Water **2014**, *6*, 1435-1452; doi:10.3390/w6051435

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Article

Global Changes and Drivers of the Water Footprint of Food Consumption: A Historical Analysis

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Received: 12 January 2014; in revised form: 12 May 2014 / Accepted: 13 May 2014 / Published: 22 May 2014

Abstract: Water is one of the most important limiting resources for food production. How much water is needed for food depends on the size of the population, average food consumption patterns and food production per unit of water. These factors show large differences around the world. This paper analyzes sub-continental dynamics of the water footprint of consumption (WF_{cons}) for the prevailing diets from 1961 to 2009 using data from the Food and Agriculture Organization (FAO). The findings show that, in most regions, the water needed to feed one person decreased even if diets became richer, because of the increase in water use efficiency in food production during the past half-century. The logarithmic mean Divisia index (LMDI) decomposition approach is used to analyze the contributions of the major drivers of WF_{cons} for food: population, diet and agricultural practices (output per unit of water). We compare the contributions of these drivers through different subcontinents, and find that population growth still was the major driver behind increasing WF_{cons} for food until now and that potential water savings through agricultural practice improvements were offset by population growth and diet change. The changes of the factors mentioned above were the largest in most developing areas with rapid economic development. With the development of globalization, the international food trade has brought more and more water savings in global water use over time. The results indicate that, in the near future and in many regions, diet change is likely to override population growth as the major driver behind WF_{cons} for food.

Keywords: food consumption; water footprint; global analysis; decomposition analysis; historical trends

1. Introduction

With population growth and economic development, water scarcity is more and more recognized as a major limiting role to sustainable development [1]. Currently, more than two billion people live in countries suffering from water stress [1]. Most of the water use is for food production [2]. With the world's population doubling every 40 years, there is a growing concern that there is not enough water for humanity to meet its food requirements [3–6].

The amount of water requirements for food depends on population numbers, the food consumption patterns and the food water productivity (*i.e.*, the production practices factor). These factors show large temporal and spatial variation. Population growth rates decline [7] and diets become richer within economic development; typically, consumption of vegetable oils and animal products increases, while starchy staples, such as cereals, become less important [8]. To produce one kilogram of animal product requires more water than to produce an equivalent mass of cereals. For example, the global average water needed to produce 1 kg of beef (15.4 m^3) is nearly 10 times larger than cereals (1.6 m^3) [9]. The amount of water a human being "eats" each day depends on food consumption patterns. Conversely, the development of agricultural technologies leads to improvements in yields and a reduction in water use [10–14]. This brings water savings indirectly. In addition, international trade can bring water savings. The international trade of agricultural products makes water resources flow between regions. According to the theory of comparative advantage, nations can gain from trade if they concentrate or specialize in the production of goods and services for which they have a comparative advantage, while importing goods and services for which they have a comparative disadvantage [15]. The trade relationship brings water savings if it is directed from a relatively more to a relatively less water-efficient country [16].

The indicators of water footprint (*WF*) and virtual water (VW) are used to analyze the link between human consumption and the appropriation of the globe's freshwater [17–19]. Many recent studies have linked the *WF* (or VW) of consumption with specific diets [20–25], including both local consumption [24,25] and internationally traded goods [16,26,27]. The evolution of the global virtual water trade network is linked to population, trade policies, socioeconomic circumstances, agricultural efficiency [16] and land requirements for food [26,28]. However, there is no comparison of the trends of the regional water footprint for food.

This study mainly assesses the changes of *WF* for food in different regions from 1961 to 2009 and the driving factors. We first describe the trends of total *WF* and per capita for food and analyze the differences across subcontinents and time. The logarithmic mean Divisia index (LMDI) decomposition method is used to quantify the influence of changes in drivers (population, diet and agricultural practices) on developments in *WF* for food, respectively. In order to evaluate the role of international trade in global water use, we also simply analyze the trends of global water savings caused by the international trade of agricultural products from 1961 to 2009.

2. Materials and Methods

2.1. Water Footprint

In this study, the definitions of *WF* are taken from the Water Footprint Network's Global Water Footprint Standard [29]. WF_{prod} is the sum of the water use of domestic water resources. WF_{cons} is defined as the total volume of freshwater that is used to produce the goods consumed by its inhabitants [22]. *WF* consists of three (green, blue and grey water) components. The *WF* of a crop (WF^{*}_{prod}) is generally calculated by dividing the consumptive water use (or the crop evapotranspiration during the crop growing period, in m^3/ha) with the crop yield (in kg/ha) [17], namely $WF^{*}_{\text{prod}} = ET/Y$. The WF^{*}_{prod} of a live animal consists of different components: the indirect water footprint of the feed and the direct water footprint related to the drinking water and service water consumed (e.g., the water used to clean its housing) [9].

The average WF^{*}_{prod} values for the main food items in different regions for the years around 2000 are aggregated basing on Mekonnen and Hoekstra's work [9,17]. All values are provided in the supporting information. For different food items, the WF^{*}_{prod} has a significant difference. Generally, animal products, pulses, nuts and oil crops have relatively high WF^{*}_{prod} values compared to other food items. Particularly, beef has the highest WF^{*}_{prod} of all food items in most regions. In contrast, sugar crops and vegetables have the lowest WF^{*}_{prod}. The WF^{*}_{prod} values of cereals are between 637 and 4658 m^3/ton. Moreover, WF^{*}_{prod} varies across different production regions, as well. This is mainly due to the differences in crop yields and evapotranspiration, which is largely caused by agricultural practices and management and climatic conditions. The WF^{*}_{prod} of cereal crops for Northern Europe (637 m^3/ton) and Western Europe (654 m^3/ton) were relatively small. In contrast, and with the exception of Southern Africa, the WF^{*}_{prod} of cereal crops is quite large in most parts of Africa, almost 3–4 times or even more than in most parts of Europe, which can largely be explained by the higher average yield in Europe (3.4 ton/ha; data from FAO [30]) compared to that observed in Africa (1.3 ton/ha; data from FAO [30]).

According to the definition of WF^{*}_{prod} (WF^{*}_{prod} = ET/Y), evapotranspiration and yield data are both needed. Time series of regional crop yield are obtained from FAOSTA. The ET values are merged from Zhang *et al*. [31,32] (1983–2000) and the MODIS Evapotranspiration Data Set [33] (2000–2009). The ET values from 1961 to 1982 were kept at a constant value of the year 1983, because of limitations of the data. The changes of cropland area, irrigated area and crop type distribution were not accounted for [34–36]. Thus, the WF^{*}_{prod} of crops was changed according to the regional crop yield and the *ET* time series:

$$WF_{i,c,n} = WF_{i,c,2000} \times \frac{Y_{i,c,2000}}{Y_{i,c,n}} \times \frac{ET_{i,n}}{ET_{i,2000}} \tag{1}$$

In this equation, the subscripts, *i*, *c* and *n*, correspond to the considered region, crop and year, respectively. $WF_{i,c,n}$ is the estimated WF^{*}_{prod} of crop *c* in country *i* for year *n* (*n* = 1961−2009); *Y* is the yield of crop *c* in the region *i* and year *n*; *ET* is the average value of land surface evapotranspiration in the region, *I*, and year *n*; and $WF_{i,c,2000}$ is the WF^{*}_{prod} from Mekonnen and Hoekstra's work [9,17] for the year 2000.

As for estimating the WF^*_{prod} of animal products in a time series, this is more complex: these WF^*_{prod} changes primarily depend on the WF^*_{prod} of the feed crops [9], but also on (among others) the conversion efficiency, farming techniques and livestock species. Some animals, such as pigs and chickens, largely rely on grain feed (mainly maize and soy, *etc*.), while animals, such as goats and beef, mainly feed on grassland [37,38]. It is expected that the yield of grasses is mainly affected by local climate and soil conditions and not significantly influenced by technological innovations [20]. In this study, we estimate the WF^*_{prod} of pork, poultry and eggs based on the average yield of maize and soy. The WF^*_{prod} values of all other animal products are assumed constants over time.

2.2. Water Footprint of Consumption

We used the methodology from Kastner *et al*. [26], which is used for the land requirements for food, to estimate the sub-continental dynamics of the water footprint of consumption (WF_{cons}) for the prevailing diets from 1961 to 2009. The methodology is summarized below.

Food supply data, which supplied by FAO [30], were a starting point for the analysis. These data cover most countries of the world over the 1961–2009 period. According to FAO, the values are not equal to actual food intake, because they include other items, such as losses during transportation and storage [26]. However, from a nutritional perspective, they are still well suited for cross-regional comparisons [39]. For all food items, we linked food supply data to water footprint of consumption (WF_{cons}) through WF^*_{prod}.

We used region-specific WF^*_{prod} to assess WF_{cons} in a given subcontinent. Region-specific WF^*_{prod} was the average of countries' WF^*_{prod} in the region; the weighted production of all countries in the region. In addition, we also considered the role of international trade: food consumed in one region can be partly from imports. We divided the amount of a particular food available in an area into two parts: imports and domestic production. The domestic production part was linked to the domestic WF^*_{prod}. For the import part, we used average world trade WF^*_{prod}; the weighted average of all exporting countries' WF^*_{prod} of the particular food, based on the amount of exports. These average world trade *WF*s will be unlike the global average WF^*_{prod} if the WF^*_{prod} of the main exporting nations have a difference with those of non-exporting, major-producing countries. The trade data in FAOSTAT includes intraregional and interregional trade.

FAOSTAT provided food supply data of more than 70 items [26]. We summarized all food into 12 categories: cereals, starchy roots, spices, pulses, vegetables, fruits, sugar and sugar crops, oil crops and vegetable oils, alcoholic beverages, tree nuts, stimulants and animal products. Animal products included beef, mutton, poultry, pork, animal fats, eggs and milk. According to FAO data, these species accounted for more than 95% of the entire daily consumption of animal products. The world is divided into 18 world regions, according to the regional classification of the United Nations Statistics Division [40]. Because the Soviet Union (USSR) collapsed in 1991, FAOSTAT allocated part of the population of Eastern European to other areas after this year. To enable the consistency of population data in time series, we corrected relevant population data based on their respective population shares. Therefore, all states of the former USSR are exclusively accounted in Eastern Europe in our study. Detailed information on classification of countries and food items are provided in the supporting information.

The whole work is primarily a statistical data analysis using the following data sources:

a) Data on WF^{*}_{prod} (period 1996–2005) of specific products from Mekonnen and Hoekstra's work [9,17];
b) Data on food consumption, production, trade and crop yield (period 1961–2009) from FAO [30];
c) Data on land surface evapotranspiration from the work of Zhang *et al*. [29,31] (1983–2006) and MOD16 [33] (2000–2009).

2.3. Decomposition Analysis

To assess the contributions of the population, diet and agricultural practices to the changes of the total water footprint of consumption (WF_{cons}), the LMDI decomposition analysis is used in this study. The LMDI decomposition method is the preferred method in various index decomposition analysis methods and is commonly used in energy studies to assess the drivers of change in energy consumption [41]. It was used in the work of Kastner *et al*. [26]. The similar application to changes in WF_{cons} for food can be used, and the following identity is set as the input for the method:

$$WF_{\text{cons}} = \text{capita} \times \frac{\text{kcal}}{\text{capita}} \times \frac{\text{m}^3}{\text{kcal}} \tag{2}$$

This equation indicates that WF_{cons} is the result of population, the water needed per unit of food output in calories (which can be considered as the agricultural practice factors: agricultural technology, nutrient, pesticides input, land management, *etc*. [19]) and per capita food consumption levels (which can be considered as the diet factor). Considering that food categories differed in WF changes and that various diets have different effects on WF_{cons}, the latter two items in the above equation were divided into 12 food categories, as mentioned above. Values for 1963, 1985 and 2007 in this article refer to 5-year means for 1961 to 1965, 1983 to 1987 and 2005 to 2009, respectively.

2.4. Water Savings through Trade

We use Chapagain's method to evaluate global water savings caused by the international trade of agricultural products [15]. This method is summarized below.

The national water saving, $WS_{n,p}$ (m^3/y), of a country, n, as a result of the trade of product p is defined as:

$$WS_{n,p} = WF_{n,p} \times (I_{n,p} - E_{n,p}) \tag{3}$$

where $WF_{n,p}$ is the water footprint (m^3/ton) of the product, p, in country n, $I_{n,p}$ is the amount of product p imported (ton/y) and $E_{n,p}$ is the amount of product p exported (ton/y).

The global water savings, $WS_{i,j,p}$ (m^3/y), through the trade of a product, p, from an exporting country, i, to an importing country, j, are defined as:

$$WS_{i,j,p} = T_{i,j,p} \times (WF_{j,p} - WF_{i,p}) \tag{4}$$

where the subscripts, i, j and p, correspond to the exporting country, the importing country and the commodity traded, respectively. The term, T, is the volume of commodity p traded from exporting country i to importing country j, and WF is the water footprint of commodity p in each country. The WF of commodity p in non-growing countries is set as 0.

The total global water savings of product p can be obtained by summation of the global savings of all trade relationships, that is:

$$WS_p = \sum_{(i,j)} WS_{i,j,p} \tag{5}$$

The term, WS_p, can have a negative sign, which indicates a net water loss instead of savings. By definition, the total global water savings of product p is also equal to the sum of the national savings of all countries, that is:

$$\sum_{(i,j)} WS_{i,j,p} = \sum_{n} WS_{n,p} \tag{6}$$

For simplicity, we use the subcontinent values instead of national values in this study to calculate the total global water savings and aggregated WS values for the 12 commodity base product categories, as mentioned above.

3. Results and Discussion

3.1. Global Changes in Food Supply and WF_{cons} for Food

Figure 1 shows the composition of the world regions used in this study. The world is divided into 18 sub-continents according to the FAO definition. The main results of regional WF_{cons} for food are depicted in Figure 2. Similar to the land required for food analysis in Karstner *et al*. [26], we only present the diet, per capita and total WF_{cons} for food. The upper rows of Figure 2 show changes in food supply per person throughout the world from 1961 to 2009, according to the FAOSTAT food supply data. The middle rows show the amount of water needed to provide this food supply; that is, the water required to feed one person in one year (in m^3 per capita and year). The lower rows depict the total WF_{cons} for food in the respective regions (in km^3 per year), accounting for all population.

Although the changes of diet have been presented in Kastner *et al*. [26], we still simply discuss it for readers to understand the link between diet and WF_{cons}. As for food supply at the global level, the general trend was a sustained growth in available food calories per person from 1961 to 2009 (from approximately 2180 to approximately 2820 kcal/capita/day). For different food categories, there are significant differences in the rates of change: the strongest increases of absolute value occurred in cereals, which is still the most important source of human energy supply. Following cereals, vegetable oils and animal products also had a significant growth. However, food categories of rich diets showed a higher relative increase (e.g., animal products, vegetables, fruits, stimulants and vegetable oils), compared with basic food items (e.g., cereals, roots and pules). This showed that a nutrition transition happened at the global level, in which people shifted towards more affluent food consumption patterns [39].

Figure 1. The world regions used in this study.

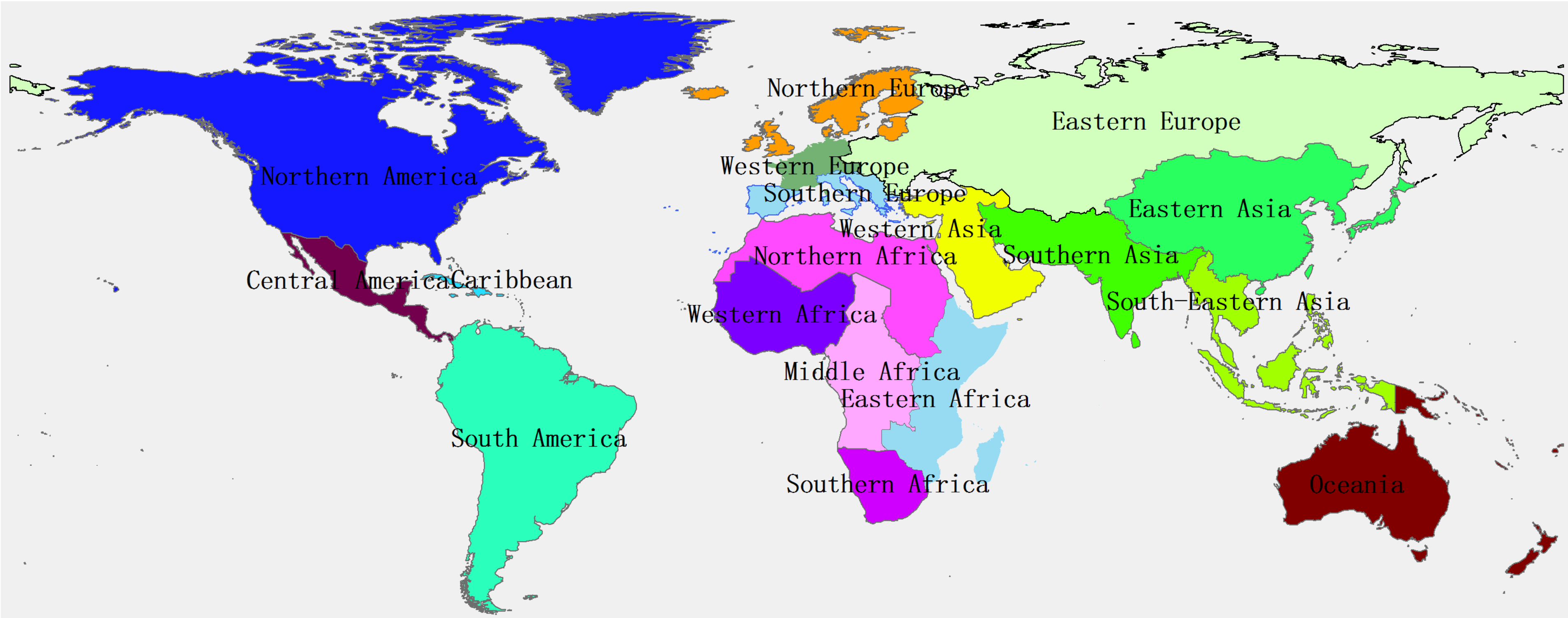
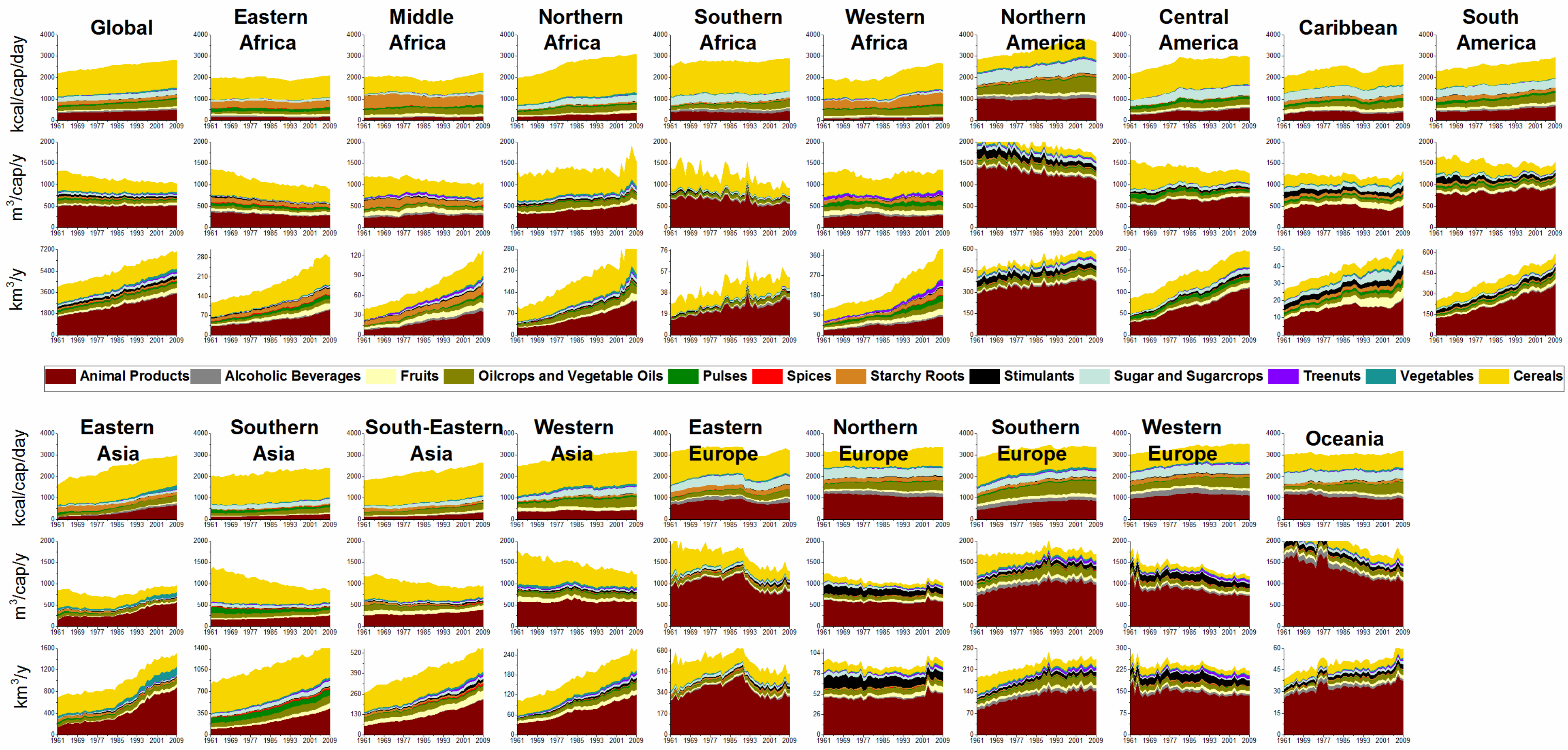


Figure 2. Global Changes in food supply and WF_{cons} for food. Changes in food supply (**top**, kcal/capita/day), per capita WF_{cons} for food (**middle**, m^3/capita/y) and total WF_{cons} for food (**lower**, km^3/y) at subcontinental levels from 1961 to 2009; the values are shown in 12 food categories.



The trends of the food supply had a significant difference in different regions. As for the total per capita food supply, not all regions experienced increases. In some developed regions, such as Oceania and Northern Europe, levels remained constant. While the poor regions, such as Middle Africa and Eastern Africa, had a very limited growth in their low levels of food supply. The highest growth rate was observed in East Asia, mostly due to the rapid increase in China. The relative composition of diets differs significantly between regions. In most less developed regions, cereals still occupied a large proportion of the diet, reaching more than 60% in the share of available food calories in Southern Asia. However, the proportion of cereals was decreasing throughout most developing regions, with the fastest decrease in East Asia. Most developed regions had a very high share of animal products: nearly one third of available food calories. While for many poorer regions, the same values were 10% or less. However, it is worth noting that a more than five-fold increase in the supply of animal food calories per capita occurred in Eastern Asia.

The middle rows show the amount of WF_{cons} for food supply shown in the upper rows. We found similar trends for water as the major trends for land in Kastner *et al*. [26] with differences in some regions. At the global level, the average water required to feed a person fell by nearly 23%, from 1335 m^3/person/y in 1961 to 1023 m^3/person/y in 2009. Cereals contributed most strongly to this decrease, dropping by more than half from 484 m^3/person/y in 1961 to 211 m^3/person/y in 2009. Most food categories had a decrease in the water required to feed a person, such as vegetable oils, pules and roots, while fruits showed slight increases, and animal products stayed relatively stable. The relative composition of food categories contributing to the per capita water footprint of consumption (CWF_{cons}) had significant changes during the study period, especially in cereals and animal products. Whereas cereals and animal products each accounted for 36% of the WF_{cons} in 1961, these values changed to 21% and 50%, respectively, in 2009. The animal products category accounted for the largest share of WF_{cons}. Across regions, CWF_{cons} was very low in most areas of Asia during the study periods. For the average CWF_{cons} from 2005 to 2009, the lowest value was 845 m^3/person/year in Southern Asia, followed by 931 m^3/person/year in South-Eastern Asia and 937 m^3/person/year in Eastern Asia. On the contrary, the highest values, with more than 1700 m^3/person/year, were found in Southern Europe and Oceania, two dry regions. It is noteworthy that Middle Africa and Northern Europe showed very similar CWF_{cons} values, at approximately 1030 m^3/person/year, while they had a large gap in terms of per capita food supply.

As a common feature, most subcontinents showed a decreasing CWF_{cons} during the study period, and cereals contributed most strongly to this decrease. This indicates that food production, especially cereal production, became more water-efficient throughout the globe. However, different regions showed significant differences in the rates of decrease. Southern Asia and Southern Africa showed the strongest relative decrease (more than 35%). The values of these two regions were relatively high at the start of the time period, and the diet in these two regions did not change much. On the contrary, almost no decline occurred in Northern Africa and Southern Europe, where a rapid diet change occurred. There was a pronounced trend from a decrease to an increase in Eastern Asia. The decrease was mainly due to crop water productivity, while the increase was due to a rapid diet change. The CWF_{cons} was dominated by food species linked to rich diets in developed areas. For example, the sum of animal products, alcoholic beverages, vegetable oils and stimulants accounted for approximately 70% to 80% of CWF_{cons} throughout Southern Europe, Western Europe, Oceania and North America.

The corresponding value was less than 40% in the poorest areas of Western, Middle and Eastern Africa.

Finally, the lower rows in Figure 2 show the total WF_{cons} for food, while taking into account the amounts of population in the respective regions. During 1961–2009, at the global level, a nearly 70% increase, from 4120 to 6978 km^3, could be observed. This was mainly driven by the growth of WF_{cons} for animal products, accounting for approximately 70% of the total increase. Fruits, vegetable oils and vegetables follow, contributing 8%, 6% and 5%, respectively. Nuts and spices revealed the largest relative increase through the half century, with 2009 levels more than triple the amount of those in 1961. In absolute numbers, only cereals showed a decrease, although pulses, as well as roots increased only slightly. In 2009, across the subcontinents, Eastern Asia had the highest WF_{cons}, followed by Southern Asia. There exist large differences in the trends of WF_{cons}: in some regions of Africa, WF_{cons} almost tripled, while in developed regions, WF_{cons} showed limited increases or even slight decreases. As a result, the share of North America, Europe and Oceania in global WF_{cons} decreased from 39% in 1961 to 24% by 2009.

3.2. Contributions of Population, Diet and Agricultural Practices to Changes in WF_{cons}

Figure 2 shows the impacts of diet change, agricultural practices change and population growth on WF_{cons} for food. In order to quantify these effects in more detail, we used the logarithmic mean Divisia index (LMDI) decomposition method [41] to assess the contributions of three major drivers for all regions over three time periods (1963–1985, 1985–2007 and 1963–2007). The result of the decomposition analysis for the whole world and the different regions is shown in Table 1; WF_{cons} values in 2007 are displayed in Table 1 to allow for a reference to relative changes.

At the global level, the effects of agricultural practice improvements did not offset that of changes in diets and the growth of population: global WF_{cons} increased by 2633 km^3, or approximately two fifths of the 2007 value, during 1963–2007. Population growth still was the main driving factor behind growing water demand. However, regional results show great differences from the global average. In many regions, water demand increased much faster, with numbers more than doubling during 1963–2007. The largest relative increases occurred in African regions, except Southern Africa. In most regions of Europe, WF_{cons} remained constant or even declined, because of minor changes in diets, relatively slow population growth and agricultural practice improvements. The impacts of diet change exceeded population growth impacts in Southern Europe and Eastern Asia, areas with fast economic development. Comparing two halves of the study period indicates that, at the global level, the impact of population growth declined, while diet change impact increased: diet change contributed 25.3% to the sum of contributions of population and diet change from 1963 to 1985; this value increased to 35.0% from 1985 to 2007.

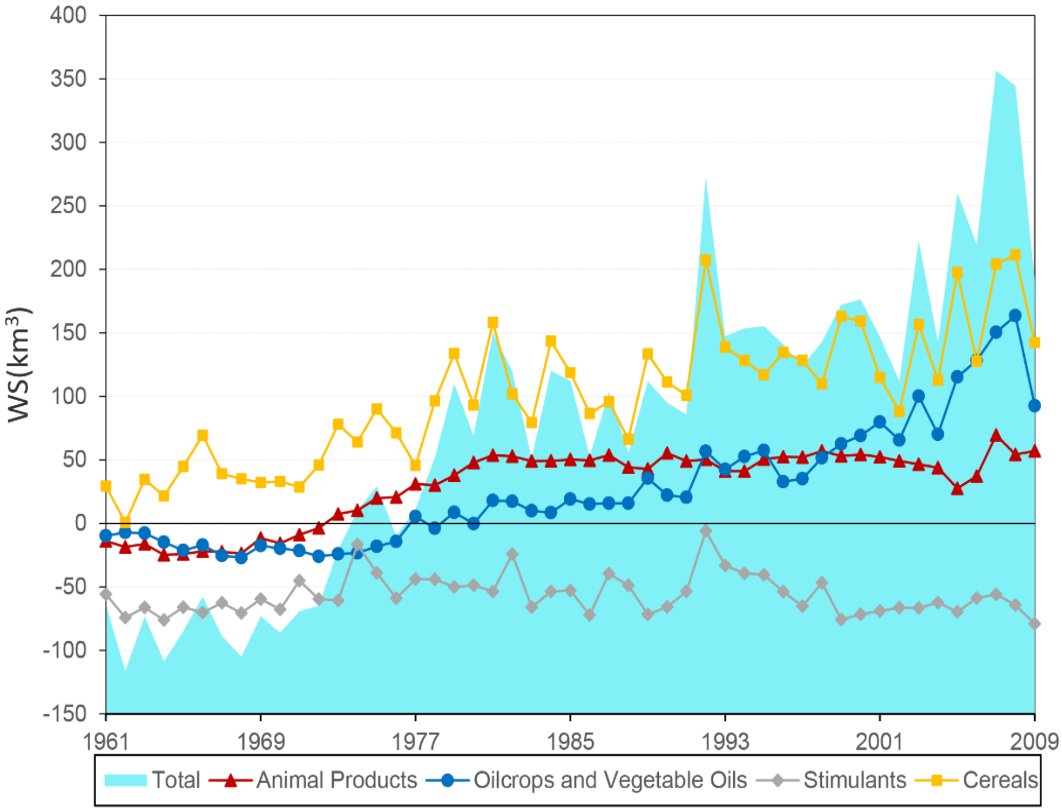
Table 1. Decomposition analysis according to the contributions of diet, agricultural practices and population to changes in WF_{cons}. Changes in WF_{cons} (Δtot) and the contributions of changes in diet (Δd), agricultural practices (Δap) and population (Δp) are presented in the table. Values were derived based on data presented in Figure 2 using the logarithmic mean Divisia index (LMDI) decomposition method; following the WF_{cons} in 2007, the results are presented for three time periods: 1963–1985, 1985–2007 and 1963–2007. All values are presented in km^3 per year.

Regions	WF_{cons}	1963–1985				1985–2007				1963–2007			
	2007	Δp	Δd	Δap	Δtot	Δp	Δd	Δap	Δtot	Δp	Δd	Δap	Δtot
World	6954	1982	671	−1494	1158	1935	1041	−1405	1571	3969	1629	−2868	2730
Eastern Africa	283	91	−5	−32	54	132	8	−32	109	230	2	−69	163
Middle Africa	120	31	4	−6	28	58	8	−15	52	89	12	−21	79
Northern Africa	332	75	43	−31	87	105	40	9	154	185	92	−36	241
Southern Africa	54	23	0	−4	19	21	5	−22	4	40	3	−21	23
Western Africa	370	82	29	−48	63	149	78	−39	188	247	133	−128	251
Northern America	579	109	24	−79	53	124	48	−106	65	232	73	−187	118
Central America	195	66	38	−47	57	64	23	−36	51	126	61	−80	107
Caribbean	50	12	6	−6	12	11	0	−1	10	23	7	−7	23
South America	552	165	23	−59	129	161	115	−114	162	330	124	−164	290
Eastern Asia	1453	327	745	−904	167	230	616	−285	561	602	1445	−1319	728
Southern Asia	1428	503	317	−563	257	534	178	−395	317	1029	548	−1004	573
South-Eastern Asia	539	178	74	−125	128	166	178	−214	129	338	223	−305	257
Western Asia	249	85	26	−45	65	113	8	−43	78	194	38	−88	144
Eastern Europe	514	122	96	−160	58	9	−58	−93	−142	115	37	−236	−83
Northern Europe	96	6	0	−17	−10	8	13	−9	12	15	14	−27	2
Southern Europe	245	31	67	−59	39	19	29	−30	18	50	92	−84	57
Western Europe	226	23	48	−92	−21	20	−6	−28	−13	43	41	−119	−34
Oceania	59	18	−2	−6	10	18	0	−10	9	35	−2	−15	19

3.3. Global Water Savings through Trade over Time

Figure 3 shows the global water savings through trade from 1961 to 2009. The shaded area shows the total global water savings from the trade of crops and animal products. Individual lines show the global water savings associated with the trade of the particular crop. Figure 3 simply lists animal products, vegetable oils, stimulants and cereals that accounted for the main part of total global water savings. Other agricultural products had relatively small values. As for the total global water savings, the value shifted from negative to positive in the late 1970s and has increased approximately 100% from the late 1970s to the early 2000s. This means that the global agricultural products trade has gone through a transition from water loss to water savings. The categories contributing most to this increase were cereals, followed by animal products and vegetable oils, while the stimulant categories showed a slight change. This indicates that cereals are always the most important part of the agricultural trade. The value of water savings associated with the trade of animal products between 1986 and 2007 is close to the result in the work of Dalin *et al*. [16]. The strongest relative increase occurred in oil crops and vegetable oils: from −11 km^3 in 1963 to 102 km^3 in 2007, reflecting a greater efficiency of oil crops and vegetable oil trade in terms of global water use. The global water loss caused by the stimulant trade remained approximately 50 km^3 over time, nearly offsetting the global water savings associated with the trade of animal products since 1980. This most likely occurred because stimulant crops (e.g., coffee) can only be grown in specific areas. Imports of numerous non-growing countries resulted in water loss.

Figure 3. Global water savings through trade during 1961–2009. Global water savings through trade during 1961–2009. The shaded area shows the total global water savings from the trade of crops and animal products. Individual lines show the global water savings associated with the trade of the particular crop.



3.4. Discussion

The method we used above gives consistent comparisons of WF_{cons} for food among different regions at different times and reveals different drivers' impacts on changes. The results show similarities and differences between subcontinents. A common feature is that a decrease occurred in the average water needed to feed a person, with increasing food availability. While regions had large differences in diets, these variations in food supply have a great relevance to the differences in income levels [8,39,42]. On the contrary, differences in CWF_{cons} are not obviously linked to income levels. For example, CWF_{cons} in many areas of Africa was very similar to that in Northern Europe (approximately 1200 m^2/person/y). However, the diets in these two regions had a large gap. Large differences in the water productivity of agriculture can explain these similarities in WF_{cons}. The high technologic input agriculture in Northern Europe is more water-efficient than the cultivation means in many areas of Africa. The findings indicate an opportunity for improvements in the nutritional situation without increasing water demand (per capita). This opportunity is particularly large in the range of low crop yields, due to the current large losses in non-productive green water evaporation [43].

Among the food categories representing increasing water demand, the most important ones are animal products, representing nearly 70% of the additional WF_{cons} since the 1960s. Thus, animal products (especially meat) have been the focus as the pressure source on natural resources for food production, as well as the potentiality for reducing this pressure [44,45]. However, the category of stimulants (*i.e.*, coffee, tea and cocoa) is also worth examining. These items are consumed in a manner that is culturally based and hardly provide energy for humans. However, their demand on water is considerable within the food consumption patterns of Western Europe and Northern European nations, reaching approximately 10% of WF_{cons}.

Decomposition analysis indicates that diet change had a very strong impact on water demand in Eastern Asia, where the dynamics in China played the most important role. China has experienced rapid economic development in the past half-century, with per capita income increasing more than tenfold during 1961–2009 [46]. Numerous studies [47,48] have focused on how food consumption patterns changed in growing economies, like China. They have found a general pattern: with economic development, population growth rates decline, while per capita food supply increases, and thus, food consumption patterns change markedly [39]. Table 1 reveals that other developing regions also follow this pattern, at a slower pace. Comparing two halves of the study period, in most regions, the contribution of diet change to water demand increased; however, the contribution of population growth decreased. Another point worth noting is that some social unrest may change food consumption patterns, thereby effecting water demand. After the revolutions of Eastern Europe, per capita income declined in most regions of Eastern Europe [46], and diet change contributed to lower water demand.

As socioeconomic development increases, international trade is becoming increasingly important to food products. We found that in the late 1970s, global water savings represented less than 1% of the water used in agriculture, and this percentage increased to 3% in the early 2000s. Food trade is playing an increasingly important role in reducing global water use. International trade has a positive effect on global water savings when trade is directed from a relatively more water-efficient country to a less water-efficient country [16]. Before the 1970s, the reason for the value of global water savings being negative was that the water-waste trade (*i.e.*, trade relationships for which the importing country has a lower *WF*) volume was larger than the water-efficient trade (*i.e.*, trade relationships for which the importing country has a higher *WF*) volume. Over the next three decades, more water-efficient countries have been increasingly exporting to less efficient countries, resulting in the growth of global water savings. In general, global water savings from international trade are effected by three factors: the proportion of water-efficient relationships, the volumes of food traded through efficient trade relationships and the gap between the product *WF* in the importing country and the exporting country [16]. Future research on global water savings through international trade may focus on these three factors.

3.5. Limitations and Uncertainties

Key concerns about the analysis of global WF_{cons} for the prevailing diets are the uncertainty and limitations. As shown in Equation 1, the change of WF^{*}_{prod} is estimated by the value of WF^{*}_{prod} in

2000, crop yield and land surface ET. However, ET varies in different growing seasons with different crops. The calculation of ET is quite difficult. In Dalin's work, a detailed model has been used to assess the evolution of different crop ET [16]. However, as the input parameters of calculating different crop ET in Dalin's work, the detailed data of cropland area, irrigated area and crop type, are only available *circa* year 2000 [16], in our work, we calculated the dynamics of land surface ET (a rough proxy to present the climatological factors) to estimate the changes of WF_{cons}. After comparison, our estimates are close to the results of Dalin's work in the same period. Therefore, this rough method can be used in global analysis. In future work at a country level, detailed modelling studies should be used.

For the calculation of the WF^*_{prod} of animal products, we estimated the WF^*_{prod} based on the average yield of maize and soy. However, there are a lot of feed products still not accounted for, because of the limitation of data. In addition, we did not account for the changes in conversion factors for different livestock types, which lack detailed data and should be considered in future work.

The increase on yields is largely due to factors, such as pesticides and fertilizers [49]. This has led to a lot of water pollution, which, as a result, would lead to much higher grey water footprints. As such, the WF^*_{prod} decrease over the years would be offset to a certain extent by an increase in grey WF^*_{prod}. We did not take this into account, because of its complexity and uncertainty; therefore, the values for footprint of food consumption could be underestimated.

The accuracy of FAO's data on food production, consumption and trade has been questioned, especially for developing nations with a relatively high reliance on subsistence farming, whose products rarely enter the marketplace and are therefore difficult to account for [50,51]. Therefore, our analyses rely primarily on the dynamics of WF_{cons} rather than its absolute level. It is acceptable for a global or sub-continental scale study, as we discussed here. A regional- or country-level study would need more accurate data statistics.

Food consumption data is provided by FAOSTAT food supply, which includes retail and household losses. In developed countries, these losses can account for about 30% of the total supply [52]. We did not consider processing losses and seed use, due to the lack of accurate statistics; therefore, the results may be underestimated.

4. Conclusions

This paper analyzed the sub-continental dynamics of the amount of water needed to supply the prevailing diets from 1961 to 2009 using data from FAO. The findings show that, in most areas, diets became richer, while the water needed to feed one person decreased, because of the growth of water use efficiency in food production during the past half-century. The LMDI decomposition approach is used to measure the contributions of the main drivers of WF_{cons} for food: changes in population, diet and agricultural practices. We compared the contributions of these drivers through different subcontinents and found that potential water savings through agricultural practices improvements were offset by population growth and diet change. The changes of the factors mentioned above were the largest in most developing areas with rapid economic development. The results indicate that in the near future and in many regions, diet change is likely to override population growth as the major driver behind WF_{cons} for food. The analysis of global water savings through the international agricultural product trade shows that the international food trade is playing an increasingly important role in reducing global water use. The total global water savings shifted from negative to positive in the late 1970s and has increased approximately 100% from the late 1970s to the early 2000s.

Our findings provide support for assessments of future water demand. The majority of the world's population lives in developing regions, which are likely to play a very important role in increasing pressures on WF_{cons} in the coming decades. Until now, global population growth was the major driver behind water demand for food. While our analysis of past trends of WF_{cons} shows that socioeconomic development not only helps with the declining of the growth rate of population, but it also speeds up diet change. As diet changes affect a significant proportion of the global population, pressures on water resources related to food consumption are expected to remain high in the near future. Moreover, to increase water use efficiency in food production, pesticides and fertilizers were widely used. They all have significant environmental impacts. Future agricultural practices should focus on how to reduce damage to the environment.

Acknowledgments

The authors are really grateful for the technical support from Mesfin Mergia Mekonnen. The work was financially supported by the National Basic Research Development Program of China (Grant Nos. 2011CB952001 and 2010CB428502), National Science Foundation of China (Grant No. 41271542), Program for New Century Excellent Talents in University (Grant No. NCET-09-0227), the National High Technology Research and Development Program of China (Grant No. 2010AA012305) and the Fundamental Research Funds for the Central Universities.

Author Contributions

Xuefeng Cui and Chen Yang designed and performed research. Chen Yang carried out the calculation, result analysis and drafted the manuscript, which was revised by all authors. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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