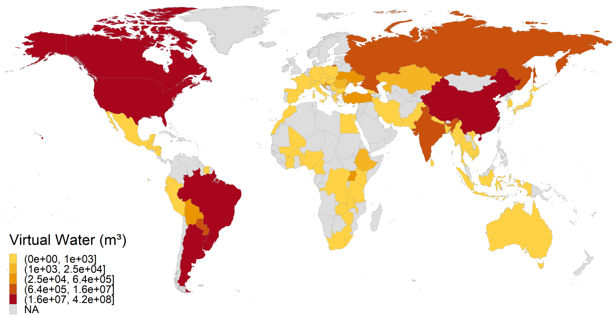

Figure C.183: Water footprint in m^3 associated with agricultural losses of soybean products used as feed in China.

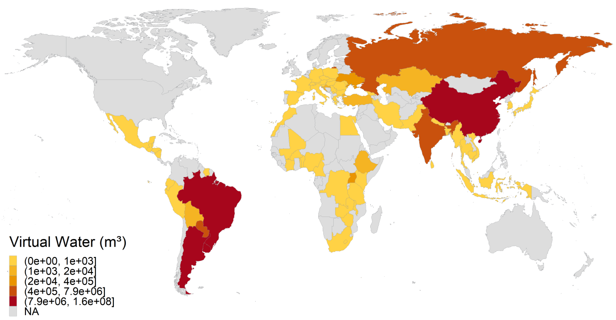

Figure C.184: Water footprint in m^3 associated with post-harvest losses of soybean products used as feed in China.

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