Paddy and Water Environment

Estimation of potential water requirements using water footprint for the target of food self-sufficiency in South Korea

--Manuscript Draft--

Manuscript Number:	PAWE-D-14-00161R2
Full Title:	Estimation of potential water requirements using water footprint for the target of food self-sufficiency in South Korea
Article Type:	Article
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Funding Information:	
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Response to Reviewers:	

Revision Note

1. #2 reviewer pointed out that the terminology "virtual water use" should be replaced by the "water footprint". However, the authors used "use of water footprint(WFU)" instead of "water footprint(WF)" . I question if the terminology "use of water footprint (WFU)" is appropriate.
   → **We replaced "use of water footprint(WFU)" by "water footprint(WF)".**

2. What is the full name of WFUper (P.1 L.13)?
   → **We changed from WFU_{per} to WF_{cap}, and added full name of WF_{cap} in page 1 as follows:**
   The WFs for per capita food consumption (WFs_{cap}) were estimated at 512.9 m^3 (1985) and 822.9 m^3 (2010).

3. Page1 line 14: "meat-centered" (P.1 L.15) should be "meat-oriented".
   → **The word was changed.**

Title Page

Estimation of potential water requirements using water footprint for the target of food self-sufficiency in South Korea

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Abstract

South Korea's food self-sufficiency ratio (SSR) dramatically decreased from 56% in 1980 to 27% in 2010, due to changes in food production and consumption patterns. Naturally, the changes in food self-sufficiency and consumption patterns will affect the world agricultural trade. This study aims to analyze trends in water footprints (WFs) on the basis of statistics for per capita food consumption in the past 25 years. The WFs for potential water requirements (WFs_{PWR}) were estimated using food production and consumption scenarios for the targets of the SSRs in 2015 and 2020. The WFs for per capita food consumption (WFs_{cap}) were estimated at 512.9 m^3 (1985) and 822.9 m^3 (2010). Cereals and meats accounted for 36.3% and 21.5% of the total WFs_{cap} in 1985, and 18.3% and 38.6% in 2010, respectively. This implies that with economic development, Korea's dietary patterns have changed from cereal to meat-oriented. To achieve the targets of 52% (2015) and 55% (2020) food SSR based on calories, additional WFs_{PWR} are estimated to be 1,255.5 Mm^3 (2015) and 1,923.9 Mm^3 (2020). Results of this study are expected to be a useful basis for making long-term policies for sustainable agricultural production and water management from technical and social perspectives.

Keywords *water footprint, food self-sufficiency, agricultural water usage, food consumption, production*

Introduction

Population growth and life-style changes have great effects on the demand and supply of food, and land and water use, the changes of which are important in water resources management. Fig. 1 illustrates the correlation between various factors related to water resources management (Oki, 2005; IPCC, 2007). Considerable increase in population, rapid industrialization and urbanization during the last half century in Korea caused higher demand for food and decreased arable lands. Many countries are not self-sufficient and depend on imports from other regions. Despite the recognized importance of the role of trade in global and regional food security, the societal reliance on both domestic production and international trade remains poorly quantified (D'Odorico et al., 2014). The food self-sufficiency ratio (SSR), determined from domestic production divided by total consumption including food, feed, seed and manufacture consumption and loss, in South Korea (Korea) fell sharply from 56% in 1980 to 27% in 2010. The SSR for grain was 29.5% in 2010, in which wheat, maize and beans were only 0.5%, 1.0% and 9.8%, respectively. The SSRs for these crops are very low compared to those for rice and starch roots with rates of 101.1% and 109.3%, respectively (MIFAFF, 2011). The average SSR for grain in Organization for Economic Cooperation and Development (OECD) countries is about 83%, much higher than that in Korea. According to a report by the Korea Rural Economic Institute, the SSR for grain in Korea ranked in the bottom 6 among the OECD countries. This explains why Korea has imported a large amount of grain such as wheat, maize and soybeans from overseas markets. Therefore, Korea has been vulnerable to instabilities in the international grain markets due to natural disasters such as floods and droughts. The demand for food in Korea is highly dependent on the imported grains. Due to international trade problems, the short supply of water for domestic agricultural production could result in the shortage of agricultural products, despite sufficient farmland and advanced agricultural techniques. Limited water supplies could lead to widespread social disruption due to conflict over competing uses in the agricultural, living, and industrial sectors. Frequent occurrence of extreme weather events -droughts, floods, heat waves- are on the increase, causing instability in crop production (IPCC, 2007). Demand for meat is still rising faster than population growth (The World Bank, 2012). Global meat production has been projected doubled in the period 1980-2015 (FAO, 2006) and this upward trend will continue given the projected doubling of meat production in the period 2000-2050 (Mekonnen and Hoekstra, 2012).

The food security situation in Korea faces challenges internally and externally. It is necessary for the Korean government to make more effective agricultural policies for stabilizing the food supply. The Korean government recognizes the necessity of enhancing its food SSR. The Ministry for Food, Agriculture, Forestry and Fisheries (MIFAFF) is planning to investigate and amend the overall status of food SSR every five years to establish a realistic target by reflecting changes in domestic and foreign situations such as DDA (Doha Development Agenda) and FTA (Free Trade Agreement). MIFAFF has set the mid-long term targets for the grain SSR from 26.7% in 2010 to 30% in 2015 then to 32% in 2020 (KREI and MIFAFF, 2011). To achieve this goal, additional agricultural water must be secured; however, discussions on the detailed quantity and security of the water have yet to be made. To estimate water resources required for crop production, various factors including cultivation areas, climate conditions, farming methods and regional features are considered. It is difficult to estimate water demand considering only the above factors because the food SSR is basically obtained from both the production and consumption figures. The virtual water concept, in which the amount of water is estimated using the amount of crop production, is more suitable for estimating the potential agricultural water required to meet the target food SSR. The concept of virtual water for product or commodity purposes, defined as the volume of water required to produce a specific amount of the product, was initially introduced by Allan (1998). Allan suggested that the industrial and agricultural product trade was also a trade of the water used for the production of those commodities. Any trade of a specific crop product means a trade of water because water is necessarily used to cultivate the crops. The water footprint (WF) is an indicator of water use that takes into account both direct and indirect water use by consumer or producer based the virtual water concept. Water usage is measured as green water and blue water as consumed water volume, and also grey water as polluted water (Hoekstra et al., 2011).

In other words, the WF could play a role as the connector between water and food because food consumption has significant impacts on water requirements. The initial studies were focused on quantification of virtual water and the WF. Hoekstra and Chapagain (2007) analyzed the WFs of nations for the period 1997-2001 considering the water use by people as a function of the consumption pattern. The global WF was 7450 Gm^3/yr or 1240 $m^3/cap/yr$, and the high WF was explained in terms of the total volume of consumption related to the gross national income of a country, water-intensive consumption patterns, climate and water-inefficient agricultural practices. The WF concept has been expanded to green, blue and grey WF. Accordingly, Mekonnenand

Hoekstra (2010a; 2010b) quantified the green, blue and grey WF of crops, derived crop products, farm animals and animal products. Chapagain and Hoekstra (2011) estimated the blue, green and grey WF of rice from production and consumption perspectives.

The WF is mainly influenced by climate and region, thus the regional WF data is required to apply the water footprint to various fields such water management and food consumption. In Korea, the WF is a hot issue and several studies about estimation of the WF have been executed in terms of agricultural products and livestock products. Yoo et al. (2009) started to calculate the virtual water content of 40 crops and Yoo et al. (2014a; 2014b) estimated the WF of paddy rice and upland crops in Korea. In addition, Lee et al. (2015) calculated the water footprint of livestock products such as beef cattle, swine, and broiler chickens in Korea. Accordingly, these WF data were applied for increasing the reliability of the results of this study.

In addition, several studies tried to apply the WF to food consumption and water use. Liu and Savenije (2008) quantified this relationship in China and concluded that the effect of food consumption patterns on China's water resources were substantial in the recent past and will be in the near future. Accordingly, China needs to strengthen the green water management and take advantage of the virtual water imports to meet the additional water requirements for food. Duarte et al. (2014) examined the water consumed in the production of vegetable and animal goods using WFs from 1860 to 2010, and a detailed analysis of the trends in water consumption and changes in compositional patterns was carried out. Recently, the WF has been used for food trade in terms of virtual water trade. Biewald et al. (2014) evaluated the impact of international food crop trade on local blue water resources in order to determine the trade-related value of the blue water usage. Dalin et al. (2014) combined a hydrological model with a trade model and quantified the volumes of irrigation and rainfall water transferred between provinces and other countries through agricultural trade in China.

Most research about WF have focused on quantification of water use and international water flow. These days, the water use is related to climate change and national policy, so several research studies tried to understand the relationship between water use and external effects. Orlowsky et al. (2014) assessed the effects of reduced water availability due to climate change using RCP (representative concentration pathways) scenarios on national water consumption and virtual water trade. In addition, Schyns and Hoekstra (2014) demonstrated the added value of detailed analysis of the human WF and virtual water flow for formulating national water policy.

Governments need to set the policy about food security and international trade, the additional water use, food consumption pattern change, and SSR at the same time because water use is related to various factors according to the previous research. However, water and food security depends on the situation in each country. Especially, Korea was one of the main crop importers due to the low SSR of wheat, maize, and soybeans, thus the government is trying to increase the SSR of food crops. The crop production is related to water use, and the WF could be used as the index for quantification of water requirements considering food consumption. Therefore, the research about projecting additional water use considering Korea's food policy should be performed for water and food security in Korea.

In this study, trends in per capita uses of blue and green water footprints were analyzed in accordance with the change of the food consumption pattern in the past 25 years and potential water requirements were estimated using the water footprint and food consumption and production scenarios for the target food self-sufficiency ratio in 2015 and 2020. The water footprint was influenced by climate and region, and the Korean water footprint data mainly were applied.

Fig. 1 The correlation between various factors related to water resources management (modified from Oki, 2005 and IPCC, 2007)

Methods and Data

Water footprint of consumption and production

The WF of product (WF_{prod}) of growing crops, trees and animals is the sum of the green, blue, and grey components:

$$WF_{prod} = WF_{blue} + WF_{green} + WF_{grey} \quad \text{(unit: m}^3\text{/ton)} \quad (1)$$

The distinction between blue and green WF is important because direct and indirect impacts (e.g. hydrological, environmental, and social impacts) and the economic costs of irrigation water used for production differ from the impacts and costs of rainwater. The grey WF is defined as the volume of water required to dilute the pollutant loads based on standards of water quality (Hoekstra et al., 2011). This study focused on the practical water use for crop and animal products of consumption and production, thus only green and blue WF was considered, not grey WF.

In this study, the WFs_{prod} suggested by Yoo et al. (2014a; 2014b) were used for the major crops cultivated in Korea, and the WFs_{prod} suggested by Lee et al. (2015) and Mekonnen and Hoekstra (2010b) were used for animal products. Table 1 shows the WFs_{prod} of major crop and animal products used in this study. WF of production or consumption is defined as the amount of water used to produce or consume certain crop and animal products. The WF of production or consumption is calculated by multiplying the consumption or production (ton) per item by the WF_{prod} of the corresponding item and then summing up the results for the food categories (Mekonnen and Hoekstra, 2010a).

$$WF[c\ or\ a] = WF_{prod}[c\ or\ a] \times P[c\ or\ a] \qquad \text{(unit: m}^3\text{)} \qquad (2)$$

where P represents the amount of consumption or production.

Statistics for per capita food consumption

Food consumption, the amount of food available for human consumption, patterns have a significant impact on crop water requirements, cultivation area and food self-sufficiency. This study is focused on water use for food consumption by people, thus the per capita food consumption was applied to calculate the WF. The WF for per capita food consumption (WF_{cap}) will enable the assessment of the changes of food consumption patterns influencing the WF. In this study, the statistics on the per capita food consumption (FC_{cap}) for 12 food categories and 21 products in 1985, 1990, 1995, 2000, and 2010 were obtained from the 'food balance sheet' (KREI, 2011). Crop and animal products are categorized as shown in Table 1.

Table 2 shows the FC_{cap} in 1985, 1990, 1995, 2000, and 2010. The total per capita food consumption increased to 397.2 kg in 1985, and then to 510 kg in 2005 and remained the same thereafter. A comparison of the FC_{cap} between 1985 and 2010 showed decreases for cereals and pulses (beans), but increases for other foods. Among these, meats and milks exhibited more than a 260% increase during the same period.

Table 1 Green and blue water footprints (WFs_{prod}) for food items (Yoo et al., 2014a; 2014b; Lee et al., 2015; Mekonnen and Hoekstra, 2010a; 2010b)

Table 2 Per capita food consumption (FC_{cap}) for 12 food categories in 1985, 1990, 1995, 2000, and 2005-2010 (KREI, 2011)

Results and Discussion

Water footprint for per capita food consumption

Results of the WFs_{cap} estimation based on the per capita food consumption for food categories (1985-2010) are shown in Fig. 2-3. Principally, To estimating these WFs_{cap}, WFs_{prod} should be based on crop water requirements and productivity during the years 1985-2010. However, since prior research about WFs_{prod} for 25 years are lacking, WFs_{cap} were estimated by using the results of Yoo et al. (2014a; 2014b) and Lee et al. (2015) based on the statistical data during last ten years. If WFs_{cap} are estimated by using WFs_{prod} for 25 years, the results would be different from the results in this study.

The total WFs_{cap} including green and blue water were estimated at 512.9 m^3 in 1985, 633.6 m^3 in 1990, 758.9 m^3 in 1995, 828.4 m^3 in 2000, 820.3 m^3 in 2005, and 822.9 m^3 in 2010. This means that as of 2010 each person drank 2,254.4 liters of water a day through food consumption. Hoekstra and Mekonnen (2012) show that the green and blue WF_{cap} of Korea was about 1400 m^3. The reason for the different results obtained with different a time span lies in different food items and WFs_{prod}. The results by Hoekstra and Mekonnen (2012) are WFs_{cap} for all the items including agriculture and livestock products as well as industrial products, while the results from this study are for major crop and animal products excluding favorite foods.

The green and blue WFs_{cap} for cereals decreased by 6 m^3 and 29 m^3 in 2010 compared with 1985, respectively. The ratio of the WF_{cap} decreased from 25% (green) and 85% (blue) in 1985 to 13.4% (green) and 65.1% (blue) in 2010. This was due to the gradual decreases in the consumption of rice, which comprises the largest proportion among cereals. The green and blue WFs_{cap} for vegetables and fruits increased from 26.5 m^3 (green) and 2.3 m^3 (blue) in 1985 to 40.5 (green) and

3.1 m³ (blue) in 2010, respectively, and the amount of their increase was 51 kg during the same period. This is because the WFs_{prod} for vegetables and fruits were much lower than those for other food items.

The total, green and blue WF_{cap} changes were about 160% (total), 177% (green) and 83% (blue) between 1985 and 2010. The reason why the green and blue WFs_{cap} show opposite trends was due to the decreases in the rice consumption, which comprises the largest proportion among blue WF. The increase of FC_{cap} was 124.7% during the same period. The reason why the total WF_{cap} increase was higher than the FC_{cap} increase was due to large increases in the consumption of animal products, the WF_{prod} of which is relatively large. Of the total WFs_{cap}, cereals and meats accounted for 36.3% and 21.5% in 1985, 20.8% and 35.8% in 2000, and 18.3% and 38.6% in 2010, respectively. Those imply that economic growth is behind the change in the general dietary pattern from cereal to meat in Korea.

Fig. 2 Green water footprints per capita for the food consumption (WFs_{cap}) during 1985-2010

Fig. 3 Blue water footprints per capita for the food consumption (WFs_{cap}) during 1985-2010

Food consumption and production for food self-sufficiency in 2015 and 2020

The food SSR can be expressed in various ways including quantity- or calorie-based SSR and grain SSR. Fig. 4 shows the SSR during the years 1975-2010. The SSRs, based on the quantity of starch roots, vegetables, fruits and eggs were above 80% during this period. The SSRs of meats and milks were above 90% before 1990, but decreased to less than 80% since 2000. The SSRs of grains and pulses (beans) were above 70% and decreased to as low as 30% during the current year.

While bulky feed's SSR is high, that of formula feed is very low. The reason for the considerably low SSRs of cereals and feeds can be attributed to the enormous amount of cereal grains imported for animal production, resulting in a decrease in the calorie-based SSR from 70% in 1980 to 50% currently. The food SSR is closely related to food security and low SSRs can cause many problems. With these in mind, the Korean government has prepared a plan to increase the calorie-based SSR to 52% in 2015 and 55% in 2020 on the basis of the 'Report on the conceptualization of food self-sufficiency ratio and adjustment of its target in Korea' (KREI and MIFAFF, 2011). The main purposes of this report were to analyze the present situation and future outlook for the food SSR and to develop possible food consumption and production scenarios for establishing the food SSR targets in 2015 and 2020.

The target SSRs of food items in 2015 and 2020 are shown in Fig. 3. The estimated SSRs for key items are also described. The SSR of rice is about 98%, and the SSR for staple food-grain, excluding feed purposes, is in the range of 62-65%. The SSRs for staple food-grains, including those used for feed purposes, are 29-30%. The SSRs for bovine, pig and poultry are 43-45%, 80-81% and 85%, respectively. The SSRs for vegetables and fruits are 85% and 75-80%, respectively. The food SSR for the energy supply is 50% higher than the base year 2010.

Detailed domestic consumption and production scenarios are prerequisites for determining the food SSR and achieving targets. The scenarios of food consumption and production suggested by the Korean government for 2015 and 2020 are shown in Table 3 (KREI and MIFAFF, 2011). The prospects for production and consumption are classified into 12 food items and 2 feed items respectively.

An increase in meat production means increased cereal grain imports for animal feed, consequently, increases in domestic feed production will be rare. Increases in the SSRs of feed and meat should happen simultaneously. Those scenarios consist of five food items - rice, barley, starch roots, vegetables and milk with a gradual decrease in production, and other food items with a gradual increase in production compared with the average production during 2006-2010. Among these scenarios, the target SSRs of wheat, pulses (beans) and bulky feed were relatively high.

Fig. 4 Trends in food self-sufficiency rates (SSRs) for the years 1975-2010 and target food SSRs for the years 2015 and 2020

Table 3 Domestic consumption and production scenarios and food self-sufficiency rates (SSRs) for the years 2015 and 2020

Water footprints for potential water requirements for food self-sufficiency in 2015 and 2020

The estimated results of the WFs for potential water requirements (WFs_{PWR}) based on domestic production and consumption scenarios for 2015 and 2020 are shown in Table 4 and Fig. 5-6. The WF_{prod} of an animal is defined as the total volume of water that was used to grow and process its feed, to provide its drinking water, and to clean its housing. Therefore, in the cases of bovines, pigs and poultry, additional WFs_{PWR} were calculated using WFs_{prod} excluding those of feeding portion. Average WFs of consumption and production during the five years from 2006 to 2010 were 36,392.0 Mm^3 (Green: 32,474.4 Mm^3, Blue: 3,917.6 Mm^3) and 18,567.2 Mm^3 (Green: 14,965.3 Mm^3, Blue: 3,601.9 Mm^3), respectively. Target WFs_{PWR} of consumption in 2015 and 2020 are 39,394.8 Mm^3 (Green: 35,716.5 Mm^3, Blue: 3,678.4 Mm^3) and 39,720.5 Mm^3 (Green: 36,174.7 Mm^3, Blue: 3,545.8 Mm^3), respectively, an increase of 8.3% (Green: 10.0%, Blue: -6.1%) and 9.1% (Green: 11.4%, Blue: -9.5%) respectively compared with current WFs. The WFs_{PWR} of production have increased by 6.8% (Green: 10.1%, Blue: -7.3%) and 10.4% (Green: 15.5%, Blue: -11.1%) to 19,822.7 Mm^3 (Green: 16,483.0 Mm^3, Blue: 3,339.7 Mm^3) and 20,491.1 Mm^3 (Green: 17,290.6 Mm^3, Blue: 3,200.5 Mm^3), respectively, compared with current WFs of production. In both scenarios, green WFs_{PWR} of production showed an increasing trend as 1,517.7 Mm^3 in 2015 and 2,325.3 Mm^3 in 2020 while blue WFs_{PWR} were decreasing to 262.2 Mm^3 in 2015 and 401.4 Mm^3 in 2020.

The total additional WFs_{PWR} of production were estimated to be 1,255.5 Mm^3 (Green: 1,517.7 Mm^3, Blue: -262.2 Mm^3) in 2015 and 1,923.9 Mm^3 (Green: 2,325.3 Mm^3, Blue: -401.4 Mm^3) in 2020 according to targets set by the Korean government. The target WFs_{PWR} decreases for crop production, excluding animal products and feeds, are -123.6 Mm^3 (Green: 155.9 Mm^3, Blue: -279.5 Mm^3) in 2015 and -127.2 Mm^3 (Green: 302.2 Mm^3, Blue: -429.4 Mm^3) in 2020. Additional WFs_{PWR} for animal production and feeds were estimated to be 1,379.0 Mm^3 (Green: 1,361.8 Mm^3, Blue: 17.3 Mm^3) and 2,051.1 Mm^3 (Green: 2,2023.1 Mm^3, Blue: 28.1 Mm^3) during the same period.

The key point from these results is that the blue WF is decreasing, while green WF is increasing. The main reason for this trend is that rice production, which primarily uses blue WF is decreasing, while feeds production which uses green WF is increasing. In Korea, agricultural water is mostly used for the production of rice. 47% of total water usage in Korea is used for agricultural purposes, and 81.6% (13.0 billion m³) of it is required for rice cultivation (MCT, 2006). The reason for this is that the management and development of agricultural water resources in Korea have been focused mainly on the protection of paddy rice fields from drought, because rice self-sufficiency has been a priority (Yoo et al., 2012).

Additional WFs_{PWR} include both blue and green water, and these values were compared with the agricultural water demand and reservoir capacity in Korea. According to the 'Report for Water Vision 2020' (MCT, 2006), the annual demand for agricultural water was 15,849 Mm³ in 2011 and this was estimated to be 15,690 Mm³ in 2016 and 15,583 Mm³ in 2020. These additional WFs are equivalent to 8.0% (2015) and 12.3% (2020) of the annual demand. The total effective capacity of agricultural reservoirs in Korea is 2,771 Mm³ and additional WFs_{PWR} in 2015 and 2020 are equivalent to 45.3% and 69.4% of the current capacity, respectively. It doesn't mean that agricultural water resources including reservoirs and pumping stations have to be secured as much as additional WFs_{PWR}, because green water occupies the most in this value. Rain-fed upland fields that rely on green water depend on climate conditions, therefore, are vulnerable to natural disaster or climate changes. This condition could give an adverse effect on the production increases and security of the crops. Therefore, a plan that can replace green water with blue water such as securing a stable irrigation water supply is required. All the above scenarios suggest that agricultural water resources be secured multilaterally to achieve the target SSR.

Imported WFs need to be increased to meet the target food SSRs (as shown in Fig. 7). The amount of imported WFs from 2006 to 2010 was 3,481.5 Mm³ for grains, 168.1 Mm³ for vegetables and fruits, 1,029.8 Mm³ for animal products, and 13,145.5 Mm³ for feeds. Under domestic production and consumption scenarios, the estimated results of imported WFs in 2015 and 2020 were 3,117.1 Mm³ and 2,940.2 Mm³ for grains, 632.0 Mm³ and 747.5 Mm³ for vegetables and fruits, 1,235.6 Mm³ and 1,285.6 Mm³ for animal products, 14,587.5 Mm³ and 14,256.2 Mm³ for feeds, respectively. These results mean that additional imported WFs would be needed for increasing the food SSRs, and the import target is 1,747.3 Mm³ in 2015 and 1,404.6 Mm³ in 2020. This means that WFs of production and import simultaneously increase as the increases in the consumption are more than changes in the domestic production for the target of food SSR. As a result, this led to the assumption that calorie-based SSRs are predicted to increase from the current 46.8% to 52% and 55% in 2015 and 2020, respectively. The SSRs of the WF, determined from the WFs of production divided by consumption, would be slightly changed from the current 51.0% to 50.3% and 51.6% during the same period.

Fig. 5 Additional green water footprint of domestic production during 2006-2010 (average), 2015 and 2020

Fig. 6 Additional blue water footprint of domestic production during 2006-2010 (average), 2015 and 2020

Fig. 7. Virtual water imports for achieving the targets of food self-sufficiency ratio (SSR)for the years 2015 and 2020

Table 4 Water footprints for potential water requirements ($WFUs_{PWR}$) in consumption and production for 2006-2010 (average), 2015 and 2020

Summary and conclusions

In this research, trends of the WFs in relation to the per capita food consumption were estimated for Korea. The WFs for potential water requirements to secure the target food SSRs for 2015 and 2020 were calculated. It is expected that the increase of the WFs for the per capita food consumption (WFs_{per}) due to the changes of eating habits will accelerate the growing consumption of the domestic WFs. The results suggest that additional WFs for potential water requirements (WFs_{PWR}) are estimated to be 1,255.5 Mm^3 and 1,923.9 Mm^3 in 2015 and 2020, respectively. The suggestions in various aspects about the results are as follows.

First, the additional WFs_{PWR} include both green water and blue water, therefore, agricultural water requirements need to be met in part by effective rainfall and irrigation water. The green water usage should be increased by increasing the effective rainfall during the crop growing period. However, there is a limit in increasing effective rainfall with the concentration of rainfall falling during summers in Korea. Therefore, a plan to increase the portion of blue water is required for the stable crop production. That is, a large portion of additional WFs should come from blue water rather than green water. Considering the difficulties in developing new water resources due to possible environmental impacts in addition to costs, more advanced and efficient management techniques should be employed on the existing water resources and enhance the efficiency in the application and allocation of water resources. Plans are available to produce other crops by converting the paddy fields into crop fields. Paddy fields use most of the agricultural water. If they are to be converted into other crop fields, then both the hardware (e.g. facilities) and software (e.g. water management techniques) expansion will be required for a smooth transfer of water from the paddy fields to other fields.

Korea desperately needs improved crop production which is closely related to cultivation land and crop production per unit area. Rapid industrialization and urbanization have created difficult situations in securing additional cultivation land; therefore, increasing the production per unit area is the only way of achieving the objective. For this purpose, several practical ways can be considered with some problems associated with them.

Additional use of fertilizers and pesticides will help to relieve the situation with regard to sustainable crop production; however, this practice will increase another problem of non-point source pollution, which in turn leads to a grey water increase. More stringent pollution mitigation measures will be required under this scenario. Two-crop farming or double cropping can be another alternative. Cultivation land in Korea consists of paddy fields (58%) and upland fields (42%), and the double cropping can be practiced mainly in the paddy fields. Although crops other than rice can be cultivated in the paddy fields after harvesting rice, the variety of cultivable crops will be limited mainly due to unfavorable climatic conditions (low air temperature, less rainfall). Expansion of greenhouse cultivation, which can be practiced year-round, will be another solution to the issue. A variety of crops that can be grown will be an advantage to the production increase; however, this practice will face unexpected problems associated with concentrated input of energy, water and fertilizers. Groundwater represents ‘blue water’ and is a source of a stable supply of agricultural water; however, excessive use of it will negatively affect the environment through its inevitable exhaustion.

The objectives of the report of KREI and MIFAFF (2011), which is referred to in this study, are as follows. The main purpose of those studies is to re-establish a target of food self-sufficiency rate reflecting changes inside and outside the country. Also, the study is aimed at examining policy measures to meet the purpose. In the report, target of food SSR results were already considered domestic and international issues of food security. In this study, results were drawn only for the relationship between food SSR and water resources at the national level. Therefore, this study has a limit in analyzing various factors and food security. That is, since food security is linked to various issues from not only geo-politics and food trade, the research to investigate the relationship between issues would be needed in the future.

In the process of estimating WF with food self-sufficiency scenarios, both the production and consumption sides as socio-economic aspects should also be considered simultaneously. In the consumption aspect, promoting food life education, introducing consumer oriented policies to expand food demand, and promoting low carbon green food life is important. In the production side, efforts to cultivate crops other rice for the stabilization of food and to diversify agricultural products quality for improvement of agricultural competitiveness and food safety towards consumer satisfaction is necessary.

Results of this study will provide information and data on technical and social aspects which are required for the agricultural water resources management. Follow-up research on the analysis of the water footprint should be carried out with particular emphasis on the sustainable agricultural production and agricultural water resources management. Final results will serve as the basis for establishing long-term policies on the agricultural water resources.

References

Allan JA (1998) Virtual water: A strategic resource global solutions to regional deficits. Ground Water 36: 545-546

Biewald A, Rolinski S, Lotze-Campen H, Schmitz C, Dietrich JP (2014) Valuing the impact of trade on local blue water. Ecological Economics 101(0): 43-53

Chapagain AK, Hoekstra AY (2011) The blue, green and grey Water footprint of rice from production and consumption perspectives 70: 749-758

Dalin C, Hanasaki N, Qiu H, Mauzerall DL, Rodriguez-Iturbe I (2014) Water resources transfers through Chinese interprovincial and foreign food trade. Proceedings of the National Academy of Sciences 111(27): 9774-9779

Duarte R, Pinilla V, Serrano A (2014) The water footprint of the Spanish agricultural sector: 1860-2010, Ecological Economics 108: 200-207

D'Odorico P, Carr JA, Laio F, Ridolfi L, Vandoni S (2014) Feeding humanity through global food trade. Earth's Future 2(9): 2014EF000250

Food and Agriculture Organization of the United Nations (FAO) (2006) World Agriculture: Towards 2030/2050. Interim Report: Rome, Italy

Hoekstra AY, Chapagain AK (2007) Water footprints of nations: water use by people as a function of their consumption pattern, Water Resources Management 21(1): 35-48

Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2011) The water footprint assessment manual: Setting the global standard, Earthscan: London, UK

Hoekstra AY, Mekonnen MM (2012) The water footprint of humanity. Proceedings of the National Academy of Sciences 109(9): 3232−3237

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate Change Impacts, adaption and vulnerability, Cambridge University Press: Cambridge, UK

Korea Rural Economic Institute (KREI) (2011) Food balance sheet, Korea Rural Economic Institute: Seoul, Republic of Korea (in Korean)

Korea Rural Economic Institute (KREI), Ministry for Food, Agriculture, Forestry and Fisheries (MIFAFF) (2011) Report on the conceptualization of food self-sufficiency ratio and adjustment of its target in Korea, Korea Rural Economic Institute: Seoul, Republic of Korea (in Korean)

Lee SH, Yoo SH, Choi JY, Kim YD and Shin A (2015) Estimation of water footprint for livestock products in Korea, Journal of the Korean Society of Agricultural Engineers (in Korean)

Liu J, Savenije HHG (2008) Food consumption patterns and their effect on water requirement in China. Hydrology Earth System Sciences 12: 887-898

Mekonnen MM, Hoekstra AY (2010a) The green, blue and grey water footprint of crops and derived crop products. Value of Water Research Report Series No. 47. UNESCO-IHE Institute for Water Education

Mekonnen MM, Hoekstra AY (2010b) The green, blue and grey water footprint of farm animals and animal products. Value of Water Research Report Series No. 48. UNESCO-IHE Institute for Water Education

Mekonnen MM, Hoekstra AY (2012) A global assessment of the water footprint of farm animal products, Ecosystems. 15(3): 401-415

Ministry of Construction and Transportation (MCT) (2006) Comprehensive Water Resources Plan-Water Vision 2020. Ministry of Construction and Transportation: Gwacheon, Republic of Korea (in Korean)

Ministry for Food, Agriculture, Forestry and Fisheries (MIFAFF) (2011) Major statistics for food, agriculture, forestry and fisheries. Ministry for Food, Agriculture, Forestry and Fisheries: Gwacheon, Republic of Korea (in Korean)

Oki T (2005) The hydrologic cycles and global circulation. Encyclopaedia of Hydrological Sciences. Anderson M.G., ed. JohnWiley and Sons: Chichester, UK

Orlowsky B, Hoekstra AY, Gudmundsson L, Seneviratne SI (2014) Today’s virtual water consumption and trade under future water scarcity. Environmental Research Letters 9(7): 074007

Schyns JF, Hoekstra AY (2014) The added value of Water Footprint Assessment for national water policy: A case study for Morocco. PLoS ONE 9(6): e99705

The World Bank (2012) Trends in the global demand for food. http://go.worldbank.org/D8VH8Y32D0 (accessed on 24 February 2012)

Yoo SH, Choi JY, Kim TG, Im JB, Chun CH (2009) Estimation of Crop Virtual Water in Korea. Journal of Korea Water Resources Association 42(11): 911-920 (in Korean)

Yoo SH, Choi JY, Nam WH, Hong E (2012) Analysis of design water requirement of paddy rice using frequency analysis affected by climate change in South Korea. Agric Water Manag 112(9): 33-42

Yoo SH, Choi JY, Lee SH, and Kim TG (2014a) Estimating water footprint of paddy rice in Korea. Paddy and Water Environment 12(1): 43-54 (in Korean)

Yoo SH, Lee SH, and Choi JY (2014b) Estimating water footprint for upland crop production in Korea, Journal of the Korean Society of Agricultural Engineers 56(3): 65-74 (in Korean)

Fig.1

Click here to download Figure: Fig. 1 The correlation between various factors related to water resources management.tif

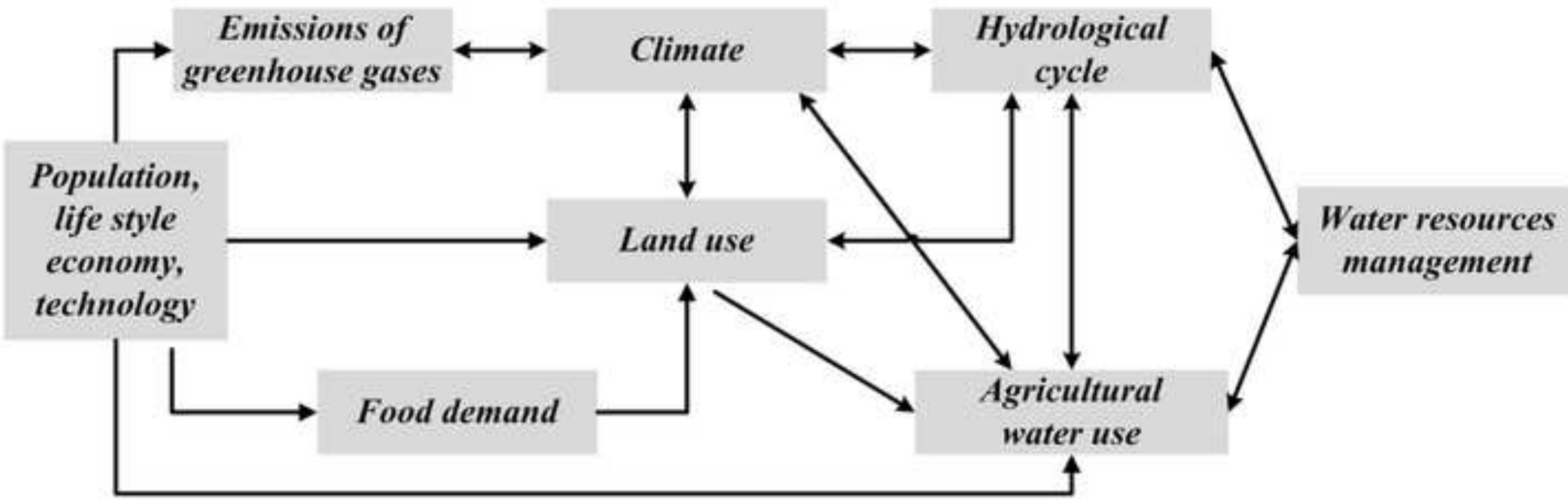

Fig.2

Click here to download Figure: Fig. 2 Green water footprints per capita for the food consumption (WFscap) during 1985-2010.tif

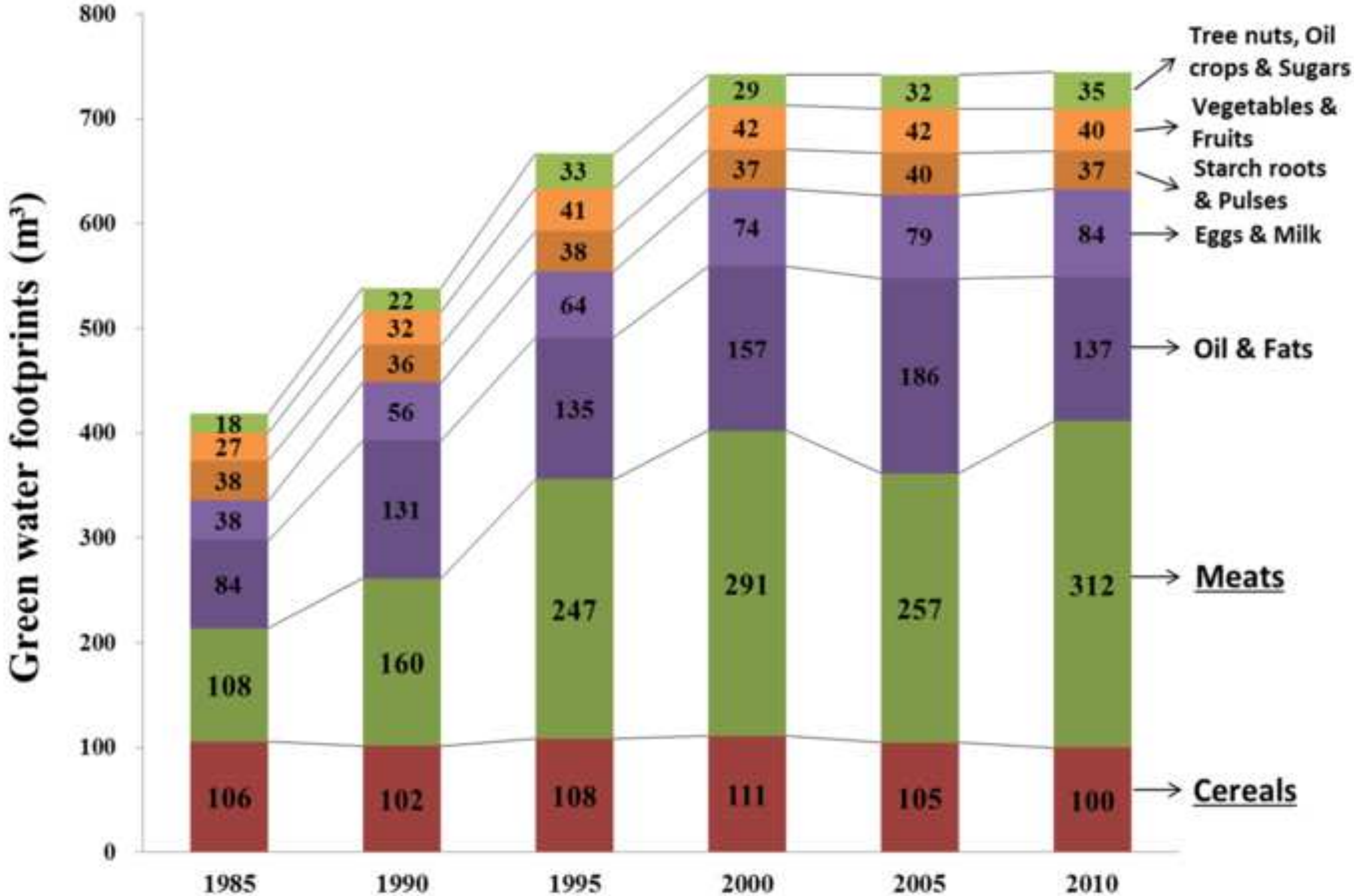

Fig.3

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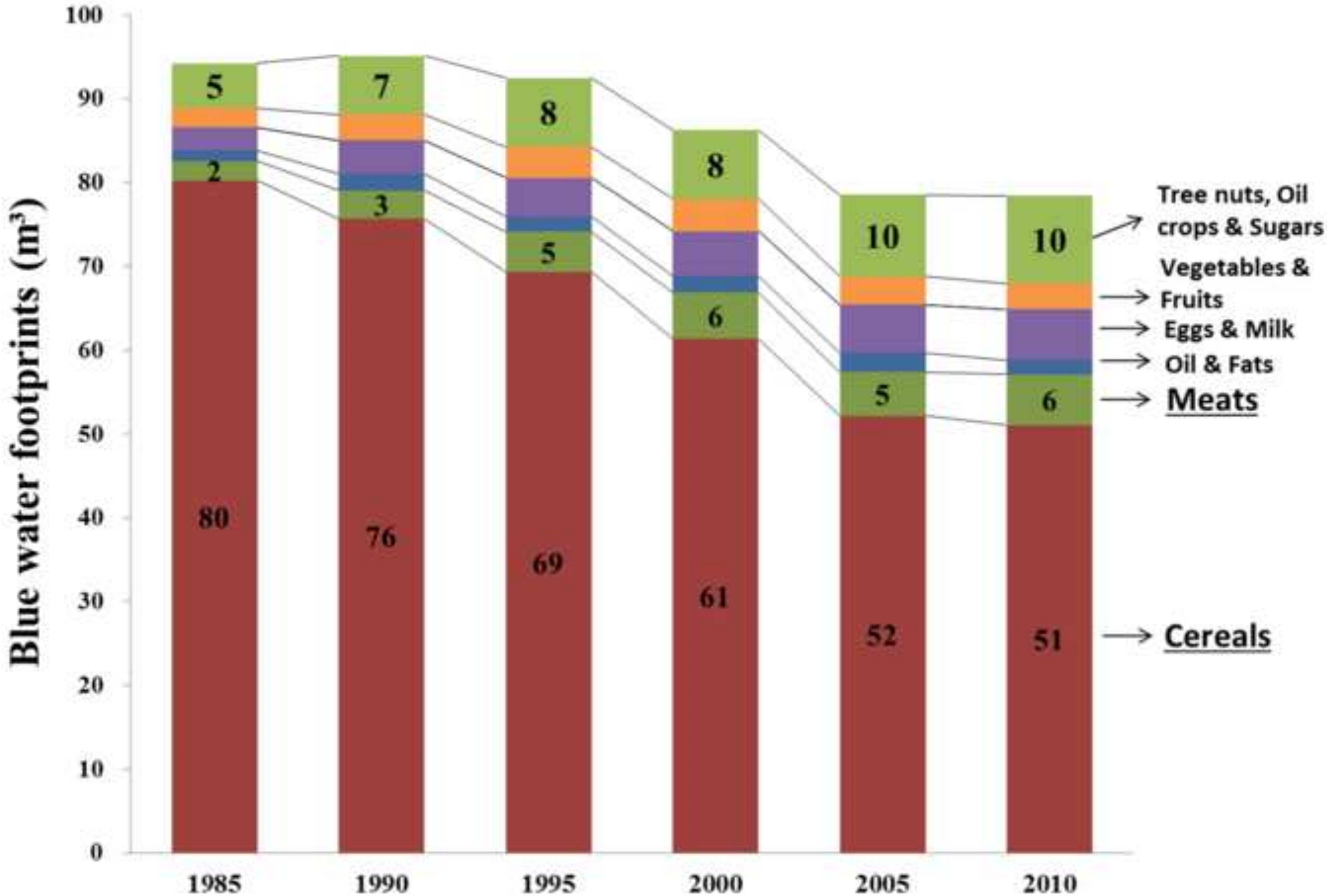

Fig. 4

Click here to download Figure: Fig. 4 Trends in food self-sufficiency rates (SSRs) for the years 1975-2010 and target food SSRs for the years 2015 and 2020.tif

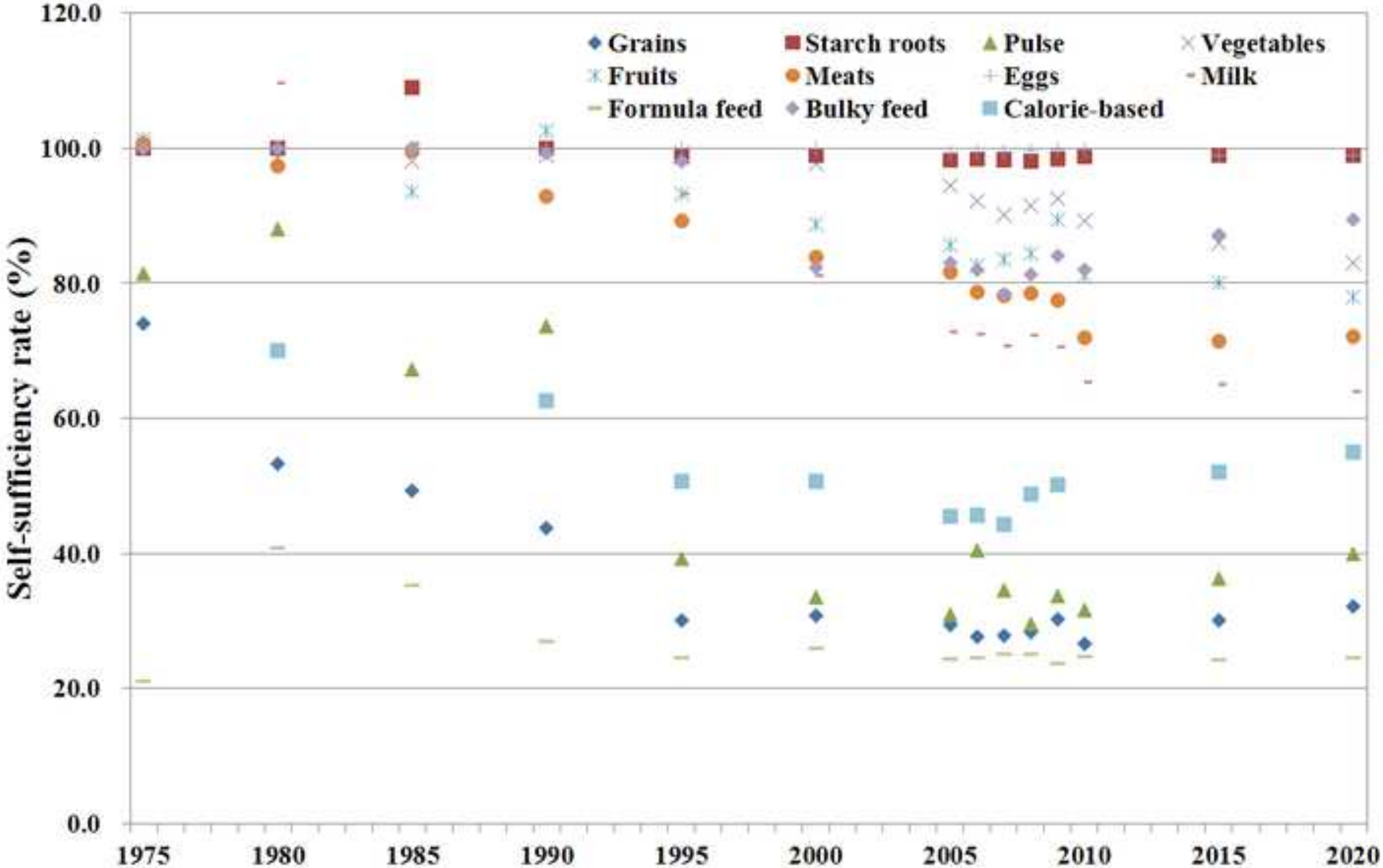

Fig.5

Click here to download Figure: Fig. 5 Additional green water footprint of domestic production during 2006-2010 (average), 2015 and 2020.tif

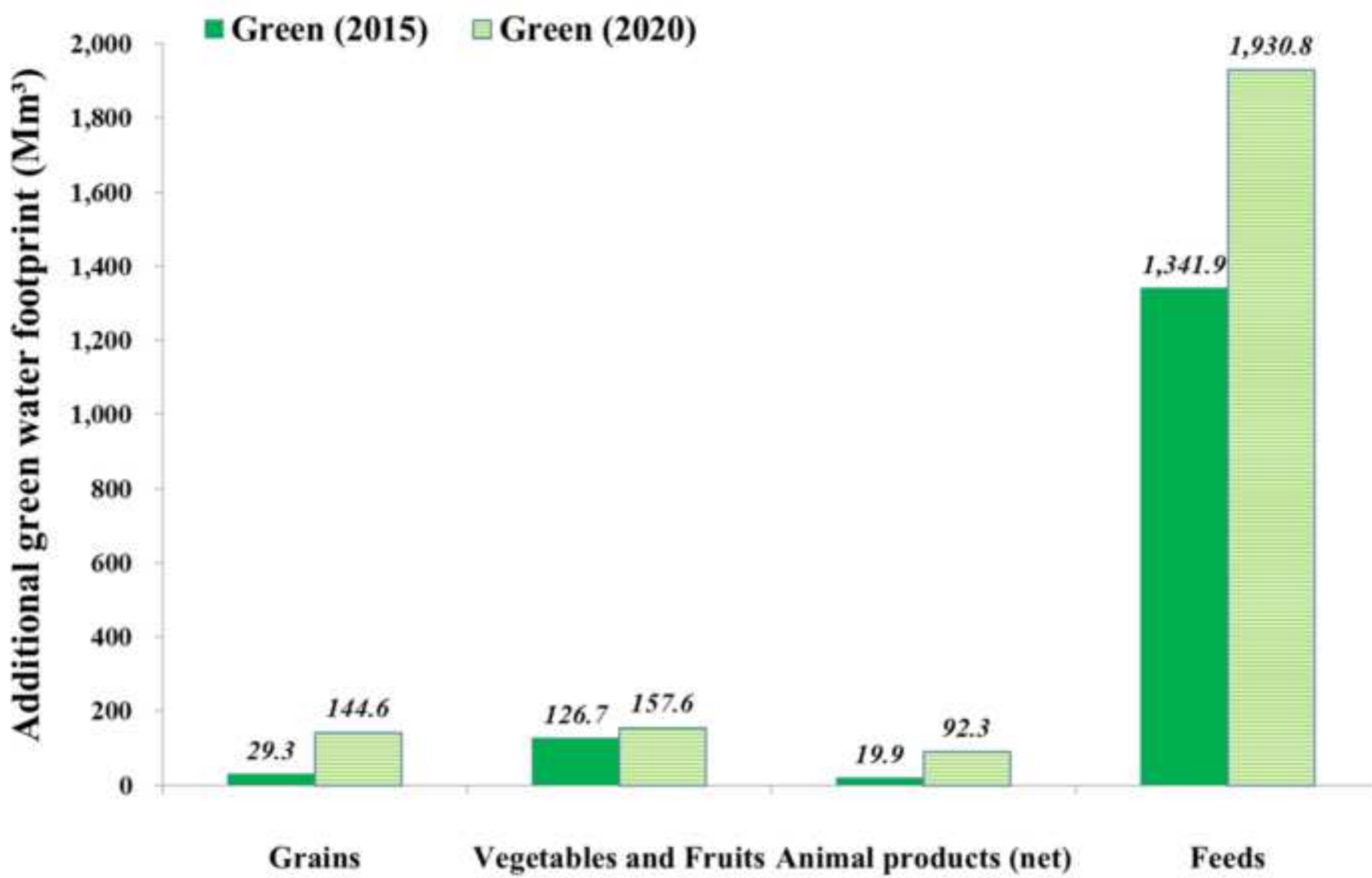

Fig.6

Click here to download Figure: Fig. 6 Additional blue water footprint of domestic production during 2006-2010 (average), 2015 and 2020.tif

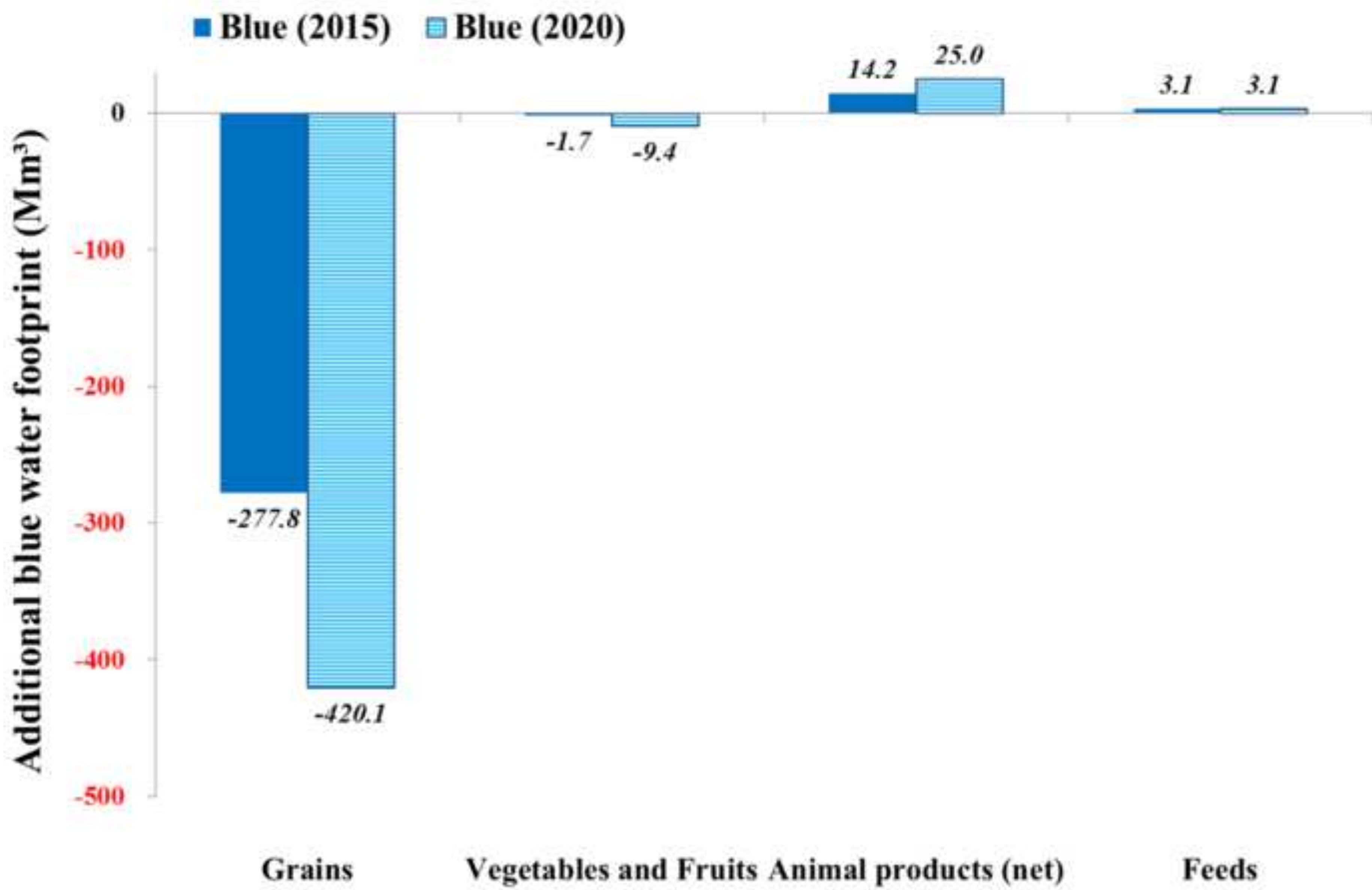

Fig.7

Click here to download Figure: Fig. 7. Virtual water imports for achieving the targets of food self-sufficiency ratio (SSR)for the years 2015 and 2020.tif

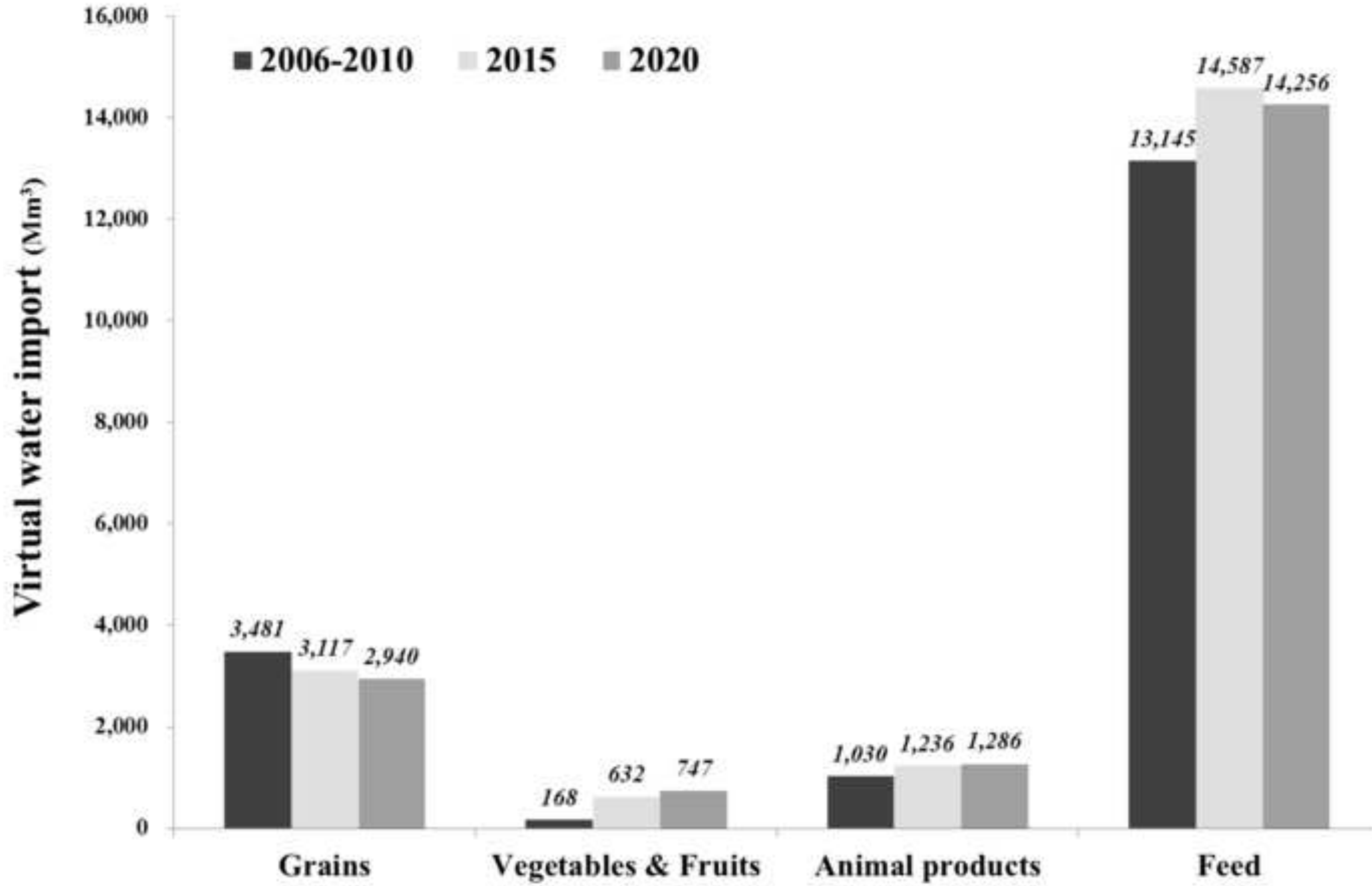

Table 1 Green and blue water footprints (WFs_{prod}) for food items (Yoo et al., 2014a; 2014b; Lee et al., 2015; Mekonnen and Hoekstra, 2010a; 2010b)

Food	WF_{prod} (m^3/ton)		Food	WF_{prod} (m^3/ton)	
	Green	Blue		Green	Blue
Cereals			**Vegetables & Fruits**		
wheat	1,060.2	-	**Vegetables**	114.7	23.2
rice	368.0	626.8	**Fruits**	573.1	-
barley	795.9	-	**Meats**		
maize	1,039.7	-	**Bovine meat**	16,813.4	209.7
cereals, others	2,298.1	-	**Pig meat**	4,071.9	163.9
Starch roots			**Poultry meat**	2,400.0	27.7
Potato	135.8	-	**Edible viscera**	8,915.7	125.3
Sweet potato	370.0	-	**Eggs & Milk**		
Sugars			**Eggs**	2,726.0	206.4
Sugars	1,108.5	455.6	**Milks**	948.1	67.2
Pulse			**Whole milk powder**	1,763.5	130.0
Soy beans	3,346.7	-	**Skim milk powder**		
Red beans	3,166.9	-	**Modified milk powder**	4,408.7	312.6
Pulses, others	2,644.0	-	**Condensed milks**		
Tree nuts & oil crops			**Oil & Fats**		
Tree nuts	3,961.9	62.2	**Animal Fats**	5,220.4	210.1
Sesame	5,556.5	-	**Vegetables Oils**	10,036.8	120.1
Oil crops, others	4,545.0	-			

Table 2 Per capita food consumption (FC_{cap}) for 12 food categories in 1985, 1990, 1995, 2000, and 2005-2010 (KREI, 2011)

Food	**Per capita food consumption (kg/yr)**					
	1985	**1990**	**1995**	**2000**	**2005**	**2010**
Cereals	185.4	175.4	173.1	166.8	150.5	145.1
Starch roots	11.9	11.0	11.0	11.8	17.0	13.8
Pulse	10.7	10.3	11.1	10.7	11.4	10.4
Tree nuts	0.8	0.5	1.7	1.5	1.3	1.5
Oil crops	0.5	0.7	1.3	0.7	0.7	0.7
Vegetables	98.6	132.6	160.6	165.9	145.5	132.2
Fruits	26.6	29.0	39.1	40.7	44.7	44.2
Meats	16.3	23.6	32.7	37.5	36.6	43.5
Eggs	6.3	7.9	8.6	8.6	9.1	9.9
Milks	19.2	31.8	38.5	49.3	54.0	57.0
Sugars	11.7	15.3	17.8	17.9	21.2	22.7
Oil and Fats	9.2	14.3	14.2	15.9	18.7	13.9

Table 3 Domestic consumption and production scenarios and food self-sufficiency rates (SSRs) for the years 2015 and 2020

Food	WF_{prod} (m^3/ton)		2015			2020		
	Green	Blue	Consumption (1000 tons)	Production (1000 tons)	SSR (%)	Consumption (1000 tons)	Production (1000 tons)	SSR (%)
Rice	368.0	626.8	4,367.0	4,280.0	98.0	4,136.0	4,053.0	98.0
Wheat	1,060.2	-	1,960.0	195.0	9.9	1,890.0	284.0	15.0
Barley	795.9	-	295.0	92.0	31.2	295.0	92.0	31.2
Pulses	3,340.0	-	468.0	170.0	36.3	498.0	201.3	40.4
Starch roots	215.2	-	851.1	840.0	98.7	851.1	840.0	98.7
Vegetables	114.7	23.2	11,200.0	9,630.0	86.0	11,200.0	9,300.0	83.0
Fruits	573.1	-	3,625.0	2,900.0	80.0	3,867.0	3,020.0	78.1
Bovine meat	-	91.2*	517.0	232.0	44.9	543.0	258.0	47.5
Pig meat	-	129.8*	952.0	762.0	80.0	976.0	781.0	80.0
Poultry	-	7.6*	635.0	508.0	80.0	701.0	561.0	80.0
Milk	1,004.8	71.2	3,111.0	2,027.0	65.2	3,142.0	2,015.0	64.1
Eggs	2,726.0	206.4	624.0	618.0	99.0	656.0	649.0	98.9
Bulky feed	494.4	-	6,777.0	5,907.0	87.2	7,931.0	7,099.0	89.5
Formula feed	1,009.3	8.5	18,342.0	4,432.0	24.2	18,035.0	4,432.0	24.6

* WFs_{prod} of three animal product are WFs_{prod} for drinking and servicing except for feeding

Table 4 Water footprints for potential water requirements (WFs_{PWR}) in consumption and production for 2006-2010 (average), 2015 and 2020

Food	Average in 2006-2010				2015				2020			
	Consumption (Mm^3)		Production (Mm^3)		Consumption (Mm^3)		Production (Mm^3)		Consumption (Mm^3)		Production (Mm^3)	
	Green WF	Blue WF	Green WF	Blue WF	Green WF	Blue WF	Green WF	Blue WF	Green WF	Blue WF	Green WF	Blue WF
Rice	1,783.6	3,037.8	1,738.2	2,960.5	1,607.1	2,737.2	1,575.1	2,682.7	1,522.1	2,592.4	1,491.5	2,540.4
Wheat	2,267.3	-	17.2	-	2,078.0	-	206.7	-	2,003.8	-	301.1	-
Barley	258.7	-	113.5	-	234.8	-	73.2	-	234.8	-	73.2	-
Pulses	1,462.3	-	502.3	-	1,563.1	-	567.8	-	1,663.3	-	672.3	-
Starch roots	206.6	-	203.2	-	183.2	-	180.8	-	183.2	-	180.8	-
Vegetables	1,217.4	246.5	1,112.8	225.3	1,284.5	260.1	1,104.4	223.6	1,284.5	260.1	1,066.6	215.9
Fruits	1,569.3	-	1,527.1	-	2,077.7	-	1,662.1	-	2,216.4	-	1,730.9	-
Bovine meat	-	35.8	-	16.2	-	47.2	-	21.2	-	49.5	-	23.5
Pig meat	-	119.1	-	92.8	-	123.6	-	98.9	-	126.7	-	101.4
Poultry	-	3.5	-	3.0	-	4.8	-	3.9	-	5.3	-	4.3
Milk	3,098.1	219.7	2,185.9	155.0	3,125.8	221.6	2,036.7	144.4	3,157.0	223.8	2,024.6	143.6
Eggs	1,521.6	115.2	1,515.6	114.8	1,701.0	128.8	1,684.7	127.6	1,788.2	135.4	1,769.2	134.0
Bulky feed	2,383.9	-	1,945.4	-	3,347.8	-	2,918.1	-	3,917.9	-	3,506.9	-
Formula feed	16,705.5	140.0	4,104.2	34.4	18,513.5	155.1	4,473.4	37.5	18,203.6	152.5	4,473.4	37.5
Total	32,474.4	3,917.6	14,965.3	3,601.9	35,716.5	3,678.4	16,483.0	3,339.7	36,174.7	3,545.8	17,290.6	3,200.5