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Global consumptive water use for crop production: The importance of green water and virtual water

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[1] Over the last 4 decades the use of blue water has received increasing attention in water resources research, but little attention has been paid to the quantification of green water in food production and food trade. In this paper, we estimate both the blue and green water components of consumptive water use (CWU) for a wide range of agricultural crops, including seven cereal crops, cassava, cotton, groundnuts, potatoes, pulses, rapeseed, soybeans, sugar beets, sugarcane, and sunflower, with a spatial resolution of 30 arc min on the land surface. The results show that the global CWU of these crops amounted to 3823 km^3 a^{-1} for the period 1998–2002. More than 80% of this amount was from green water. Around 94% of the world crop-related virtual water trade has its origin in green water, which generally constitutes a low-opportunity cost of green water as opposed to blue water. High levels of net virtual water import (NVWI) generally occur in countries with low CWU on a per capita basis, where a virtual water strategy is an attractive water management option to compensate for domestic water shortage for food production. NVWI is constrained by income; low-income countries generally have a low level of NVWI. Strengthening low-income countries economically will allow them to develop a virtual water strategy to mitigate malnutrition of their people.

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1. Introduction

[2] Global water withdrawals have almost doubled over the past 40 years [*Gleick*, 2003a]. To increase food production, the irrigated area has been expended from 138 million ha in 1961 to 277 million ha in 2003 [*Food and Agriculture Organization of the United Nations* (*FAO*), 2006]. In the coming decades, water uses will continue to increase as a result of demographic and economic growth [*Rosegrant and Ringler*, 2000].

[3] Understanding the geographic distribution of both water resources and agriculture water requirements allows the prediction of future trends in agricultural production and trade. Several efforts have been made to sketch global patterns of water use for agriculture and other sectors such as industry, urban and rural domestic water supply (Table 1). Despite the progress made in these water use assessments, studies either lack spatial details or are limited to blue water uses, or focus on water withdrawal while ignoring consumptive water uses. In addition these assessments are generally conducted at national or regional level, thus disguising the spatial distribution of supply and demand within a country or region. Finer spatial resolution is necessary, especially for large countries such as China and the USA comprising a range of different climatic conditions.

[4] Water resources can be divided into green and blue water. The concept of green water was first introduced by *Falkenmark* [1995] referring to the total crop evaporation during crop growth. Later, green water resource has been generally used to refer to the water that comes from precipitation, is stored in the soil, and subsequently fed back to the atmosphere [*Falkenmark and Rockström*, 2006; *Savenije*, 2000] through crop evaporation. In contrast, blue water refers to the water in rivers, lakes, reservoirs, ponds and aquifers [*Rockström*, 1999]. Both green and blue water resources are important for food production. Rain-fed agriculture uses green water only, while irrigated agriculture uses both green and blue water. Without considering green water, water use assessments are incomplete.

[5] Consumptive water use (CWU) here is consistent with the term used by *Falkenmark and Lannerstad* [2005]. It has the same meaning as another term "water depletion" (the water use or removal from a water basin that renders it unavailable for further use) defined by *Molden* [1997]. For crop production, CWU refers to the total evaporative use of a crop during the crop growth period, often termed "evapotranspiration." Here the term total crop evaporation is used in agreement with *Savenije* [2004]. It needs to be pointed out that CWU is different from the term "water consumption" defined by *Gleick* [2003b], which refers to the water withdrawn from a source and made unusable for reuse in the same water basin.

[6] In many water scarce countries, an increasing amount of food is imported to meet domestic food demand [*Yang et al.*, 2006]. For these countries, importing food is equivalent to importing virtual water to mitigate the physical lack of water for domestic food production. Virtual water is defined

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Table 1. Important Studies on Global Water Use Assessment

Literature	Spatial Resolution	"Water" Resolution[a]	Type of Water Uses[b]
Shiklomanov [2000]	country	BWW	A, I, M, R
Postel et al. [1996]	world	CWU, BWU	A, I, M, R
Raskin et al. [1997]	country	BWW	A, I, M
Seckler et al. [1998]	country[c]	BWW, CBWU	A, I, M
Döll et al. [1999]	30 arc min	BWW, CBWU	A
Rockström et al. [1999]	world	CWU[d]	A
Shiklomanov [2000]	country	BWW, CBWU	A, I, M, R
Vörösmarty et al. [2000]	30 arc min	BWW	A, I, M
Alcamo et al. [2000]	30 arc min	BWW, CBWU	A, I, M
Döll and Siebert [2002]	30 arc min	irrigation water requirements	A
Chapagain and Hoekstra [2004]	country	CWU[d]	A

[a] BWW, blue water withdrawal; CWU, consumptive water use; CBWU, consumptive blue water use.

[b] A, agriculture; I, industry; M, municipalities; R, reservoir.

[c] China and India are split into two parts. Any other country is treated as one simulation unit.

[d] There is no separation between green and blue water use.

as the volume of water required to produce a commodity or service. The concept was introduced by Allan in the early 1990s [*Allan*, 1994] when studying the option of importing food (defined as virtual water) as opposed to liquid water to partly solve the water scarcity problems in the Middle East. Through food trade, the water used in exporting countries becomes virtual water in importing countries [*Oki and Kanae*, 2004]. With population growth and economic development, water resources are under pressure in an increasing number of countries. Unraveling the relationship between a country's CWU and virtual water trade can improve the understanding of water-food-trade relationship, and help formulate appropriate policies to deal with water scarcity. So far, this relationship has not been systematically analyzed.

[7] In this paper, we quantify CWU in food production and investigate CWU-virtual water trade relations. CWU at the global level is assessed with a spatial resolution of 30 arc min (about 50 km × 50 km in each grid near the equator). Special attention is given to the green water component of CWU for the production of 17 major crops. Virtual water trade is quantified for each crop and is summed up as a common yardstick in investigating CWU-virtual water trade relations. On the basis of the CWU and the quantity of virtual water trade, we calculate the green water proportion in both domestic crop production and virtual water trade, and examine the virtual water trade and CWU for low-, middle- and high-income countries.

2. Methods and Data

2.1. Calculation of Crop Yield, Evaporation, and Crop Water Productivity

[8] A GEPIC model has been used to simulate crop yield, total evaporation (E), and crop water productivity (CWP) for individual crops in each grid cell at the spatial resolution of 30 arc min covering the entire world. The GEPIC model is a GIS-based EPIC model designed to simulate the spatial and temporal dynamics of the major processes of the soil-crop-atmosphere-management system [*Liu et al.*, 2007a, 2007b, 2008]. Crop yield is estimated by multiplying the aboveground biomass at maturity with a water stress adjusted harvested index [*Williams et al.*, 1989]. Reference crop evaporation is calculated with a Hargreaves method [*Hargreaves and Samani*, 1985]. Potential crop transpiration is calculated by considering reference crop evaporation and a leaf area index, while potential soil water evaporation is simulated by considering reference crop evaporation and a soil cover index. Potential crop transpiration is reduced to actual crop transpiration (E_t) when soil water content is lower than a certain percentage of field capacity. Actual soil water evaporation is estimated on the basis of the top 0.2 m of soil and snow cover. The sum of crop transpiration (E_t) and soil evaporation (E_s) is the total evaporation E. The sum of E_s and E_t is often called evapotranspiration (ET). This term, commonly used in agricultural engineering, in fact stands for the total evaporation from crop growth, here indicated by the total evaporation E [*Savenije*, 2004]. Detailed description of the GEPIC model can be found in work by *Liu* [2009] and *Liu et al.* [2007b], while the EPIC model is described by *Williams et al.* [1989].

2.2. Consumptive Water Use at the Grid and National Level

[9] The product of crop harvested area A and total evaporation E during a crop growing period is defined as consumptive water use (CWU). CWU in each grid cell is calculated as

$$CWU[i] = 10 \times \sum_{p=1}^{N} (E_0[p,i] \times A_0[p,i] + E_1[p,i] \times A_1[p,i]) \quad (1)$$

where CWU[i] is the consumptive water use in a grid cell i ($m^3\ a^{-1}$). E_0 and E_1 are evaporation ($mm\ a^{-1}$) under rain-fed and irrigated conditions, respectively. A_0 and A_1 are harvested area (m^2) under rain-fed and irrigated conditions, respectively, and p is crop code. The constant 10 is used to convert mm a^{-1} into $m^3\ ha^{-1}\ a^{-1}$. N is the number of crops considered. In this paper, we selected 16 individual crops (barley, cassava, cotton, groundnuts, maize, millet, potatoes, rapeseed, rice, rye, sorghum, soybeans, sugarcane, sugar beets, sunflower, and wheat) and one crop category (pulses). For convenience, we call these crops and the crop category "17 major crops." Hence, N = 17 in this paper. The selection of the crops is based on the importance of crop commodities and the availability of data. The 17 major crops account for 63% of the total cropland area [*Ramankutty et al.*, 2008], and about three quarters of the total global crop production over the period 1998–2002 (FAO statistical databases, 2006, Food and Agriculture Organization of the United Nations, Rome, available at http://faostat.fao.org/default.aspx). The cereal crops included represent about 96% of the total global cereal harvested area and 98% of the total global cereal production (FAO statistical databases, http://faostat.fao.org/default.aspx).

[10] For irrigated agriculture, flexible automatic irrigation is set to calculate irrigation depth with the following assumptions: the model schedules an irrigation event when biomass production in 1 day is less than 90% of its potential that could have been produced had sufficient water been available. Water is always readily available when crops need it. The water amount applied in each irrigation event aims at bringing soil moisture content to field capacity, but it is limited to the depth between 30 and 100 mm d^{-1}; the interval between two neighboring irrigation events is always higher than 7 days. These assumptions are often used when exact irrigation schedules are not available [see *Cavero et al.*, 1999]. At the national level, CWU in a country *c* is calculated as the sum of the CWU of all grid cells within this country.

[11] Two issues need to be clarified here. First, since we focus on consumptive water use, water losses in delivery process are not included. Irrigation depth refers to water height added to the soil in the vicinity to crops. Second, the estimation of the consumptive blue water use does not take surface storage into account because automatic irrigation generally keeps soil moisture content not higher than field capacity. This means that the consumptive blue water use estimated refers only to the irrigation that goes into total crop evaporation. In reality, surface storage can be significant, especially for paddy rice. Because of lack of the relevant data, surface detention storage is not considered in this study.

2.3. Green Water Proportion of Consumptive Water Use

[12] The part of CWU coming from precipitation is defined as the green water use, while the part stemming from irrigation is defined as blue water use. The green water proportion (in %) is calculated as the ratio of green water use to total CWU.

[13] In rain-fed agricultural systems, green water is the only contributor to CWU. In irrigated agricultural systems, both green water and blue water contribute to CWU. In order to quantify the green water proportion of CWU in irrigated systems, two different soil water balances are performed for irrigated crops according to *FAO* [2005]. In the first soil water balance, it is assumed that soil does not receive any irrigation water. Seasonal evaporation computed with this assumption is referred to as E_0. In the second soil water balance, it is assumed that soil receives sufficient irrigation. Seasonal evaporation computed with this assumption is referred to as E_1. Green water proportion g_1 of crop *p* under irrigated conditions in grid cell *i* is calculated as

$$g_1[p,i] = \frac{E_0[p,i]}{E_1[p,i]} \tag{2}$$

[14] When both rain-fed and irrigated systems are taken into account, green water proportion *g* in a grid cell *i* is calculated as

$$g[i] = \frac{\sum_{p=1}^{N} (E_0[p,i] \times A_0[p,i] + E_1[p,i] \times A_1[p,i] \times g_1[p,i])}{\sum_{p=1}^{N} (E_0[p,i] \times A_0[p,i] + E_1[p,i] \times A_1[p,i])} \tag{3}$$

The national average green water proportion *g* in country *c* is estimated as the ratio of total national annual green water use to the total national annual CWU:

$$g[c] = \frac{\sum_{i=1}^{I_c} (CWU[i_c] \times g[i_c])}{\sum_{i=1}^{I_c} (CWU[i_c])} \tag{4}$$

where *g*[c] is the green water proportion in country *c*. *CWU*[i$_c$] and *g*[i$_c$] are consumptive water use and green water proportion in grid cell i_c, respectively. The subscript *c* indicates that grid *i* is located in country *c*. I_c is the total number of grids in country *c*.

2.4. Crop Water Productivity at the Grid and National Level

[15] CWP in each grid cell is calculated as the ratio of crop yield to *E*. The national average CWP of crop *p* in country *c* is estimated as

$$CWP[p,c] = \frac{\sum_{i=1}^{I_c} (Y_0[p,i_c] \times A_0[p,i_c] + Y_1[p,i_c] \times A_1[p,i_c])}{10 \times \sum_{i=1}^{I_c} (E_0[p,i_c] \times A_0[p,i_c] + E_1[p,i_c] \times A_1[p,i_c])} \tag{5}$$

where *CWP*[*p,c*] is the national average CWP (in kg m^{-3}) of crop *p* in country *c*. $Y_0[p, i_c]$ and $Y_1[p, i_c]$ are crop yield of crop *p* under rain-fed and irrigated conditions, respectively, in grid cell i_c. All the other symbols have the same meaning as above.

2.5. Calculation of Net Virtual Water Import (NVWI) and Export (NVWE)

[16] The net virtual water import in country *c* (*NVWI*[*c*] in m^3 per capita per year) was calculated as

$$NVWI[c] = \frac{\sum_{p=1}^{N} \left(\frac{IMP[p,c]}{CWP[p,c]} - \frac{EXP[p,c]}{CWP[p,c]} \right)}{Pop[c]} \tag{6}$$

where *IMP*[*p,c*] and *EXP*[*p,c*] are the annual imports and exports of crop *p* in country *c* (in kg a^{-1}). For an importing country *c*, provided that the imported crop *p* is not produced domestically, the world average CWP for crop *p* is used. *Pop*[*c*] represents the population in country *c*.

[17] When *NVWI*[*c*] has a positive sign, country *c* is a net importing country in respect to virtual water trade; the

Table 2. Data Sets and Their Sources Used in This Study

Data Sets	Spatial Reference	Source
Harvest area of major crops	30 arc min	*Ramankutty et al.* [2008]
Harvest area of major irrigated crops	30 arc min	*Portmann et al.* [2008]
Weather data[a]	30 arc min	*Mitchell and Jones* [2005]
Soil parameters	5 arc min	*Batjes* [2006]
Crop fertilizer application	county averages	*International Fertilizer Industry Association* [2002]
Digital elevation model	30 arc sec	*EROS Data Center* [1998]
Terrain slope	30 arc sec	U.S. Geological Survey[b]

[a] Weather data include monthly precipitation and minimum and maximum temperature.

[b] HYDRO1k, 2000, available at http://edc.usgs.gov/products/elevation/gtopo30/hydro/index.html.

opposite sign indicates a net exporting country. In the net exporting countries, the total net virtual water export, *NVWE*[*c*], is calculated with the same procedure as to *NVWI*[*c*], but expressed as a negative quantity.

2.6. Data

[18] The input data for the GEPIC model are summarized in Table 2. The crop distribution maps describe the total harvested area of each of the primary crops on a grid basis. The data on the harvested area of the primary crops for the year 2000 are obtained from the Center for Sustainability and the Global Environment (SAGE) of the University of Wisconsin at Madison, USA [*Ramankutty et al.*, 2008]. The data on the harvested area of the irrigated crops for the period 1998–2002 are taken from the Institute of Physical Geography of the University of Frankfurt (Main), Germany [*Portmann et al.*, 2008]. Both data sets are available with a spatial resolution of 30 arc min. In this study, the harvested area of the rain-fed crops in each grid cell is the difference between the total harvested area and the harvested area of the irrigated crops. This value cannot become negative. To our best knowledge, these maps are the most recent, and most detailed available data sets for land uses for the different crop types.

[19] The SAGE data are consistent with the statistical data from the Food and Agriculture Organization of the United States (FAO). For example, the harvested area of wheat is 209 million ha from SAGE and 212 million ha from FAO in 2000. For rice, the harvested area is 153 and 154 million ha from SAGE and FAO, respectively. The maps from *Portmann et al.* [2008] are currently the only source that provides high spatial resolution and crop-specific irrigated area at the global level. The maps are generated on the basis of the global map of irrigated area (GMIA) from FAO [*Siebert et al.*, 2007] (the latest version, 4.0.1). Hence, they are consistent with the GMIA, which is so far the most commonly referenced irrigation map in global water use assessments.

[20] The amount of fertilizer applied per country and crop is derived from the statistical report by the International Fertilizer Industry Association (IFA), the International Fertilizer Development Center (IFDC), the International Potash Institute (IPI), the Phosphate and Potash Institute (PPI), and the Food and Agriculture Organization of the United Nations (FAO) [*International Fertilizer Industry Association* (*IFA*), 2002]. The report provides the information on crop-specific application rate of nitrogen (N), phosphate (P_2O_5), and potash (K_2O) for major crops (including the 17 major crops) in 88 countries. These countries consumed around 94% of the total world fertilizer in 2000 (FAO statistical databases, http://faostat.fao.org/default.aspx). This data set only provides data for one specific year within the range from 1995 to 2001. Another source of fertilizer data is FAO, which reports the annual consumption rate of N, P_2O_5, and K_2O from 1961 to 2004 (FAO statistical databases, http://faostat.fao.org/default.aspx). By assuming the fertilizer application rate by a certain crop from *IFA* [2002] is proportional to the annual consumption rate from FAO statistical databases http://faostat.fao.org/default.aspx), the application rate of fertilizer for each crop was estimated for individual years, and was used in the GEPIC model.

[21] Historical monthly data on maximum temperature, minimum temperature, precipitation and number of wet days between 1998 and 2002 are obtained with a spatial resolution of 30 arc min from the Climate Research Unit of the University of East Anglia (CRU TS2.1) [*Mitchell and Jones*, 2005]. A monthly to daily weather converter (MODAWEC) model is used to generate the daily weather data [*Liu et al.*, 2009]. Soil parameters of soil depth, percent sand and silt, bulk density, pH, organic carbon content are taken from *Batjes* [2006]. Soil parameters are available for 5 soil layers (0–20, 20–40, 40–60, 60–80, 80–100 cm). The simulation resolution in this study is 30 arc min. All the data sets with different spatial resolution were first converted into the simulation resolution of 30 arc min [*Liu et al.*, 2007b]. Domestic crop production, imports and exports over the period of 1998–2002 were collected from FAO statistical database http://faostat.fao.org/default.aspx). High-, middle- and low-income countries were identified on the basis of the classification from *World Bank* [2005].

2.7. Validation of the Model

[22] Because of the lack of statistical yield on high spatial resolution, we aggregated the simulated 30 arc min crop yield into national averages and compared them with the national statistical yields from FAOSTAT. This validation method is the same as used by *Liu et al.* [2007b]. The simulated and statistical yields are quite comparable though with more or less scattering depending on the crop (Figure 1). To further the validation, we followed *Liu et al.* [2007b] and used several statistical indices (see Table 3). The results show the normalized mean square error (NMSE) values are all lower than 0.4. According to the criterion of NMSE [*Hanna*, 1988], the model performed well for all the crops. The Nash-Sutcliffe efficiency (EF) and R^2 indices showed that pulses were not simulated as well as other crops. This may be caused by the fact that pulses are a group of crops, and we used peas as a proxy for all pulses.

3. CWU and Green Water Proportion

3.1. Spatial Distribution of CWU

[23] The spatial distribution of CWU is shown in Figure 2. The highest CWU per grid cell (e.g., >300 million $m^3\ a^{-1}$) was found in most part of India, in the river basins of the Yellow River, the Huai River, the Hai River, and the Yangtze in China, in the Mississippi river basin in North

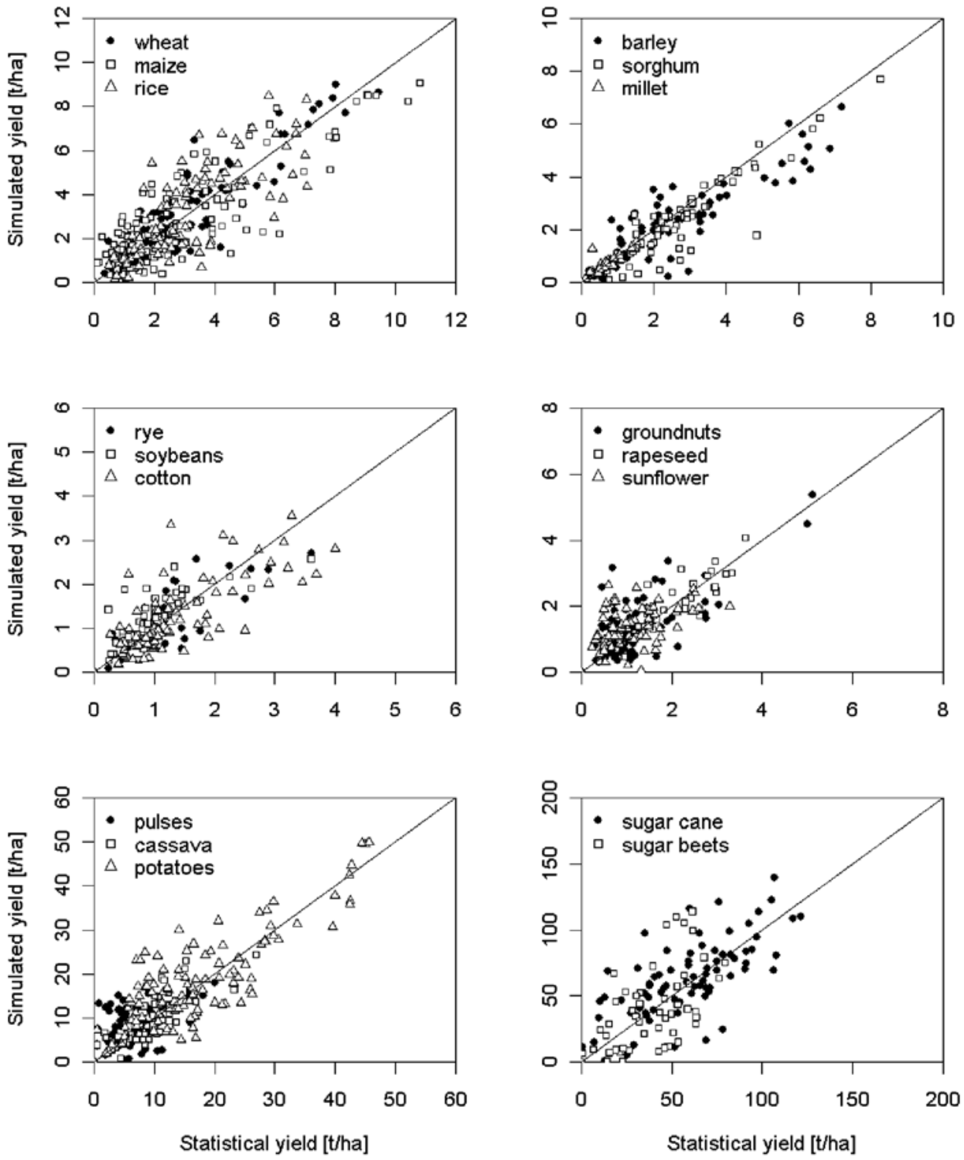

Figure 1. Comparison between simulated and statistical yields for 17 crops at the national level (1998–2002 average).

America, and some part of the Parana and Sao Francisco river basins in South America (Figure 2). These regions mainly contained grid cells with a high fraction of arable lands and permanent crops [*Ramankutty et al.*, 2008].

[24] The global annual average CWU was estimated to be 3823 km^3 a^{-1} for the period 1998–2002. Of the global CWU, over two thirds can be attributed to cereal crops (Figure 3). Wheat and rice account for two thirds of the CWU of cereal crops.

[25] Earlier studies estimated that the global CWU ranged from 2285 to 5500 km^3 a^{-1} in croplands [*Postel et al.*, 1996; *Shiklomanov*, 2000]. *Zehnder* [1997] estimated for the period 1992 to 1994 a global annual CWU of 3536 km^3 a^{-1}. In this number vegetables and fruits are not included, but meat production and preharvested and postharvested loss are part of the total. Recent studies used a finer “crop” and spatial resolution, and global CWU was calculated on the basis of crop production of individual crops in different climate zones or individual countries. *Rockström et al.* [1999] estimated global CWU for agricultural food production on the basis of individual crop production for the period 1992–1996 in temperate and tropical climate zones. The ranges of crop water productivity in both climate zones were collected for different crops from published materials. A total CWU of 6800 km^3 a^{-1} was estimated for all the crops, of which 3515 km^3 a^{-1} was for the 17 major crops studied here. The remaining of 3285 km^3 a^{-1} was mostly for forage, oil palm, natural rubber/gums, fruits and vegetables, and cereals and roots/tubers not included in this study. The study of Rockström covered a period 6 years before ours. For comparison, it was necessary to adjust his data to the same period. The adjustment method was rather straightforward. For the annual production, the rates of 1998–2002 were applied, while the CWP values used by *Rockström et al.* [1999] were unchanged. The thus adjusted average CWU for the 17 major crops became 3677 km^3 a^{-1} (with a range of CWU between 2529 and 5554 km^3 a^{-1}), very close to our estimate. *Chapagain and Hoekstra* [2004] calculated the CWU for

Table 3. Statistical Indices for the Assessment of the Model Performance

Crop	N[a]	NMSE[b]	EF[c]	*d*[d]	R^2	Slope	Intercept
Wheat	102	0.088	0.812	0.955	0.834	0.966	0.155
Maize	124	0.163	0.719	0.934	0.721	0.767	0.665
Rice	86	0.150	0.389	0.863	0.566	0.880	0.507
Barley	70	0.087	0.746	0.952	0.780	0.745	0.329
Sorghum	63	0.059	0.763	0.956	0.827	0.918	−0.123
Millet	40	0.055	0.663	0.924	0.673	0.747	0.192
Rye	28	0.141	0.560	0.897	0.594	0.721	0.300
Soybeans	57	0.104	0.417	0.901	0.575	0.690	0.511
Cotton	74	0.172	0.493	0.886	0.552	0.699	0.297
Groundnuts	85	0.234	0.342	0.860	0.491	0.729	0.498
Rapeseed	43	0.045	0.739	0.938	0.753	0.829	0.382
Sunflower	62	0.174	0.119	0.800	0.155	0.349	0.998
Pulses	71	0.241	0.043	0.781	0.134	0.358	5.945
Cassava	64	0.108	0.587	0.901	0.660	0.874	1.490
Potatoes	110	0.107	0.641	0.918	0.680	0.809	4.534
Sugarcane	78	0.125	0.305	0.843	0.464	0.721	20.034
Sugar beets	50	0.396	0.223	0.709	0.312	0.876	6.029

[a] Number of simulated countries.

[b] Normalized mean square error.

[c] Nash-Sutcliffe efficiency.

[d] Index of agreement.

164 crops on the basis of national average crop production and national average CWP for the period 1997–2001 [*Chapagain and Hoekstra*, 2004]. The CWU for all the crops was 6390 $km^3\ a^{-1}$, among which about 70% (or 4482 $km^3\ a^{-1}$) was for the 17 major crops investigated here. Because the study period was close to ours, no adjustments were needed. The 4482 $km^3\ a^{-1}$ is 17% higher than our estimate. The higher value is mainly due to the overestimation of the consumptive water use for rice production in their study, a point we would like to address below. During the publication of this article, we realize that *Rost et al.* [2008] recently published their work on the estimation of global green and blue water uses with a high spatial resolution of 30 arc min. They calculate CWU of over 7200 km^3 in cropland. Since the CWU for each crop is not explicitly included, the CWU of the 17 major crops is not calculated here for comparison.

[26] Although the overall CWU of our study compares well with others, differences are significant in the values for maize, rice and soybean in the case of *Rockström et al.* [1999], and for rice, soybean and pulses in the case of *Chapagain and Hoekstra* [2004] (Figure 4). Our world average CWP is 2.190 kg m^{-3} for maize. This number is close to the world average of 1.800 kg m^{-3} reported by *Zwart and Bastiaanssen* [2004], who estimated this number from 27 reports not older than 25 years. Rockström reports a range between 0.687 and 1.066 kg m^{-3} and Chapagain and Hoekstra estimates a value of 1.100 kg m^{-3}. Both values are below the world average of CWP reported by *Zwart and Bastiaanssen* [2004]. Chapagain and Hoekstra calculated CWP for rice of 0.45 kg m^{-3}, much lower than the values from Zwart and Bastiaanssen (1.090 kg m^{-3}) and the present study (0.60 kg m^{-3}). For soybean and pulses, the lack of information makes a comparison with other studies not possible.

[27] Despite a rather high agreement of our data with other studies, we believe our estimations to be on the conservative side. The FAO statistics on crop production only include the quantities of commodities sold in the market and the quantities consumed or used by the producers. They do not include preharvested and postharvested losses and parts of crop not harvested for any reason (FAO statistical databases, http://faostat.fao.org/default.aspx). These losses might consume more than 20% of the CWU on the field [*Rockström et al.*, 1999]. Some estimates go to values as high as 40% [*Zehnder*, 1997].

3.2. Spatial Distribution of Consumptive “Green” and “Blue” Water Use

[28] Green water accounts for the main part of CWU (Figure 5). In Africa, South America, Europe and Oceania,

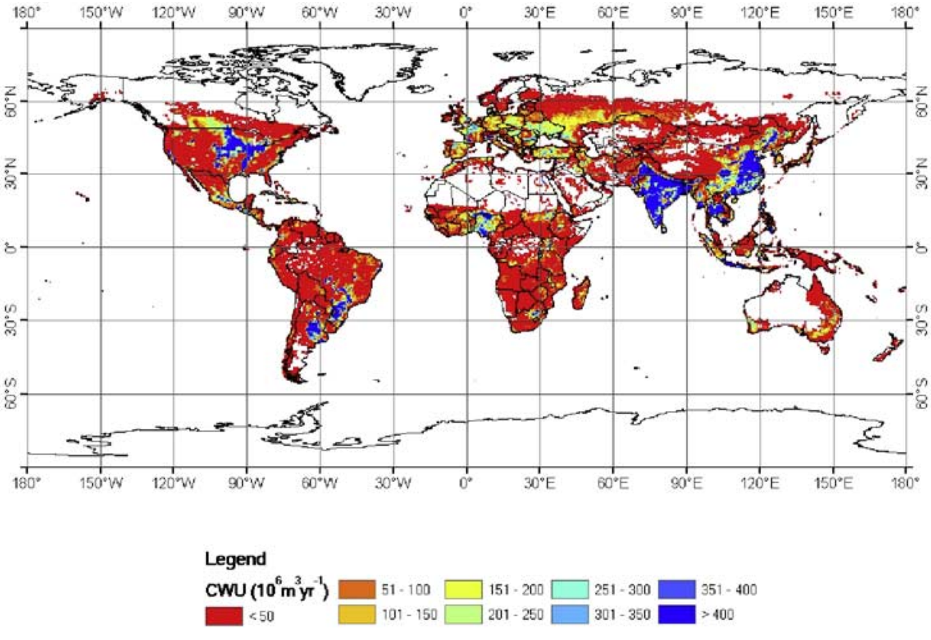

Figure 2. Spatial distribution of consumptive water use (CWU) for crop production per grid cell of 30 arc min (average over 1998–2002).

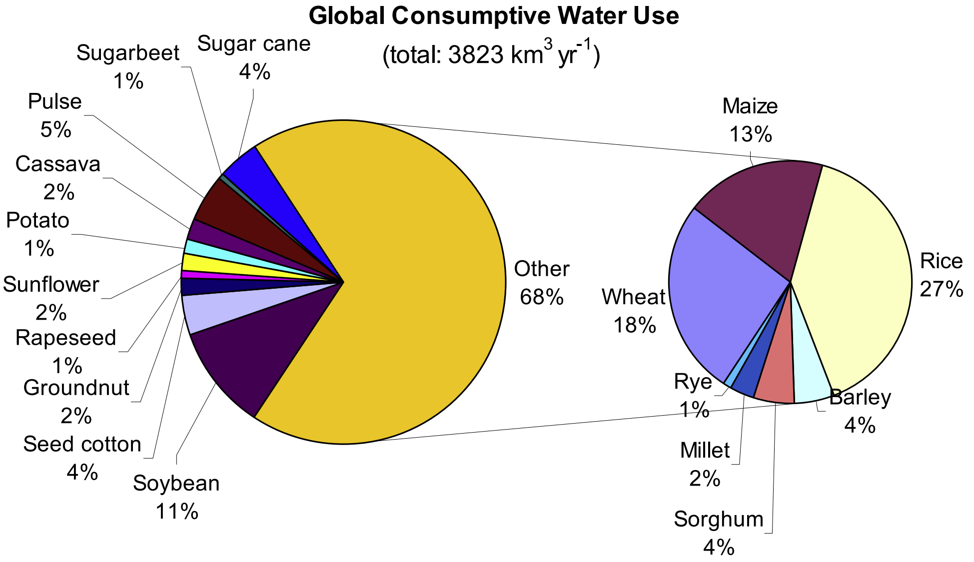

Figure 3. Global consumptive water use for individual crops (average over 1998–2002).

green water constitutes more than 95% of CWU in most grids. Grids with low green water proportion are mainly found western part of the USA, Middle East and North Africa (MENA), Pakistan, Iran, Afghanistan, in the eastern part of China, and some part of India. Those regions are the largest areas with high irrigation density [*Döll and Siebert*, 2000].

[29] On global average, green water accounts for 81% of CWU. This is close to the estimate of 75% reported by *Postel et al.* [1996], who calculated the CWU in cultivated land by dividing the co-opted net primary production (NPP) by the global average biomass produced per cubic meter of water. The same authors estimated the total consumptive blue water use by multiplying the total irrigation by an assumed ratio of consumption to withdrawal. The very high irrigation application rate assumed by *Postel et al.* [1996] (i.e., 1200 mm a^{-1} in agricultural land) is a very important reason for the lower value of green water proportion estimated. *Rost et al.* [2008] estimated that 85% of the CWU in cropland is from green water when the contribution of nonrenewable and nonlocal blue water to irrigation is considered. This is an estimate close to ours here.

[30] For most crops, green water accounts for more than two thirds of the consumptive water use except for cotton (Figure 6). Cotton has the green water proportion of 56%, the lowest among all crops. This proportion closes to the value of 48% reported by *Chapagain et al.* [2006]. Globally, about 73% of the global cotton production is from irrigated fields [*Soth et al.*, 1999]. The main cotton producers are arid regions such as Egypt, Uzbekistan, Pakistan, and northwest China [*Chapagain et al.*, 2006]. Rice has a green water proportion of 67%, which represents the lowest green water proportion next to cotton. Cassava is a highly drought tolerant crop, and thus is less dependent on irriga-

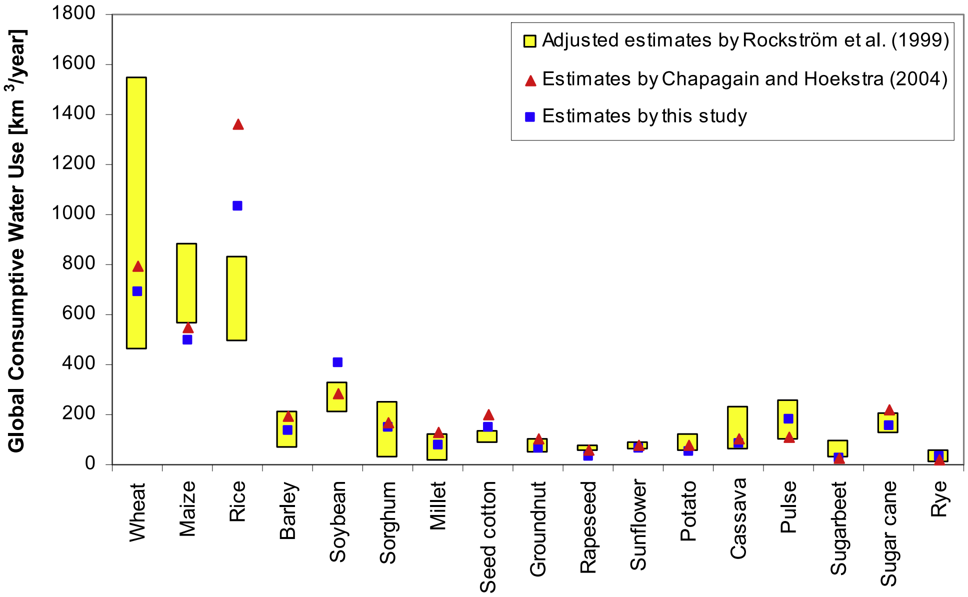

Figure 4. Comparison of global consumptive water use for 17 major crops.

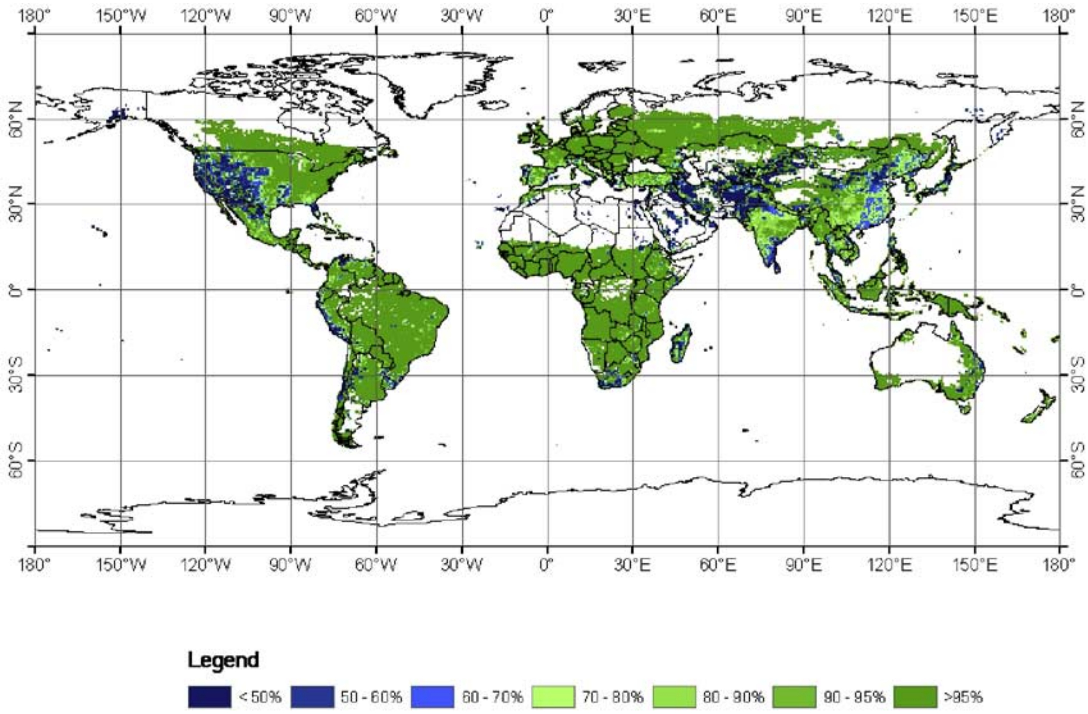

Figure 5. Spatial distribution of green water proportion in consumptive water use for crop production.

tion [*Santisopasri et al.*, 2001]. With almost 100%, it has the highest green water proportion of all crops.

[31] At the national levels, over 80% of agricultural production depends on green water (Figure 7). In Canada, Brazil, Argentina, many African and European countries, and Australia, no less than 90% of CWU has its origin in green water. Arid and warm zones such as many countries in the MENA region show a low green water proportion. About 80% of the MENA region has annual rainfalls of less than 100 mm a^{-1} [*Mubarak*, 1998]. The lack of rainfall coupled with high evaporation makes irrigation crucially important for agriculture production. China has a green water proportion of 68%.

[32] According to our calculations, consumptive "blue" water use (CBWU) was 720 km^3 a^{-1} for the production of the selected crops. The 17 crops accounted for around 84% of the total global harvested area of irrigated crops [*Portmann et al.*, 2008]. Assuming all the rest of crops have the same amount of irrigation per unit of harvested area as the average of the 17 crops considered in this study, we

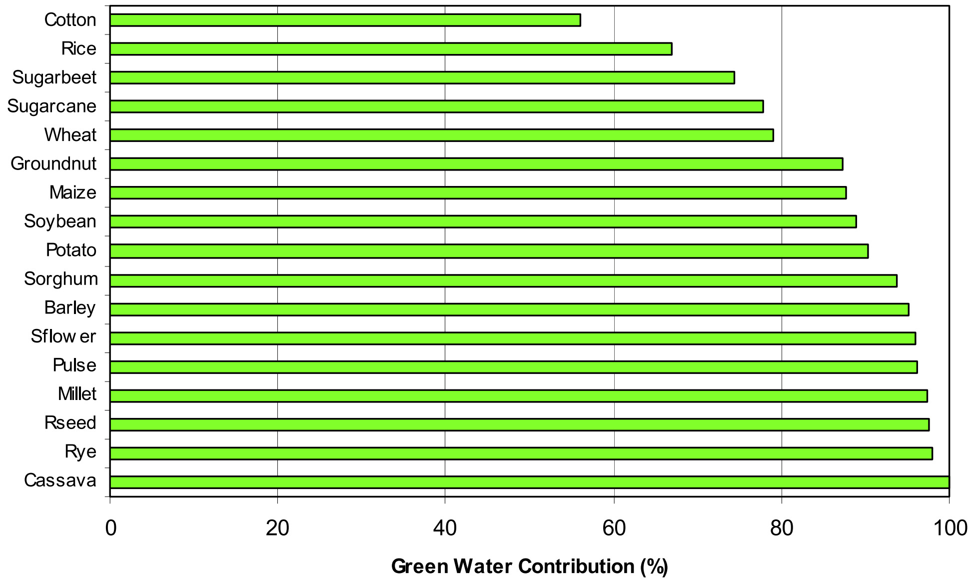

Figure 6. Global average green water proportion for individual crops.

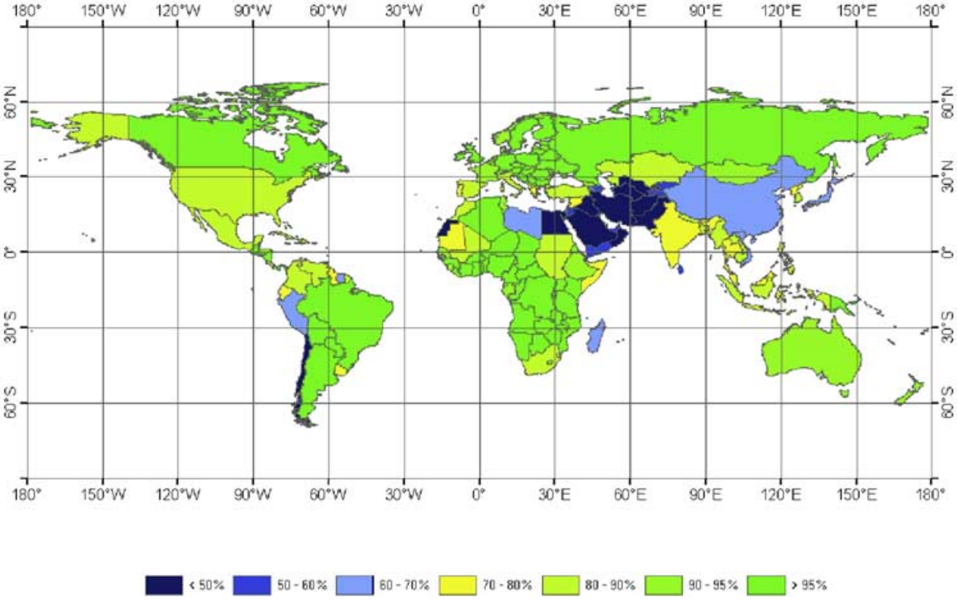

Figure 7. Green water proportion at the national level.

derive the global CBWU of 860 km^3 a^{-1} in cropland. Statistical data on global CBWU are not available, but can be roughly estimated. *FAO* [2008] provides national data on agricultural water withdrawal, and *Rohwer et al.* [2007] indicates irrigation efficiency for each country. Irrigation efficiency reflects the fraction of water diverted from a source for irrigation purposes and available for beneficial crop evapotranspiration. Hence, multiplying agricultural water withdrawal with irrigation efficiency and summing up these products for all the countries give global CBWU. In addition to irrigation, agricultural water withdrawal is also used for rural domestic purposes. Assuming 90% of agricultural water withdrawal is used for irrigation (this figure is set on the basis of the situation in China, which is 91% (China water resources bulletins, Ministry of Water Resources, available at http://www.mwr.gov.cn/)), global CBWU would be around 830 km^3 a^{-1}, very close to our estimate.

[33] It should be pointed out that our estimate of global CBWU is lower than the estimate by *Döll and Siebert* [2002]. They estimated net irrigation requirement for rice and nonrice crops on the basis of a 0.5° digital global map of irrigated areas for the year 1995 (without crop-specific irrigation data) and long time series of monthly climatic variables. The world net irrigation requirement was estimated at 1092 km^3 a^{-1}. There are many reasons for the discrepancies between our estimate and Döll and Siebert's, e.g., different data sets of irrigation maps, different representatives of crops, and different computer models. A direct comparison of computing results from both the studies is difficult because of these differences. Some other estimates are much larger than the estimates from this study and Döll and Siebert's study. For example, *Shiklomanov* [2000] estimated the world CBWU as 1753 km^3 a^{-1} on the basis of the irrigated areas in individual countries, while *Postel et al.* [1996] gave a value of 1870 km^3 a^{-1} on the basis the world total irrigated area, average water application rate of 1200 mm a^{-1}, and a ratio of consumption to withdrawal of 65%. These two estimates were based on national or global average data, and therefore were limited by low spatial resolution in estimation.

4. Sensitivity Analysis

[34] Process-based crop models, like EPIC, are often sensitive to some parameters in the model. *Wang et al.* [2005] tested the sensitivity of crop yield to six most important parameters in the EPIC model: biomass-energy ratio (WA), harvested index (HI), potential heat units (PHU), water stress-harvested index (PARM(3)), SCS curve number index coefficient (PARM(42)), and difference of soil water contents at field capacity and wilting point (DIFFW). Maize yield was reported to be sensitive to DIFFW, WA, PHU and HI with a decreasing order, and it was barely sensitive to PARM(3) and PARM(42). We checked the sensitivity of CWU to these six parameters in the selected ten sites for wheat, maize and rice. In addition, the sensitivity to the water stress factor to trigger automatic irrigation (BIR) and N fertilizer application (N) was also analyzed here. BIR was first set as 0.9, which means that irrigation will be triggered when biomass production in a day is lower than 90% of the potential biomass that could have been produced had water been available. The sensitivity analysis was carried out by altering the value of a single parameter or input by ±10%, while holding all others constant.

[35] The results show that, in general, CWU was more sensitive to HI, WA and PHU, less sensitive to BIR and FER, and not sensitive to PARM(3), PARM(42) and DIFFW. For HI, WA and PHU, the sensitivity varied at different locations for various crops (Table 4). For instance, HI was the most sensitive parameter for the three crops in Tuanlin, Ludhiana, New Delhi, Bauru, Chartres, Midura and Vryburg. However, WA became the most sensitive one for maize in Florica and Bushland. For our simulation, sufficient water was always available when biomass production is below 90% of its potential. This assumption led to insensitivities of PARM(42) and DIFFW for CWU in our

Table 4. Relative Percentage Change in CWU for Wheat, Maize, and Rice in the 10 Selected Sites With Changes in Inputs[a]

		WA		HI		PHU		BIR		FER	
Sites	Crops	+10	−10	+10	−10	+10	−10	+10	−10	+10	−10
Luancheng	wheat	−17.2	32.4	−17.7	21.5	12.2	0.9	3.4	−1.1	−4.9	0.7
	maize	−9.0	22.3	−9.0	22.2	4.9	0.0	0.5	0.0	−0.1	0.1
	rice	−8.8	21.8	−9.0	22.5	−1.5	−0.5	2.9	0.0	0.1	0.0
Tuanlin	wheat	−3.1	10.4	−9.6	20.2	5.9	−4.7	0.3	0.0	−5.3	0.6
	maize	−6.6	16.8	−9.2	19.8	2.1	1.4	0.0	0.0	−1.2	0.2
	rice	−8.9	21.7	−9.1	22.3	−2.1	−0.6	1.1	0.0	0.0	0.0
Ludhiana	wheat	−2.7	10.4	−10.2	23.5	−37.5	−6.6	6.3	0.0	−7.4	0.9
	maize	−5.5	3.7	−11.7	26.6	5.6	−3.1	1.0	0.0	−2.9	0.8
	rice	−4.5	13.6	−8.1	19.4	−0.4	6.3	0.1	0.0	−3.0	0.4
New Delhi	wheat	−8.8	20.6	−10.3	21.7	−6.1	15.1	0.0	0.0	−0.2	0.0
	maize	−5.8	16.4	−9.1	21.0	9.0	11.2	1.4	0.0	0.0	0.0
Florida	rice	−9.1	22.4	−9.9	21.8	5.6	−1.8	0.3	0.0	0.0	0.0
	maize	−9.1	22.3	−9.0	22.1	4.6	−2.8	3.0	0.0	0.0	0.0
Bushland	wheat	−3.6	9.4	−6.0	16.6	8.3	25.6	1.9	0.0	0.2	−0.5
	maize	−11.9	26.7	−8.6	21.2	1.7	0.2	3.6	0.0	0.0	0.0
	rice	−9.6	23.9	−9.1	21.2	−1.7	4.1	10.4	0.0	0.0	0.0
Bauru	wheat	−5.2	15.0	−9.6	20.6	4.5	2.5	1.0	0.0	0.0	0.0
	maize	−5.8	9.6	−8.3	13.0	5.8	−4.7	5.4	0.0	−2.0	0.0
	rice	−3.1	7.6	−7.0	16.2	6.1	−0.5	1.6	0.0	0.1	0.0
Chartres	wheat	−1.5	2.5	−6.8	15.9	22.4	−30.1	1.9	0.0	−5.7	0.7
	maize	−2.4	6.2	−10.0	20.1	0.0	−12.6	1.3	0.0	−6.2	−0.6
	rice	−3.1	6.8	−6.2	14.1	5.8	−6.1	4.0	0.0	−0.1	0.1
Mildura	wheat	−6.5	14.1	−9.1	20.8	13.7	−2.8	2.5	0.0	0.0	0.0
	maize	−2.0	1.8	−9.1	26.9	11.4	−4.6	6.5	0.0	0.1	0.0
	rice	−2.3	6.8	−9.5	18.1	−10.0	−10.7	5.4	0.0	−0.2	0.0
Vryburg	wheat	−8.9	20.2	−8.9	20.2	12.4	−6.9	8.0	0.0	0.4	0.0
	maize	−8.9	24.1	−8.9	24.1	13.4	−7.6	0.0	0.0	0.0	0.0
Means of all sites	rice	−6.7	15.7	−9.8	20.3	4.1	−0.9	2.6	−0.1	−2.3	0.2
	maize	−6.8	14.8	−9.3	21.8	5.5	−3.8	2.4	0.0	−1.4	0.1
	rice	−5.8	14.8	−8.4	19.4	0.6	0.4	3.4	0.0	−0.4	0.1

[a]Values are given in percent.

simulation. At the same time water-stressed HI was always larger than the lower limit of HI, resulting in an insensitivity of CWU to PARM(3). The findings of the sensitivity analysis are similar to those from *Liu* [2009], where a sensitivity analysis is conducted for maize, wheat and rice on a global scale with spatial resolution of 30 arc min. It is found that crop water productivity is more sensitive to HI, WA and PHU than other parameters.

[36] The importance of collecting spatially distributed crop parameters; that is, HI, WA, and PHU for improving the accuracy of crop growth models became obvious from our calculations. As far as we know, there are few efforts in collecting these data on a global scale.

5. Relations Between CWU and Virtual Water Trade

5.1. Net Virtual Water-Exporting Countries

[37] Australia is with its almost 2500 m^3 per capita per year the most important net virtual water-exporting country on a per capita basis. It is followed by Canada (2137) and Argentina (1372), and France, Paraguay, Hungary, the USA, and Denmark exporting between 350 and 900 m^3 per capita per year (Figure 8).

[38] Green water accounts for 94.4% of the global virtual water export. It can be concluded that green water dominates global virtual water trade. Ten major virtual water-exporting countries (Figure 9) account for 94% of global total virtual water export. Interestingly, in the ten exporting countries, the proportions of green water in exports are generally higher than the proportions of green water in domestic production (except for Thailand). For instance, in the USA, green water accounts for almost 90% of NVWE. In this country's CWU, the green water proportion is 83%. This is not surprising since green water rarely has competitive users, while blue water has several, e.g., industry and households. The opportunity cost of irrigation water is high. Exporting green water constitutes a low opportunity cost in water use as opposed to exporting blue water, holding other factors constant [*Yang et al.*, 2006]. This can partly explain the higher proportion of green water in crop trade than in domestic crop production. The lower proportion of green water in exports in Thailand is mainly due to a large amount of rice exports.

[39] CWU per capita increases when water is abundant and the climatic and pedological conditions are favorable. The result is a higher level of NVWE. Good examples are Australia, Canada and Argentina. NVWE becomes negligible with CWU below a level around 1000 m^3 per capita per year (Figure 8). Such a level is logical, since each country has to first provide food to its own people. *Zehnder et al.* [2003] have already postulated the need of 1000 to 1300 m^3 water per year to produce the food for one person for a diet comprising 20% meat. *Haddadin* [2003] presents the need of 614–1017 m^3 water per year to meet the food diet in lower middle income countries. Of this water, 385–560 m^3 is for vegetarian food. We estimated the CWU for crop production in developed countries because they constitute

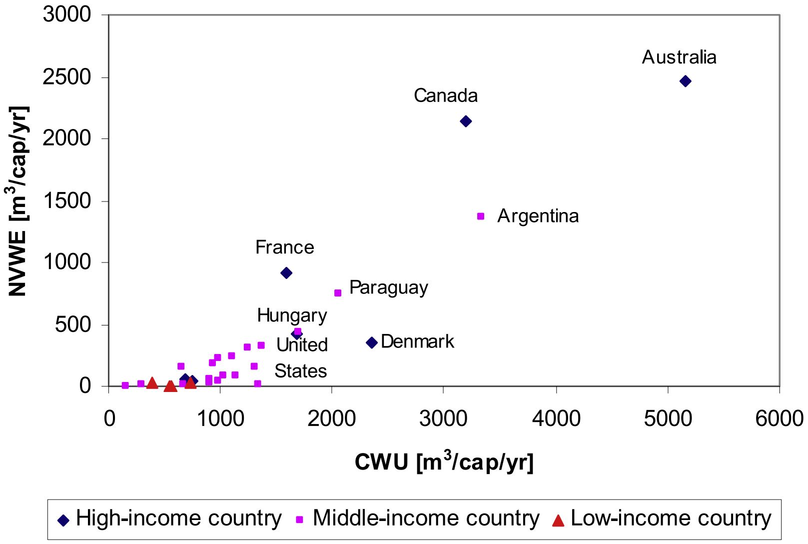

Figure 8. Relationship between net virtual water export (NVWE) and consumptive water use (CWU) in net exporting countries.

the main food exporters. Here, the average daily calorie intakes are about 3280 kcal per capita per year, with a meat proportion of 26% (FAO statistical databases, http://faostat.fao.org/default.aspx). The vegetarian dietary water requirement is about 0.00041 m^3 $kcal^{-1}$ [*Rockström*, 2003]. Thus, the caloric intake from vegetal products requires about 360 m^3 (3280 × 74% × 0.00041 × 365) of water per capita per year, if preharvested and postharvested losses are not taken into account. In fact, only a part of domestic crop supply is used for direct human diet consumption in developed countries. For instance, one third of the domestic cereal and starchy root supplies are currently used for direct human diet consumption, the rest are mainly fed to animals (FAO statistical databases, http://faostat.fao.org/default.aspx). This means that the amount of CWU to meet the total crop requirements for human diet consumption, animal feed and other purposes can be triple that of 360 m^3, or 1080 m^3 per capita per year. This number is close to the level below which NVWE becomes negligible. The level can be regarded as the CWU for meeting domestic crop food needs (both for human diet consumption or other purposes including animal feed) in the developed countries.

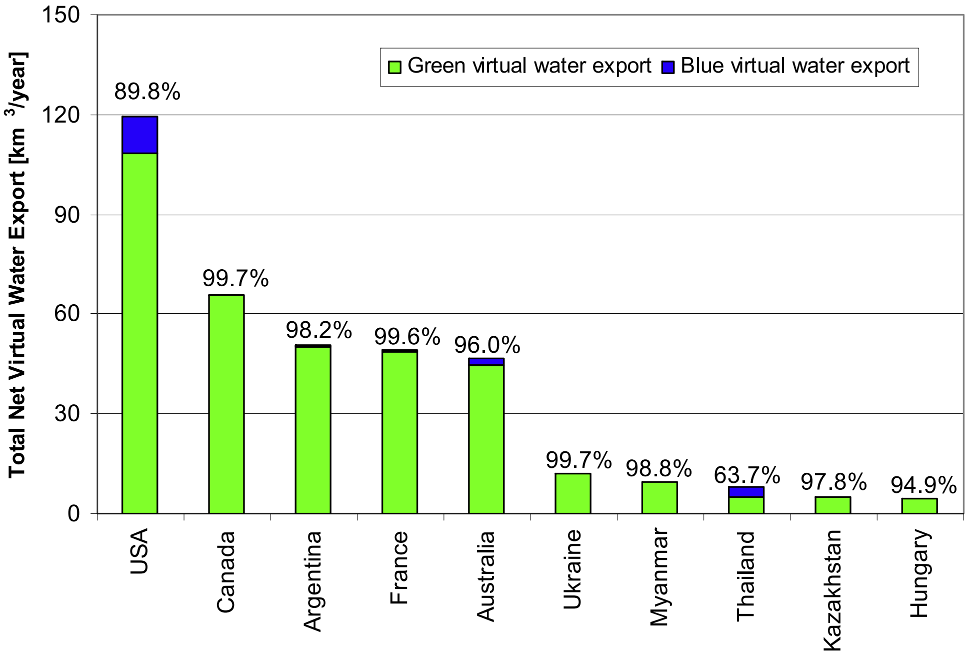

Figure 9. Total net blue and green virtual water export in major exporting countries and green water proportion in total virtual water export (average over 1998–2002). Green water proportions are marked as percentage above individual countries.

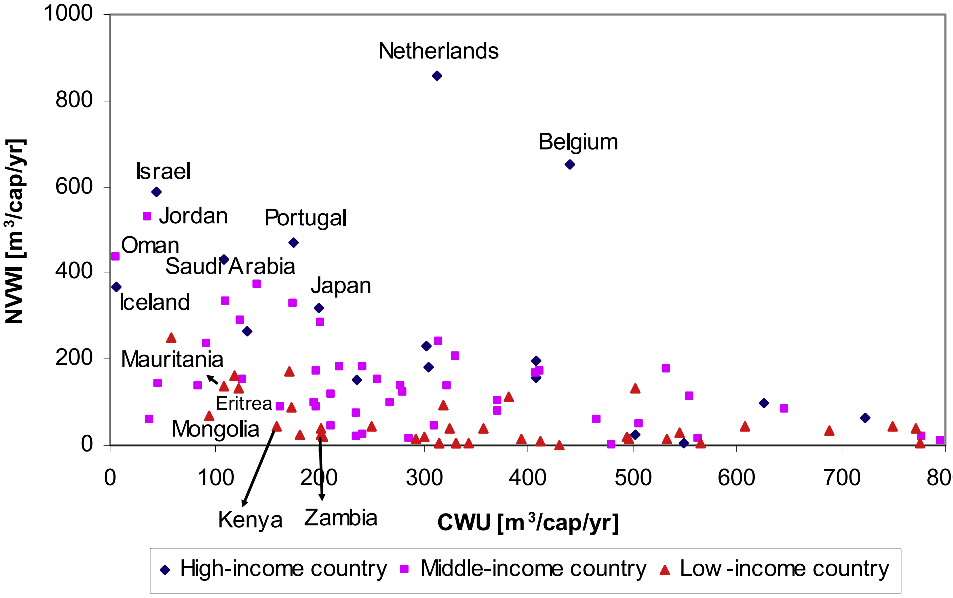

Figure 10. Relationship between net virtual water import (NVWI) and consumptive water use CWU in importing countries.

These data do not include fully the preharvested and postharvested losses and the vegetable and fruit production, and are therefore relatively conservative estimates.

5.2. Net Virtual Water-Importing Countries

[40] The Netherlands and Belgium are the two top net virtual water-importing countries on a per capita basis. Net virtual water import (NVWI) into the two countries is about 860 and 650 m^3 per capita per year, respectively (Figure 10). Both countries are big meat exporters with over 120 kg per capita per year of meat exports. A large amount of imported crop products is used as feed for livestock (FAO statistical databases, http://faostat.fao.org/default.aspx).

[41] Israel and Jordan are the third and fourth biggest importing countries with a NVWI of over 500 m^3 per capita per year. Both countries show a very low CWU of less than 50 m^3 per capita per year. Their NVWI is to compensate for the lack of water, a fact which is seen in all the MENA countries. Besides the 17 crops, Israel is importing also substantial amounts of meat and dairy products, which almost doubles the NVWI calculated here [*Yang and Zehnder*, 2002b] [*Yang et al.*, 2007].

[42] The CWU threshold above which NVWE becomes significant in net virtual water-exporting countries is much higher than the threshold below which NVWI becomes significant in net virtual water-importing countries. Net virtual water-exporting countries are mostly high- and middle-income countries. A large amount of crop products are used for animal feed. In contrast, there is a number of low-income net virtual water-importing countries. In the poor countries, crop imports may mostly be consumed to meet human's diet requirements. For instance, in Zimbabwe, almost 90% of cereals were used for food, and only less than 3% of the cereals were used for animal feeds (FAO statistical databases, http://faostat.fao.org/default.aspx). The consumption patterns of crop products in different countries may partly explain the difference of the thresholds.

[43] Countries respond to CWU differently when CWU is below 250 m^3 per capita per year. The results show that NVWI is affected by the levels of incomes. High- and middle-income countries generally have larger NVWI than low-income countries with a similar level of CWU (Figure 10). For example, CWU in Japan and Zambia is about 200 m^3 per capita per year. The NVWI in Japan is over 300 m^3 per capita per year, while it is negligible in Zambia. Apparently, the economic situation of a country is decisive with respect to the extent the world food market tapped to satisfy internal nutritional needs.

[44] For some low-income countries, NVWI remains at a low level even with a low CWU. This means that part of the population is undernourished or obtains their calories from other sources than the 17 major crops. For instance, in Eritrea, the sum of CWU and NVWI is 261 m^3 per capita per year. The calorie intakes from animal products and other vegetal foods are also low. In fact, this country is being confronted with serious food security problem and 73% of its population is undernourished (Table 5). Mauritania has similar levels of CWU and NVWI to Eritrea. However, the undernourishment prevalence is much lower, largely because almost 50% of the calorie intakes are obtained from grazing animals and their products, and other vegetal products such as sugar, sweeteners, and vegetable oils. Another interesting case is Mongolia. Although both CWU and NVWI are very low, the food security situation is satisfactory at the national level. More than 40% of the calories intakes are from meat and other animal products from grazing herds. The rural areas rely even to a higher percentage on meat and animal products [*FAO*, 2006; FAO statistical databases, http://faostat.fao.org/default.aspx].

6. Concluding Remarks

[45] This study made a first major effort in estimating explicitly green and blue water uses in crop production on a global scale on the basis of grid cell data. The results show that green water accounts for 81% of the CWU for crop production of 17 major crops. About 94% of the virtual water trade among countries has its origin in green water.

Table 5. Daily Caloric Intake in Low-Incoming Countries With CWU Less Than 250 m^3 per Capita

Country[a]	Prevalence of Undernourishment in Total Population[b] (%)	Daily Caloric Intake[c]	Calorie Intake Component[c]: Seventeen Major Crops (%)	Fruits and Vegetables (%)	Other Vegetal Products[d] (%)	Meat (%)	Other Animal Products[e] (%)
Eritrea	73	1523	78	0	14	3	4
Ethiopia	46	1803	63	1	31	2	3
Zambia	49	1890	78	1	15	3	2
Sierra Leone	50	1919	71	3	23	1	3
Yemen	36	2030	69	1	22	3	4
Haiti	47	2080	55	7	31	4	3
Kenya	33	2147	60	6	22	3	9
Mongolia	28	2229	51	1	6	26	16
Guinea	26	2343	58	12	27	1	3
Mauritania	10	2776	55	2	26	5	12

[a] Papua New Guinea and Bhutan also have CWU lower than 250 m^3 per capita per year, but the data on daily caloric intake are not available.

[b] Prevalence of undernourishment data reflect the years 2000–2002 [*FAO*, 2006].

[c] Values are calories per capita per day. Calorie intake data reflect the year 2000 [*FAO*, 2006].

[d] Other vegetal products include vegetable oils; sugar and sweeteners; tree nuts; stimulants; spices; cereals except for wheat, rice, barley, maize, rye, millet and sorghum; starchy roots except for cassava and potatoes; and oil crops except for soybean, groundnut, sunflower, and rapeseed.

[e] Other animal products include animal fats, eggs, fish, seafood, and other aquatic products and edible offal.

Green water comes from rainfall; it is a "free gift" in terms of supply. This study shows that virtual water flows are often closely related to domestic water availability. Virtual water import is the most direct way to compensate for a lack of green or blue water, when the national economic situation permits it. High- and middle-income countries do already import virtual water at quite high CWU levels. The reasons can be many; for example, local production of certain crops is more expensive than importing them, or water is used for economically more attractive purposes. This later point can also apply to developing countries. Many water scarce countries have favorable climatic conditions for the production of high-value export crops. The economic gain from these agricultural products would allow satisfying the countries' basic food need from the global food market, besides strengthening the national economy [*Yang and Zehnder*, 2002a]. Two basic requirements have to be met if a country chooses to play the virtual water card. First, it must abandon or loosen up the principle of national food self-sufficiency, a step which even many industrialized countries will have difficulties to implement. Second, it requires an infrastructure to make best use of the profits from cash crop production. This requirement is difficult to fulfill in many poor countries [*Yang and Zehnder*, 2002a]. In any case, a better awareness of the role of green water in all its aspects can help countries to ease the water stress and economic difficulties linked to it.

[46] In the past, water policies have been focused on the management of blue water resources. Massive blue water infrastructure, such as dams, aqueducts, and pipelines, has been constructed. In contrast, green water management in rain-fed agriculture has often been marginalized by water resources planners [*Savenije*, 2000]. Green water management helps the effective use of rainfall. By strengthening rainfall management, it is possible to double or even quadruple maize yields in sub-Saharan Africa [*Rockström*, 2003]. Rainwater harvesting is a promising approach for green water management in the semiarid tropics of Asia and Africa. Experiments with rainwater harvesting increased yield by a factor of 2 to 3 in Burkina Faso, Kenya, Niger, Sudan and Tanzania as compared to the current yield levels [*FAO*, 2000]. Additional spending in many of the rain-fed areas allowed more poor people to raise above the poverty line, than would be expected with investments in irrigation infrastructure [*Rosegrant et al.*, 2002]. Green water management is not only limited to "infrastructure" and management technologies. Biotechnological advances may also be helpful. For example, a hybrid "New Rice for Africa," which was developed to grow in the uplands of West Africa, produces more than 50% more grain than current varieties when cultivated in traditional rain-fed systems without fertilizer [*FAO*, 2000].

[47] Finally, we would like to acknowledge the uncertainties existing in the estimations in green and blue water uses in crop production and the results based on them. Our estimations used the maps of irrigation areas for specific crops generated by *Portmann et al.* [2008] on the basis of the FAO's GMIA. Total harvested area of the irrigated crops based on this source is about 312 million ha. This figure is smaller than the estimate in the global irrigated area map (GIAM) produced by the International Water Management Institute (IWMI). The GIAM from IWMI is generated with a great variety of remote sensed data at different geographical and time scales [*Thenkabail et al.*, 2006]. According to this source, the global total annualized irrigated area was about 399 million ha. Hence, the global harvested area of irrigated crops from *Portmann et al.* [2008] is around 20% lower than that from IWMI. We compared the national irrigated area in 160 countries, where data are available for both sources. These countries account for 99.8% of the total global irrigated area. The discrepancies of the two sources are large for the countries with small irrigated areas. However, it is found that the higher global irrigated area from IWMI is mainly caused by the higher values for China, India and the USA, or the three largest countries in terms of irrigated area. The statistics of FAO are based on secondary statistics from its member countries, which may contain large errors. For example, some 60% of irrigation in India now is practiced using groundwater, most of which is privately developed and not necessarily recorded in gov-

ernmental statistics [*Thenkabail et al.*, 2006]. Thus, crop area under irrigation may be underestimated by FAO when private irrigation is taken into account [*Faurès*, 2007], so does the harvested area of irrigated crops from *Portmann et al.* [2008]. From this point of view, our findings may overestimate the green water proportion in the countries with a large amount of privately developed irrigation schemes, e.g., in India. Because of an absence of crop-specific irrigation areas in the IWMI irrigation map, we cannot use it to estimate CWU of the 17 crops in this study and hence cannot make comparison with the estimate on the basis of Portmann's irrigation maps. On the other hand, we assume that irrigation is always readily available when crops need it. In regions with severe water scarcity, blue water uses are extremely competitive. Evidences have shown a reallocation of water uses from irrigation to domestic and industrial purposes [*Yang and Zehnder*, 2001]. The assumption of sufficient irrigation is likely to overestimate the blue water contribution, and underestimate the green water proportion in the water scarce regions. The extent to which the overestimation and underestimation are offset to each other remains unknown at this point. Comprehensive quality assessments of the harvested area of the irrigated crops and in situ measurement of irrigation depth are helpful for reducing the uncertainty in the estimates. Both issues need scientific attentions in the future research.

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