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The water footprint of sweeteners and bio-ethanol from sugar cane, sugar beet and maize

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THE WATER FOOTPRINT OF SWEETENERS AND BIO-ETHANOL FROM SUGAR CANE, SUGAR BEET AND MAIZE

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Summary

Sugar cane and sugar beet are used for sugar for human consumption. In the US, maize is used, amongst others, for the sweetener High Fructose Maize Syrup (HFMS). Sugar cane, sugar beet and maize are also important for bio-ethanol production. The growth of crops requires water, a scarce resource. The aim of this study is to assess the green, blue and grey water footprint (WF) of sugar, HFMS and ethanol in the main producing countries. In addition, an impact assessment is carried out for sugar cane and beet production in three large river basins: the Dnjepr, Indus and Ganges basins.

The WF of sweeteners and ethanol depends on crop type, agricultural practice and climate. The WFs of cane sugar for the main producing countries appear to be 1285 m^3/ton for Brazil and 1570 m^3/ton for India. The weighted global average is 1500 m^3/ton (45% green, 49% blue, 6% grey). The WFs of beet sugar for the main producing countries are: 545 m^3/ton for France; 580 m^3/ton for Germany; 1025 m^3/ton for the US; 1430 m^3/ton for the Russian Federation; and 1900 m^3/ton for the Ukraine. The weighted global average is 935 m^3/ton (35% green, 49% blue, 16% grey). The average WF of HFMS 55 produced in the US is 720 m^3/ton. The global average WF of HFMS 55 is 1125 m^3/ton (50% green, 36% blue, 14% grey). The WF of ethanol from sugar cane in Brazil is 2450 litre/litre, in the US 2775 litre/litre and in India 2995 litre/litre. The weighted global average is 2855 litre/litre. The WFs of ethanol from sugar beet for the main producers are: 790 litre/litre for France; 845 litre/litre for Germany; 1290 litre/litre for the US; 2075 litre/litre for the Russian Federation; and 2780 litre/litre for the Ukraine. The weighted global average WF is 1355 litre/litre. The WF of ethanol from maize in the US is 1220 litre/litre. The weighted global average WF is 1910 litre/litre.

The WF of sugar cane contributes to water stress in the Indus and Ganges basins. In the Black Sea area, the main problem is pollution from industry and excessive fertilizer application. In that area sugar beet shows a large grey WF and is one of the contributors to pollution.

The results of this study may form the basis for or at least trigger more detailed local impact assessments. The study shows that the water footprint of sweetener or ethanol strongly depends on its source (which crop) and origin (which country, climate and agricultural system). Besides, the relative contributions of the green, blue and grey components differ greatly from place to place. The existing differences may be reason to prioritise from where to best source sweeteners and bio-ethanol. Alternatively, instead of switching to another source or place, one could analyse the potential for reducing the water footprints in those cases where footprints are currently relatively high.

1. Introduction

Sweeteners form an important component of human food, while the demand for ethanol for transportation is rising. Sugar cane, sugar beet and maize (corn) are crops with a large contribution to the global agricultural production (FAO, 2008c). Sugar and other sweeteners, for example syrups, are widely used ingredients for many foods and drinks, such as ice cream, cakes and cola. Sugar is derived from sugar crops, mainly sugar cane and sugar beet. Some sugar is made from sweet sorghum and sugar palm. Other crops that provide sweeteners are starch crops, such as maize. The food industry uses starch crops for sweeteners, such as maize for High Fructose Maize Syrups (HFMS). In the United States, maize is used for the production of HFMS. Sugar and starch crops are not only the basis for the production of sugar, but also for ethanol, a fuel. During the last three decades, global ethanol production has increased rapidly. The increase can partially be attributed to possibilities to blend ethanol with gasoline. In Brazil, the growth of ethanol production is mainly caused by the increase of the number of motor vehicles that use a combination of petrol and ethanol as a transportation fuel (Johnson, 2009). In 2005, the US and Brazil were the largest producers of ethanol. US ethanol production is mainly based on maize, Brazilian ethanol production on sugar cane. Agricultural production of sugar and starch crops requires water for crop growth. Especially sugar cane is regarded as a water intensive crop (WWF, 2003).

The Water Footprint (WF) concept, introduced by Hoekstra (2003), is an indicator to express the water use in the production chain of commodities. The WF of a commodity is defined as the total volume of freshwater that is consumed or polluted during the whole production process. For agricultural commodities, water consumption mainly refers to crop water consumption during the growing period and water pollution mainly relates to the leaching of fertilisers and pesticides that are applied to the field (Hoekstra and Chapagain, 2008). Hoekstra and Hung (2002) have made a first estimation of the freshwater needed to produce crops in almost all countries of the world; Chapagain and Hoekstra (2004) produced an improved dataset for an even broader range of agricultural products, again worldwide. Subsequent studies for specific products, e.g. for cotton (Chapagain et al., 2006), for coffee and tea (Chapagain and Hoekstra, 2007) and for bioenergy (Gerbens-Leenes et al., 2009) provide more detail on specific WFs of crops and crop products. Chapagain and Hoekstra (2004) have calculated the WFs of sugar and starch crops for all producing countries, but they did not make a distinction between green, blue and grey water, and did not take ethanol production into account. This study assesses the WF of natural sweeteners and ethanol derived from the three most relevant crops: sugar cane, sugar beet and maize. The study has three objectives: (i) to calculate the green, blue and grey WF of sweeteners and ethanol produced from sugar cane, sugar beet and maize for the main producing countries and locations, (ii) to assess the most favourable production lines and locations and (iii) to assess the impact of the WF of the sugar and starch crop production on the water resources in some of the main production areas.

2. Sweeteners and bio-ethanol

Sugars are carbohydrates derived from plants (Coultate, 1989; Cheesman, 2004). Table sugar refers to sucrose, made up of a molecule of glucose and fructose. Table sugar is called cane sugar when it is derived from sugar cane and beet sugar when obtained from sugar beet. High fructose syrups (HFS) contain a mixture of fructose and glucose. A frequently used blend is High Fructose Maize Syrup 55 (HFMS 55), a blend of 55% fructose and 45% glucose made from maize with the sweetness of table sugar (Ensymm, 2005). In the US, where maize is called corn, HFMS is known as HFCS. Sugar cane is the ingredient for 70% of the globally produced sugar, sugar beet is the ingredient for the remaining 30%. Figure 1 gives an overview of the global sweeteners and bio-ethanol production. Table 1 shows that Brazil is the largest producer of sugar and ethanol from sugar cane. India has a large share in the global sugar from sugar cane production, but a very small share in the global bio-ethanol production. The US is a large bio-ethanol producer, mainly made from maize.

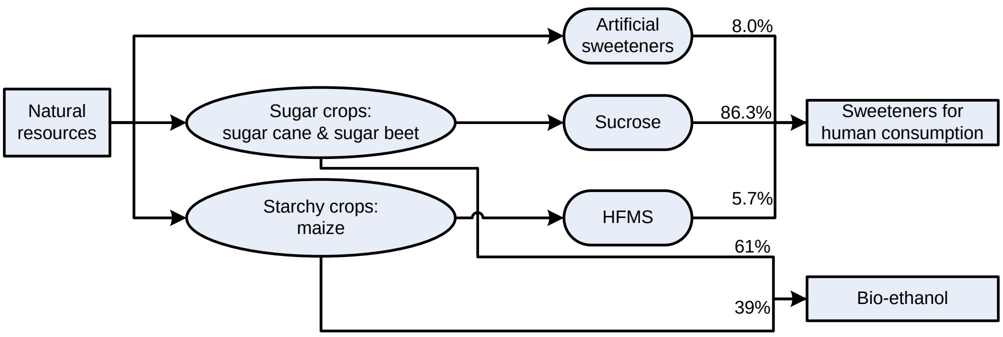

Figure 1. Overview of the global sweeteners and bio-ethanol production (sources: Berg, 2004; Campos, 2006; International Sugar Organization, 2007; Van der Linde et al., 2000).

Table 1. Global production of sugar cane, raw cane sugar and bio-ethanol over the period 2001-2006 (Source: FAO, 2008c).

Country	Contribution to global sugar cane production (%)	Contribution to global cane sugar production (%)	Contribution to global bio-ethanol production (%)	Main feedstock ethanol
Brazil	30	24	32	Sugar cane
India	21	17	1	Sugar cane
China	7	9	3	Maize, sugar crops, maize
Thailand	4	6	1	Sugar cane
Pakistan	4	3	-	-
Mexico	4	5	-	-
Colombia	3	2	-	-
Australia	3	5	-	-
US	2	3	43	Maize
Indonesia	2	2	-	-

- : less than 1%

Figure 2 shows the production system used to make either cane sugar or ethanol from sugar cane. Information was derived from Cornland et al. (2001), Moreira (2007), Shleser (1994), Smeets et al. (2006), and Silva (2006). The main products are sucrose (cane sugar) and ethanol, but the figure shows that there are also various intermediate products and by-products that have a value by themselves. Sugar cane juice is the main intermediate product that forms the ingredient for the production of both sucrose and ethanol. The juice can be processed into either sucrose or ethanol, although the molasses that are by-product in the production of sucrose can be used again for the production of ethanol. Traditional water use in a sugar cane mill is about 21 m^3 per ton of processed cane (Macedo, 2005). New techniques have decreased water use to 0.92 m^3/ton of cane. The São Paolo State Plan on water resources estimated the water use in 1990 at 1.8 m^3 per ton of cane (Macedo, 2005).

Sugar beet is a root crop cultivated in a temperate climate. The main producers are France, the US, Germany, the Russian Federation, Turkey, Ukraine, Poland, Italy and China (FAO, 2008c). Although sugar beet has the highest yield of ethanol per hectare (Rajagopal and Zilberman, 2007), the use of sugar beet for ethanol is still limited compared to sugar cane. Figure 3 shows the production steps applied to make either beet sugar or ethanol from sugar beet (Cheesman, 2004; Vaccari et al., 2005; Henke et al., 2006; CIBE/CEFS, 2003). The basis for the production of either sucrose or ethanol is sugar beet juice, which is obtained by washing, cutting and filtering the harvested sugar beet. In the case of sucrose production, the molasses can again be used for ethanol. The process water use in the sugar beet plant concerns the washing of the sugar beets. Water consumption in traditional sugar beet plants ranges from 2.5 to 4.5 m^3/ton beet (Vaccari et al., 2005). Modern plants sometimes not even have a fresh water intake. Fornalek (1995), for example, shows that the water use in a Polish plant reduced from 105 m^3/ton in 1950 to 10 m^3/ton sugar in 1995.

In the US, the production and consumption of High Fructose Maize Syrup (HFMS) has increased since 1970, while the consumption of sugar from sugar cane and sugar beet has decreased significantly (USDA / Economic Research Service, 2006). Maize is a C4-crop that belongs to the grass family. It grows in moderate and sub-tropical climates. The US and China are the main global producers (FAO, 2008c). About half of the maize is used for animal feed, the other half for other purposes, such as direct food, HFMS and ethanol. Ethanol production is expected to require about 40% of all the US maize in 2019 (Economic Research Service/USDA, 2009). The starch in the maize is the ingredient for HFMS and ethanol. There are two production processes, wet milling and dry milling. Depending on the type of production process, industry also produces by-products with an economic value. Wu (2008) has estimated that the water use is about 3.45 litre of water per litre of (denatured) ethanol produced by dry milling and 3.92 litre by wet milling. Shapouri and Gallagher (2005) have estimated that ethanol production requires between one and eleven litres of water per litre of ethanol produced, with an average of 4.7 litres. Using Wu's assumption, with an average yield of approximately 503 litre of (denatured) ethanol per ton of grain for dry mills and 490 litre of ethanol for wet mills, the water use is about 1735 litre per ton of maize processed by dry milling and 1921 litre per ton by wet milling. Bio-ethanol (C_2H_5OH) is a liquid biofuel. Of the globally available ethanol, about 75% is used as transportation fuel (Worldwatch Institue, 2007). Industry produces 95% of all the ethanol by fermenting sugar and starch from crops, the remainder is synthetic ethanol.

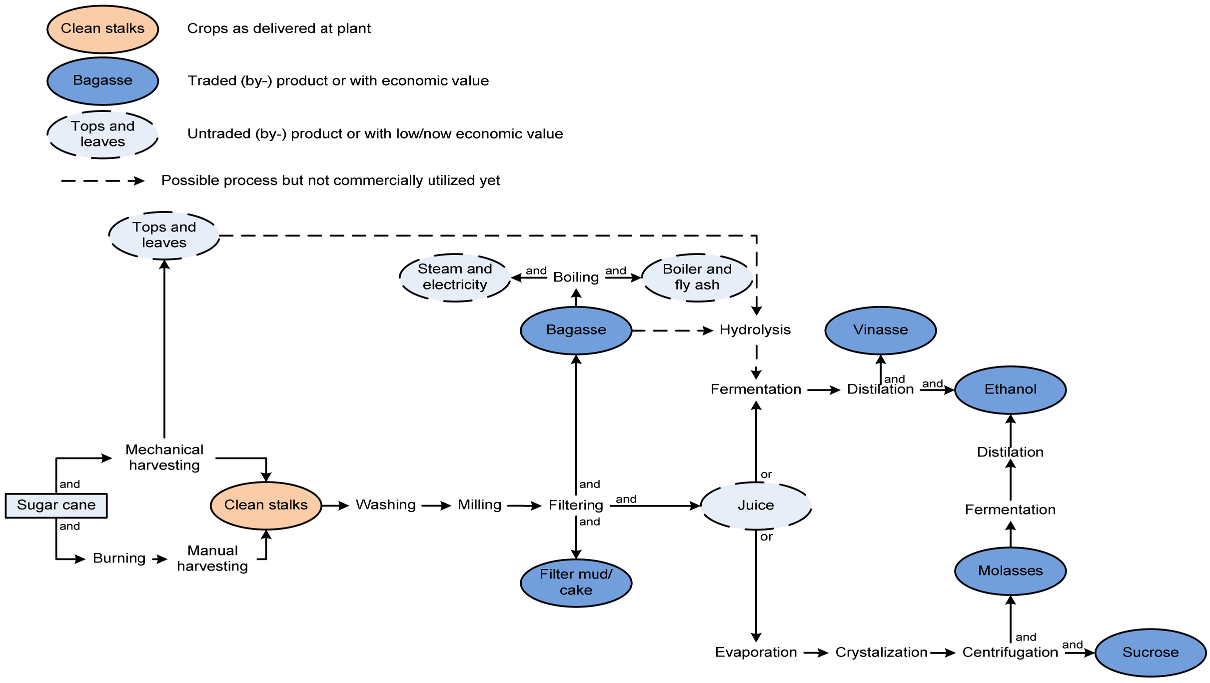

Figure 2. The production system for cane sugar and cane-ethanol (sources: Cornland et al., 2001; Moreira, 2007; Shleser, 1994; Smeets et al., 2006).

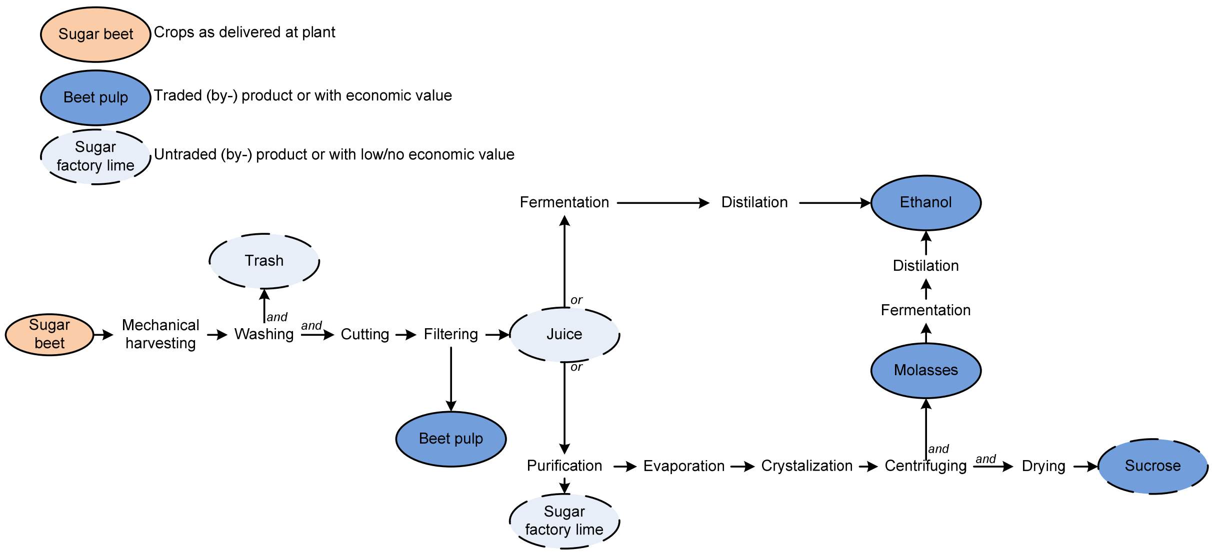

Figure 3. The production system for beet sugar and beet-ethanol (source: CIBE/CEFS, 2003).

3. Method and data

This study calculates the WF of sweeteners and bio-ethanol from sugar cane, sugar beet and maize for the main producing countries, as well as for the main producing states in the US using the methodology of Hoekstra and Chapagain (2008). The water footprint of a product is the total volume of freshwater used to produce the product, summed over the various steps of the production chain. The WF has three components: the green, blue and grey WF. The green WF refers to the volume of rainwater that evaporates during the production process. The blue WF refers to the volume of surface water and groundwater that evaporates as a result of the production of the product. For crops, the blue WF is the evapotranspiration of irrigation water. For industrial production, the blue WF is the amount of fresh water withdrawn from ground or surface water that does not return to the system from which it came. The grey WF of a product is an indicator of freshwater pollution that can be associated with the production of a product over its full supply chain. It is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. It is calculated as the volume of water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards.

Calculations were done for the 19 or 20 main producing countries. These countries were, in order of decreasing production (FAO, 2008c):

- sugar cane: Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Australia, United States, Philippines, Indonesia, Cuba, South Africa, Argentina, Guatemala, Egypt, Vietnam, Venezuela and Peru;
- sugar beet: France, United States, Germany, Russian Federation, Turkey, Ukraine, Poland, Italy, China, United Kingdom, Spain, Belgium-Luxembourg, the Netherlands, Iran, Japan, Egypt, Czech Republic, Serbia, Morocco and Denmark;
- maize: the United States, China, Brazil, Mexico, Argentina, France, India, Indonesia, Italy, South Africa, Canada, Romania, Hungary, Egypt, Nigeria, Serbia and Montenegro, Ukraine, the Philippines, Spain and Thailand.

For maize, calculations were also done separately for the main producing states in the US (USDA/Agricultural Statistics Service, 2008): Illinois (Chicago and Moline), Indiana (Evansville and Fort Wayne), Iowa (Des Moines and Indianapolis), Michigan (Detroit and Huron), Minnesota (Duluth and Minneapolis), Nebraska (Lincoln) North Carolina (Burlington), Pennsylvania (Philadelphia) and Wisconsin (Green Bay and Madison).

The calculation of the crop water requirement (m^3/ha) was done by applying the calculation model CROPWAT 4.3 (FAO, 2008b) which applies the FAO Penman-Monteith method (Allan et al., 1998) to estimate reference evapotranspiration. The irrigation requirement is calculated as the difference between the crop water requirement and the effective rainfall. It is assumed in this study that irrigation requirements are actually met, which may lead to some overestimation of water use in some cases. On the other hand, evaporation losses in irrigation have not been included, which may lead to some underestimation in some other cases. Climate data for CROPWAT were derived from the CLIMWAT database (FAO, 2008a). When data were not available from

CLIMWAT, they were obtained from the Global Climate Data Atlas of Müller and Hennings (2000). The selection of weather stations was based on the locations of major production areas in a country from Ramankutty (2008). For sugar beet and maize, the study assumed that the growing season starts when the average temperature is above 10 ˚C, using a two-week interval, and when sufficient rainfall is available. For sugar cane, it was assumed that the start of the growing season coincides with the start of the rain season. For sugar crops, the WF was calculated on the basis of multiple weather stations per country; for maize one weather station was selected for the main production region. For maize in the US multiple weather stations were selected.

Farmers apply fertilizers and pesticides to grow crops. Part of these substances leach to the groundwater and contribute to the grey WF. This study looks at nitrogen only, which will lead to a conservative estimate of grey WFs in cases where other nutrients or pesticides actually constitute a larger problem than nitrogen. We have assumed that 10% of the total nitrogen application leaches to free water bodies (following Chapagain et al., 2006). As a proxy for ambient water quality standards we took the drinking water quality standards of the EPA (1995) and the WHO (2006). These organisations recommend a maximum value for nitrogen in drinking water of 10 mg/litre (NO_3-N). The grey WF was estimated by dividing the nitrogen load to the water by the maximum concentration of nitrogen of 0.01 kg/m^3. Nitrogen application rates were taken from the FAO (2007).

Yields for sugar cane, sugar beet and maize have been taken from the FAOSTAT database (FAO, 2008c). For maize, the database gives yields of the grains. In this study, WFs have been calculated based on all economically valuable parts of the crop. Stover forms 56% of the total maize crop and has an economic value. This study therefore did not neglect the stover and estimated the total yield by including the maize stover: $Y = y + stover$, where y is the maize yield according to the FAO (2008c) and *stover* is $56/44 \times y$. Regional data on maize yields in the US were obtained from the USDA/Agricultural Statistics Service (2008). The green, blue and grey WF of the harvested crop have been calculated by dividing the total green, blue and grey WF over the growing period by the yield.

Sugar cane, sugar beet and maize provide different products, such as sugar and ethanol, and by-products, such as stover and bagasse. The WFs of the various crop products are calculated based on the WFs of the harvested crops, the process water requirements and the product and value fractions of the crop products, following the method of Hoekstra and Chapagain (2008). Product fractions have been obtained from Allen et al. (1997) for sugar cane and from Kranjc et al. (2006) for sugar beet. Each product or by-product has a market price (US$/ton) and contributes to the market price of the root product. Value fractions per crop product (or by-product) have been estimated based on prices given in the SITA-database (UNCTAD/WTO, 2007). For the six main producing countries, the study took the average export price for the period 1996-2005. The countries that together account for more than 80% of total export were used to calculate the value of a (by) product. When less than three countries account for 80% of the export, a minimum of three importing countries was used.

When no data were available in SITA, the study used other sources. For raw cane sugar and molasses the price is based on the export price as received from SITA. The value of bagasse is based on the amount of energy that can be produced by burning it to generate electricity and steam. Several studies (Paturau, 1989; Mohee and Beeharry, 1999; Leal, 2005) give ranges of energy production between 360 and 510 kWh per ton of bagasse. With an average price of 0.04 US $/kWh, the study calculated the value fraction of bagasse.

Filter cake and vinasse are often used as fertilizer. The value of filter cake was determined on the basis of its value as fertilizer. According to Leal (2005) and Moreira (2007) fertilizer use can be reduced by approximately 50% when vinasse and filter cake are used. For the calculation of the WF of ethanol from sugar cane, the study assumed that the values of filter cake and vinasse are the same. The US Department of Agriculture (USDA /Economic Research Service, 2006) has estimated the total fertilizer costs for sugar cane at US$ 100 per hectare for the period 1996 - 2005. With the use of vinasse and filter cake, this can be reduced to US$50, giving a value for filter cake and vinasse of US$50 ($25 per hectare for filter cake and $25 for vinasse). The application rates of 2600 kg filter cake/ha and 1635 kg vinasse (dry matter)/ha result in a value for filter cake of US$10/ton and US$15/ton for vinasse. The value of filter cake was also used for the assessment of the value fractions in sugar production. For the by-products of ethanol from sugar cane, the study used the same values.

Ethanol is not included in SITA. The study used the average of current and expected prices, as determined by FAPRI (2008). The ethanol price is based on the average US price (US$ 0.51) and Brazilian price (US$ 0.37) which makes an average of US$ 0.44. Sugar is the most valuable product of sugar beet processing. According to ISR (2005), the total value of by-products (molasses, beet pulp and lime) is €14 per ton of sugar beet. This corresponds to the market values as reported by SITA on which this study based the calculation of the value fractions. For the production of ethanol from sugar beets, the study included one by-product, beet pulp. Data on the value of ethanol from sugar beet and sugar cane came from FAPRI (2008). The value of sugar beet pulp was based on information from the USDA (2006) (US$6 per ton) and ISR (2005) (molasses, beet pulp and lime €14 per ton). Based on this information, the study estimated the value of beet pulp at US$10 per ton of beet pulp, which corresponds to the SITA-database. The value fractions of maize based ethanol and HFMS's by-products were based on the USDA cost of production survey (Shapouri and Gallagher, 2005). The value of HFMS 55 is based on the average US Midwest price as provided by the Economic Research Service / USDA (2009). For prices of maize gluten meal, maize gluten feed, crude maize oil, DDGS and HFMS 55, prices from 2000–2003 are available. Although stover is generally left on the field, this study took it into account because it represents an economic value for farmers. Stover reduces the amount of fertilizer that has to be applied. Less than 5% of the stover is harvested and used for animal bedding and feed (ILSR, 2002).

In addition to the water use in agriculture, the study includes the process water use for the processing of the harvested crops into crop products. To compare the WF of sugar with the WF of HFMS, the relative sweetness of both sweeteners has to be taken into account. HFMS 55 has the same sweetness equivalent as sugar. This means that the WFs of sugar and HFMS are compatible. For ethanol, results are presented in litre water per litre ethanol. WFs expressed in m^3/ton (=litre/kg) have been converted to WFs in litre/litre by multiplying by ethanol's density (0.789 kg/litre).

Table 2 shows the average product and value fractions of sugar, HFMS, ethanol and by-products. For maize, the table shows the results for wet milling and for dry milling.

Table 2. Average product and value fractions for main and by-products from sugar cane, sugar beet and maize.

Production process	Product	Product fraction	Value fraction
Sugar from sugar cane	Sugar, raw	0.14	0.87
	Molasses	0.03	0.05
	Bagasse	0.14	0.07
	Filter cake	0.04	0.01
	Water and residue	0.65	0.00
Ethanol from sugar cane	Ethanol	0.06	0.89
	Bagasse	0.14	0.09
	Vinasse	0.03	0.01
	Filter cake	0.04	0.01
	Water and residue	0.63	0.00
Sugar from sugar beet	Sugar, raw	0.16	0.89
	Beet pulp	0.05	0.06
	Molasses	0.04	0.05
	Water and residue	0.75	0.00
Ethanol from sugar beet	Ethanol	0.09	0.92
	Beet pulp	0.05	0.08
	Water and residue	0.86	0.00
HFMS 55 by wet milling maize	HFMS 55	0.36	0.73
	Stover	0.54	0.15
	Maize gluten feed	0.10	0.04
	Maize gluten meal	0.02	0.04
	Maize oil	0.01	0.04
	Water and residue	-	0.00
Ethanol by wet milling maize	Ethanol	0.15	0.65
	Stover	0.54	0.21
	Maize gluten feed	0.10	0.05
	Maize gluten meal	0.02	0.05
	Maize oil	0.01	0.04
	Water and residue	0.18	0.00
Ethanol by dry milling maize	Ethanol	0.15	0.66
	Stover	0.54	0.22
	DDGS	0.14	0.12
	Water and residue	0.17	0.00

4. Results

4.1 The water footprint of natural sweeteners

The WF of cane sugar

The WF (m^3/ton) of unprocessed sugar cane shows large differences among countries. Two factors influence these results: differences in crop water requirements (CWRs) and differences in yields (ton/ha). CWRs vary between 1233 and 2082 mm per cropping season. Crop yields vary even more, between 31 and 119 ton/ha. Peru, Egypt, Colombia and Guatemala all report high yields resulting in low WFs, while China benefits from a low average CWR. Mexico and Brazil have favourable CWRs and yields above average, resulting in relatively small WFs. Cuba and Pakistan report low yields, resulting in a relatively large WF. Peru, Egypt, Australia, India and Pakistan have a large blue WF and depend almost completely on irrigation. In general, the grey WF contributes only to a small extent to the total WF. Figure 4 shows the total WF for sugar cane within the nineteen main producing countries. Brazil and India are the largest producers and have a large national WF for unprocessed sugar cane. Brazil requires 82 billion m^3 of water to produce sugar cane, India 73 billion m^3 and Pakistan 23 billion m^3. Figure 5 shows the green, blue and grey WF of cane sugar per unit of sugar for the selected countries. The total WF of cane sugar varies between 875 m^3/ton in Peru and 3340 m^3/ton in Cuba, a difference of almost a factor of four. The WF of cane sugar produced in Brazil, the world's largest producer, is 1285 m^3/ton; the global average is 1500 m^3/ton (45% green, 49% blue and 6% grey). The application of nitrogen for crops (kg/ha) differs among countries, but does not result in large differences of the grey WF. The contribution of the grey to the total WF varies between 4% and 11%. The presented results do not include the process water, which is 5 m^3 per ton of sugar for production processes that recycle the water and 120 m^3 for processes without recycling.

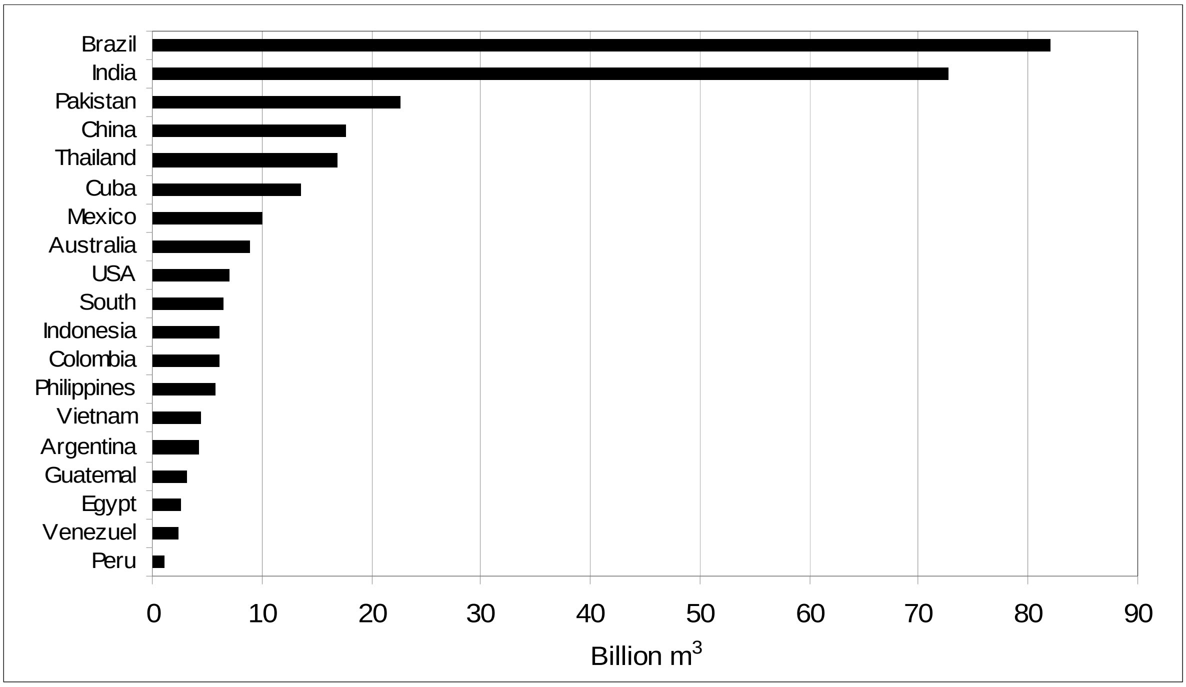

Figure 4. The total water footprint for sugar cane within the main producing countries.

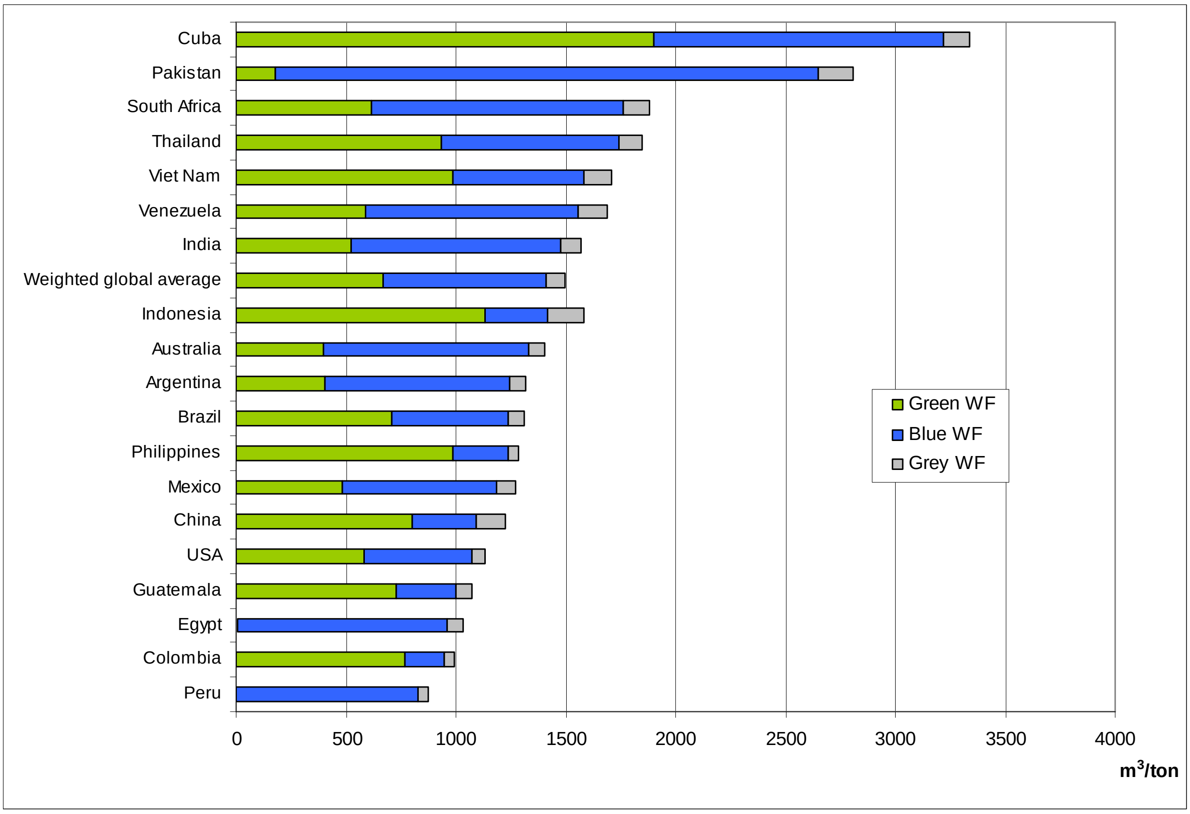

Figure 5. The green, blue and grey water footprint of cane sugar per unit of sugar for the main sugar cane producing countries.

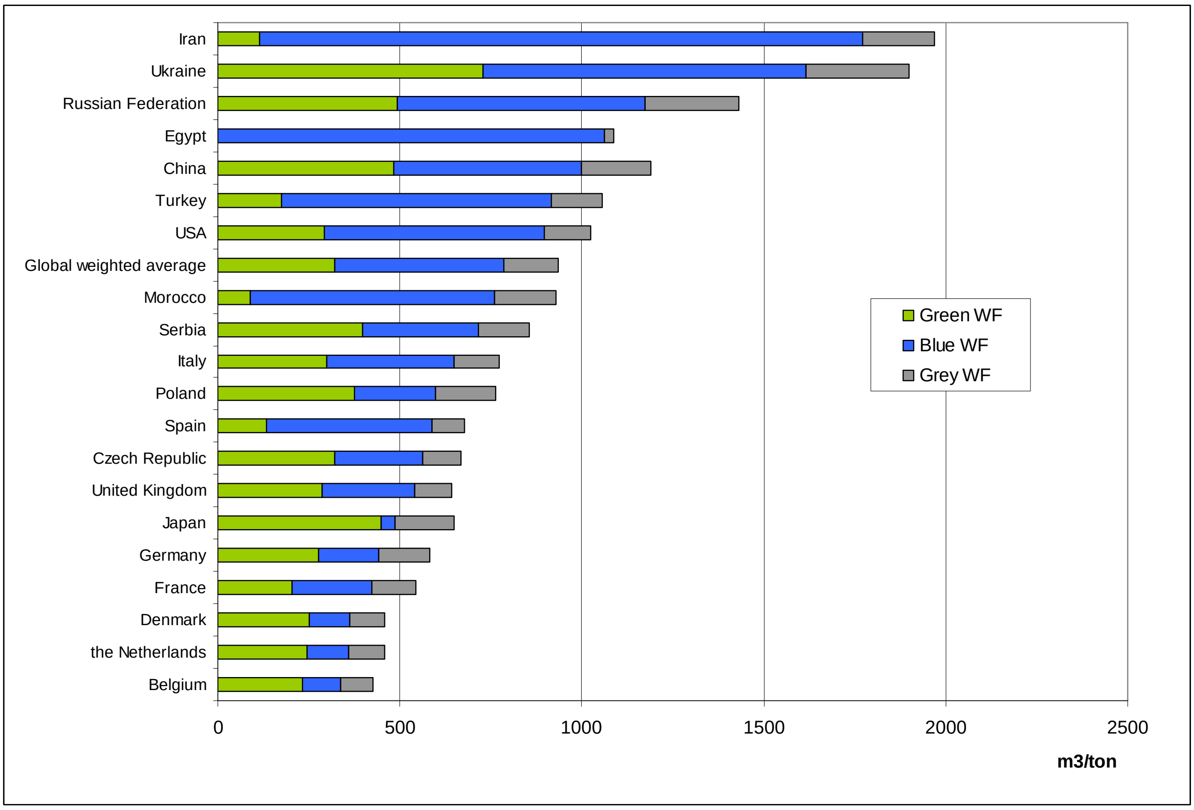

Figure 6. The green, blue and grey water footprint of beet sugar per unit of sugar for the main sugar beet producing countries.

The WF of beet sugar

Figure 6 shows the green, blue and grey WFs of beet sugar. The global average WF is 935 m^3/ton (35% green, 49% blue and 16% grey). The total WF and also the blue WF in particular are largest in Iran, where sugar beet production depends almost completely on irrigation. The large WF of the Ukraine and the Russian Federation is caused by low yields (21.2 ton/ha and 23.4 ton/ha respectively) and not by large CWRs (623 and 494 mm/cropping season). France (518 mm/cropping season) and Japan (519 mm/cropping season) have similar CWRs but lower WFs. Countries in north-west Europe have relatively small WFs. This is due to favourable climate conditions and high yields. The grey WF varies between 26 m^3/ton for sugar produced in Egypt and 280 m^3/ton in the Ukraine. The countries with large WFs (Iran, Ukraine, Russian Federation and China) also have relatively large grey WFs. The contribution of the grey WF to the total WF increases with decreasing total WFs. The amount of process water for sugar from sugar beet is approximately the same as for sugar cane. When the process water is taken into account, an additional 10 to 25 m^3 has to be added to the WFs.

The WF of HFMS

The WFs for maize (including stover) vary between 280 m^3/ton in Argentina and 1655 m^3/ton in India. The WF in the US, the world's largest producer, is 367 m^3/ton, the weighted global average is 561 m^3/ton. Argentina profits from a favourable CWR, resulting in a relatively small WF. Yields (including stover) vary between 3.3 ton/ha in Nigeria and 20.9 ton/ha in Spain. Spain has a small WF, Nigeria a large one. France, Germany and Italy have high yields resulting in relatively low WFs. The grey WF varies between 7 m^3/ton for maize grown in Indonesia and 139 m^3/ton for maize from Egypt. Ukraine, Romania, Nigeria and Egypt depend on irrigation, with less than 40% of the WF covered by green water. Figure 7 shows the green, blue and grey WF of HFMS 55 for the twenty main maize producing countries. HFMS produced from Indian maize has the largest WF (3325 m^3/ton), HFMS from Argentinean maize the smallest WF (565 m^3/ton). The weighted global average WF of HFMS 55 is 1125 m^3/ton (50% green, 36% blue and 14% grey).

HFMS from the United States

The CWRs for maize in the US vary between 492 mm/cropping season in Duluth, Minnesota, and 694 mm/cropping season in Lincoln, Nebraska. Irrigation requirements vary between 200 and 450 mm/cropping season. Total yields (grains and stover) vary from 14.1 ton/ha in North Carolina to 23.5 ton/ha in Illinois. The total WF varies between 291 m^3 per ton in Duluth (MN) and 465 m^3/ton in Burlington (NC). The weighted average total WF of unprocessed maize grown in the US is 358 m^3/ton. The green WF varies from 139 m^3/ton in Indianapolis (IA) to 222 m^3/ton in Burlington (NC). The blue WF varies from 82 m^3/ton in Duluth (MN) to 240 m^3/ton in Huron (MI). The grey WF varies from 48 m^3/ton in Green Bay and Madison (WI) to 103 m^3/ton in Burlington. In general, the states in the Corn Belt show the lowest WFs . Figure 8 shows the green, blue, grey WFs of HFMS 55 in the US. The average WF of HFMS in the US is 720 m^3/ton; the smallest value is 585 m^3/ton in Duluth (MN), the largest value is 935 m^3/ton in Burlington (NC). The US weighted average grey WF is 130 m^3/ton or 18% of the total WF. The relative grey WF is larger than for cane or beet sugar. The process water of maize processing is small compared to the WF of maize growing, about 3 to 5 m^3/ton.

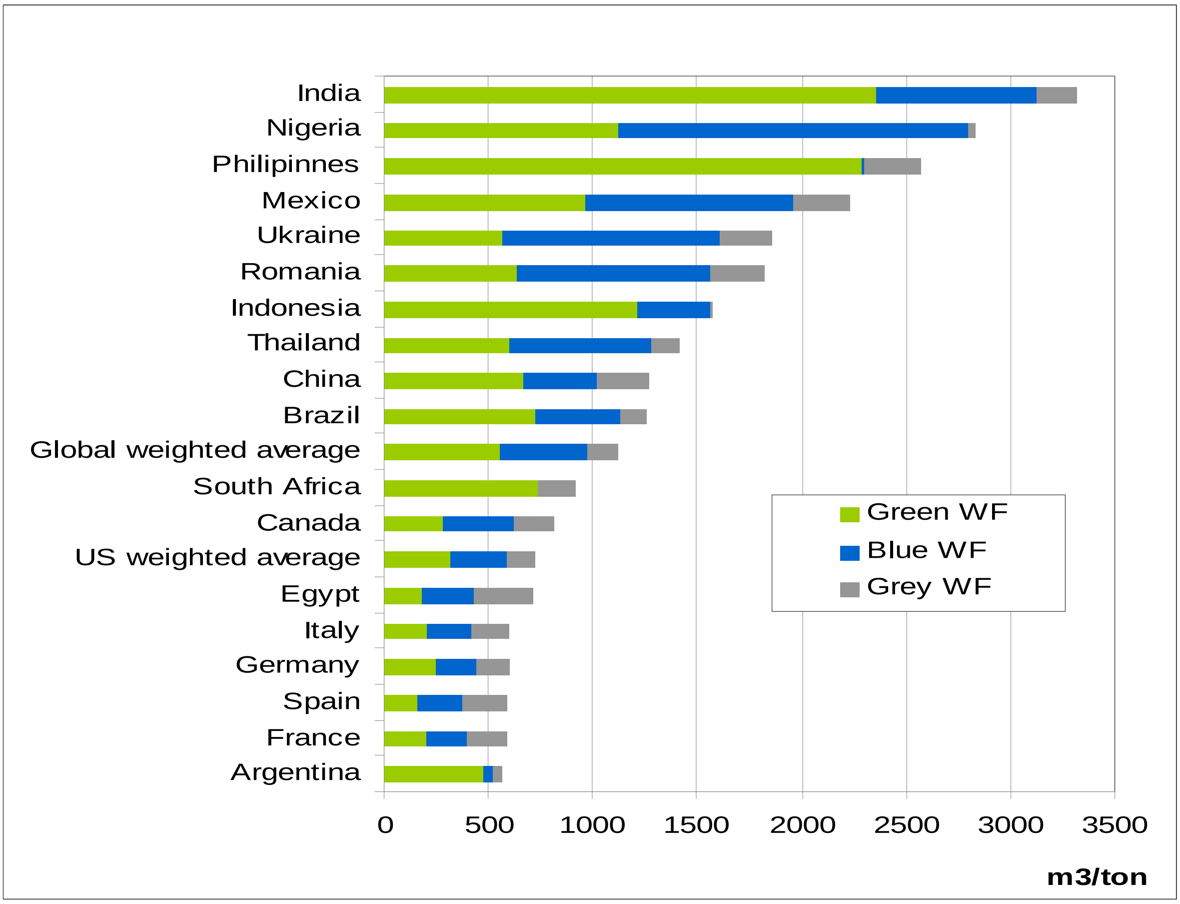

Figure 7. The green, blue and grey water footprint of HFMS 55 for the main maize producing countries.

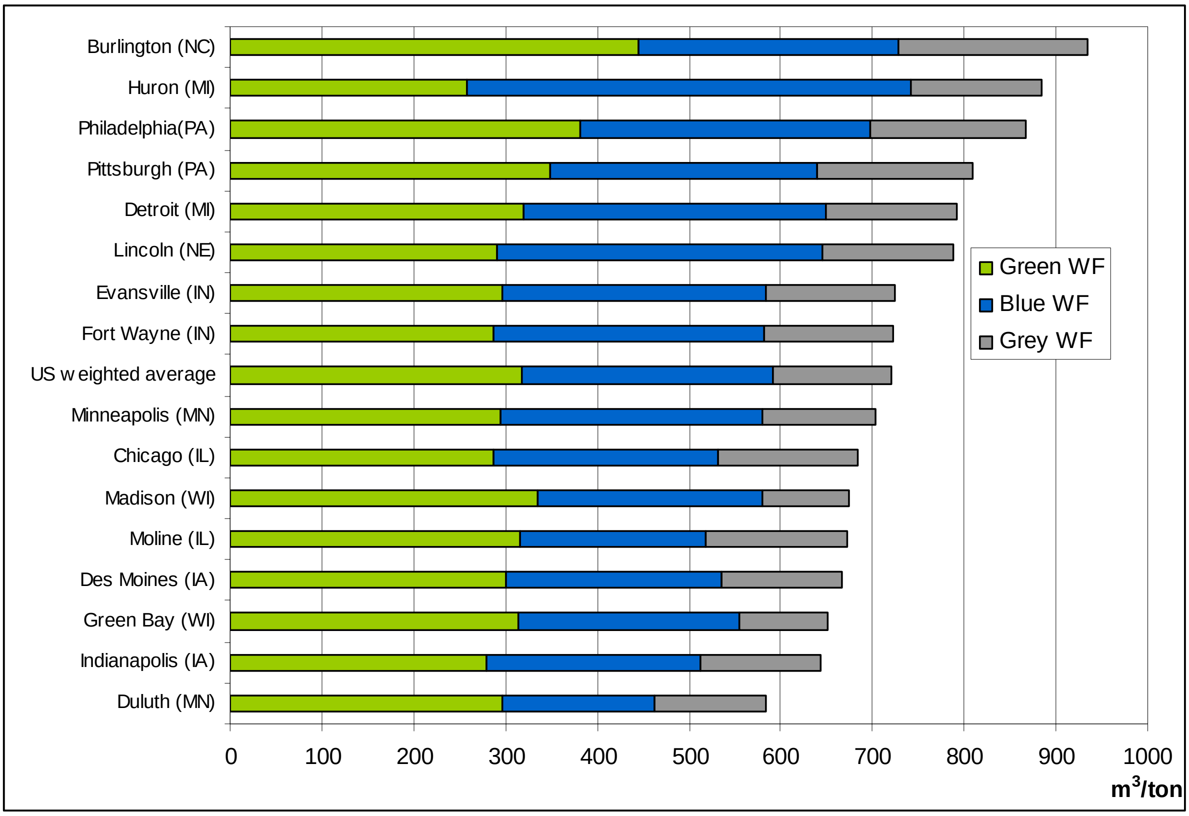

Figure 8. The green, blue and grey water footprint of HFMS 55 produced in the US.

4.2 The water footprint of ethanol

Figure 9 shows the green, blue and grey WFs of ethanol from sugar cane for the main producing countries. The weighted global average total WF is 2855 litre water per litre ethanol. The WF of ethanol is – under current conditions – smallest in Peru, Colombia and Egypt and largest in Cuba and Pakistan. Egypt and Peru, however, entirely depend on irrigation (blue water), whereas Colombia, Guatemala, China and the Philippines, for example, depend much more on rain (green water). Pakistan has the largest blue WF. The grey WF varies from 62 litre/litre in Egypt to 246 litre/litre in Australia. On average, the grey WF is 6% of the total WF.

Figure 10 shows the green, blue and grey WF of ethanol from sugar beet for the twenty main producing countries. Total WFs range from 615 (Belgium) to 2855 litre water per litre of ethanol (Iran). The weighted global average is 1355 litre water per litre ethanol. Iran, Egypt, Ukraine and Turkey have large blue WFs and Japan, Denmark, the Netherlands and Belgium have small blue WFs. Ukraine, Iran and the Russian Federation have large grey WFs, Denmark, the Netherlands and Belgium small grey WFs.

Figure 11 shows the green, blue and grey WFs of ethanol from maize (wet milling). The total WF ranges from about 1000 litre of water per litre of ethanol in Argentina, France, Spain, Germany and Italy to 5630 litre/litre in India. The global average total WF is 1910 litre/litre (50% green, 36% blue, 14% grey). The blue WFs are large in Nigeria, India, Mexico, Ukraine and Romania and small in Argentina, France, Spain, Germany and Italy. The grey WFs are relatively large in Egypt, Spain and France. Figure 12 shows the green, blue and grey WFs of ethanol from maize produced in the US. The WF is largest for Burlington (NC) and smallest for Duluth (MN). The weighted US average total WF is 1220 litre/litre, i.e. 64% of the global average. The difference between the WFs of the ethanol from the dry and wet milling production methods is very small, because process water use is small compared to the water use in growing the maize.

The global weighted average WF of ethanol increases in the following order: (1) ethanol from sugar beet (1355 litre/litre), (2) ethanol from maize (1910 litre/litre) and (3) ethanol from sugar cane (2855 litre/litre ethanol). In the US, where maize is the main feedstock, the order is different: (1) ethanol from maize (1220 litre/litre), (2) ethanol from sugar beet (1290 litre/litre) and (3) ethanol from sugar cane (2775 litre/litre ethanol). Ethanol from sugar cane generally has the largest total but also the largest blue water footprint.

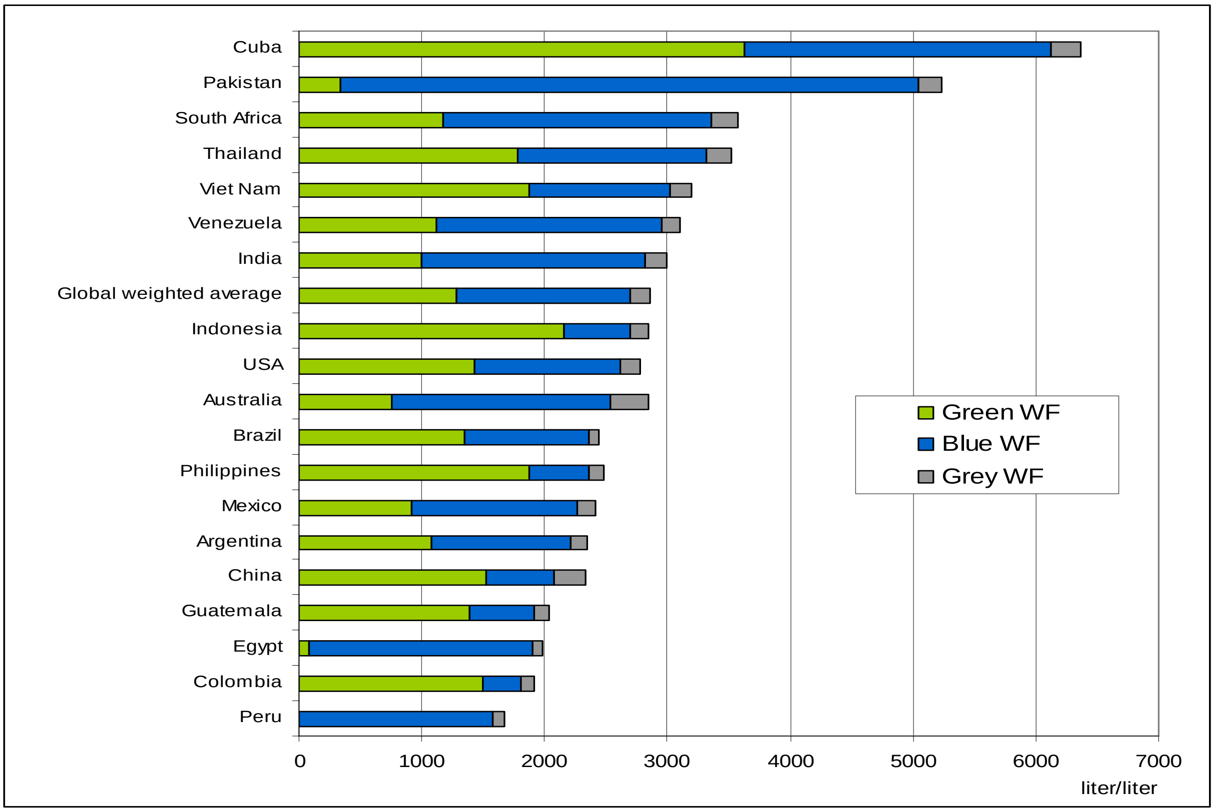

Figure 9. The green, blue and grey water footprint of ethanol from sugar cane for the main sugar cane producing countries.

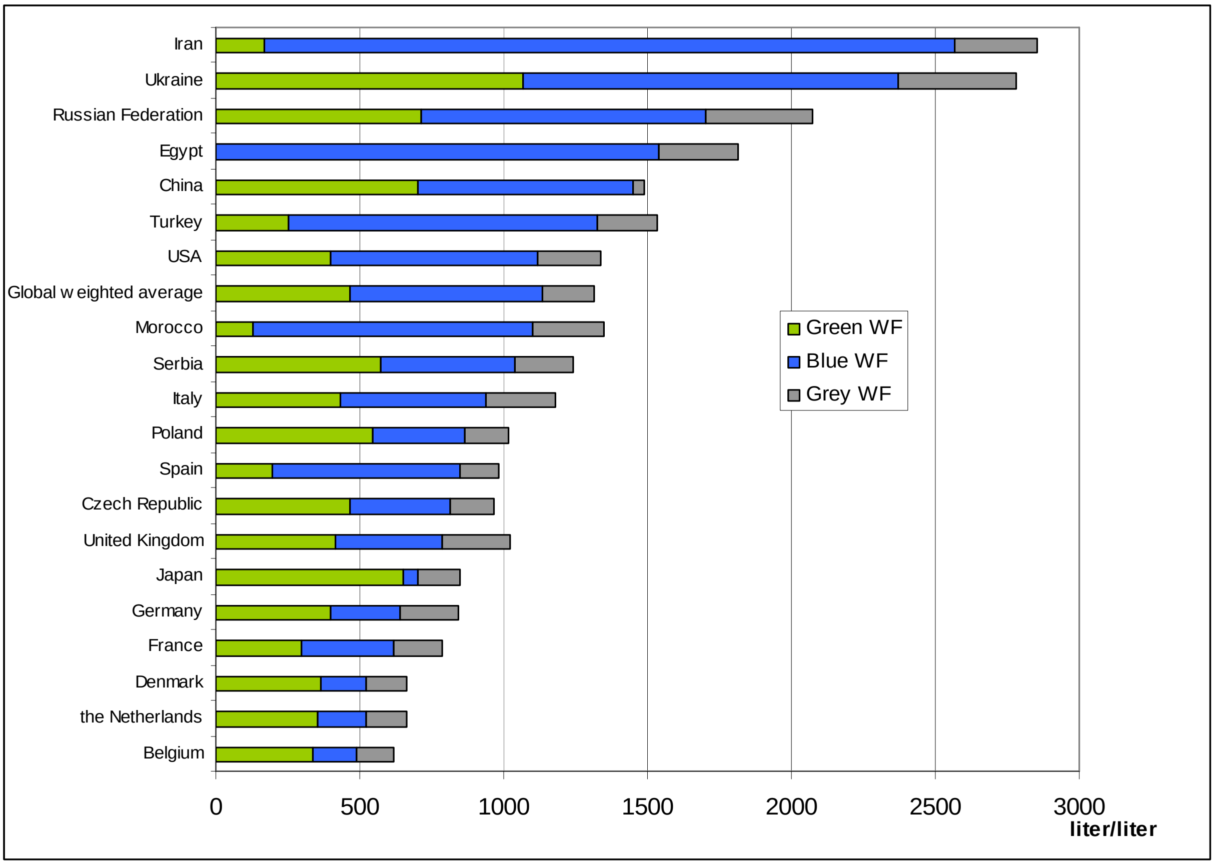

Figure 10. The green, blue and grey water footprint of ethanol from sugar beet for the main producing countries.

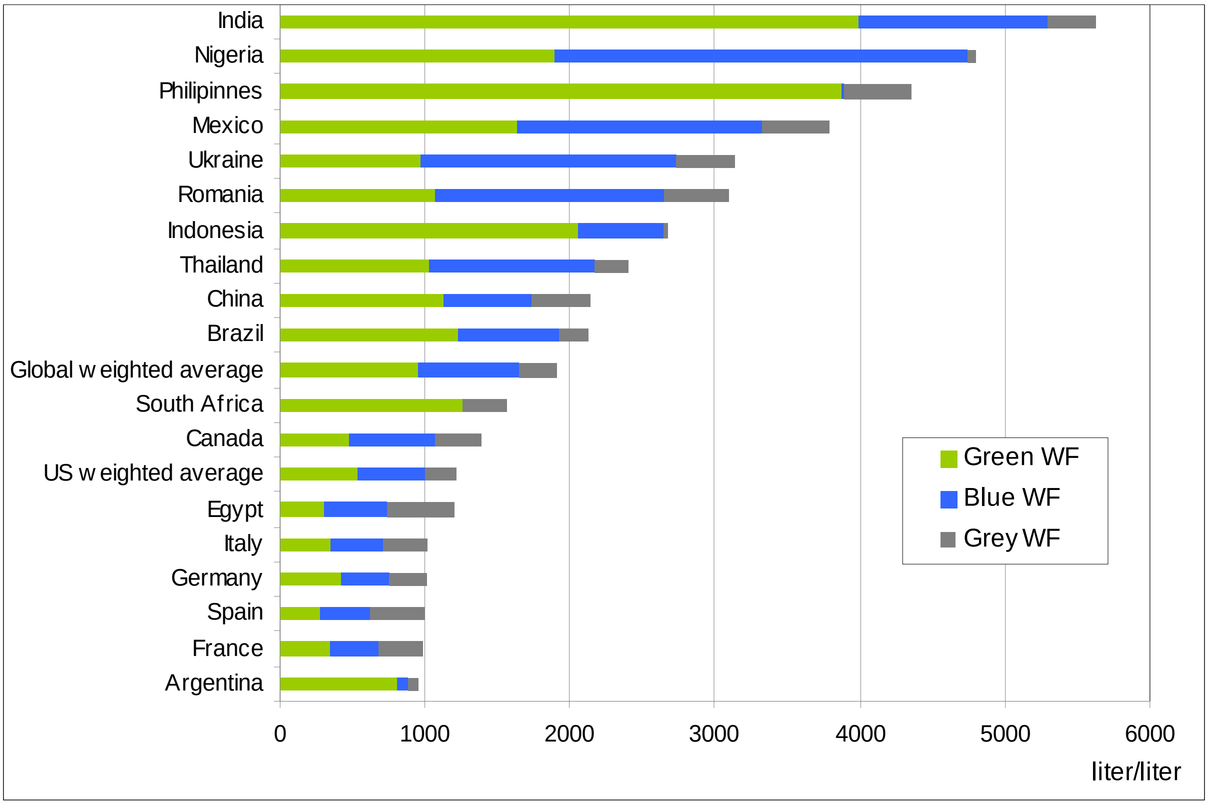

Figure 11. The green, blue and grey water footprint of ethanol from maize for the main producing countries produced by wet milling.

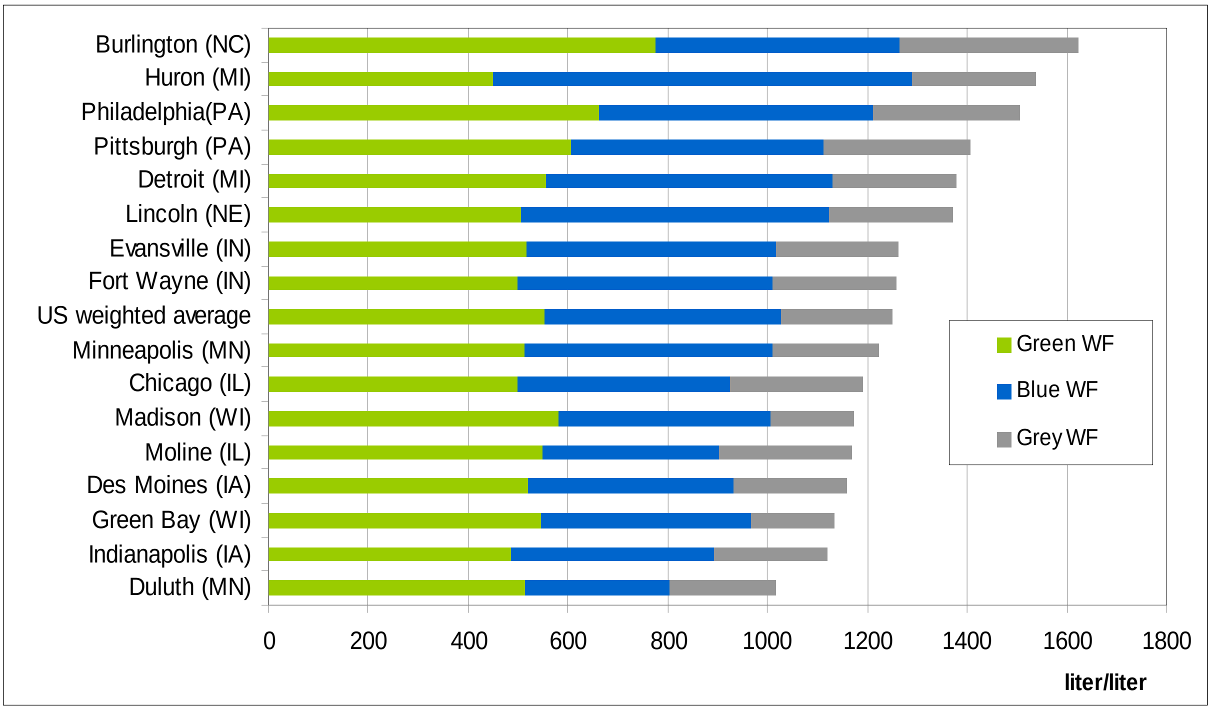

Figure 12. The green, blue and grey water footprint of ethanol from maize for sixteen locations in the US produced by dry milling. The figure also shows the US weighted average values.

5. Impact assessment

Van Oel et al. (2009) proposed three indicators for assessing the environmental impact of WFs: (1) the water competition level; (2) the withdrawal-to-availability ratio; and (3) the withdrawal-to-availability ratio including the environmental water requirements. The first commonly used indicator of water scarcity is the size of the population of an area divided by the total runoff in that area, called the water competition level (Falkenmark, 1989) or water dependency (Kulshreshtha, 1993). The inverse ratio gives a measure of the per capita water availability. Falkenmark (1989) proposes to consider regions with more than 1700 m^3 per capita per year as 'water sufficient', which means that only general water management problems occur. Between 1000-1700 m^3/cap/yr would indicate 'water stress', 500-1000 m^3/cap/yr 'chronic water scarcity' and less than 500 m^3/cap/yr 'absolute water scarcity'. This classification is based on the idea that 1700 m^3 of water per capita per year is sufficient to produce the food and other goods and services consumed by one person. In Falkenmark's indicator 'runoff' is taken as a measure of water availability. Runoff can refer to locally generated runoff (in FAO terminology then called the internal renewable water resources, IRWR), but it can also include inflows from other areas (in FAO terminology then called the total renewable water resources, TRWR).

A second common indicator of water scarcity is the ratio of water withdrawal in a certain area to the total runoff in that area, also termed the water utilization level (Falkenmark, 1989), the withdrawal-to-availability ratio (Alcamo et al., 2000, 2003) or the use-to-resource ratio (Raskin et al., 1996). The third indicator, the water stress indicator, has been proposed by Smakhtin et al. (2004), who have modified the withdrawal-to availability ratio by accounting for the environmental water requirements, which are subtracted from runoff. All three water scarcity indicators can be applied to either countries or river basins. Table 3 shows the classification of water scarcity according the water-to-availability ratio and the water stress indicator.

Table 3. Classification of water scarcity according the withdrawal-to-availability ratio and the water stress indicator (Sources: Alcamo et al., 2003; Smakthin et al., 2004).

Withdrawal-to-availability ratio		Water stress indicator	
< 0.2	No water stress	< 0.3	Environmentally safe, slightly exploited
0.2 – 0.4	Medium water stress	0.3 – 0.6	Moderately exploited
0.4 – 0.8	High water stress	0.6 – 1.0	Environmentally water stressed, heavily exploited
0.8 >	Severe water stress	1.0 >	Environmental water scarce, overexploited

Three river basins that currently experience some degree of water stress, are the Dnieper basin in the Ukraine, where sugar beet is grown and the Indus and Ganges basins in India and Pakistan, where sugar cane is cultivated. These cases will be discussed in a little more detail below; data on where the sugar beet and sugar cane are grown and where therefore the water footprints of sugar production are located, will be combined with spatial information on the withdrawal-to-availability ratio.

5.1 Dnieper basin in the Ukraine

The Ukraine belongs to the largest net exporters of virtual water (Hoekstra and Hung, 2002; Hoekstra and Chapagain, 2008). For the Ukraine, sugar beet is an important crop. An estimated 47% of the total WF of sugar beet in the Ukraine is blue water. The Dnieper is the main river in Ukraine. Agriculture accounts for more than 90% of total water consumption in Central Asia (UNECE, 2006). Surface water is overexploited for irrigation and groundwater is overused for public freshwater supply. Figure 13 compares the sugar beet growing areas in the Ukraine with a map of the water withdrawal-to-availability ratios. It shows that the main sugar beet producing areas are in the centre of the country. The areas that have the largest water stress are on the Krim and in the south. The map shows that the area where the sugar beet is grown belongs to the areas with relatively low water withdrawal-to-availability ratio, so sugar beet production is not located in the most water-stressed parts of the Ukraine.

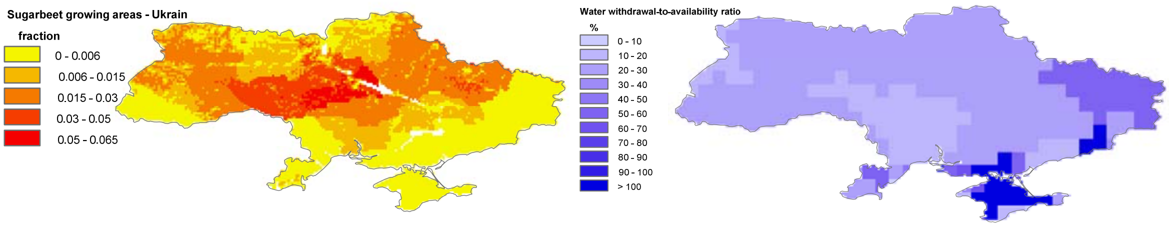

Figure 13. Sugar beet growing areas (Ramankutty, 2008) and water withdrawal-to-availability ratio in the Ukraine.

The main problem is water pollution. Pollution in the Dnieper has already caused environmental damage to the Black Sea ecosystem. In 1992, the Russian Federation's Committee on Fishing reported almost one thousand cases in which water bodies were completely contaminated by agricultural runoff. Besides pollution by excessive use of fertilizers, industrialization and the lack of waste water treatment also influence the water quality. Future impacts might include effects of climate change and the construction of dams (Palmer et al., 2008).

5.2 The Ganges and Indus basins in India and Pakistan

The Ganges is the largest river of India. Although it is one of the most humid areas, with annual precipitation above 10 metres at some locations, during some periods of the year the basin experiences severe water stress. Studies by Rosegrant et al. (2002), Alcamo and Henrichs (2002), Alcamo et al. (2003) and Smakhtin (2004) all envisage more serious water scarcity in the Ganges basin in future. The Indus originates on the Tibetan Plateau and finds its way through India and Pakistan to the Arabian Sea. The river basin area is over a million square kilometres, of which 320,000 square kilometres belong to India. For Pakistan, the Indus is the largest river. Since the independency of the countries in 1947, they almost went to war over the Indus water. After a long struggle in 1960, India and Pakistan signed the Indus Water Treaty (Postel and Wolf, 2001). Already before the independency, the allocation of Indus water was a problem between the states of British India (Beach et al., 2000). Agriculture is important in the Indus basin. Figure 14 shows the areas where sugar cane is cultivated and the water-to-availability ratio. In India, sugar cane cultivation occurs south of the Himalaya and in the south west. Although the main sugar cane producing area in India is not the most water scarce one in the country, the water withdrawal-to-availability ratio is high, between 40 and 50%. In the southwest, the water stress is even higher, between 90 and 100 %. In Pakistan, sugar cane is grown in the Indus basin, an area that has severe water stress.

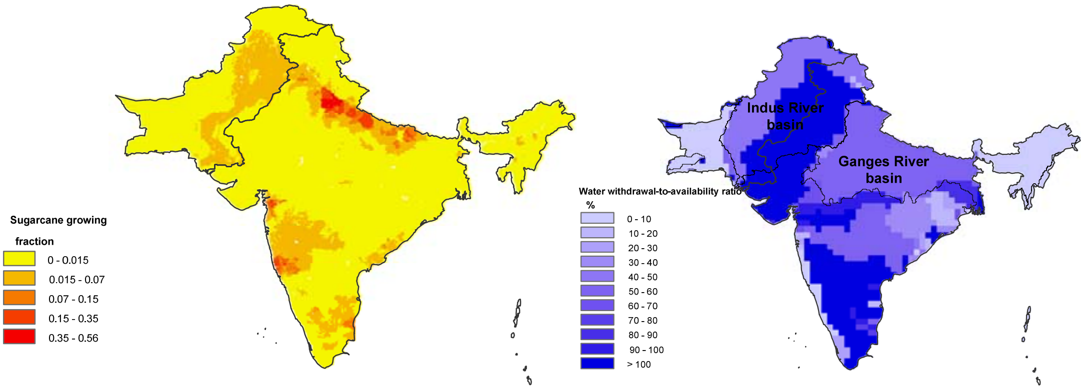

Figure 14. Sugar cane areas in India and Pakistan (Ramankutty, 2008) and water withdrawal-to-availability ratio for the Indus and Ganges basin.

From the total Indus discharge in Pakistan, only a small part drains to the Arabian Sea, while most of the water is directed to canals for various utilizations. Groundwater in the basin is overexploited and groundwater quality is deteriorating, also causing soil salinization. Besides the problem of the available resources, there are problems regarding the maintenance of the water infrastructure, governance, trust, and productivity in the Pakistani part of the basin (Royal Netherlands Embassy in Islamabad, Pakistan and Netherlands Water Partnership, 2007).

6. Discussion

This study has made several assumptions. First, it adopted the assumption that crop water use is the same as CWR, assuming that blue water requirements are always met. This does not correspond to the actual situation in many countries where irrigation is not common or for regions where irrigation is sometimes not even possible due to water scarcity. For those situations, the study overestimates the WF. On the other hand, the study did not include evaporation losses of irrigation water during storage, transport or application to the field, which implies that WFs are underestimated. Second, assumptions were made regarding the yield of crops. Data on yields for sugar beet, sugar cane and maize were derived from the FAO (2008c). Sugar beet and sugar cane have a large harvest index compared to maize (Penning de Vries et al., 1989). This means that a large part of the total biomass of the sugar beet and sugar cane plant is harvested. Only leaves remain on the field, a small fraction of the total plant biomass. The relatively small harvest index of maize (0.45) means that only 45% of the total plant biomass is harvested in the form of grains. The rest, the stover, remains on the land. The stover has an economic value as a fertilizer. This study allocated part of the WF to the by-product stover, which decreases the WF of the main products HFMS 55 and maize-based ethanol. Third, the study used the allocation method of Hoekstra and Chapagain (2008) based on product fractions and value fractions. This means that WFs depend on product prices that often depend on fluctuating prices of commodities on the world market. This means that the WFs would also fluctuate over the years. This has been solved by taking average prices over the period 1996-2005. Fourth, this study assumed low values for process water use for both sweetener and ethanol production. Although there is large variation in literature on process water use – Cheesman (2004) for example reports a large variation in process water use – modern industry recycles its process water and reduces its process water use to almost zero. For the grey WF, the recycling of the process water and waste water treatment are important. The study assumed that industry recycles its process water and does not release any waste water. In this way, it probably underestimates the process water use. The process water use, however, is small compared to the total WF. The assumption will therefore not have a large impact on the results.

There are several sensitivities related to the data used. The study used many different data sources that all have their own uncertainties. The data on yields, for example, were taken from the FAO and the USDA. These data derive from national statistics and are probably all gathered in a different way. Another uncertainty is the specific location where a crop is produced. For example, different sources give different production locations for sugar cane in Peru. This has a large effect on the WFs, because rainfall west of the Andes mountains is negligible, east of the Andes it is so large that no irrigation of sugar cane is needed. The assumptions and uncertainties imply that results cannot be interpreted at face value, but that the results are indicative. The differences in calculated WFs for sweeteners and ethanol from sugar cane, sugar beet and maize are so great that general conclusions can be drawn about the relative WFs of different crops and production locations.

7. Conclusions

The weighted global average WF of cane sugar is 1500 m^3/ton, of HFMS 55 1125 m^3/ton and of beet sugar 935 m^3/ton. The weighted global average WF of cane-ethanol is 2855 litre/litre, of maize-ethanol 1910 litre/litre and of beet-ethanol 1355 litre/litre. Globally, sugar beet is the most favourable crop for sugar and for ethanol, followed by maize. The US is the only country that uses maize on a large scale as feedstock for sweetener and ethanol production. In the US, maize is the favourable feedstock with the smallest WF for sweetener as well as for ethanol. The weighted average WF for HFMS 55 in the US is 720 m^3/ton, while the average WF for beet sugar is 1025 m^3/ton and for cane sugar 1135 m^3/ton. The weighted average WF of maize-ethanol in the US is 1220 litre/litre, while the average WF for beet-ethanol is 1290 litre/litre and for cane-ethanol 2775 litre/litre.

The differences in WFs are mainly caused by two variables: CWRs and yields. CWRs show variation and depend on factors such as crop type, climate and soil characteristics. Some countries, for example Egypt, depend on irrigation, while other countries, for example Japan growing sugar beet, have small irrigation requirements. The yield levels differ between countries because of growing conditions and agricultural practices. All WF estimates are based on current conditions, so they do not reflect what is technologically possible. Particularly many of the large water footprints found can be reduced if better practices were adopted.

In general, the grey WF is only a small part, about 10%, of the total WF. In some countries, however, the grey WF of maize-based products contributes to 20% of the total WF. When more strict ambient water quality standards are used in calculating the WF, and when pesticides would be included as well, the grey component of the WF can easily increase by a factor of 10 or even 100.

At present, water stress is a problem in many parts of the world. An expansion of water stressed areas is expected. Furthermore, these stressed areas will suffer longer and have more severe stress in the future due to climate change, population and economic growth and expansion of irrigated agriculture. Especially sugar cane is grown in water scarce river basins, as was indicated for the Indus and Ganges basins. Sugar beet also has an impact on water quantity and water quality in major river basins, such as the basins of the Dnieper, where especially the grey WF is important.

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References

Alcamo, J., Henrichs, T. and Rösch, T. (2000) World water in 2025: Global modelling and scenario analysis for the World Commission on Water for the 21st century, Kassel World Water Series, Report, No.2, University of Kassel.

Alcamo, J. and Henrichs, T. (2002) Critical regions: A model-based estimation of world water resources sensitive to global changes. Aquatic Sciences 64, 352–362.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B. Rösch, T., Siebert, S. (2003) Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrological Sciences–Journal–des Sciences Hydrologiques, 48(3), 339-348.

Allan, R.G., Pereira, L.S., Raes, D., Smith, M. (1998) Crop evapotranspiration - Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No.56, FAO, Rome, Italy. www.fao.org/docrep/X0490E/x0490e00.htm#Contents

Allen, C.J., Mackay, M.J., Aylward, J.H., Campbell, J.A. (1997) New technologies for sugar milling and by-product modification, In: Keating, B.A. and JR Wilson (eds.) Intensive sugar cane production: meeting the challenges beyond 2000, CAB International, Wallingford, UK, pp 267-285.

Beach, H.L., Hamner, J., Hewitt, J.J., Kaufman, E., Kurki, A., Oppenheimer, J.A. and Wolf, A.T. (2000) Transboundary freshwater dispute resolution: Theory, practice, and annotated references, United Nations University Press, Tokyo, Japan.

Berg, C. (2004) World fuel ethanol, Analysis and outlook. Presentation prepared for the Ministry of Economy, Trade and Industry of Japan. www.meti.go.jp/report/downloadfiles/g30819b40j.pdf

Campos, L.O. (2006) Still time to fuel up. Credit Suisse First Boston, USA.

Chapagain, A.K. and Hoekstra, A.Y. (2004) Water footprints of nations, Value of Water Research Report Series No.16, UNESCO-IHE, Delft, the Netherlands.

Chapagain, A.K., and Hoekstra, A.Y. (2007) The water footprint of coffee and tea consumption in the Netherlands, Ecological Economics 64(1): 109-118.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., Gautam, R. (2006) The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries, Ecological Economics, 60(1): 186-203.

Cheesman, O.D. (2004) Environmental impacts of sugar production, CABI Publishing, Wallingford, Oxfordshire, UK.

CIBE/CEFS (2003) Environmental report, beet growing and sugar production in Europe, International Confederation of European Beet Growers (CIBE), Paris, France and Comité Européen des Fabricants de Sucre (CEFS), Brussels, Belgium.

Cornland, D.W., Johhson, F.X., Yamba, F., Chidumayo, E.N., Morales, M.M., Kalumiana, O., Mtonga-Chidumayo, S.B. (2001) Sugarcane resources for sustainable development: A case study in Luena, Zambia, Stockholm Environment Institute, Stockholm, Sweden.

Coultate, T.P. (1989) Food, the chemistry of its component. 2nd edition. Royal Society of Chemistry, London, UK.

Economic Research Service/USDA (2009) USDA Feed Grains Baseline 2009-18. www.ers.usda.gov/Briefing/corn/2009baseline.htm.

Ensymm (2005) Project study for the enzymatic production of high fructose syrup (HFS). Ensymm Company, Düsseldorf, Germany.

EPA (1995) AP 42, Compilation of air pollutant emission factors. Volume I: Stationary point and area sources. Fifth edition. Office of air quality planning and standards, Office of Air and Radiation, Environmental Protection Agency, US.

Falkenmark, M. (1989) The massive water scarcity now threatening Africa: Why isn't it being addressed? Ambio 18(2), 112-118.

FAO (2007) FERTISTAT. Food and Agriculture Organization. Rome, Italy. www.fao.org/ag/agl/fertistat.

FAO (2008a) CLIMWAT, Food and Agriculture Organization. Rome, Italy. www.fao.org/nr/water/infores_databases_climwat.html.

FAO (2008b) CROPWAT 4.3 decision support system, Food and Agriculture Organization. Rome, Italy. www.fao.org/nr/water/infores_databases_cropwat.html.

FAO (2008c) FAOSTAT, Food and Agriculture Organization. Rome, Italy, http://faostat.fao.org/default.aspx.

FAPRI (2008) US and world agricultural outlook, US Food and Agricultural Policy Research Institute, Ames, Iowa, US.

Fornalek, W. (1995). The preparation of production technology of new kinds of sugar consumption, [Opracowanie technologii produkcji nowych rodzajów cukru konsumpcyjnego.] Research Object: 05.02.01, Research Subject: E08.01, Institute of sugar industry, Leszno, Poland.

Gerbens-Leenes W., Hoekstra, A.Y, Van der Meer, T.H. (2009) The water footprint of bioenergy, Proceedings of the National Academy of Science, 106(25): 10219-10223.

Henke S., Bubník Z., Hinková A., Pour V. (2006) Model of a sugar factory with bio-ethanol production in program Sugars™. Journal of Food Engineering 77: 416-420.

Hoekstra A.Y. (2003) Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade, Delft, the Netherlands, 12-13 December 2002, Value of Water Research Report Series No. 12, IHE, Delft, The Netherlands.

Hoekstra A.Y. and Chapagain A.K. (2008) Globalization of water, Sharing the planet's freshwater resources, Blackwell Publishing Ltd. Oxford, UK.

Hoekstra, A.Y. and Hung, P.Q. (2002) Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade, Value of Water Research Report Series No. 11, IHE, Delft, The Netherlands.

ILSR (2002) Talking about corn stover with Jim Hettenhaus, The carbohydrate economy, Volume No. 4, Issue No. 2, summer 2002, Minneapolis, USA.

ISR (2005) Sugar beet growing in The Netherlands, Institute of Sugar beet Research, Bergen op Zoom, the Netherlands.

International Sugar Organization (2007) Statistical bulletin 2007. Vol. 66, No. 12, London, UK.

Johnson K. (2009) Brazil's Bet: Ethanol surpasses gasoline in Brazil. Wall Street Journal, Wednesday June 3 2009.

Kulshreshtha, S.N. (1993) World water resources and regional vulnerability: Impact of future changes, Research Report RR-93-10, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Kranjc, D., Mele, M., Glavič, P. (2006) Improving the economic and environmental performances of the beet sugar industry in Slovenia: increasing fuel efficiency and using byproducts for ethanol, Journal of Cleaner Production 15: 1240-1252.

Leal, M.R.L.V. (2005) Better sugar; better business, mill issues and co-products, WWF workshop, London, UK.

Macedo, I.C. (2005) Sugar cane's energy, twelve studies on Brazilian sugar cane agribusiness and its sustainability. UNICA, Berlendis & Vertecchia, São Paulo, Brazil.

Mohee, R. and Beeharry, R.P. (1999) Life cycle analysis of compost incorporated sugarcane bioenergy systems in Mauritius. Biomass and Bioenergy 17: 73 - 83.

Moreira, J.R. (2007) Water use and impacts due ethanol production in Brazil, www.iwmi.cgiar.org/EWMA/files/papers/Jose_Moreira.pdf

Müller, M.J. and Hennings, D (2000) The global climate data atlas on cd-rom. Release 1.0.

Palmer, M.A., Liermann, C.A.R., Nilsson, C. Flörke, M. Alcamo, J. Lake, P.S., Bond, N. (2008) Climate change and the world's river basins: anticipating management options. Frontiers in ecology and the environment, The ecological society of America.

Paturau, J.M. (1989). By-products of the cane sugar industry: An introduction to their industrial utilization. Elsevier, Amsterdam/New York.

Penning de Vries, F.W.T., Jansen, D.M., Ten Berge, H.F.M., Bakema, A. (1989) Simulation of ecophysiological processes of growth in several annual crops, pp. 63-64, Centre for Agricultural Publishing and Documentation (Pudoc), Wageningen, the Netherlands.

Postel, S.L., and Wolf, A.T. (2001) Dehydrating conflict. Foreign Policy (September): 2–9.

Rajagopal D. and Zilberman, D. (2007) Review of environmental, economic and policy aspects of biofuels, policy research, Working Paper 4341. The World Bank, Washington, D.C., US.

Raskin, P.D., Hansen, E. and Margolis, R.M. (1996) Water and sustainability: global patterns and long-range problems, Natural Resources Forum 20(1): 1-5.

Ramankutty, N. (2008) http://geomatics.geog.mcgill.ca/~navin/pub/Data/175crops2000/ArcASCII.

Rosegrant, M.W., Cai, X., Cline, S.A. (2002) World water and food to 2025: Dealing with scarcity, International Food Policy Research Institute (IFPRI), Washington, D.C., US.

Royal Netherlands Embassy in Islamabad, Pakistan and Netherlands Water Partnership (2007) Workshop on the water situation in Pakistan. The Hague, the Netherlands.

Shleser, R. (1994) Ethanol production in Hawaii, processes, feedstocks, and current economic feasibility of fuel grade ethanol production in Hawaii. State of Hawaii, Department of business, economic development & tourism. Honolulu, Hawaii, USA.

Silva, J.F. (2006) Industrial processing integration of alcohol and sugar production, Cogeneration of electricity. Presentation during the World Bank Seminar on Brazil's Ethanol Experience and its Transferability.

Shapouri, H. and Gallagher, P. (2005) USDA's 2002 ethanol cost-of-production survey, Agricultural Economic Report Number 841. USDA, US.

Smakhtin, V., Revenga, C., Döll, P. (2004) A pilot global assessment of environmental water requirements and scarcity, Water international 29(3): 307–317.

Smeets, E., Junginger, M., Faaij, A., Walter, A., Dolzan, P. (2006) Sustainability of Brazilian bio-ethanol. Copernicus Institute - Department of Science, Technology and Society, Utrecht, The Netherlands.

UNCTAD/WTO (2007) Statistics for International Trade Analysis (SITA), version 1.1, programmed by LEI.

UNECE (2006) Integrate water resources management (IWRM) including transboundary river basin issues. Working paper No.3. www.unece.org/env/water/meetings/wgwm/4meeting/wp3e.pdf

USDA/ Economic Research Service (2006). ERS Loss-adjusted Food availability Data, April 2006. www.ers.usda.gov/data/foodconsumption/foodguideindex.htm.

USDA/ Agricultural Statistics Service (2008) Agricultural Statistics 2008. United States Government Printing Office, Washington, US.

USDA (2006) Corn and soybeans: Production costs and returns. www.nass.usda.gov/Statistics_by_State/Minnesota/Publications/Annual_Statistical_Bulletin/agstatbk2006/page088093.pdf.

Vaccari, G., Tamburini, E., Sgualdinoa, G., Urbaniecb, K., Klemeš, J. (2005) Overview of the environmental problems in beet sugar processing: possible solutions, Journal of Cleaner Production 13, 499-507.

Van der Linde, M., Minne, V., Wooning, A., Van der Zee, F. (2000) Evaluation of the common organisation of the markets in the sugar sector. NEI, Rotterdam, The Netherlands.

Van Oel P.R., Mekonnen M.M., Hoekstra A.Y. (2009) The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment, Ecological Economics 69(1), 82-92.

WHO (2006) Guidelines for drinking-water quality. 3rd edition incorporating 1st addendum. World Health Organization, www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.html.

Worldwatch Institute (2007) Biofuels for transport, global potential and implications for sustainable energy and agriculture. Earthscan, London, UK.

Wu, M. (2008) Analysis of the efficiency of the US ethanol industry 2007, Renewable Fuels Association, Washington, USA, http://www.ethanolrfa.org/objects/documents/1652/2007_analysis_of_the_efficiency_of_the_us_ethanol_industry.pdf.

WWF (2003) Agricultural water use and river basin conservation, World Wide Fund for Nature, Gland, Switzerland, http://assets.panda.org/downloads/agwaterusefinalreport.pdf.

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