



Water footprint scenarios for 2050: A global analysis



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ABSTRACT

This study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bioenergy use) and technological development. The objective of the study is to understand the changes in the water footprint (WF) of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, we assess virtual water flows between the regions of the world to show dependencies of regions on water resources in other regions under different possible futures. We constructed four scenarios, along two axes, representing two key dimensions of uncertainty: globalization versus regional self-sufficiency, and economy-driven development versus development driven by social and environmental objectives. The study shows how different drivers will change the level of water consumption and pollution globally in 2050. The presented scenarios can form a basis for a further assessment of how humanity can mitigate future freshwater scarcity. We showed with this study that reducing humanity's water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns change. This study can help to guide corrective policies at both national and international levels, and to set priorities for the years ahead in order to achieve sustainable and equitable use of the world's fresh water resources.

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1. Introduction

Competition over freshwater resources has been increasing during decades due to a growing population, economic growth, increased demand for agricultural products for both food and non-food use, and a shift in consumption patterns towards more meat and sugar based products (De Fraiture and Wichelns, 2010; Falkenmark et al., 2009; Shen et al., 2008; Strzepek and Boehlert, 2010). It looks like today's problems related to freshwater scarcity and pollution will be aggravated in the future due to a significant increase in demand for water and a decrease in availability and quality. Many authors have estimated that our dependency on water resources will increase significantly in the future and this brings problems for future food security and environmental sustainability (Alcamo et al., 2003a; Bruinsma, 2003, 2009; Rosegrant et al., 2002, 2009). A recent report estimates that global water withdrawal will grow from 4500 billion m³/year today to 6900 billion m³/year by 2030 (McKinsey, 2009).

Scenario analysis is a tool to explore the long-term future of complex socio-ecological systems under uncertain conditions. This method can and indeed has been used to assess possible changes to global water supply and demand. Such studies have been an interest not only of scientists but also of governmental agencies, businesses, investors and the public at large. Many reports have been published to assess the future status of water resources since the 1970s (Falkenmark and

Lindh, 1976; Kalinin and Bykov, 1969; Korzun et al., 1978; L'vovich, 1979; Madsen et al., 1973; Schneider, 1976). Water scenario studies address changes in future water availability and/or changes in future water demand. Some of the recent scenario studies focused on potential impacts of climate change and socio-economic changes on water availability (e.g. Arnell, 1996, 2004; Fung et al., 2011; Milly et al., 2005). Other scenario studies also included the changes in water demand (Alcamo et al., 1996, 2000, 2003a,b, 2007; Rosegrant et al., 2002, 2003; Seckler, 1998; Shiklomanov, 2000; Vörösmarty et al., 2000). Change in water footprints per dietary preference in Europe is recently addressed by Vanham et al. (2013).

The major factors that will affect the future of global water resources are: population growth, economic growth, changes in production and trade patterns, increasing competition over water because of increased demands for domestic, industrial and agricultural purposes and the way in which different sectors of society will respond to increasing water scarcity and pollution. These factors are also mentioned in *Global Water Futures 2050*, a preparatory study on how to construct the upcoming generation of water scenarios by UNESCO and the United Nations World Water Assessment Program (Cosgrove and Cosgrove, 2012; Gallopin, 2012). In this study, ten different drivers of change are identified as critical to assess water resources in the long-term future: demography, economy, technology, water stocks, water infrastructure, climate, social behavior, policy, environment and governance.

In this study, we focus on water demand scenarios. In Table 1, we compare the scope of the current study with other recent water demand scenario studies. Vörösmarty et al. (2000) estimated agricultural, industrial and domestic water withdrawal for 2025, distinguishing single

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Table 1
Comparison of existing global water demand scenarios with the current study.

Study	Study characteristics	Sectoral disaggregation	Drivers used to estimate future water demand (no. of trajectories distinguished)
Vörösmarty et al. (2000)	Time horizon: 2025 Spatial scale: 30' grid resolution Scenarios: 1 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Shiklomanov (2000)	Time horizon: 2025 Spatial scale: 26 regions Scenarios: 1 Scope: Blue water withdrawal and consumption	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Rosegrant et al. (2002, 2003)	Time horizon: 2025 Spatial scale: 69 river basins Scenarios: 3 Scope: blue water withdrawal and consumption	Agriculture: 16 sub-sectors Industry Domestic	Population growth (1) Urbanization (1) Economic growth (1) Technology change (3)
Alcamo et al. (2003a)	Time horizon: 2025 Spatial scale: 0.5° spatial resolution Scenarios: 1 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Alcamo et al. (2007)	Time horizon: 2025/2055/2075 Spatial scale: 0.5° spatial resolution Scenarios: 2 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (2) Economic growth (2) Technology change (1)
Shen et al. (2008)	Time horizon: 2020/2050/2070 Spatial scale: 9 regions Scenarios: 4 Scope: blue water withdrawal	Agriculture Industry Domestic	Population growth (4) Economic growth (4) Technology change (4)
De Fraiture and Wichelns (2010)	Time horizon: 2050 Spatial scale: 115 socio-economic units Scenarios: 4 Scope: green and blue water consumption	Agriculture: 7 sub-sectors Industry: 2 sub-sectors Domestic	Population growth (1) Economic growth (1) Production and trade patterns change (4) Technology change (4) Consumption patterns—diet (1)
Current study	Time horizon: 2050 Spatial scale: 227 countries, 16 regions Scenarios: 4 Scope: green and blue water consumption, pollution as gray water footprint	Agriculture: 20 sub-sectors Industry Domestic	Population growth (3) Economic growth (4) Production and trade patterns change (4) Technology change (2) Consumption patterns—diets (2) Consumption patterns—biofuel (3)

trajectories for population growth, economic development and change in water use-efficiency. Shiklomanov (2000) assessed water withdrawals and water consumption for 26 regions of the world for the year 2025. Another global water scenario study was undertaken by Rosegrant et al. (2002, 2003), who addressed global water and food

security for the year 2025. Compared to other recent studies, their study includes the most extensive list of drivers of change: population growth, urbanization, economic growth, technology change, policies and water availability constraints. Alcamo et al. (2003a) analyzed the change in water withdrawals for future business-as-usual conditions in 2025 under the assumption that current trends in population, economy and technology continue. A more recent assessment by Alcamo et al. (2007) improved their previous study by distinguishing two alternative trajectories for population and economic growth, based on the A2 and B2 scenarios of the IPCC for the years 2025, 2055 and 2075. Shen et al. (2008) studied changes in water withdrawals in the agricultural, industrial and domestic sectors for the years 2020, 2050 and 2070. One of the most extensive water demand scenario studies was done by De Fraiture et al. (2007) and De Fraiture and Wichelns (2010). These studies focused on alternative strategies for meeting increased demands for water and food in 2050. They elaborated possible alternatives under four scenarios for 115 socio-economic units (countries and country groups). None of the global scenario studies addressed the question of how alternative consumer choices influence the future status of the water resources except Rosegrant et al. (2002, 2003). In addition, the links between trends in consumption, trade, social and economic development have not yet been fully integrated.

The current study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bio-energy use) and technological development. It goes beyond the previous global water demand scenario studies by a combination of factors: (i) it addresses blue and green water consumption instead of blue water withdrawal volumes; (ii) it considers water pollution in terms of the gray water footprint; (iii) it analyses agricultural, domestic as well as industrial water consumption; (iv) it disaggregates consumption along major commodity groups; and (v) it integrates all major critical drivers of change under a single, consistent framework. In particular, integrating all critical drivers is crucial to define policies for wise water governance and to help policy makers to understand the long-term consequences of their decisions across political and administrative boundaries.

We have chosen in this study to look at water footprint scenarios, not at water withdrawal scenarios as done in most of the previous studies. We explicitly distinguish between the green, blue and gray water footprints. The green water footprint refers to the consumptive use of rainwater stored in the soil. The blue water footprint refers to the consumptive use of ground or surface water. The gray water footprint refers to the amount of water contamination and is measured as the volume of water required to assimilate pollutants from human activities (Hoekstra et al., 2011).

The objective of the study is to understand the changes in the water footprint of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, we assess virtual water flows between the regions of the world to show dependencies of regions on water resources in other regions under different possible futures.

2. Method

2.1. Scenario description

For constructing water footprint scenarios, we make use of global scenario exercises of the recent past as much as possible. This brings two main advantages: building our scenarios on well-documented possible futures and providing readers quick orientation of the storylines. As a starting point, we used the 2×2 matrix system of scenarios developed by the IPCC (Nakicenovic et al., 2000). These scenarios are structured along two axes, representing two key dimensions of uncertainty: globalization versus regional self-sufficiency, and economy-driven development versus development driven by social and environmental objectives. The two axes create four quadrants, each of which represents

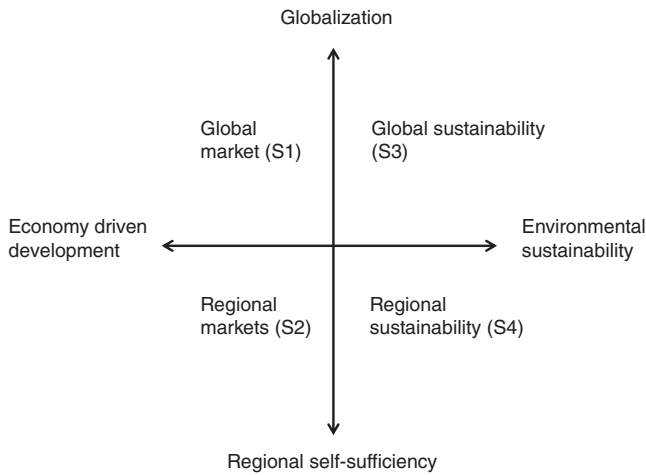


Fig. 1. The four scenarios distinguished in this study.

a scenario: global markets (S1), regional markets (S2), global sustainability (S3) and regional sustainability (S4) (Fig. 1). Our storylines resemble the IPCC scenarios regarding population growth, economic growth, technological development and governance. For the purpose of our analysis, we had to develop most of the detailed assumptions of the scenarios ourselves, but the assumptions were inspired from the storylines of the existing IPCC scenarios. The scenarios are consistent and tell reliable stories about what may happen in future. It is important to understand that our scenarios are not predictions of the future; they rather show alternative perspectives on how water footprints may develop towards 2050.

First, we constructed a baseline for 2050, which assumes a continuation of the current situation into the future. The four scenarios were constructed based on the baseline by using different alternatives for the drivers of change. The baseline constructed for 2050 assumes the per capita food consumption and non-food crop demand as in the year 2000. It also considers technology, production and trade as in the year 2000. The increase in population size is taken from the medium-fertility population projection of the United Nations (UN, 2011). Economic growth is projected as described in IPCC scenario B2. Climate change is not taken into account. Therefore, changes in food and non-food consumption and in the water footprint of agriculture and domestic water supply are only subject to population growth. The industrial water footprint in the baseline depends on economic growth.

Scenario S1, *global market*, is inspired by IPCC's A1 storyline. The scenario is characterized by high economic growth and liberalized international trade. The global economy is driven by individual consumption and material well-being. Environmental policies around the world

heavily rely on economic instruments and long-term sustainability is not in the policy agenda. Trade barriers are gradually removed. Meat and dairy products are important elements of the diet of people. A rapid development of new and efficient technologies is expected. Energy is mainly sourced from fossil fuels. Low fertility and mortality are expected.

Scenario S2, *regional markets*, follows IPCC's A2 storyline. It is also driven by economic growth, but the focus is more on regional and national boundaries. Regional self-sufficiency increases. Similar to S1, environmental issues are not important factors in decision-making, new and efficient technologies are rapidly developed and adopted, and meat and dairy are important components in the diets of people. Fossil fuels are dominant, but a slight increase in the use of biofuels is expected. Population growth is highest in this scenario.

Scenario S3, *global sustainability*, resembles IPCC's B1 storyline. The scenario is characterized by increased social and environmental values, which are integrated in global trade rules. Economic growth is slower than in S1 and S2 and social equity is taken into consideration. Resource efficient and clean technologies are developed. As the focus is on environmental issues, meat and dairy product consumption is decreased. Trade becomes more global and liberalized. Reduced agro-chemical use and cleaner industrial activity is expected. Population growth is the same as for S1.

Scenario S4, *local sustainability*, is built on IPCC's B2 storyline and dominated by strong national or regional values. Self-sufficiency, equity and environmental sustainability are at the top of the policy agenda. Slow long-term economic growth is expected. Personal consumption choices are determined by social and environmental values. As a result, meat consumption is significantly reduced. Pollution in the agricultural and industrial sectors is lowered. Biofuel use as an energy source is drastically expanded.

These scenarios are developed for 16 different regions of the world for the year 2050. We used the country classification and grouping as defined in Calzadilla et al. (2011a). The regions covered in this study are: the USA; Canada; Japan and South Korea (JPK); Western Europe (WEU); Australia and New Zealand (ANZ); Eastern Europe (EEU); Former Soviet Union (FSU); Middle East (MDE); Central America (CAM); South America (SAM); South Asia (SAS); South-east Asia (SEA); China (CHI); North Africa (NAF); Sub-Saharan Africa (SSA) and the rest of the world (RoW).

2.2. Drivers of change

We identified five main drivers of change: population growth, economic growth, consumption patterns, global production and trade pattern and technology development. Table 2 shows the drivers and associated assumptions used in this study.

Table 2 Drivers and assumptions per scenario.

Driver	Scenario S1: Global market	Scenario S2: Regional markets	Scenario S3: Global sustainability	Scenario S4: Regional sustainability
Population growth	Low-fertility	High-fertility	Low-fertility	Medium-fertility
Economic growth ^a	A1	A2	B1	B2
Consumption patterns	Western high meat	Western high meat	Less meat	Less meat
Diet	Western high meat	Western high meat	Less meat	Less meat
Bio-energy demand	Fossil-fuel domination	Biofuel expansion	Drastic biofuel expansion	Drastic biofuel expansion
Global production and trade pattern	Trade liberalization (A1B + TL2)	Self-sufficiency (A2 + SS1)	Trade liberalization (A1B + TL1)	Self-sufficiency (A2 + SS2)
Technology development	Decrease in blue water footprints in agriculture	Decrease in blue water footprints in agriculture	Decrease in green and gray water footprints in agriculture Decrease in blue and gray water footprints in industries and domestic water supply	Decrease in green and gray water footprints in agriculture Decrease in blue and gray water footprints in industries and domestic water supply

^a The scenario codes refer to the scenarios as used by the IPCC (Nakicenovic et al., 2000).

2.3. Population growth

Changes in population size are a key factor determining the future demand for goods and services, particularly for food items (Godfray et al., 2010; Kearney, 2010; Lutz and KC, 2010; Schmidhuber and Tubiello, 2007). The IPCC scenarios (A1, A2, B1, and B2) used population projections from both the United Nations (UN) and the International Institute for Applied Systems Analysis (IIASA). The lowest population trajectory is assumed for the A1 and B1 scenario families and is based on the low population projection of IIASA. The population in the A2 scenario is based on the high population projection of IIASA. IPCC uses UN's medium-fertility scenario for B2. We used UN-population scenarios (UN, 2011) for all our scenarios: the UN high-fertility population scenario for S2, the UN medium-fertility population scenario for S4 and the UN low-fertility population scenario for S1 and S3. Population projections are given in Table 3.

2.4. Economic growth

We assumed that the water footprint of industrial consumption is directly proportional to the gross domestic product (GDP). We used GDP changes as described in IPCC scenarios A1, A2, B1, and B2 for S1, S2, S3 and S4, respectively. The changes in GDP per nation are taken from the database of the Centre for International Earth Science Information Network of Columbia University (CIESIN, 2002).

2.5. Consumption patterns

We distinguished two alternative food consumption patterns based on Erb et al. (2009):

- 'Western high meat': economic growth and consumption patterns accelerate in the coming decades, leading to a spreading of western diet patterns. This scenario brings all regions to the industrialized diet pattern.
- 'Less meat': each regional diet will develop towards the diet of the country in the region that has the highest calorie intake in 2000, but only 30% of the protein comes from animal sources.

We used the 'western high meat' alternative for S1 and S2 and the 'less meat' for S3 and S4. Erb et al. (2009) provide food demand per region in terms of kilocalories per capita for 10 different food categories: cereals; roots and tubers; pulses; fruits and vegetables; sugar crops; oil crops; meat of ruminants; pig meat, poultry meat and eggs; milk, butter and other dairy products; and other crops. We converted kilocalorie intake per capita to kg/cap by using conversion factors taken from FAO for the

Table 3
Population projections.

Region code	Region	S1-2050	S2-2050	S3-2050	S4-2050
1	USA	357,007,000	452,394,000	357,007,000	403,100,000
2	CAN	38,845,000	48,791,000	38,845,000	43,641,000
3	WEU	385,569,000	487,475,000	385,569,000	434,634,000
4	JPK	119,338,000	151,811,000	119,338,000	134,930,000
5	ANZ	32,903,000	41,515,000	32,903,000	37,063,000
6	EEU	93,422,000	122,034,000	93,422,000	107,097,000
7	FSU	239,902,000	320,767,000	239,902,000	278,366,000
8	MDE	403,048,000	525,568,000	403,048,000	461,667,000
9	CAM	225,896,000	304,142,000	225,896,000	262,882,000
10	SAM	419,973,000	564,683,000	419,973,000	488,073,000
11	SAS	1,990,834,000	2,660,586,000	1,990,834,000	2,308,540,000
12	SEA	655,577,000	872,810,000	655,577,000	759,206,000
13	CHI	1,130,211,000	1,479,309,000	1,130,211,000	1,295,603,000
14	NAF	200,112,000	265,577,000	200,112,000	231,496,000
15	SSA	1,731,742,000	2,204,177,000	1,731,742,000	1,960,102,000
16	RoW	81,243,000	98,602,000	81,243,000	89,589,000
17	World	8,105,622,000	10,600,241,000	8,105,622,000	9,295,989,000

year 2000 (FAO, 2012). We also took seed and waste ratios per food category into account while calculating the total food demand in 2050.

Per capita consumption patterns for fiber crops and non-food crop products were kept constant as it was in 2000. It is assumed that the change in demand for these items is only driven by population size. Per capita consumption values are taken from FAOSTAT for the year 2000 (FAO, 2012).

We integrated three different biofuel consumption alternatives into our scenarios. We used biofuel consumption projections as described by Msangi et al. (2010). They used the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to estimate biofuel demand for 2050 for three different alternatives:

- Baseline: Biofuel demand remains constant at 2010 levels for most of the countries. This scenario is a conservative plan for biofuel development. This is used in S1.
- Biofuel expansion: In this scenario, it is assumed that there will be an expansion in biofuel demand towards 2050. It is based on current national biofuel plans. This is applied in S2.
- Drastic biofuel expansion: Rapid growth of biofuel demand is foreseen for this scenario. The authors developed this scenario in order to show the consequences of going aggressively for biofuels. This option is used for the S3 and S4 scenarios.

Msangi et al. (2010) provide biofuel demand in 2050 in terms of crop demands for the USA, Brazil and the EU (Table 4). We translated their scenarios to the regions as defined in our study by using the biofuel demand shares of nations for the year 2000. The demand shares are taken from the US Energy Information Administration (EIA, 2012).

2.6. Global production and trade pattern

The regional distribution of crop production is estimated based on Calzadilla et al. (2011a), who estimated agricultural production changes in world regions by taking climate change and trade liberalization into account. They used a global computable general equilibrium model called GTAP-W for their estimations. The detailed description of the GTAP-W and underpinning data can be found in Berritella et al. (2007) and Calzadilla et al. (2010, 2011b). In their study, trade liberalization is implemented by considering two different options:

- Trade liberalization 1 (TL1): This scenario assumes a 25% tariff reduction for all agricultural sectors. In addition, they assumed zero export subsidies and a 50% reduction in domestic farm support.
- Trade liberalization 2 (TL2): It is a variation of the TL1 case with 50% tariff reduction for all agricultural sectors.

In addition, Calzadilla et al. (2011a) elaborated potential impacts of climate change on production and trade patterns considering IPCC A1B and A2 emission scenarios. In total, they constructed 8 scenarios for 2050 considering two climate scenarios (A1B and A2), two trade

Table 4
Biofuel demand in 2050 for different scenarios (in tons.).

Crop	Region	Baseline	Biofuel expansion	Drastic biofuel expansion
Cassava	World	660,000	10,640,000	21,281,000
	EU	97,000	1,653,000	3,306,000
Maize	USA	35,000,000	130,000,000	260,000,000
	RoW	2,021,000	30,137,000	60,274,000
	Brazil	16,000	197,000	394,000
Oil seeds	EU	1,563,000	18,561,000	37,122,000
	USA	354,000	3,723,000	7,447,000
	RoW	530,000	5,172,000	10,344,000
Sugar	Brazil	834,000	14,148,000	28,297,000
	USA	265,000	5,840,000	11,680,000
	RoW	163,000	2,785,000	5,571,000
Wheat	EU	1,242,000	15,034,000	30,067,000
	RoW	205,000	3,593,000	7,185,000

Source: Msangi et al. (2010).

liberalization scenarios (TL1 and TL2) and their combinations (A1B + TL1, A1B + TL2, A2 + TL1, A2 + TL2). For the S1 and S3 scenarios, we considered production changes as estimated in A1B + TL2 and A1B + TL1 respectively. We used the A2 for the S2 and S4 scenarios but we also introduced self-sufficiency options to S2 and S4 as described below:

- Self-sufficiency (SS1): This alternative assumes 20% of reduction in import of agricultural products (in tons) by importing regions compared to the baseline in 2050. Therefore, exporting regions are reducing their exports by 20%. This is applied in S2.
- Self-sufficiency (SS2): In this alternative, we assumed 30% reduction in imports by importing nations relative to the baseline in 2050. This option is used for S4.

2.7. Technology development

The effect of technology development is considered in terms of changes in water productivity in agriculture, wastewater treatment levels and water use efficiencies in industry. For scenarios S3 and S4, we assumed that the green water footprints of crops get reduced due to yield improvements and for scenarios S1 and S2 we assumed that the blue water footprints of crops diminish as a result of improvements in irrigation technology. We assigned a percentage decrease to green and blue water footprints for each scenario based on the scope for improvements in productivity as given in De Fraiture et al. (2007), who give levels of potential improvement per region in a qualitative sense. For scenarios S1 and S2 we assume reductions in blue water footprints in line with the scope of improved productivity in irrigated agriculture per region as given by De Fraiture et al. (2007). For scenarios S3 and S4 we assume reductions in green water footprints in line with the scope for improved productivity in rainfed agriculture per region, again taking the assessment by De Fraiture et al. (2007) as a guideline. For scenarios S3 and S4 we took reductions in gray water footprints similar to the reductions in green water footprints. To quantify the qualitative indications of reduction potentials in De Fraiture et al. (2007), we assigned a reduction percentage of 20% to 'some' productivity improvement potential, 30% to 'good' productivity improvement potential and 40% for 'high' productivity improvement potential.

To reflect improvements in wastewater treatment levels and blue water use efficiencies, we applied a 20% reduction in the blue and gray water footprints of industrial products and domestic water supply in S3 and S4 (β factor). β factor is 1 if there is no reduction and 0.8 if a reduction is applied in the scenarios.

2.8. Estimation of water footprints

This study follows the terminology of water footprint assessment as described in the *Water Footprint Assessment Manual* (Hoekstra et al., 2011). The water footprint is an indicator of water use that looks at both direct and indirect water use of a consumer or producer. Water use is measured in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time. The water footprint of an individual or community is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community. The 'water footprint of national (regional) production' refers to the total freshwater volume consumed or polluted within the territory of the nation (region). This includes water use for making products consumed domestically but also water use for making export products. It is different from the 'water footprint of national (regional) consumption', which refers to the total amount of water that is used to produce the goods and services consumed by the inhabitants of the nation (region). This refers to both water use within the nation (region) and water use outside the territory of the nation (region), but is restricted to the water use behind the products consumed within the nation (region). The water footprint of

national (regional) consumption thus includes an internal and external component. The internal water footprint of consumption is defined as the use of domestic water resources to produce goods and services consumed by the national (regional) population. It is the sum of the water footprint of the production minus the volume of virtual-water export to other nations (regions) insofar as related to the export of products produced with domestic water resources. The external water footprint of consumption is defined as the volume of water resources used in other nations (regions) to produce goods and services consumed by the population in the nation (region) considered. It is equal to the virtual-water import minus the volume of virtual-water export to other nations (regions) because of re-export of imported products.

2.8.1. Water footprint of agricultural consumption and production

2.8.1.1. Regional consumption of food items. The food consumption $c_f(c,r)$ n ton/year related to commodity group c in region r in the year 2050 is defined as:

$$c_f(c,r) = \text{pop}(r) \times \text{kcal}(c,r) \times f_{\text{ton/kcal}} \quad (1)$$

where $\text{pop}(r)$ is the population in region r in 2050 and $\text{kcal}(c,r)$ the daily kilocalorie intake per capita related to commodity group c in region r in this year. The coefficient $f_{\text{ton/kcal}}$ the conversion factor from kcal/cap/day to ton/cap/year, which is obtained from FAO (2012). Population and kcal values per region for the year 2050 are obtained from UN (2011) and Erb et al. (2009), respectively.

2.8.1.2. Regional consumption of fibers and other non-food items. The fiber and other non-food consumption $c_{nf}(c,r)$ in ton/year, related to commodity group c in region r in 2050 is defined as:

$$c_{nf}(c,r) = \sum_n (\text{pop}(n) \times f_c(c,n)|_{t=2000}), \quad (2)$$

where $f_c(c,n)|_{t=2000}$ is the per capita demand for commodity group c in nation n that is located in region r , in 2000, which is obtained from FAO (2012).

2.8.1.3. Regional consumption of biofuel. Crop use for biofuels $c_b(c,r)$ in ton/year, related to commodity group c in region r in 2050 is defined as:

$$c_b(c,r) = \sum_n (C_b(c) \times f_b(n)|_{t=2000}) \quad (3)$$

where $C_b(c)$ is the crop use for biofuels in 2050 regarding commodity group c , taken according to one of the scenarios as defined in Msangi et al. (2010), and $f_b(n)|_{t=2000}$ the energy crop share in 2000 of nation n that is located in region r is taken from EIA (2012).

2.8.1.4. Global consumption. Total consumption for each commodity group in the world, in ton/year, is calculated as:

$$C_f(c) = \sum_r c_f(c,r) \quad (4)$$

$$C_{nf}(c) = \sum_r c_{nf}(c,r) \quad (5)$$

$$C_b(c) = \sum_r c_b(c,r). \quad (6)$$

2.8.1.5. Global production. We assume that, per commodity group, total production meets total consumption:

$$P_f(c) = C_f(c) \quad (7)$$

$$P_{nf}(c) = C_{nf}(c) \quad (8)$$

$$P_b(c) = C_b(c). \quad (9)$$

2.8.1.6. Production shares of the regions. The expected production $p(c,r)$ (ton/year) related to commodity group c in region r is defined as the multiplication of the production share $f_p(c,r)$ of region r and the total production of commodity group c in the world.

$$p(c,r) = P(c) \times f_p(c,r) \quad (10)$$

Production shares of the regions per scenario are taken from [Calzadilla et al. \(2011a\)](#).

2.8.1.7. Trade. The surplus $s(c,r)$ (ton/year) related to commodity group c in region r is defined as the difference between in production p and consumption c :

$$s(c,r) = p(c,r) - c(c,r). \quad (11)$$

Net import i (ton/year) per commodity group and per region is equal to the absolute value of the surplus if s is negative. Similarly, net export e is equal to the surplus if s is positive:

$$i(c,r) = \begin{cases} |s|, & s < 0 \\ 0, & s \geq 0 \end{cases} \quad (12)$$

$$e(c,r) = \begin{cases} 0, & s \leq 0 \\ s, & s > 0 \end{cases}. \quad (13)$$

Trade, T (tons/year) of commodity group c , from exporting region r_e to importing region r_i is estimated as:

$$T(c, r_e, r_i) = i(c, r_i) \times f_e(c, r_e), \quad (14)$$

where $i(c, r_i)$ refers to the amount of import of commodity group c by importing region r_i and f_e to the export fraction of exporting region r_e , which is calculated as the share of export of region r_e in the global export of commodity group c .

2.8.1.8. Unit water footprint per agricultural commodity group per region. The unit water footprint, $WF(c,r)$ (m^3/ton), of commodity group c produced in region r is calculated by multiplying the unit WF of the commodity group in 2000 with a factor, α , to account for productivity increase:

$$WF(c,r) = WF(c,r)|_{t=2000} \times \alpha(r). \quad (15)$$

The factor α is determined per scenario as described in [Section 2.2](#). The unit water footprints of commodities per region in 2000 are obtained from [Mekonnen and Hoekstra \(2010a,b\)](#).

2.8.1.9. Water footprint of agricultural production. The water footprint of production related to commodity group c in region r is calculated as:

$$WF_{p,a}(c,r) = p(c,r) \times WF(c,r). \quad (16)$$

2.8.1.10. Virtual water flows. The net virtual water flow VW ($m^3/year$) from exporting region r_e to importing region r_i as a result of trade in commodity group c is calculated by multiplying the commodity trade $T(c, r_e, r_i)$ between the regions and the unit water footprint $WF(c,r)$ of the commodity group in the exporting region:

$$VW(c, r_e, r_i) = T(c, r_e, r_i) \times WF(c, r_e). \quad (17)$$

2.8.1.11. Water footprint of consumption of agricultural commodities. The water footprint of consumption $WF_{c,a}(c,r)$ ($m^3/year$) related to the consumption of commodity group c in region r is calculated as the water footprint of production of that commodity, $WF_p(c,r)$ in region r plus the net virtual-water import to the region related to that commodity.

$$WF_{c,a}(c,r) = WF_p(c,r) + \sum_{r_e} VW(c, r_e, r_i) \quad (18)$$

2.8.2. Water footprint of industrial consumption and production

2.8.2.1. Water footprint of consumption of industrial commodities. The water footprint related to the consumption of industrial commodities $WF_{c,i}(r)$ ($m^3/year$) in region r in 2050 is calculated by multiplying the water footprint of industrial consumption in 2000 by the growth in GDP and a factor β representing productivity increase (see [Section 2.2](#)).

$$WF_{c,i}(r) = \sum_n \left(WF_{c,i}(n)|_{t=2000} \times \frac{GDP_{2050}(n)}{GDP_{2000}(n)} \times \beta \right) \quad (19)$$

The water footprint related to consumption of industrial commodities in nation n in 2000 is taken from [Mekonnen and Hoekstra \(2011\)](#). GDP changes are taken from [CIESIN \(2002\)](#).

2.8.2.2. Water footprint of industrial production. The water footprint of industrial production $WF_{p,i}(r)$ ($m^3/year$) in region r in 2050 is calculated by multiplying the global water footprint of industrial consumption in 2050 by the share of the water footprint of industrial production of region r in the global water footprint of industrial production in 2000.

$$WF_{p,i}(r) = \sum_r WF_{c,i}(r) \times \frac{WF_{p,i}(r)}{\sum_r WF_{p,i}(r)} \Big|_{t=2000} \quad (20)$$

The water footprint of industrial production per region r in 2000 is taken from [Mekonnen and Hoekstra \(2011\)](#).

2.8.3. Water footprint of domestic water supply

The water footprint of domestic water supply per region in 2050, $WF_{dom}(r)$ ($m^3/year$), is calculated by multiplying the population in 2050 with the water footprint of domestic water supply per capita in 2000 and factor β representing productivity increase:

$$WF_{dom}(r) = \sum_n \left(pop(n) \times WF_{dom,cap}(n)|_{t=2000} \times \beta \right). \quad (21)$$

The data for the water footprint of domestic water supply in 2000 are taken from [Mekonnen and Hoekstra \(2011\)](#).

3. Results

3.1. Water footprint of production

The WF of production in the world in 2050 has increased by 130% in S1 relative to the year 2000 ([Table 5](#)). In S2, the WF of production shows an increase of 175%, in S3 30% and in S4 46%. The increase in the total WF of production is highest for industrial products in S1 (600%). The WF of agricultural production is higher in S1 and S2 (112 and 180% more than 2000 values) than in S3 and S4 (18 and 38% more than 2000). Among the scenarios, S2, the scenario with the highest populations and high meat consumption, has the largest WF of production. The WF of production related to domestic water supply increases by 18% in S1, 55% in S2, –6% in S3 and 9% in S4.

In 2000, approximately 91% of the total WF of production is related to agricultural production, 5% to industrial production and 4% to

Table 5

Percentage change in the water footprint of production compared to 2000. 'A' refers to WF of agricultural production, 'D' refers to WF of domestic water supply, 'I' refers to WF of industrial production and 'T' refers to total WF.

Region	S1				S2				S3				S4			
	A	D	I	T	A	D	I	T	A	D	I	T	A	D	I	T
USA	105	24	16	87	154	57	20	128	49	-1	-9	38	59	12	-13	46
Canada	139	26	57	118	193	58	44	161	84	1	37	70	80	13	18	66
WEU	19	-3	-45	12	51	22	-28	42	-34	-23	-57	-36	-28	-13	-46	-29
JPK	-52	-20	-16	-46	-24	1	-15	-21	-75	-36	-31	-68	-60	-28	-34	-55
ANZ	221	40	-75	217	255	77	-50	251	55	12	-77	54	34	26	-57	33
EEU	50	-24	833	150	85	0	274	107	-17	-39	393	36	-17	-30	355	31
FSU	46	-18	1,649	135	83	10	531	105	-12	-34	735	30	-11	-24	529	19
MDE	40	44	208	46	157	88	80	151	1	15	122	5	78	32	41	74
CAM	143	21	341	142	204	63	127	196	37	-3	198	39	44	13	142	45
SAM	372	24	474	361	441	66	158	422	172	-1	262	168	149	15	160	144
SAS	67	38	1,160	84	149	85	353	150	-10	11	1,495	16	25	28	653	36
SEA	127	32	953	151	191	76	257	188	32	6	458	45	37	22	400	49
CHI	89	-12	1,885	137	127	16	338	129	-22	-29	555	-6	-22	-19	967	6
NAF	32	43	533	44	81	90	236	85	2	14	651	17	27	32	112	29
SSA	179	122	863	181	367	183	243	364	78	78	649	81	184	101	335	184
RoW	114	-9	71	106	195	11	12	177	12	-27	-11	9	34	-20	110	36
World	112	18	601	130	180	55	158	175	18	-6	311	30	38	9	261	46

domestic water supply. The WF of industrial production increases its share in the total for the S1, S2 and S4 scenarios.

In all scenarios, the WF of production is dominated by the green component. However, the share of the green component decreases from 76% in 2000 to 74% in 2050 in S1 (Fig. 2). The share of the blue component decreases from 10% in 2000 to 7% in 2050 in S1. The gray WF increases its share from 14% in 2000 to 19% in S1. The shares of the green, blue and gray WF of production in S2 are 82, 7, and 11% respectively. The share of the green component falls down to 68 and 69% in S3 and S4, while an increase is observed in the share of blue WF.

Among the regions, SAM and ANZ show the highest increase in the total WF of production in S1. The increase in ANZ is 217% for S1, 251% for S2, 54% for S3 and 33% for S4. The increase is quite significant for SAM as well (361, 422, 168, and 144% for S1, S2, S3 and S4, respectively). SSA increases its water footprint of production 181% in S1, 364% in S2, 81% in S3 and 184% in S4. The USA, CAM, Canada, SEA, EEU, FSU, MDE, NAF and SAS are the other regions, which have a larger WF of production in 2050 compared to 2000 in all scenarios.

The WF of JPK's production decreases for all scenarios. The change is -46% for S1, -21% for S2, -68% for S3 and -55% for S4. This relates to the fact that JPK increasingly externalizes its WF of consumption towards 2050. The WF of production in WEU increases in S1 and S2 by 12 and 42%, respectively, but decreases for S3 and S4, by 36 and 29% relative to 2000 values. Despite the increase in the WF of production in China in S1 and S2 (by 137 and 129%), a decrease is observed in S3 (6%).

The WF of industrial production shows a drastic increase relative to 2000 for CHI, FSU and SAS in S1. Industrial WFs in these regions increase by a factor of more than 10 times, up to 18 times for CHI. Other regions with high industrial WF increase in S1 are SSA, NAF, SEA, SAM and CAM.

These regions have a larger WF of industrial production in S2 as well. WEU, ANZ and JPK have a smaller WF of industrial production in 2050 compared to 2000, in all scenarios.

We run a scenario with a changed global production pattern under trade liberalization (TL1) as the only driver of change to the baseline in 2050. We applied changes in global production as described in Caldazilla et al. (2011). The results are shown in Fig. 3. Change in global agricultural production due to trade liberalization has a limited effect on the global WF of production (Fig. 3). On a regional basis, it increases the WF of production in Canada, CHI, JPK, ANZ, MDE, SAM and SEA and decreases the WF in the USA, WEU, EEU, FSU, CAM, NAF, SSA and SAS. However, in all cases the change is not more than 2%.

3.2. Virtual water flows between regions

Net virtual water import per region for each scenario is given in Table 6. The regions WEU, JPK, SAS, MDE, NAF and SSA are net virtual water importers for all scenarios in 2050. The USA, Canada, ANZ, EEU, FSU, CAM, SAM, SEA and CHI are net virtual water exporters in 2050.

All net virtual water-exporting regions in 2000 stay net virtual water exporters in all 2050 scenarios. Net virtual water export from these regions increases in S1 and S2 compared to 2000, except for Canada and SEA. SAM, FSU and the USA substantially increase their net virtual water export in S1 and S2. SAM becomes the biggest virtual water exporter in the world in 2050 for all scenarios and increases its net virtual water export around 10 times in S1 and S2. The change is also large in S3 and S4, with an increase by a factor 6 and 5, respectively. Another region that will experience a significant increase in net virtual water export is the FSU. Compared to 2000, the net virtual water flow leaving this region becomes 9 times larger in S1, 6 times in S2 and S3, and 4 times in S4. The net virtual water export from the USA increases by a factor 3 in both S1 and S2 relative to 2000. The net virtual export from the USA decreases in S3 and S4 compared to 2000. Although Canada continues to be a net virtual water exporter in 2050, its virtual water export decreases below the levels of 2000 for S1, S3 and S4. Despite still being a net virtual water exporter in 2050, SEA experiences a decrease in the net virtual water export volumes compared to 2000 in all scenarios.

All net virtual water-importing regions in 2000 stay net virtual water importers in 2050 for all scenarios, except CAM and CHI, which become net virtual water exporters in 2050. The net virtual water import by WEU stays below the 2000 volume for S2 and S4. Although JPK has a slightly higher net virtual water import in S1 and S2 than 2000, it decreases its net virtual water import for the other scenarios. SSA is the region where the highest increase in virtual water import is observed in 2050. Its net virtual water import rises drastically in S1 and

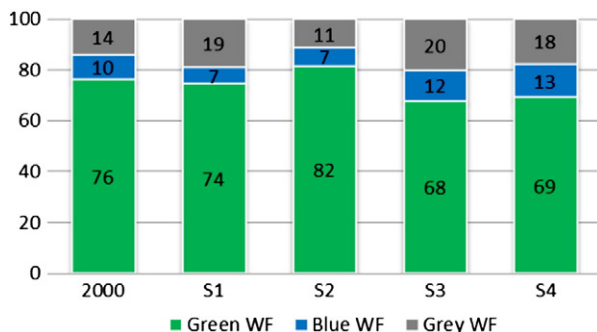


Fig. 2. Green, blue and gray WF of production as a percentage of total WF in 2000 and 2050 according to the four scenarios.

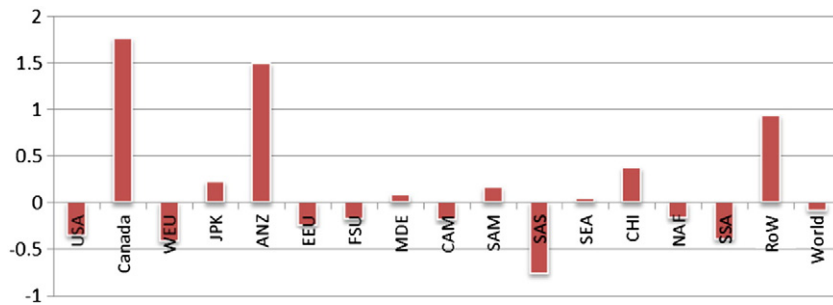


Fig. 3. Percentage change of the WF of production by trade liberalization compared (TL1) to the baseline in 2050.

S2 compared to 2000. Other regions with a significant increase in net virtual water import are MDE and SAS. The net virtual water import is the highest in S1 for all importing regions except SAS and NAF. WEU shows a different pattern, where the net virtual water import is the highest in S3.

The regions show similar patterns for the virtual water flows related to trade crop products. For the virtual water flows related to trade in animal products, this is slightly different. The USA, Canada, WEU, ANZ, EEU, FSU, CAM, SAM and CHI are net virtual water exporters and JPK, MDE, SAS, SEA, NAF and SSA are net virtual water importers regarding trade in animal products.

The net virtual water flows related to industrial products in 2050 have a completely different structure. The USA, Canada, WEU, JPK, ANZ, EEU, MDE, CAM, SAM, NAF and SSA are the virtual water importers and FSU, SEA and CHI are net virtual water exporters related to trade in industrial products in all scenarios. SAS is a net virtual water importer in S1 and S4 and a net virtual water exporter in S2 and S3 regarding trade in industrial products. Most of the virtual water export related to industrial products comes from considering industrial products. In all regions, both net virtual water imports and exports are the highest in the S1 scenario regarding trade in industrial products. Interregional virtual water trade related to industrial products decreases from S2 to S4.

Regarding interregional blue virtual water flows, the USA, ANZ, FSU, CAM, SAM and CHI are the net exporters and Canada, JPK, SAS and SSA are the net importers in all scenarios and in 2000. Despite being a net blue virtual importer in 2000, WEU becomes a net blue virtual water exporter in S2 and S4. NAF, a net blue virtual water importer in 2000, becomes a net blue virtual water exporter in S1 and S2. In all scenarios, the biggest net blue virtual water importers are SSA and SAS, whereas the biggest net blue virtual water exporters are SAM and CHI.

CHI and FSU are the biggest net virtual water exporting regions in terms of the gray component. Other net exporting regions are Canada, SEA, SAM and ANZ, for all scenarios. The USA, WEU, JPK, MDE, CAM, SAS, NAF and SSA are the net gray virtual water importing regions in all scenarios. EEU is a net importer of gray virtual water in S1, S3 and S4 but a net exporter in S2.

3.3. Water footprint of consumption

The WF of consumption in the world increases by +130% relative to 2000 for the S1 scenario. It increases by +175% in S2, +30% in S3 and +46% in S4 (Table 7).

The WF of consumption increases significantly for the regions SSA and MDE in all scenarios. The biggest change is observed in SSA with an increase by +355% in S1, +531% in S2, +181% in S3 and +262% in S4. MDE is the region with the second highest increase: +207% for S1, +294% for S2, +106% for S3 and +146% for S4.

The USA, Canada, ANZ, CAM, SAM, EEU, SAS, SEA and NAF are the other regions with a larger WF of consumption in 2050 relative to 2000. WEU, JPK, FSU and CHI have a larger WF of consumption in S1/S2 and a smaller in S3/S4 relative to 2000. In many regions of the world, S2 shows the largest WF of consumption. S4 shows larger WF values than S3.

The largest component of the total WF of consumption is green (67–81% per scenario), followed by gray (10–20%) and blue (7–13%). Consumption of agricultural products has the largest share in the WF of consumption, namely 85–93% for all scenarios. The share of domestic water supply is 2–3% and of industrial products 4–13%.

The WF of consumption of agricultural products is 112%, 180%, 18% and 38% higher in 2050 than 2000 in S1, S2, S3 and S4, respectively. SSA and MDE show the highest increase in all scenarios. WEU, JPK,

Table 6
Net virtual water import per region ($Gm^3/year$). 'A' refers to the net virtual water import related to agricultural products, 'I' to the net virtual water import related to industrial products and 'T' to the total net virtual water import.

	2000			S1			S2			S3			S4		
	A	I	T	A	I	T	A	I	T	A	I	T	A	I	T
USA	-117	27	-91	-377	92	-284	-350	48	-303	-101	57	-44	-101	39	-62
Canada	-42	-1	-43	-43	4	-39	-48	1	-47	-37	2	-35	-31	2	-29
WEU	59	43	102	3	101	104	6	60	66	42	70	112	24	38	61
JPK	90	9	99	89	22	111	89	11	100	55	15	71	43	9	52
ANZ	-72	3	-70	-140	5	-134	-154	3	-151	-102	4	-97	-82	2	-80
EEU	-8	-2	-10	-59	46	-13	-63	3	-60	-46	11	-35	-36	15	-21
FSU	-9	-34	-43	-183	-198	-381	-200	-77	-277	-150	-109	-259	-119	-56	-174
MDE	20	5	25	416	50	465	402	14	416	261	30	291	198	11	209
CAM	14	3	18	-127	41	-86	-117	11	-106	-83	23	-60	-59	12	-48
SAM	-174	1	-173	-1,695	34	-1,661	-1,736	6	-1,730	-1,007	15	-992	-801	10	-792
SAS	232	-8	224	1,056	14	1,070	1,117	-12	1,105	625	-29	596	509	7	515
SEA	-191	-12	-203	-146	-33	-179	-149	-16	-165	-140	-25	-166	-102	-11	-113
CHI	116	-38	78	-171	-244	-415	-152	-66	-218	-101	-103	-204	-63	-97	-159
NAF	60	0	60	66	14	80	84	3	87	47	11	59	46	3	49
SSA	3	1	4	1,249	20	1,269	1,223	3	1,226	720	12	732	564	6	569
RoW	21	3	24	60	31	92	49	8	56	15	14	29	10	11	21

Table 7

Percentage change of the WF of consumption relative to 2000. 'A' refers to the WF of agricultural products, 'D' refers to the WF domestic water supply, 'I' refers to the WF of industrial products and 'T' refers to the total WF.

Region	S1				S2				S3				S4			
	A	D	I	T	A	D	I	T	A	D	I	T	A	D	I	T
USA	29	24	112	41	83	57	69	80	29	-1	50	30	39	12	28	36
Canada	48	26	95	54	91	58	52	83	5	1	55	13	14	13	38	18
WEU	19	-3	112	28	52	22	65	52	-27	-23	52	-19	-24	-13	12	-20
JPK	11	-20	113	19	39	1	50	38	-36	-36	58	-26	-29	-28	15	-25
ANZ	172	40	107	171	201	77	62	199	20	12	73	20	5	26	13	5
EEU	12	-24	1024	143	45	0	285	75	-47	-39	438	17	-41	-30	419	20
FSU	6	-18	975	61	39	10	268	51	-44	-34	366	-20	-37	-24	340	-15
MDE	198	44	720	207	309	88	229	294	99	15	436	106	153	32	152	146
CAM	100	21	865	115	165	63	264	163	9	-3	490	20	24	13	292	30
SAM	117	24	722	126	181	66	204	177	21	-1	370	27	29	15	231	32
SAS	128	38	1206	143	214	85	313	212	27	11	1399	49	55	28	676	64
SEA	96	32	769	117	160	76	169	156	2	6	317	13	16	22	338	27
CHI	79	-12	1391	113	117	16	205	116	-29	-29	346	-18	-25	-19	771	-3
NAF	65	43	811	81	122	90	298	125	25	14	881	45	50	32	171	52
SSA	353	122	1415	355	538	183	334	531	179	78	969	181	263	101	486	262
RoW	212	-9	893	240	274	11	211	259	37	-27	366	52	51	-20	400	67
World	112	18	596	130	180	55	157	175	18	-6	308	30	38	8	259	46

EEU, CHI and FSU demonstrate increases in WF of consumption in S1/S2 and decreases in S3/S4 compared to 2000. S2 is the scenario with the largest WF related to consumption of agricultural products in all regions and S3 shows the smallest values among all scenarios.

Two factors determine the WF of domestic water supply in the scenarios: population size and productivity (Eq. (21), Section 2.3.3). The scenario with the highest population projection, S2, has therefore the largest WF related to domestic water supply. S3 has the lowest values as it has a relatively low population size and a reduced WF per household. The regions that show reduction in WF of domestic water supply in S1, have population sizes lower than 2000. The reductions in S3 are due a combination of lower estimates of population and reduced per capita domestic water use. Regarding the WF of consumption of industrial products, all regions show a significant increase compared to 2000, in all scenarios.

Fig. 4 shows the contribution of different consumption categories to the total WF of consumption for 2000 and for different scenarios. Consumption of cereals has the largest share (26%) in the total WF in

2000. Other products with a large share are meat (13%), oil crops (12%), poultry (10%), vegetables and fruits (8%) and dairy products (8%). Meat consumption becomes the major contributor to the WF of consumption in S1 and S2 (19–20%). Oil crops, vegetables, and fruits are the other consumption categories that have a large contribution to the total WF of consumption in S1 and S2. The share of cereals decreases to 19% in S2 and to 17% in S1. Cereal consumption has the largest share (30%) in S3 and S4, which are characterized by low meat content diets. Oil crops follow cereals with 16%. The share of meat consumption decreases in these scenarios to 13%. Consumption of industrial products becomes another significant contributor in S3 and S4 (7%).

Cereals are the largest contributor to the blue WF of consumption in all scenarios. Its share is 25% in S1 and S2, and 39% in S3 and S4. Cereals are followed by vegetables and fruits in S1 and S2 (17%) and by oil crops for S3 and S4 (14%). Other product groups with a large share in the blue WF of consumption are meat, poultry, dairy products and sugar crops. The gray WF of consumption is dominated by industrial products and domestic water supply in all scenarios. The share of industrial products

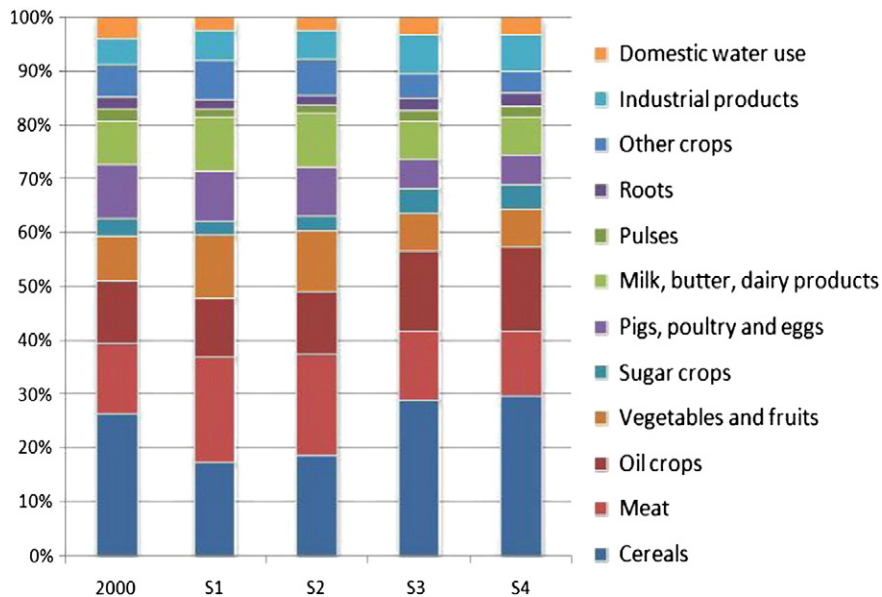


Fig. 4. The contribution of different consumption categories to the total WF of consumption in the world.

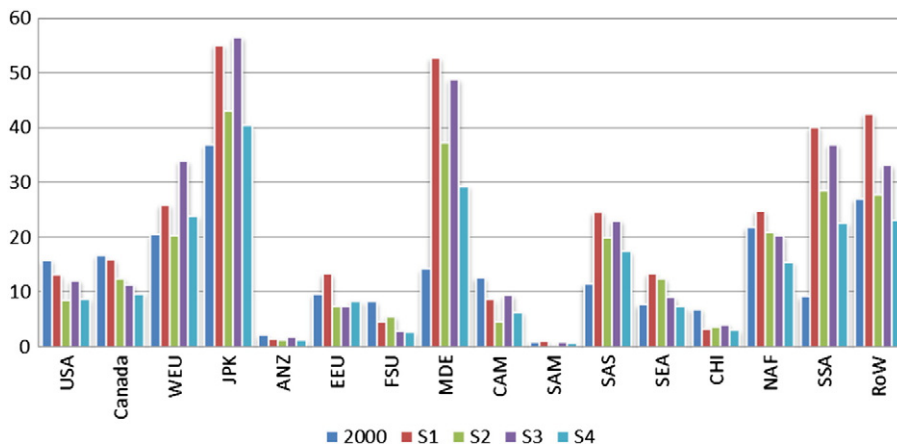


Fig. 5. The share of the external water footprint of consumption in the total WF of consumption (%).

in the gray WF of consumption increases to 36% in S1 and S2 and 43% in S3 and S4, while it is 28% in 2000. The WF related to domestic water supply is the second largest contributor to the gray WF of consumption, with 18% for all scenarios.

The share of the external WF of consumption in the total is given in Fig. 5. Regions with large external WFs apparently depend upon freshwater resources in other regions. The regions with a large share of external footprint in 2000, like JPK and MDE, increase their dependency on external water resources in 2050 significantly. For example, the share of the external WF in JPK will go up to 55% in S1 and to 56% in S3, in which trade is relatively liberalized compared to 2000. Our scenarios show that WEU, JPK, MDE, SAS, SEA and SSA increase their share of external WF while the other regions decrease their dependencies. The regions with increased production, like the USA, Canada and ANZ, decrease their external WF of consumption.

Fig. 6 shows the change in the WF of consumption per capita per region for different scenarios relative to 2000 volumes. The world average WF of consumption per capita increases by +73% in S1, +58% in S2, -2% in S3 and 10% in S4 compared to 2000 volumes. All the regions increase their WF of consumption per capita in S1 and S2 compared to 2000. Canada, WEU, JPK, FSU, CAM, SEA, ANZ, CHI decrease their WF of consumption per capita in S3 compared to 2000. The other regions have a larger WF of consumption per capita in S3 than 2000. Most of the regions have smaller WFs of consumption per capita in S4 than 2000 except EEU, MDE and SSA. The regions with relatively low meat consumption in 2000 experience the biggest change in S1 and S2, which assume western meat diet patterns in 2050. SSA is a good example for this, where per capita WF of consumption increases by +92% in S2. The change in the regions with high meat diet in 2000 already (the USA, Canada and WEU) is lower than in other regions in S1 and S2. In the year 2000, the USA has the largest WF per capita in the world. Other regions with a large per capita WF of consumption are Canada, ANZ, FSU and WEU. In 2050, for the S1 and S2 scenarios, EEU has the largest WF per capita and is followed by the USA, FSU and Canada. WEU goes down in the ranking and has a smaller WF of consumption per capita than the average of the world in 2050. The regions with larger WF of consumption per capita than the world average in 2000 also have higher values in S3 and S4, except WEU. The regions with relatively small WFs will continue to have lower values per capita in all scenarios (SEA, CHI, and SAS). Among the scenarios, S1 demonstrates the largest WF of consumption per capita and S4 shows the smallest.

4. Discussion and conclusion

This study is the first global water footprint scenario study. It explores how the water footprint of humanity will change towards 2050 under four alternative scenarios, which differ from each other in terms

of specific trajectories for the main drivers of change. Although we included the major drivers of change in our analysis, some of them were kept outside the scope of this study. First, we excluded the impact of resource availability. The constraints related to water and land availability are only addressed implicitly in the production and trade scenarios. A future step would be to integrate such limitations explicitly. We excluded CO₂ fertilization effects in yields and climate change effects on crop water use. Another limitation is that we assumed a homogeneous and single industrial sector in estimating the water footprint of industrial production and consumption. Biofuel projections for each scenario are taken from Msangi et al. (2010) which quantified biofuel projections per scenario according to the national biofuel policies valid before 2010. However, the EU has recently announced that they would reduce their biofuel-use target for 2020 by half. Therefore, our WF of biofuel estimates are higher than current biofuel targets announced by the EU.

This study has uncertainties related to input data used and the limitations of the related studies in addition to simplifications of the model used for calculations. The unit water footprints are taken from Mekonnen and Hoekstra (2010a) who explains that the uncertainties related to unit water footprints are in the range of ±10–20% compared to observed data and ±5–10% compared to the other modeling exercises. They explained that the differences are due to data regarding cultivated and irrigated areas, growing periods, crop parameters, soil and climate used in their model. Furthermore, the model used in calculation in this study simplifies the trade between the countries by aggregation of national trade to regional, which brings additional uncertainties into the results. The outcomes of this study should be interpreted considering limitations and uncertainties associated with it.

Our analysis shows that water footprints can radically change from one scenario to another and are very sensitive to the drivers of change. Among all the scenarios, WF of production and consumption are the highest in S2, regional markets, which is driven by high population growth with increased meat and dairy consumption. S1, global market, has the second largest WF of production and consumption. Its storyline has one of the lowest population sizes but is characterized by high economic growth and increased meat and dairy products. S3 and S4 are characterized by increased population but decreased meat and dairy product consumption compared to the year 2000.

The study shows how different drivers will change the level of water consumption and pollution globally in 2050. These estimates can form a basis for a further assessment of how humanity can mitigate future freshwater scarcity. We showed that reducing humanity's water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns and other drivers change. This study can help to guide corrective policies at both national and international levels, and to set priorities for the years ahead in order to achieve sustainable and equitable use of the world's fresh water resources.

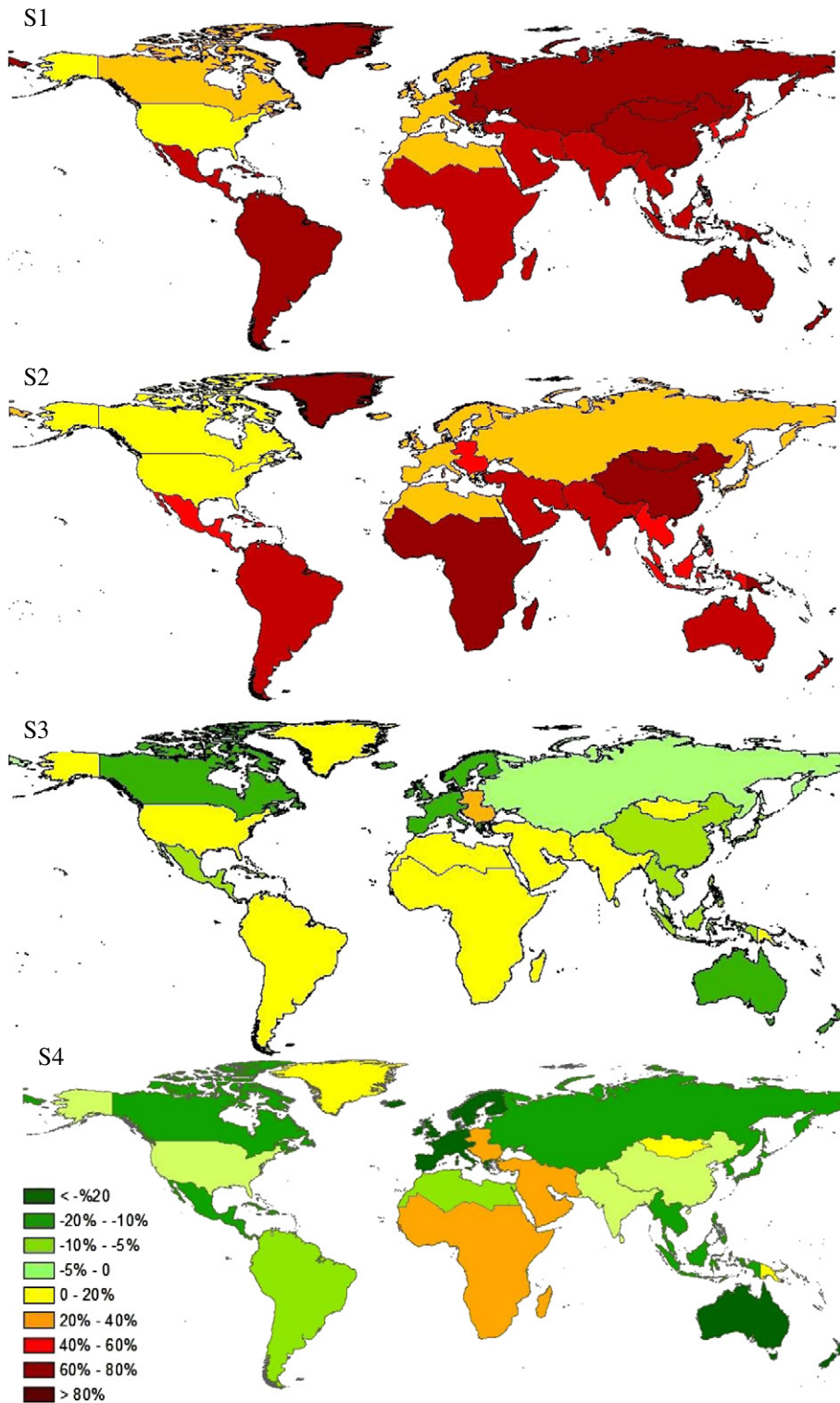


Fig. 6. Percentage change of the WF of consumption per capita relative to 2000.

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