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The green, blue and grey water footprint of crops and derived crop products

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Abstract

This study quantifies the green, blue and grey water footprint of global crop production in a spatially-explicit way for the period 1996–2005. The assessment is global and improves upon earlier research by taking a high-resolution approach, estimating the water footprint of 126 crops at a 5 by 5 arc min grid. We have used a grid-based dynamic water balance model to calculate crop water use over time, with a time step of one day. The model takes into account the daily soil water balance and climatic conditions for each grid cell. In addition, the water pollution associated with the use of nitrogen fertilizer in crop production is estimated for each grid cell. The crop evapotranspiration of additional 20 minor crops is calculated with the CROPWAT model. In addition, we have calculated the water footprint of more than two hundred derived crop products, including various flours, beverages, fibres and biofuels. We have used the water footprint assessment framework as in the guideline of the water footprint network.

Considering the water footprints of primary crops, we see that global average water footprint per ton of crop increases from sugar crops (roughly 200 m^3 ton^{-1}), vegetables (300 m^3 ton^{-1}), roots and tubers (400 m^3 ton^{-1}), fruits (1000 m^3 ton^{-1}), cereals (1600 m^3 ton^{-1}), oil crops (2400 m^3 ton^{-1}) to pulses (4000 m^3 ton^{-1}). The water footprint varies, however, across different crops per crop category and per production region as well. Besides, if one considers the water footprint per kcal, the picture changes as well. When considered per ton of product, commodities with relatively large water footprints are: coffee, tea, cocoa, tobacco, spices, nuts, rubber and fibres. The analysis of water footprints of different biofuels shows that bio-ethanol has a lower water footprint (in m^3 GJ^{-1}) than biodiesel, which supports earlier analyses. The crop used matters significantly as well: the global average water footprint of bio-ethanol based on sugar beet amounts to 51 m^3 GJ^{-1}, while this is 121 m^3 GJ^{-1} for maize.

The global water footprint related to crop production in the period 1996–2005 was 7404 billion cubic meters per year (78% green, 12% blue, 10% grey). A large total water footprint was calculated for wheat (1087 Gm^3 yr^{-1}), rice (992 Gm^3 yr^{-1}) and

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maize (770 $Gm^3 yr^{-1}$). Wheat and rice have the largest blue water footprints, together accounting for 45% of the global blue water footprint. At country level, the total water footprint was largest for India (1047 $Gm^3 yr^{-1}$), China (967 $Gm^3 yr^{-1}$) and the USA (826 $Gm^3 yr^{-1}$). A relatively large total blue water footprint as a result of crop production is observed in the Indus River Basin (117 $Gm^3 yr^{-1}$) and the Ganges River Basin (108 $Gm^3 yr^{-1}$). The two basins together account for 25% of the blue water footprint related to global crop production. Globally, rain-fed agriculture has a water footprint of 5173 $Gm^3 yr^{-1}$ (91% green, 9% grey); irrigated agriculture has a water footprint of 2230 $Gm^3 yr^{-1}$ (48% green, 40% blue, 12% grey).

1 Introduction

Global freshwater withdrawal has increased nearly seven-fold in the past century (Gleick, 2000). With a growing population, coupled with changing diet preferences, water withdrawals are expected to continue to increase in the coming decades (Rosegrant and Rigler, 2000; Liu et al., 2008). With increasing withdrawals, also consumptive water use is likely to increase. Consumptive water use in a certain period in a certain river basin refers to water that after use is no longer available for other purposes, because it evaporated (Perry, 2007). Currently, the agricultural sector accounts for about 85% of global freshwater consumption (Shiklomanov, 2000; Hoekstra and Chapagain, 2007).

The aim of this study is to estimate the green, blue and grey water footprint of crops and crop products in a spatially-explicit way. We quantify the green, blue and grey water footprint of crop production by using a grid-based dynamic water balance model that takes into account local climate and soil conditions and nitrogen fertilizer application rates and calculates the crop water requirements, actual crop water use and yields and finally the green, blue and grey water footprint at grid level. The model has been applied at a spatial resolution of 5 by 5 arc min. The model's conceptual framework is based on the CROPWAT approach (Allen et al., 1998).

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The concept of "water footprint" introduced by Hoekstra (2003) and subsequently elaborated by Hoekstra and Chapagain (2008) provides a framework to analyse the link between human consumption and the appropriation of the globe's freshwater. The water footprint of a product is defined as the total volume of freshwater that is used to produce the product (Hoekstra et al., 2009). The *blue* water footprint refers to the volume of surface and groundwater consumed (evaporated) as a result of the production of a good; the *green* water footprint refers to the rainwater consumed. The *grey* water footprint of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

There are various previous studies on global water use for different sectors of the economy, most of which focus on *water withdrawals*. Studies of global *water consumption* (evaporative water use) are scarcer. There are no previous global studies on the grey water footprint in agriculture. L'vovich et al. (1990) and Shiklomanov (1993) estimated blue water consumption at a continental level. Postel et al. (1996) made a global estimate of consumptive use of both blue and green water. Seckler et al. (1998) made a first global estimate of consumptive use of blue water in agriculture at country level. Rockström et al. (1999) and Rockström and Gordon (2001) made some first global estimates of green water consumption. Shiklomanov and Rodda (2003) estimated consumptive use of blue water at county level. Hoekstra and Hung (2002) were the first to make a global estimate of the consumptive water use for a number of crops per country, but they did not explicitly distinguish consumptive water use into a green and blue component. Chapagain and Hoekstra (2004) and Hoekstra and Chapagain (2007, 2008) improved this study in a number of respects, but still did not explicitly distinguish between green and blue water consumption.

All the above studies are based on coarse spatial resolutions that treat the entire world, continents or countries as a whole. In recent years, there have been various attempts to assess global water consumption in agriculture at high spatial resolution. The earlier estimates focus on the estimation of blue water withdrawal (Gleick, 1993; Alcamo et al., 2007) and irrigation water requirements (Döll and Siebert, 2002). More

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recently, a few studies have separated global water consumption for crop production into green and blue water. Rost et al. (2008) made a global estimate of agricultural green and blue water consumption with a spatial-resolution of 30 by 30 arc min without showing the water use per crop, but applying 11 crop categories in the underlying model. Siebert and Döll (2008, 2010) have estimated the global green and blue water consumption for 24 crops and 2 additional broader crop categories applying a grid-based approach with a spatial-resolution of 5 by 5 arc min. Liu et al. (2009) and Liu and Yang (2010) made a global estimate of green and blue water consumption for crop production with a spatial-resolution of 30 by 30 arc min. Liu et al. (2009) distinguished 17 major crops, while Liu and Yang (2010) considered 20 crops and 2 additional broader crop categories. Hanasaki et al. (2010) present the global green and blue water consumption for all crops but assume one dominant crop per grid cell at a 30 by 30 arc min resolution.

2 Method

The green, blue and grey water footprints of crop production were estimated following the calculation framework of Hoekstra et al. (2009). The computations of crop evapotranspiration and yield, required for the estimation of the green and blue water footprint in crop production, have been done following the method and assumptions provided by Allen et al. (1998) for the case of crop growth under non-optimal conditions. The grid-based dynamic water balance model used in this study computes a daily soil water balance and calculates crop water requirements, actual crop water use (both green and blue) and actual yields. The model is applied at a global scale using a resolution of 5 by 5 arc min (Mekonnen and Hoekstra, 2010). We estimated the water footprint of 146 primary crops and more than two hundred derived products. The grid-based water balance model was used to estimate the crop water use for 126 primary crops; for the other 20 crops, which are grown in only few countries, the CROPWAT 8.0 model was used.

The actual crop evapotranspiration (ET_a, mm day^{-1}) depends on climate parameters (which determine potential evapotranspiration), crop characteristics and soil water availability (Allen et al., 1998):

$$ET_a[t] = K_c[t] \times K_s[t] \times ET_o[t] \tag{1}$$

where K_c is the crop coefficient, $K_s[t]$ a dimensionless transpiration reduction factor dependent on available soil water and $ET_o[t]$ the reference evapotranspiration (mm day^{-1}). The crop coefficient varies in time, as a function of the plant growth stage. During the initial and mid-season stages, K_c is a constant and equals $K_{c,ini}$ and $K_{c,mid}$, respectively. During the crop development stage, K_c is assumed to linearly increase from $K_{c,ini}$ to $K_{c,mid}$. In the late season stage, K_c is assumed to decrease linearly from $K_{c,mid}$ to $K_{c,end}$. The value of K_s is calculated on a daily basis as a function of the maximum and actual available soil moisture in the root zone.

$$K_s[t] = \begin{cases} \frac{S[t]}{(1-p)\times S_{max}[t]} & \text{if} \quad S[t] < (1-p) \times S_{max}[t] \\ 1 & \text{otherwise} \end{cases} \tag{2}$$

where $K_s[t]$ is a dimensionless transpiration reduction factor dependent on the available soil water, with a value between zero and one; $S[t]$ the actual available soil moisture at time t (in mm); $S_{max}[t]$ the maximum available soil water in the root zone, i.e., the available soil water in the root zone when soil water content is at field capacity (mm); and p the fraction of S_{max} that a crop can extract from the root zone without suffering water stress (dimensionless).

In the case of rain-fed crop production, blue crop water use is zero and green crop water use (m^3 ha^{-1}) is calculated by summing up the daily values of ET_a (mm day^{-1}) over the length of the growing period. In the case of irrigated crop production, the green and blue water use is calculated by performing two different soil water balance scenarios as proposed in Hoekstra et al. (2009) and also applied by FAO (2005), Siebert and Döll (2010) and Liu and Yang (2010). The first soil water balance scenario is carried out

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based on the assumption that the soil does not receive any irrigation, but using crop parameters of irrigated crops (such as rooting depth as under irrigation conditions). The second soil water balance scenario is carried out with the assumption that the amount of actual irrigation is sufficient to meet the irrigation requirement, applying the same crop parameters as in the first scenario. The green crop water use of irrigated crops is assumed to be equal to the actual crop evapotranspiration as was calculated in the first scenario. The blue crop water use is then equal to the crop water use over the growing period as simulated in the second scenario minus the green crop water use as estimated in the first scenario.

Crop growth and yield are affected by water stress. To account for the effect of water stress, a linear relationship between yield and crop evapotranspiration was proposed by Doorenbos and Kassam (1979):

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{\sum ET_a[t]}{\sum CWR[t]}\right) \tag{3}$$

where K_y is a yield response factor (water stress coefficient), Y_a the actual harvested yield (kg ha^{-1}), Y_m the maximum yield (kg ha^{-1}), ET_a the actual crop evapotranspiration in mm period^{-1} and CWR the crop water requirement in mm period^{-1} (which is equal to $K_c \times ET_0$). K_y values for individual periods and the complete growing period are given in Doorenbos and Kassam (1979). The maximum yield values for each crop were obtained by multiplying the corresponding national average yield values by a factor of 1.2 (Reynolds et al., 2000). The actual yields, which are calculated per grid cell, are averaged over the nation and compared with the national average yield data (for the period 1996–2005) obtained from FAO (2008a). The calculated yield values are scaled to fit the national average FAO yield data.

The green and blue water footprints of primary crops (m^3 ton^{-1}) are calculated by dividing the total volume of green and blue water use (m^3 yr^{-1}), respectively, by the quantity of the production (ton yr^{-1}).

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The grey water footprint of crop production, which is an indicator of the volume of freshwater pollution, is calculated by quantifying the volume of water needed to assimilate the nutrients that reach ground- or surface water. Nutrients leaching from agricultural fields are a main cause of non-point source pollution of surface and subsurface water bodies. In this study we have quantified the grey water footprint related to nitrogen use only. The grey component of the water footprint ($m^3 ton^{-1}$) is calculated by multiplying the fraction of nitrogen that leaches or runs off by the nitrogen application rate ($kg\,ha^{-1}$) and dividing this by the difference between the maximum acceptable concentration of nitrogen ($kg\,m^{-3}$) and the natural concentration of nitrogen in the receiving water body ($kg\,m^{-3}$) and by the actual crop yield ($ton\,ha^{-1}$).

The water footprints of crops as harvested have been used as a basis to calculate the water footprints of derived crop products based on product and value fractions and water footprints of processing steps following the method as in Hoekstra et al. (2009). The water footprint per unit of energy for ethanol and biodiesel producing crops was calculated following the method as applied in Gerbens-Leenes et al. (2009).

3 Data

Monthly long-term average reference evapotranspiration data at 10 by 10 arc min resolution were obtained from FAO (2008c). The 10 by 10 arc min data were converted to 5 by 5 arc min resolution by assigning the 10 by 10 min data to each of the four 5 by 5 min grid cells. Following the CROPWAT approach, the monthly average data were converted to daily values by curve fitting to the monthly average through polynomial interpolation.

Monthly values for precipitation, number of wet days and minimum and maximum temperature for the period 1996–2002 with a spatial resolution of 30 by 30 arc min were obtained from CRU-TS-2.1 (Mitchell and Jones, 2005). The 30 by 30 arc min data were assigned to each of the thirty-six 5 by 5 arc min grid cells contained in the 30 by 30 arc min grid cell. Daily precipitation values were generated from the monthly average

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values using the CRU-dGen daily weather generator model (Schuol and Abbaspour, 2007).

Crop growing areas on a 5 by 5 arc min grid cell resolution were obtained from Monfreda et al. (2008). For countries missing grid data in Monfreda et al. (2008), the MICRA2000 grid database as described in Portmann et al. (2010) was used to fill the gap. The harvested crop areas as available in grid format were aggregated to a national level and scaled to fit national average crop harvest areas for the period 1996–2005 obtained from FAO (2008a).

Grid data on the irrigated fraction of harvested crop areas for 24 major crops were obtained from the MICRA2000 database (Portmann et al., 2010). For the other 102 crops considered in the current study, we used the data for "other perennial" and "other annual crops" as in the MICRA2000 database, depending on whether the crop is categorised under "perennial" or "annual" crops.

Crop coefficients (K_c's) for crops were obtained from Chapagain and Hoekstra (2004). Crop planting dates and lengths of cropping seasons were obtained from FAO (2008d), Sacks et al. (2010), Portmann et al. (2010) and USDA (2004). For some crops, values from Chapagain and Hoekstra (2004) were used. We have not considered multi-cropping practices. Grid-based data on total available water capacity of the soil (TAWC) at a 5 by 5 arc min resolution were taken from ISRIC-WISE (Batjes, 2006). An average value of TAWC of the five soil layers was used in the model.

Country-specific nitrogen fertilizer application rates by crop have been estimated based on Heffer (2009), FAO (2006, 2009) and IFA (2009). Since grid-based fertilizer application rates are not available, we have assumed that crops receive the same amount of nitrogen fertilizer per hectare in all grid cells in a country. We have further assumed that on average 10% of the applied nitrogen fertilizer is lost through leaching, following Chapagain et al. (2006). The recommended maximum value of nitrate in surface and groundwater by the World Health Organization and the European Union is 50 mg nitrate (NO_3) per litre and the maximum value recommended by US-EPA is 10 mg per litre measured as nitrate-nitrogen (NO_3-N). In this study we have used the standard

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of 10 mg per litre of nitrate-nitrogen (NO_3-N), following again Chapagain et al. (2006). Because of lack of data, the natural nitrogen concentrations were assumed to be zero.

For the calculation of the water footprints of derived crop products we used product and value fraction. Most of these fractions have been taken from FAO (2003) and Chapagain and Hoekstra (2004).

Data on the dry mass of crops, the carbohydrate content of ethanol providing crops, the fat content of biodiesel providing crops and the higher heating value of ethanol and biodiesel were taken from Gerbens-Leenes et al. (2008a,b) and summarized in Table 1.

4 Results

4.1 The global picture

The global water footprint of crop production in the period 1996–2005 was 7404 $Gm^3 yr^{-1}$ (78% green, 12% blue, and 10% grey). Wheat takes the largest share in this total volume; it consumed 1087 $Gm^3 yr^{-1}$ (70% green, 19% blue, 11% grey). The other crops with a large total water footprint are rice (992 $Gm^3 yr^{-1}$) and maize (770 $Gm^3 yr^{-1}$). The contribution of the major crops to the global water footprint related to crop production is presented in Fig. 1. The global average green water footprint related to crop production was 5771 $Gm^3 yr^{-1}$, of which rain-fed crops use 4701 $Gm^3 yr^{-1}$ and irrigated crops use 1070 $Gm^3 yr^{-1}$. For most of the crops, the contribution of green water footprint toward the total consumptive water footprint (green and blue) is more than 80%. Among the major crops, the contribution of green water toward the total consumptive water footprint is lowest for date palm (43%) and cotton (64%). The proportion of green water in the total evaporative (green plus blue) water footprint for the major crops is show in Fig. 3. The global average blue water footprint related to crop production was 899 $Gm^3 yr^{-1}$. Wheat (204 $Gm^3 yr^{-1}$) and rice (202 $Gm^3 yr^{-1}$) have large blue water footprint together accounting for 45% of the global blue water footprint. The grey water footprint related to the use of nitrogen fertilizer in crops cultivation was

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733 $Gm^3\,yr^{-1}$. Wheat (123 $Gm^3\,yr^{-1}$), maize (122 $Gm^3\,yr^{-1}$) and rice (111 $Gm^3\,yr^{-1}$) have large grey water footprint together accounting for about 56% of the global grey water footprint.

The green, blue, grey and total water footprints of crop production per grid cell are shown in Fig. 2. Large water footprints per grid cell (>400 $mm\,yr^{-1}$) are found in the Ganges and Indus River Basins (India, Pakistan and Bangladesh), in Eastern China and in the Mississippi River Basin (USA). These locations are the same locations as where the harvested crop area takes a relative large share in the total area (Monfreda et al., 2008).

Globally, 86.5% of the water consumed in crop production is green water. Even in irrigated agriculture, green water often has a very significant contribution to total water consumption. The share of the blue water footprint in total water consumption (green plus blue water footprint) is shown in Fig. 3. The share of the blue water footprint is largest in arid and semi-arid regions. Regions with a large blue water proportion are located, for example, in the western part of the USA, in a relatively narrow strip of land along the west coast of South America (Peru-Chile), in Southern Europe, North Africa, the Arabian Peninsula, Central Asia, Pakistan and Northern India, Northeast China and parts of Australia.

4.2 The water footprint of primary crops and derived crop products per ton

The average water footprint per ton of primary crop differs significantly among crops and across production regions. Crops with a high yield or large fraction of crop biomass that is harvested generally have a smaller water footprint per ton than crops with a low yield or small fraction of crop biomass harvested. When considered per ton of product, commodities with relatively large water footprints are: coffee, tea, cocoa, tobacco, spices, nuts, rubber and fibres (Table 2). For food crops, the global average water footprint per ton of crop increases from sugar crops (roughly 200 $m^3\,ton^{-1}$), vegetables (∼300 $m^3\,ton^{-1}$), roots and tubers (∼400 $m^3\,ton^{-1}$), fruits (∼1000 $m^3\,ton^{-1}$),

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cereals (~1600 m^3 ton^{-1}), oil crops (~2400 m^3 ton^{-1}), pulses (~4000 m^3 ton^{-1}), spices (~7000 m^3 ton^{-1}) to nuts (~9000 m^3 ton^{-1}). The water footprint varies, however, across different crops per crop category. Besides, if one considers the water footprint per kcal, the picture changes as well. Vegetables and fruits, which have a relatively small water footprint per kg but a low caloric content, have a relatively large water footprint per kcal.

Global average water footprints of selected primary crops and their derived products are presented in Table 3. The results allow us to compare the water footprints of different products:

- The average water footprint for cereal crops is 1644 m^3 ton^{-1}, but the footprint for wheat is relatively large (1827 m^3 ton^{-1}), while for maize it is relatively small (1222 m^3 ton^{-1}). The average water footprint of rice is close to the average for all cereals together.
- Sugar obtained from sugar beet has a smaller water footprint than sugar from sugar cane. Besides, the blue component in the total water footprint of beet sugar (20%) is smaller than for cane sugar (27%).
- For vegetable oils we find a large variation in water footprints: maize oil 2600 m^3 ton^{-1}; cotton-seed oil 3800 m^3 ton^{-1}; soybean oil 4200 m^3 ton^{-1}; rapeseed oil 4300 m^3 ton^{-1}; palm oil 5000 m^3 ton^{-1}; sunflower oil 6800 m^3 ton^{-1}; groundnut oil 7500 m^3 ton^{-1}; linseed oil 9400 m^3 ton^{-1}; olive oil 14500 m^3 ton^{-1}; castor oil 24700 m^3 ton^{-1}.
- For fruits we find a similar variation in water footprints: water melon 235 m^3 ton^{-1}; pineapple 255 m^3 ton^{-1}; papaya 460 m^3 ton^{-1}; orange 560 m^3 ton^{-1}; banana 790 m^3 ton^{-1}; apple 820 m^3 ton^{-1}; peach 910 m^3 ton^{-1}; pear 920 m^3 ton^{-1}; apricot 1300 m^3 ton^{-1}; plums 2200 m^3 ton^{-1}; dates 2300 m^3 ton^{-1}; grapes 2400 m^3 ton^{-1}; figs 3350 m^3 ton^{-1}.
- For alcoholic beverages we find: a water footprint of 300 m^3 ton^{-1} for beer and 870 m^3 ton^{-1} for wine.

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- The water footprints of juices vary from tomato juice (270 m^3 ton^{-1}), grapefruit juice (675 m^3 ton^{-1}), orange juice (1000 m^3 ton^{-1}) and apple juice (1100 m^3 ton^{-1}) to pineapple juice (1300 m^3 ton^{-1}).
- The water footprint of coffee (130 l cup^{-1}, based on use of 7 g of roasted coffee per cup) is much larger than the water footprint of tea (27 l cup^{-1}, based on use of 3 g of black tea per cup).
- The water footprint of cotton fibres is substantially larger than the water footprints of sisal and flax fibres, which are again larger than the water footprints of jute and hemp fibres.

One should be careful in drawing conclusions from the above product comparisons. Although the global average water footprint of one product may be larger than the global average water footprint of another product, the comparison may turn out quite differently for specific regions.

4.3 The water footprint of biofuels per GJ and per litre

The water footprint of biofuel varies across both crops and countries. The variation is due to differences in crop yields across countries and crops, differences in energy yields across crops and differences in climate and agricultural practices across countries. Table 4 shows the global average water footprint of biofuel for a number of crops providing ethanol and some other crops providing biodiesel. Among the crops providing ethanol, sorghum has the largest water footprint, with 7000 l of water per litre of ethanol, which is equivalent to 300 m^3 GJ^{-1}. Bio-ethanol based on sugar beet has the smallest global average water footprint, with 1200 l of water per litre of ethanol, equivalent to 50 m^3 GJ^{-1}. In general, biodiesel has a larger water footprint per unit of energy obtained than bio-ethanol, a finding that is consistent with Gerbens-Leenes et al. (2009). Among the crops studied here, biodiesel from coconuts has the largest water footprint: 4750 m^3 GJ^{-1}. Biodiesels from oil palm, rapeseed and groundnuts are

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more efficient, with water footprints in the range 150–200 $m^3\,GJ^{-1}$. The largest blue water footprint is observed for biodiesel from cotton: 177 $m^3\,GJ^{-1}$ (32% of the total water footprint).

4.4 The total water footprint of crop production at national and sub-national level

At the country level, the largest total water footprints were estimated for India (1047 $Gm^3\,yr^{-1}$), China (967 $Gm^3\,yr^{-1}$), the USA (826 $Gm^3\,yr^{-1}$), Brazil (329 $Gm^3\,yr^{-1}$), Russia (327 $Gm^3\,yr^{-1}$) and Indonesia (318 $Gm^3\,yr^{-1}$). These six countries together account for about half of the global total water footprint related to crop production. The largest green water footprints are also found in these six countries: India (716 $Gm^3\,yr^{-1}$), China (624 $Gm^3\,yr^{-1}$), the USA (612 $Gm^3\,yr^{-1}$), Russia (305 $Gm^3\,yr^{-1}$), Brazil (304 $Gm^3\,yr^{-1}$) and Indonesia (286 $Gm^3\,yr^{-1}$). Data per country are shown in Table 5 for the largest producers. At sub-national level (state or province level), the largest green water footprints can be found in Uttar Pradesh (88 $Gm^3\,yr^{-1}$), Maharashtra (86 $Gm^3\,yr^{-1}$), Karnataka (65 $Gm^3\,yr^{-1}$), Andhra Pradesh (61 $Gm^3\,yr^{-1}$), and Madhya Pradesh (60 $Gm^3\,yr^{-1}$), all in India. The largest blue water footprints were calculated for India (231 $Gm^3\,yr^{-1}$), China (119 $Gm^3\,yr^{-1}$), the USA (96 $Gm^3\,yr^{-1}$) and Pakistan (74 $Gm^3\,yr^{-1}$). These four countries together account for 58% of the total blue water footprint related to crop production. At sub-national level, the largest blue water footprints were found in: Uttar Pradesh (59 $Gm^3\,yr^{-1}$) and Madhya Pradesh (24 $Gm^3\,yr^{-1}$) in India; Punjab (50 $Gm^3\,yr^{-1}$) in Pakistan; and California (20 $Gm^3\,yr^{-1}$) in the USA. Large grey water footprints were estimated for China (224 $Gm^3\,yr^{-1}$), the USA (118 $Gm^3\,yr^{-1}$) and India (99 $Gm^3\,yr^{-1}$).

4.5 The total water footprint of crop production at river basin level

At the river basin level, large water footprints were calculated for the Mississippi, Ganges, Yangtze, Indus and Parana River Basins (Table 6). These five river basins

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together account for 23% of the global water footprint related to crop production. The largest green water footprint was calculated for the Mississippi river basin (424 $Gm^3 yr^{-1}$). The largest blue water footprints were found in the basins of the Indus (117 $Gm^3 yr^{-1}$) and Ganges (108 $Gm^3 yr^{-1}$). These two river basins together account for 25% of the global blue water footprint. Both basins are under severe water stress (Alcamo et al., 2007).

4.6 The water footprint in irrigated versus rain-fed agriculture

For most of the crops, the global average consumptive water footprint (blue plus green water footprint) per ton of crop was lower for irrigated crops than for rain-fed crops (Table 7). This is because, on average, irrigated yields are larger than rain-fed yields. For wheat, the water footprint per ton in irrigated and rain-fed agriculture are very similar at the global scale. For soybean, sugarcane and rapeseed, the water footprints per ton were substantially smaller in rain-fed production. The reason is that, although yields are higher under irrigation, there is more water available to meet crop water requirements, leading to an actual evapotranspiration that will approach or equal potential evapotranspiration. Under rain-fed conditions, the actual evapotranspiration over the growing period is generally lower than the potential evapotranspiration. Globally, rain-fed agriculture has a water footprint of 5173 $Gm^3 yr^{-1}$ (91% green, 9% grey); irrigated agriculture has a water footprint of 2230 $Gm^3 yr^{-1}$ (48% green, 40% blue, 12% grey).

5 Discussion

In order to compare our estimates with previous studies, we have selected those studies which estimated the water footprint in global crop production and made an explicit distinction between green and blue water (Table 8). The study by Chapagain and Hoekstra (2004) did not take a grid-based approach and also did not make the green-blue distinction per crop and per country, unlike the current study and the studies by Rost et al. (2008), Liu and Yang (2010), Siebert and Döll (2010) and Hanasaki et al. (2010).

A comparison of our estimates with earlier studies shows that the order of magnitude is similar in all studies. The estimate of the total water footprint related to crop production by Hanasaki et al. (2010) is 6% higher than our estimate, while the estimate of Liu and Yang (2010) is 11% lower. Our study is at the high side regarding the estimation of the global green water footprint and at the low side regarding the blue water footprint. Although there are major differences in applied models and assumptions, the models agree on the dominant role of green water in global crop production. The study by Rost et al. (2008) gives a higher green water footprint than the other studies, but this can be explained by the fact that evapotranspiration from croplands is estimated here over the whole year, instead of over the growing periods of the crops. The differences in the outcomes of the various studies can be due to a variety of causes, including: type of model, spatial resolution, period considered and data regarding cultivated and irrigated areas, growing periods, crop parameters, soil and climate.

Chapagain and Hoekstra (2004) have estimated the global water footprint of crop production distinguishing between green and blue only at the global level, but not per country and per crop. Our estimate of the total (green plus blue) water footprint is 4% higher than that of Chapagain and Hoekstra (2004). The total water footprint per country estimated in the current study compares reasonably well with the estimates by Chapagain and Hoekstra (2004), with an r^2 value of 0.96 (Fig. 4a). The trend line ($y=1.06x$) almost fits the 1:1 line. The close agreement between the two studies and the slightly higher estimate in the current study is surprising. Due to limited data availability at the time, Chapagain and Hoekstra (2004) estimated crop water consumption based on the assumption of no water stress, so that actual equals potential evapotranspiration and their estimate is expected to be at the high side. There could be a number of reasons for the lower estimate in Chapagain and Hoekstra (2004). Some of the differences are observed in the larger countries such as the USA, Russia, China and Brazil. Chapagain and Hoekstra (2004) have taken national average climatic data to

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calculate crop evapotranspiration, which in particular for the large countries mentioned above has led to a different estimate compared to the current study. There are also differences between the two studies in the planting and harvesting dates and thus the length of growing period for the different crops considered.

The estimate of the total water footprint by Liu and Yang (2010) is 11% lower than our estimate, which is almost completely due to their lower estimate of the green component. In Fig. 4b, the total (green plus blue) water footprints by country as estimated in the current study are plotted against the results from Liu and Yang (2010). There is a close agreement between the two studies with an r^2 value of 0.96. The differences between the two studies can be partially explained by differences in the method used to estimate reference evapotranspiration. The blue water footprint per country as computed in this study compares to the result from Liu and Yang (2010) as shown in Fig. 5a. The correlation is reasonably well, with an r^2 value of 0.78.

The computed total (green plus blue) water footprint is almost the same as the value found by Siebert and Döll (2010). However, the green water footprint estimated by Siebert and Döll (2010) is 4.6% lower than in the current study, while their blue water footprint estimate is 31% higher. At country level, the blue water footprint estimates in the two studies correlate well, with an r^2 value of 0.99, but our estimates are consistently lower (Fig. 5b). For most crops there is a good agreement between the current estimate of the total blue water footprint and the one by Siebert and Döll (2010). However, their total blue water footprint estimate for rice (307 $Gm^3 yr^{-1}$) is 52% higher than our estimate (202 $Gm^3 yr^{-1}$). The reason for the difference could be differences in the planting and harvesting dates and thus the length of the growing period in the two studies.

The national blue water footprints estimated in the current study were further compared with statistics on agricultural water withdrawals per country as available from AQUASTAT (FAO, 2008b). Since water withdrawals are higher than actual blue water consumption, we first estimated the latter by multiplying the water withdrawal per country by the irrigation efficiency. Overall irrigation efficiency data per country were obtained from Rohwer et al. (2007), whereby irrigation efficiency refers here to the fraction of water diverted from the water source that is available for beneficial crop evapotranspiration. The blue water footprint per country computed in the current study generally compares well with the derived values based on AQUASTAT and Rohwer et al. (2007), with an r^2 value of 0.94 (Fig. 6a). Compared to the AQUASTAT values, our estimates are slightly lower (6%). A reason may be that water withdrawals in agriculture do not refer to withdrawals alone; water withdrawn for domestic needs and animal breeding may constitute 5–8% of the agricultural water withdrawal (Shiklomanov, 2000). Assuming that water withdrawal for irrigation equals agricultural water withdrawal may thus lead to a slight overestimation of the blue water footprint from the statistics.

The blue water footprints estimated in the current study can also be compared with consumptive water use in irrigation on the level of federal states in the USA. Hutson et al. (2004) provide irrigation water withdrawal at federal state level for the year 2000. Consumptive blue water use for the year 2000 was derived using the ratio of consumptive water use to water withdrawal for irrigation at state level for the year 1995 (Solley et al., 1998). Our estimated blue water footprints at federal state level correlate well with the statistic data, at least for states with high irrigation water use. The blue water footprints at the state level obtained in the current study, however, are generally lower than the values obtained from the statistics (Fig. 6b).

The calculated national blue water footprints were further compared to the irrigation water requirements for 90 developing countries as estimated by FAO (2005) for the year 2000. As can be seen in Fig. 7, the calculated national blue water footprints are consistently lower than the national irrigation requirements from FAO (2005), which can be understood from the fact that irrigation requirements are generally met only partially.

The water footprint per ton of crop has been compared with results from Chapagain and Hoekstra (2004) and Siebert and Döll (2010). The global average water footprint per ton of crop correlates well with Chapagain and Hoekstra (2004), with an r^2 value of 0.97 (Fig. 8a). The comparison with Siebert and Döll (2010) also shows a good

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agreement, with an r^2 value of 0.995 (Fig. 8b). Out of the 22 crops compared, for 13 crops (including wheat, rice, maize, barley and sugar cane) the difference is within ±10%. Large differences (±20%) were observed for rye, cassava and millet. The reason for the larger differences probably lies in the average yield used in the two studies. We used national average yield data from FAOSTAT, which apparently differ from the yield data from Monfreda et al. (2008) which were used by Siebert and Döll (2010).

Since all studies depend on a large set of assumptions with respect to modelling structure, parameter values and datasets used, as it was already pointed out by Mekonnen and Hoekstra (2010), it is difficult to attribute differences in estimates from the various studies to specific factors; also it is difficult to assess the quality of our new estimates relative to the quality of earlier estimates. The quality of data used defines the accuracy of the model output. All studies suffer the same sorts of limitations in terms of data availability and quality and deal with that in different ways. In future studies it would be useful to spend more effort in studying the sensitivity of the model outcomes to assumptions and parameters and assessing the uncertainties in the final outcome.

6 Conclusions

The study shows that the global water footprint of crop production for the period 1996–2005 was 7404 $Gm^3 yr^{-1}$. The large fraction of green water (78%) confirms the importance of rain. The fraction of blue water is smaller (12%), but as the spatial analysis shows, the regions where blue water footprints are large are often arid and semi-arid regions where water scarcity is high. The share of the grey water footprint is relatively small as well (10%), but this is a conservative estimate, because we have analysed the required assimilation volume for leached nitrogen fertilizers only, leaving out relevant pollutants such as phosphorus and pesticides.

The finding in this study agrees with earlier studies that green water plays a prominent role in the global crop production. As shown by Rockström et al. (2009), most

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countries in theory have a green water based self-sufficiency potential and are in a position to produce their entire food requirement locally. Rockström et al. (2003) showed that there is great opportunity to improve water productivity through improving yield levels as much as four folds within the available water balance in rain-fed agriculture. This offers a good opportunity to increase food production from rain-fed agriculture by raising water productivity without requiring additional blue water resources (Critchely and Siegert, 1991; Rockström and Barron, 2007; Rockström et al., 2003, 2007a,b). However, in semi-arid and arid regions the available precipitation is quite low and crop production without additional use of blue water is almost impossible. Globally, the current cereal production would be significantly lower if no blue water is applied (Hoff et al., 2010; Rost et al., 2009; Siebert and Döll, 2010). Therefore, a carefully balanced green-blue water use strategy would be required to address the issue of increasing water demand in a world of limited freshwater resources. For further research it is important to assess the spatiotemporal variability of blue water availability and how much blue water can sustainably be used in a certain catchment without adversely affecting the ecosystem.

There are a number of uncertainties in the estimation of the green, blue and grey water footprints. In particular, the uncertainties related to the input data used in the model are high. A number of assumptions were made due to a lack of data. The uncertainties include:

- Crop-specific irrigation maps are available only for a limited number of crops. Irrigation maps for the other crops were derived from the MICRA2000 database through the simple assumption that all crops in a country belonging to a certain crop category (annuals/perennials) would have the same fraction of irrigated area out of the total harvested area. This assumption will lead to an underestimation of the irrigated area and thus the blue water footprint of crops which are most likely to be irrigated and an overestimation of the blue water footprint for those minor crops which are actually not irrigated.

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- The planting and harvesting dates and thus the length of the growing period used in the study are available only at country level, thus do not reflect possible variation within a country and across varieties of the same crop. Crop planting and harvesting dates are provided in the literature as a range of dates (FAO, 2008d; USDA, 1994). The choice of the planting and harvesting dates out of these ranges obviously influences the final crop water footprint estimate.
- The rooting depth for both rain-fed and irrigated crops are defined based on the crop characteristics. However, such assumption neglects the fact that actual rooting depth depends also on the soil type.
- The soil water holding capacity is derived based on the dominant soil type. However, farmers may plant in the parts of the grid cell with better soils, which may have a different water holding capacity to that defined for the dominant soil type.
- For irrigated agriculture, the irrigation is assumed to be sufficient to meet the irrigation requirement. However, farmers may decide to supply irrigation water below the level of optimal yield, in particular in those regions where water is scarce. The assumption of sufficient irrigation may lead to an overestimation of the blue water footprint.
- Fertilizer application rates per crop per country are not available for most crops. The rates used in this study are based on different sources and a number of assumptions. All grid cells of the same crop in a country are assumed to receive the same fertilizer application rate. However, irrigated crops generally receive more fertilizer than rain-fed ones. Besides, most small subsistence farmers likely use no or less fertilizer.
- The grey water footprint is estimated based on a simplified approach, which gives a rough estimate; it leaves out local factors that influence the precise leaching and runoff rates, such as rainfall intensity, soil property, slopes and the amount of already mineralized nitrogen in the upper soil layer. Systematic comparison

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of the estimate from such simplified approach with other regression models (De Willigen, 2000; Roy et al., 2003; Liu et al., 2010) might be required to test the uncertainties and limitation of our approach. Liu et al. (2010) estimated, for the first time, global nitrogen flows of 6 nitrogen inputs and 5 nitrogen outputs including nitrogen leaching at high resolution (5 by 5 arc min grid). Their approach is very innovative and could be useful to conduct in-depth grey water assessment in the future.

- The model used to estimate the yield at grid level is a simplified linear model which accounts for the effect of water deficit on yield reduction only, leaving out other factors, such as fertilizer application rate, soil salinity and crop growing characteristics.
- Although intercropping and multi-cropping are practiced in most part of the world, we have not considered those practices explicitly.

In a global study like this one, because of lack of data, several assumptions and expert guesses were made. At this stage it seems difficult to reduce the uncertainties. Therefore, the water footprint values at a smaller spatial scale, in particular at the grid cell level, should be interpreted with care.

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Table 1. Characteristics of ten ethanol providing and seven biodiesel providing crops.

Sugar and starch crops	Dry mass fraction (%)	Fraction of carbohydrates in dry mass ($g\,g^{-1}$)	Ethanol per unit of carbohydrate ($g\,g^{-1}$)	Energy yield* ($GJ\,ton^{-1}$)	Bio-ethanol yield** ($l\,ton^{-1}$)
Barley	85%	0.76	0.53	10.2	434
Cassava	38%	0.87	0.53	5.20	222
Maize	85%	0.75	0.53	10.0	428
Potatoes	25%	0.78	0.53	3.07	131
Rice, paddy	85%	0.76	0.53	10.2	434
Rye	85%	0.76	0.53	10.2	434
Sorghum	85%	0.76	0.53	10.2	434
Sugar beet	21%	0.82	0.51	2.61	111
Sugar cane	27%	0.57	0.51	2.33	99
Wheat	85%	0.76	0.53	10.17	434
Oil crops	**Dry mass fraction (%)**	**Fraction of fat in dry mass ($g\,g^{-1}$)**	**Biodiesel per unit of fat ($g\,g^{-1}$)**	**Energy yield* ($GJ\,ton^{-1}$)**	**Biodiesel yield** ($l\,ton^{-1}$)**
Coconuts	50%	0.03	1	0.57	17
Groundnuts, with shell	95%	0.39	1	14.0	421
Oil palm fruit	85%	0.22	1	7.05	213
Rapeseed	74%	0.42	1	11.7	353
Seed cotton	85%	0.23	1	7.37	222
Soybeans	92%	0.18	1	6.24	188
Sunflower seed	85%	0.22	1	7.05	213

* Based on a higher heating value of 29.7 $kJ\,g^{-1}$ for ethanol and 37.7 $kJ\,g^{-1}$ for biodiesel.
** Based on a density of 0.789 $kg\,l^{-1}$ for ethanol and 0.88 $kg\,l^{-1}$ for biodiesel (Alptekin and Canakci, 2008).

Table 2. Global average water footprint of 14 primary crop categories. Period: 1996–2005.

Primary crop category	Water footprint ($m^3\,ton^{-1}$) Green	Blue	Grey	Total	Caloric value* ($kcal\,kg^{-1}$)	Water footprint ($l\,kcal^{-1}$)
Sugar crops	130	52	15	197	290	0.68
Fodder crops	207	27	20	253		
Vegetables	194	43	85	322	240	1.34
Roots and tubers	327	16	43	387	830	0.47
Fruits	727	147	93	967	460	2.10
Cereals	1232	228	184	1644	3200	0.51
Oil crops	2023	220	121	2364	2900	0.81
Tobacco	2021	205	700	2925		
Fibres, vegetal origin	3375	163	300	3837		
Pulses	3180	141	734	4055	3400	1.19
Spices	5872	744	432	7048	3000	2.35
Nuts	7016	1367	680	9063	2500	3.63
Rubber, gums, waxes	12 964	361	422	13 748		
Stimulants	13 731	252	460	14 443	880	16.4

* Source: FAO (2008a).

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Table 3. Global average water footprint of primary crops and derived crop products. Period: 1996–2005.

FAOSTAT crop code	Product description	Global average water footprint (m^3 ton^{-1}) Green	Blue	Grey	Total
15	Wheat	1277	342	207	1827
	Wheat flour	1292	347	210	1849
	Wheat bread	1124	301	183	1608
	Dry pasta	1292	347	210	1849
	Wheat pellets	1423	382	231	2036
	Wheat, starch	1004	269	163	1436
	Wheat gluten	2928	785	476	4189
27	Rice, paddy	1146	341	187	1673
	Rice, husked (brown)	1488	443	242	2172
	Rice, broken	1710	509	278	2497
	Rice flour	1800	535	293	2628
	Rice groats and meal	1527	454	249	2230
44	Barley	1213	79	131	1423
	Barley, rolled or flaked grains	1685	110	182	1977
	Malt, not roasted	1662	108	180	1950
	Malt, roasted	2078	135	225	2437
	Beer made from malt	254	16	27	298
56	Maize (corn)	947	81	194	1222
	Maize (corn) flour	971	83	199	1253
	Maize (corn) groats and meal	837	72	171	1081
	Maize (corn), hulled, pearled, sliced or kibbled	1018	87	209	1314
	Maize (corn) starch	1295	111	265	1671
	Maize (corn) oil	1996	171	409	2575
71	Rye	1419	25	99	1544
	Rye flour	1774	32	124	1930
75	Oats	1479	181	128	1788
	Oat groats and meal	2098	257	182	2536
	Oats, rolled or flaked grains	1998	245	173	2416
79	Millet	4306	57	115	4478
83	Sorghum	2857	103	87	3048
89	Buckwheat	2769	144	229	3142
116	Potatoes	191	33	63	287
	Tapioca of potatoes	955	165	317	1436
	Potato flour and meal	955	165	317	1436
	Potato flakes	694	120	230	1044
	Potato starch	1005	173	333	1512
122	Sweet potatoes	324	5	53	383
125	Manioc (cassava)	550	0	13	564
	Tapioca of cassava	2750	1	66	2818
	Flour of cassava	1833	1	44	1878
	Dried cassava	1571	1	38	1610
	Manioc (cassava) starch	2200	1	53	2254
136	Taro (coco yam)	587	3	15	606
137	Yams	341	0	1	343
156	Sugar cane	139	57	13	210
	Raw sugar, cane	1107	455	104	1666
	Refined sugar	1184	487	111	1782
	Fructose, chemically pure	1184	487	111	1782
	Cane molasses	350	144	33	527
157	Sugar beet	82	26	25	132
	Raw sugar, beet	535	167	162	865
176	Beans, dry	3945	125	983	5053
181	Broad beans, horse beans, dry	1317	205	496	2018
187	Peas, dry	1453	33	493	1979
191	Chick peas	2972	224	981	4177
195	Cow peas, dry	6841	10	55	6906

Table 3. Continued.

FAOSTAT crop code	Product description	Global average water footprint ($m^3 ton^{-1}$) Green	Blue	Grey	Total
197	Pigeon peas	4739	72	683	5494
201	Lentils	4324	489	1060	5874
217	Cashew nuts	12 853	921	444	14 218
220	Chestnuts	2432	174	144	2750
221	Almonds, with shell	4632	1908	1507	8047
	Almonds, shelled or peeled	9264	3816	3015	16 095
222	Walnuts, with shell	2805	1299	814	4918
	Walnuts, shelled or peeled	5293	2451	1536	9280
223	Pistachios	3095	7602	666	11 363
224	Kola nuts	23 345	26	19	23 391
225	Hazelnuts, with shell	3813	1090	354	5258
	Hazelnuts, shelled or peeled	7627	2180	709	10 515
226	Areca nuts	10 621	139	406	11 165
236	Soya beans	2037	70	37	2145
	Soya sauce	582	20	11	613
	Soya paste	543	19	10	572
	Soya curd	2397	83	44	2523
	Soy milk	3574	123	65	3763
	Soya bean flour and meals	2397	83	44	2523
	Soybean oil, refined	3980	137	73	4190
	Soybean oilcake	1690	58	31	1779
242	Groundnuts in shell	2469	150	163	2782
	Groundnuts shelled	3526	214	234	3974
	Groundnut oil , refined	6681	405	442	7529
	Groundnut oilcake	1317	80	87	1484
249	Coconuts	2669	2	16	2687
	Copra	2079	1	12	2093
	Coconut (husked)	1247	1	7	1256
	Coconut (copra) oil , refined	4461	3	27	4490
	Coconut/copra oilcake	829	1	5	834
	Coconut (coir) fibre, processed	2433	2	15	2449
254	Oil palm	1057	0	40	1098
	Palm nuts and kernels	2762	1	105	2868
	Palm oil, refined	4787	1	182	4971
	Palm kernel/babassu oil, refined	5202	1	198	5401
	Palm nut/kernel oilcake	802	0	31	833
260	Olives	2470	499	45	3015
	Olive oil, virgin	11 826	2388	217	14 431
	Olive oil, refined	12 067	2437	221	14 726
265	Castor oil seeds	8423	1175	298	9896
	Castor oil	21 058	2938	744	24 740
267	Sunflower seeds	3017	148	201	3366
	Sunflower seed oil, refined	6088	299	405	6792
	Sunflower seed oilcake	1215	60	81	1356
270	Rapeseed	1703	231	336	2271
	Rape oil, refined	3226	438	636	4301
	Rape seed oilcake	837	114	165	1115
280	Safflower seeds	6000	938	283	7221
289	Sesame seed	8460	509	403	9371
	Sesame oil	19 674	1183	936	21 793
292	Mustard seeds	2463	1	345	2809
296	Poppy seeds	1723		464	2188
299	Melon seed	5087	56	41	5184
	Cotton seeds	730	418	141	1288
328	Seed cotton	2282	1306	440	4029
	Cotton lint	5163	2955	996	9113
	Cotton linters	1426	816	275	2516
	Cotton-seed oil, refined	2168	1241	418	3827

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Table 3. Continued.

FAOSTAT crop code	Product description	Global average water footprint ($m^3\,ton^{-1}$) Green	Blue	Grey	Total
	Cotton seed oilcake	471	270	91	832
	Cotton, not carded or combed	11 779	6741	2271	20 791
	Cotton yarn waste (including thread waste)	2168	1241	418	3827
	Garneted stock of cotton	3253	1862	627	5742
	Cotton, carded or combed	12 228	6998	2358	21 583
	Cotton fabric, finished textile	12 285	7030	2369	21 684
333	Linseed	4730	268	170	5168
	Linseed oil, refined	8618	488	310	9415
	Linseed oilcake	2816	160	101	3077
336	Hempseed	3257	12	417	3685
358	Cabbages and other brassicas	181	26	73	280
366	Artichokes	478	242	98	818
367	Asparagus	1524	119	507	2150
372	Lettuce	133	28	77	237
373	Spinach	118	14	160	292
388	Tomatoes	108	63	43	214
	Tomato juice unfermented and not spirited	135	79	53	267
	Tomato juice, concentrated	539	316	213	1069
	Tomato paste	431	253	171	855
	Tomato ketchup	270	158	107	534
	Tomato puree	360	211	142	713
	Peeled tomatoes	135	79	53	267
	Tomato, dried	2157	1265	853	4276
393	Cauliflowers and broccoli	189	21	75	285
	Brussels sprouts	189	21	75	285
394	Pumpkins, squash and gourds	228	24	84	336
397	Cucumbers and gherkins	206	42	105	353
399	Eggplants (aubergines)	234	33	95	362
401	Chillies and peppers, green	240	42	97	379
402	Onions (incl. shallots), green	176	44	51	272
403	Onions, dry	192	88	65	345
406	Garlic	337	81	170	589
	Garlic powder	313	655	2265	313
414	Beans, green	320	54	188	561
417	Peas, green	382	63	150	595
423	String beans	301	104	143	547
426	Carrots and turnips	106	28	61	195
430	Okra	474	36	65	576
446	Maize, green	455	157	88	700
461	Carobs	4557	334	703	5594
486	Bananas	660	97	33	790
489	Plantains	1570	27	6	1602
490	Oranges	401	110	49	560
	Orange juice	729	199	90	1018
495	Tangerines, mandarins, clement	479	118	152	748
497	Lemons and limes	432	152	58	642
507	Grapefruit	367	85	54	506
515	Apples, fresh	561	133	127	822
	Apples, dried	4678	1111	1058	6847
	Apple juice unfermented and not spirited	780	185	176	1141
521	Pears	645	94	183	922
526	Apricots	694	502	92	1287
530	Sour cherries	1098	213	99	1411
531	Cherries	961	531	112	1604
534	Peaches and nectarines	583	188	139	910
536	Plums and sloes	1570	188	422	2180
544	Strawberries	201	109	37	347
547	Raspberries	293	53	67	413

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Table 3. Continued.

FAOSTAT crop code	Product description	Global average water footprint (m^3 ton^{-1}) Green	Blue	Grey	Total
549	Gooseberries	487	8	31	526
550	Currants	457	19	23	499
552	Blueberries	341	334	170	845
554	Cranberries	91	108	77	276
560	Grapes	425	97	87	608
	Grapes, dried	1700	386	347	2433
	Grapefruit juice	490	114	71	675
	Grape wines, sparkling	607	138	124	869
567	Watermelons	147	25	63	235
569	Figs	1527	1595	228	3350
571	Mangoes, mangosteens, guavas	1314	362	124	1800
572	Avocados	849	283	849	1981
574	Pineapples	215	9	31	255
	Pineapple juice	1075	45	153	1273
577	Dates	930	1250	98	2277
591	Cashew apple	3638	34	121	3793
592	Kiwi fruit	307	168	38	514
600	Papayas	399	40	21	460
656	Coffee, green	15 249	116	532	15 897
	Coffee, roasted	18 153	139	633	18 925
661	Cocoa beans	19 745	4	179	19 928
	Cocoa paste	24 015	5	218	24 238
	Cocoa butter, fat and oil	33 626	7	305	33 938
	Cocoa powder	15 492	3	141	15 636
	Chocolate	16 805	198	193	17 196
667	Green and black tea	7232	898	726	8856
677	Hop cones	2382	269	1414	4065
	Hop extract	9528	1077	5654	16 259
687	Pepper of the genus Piper	6540	467	604	7611
689	Chillies and peppers, dry	5869	1125	371	7365
692	Vanilla beans	86 392	39 048	1065	12 6505
693	Cinnamon (canella)	14 853	41	632	15 526
698	Cloves	59 834	30	1341	61 205
702	Nutmeg, mace and cardamoms	30 683	2623	1014	34 319
711	Anise, badian, fennel, coriander	5369	1865	1046	8280
	Coriander seeds	5369	1865	1046	8280
720	Ginger	1525	40	92	1657
748	Peppermint	206	63	19	288
773	Flax fibre and tow	2637	443	401	3481
	Flax fibre, otherwise processed but not spun	2866	481	436	3783
	Flax tow and waste	581	98	88	767
777	Hemp fibre and tow	1824		624	2447
	True hemp fibre processed but not spun	2026		693	2719
780	Jute and other textile bast fibres	2356	33	217	2605
788	Ramie	3712	201	595	4507
789	Sisal	6112	708	222	7041
	Sisal textile fibres processed but not spun	6791	787	246	7824
800	Agave fibres	6434	9	106	6549
809	Manila fibre (Abaca)	19 376	246	766	20 388
	Abaca fibre, processed but not spun	21 529	273	851	22 654
826	Tobacco, unmanufactured	2021	205	700	2925
836	Natural rubber	12 964	361	422	13 748

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Table 4. Global average water footprint of biofuel for ten crops providing ethanol and seven crops providing biodiesel. Period: 1996–2005.

Crop	Water footprint per unit of energy			Water footprint per litre of biofuel		
	Green	Blue	Grey	Green	Blue	Grey
Crops for ethanol	m^3 per GJ ethanol			litres water per litre ethanol		
Barley	119	8	13	2796	182	302
Cassava	106	0	3	2477	1	60
Maize	94	8	19	2212	190	453
Potatoes	62	11	21	1458	251	483
Rice, paddy	113	34	18	2640	785	430
Rye	140	2	10	3271	58	229
Sorghum	281	10	9	6585	237	201
Sugar beet	31	10	10	736	229	223
Sugar cane	60	25	6	1400	575	132
Wheat	126	34	20	2943	789	478
Crops for biodiesel	m^3 per GJ biodiesel			litres water per litre biodiesel		
Coconuts	4720	3	28	15 6585	97	935
Groundnuts	177	11	12	5863	356	388
Oil palm	150	0	6	4975	1	190
Rapeseed	145	20	29	4823	655	951
Seed cotton	310	177	60	10 274	5879	1981
Soybeans	326	11	6	10 825	374	198
Sunflower	428	21	28	14 200	696	945

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Table 5. The water footprint of crop production in selected countries (1996–2005).

Country	Water footprint of crop production ($Gm^3\,yr^{-1}$)			
	Green	Blue	Grey	Total
India	716.0	231.4	99.4	1047
China	623.9	118.9	223.8	967
USA	612.0	95.9	118.2	826
Brazil	303.7	8.9	16.0	329
Russia	304.8	10.4	11.6	327
Indonesia	285.5	11.5	20.9	318
Nigeria	190.6	1.1	0.6	192
Argentina	157.6	4.3	5.0	167
Canada	120.3	1.6	18.2	140
Pakistan	40.6	74.3	21.8	137
World	5771	899	733	7404

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Table 6. The water footprint of crop production in selected river basins (1996–2005).

River basin*	Water footprint of crop production ($Gm^3 yr^{-1}$) Green	Blue	Grey	Total
Mississippi	424	40	70	534
Ganges	260	108	39	408
Yangtze (Chang Jiang)	177	18	61	256
Indus	102	117	34	253
Parana	237	3.2	9.4	250
Niger	186	1.7	0.5	188
Nile	131	29	6.9	167
Huang He (Yellow River)	80	21	31	132
Nelson	108	1.5	18	128
Danube	106	1.8	11	119
Krishna	89	21	8.7	118
Volga	101	3.4	3.9	108
Ob	92	1.8	1.8	95
World	5771	899	733	7404

* River basins grid data from Global Runoff Data Centre (2007).

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Table 7. The water footprint of rain-fed and irrigated agriculture for selected crops (1996–2005).

Crop	Farming system	Yield (ton ha^{-1})	Total water footprint related to crop production (Mm^3 yr^{-1})				Water footprint per ton of crop (m^3 ton^{-1})			
			Green	Blue	Grey	Total	Green	Blue	Grey	Total
Wheat	Rain-fed	2.48	610	0	65	676	1629	0	175	1805
	Irrigated	3.31	150	204	58	411	679	926	263	1868
	Global	2.74	760	204	123	1087	1278	342	208	1828
Maize	Rain-fed	4.07	493	0	85	579	1082	0	187	1269
	Irrigated	6.01	104	51	37	192	595	294	212	1101
	Global	4.47	597	51	122	770	947	81	194	1222
Rice	Rain-fed	2.69	301	0	30	331	1912	0	190	2102
	Irrigated	4.67	378	202	81	661	869	464	185	1519
	Global	3.90	679	202	111	992	1146	341	187	1673
Apples	Rain-fed	8.93	24	0	6	30	717	0	167	883
	Irrigated	15.91	8	8	2	18	343	321	71	734
	Global	10.92	33	8	7	48	561	133	127	822
Soybean	Rain-fed	2.22	328	0	5	333	2079	0	33	2112
	Irrigated	2.48	24	12	1	37	1590	926	85	2600
	Global	2.24	351	12	6	370	2037	70	37	2145
Sugarcane	Rain-fed	58.70	95	0	7	102	164	0	13	176
	Irrigated	71.17	85	74	10	169	120	104	14	238
	Global	64.96	180	74	17	271	139	57	13	210
Coffee	Rain-fed	0.68	106	0	4	110	15 251	0	523	15 774
	Irrigated	0.98	1	1	0	2	8668	4974	329	13 971
	Global	0.69	108	1	4	112	15 249	116	532	15 897
Rapeseed	Rain-fed	1.63	62	0	12	74	1783	0	356	2138
	Irrigated	1.23	4	9	1	14	1062	2150	181	3394
	Global	1.57	66	9	13	88	1703	231	336	2271
Cotton	Rain-fed	1.35	90	0	13	103	3790	0	532	4321
	Irrigated	2.16	41	75	13	129	1221	2227	376	3824
	Global	1.73	132	75	25	233	2282	1306	440	4029
All crops	Rain-fed	–	4701	0	472	5173	–	–	–	–
	Irrigated	–	1070	899	261	2230	–	–	–	–
	Global	–	5771	899	733	7404	–	–	–	–

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Table 8. Comparison between the results from the current study and the results from previous studies.

Study	Period	Global water footprint related to crop production ($Gm^3 yr^{-1}$)		
		Green	Blue	Total
Chapagain and Hoekstra (2004), Hoekstra and Chapagain (2007), Hoekstra and Chapagain (2008)	1997–2001	5330	1060	6390
Rost et al. (2008)	1971–2000	7250*	600–1258	7850–8508*
Liu and Yang (2010)	1998–2002	4987	951	5938
Siebert and Döll (2010)	1998–2002	5505	1180	6685
Hanasaki et al. (2010)	1985–1999	5550	1530	7080
Current study, green and blue only	1996–2005	5771	899	6670

* Unlike the other values, this value includes the evapotranspiration from cropland outside the growing period.

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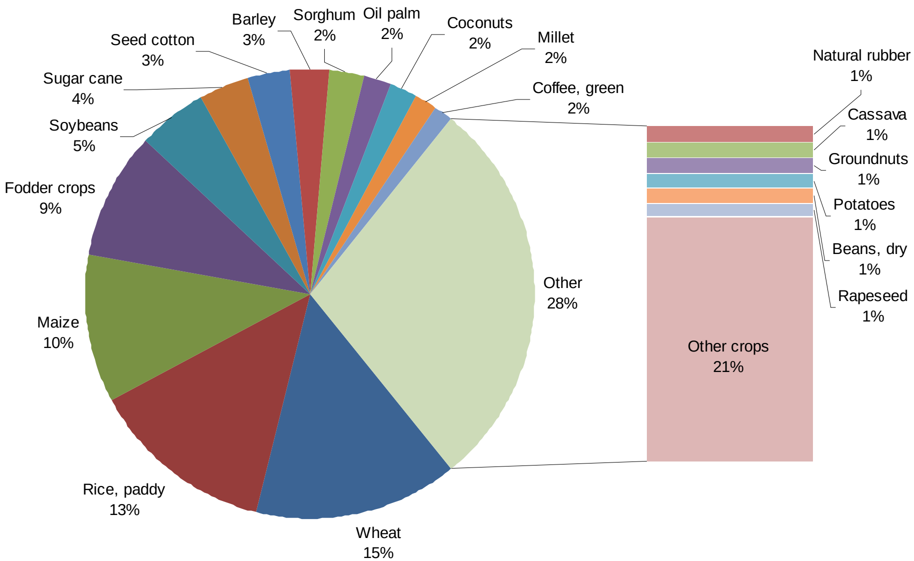

Fig. 1. Contribution of different crops to the total water footprint of crop production. Period: 1996–2005.

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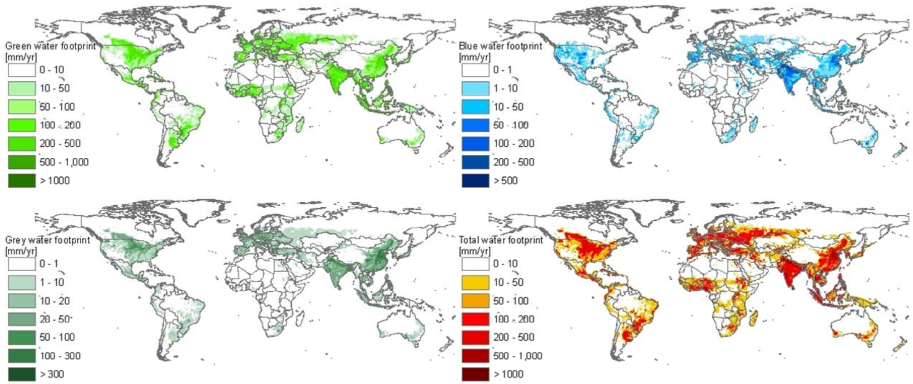

Fig. 2. The green, blue, grey and total water footprint of crop production estimated at a 5 by 5 arc min resolution. The data are shown in mm yr^{-1} and have been calculated as the aggregated water footprint per grid cell (in $m^3\,yr^{-1}$) divided by the area of the grid cell. Period: 1996–2005.

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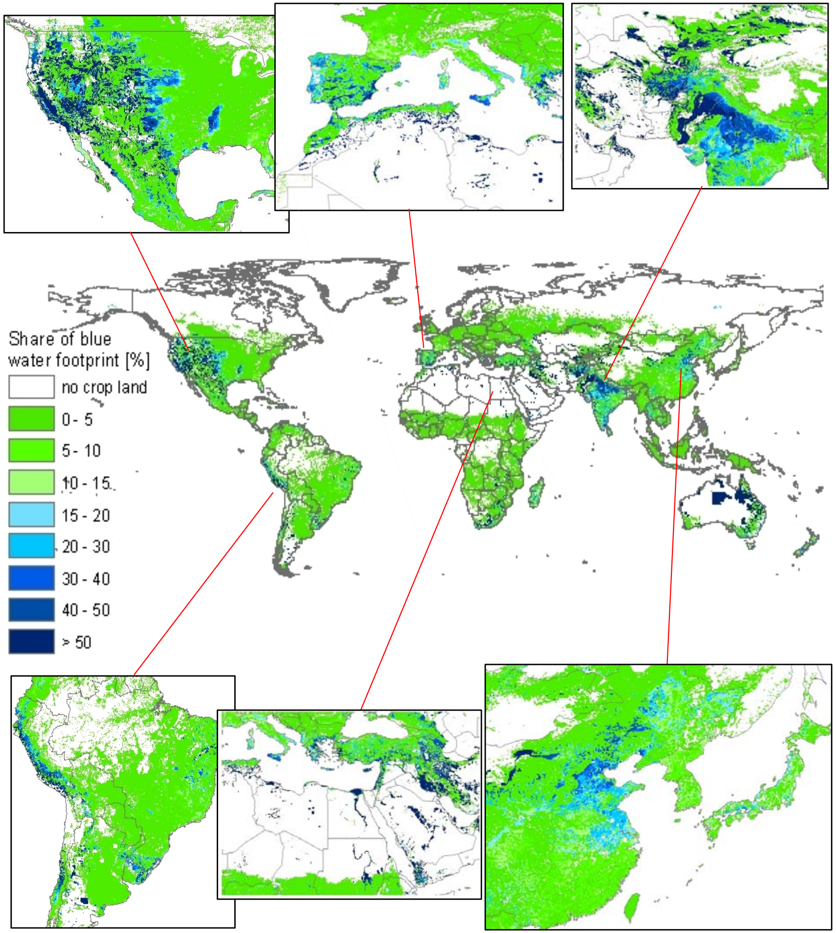

Fig. 3. Contribution of the blue water footprint to the total consumptive (green and blue) water footprint of crop production. Period: 1996–2005.

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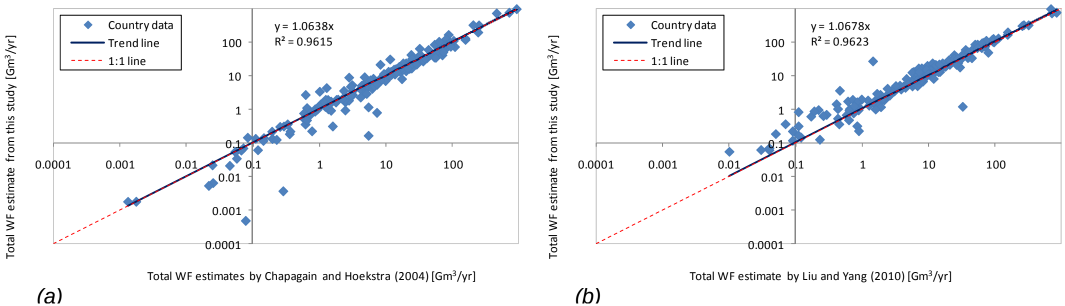

Fig. 4. Comparison of national (green plus blue) water footprints related to crop production as estimated in the current study with results from **(a)** Chapagain and Hoekstra (2004), and **(b)** Liu and Yang (2010).

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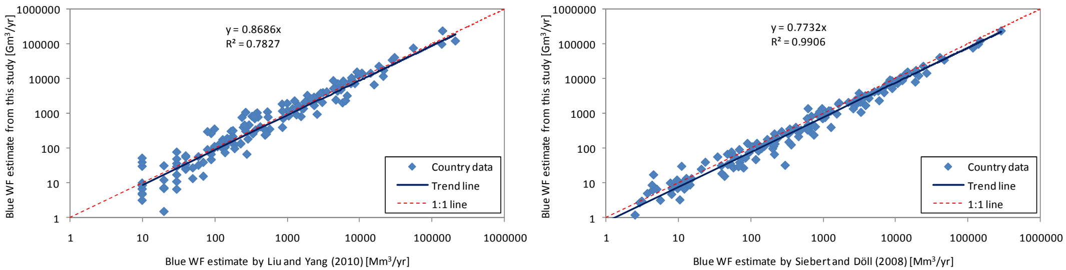

(a) *(b)*

Fig. 5. Comparison of national blue water footprints related to crop production as estimated in the current study with results from **(a)** Liu and Yang (2010) and **(b)** Siebert and Döll (2008).

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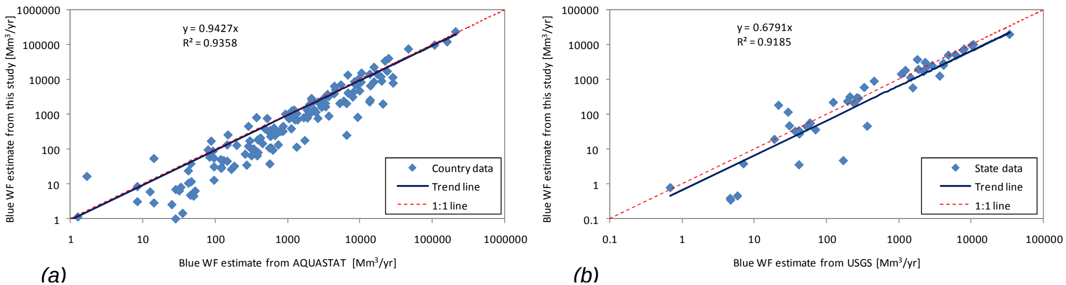


Fig. 6. Comparison of blue water footprints related to crop production as estimated in the current study with results from **(a)** AQUASTAT (FAO, 2008b) for developing countries, and **(b)** USGS (Hutson et al., 2004; Solley et al., 1998) for the states in the USA.

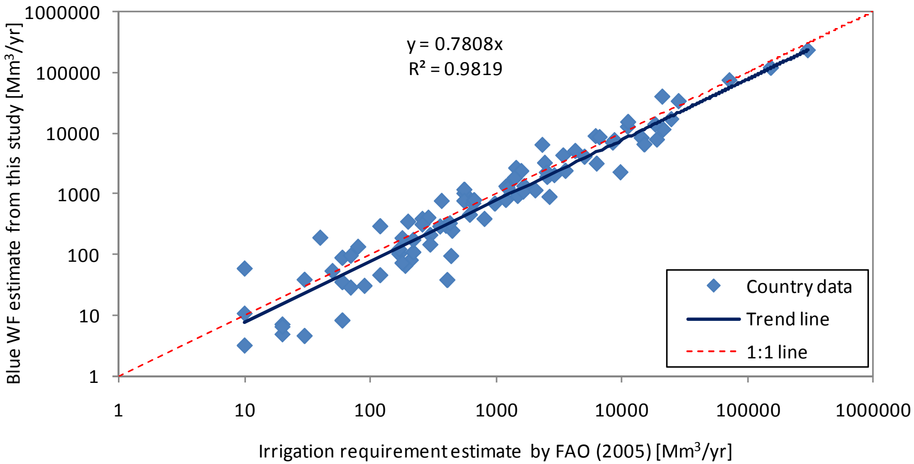
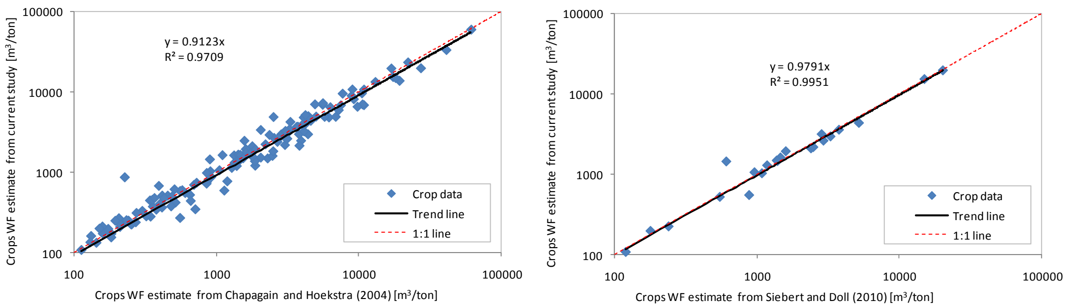


Fig. 7. Comparison of national blue water footprints related to crop production as estimated in the current study with national irrigation requirements as estimated by FAO (2005).



(a) *(b)*

Fig. 8. Comparison of global average crops water footprint (green plus blue) as estimated in the current study with results from **(a)** Chapagain and Hoekstra (2004), and **(b)** Siebert and Döll (2008).

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