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Review

The Water Footprint of Global Food Production

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Abstract: Agricultural production is the main consumer of water. Future population growth, income growth, and dietary shifts are expected to increase demand for water. The paper presents a brief review of the water footprint of crop production and the sustainability of the blue water footprint. The estimated global consumptive (green plus blue) water footprint ranges from 5938 to 8508 km³/year. The water footprint is projected to increase by as much as 22% due to climate change and land use change by 2090. Approximately 57% of the global blue water footprint is shown to violate the environmental flow requirements. This calls for action to improve the sustainability of water and protect ecosystems that depend on it. Some of the measures include increasing water productivity, setting benchmarks, setting caps on the water footprint per river basin, shifting the diets to food items with low water requirements, and reducing food waste.

Keywords: agriculture; food production; sustainable diet; food waste; water sustainability

1. Introduction

Agriculture is by far the largest user of water. Agricultural production needs to increase by almost 50% by 2050 compared to 2012 to meet the rising demand for food, fiber, and biofuels. This is probably going to require more water. Most of the increase in agricultural production is expected to occur in Sub-Saharan Africa and South Asia, where the agricultural output will need to more than double by 2050 [1]. The expected increase in the rest of the world is around 30%. Agricultural production has increased by 260% between 1961 and 2018 [2]. During the same period, the harvested crop area increased by 47%, suggesting that 113% of the increase in production is linked to an increase in crop yield. The increase in crop yield between 1961 and 1990 was 72%, but between 1991 and 2018, the increase was 43%, indicating that yields are now rising at a slower rate than in previous decades [2]. The increase in crop yields was largely due to increased irrigation, improved crop varieties, agrochemical inputs, and improved soil and water management. However, the increase in crop productivity is not expected to continue indefinitely. In most parts of the world, yields for major crops have begun to stagnate [3,4]. Climate change, soil degradation, and salinization of irrigated areas will potentially limit future increases in production. Ray et al. [5] have shown that with the current rate of yield increase, it is not possible to meet the expected food demand by 2050. They have argued that some level of cropland expansion is needed to meet the food production deficits but at a higher environmental cost to biodiversity.

The amount of food available for human consumption is affected by the allocation of crops to other nonfood uses such as animal feed, bioenergy, and industrial uses. Globally, only 67% of the crop produced (by mass) or 55% of the calories produced is available for direct human consumption [6]. The remaining crop was allocated to animal feed (24% by mass) and other industrial use, including

bioenergy (9% by weight). Animal production is less efficient than crop production in converting feed to human edible food [7–10]. As a result, only 12% of the 36% of the global calories used for animal feed will ultimately contribute to human diets [6].

In 2011, the global water footprint (WF) of agricultural production was 8362 km³/year (80% green, 11% blue, and 9% grey) [11]. World water demand is expected to increase by 20%–30% between 2010 and 2050 [12]. Demand for land and water resources has increased significantly, and these resources are expected to be scarcer in the future. Efficient water management in agriculture is needed to meet the growing demand for food and reduce poverty and hunger in a sustainable manner. The question is how the world will feed the global population without further impacting the freshwater and ecosystems. Several researchers have advocated for sustainable intensification [10,13–16], dietary changes, and reduction of food waste and loss [17–19] to feed the world. A number of studies have shown the value of virtual water trade in global water saving, reducing water scarcity, and it will help to reduce the risk of water scarcity [20–23]. This paper provides a brief review of the WF of food production, the water demand for different food products and diets, and the WF of food loss and waste. Finally, the paper presents the unsustainability of the current crop production showing the contribution of the main crops and countries toward the unsustainable blue WF.

2. The Water Footprint of Food

2.1. The Water Footprint of Different Food Products

Many global studies have assessed the water needed to produce crops at a high spatial resolution [24–30]. Estimates of the global consumptive (green plus blue) WF of crop production range from 5938 to 8508 km³/year (Table 1). The differences in the WF estimates are due to differences in the modeling approach, input data, including climate and cultivated area, the number of crops and their specification, and the models used. In terms of product coverage, Mekonnen and Hoekstra [29] explicitly estimated the WF of 146 individual crops, while the other authors included 20 or fewer individual crops and grouped the rest of the crops into two or four major groups. Although the estimated future global WF related to crop production under climate and land use change [31] was within the range of the estimates for the current period, Huang, Hejazi, Tang, Vernon, Liu, Chen, and Calvin [31], projected that the WF under climate and land use change will crease by as much as 22%. The increase in the WF is particularly large for the blue WF, which will increase by 70% by 2090, due to expansion in global irrigated area.

About 86% of the consumptive WF of crop production was related to the production of crops that can be used directly for human food consumption [29]. The other 14% was for fodder crops, fiber, rubber, and tobacco. Some of the food crops, such as maize, rapeseed, palm oil fruit, soybeans, and sunflower, are also used for biofuel production. This will lower the total WF that is used for human food consumption.

The total WF related to the production of crops that are used for human consumption across the world is shown in Figure 1. The WF is very large in the Indus River Basin, most parts of India, Eastern China, the northeast of the US, the Nile delta in Egypt, the western part of Indonesia, and many countries in Europe. The pie chart shows the major countries with a large share of the total global WF. India, China, and the US account for 38% of the total global green, blue, and grey WF.

Table 1. Estimates of the consumptive water footprint (WF) of global crop production.

Study	Period	Products Coverage	Global Water Footprint Related to Crop Production (km ³ /year)		
			Green	Blue	Total
Hoekstra and Chapagain [32]	1997–2001	164 individual crops	5330	1060	6390
Siebert and Döll [24]	1998–2002	20 individual crops and 6 major groups	5505	1180	6685
Liu and Yang [25]	1998–2002	17 individual crops and 5 major groups	4987	951	5938
Hanasaki, Inuzuka, Kanae and Oki [27]	1985–1999	Assumed 1 major crop per grid	5550	1530	7080
Fader, Gerten, Thammer, Heinke, Lotze-Campen, Lucht and Cramer [28]	1998–2002	12 crop functional types	6000	923	6923
Mekonnen and Hoekstra [29]	1996–2005	146 individual crops	5771	899	6670
Rost, Gerten, Bondeau, Lucht, Rohwer and Schaphoff [30]	1971–2000	12 crop functional types	7250 ¹	600–1258	7850–8508 ¹
Huang, Hejazi, Tang, Vernon, Liu, Chen and Calvin [31]	1971–2000		4887	1121	6008
	2071–2099	12 crop categories	5440	1909	7349

¹ Total evapotranspiration from cropland, including the non-growing period.

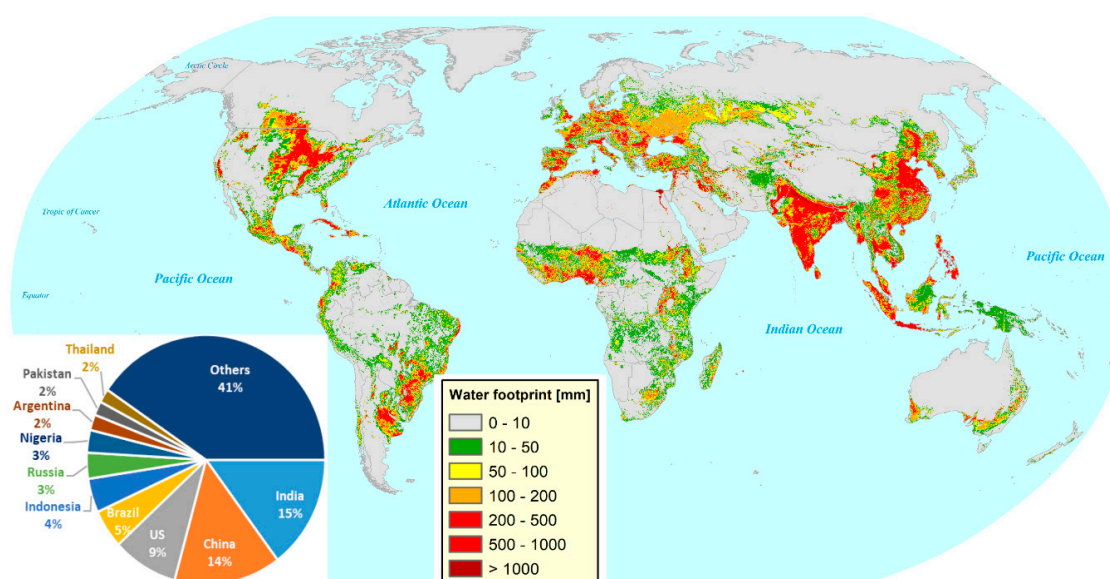


Figure 1. The total (green, blue, and grey) WF of food crops production. The WF of fiber crops, rubber, tobacco, and fodder crops is excluded. The pie chart shows the contribution of countries to total WF. Data source from Mekonnen and Hoekstra [29].

The first estimate of the WF (cubic meter per tonne of crop) for 38 crops for a large number of countries was done by Hoekstra and Hung [33]. That study was further improved by Hoekstra and Chapagain by including a large number of primary and processed crop and animal products [32,34–36]. Mekonnen and Hoekstra [29] estimated the green, blue, and grey WF (cubic meter per tonne of product) for 354 primary and processed crop products. The WF of the primary crops was done at 5 arc-minute spatial resolution. In 2012, Mekonnen and Hoekstra [37] estimated the WF (cubic meter per tonne of

product) for 106 animal products classifying the animal production into grazing, mixed, and industrial systems. Together, these databases are a rich source of data for other WF studies.

Figure 2 presents the WF of selected crop and animal products in terms of physical weight (L/kg) and nutritional energy content (L/kcal). The WF of food products differs significantly among crop and animal products. On average, the WF of animal food products is larger than the WF of crop food products with equivalent nutritional energy value. Especially, beef has a large WF, much larger than WFs of pork or chicken meat. However, animal feed of cows mainly consists of roughages from pasture land that are not human edible, while pigs and chickens consume crops from high-quality arable land that humans can also eat [37,38].

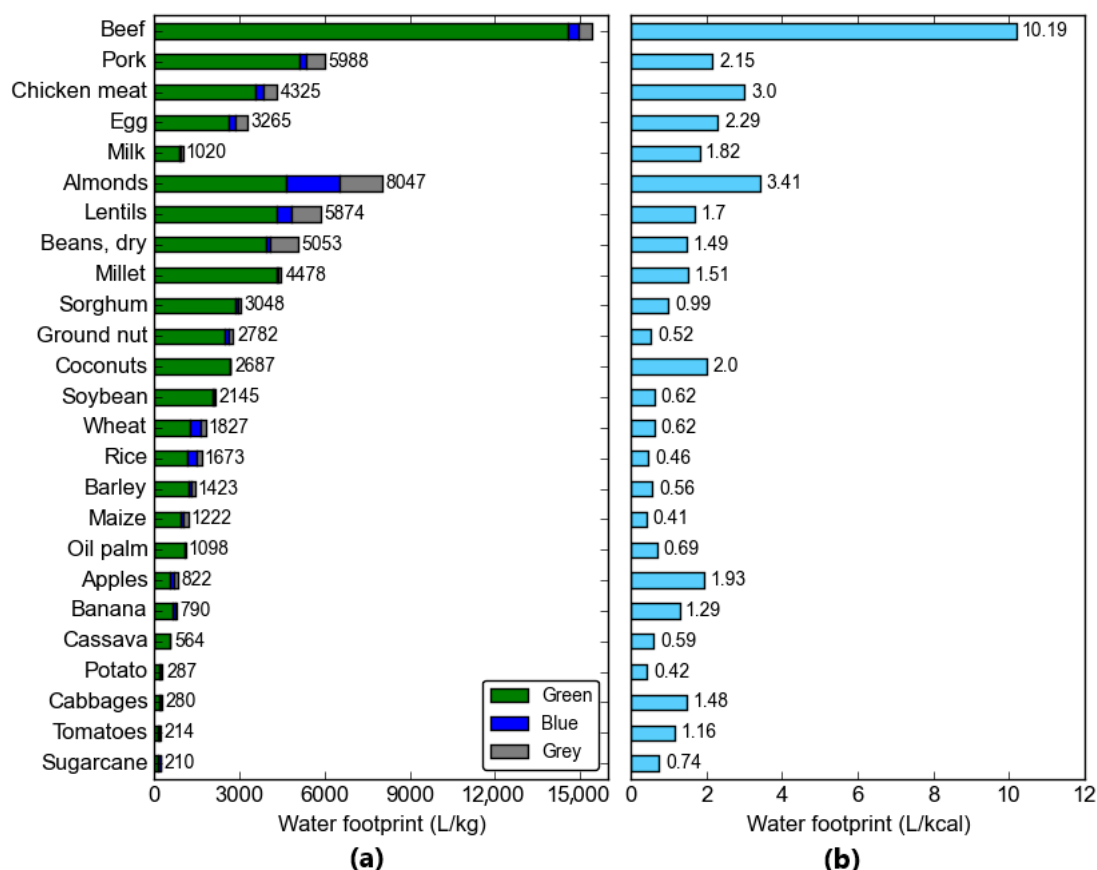


Figure 2. The WF of selected crop and animal products: (a) WF in a liter of water per kg of product, (b) WF in a liter of water per kcal of nutritional energy contained in the product. Data source from Mekonnen and Hoekstra [29] and Mekonnen and Hoekstra [37].

The first attempt to systematically quantify the WF of aquaculture was made by Pahlow et al. [39]. The study showed that the average WF of commercially fed fish was 1974 m³/tonne (83% green, 9% blue, and 8% grey). The study points out that aquafeed production could place considerable pressure on the water system in the form of water consumption and pollution. These pressures on the freshwater system from aquafeed production should be taken into account in order to develop aquaculture more sustainably.

2.2. The Water Footprint of Different Diets

In the next decades, the global demand for animal and processed food products is expected to increase [16,40]. These dietary shifts will influence the water, energy, land, and carbon footprints of people. The recent FAO and WHO report defines Sustainable Healthy Diets as “... dietary patterns that promote all dimensions of individuals’ health and wellbeing; have low environmental pressure and impact;

are accessible, affordable, safe and equitable; and are culturally acceptable" [41]. The document further underlines the need for national food-based dietary guidelines to take the social, cultural, economic, ecological, and environmental circumstances of the country into consideration.

A large number of studies suggested that a healthy diet with reduced amounts of animal-based food products will have a corresponding benefit in terms of reducing environmental impacts and resource use [18,40,42–49]. Hoekstra was among the first that studied the effect of diet on the WF of consumption [42,43]. On average, the WF of animal food products is much larger than WFs of crop food products with equivalent nutritional energy value, as shown by Mekonnen and Hoekstra [37]. The average WF per calorie for beef was 20 times larger than for cereals and starchy roots. Per unit of protein, the WF of beef was 6 times larger than the WF of pulses. Therefore, replacing animal-based food products with the nutritionally equivalent plant-based products will reduce the WF of consumption. Hoekstra [43] showed that replacing meat-based diets by nutritionally equivalent plant-based diets would reduce the overall WF of consumption by 36% in industrial countries and by 15% in developing countries. Vanham, Mekonnen, and Hoekstra [47] showed that the WF of EU28 food consumption will reduce by 23% by shifting from current to healthy and by 38% to vegetarian diets. The WF reduction was mainly due to the reduction in the consumption of meat. In another similar study, Vanham, Hoekstra, and Bidoglio [48] showed that replacing the current diets with vegetarian diets would reduce the WF of consumption by 27% to 41% for different regions of EU28. In a more comprehensive global study covering 140 countries, Kim, Santo, Scatterday, Fry, Synk, Cebron, Mekonnen, Hoekstra, de Pee, Bloem, Neff, and Nachman [46] assessed the WF of 9 increasingly plant-based diets that aligned with the criteria for a healthy diet. The result showed that plant-based diets with modest amounts of low-food chain animals (i.e., forage fish, bivalve mollusks, insects) had relatively small WFs compared to exclusively plant-based (vegan) diets. However, the magnitude of changes in the WF varies widely from country to country due to variations in dietary changes, patterns of reference consumption, trends in food imports, and the water intensity of food products. The findings underscore the importance of trade, culture, and nutrition in the analysis of the WF of dietary patterns.

Healthy diets, however, do not always reduce the WF of consumption, especially if animal products are replaced by foods such as fruits and pulses with relatively large WFs [44,50–52]. Dietary recommendations should, therefore, aim to promote a healthy diet with minimal environmental impacts. In addition, these studies underscore the importance of dietary management and improving nutritional water productivity in order to decrease the pressure on water resources.

2.3. Water Lost with Food Loss and Waste

The world is paying more attention to the problem of food loss and waste, as reflected in Target 12.3 of the Sustainable Development Goals (SDGs), which calls for the per capita global food waste to be halved by 2030. FAO's 2019 report on the State of Food and Agriculture was fully dedicated to the issue of food loss and waste, further underpinning the importance of addressing the issue [53,54]. Approximately one-third by weight and one-quarter by calories of food produced globally for human consumption was lost or wasted in 2009 [55,56].

Reducing food loss and waste will help to improve food security and alleviate the pressure on natural resources that have been used to produce it. Kummu, de Moel, Porkka, Siebert, Varis, and Ward [19] estimated that the WF of food loss and waste was 215 km³/year or 12%–15% of the global consumptive WF. Approximately three-quarters of the WF of food loss and waste is related to cereals and fruits and vegetables. Mekonnen and Fulton [50] found that reducing food loss and waste in the US food system was more effective than shifting from current to vegan or vegetarian diets to reduce the WF of consumption.

3. From Quantification to Sustainability Assessment

Over the last few years, the assessment of WFs of national consumption and production has shown significant improvement in terms of product coverage, spatial and temporal detail, and sustainability

assessment [57]. Hoekstra and Hung [33] were the first to estimate the WF of national consumption of 38 crops for a large number of countries. The second global assessment made a number of improvements in terms of product coverage by including all crops and livestock products and other refinements [32,36]. The third global study made further refinements by assessing the national water footprints of production and consumption at a high spatial and temporal resolution [11,58]. In addition to the global studies on the WF of crop production mentioned earlier [24–29,59], other national [60–64], regional or basin [65,66], and global studies [28,67] have also traced and mapped the WF of consumption per country, but none of these studies assessed the sustainability of the blue WF of consumption at the place of production. The blue WF is unsustainable if it is above the available renewable blue water and violates the environmental flow requirements.

Van Oel et al. [68] carried out the first assessment of the sustainability of the WF in relation to Dutch consumption. In a case study for France, Erclin et al. [69] assessed the sustainability of the WF of consumption of France, identifying priority basins and products. Hoekstra and Mekonnen [70] assessed the sustainability and water-use efficiency of the UK's WF of consumption. There are more recent works that have assessed the unsustainable blue WF of consumption for a single country or EU as a whole [71,72]. A few studies have assessed the sustainability of the WF of crop production and virtual water flows at a global level [73–75]. Other studies focused on sustainability of groundwater use [76–80].

In a more detailed global study, Mekonnen and Hoekstra [81] estimated that 513 km³/year, or 57% of the blue WF, related to crop production, was unsustainable. Approximately 75% of the global unsustainable blue WF is related to the production of only six crops (Figure 3a). These are wheat, rice, cotton, sugar cane, fodder, and maize. Five countries account for about 70% of the unsustainable blue WF (Figure 3b), India, China, the US, Pakistan, and Iran. Of the total unsustainable blue WF, 90% was for food and fodder crops, while only 10% was for fiber crops, rubber, and tobacco. Figure 4 shows the sustainable and unsustainable blue WF for global cereal production. The unsustainable portion of the blue WF is large in the Indus and Ganges river basins in India and Pakistan, in the north-eastern part of China, and in the US. High Plains aquifer. The study also showed that some 25% of global blue water can be saved by reducing the WF of each crop to the benchmark level.

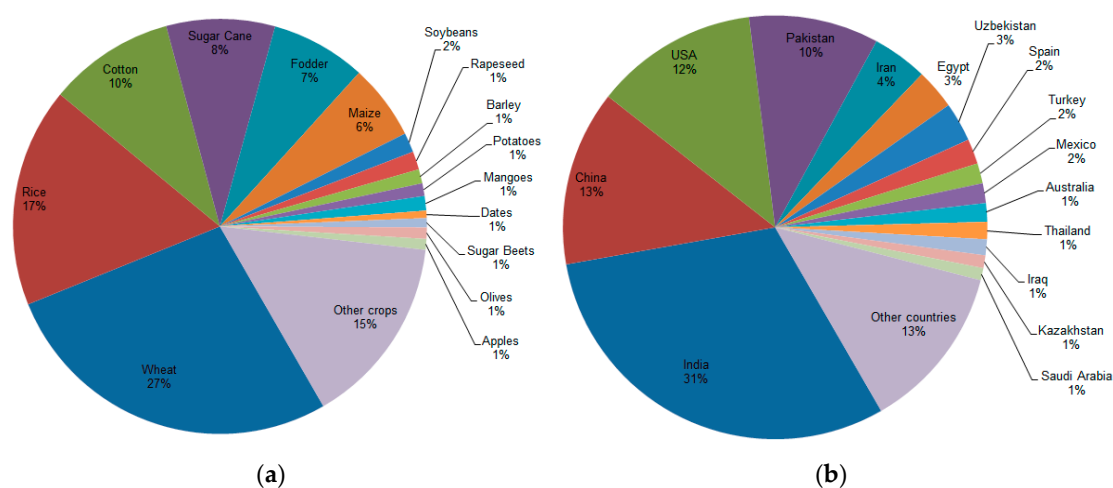


Figure 3. The unsustainable blue WF related to crop production: (a) Contribution of different crops toward the global blue unsustainable blue WF of crop production; (b) location of the unsustainable blue WF of crop production. Data source from Mekonnen and Hoekstra [81].

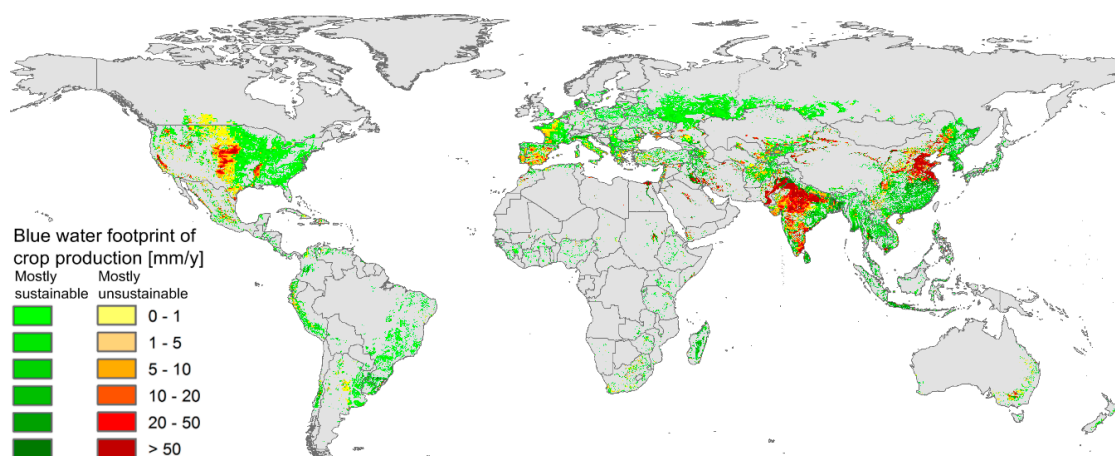


Figure 4. The sustainable (green) and unsustainable (yellow to dark red) parts of the blue WF of global cereals production. Data source from Mekonnen and Hoekstra [81].

4. Discussion

This paper provided a brief review of the WF of food production, the WF of different diets, and the volume of water lost due to food loss and waste. It also showed that global crop production leads to unsustainable use of blue water. Many regions of the world experience high water scarcity, depletion of groundwater, and deterioration of water quality [78,82,83]. In addition, the global WF associated with crop production is rapidly increasing, driven by growing demands for food and energy due to population growth, dietary changes, and increased per capita consumption. Changes in climate and land use will further put additional pressure on the available water resources [31].

We need to reduce the WF in many parts of the world to improve the sustainability of global water use. No single measure is a panacea for the global water problem. A combination of technological, behavioral, and policy instruments is needed. To this end, Hoekstra [84] has proposed three pillars under wise water allocation: (i) Setting upper limits on the WF per river basin; (ii) setting WF benchmarks per product; and (iii) fair WF shares per community. In a recent global study, Hogeboom et al. [85] estimated monthly blue WF caps that can be used by humans for all river basins in the world. In a case study for the Yellow River Basin, Zhuo et al. [86] assessed the role of reservoirs in the monthly blue WF caps in the basin. Mekonnen and Hoekstra [87] have made the first attempt to set a WF benchmark for all crops produced in the world. The study showed that the global consumptive WF can be reduced by as much as 39% by lowering the WF of all crops to the respective WF benchmarks. In a case study for wheat produced in China, Zhuo et al. [88] showed the value of setting the WF benchmark for the different climate conditions. Improving the water productivity of crop production through soil and water management, in combination with improved crop breeding, is one of the most effective measures to reduce the WF and keep it below the benchmark level [89–91]. Changing the pattern of consumption and reducing food losses and waste is another effective measure to reduce the pressure on water systems [17–19,47,49,50,92]. Virtual water trade from water abundant and highly productive regions to regions with limited water resources will help to reduce the risk of water scarcity and trespassing the environmental flow requirement. Economic valuation also needs to be integrated with the assessment of water footprints and virtual water flows in order to allocate water efficiently on a global scale [93,94].

5. Conclusions

Agricultural production is the main consumer of water, especially the production of animal foods, which have large WFs. Of the meat types, beef has the largest WF, WFs of pork and chicken meat are smaller. In general, vegetarian diets have smaller WFs. However, some foods of vegetal origin also have relatively large WFs, e.g., almonds or lentils. If more sustainable diets are promoted,

it is important to take these WFs into account. For most foods, WFs are dominated by the green WFs, while blue and grey WFs are much smaller. However, the blue and grey WFs have a large environmental impact. Of the total global blue WF, 57% is unsustainable. This unsustainable footprint is dominated by only six crops, wheat, rice, cotton, sugar cane, fodder, and maize, and are located in only five countries, India, China, the US, Pakistan, and Iran. Population growth and dietary shifts, e.g., larger meat consumption, is expected to increase demand for water. The estimated global WF ranges from 5938 to 8508 km³/year, increasing by as much as 20% to 30% between 2010 and 2050. To improve sustainable water use, Hoekstra has proposed (i) to set an upper limit on the WF per river basin; (ii) set WF benchmarks per product; and (iii) define fair WF shares per community. In combination with virtual water trade and economic valuation, these measures will help to avoid unsustainable water use.

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