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Review

The water footprint of sweeteners and bio-ethanol

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ABSTRACT

An increasing demand for food together with a growing demand for energy crops result in an increasing demand for and competition over water. Sugar cane, sugar beet and maize are not only essential food crops, but also important feedstock for bio-ethanol. Crop growth requires water, a scarce resource. This study aims to assess the green, blue and grey water footprint (WF) of sweeteners and bio-ethanol from sugar cane, sugar beet and maize in the main producing countries. The WFs of sweeteners and bio-ethanol are mainly determined by the crop type that is used as a source and by agricultural practise and agro-climatic conditions; process water footprints are relatively small. The weighted global average WF of sugar cane is 209 m^3/tonne; for sugar beet this is 133 m^3/tonne and for maize 1222 m^3/tonne. Large regional differences in WFs indicate that WFs of crops for sweeteners and bio-ethanol can be improved. It is more favourable to use maize as a feedstock for sweeteners or bio-ethanol than sugar beet or sugar cane. The WF of sugar cane contributes to water stress in the Indus and Ganges basins. In the Ukraine, the large grey WF of sugar beet contributes to water pollution. In some western European countries, blue WFs of sugar beet and maize need a large amount of available blue water for agriculture. The allocation of the limited global water resources to bio-energy on a large scale will be at the cost of water allocation to food and nature.

Contents

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1. Introduction

Fresh water of adequate quality is a prerequisite to feed the growing world population and to sustain nature. Freshwater availability and quality vary in time and space. The need for more food in combination with a shift from fossil energy towards bio-energy leads to a growing demand for fresh water (UNEP, 2009). Increased global use of biofuels like bio-ethanol leads to a substantial increase in global agricultural water use, which enlarges water competition (Berndes, 2002; De Fraiture et al., 2008) and contributes to further water quality deterioration from the seepage of fertilisers and pesticides (UNEP, 2009). There are various signs that water consumption and pollution exceed sustainable levels, for example in the Ganges and Indus river basins in India and Pakistan (Alcamo et al., 2003; Mekonnen and Hoekstra, 2010).

The growing public interest in biofuels originates from the aim to reduce CO_2 emissions from fossil fuels, but biofuels are also considered relevant in promoting rural development and securing an energy source for the long-term future (UNEP, 2009). Not only developed countries, such as the countries of the European Union (European Commission, 2009), but also large developing countries like China (Yang et al., 2009) and India (Government of India, 2008) aim to partially replace traditional transport fuels from fossil sources by renewables, such as bio-ethanol from sugar and starch crops. During the last three decades, global bio-ethanol production has increased rapidly. In 2005, the US and Brazil were the largest producers. US production is based on maize and Brazilian production on sugar cane (Berg, 2004). In developed countries, transport accounts for about one third of total energy use (Blok, 2006; IEA, 2006), which means that a shift towards biofuels will take large efforts. First-generation bio-ethanol is mainly produced from sugar crops (61%), especially from sugar cane and to a lesser extent from sugar beet, or from grains, especially maize (corn) (39%) (Berg, 2004). In the future, also crop residues may be used for biofuels. A recent study, however, concluded that the use of crop residues for biofuels, so termed second-generation biofuels, needs to be critically evaluated because of the positive effects of crop residues on soil quality and carbon sequestration by the soil (Lal, 2005), which redirects the interest to first-generation biofuels like bio-ethanol.

Sugar cane, sugar beet and maize are important food crops with a large contribution to global agricultural food production (FAO, 2011). Sugar cane contributes to 29% of the total world crop production, maize 14% and sugar beet 4%. There is concern that increased bio-ethanol production will increase food prices and decrease food security (FAO, 2008; Fischer et al., 2009; Pimentel et al., 2009). Moreover, agricultural crops, such as sugar cane, are water intensive (WWF, 2003). Today, agriculture accounts for 86% of the global freshwater consumption (Hoekstra and Chapagain, 2008). An important question is whether we apply scarce water resources for food or for fuel. This requires detailed information about how much water is needed to produce food and fuel.

A tool to calculate water needs for consumer products is the water footprint (WF) concept (Hoekstra, 2003; Hoekstra et al., 2011; Hoekstra and Chapagain, 2008), an indicator of freshwater use that includes direct and indirect water use along product supply chains. The WF is a multi-dimensional indicator, giving water consumption volumes by source and polluted volumes by type of pollution. The tool distinguishes between green, blue and grey waters and in this way gives a comprehensive and complete overview of freshwater use and pollution. The *blue* WF refers to surface and groundwater volumes consumed (evaporated or incorporated into the product) as a result of the production of a good; the *green* WF refers to the rainwater consumed. The *grey* WF of a product refers to the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards. Hoekstra and Hung (2002) made a first global estimation of freshwater needed to produce crops; Chapagain and Hoekstra (2004) made the first global dataset for all agricultural products. Subsequent studies, e.g. for cotton (Chapagain et al., 2006) and coffee and tea (Chapagain and Hoekstra, 2007) provide detailed WFs of crops and derived crop products. Sugar crops are among the most important food crops that, at the same time, are used to produce growing amounts of bio-ethanol. Several studies assessed bio-ethanol water requirements. Chiu et al. (2009) and King and Webber (2008) made assessments for US bio-ethanol from maize focussing on irrigation water. Dominguez-Faus et al. (2009) made an assessment for US bio-ethanol, also including evapotranspiration. Gerbens-Leenes et al. (2009) calculated green and blue WFs for bio-ethanol and included the main producing countries. Detailed global analyses are needed to estimate how much water is required for the production of food and biofuel and where overexploitation or pollution of water may occur. The aim of this study is to extend existing studies and assess the water requirements of three crops that are important for food but feedstock for bio-ethanol as well. Objectives are: (i) to calculate the green, blue and grey WFs of sweeteners and bio-ethanol from sugar cane, sugar beet and maize for the main producing countries and locations, (ii) to assess favourable production lines and locations and (iii) to evaluate the environmental sustainability of WFs of sugar cane and sugar beet production in three important production areas, as well as environmental sustainability of sugar cane, sugar beet and maize production on a national and global level. Detailed WFs of sweeteners and bio-ethanol give an indication of the feasibility of using sugar and starch crops for biofuels from a water perspective and show where and how they can be produced in the most water efficient way.

2. Bio-ethanol and sweeteners

Bio-ethanol is a liquid biofuel. Globally, 75% is used for transportation (Worldwatch Institute, 2007). Industry produces 95% of the bio-ethanol by fermenting sugar and starch (carbohydrates), mainly from sugar cane, beet and maize (Berg, 2004). Sweeteners (sugars and syrups) are plant carbohydrates (Cheesman, 2004; Coultate, 1989) used for food. Cane sugar derives from sugar cane, beet sugar from sugar beet. High fructose syrups (HFS), for example High Fructose Maize Syrup 55 (HFMS 55), is made from maize (Ensymm, 2005). In the US, where maize is called corn, HFMS is known as HFCS. Sugar cane provides 70% of global sugar, sugar beet the remaining 30%. Fig. 1 gives an overview of global sweeteners and bio-ethanol production. Sugar cane is a perennial crop growing in tropical climates. Over the period 1998–2007, Brazil produced 30% of the global sugar cane, India 21%, China 7%, and Thailand and Pakistan 4% each (FAO, 2011).

Fig. A1 in Appendix A shows the production systems for sugar and bio-ethanol from sugar cane (see also Gerbens-Leenes and Hoekstra, 2009). Cane juice is an intermediate product for sucrose (cane sugar) and ethanol. Molasses, a by-product, can also be used for ethanol production (Cornland et al., 2001; Moreira, 2007; Shleser, 1994; Silva, 2006; Smeets et al., 2006).

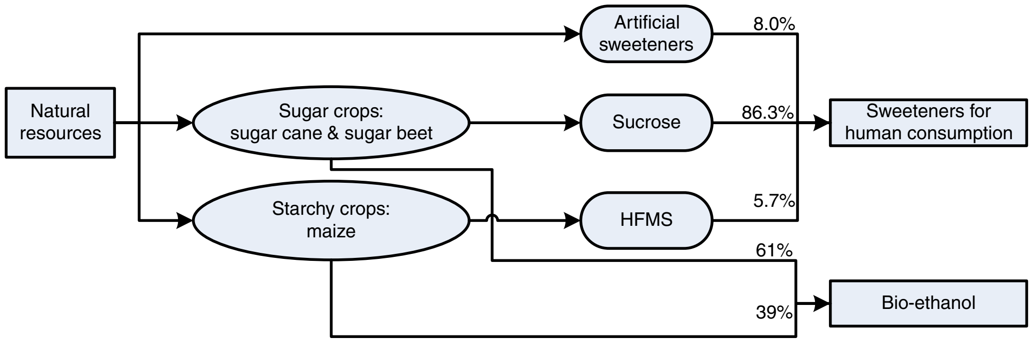

Fig. 1. Overview of the global sweeteners and bio-ethanol production.
Sources: Berg (2004), Campos (2006), International Sugar Organization (2007), and Van der Linde et al. (2000).

Sugar beet is a root crop growing in temperate climates. The main producers are France (12% of global production), the US (11%), Germany (10%), the Russian Federation (8%), Turkey (6%), the Ukraine (6%), Poland (5%), Italy (4%) and China (4%) (FAO, 2011). Although sugar beet has high ethanol yields per hectare (Rajagopal and Zilberman, 2007), the use for ethanol is limited compared to sugar cane. Fig. A2 in Appendix A shows the production systems for sugar and bio-ethanol from sugar beet (Cheesman, 2004; CIBE/CEFS, 2003; Henke et al., 2006; Vaccari et al., 2005). The basis for beet sugar and bio-ethanol production is beet juice. Molasses also provide bio-ethanol.

Since 1970, HFMS consumption in the US increased, whilst cane and beet sugar consumption decreased significantly (USDA/Economic Research Service, 2006). Maize grows in moderate and sub-tropical climates. The US (40% of global production) and China (20% of global production) are the main producers (FAO, 2011). About half of the maize is used for animal feed, the other half for industrial purposes, such as bio-ethanol and HFMS. In 2019, bio-ethanol production is expected to require 40% of the maize grown in the US (Economic Research Service/USDA, 2009). For HFMS and bio-ethanol, there are two production processes: wet and dry milling. Depending on process type, the industry also produces economically valuable by-products.

3. Method and data

The method used in this study is the global standard for water footprint assessment, which is the most comprehensive method assessing water requirements developed so far (Hoekstra et al., 2011). The method is supported by the Water Footprint Network that includes over 150 partners, including for example WWF, the World Business Council for Sustainable Development and many universities. We calculated green, blue and grey water footprints (WFs) of sweeteners and bio-ethanol from sugar cane, sugar beet and maize for main producing countries, as well as for main producing states in the US.

3.1. Crop water footprints

We derived data on crop WFs from Mekonnen and Hoekstra (2010) who have recently developed a new method of estimating green and blue water consumption at a high spatial resolution. That method takes actual irrigation rather than irrigation requirements into account. Earlier studies calculated blue WFs as differences between crop water requirements and effective rainfall, assuming irrigation requirements are met. In many cases, this leads to an overestimation of blue water use. The new method is a large improvement of water use estimates compared to the earlier WF calculations. We adopted average data on WFs of sugar cane, sugar beet and maize for twenty main producing countries over the period 1996–2005. These countries were, in order of decreasing production (FAO, 2011): Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Australia, the United States, the Philippines, Indonesia, Cuba, South Africa, Argentina, Guatemala, Egypt, Vietnam, Venezuela and Peru for *sugar cane*; France, the United States, Germany, the Russian Federation, Turkey, the

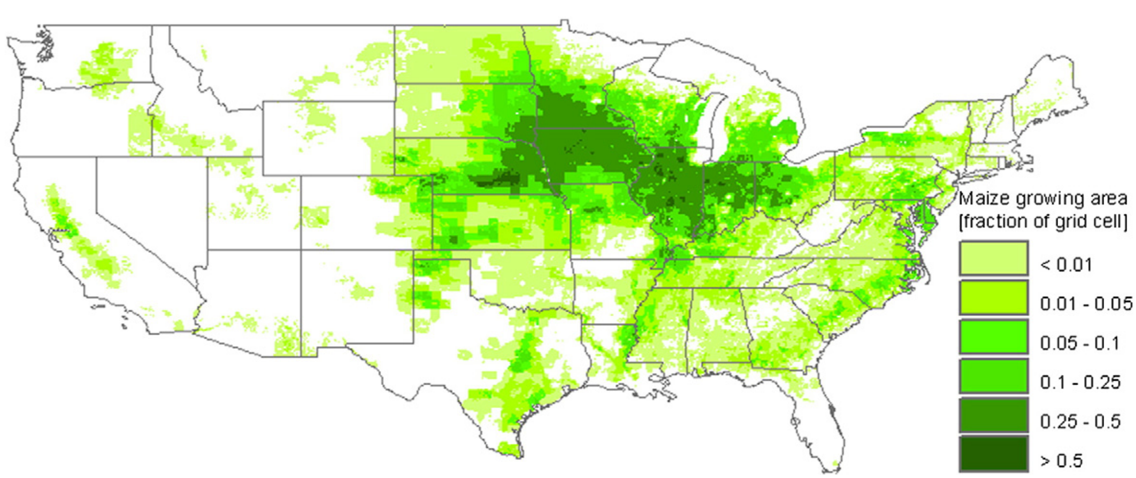

Fig. 2. The US corn belt, including the main maize producing states Illinois, Indiana , Iowa , Michigan, Minnesota, Nebraska, North Carolina, Pennsylvania and Wisconsin.
Source: Monfreda et al. (2008).

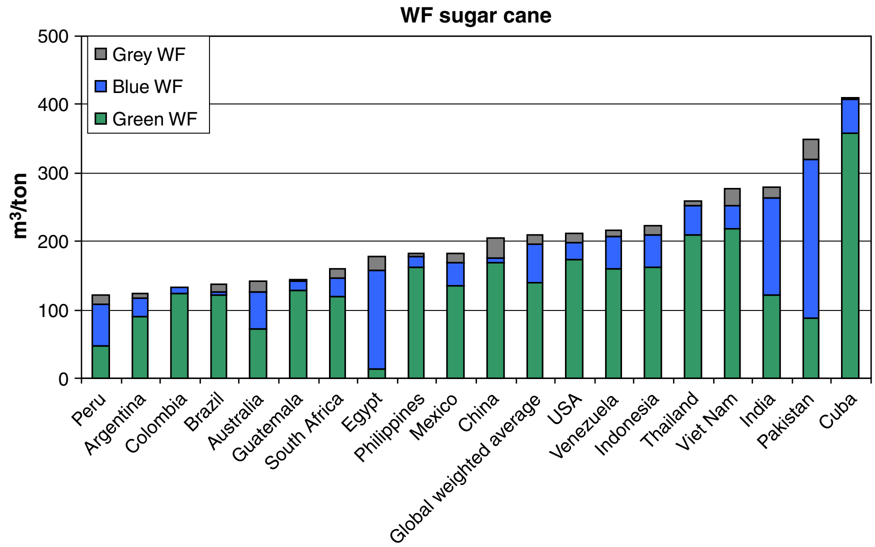

Fig. 3. The water footprint of sugar cane for the main producing countries including the weighted global average value.

Ukraine, Poland, Italy, China, the United Kingdom, Spain, Belgium–Luxembourg, the Netherlands, Iran, Japan, Egypt, Czech Republic, Serbia, Morocco and Denmark for *sugar beet*; and the United States, China, Brazil, Mexico, Argentina, France, India, Indonesia, Italy, South Africa, Canada, Romania, Hungary, Egypt, Nigeria, Serbia and Montenegro, the Ukraine, the Philippines, Spain and Thailand for *maize*. The US is responsible for 40% of global maize production, mainly in the so-termed corn belt (Fig. 2). Moreover, the US aims to increase bio-ethanol production. For maize (corn), the study therefore included the main producing US states: Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, North Carolina, Pennsylvania and Wisconsin (USDA/Agricultural Statistics Service, 2008).

To grow crops, farmers apply fertilisers containing nitrogen and phosphorus and pesticides that partly leach to groundwater and contribute to grey WFs. We took nitrogen as an indicator for grey WFs, assuming that on average 10% of total nitrogen applications leach to groundwater or run off to surface water streams (Chapagain et al., 2006). For the assessment of grey WFs, we adopted data from Mekonnen and Hoekstra (2010).

3.2. The water footprint of sugar, HFMS and bio-ethanol

For the assessment of the WF of sugar, HFMS and bio-ethanol, the complete production chain needs to be taken into account, including water use for crop processing into final products. Process water for cane sugar varies between 1 and 21 m^3 per tonne (Macedo, 2005; Moreira, 2007). For sugar beet, plant process water use concerns beet washing. Water consumption ranges from 0 to 4.5 m^3 per tonne beet (Vaccari et al., 2005). For the production of bio-ethanol, Wu (2008) estimated water use of 3.5 l per litre bio-ethanol for dry milling and 3.9 l for wet milling. Shapouri and Gallagher (2005) estimated that bio-ethanol production requires between 1 and 11 l of water per litre bio-ethanol, with an average of 4.7 l. Using Wu's assumption, with an average yield of 503 l of bio-ethanol per tonne of grain for dry mills and 490 l of bio-ethanol for wet mills, water use is 1.7 m^3 per tonne maize (dry milling) or 1.9 m^3 per tonne (wet milling).

The production of sugar and bio-ethanol also generates by-products with an economic value. To calculate the WF of these products and by-products, we adopted the allocation methodology as in Hoekstra et al.

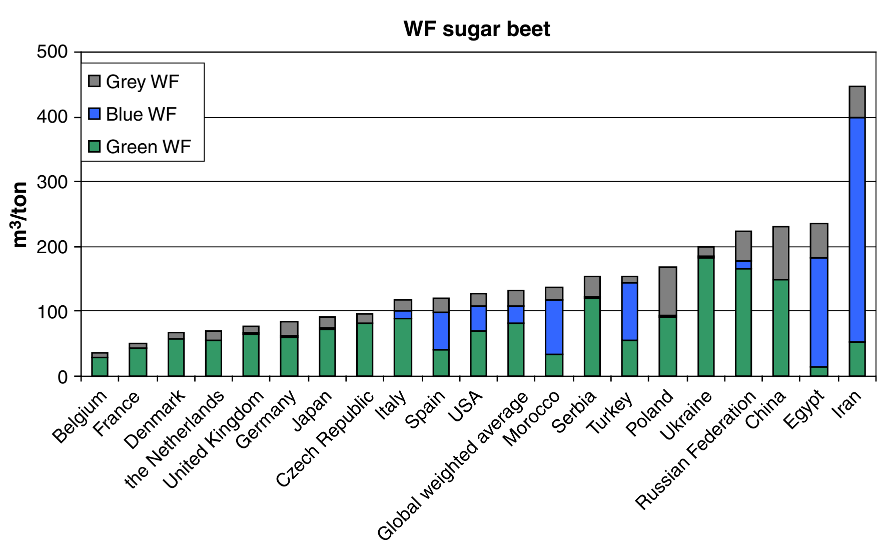

Fig. 4. The water footprint of sugar beet for the main producing countries including the weighted global average value.

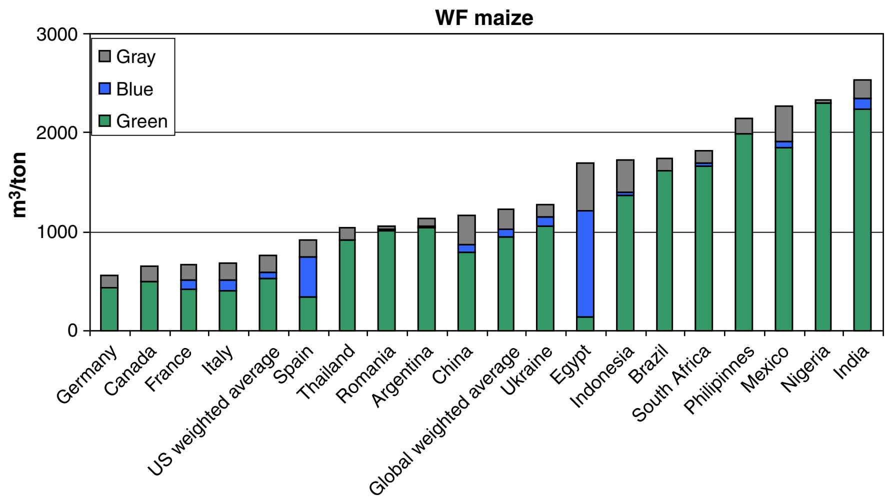

Fig. 5. The water footprint of maize for the main producing countries including the weighted global average value.

(2011). We allocated the WF of the crop over crop products by dividing the crop WF (WF_{crop}) by the product fraction $f_p[p]$. The product fraction is defined as the ratio of the product mass (kg) to the aggregated mass of the crop (kg). Next, we distributed the WF over all the products with an economic value according to their value fraction $f_v[p]$. The value fraction is defined as the ratio of the product with an economic value to the aggregated market value of all products obtained from the crop. Finally, to calculate the WF of a product $WF_{prod}[p]$, one needs to add the process water footprint $WF_{proc}[p]$. The WF of product or by-product p is calculated according to:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \frac{WF_{crop}}{f_p[p]}\right) \times f_v[p] \quad (1)$$

The assessment of product and value fractions is given in Appendix A. To provide a better insight into the differences among WFs for similar products derived from different crops, we introduced the WF allocation factor defined as the ratio of the value fraction to the product fraction.

3.3. Sustainability assessment

A sustainability assessment aims to compare human footprints with the carrying capacity of the earth (Hoekstra et al., 2011). To make an environmental sustainability assessment for water, one will need to put blue and green WFs in the context of the blue and green water availability in the catchment where the footprints occur. Similarly, the grey WF in a catchment is to be regarded in the context of the waste assimilation capacity in the catchment (Hoekstra et al., 2011). An environmental sustainability assessment for water consists of four steps; (i) identification of sustainability criteria; (ii) identification of hotspots; (iii and iv) identification and quantification of primary and secondary impacts in the hotspots.

3.4. Environmental sustainability of the blue water footprint

Blue water availability in a catchment – the amount of water available for humans to use – is defined as the natural run-off in the catchment minus the environmental flow requirement. As a rule of thumb, environmental flow requirements are about 80% of natural runoff if one does not allow more than a slight modification of the ecological status of the river (Hoekstra et al., 2011). To estimate the environmental sustainability of sugar cane, sugar beet and maize, we calculated the fraction of available blue water for agriculture in a country needed to grow those crops. Available blue water for agriculture in a country was calculated by subtracting environmental flow requirements and 5% of industrial and household water withdrawals from the total renewable water resources. The factor 0.05 is applied to convert withdrawals to consumptive use (AQUASTAT, 2011). We derived data on renewable water resources and industrial and domestic water withdrawals from AQUASTAT (2011).

3.5. Hotspots

We selected three hotspots where large-scale sugar production takes place, but do not give a detailed analysis of impacts. The hotspots are three river basins experiencing water stress: the Dnieper basin (Ukraine), with sugar beet, and the Indus and Ganges basins (India and Pakistan), with sugar cane. The study discusses water stress in these basins by combining data on sugar beet and sugar cane locations, WFs and information on withdrawal-to-availability ratios.

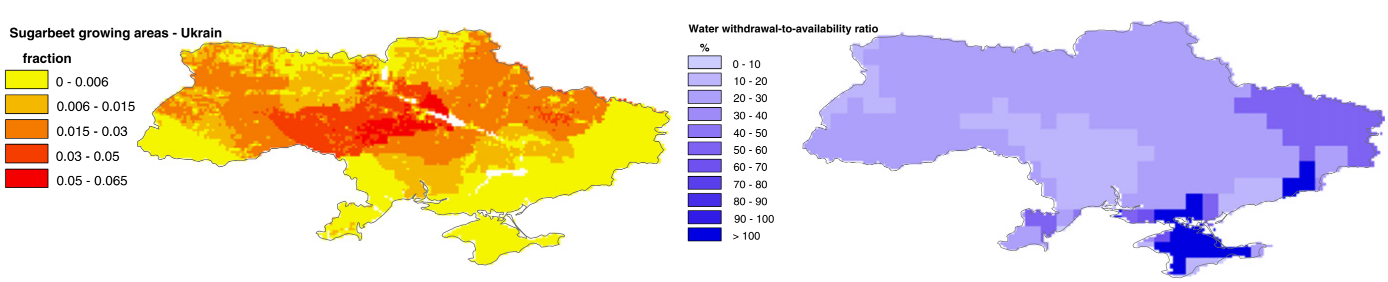

Fig. 6. Sugar beet growing areas (Ramankutty, 2008) and water withdrawal-to-availability ratio in the Ukraine.

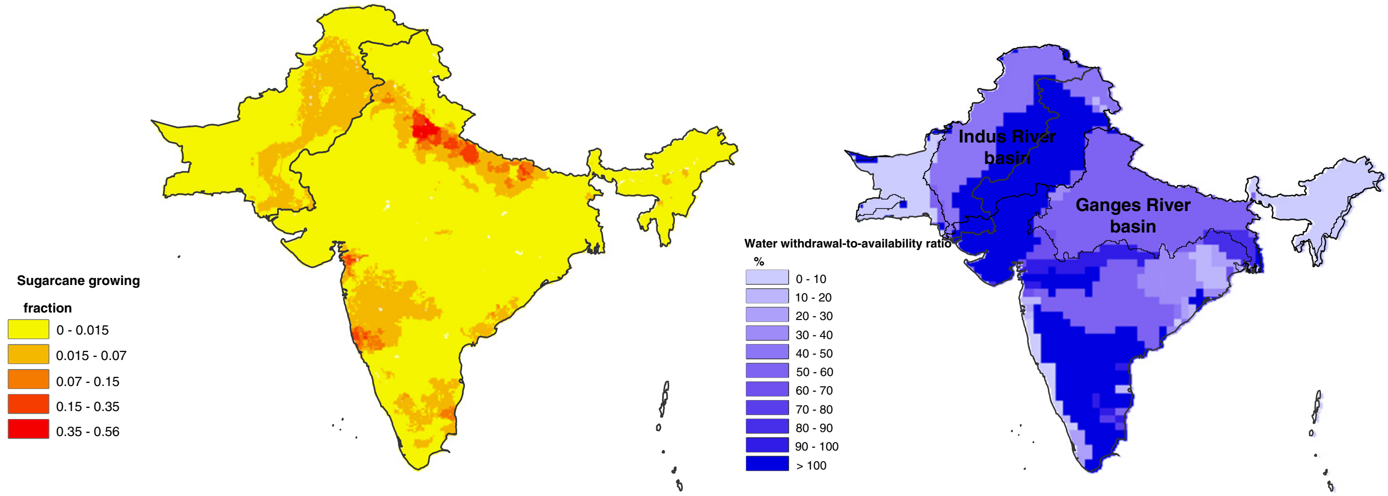

Fig. 7. Sugar cane areas in India and Pakistan (Ramankutty, 2008) and water withdrawal-to-availability ratio for the Indus and Ganges basin.

3.6. Environmental sustainability in a global context

Because of international commodity trade, places of production and places of consumption do not necessarily coincide. Given that also many water-intensive commodities are internationally traded, the indirect demand for water that underlies the consumption of water-intensive commodities in a river basin does not need to match the supply of freshwater resources in that basin. Rather, water demand and supply need to match at the global level. The amount of globally available water is limited, however. Estimates suggest that the annual global green WF of agriculture is 5771 Gm^3, the blue WF 899 Gm^3 and the grey WF 734 Gm^3 (Mekonnen and Hoekstra, 2010). From a sustainability perspective, it is necessary to improve the wise use of globally available water. Therefore, we also assessed the fraction of globally applied green, blue and grey waters for sugar cane, beet and maize.

4. Results

4.1. The water footprint of sugar cane, sugar beet and maize

Fig. 3 shows the WFs of sugar cane (m^3/tonne), Fig. 4 the WFs of sugar beet and Fig. 5 the WFs of maize. There are large differences for similar crops that are caused by differences in climate and differences in yields (tonne per ha). Some countries have unfavourable WFs, far above the global average, e.g. for sugar cane Cuba, Pakistan, India, Vietnam and Thailand. Egypt, India and Pakistan heavily rely on blue water for irrigation. For sugar beet, Iran, China, Egypt and Ukraine have WFs far above the global average, whilst western European countries have WFs below the global average. Especially grey WFs are great for Poland and China indicating that much nitrogen is leaking or applied in too large amounts, polluting water bodies. For maize, developing

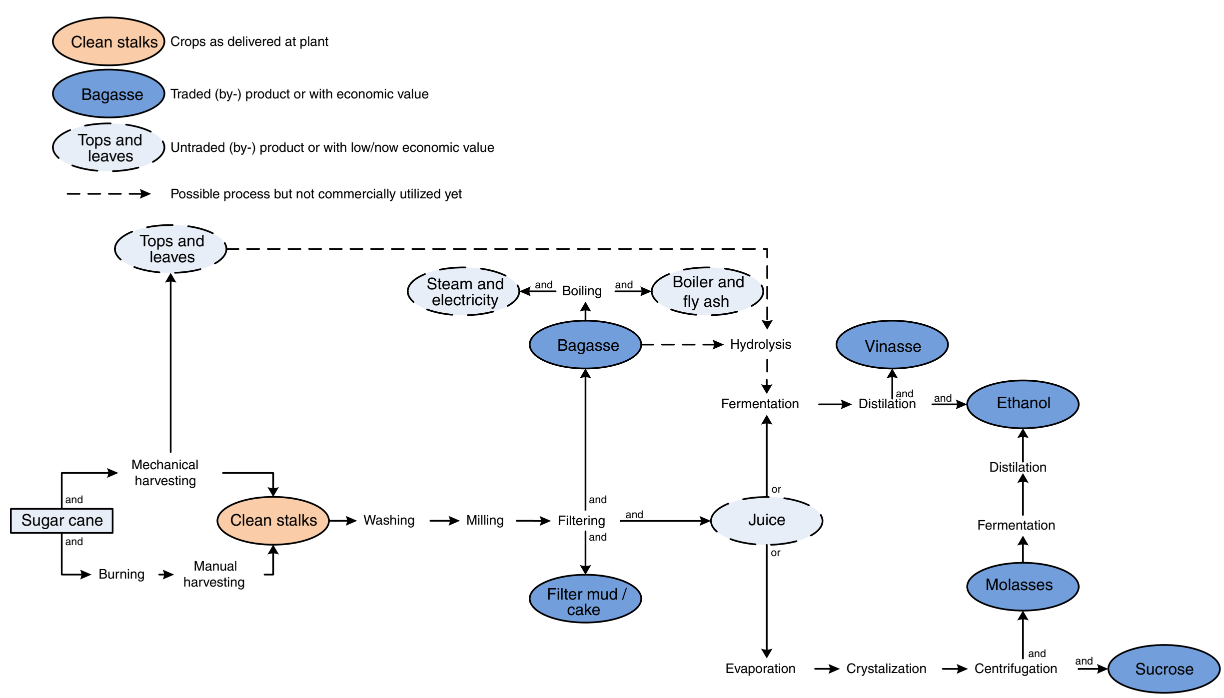

Fig. A1. The cane sugar production system.
Sources: Cornland et al. (2001), Moreira (2007), Shleser (1994), and Smeets et al. (2006).

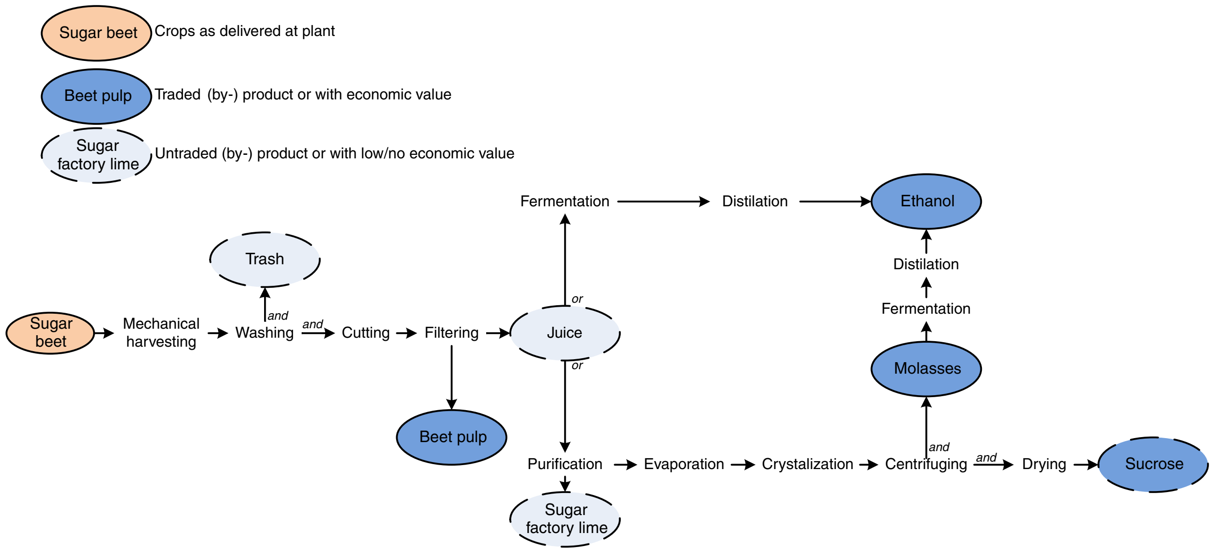

Fig. A2. The beet sugar production system.
Source: CIBE/CEFS (2003).

countries like India, Nigeria, Mexico and the Philippines have relatively great WFs, whilst developed countries like Germany, France, the US, Canada and Spain have relatively small WFs. For all three crops, Egypt almost completely relies on irrigation.

Table 1 gives the WFs for the main maize producing states in the US, as well as the US weighted average. Variation among states is small, with Nebraska and Illinois the only exceptions. Nebraska uses a relatively great amount of blue water, Illinois has a great grey WF and in this way these states influence the average US values. US values, however, are much smaller than global averages, indicating relatively favourable production and climatic circumstances.

4.2. The WF of sugar, HFMS and bio-ethanol

The WFs of sugar, HFMS and bio-ethanol are a function of crop WFs, product and value fractions and process water use (Eq. (1)). Table 2 gives the product and value fractions that determine the WF multiplication ratio. It shows that for the production of sugar or bio-ethanol, maize is the most favourable crop with a multiplication ratio of 2.0 and 4.3 respectively. Sugar cane is the most unfavourable crop, requiring more than six times the crop WF to produce sugar (m^3 per tonne) and fifteen times the crop WF to produce bio-ethanol (m^3 per tonne). Results for WFs of crops indicate that process water use is almost negligible compared to crop WFs.

5. Environmental sustainability assessment

5.1. Environmental sustainability of the blue water footprint

In eight of the twenty main sugar cane producing countries, sugar cane production requires a substantial share (5% or more) of total available blue water for agriculture. These countries are Guatemala (5%), Mexico (7%), Thailand (10%), India (13%), Egypt (23%), South Africa (25%), Pakistan (48%) and Cuba (78%). Half of the sugar beet producing countries show blue water requirements of 5% or more of total available water for agriculture in the country. These countries are France (5%), Germany (5%), Turkey (6%), Belgium (6%), Iran (6%), Poland (7%), Morocco (8%), the Czech Republic (8%), Denmark (10%) and Ukraine (12%). For maize, also half of the producing countries show blue water footprints of 5% or more of total available water for agriculture in the country. These countries are Italy (5%), China (7%), France (7%), South Africa (8%), Nigeria (8%), the US (9%), Ukraine (12%), Romania (13%), Mexico (14%) and Egypt (16%). It can be expected that in countries that rely on irrigation, e.g. in Egypt, Pakistan or India, irrigation requires a substantial share of available water. An unexpected result is that this is also the case for some western European countries that are not known as countries encountering water stress, e.g. Denmark, Belgium, Germany and France. The reason is that a great part of available water is consumed by industry, whilst eighty percent is allocated to the environment.

5.2. Hotspots

5.2.1. Dnieper basin in the Ukraine

Ukraine is a large net exporter of virtual water (Hoekstra and Chapagain, 2008; Hoekstra and Hung, 2002) with large production of sugar beet. 47% of the total sugar beet WF in Ukraine is blue water. The Dnieper is the main river in Ukraine. Agriculture uses 90% of total water consumption in Central Asia (UNECE, 2006). Surface water is overexploited for irrigation and groundwater is overused for public freshwater supply. Fig. 6 compares sugar beet growing areas in Ukraine with a map of water withdrawal-to-availability ratios,

Table 1
Green, blue and grey WFs for the main maize producing states in the US, the US weighted average values and standard deviations.

US state	Green WF m^3 per tonne	Blue WF	Grey WF
Illinois	578	5	192
Indiana	526	7	172
Iowa	553	2	177
Michigan	466	14	163
Minnesota	525	4	165
Nebraska	443	191	153
North Carolina	528	4	152
Pennsylvania	458	3	158
Wisconsin	465	3	158
US weighted average	522	63	176
US SD	±127	±63	±78

Table 2
Product fractions, value fractions and WF multiplication ratios for sugar, HFMS and bio-ethanol from sugar cane, sugar beet and maize.

Product	Product fraction	Value fraction	WF multiplication ratio
Cane sugar	0.14	0.87	6.2
Beet sugar	0.16	0.89	5.6
Maize sweetener (HFMS)	0.36	0.73	2.0
Cane bio-ethanol	0.06	0.89	14.8
Beet bio-ethanol	0.09	0.92	10.2
Maize bio-ethanol	0.15	0.65	4.3

showing main beet producing areas in central Ukraine. Areas with large water stress are on the Krim and in the south. Sugar beet areas have relatively low water withdrawal-to-availability ratios and are not located in the most water-stressed parts of Ukraine.

An important problem is water pollution (Fabry et al., 1993). Pollution in the Dnieper causes environmental damage to the Black Sea ecosystem. Besides pollution by excessive use of fertilisers, industrialization and lack of waste water treatment also influence water quality. Future impacts might include effects of climate change and the construction of dams (Palmer et al., 2008). The relatively large grey WF of sugar beet in combination with large production contributes to the total grey WF of the catchment.

5.2.2. The Ganges and Indus basins in India and Pakistan

The Ganges is the largest river of India. Although annual precipitation is locally above ten metres, periodically the basin experiences severe water stress. Studies by Rosegrant et al. (2002), Alcamo and Henrichs (2002), Alcamo et al. (2003) and Smakhtin et al. (2004) envisage 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 km^2 belong to India. For Pakistan, the Indus is the largest river. Agriculture is important in the Indus basin. Fig. 7 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. The green WF of sugar cane varies between 92 (Rajasthan) and 102 (Delhi) m^3 per tonne in an area outside the Ganges basin, and 300 (Assam) and 315 (Tripura) m^3 per tonne inside the basin in the North East of the country (Mekonnen and Hoekstra, 2010). The blue WF varies between 10 (Tripura) and 25 (Assam) on the one hand, and 169 (Delhi) and 192 (Rajasthan) m^3 per tonne. Grey WFs range between 9 m^3 per tonne in Assam and Tripura and 17 m^3 per tonne in the rest of the country. The Indian average values are 141 (green), 104 (blue) and 17 (grey) m^3 per tonne. For maize, green WFs range between 1330 (Arunachal Pradesh) and 3537 (Daman and Diu) m^3 per tonne; blue WFs between 0 (large part of India) and 453 (Karnataka), whilst grey WFs range between 156 (Assam) and 335 (Daman and Diu) m^3 per tonne. The Indian average values are 2239 (green), 103 (blue) and 195 (grey) m^3 per tonne. In India, sugar beet is not a common crop. The results for sugar cane and maize in combination with results form Table 2 show that in India sugar cane is the most favourable crop for sugar and bio-ethanol, but also that there are great differences among regions. The main sugar cane producing area in India is water scarce, showing a water withdrawal-to-availability ratio 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 with severe water stress.

From total Indus discharge in Pakistan, only a small part drains to the Arabian Sea, most water flows to canals for utilisation. Groundwater is overexploited and groundwater quality is deteriorating, causing soil salinization. Problems occur regarding maintenance of water infrastructure, governance, trust and productivity in the Pakistani part of the basin (Royal Netherlands Embassy in Islamabad, Pakistan and Netherlands Water Partnership, 2007). The large WFs for sugar cane in the water scarce Ganges and Indus basins have a negative impact on environmental sustainability.

5.3. Environmental sustainability in a global context

Globally, the production of sugar cane, beet and maize requires a small share of total green water for agriculture, 2.2, 0.2 and 2.7% respectively. The share of blue water is larger, however, 15.9, 2.1 and 11.7% respectively, indicating that the crops grown for sugar and bio-ethanol have relatively large irrigation requirements.

6. Discussion

The WF is a volumetric measure, showing freshwater consumption and pollution in time and space, providing information on how water resources are allocated to different purposes. The WF of sugar or bio-ethanol shows the 'water allocated' to that product that cannot be allocated to another product. The appropriated water volume for a process or product provides key information in the allocation discussion, but does not provide information on whether it contributes to an immediate problem of water scarcity or pollution within the catchment where it occurs. For the purpose of visualising the local impact, one will need to put the green and blue WF of a specific product in the context of the green and blue water availability in the catchment where the footprint occurs. The grey WF of a specific product in a catchment needs to be regarded in the context of the water pollution level in the catchment. It is relevant to know the size and colour of a WF, to know when and where it occurs and in which context (degree of water scarcity, water pollution level). Aggregating this information into three indices or synthesising the three into one overall index means that all information is covered. It should also be noted that the WF sustainability indices account for environmental sustainability only, not social or economic ones.

Our sustainability analysis at a hotspot level indicated that sugar cane production in India and Pakistan aggravates water stress. This is an expected result (WWF, 2005). Especially in densely populated poor developing countries, water scarcity occurs in a complex context. Water is not only needed to grow sugar cane, but also for other water intensive crops like rice, the basic staple food in India and Pakistan (FAO, 2011). Our environmental blue water sustainability assessment, however, also provided unexpected results. It showed that in some countries without hotspot areas, e.g. in western Europe, the production of sugar beet and maize takes an important share of blue water available for agriculture. This has to do with the large water requirements of industry and the allocation of water to nature. In western countries, the industrial water requirements are relatively large (AQUASTAT, 2011). When industrial water requirements in developing countries also increase, this will cause competition with agriculture, increasing water stress situations. Our analysis on a global scale showed that today, the production of crops for sugar and bio-ethanol requires a substantial share of available blue water. When more bio-ethanol is produced, this might require more blue water if production is continued along existing lines. Our analysis, however, also indicated that some countries have WFs far above global average values, indicating that there is space for more efficient production.

The US is the only country that uses maize on a large scale as feedstock for sweetener and bio-ethanol production. In the US, maize is the favourable feedstock with the smallest WF for sweetener as well as for bio-ethanol. The weighted average WF for maize in the US is 763 m^3/tonne, which is below the global average. Only in Nebraska, maize production has great irrigation requirements.

Another issue is that crops for sugar and bio-ethanol, sugar cane, sugar beet and maize grow in different climates. This means that local conditions determine which crop is grown and farmers cannot easily shift to another crop. However, the amount of water to produce a unit of product differs, in combination with water availability. This means that in order to use globally available water in the most efficient way for the production of sweeteners and bio-ethanol, also crop types and locations need to be taken into account. With respect to environmental sustainability, there are more aspects than water alone. Environmental impacts also include impacts on soil health, e.g. compaction, erosion, salinisation and acidification, impacts on biodiversity, e.g. habitat destruction for cane cultivation, impacts of intensive use of chemicals, and air pollution, e.g. caused by pre-harvest burning around sugar cane fields (Cheesman, 2004; WWF, 2005). We focused on the water perspective of sweeteners and bio-ethanol production, which can be used to formulate better management practises for sugar cane, beet and maize production. With annual production expanding (WWF, 2005), better practises are needed.

The study made several assumptions. First, we used the allocation method of Hoekstra and Chapagain (2008) based on product fractions and value fractions, resulting in WFs depending on fluctuating world product prices, giving fluctuating WFs. The study therefore took average prices for 1996–2005. Second, this study assumed small process water use. With large variation in literature on process water use (e.g. Cheesman, 2004), modern industry recycles water and reduces use to almost zero. For the grey WF, process water recycling and waste water treatment are important. We assumed industry recycles process water and does not release waste water, probably underestimating process water use. The assumption does not have a large impact on results, because process water use is small compared to total WFs.

When compared to earlier studies, our results fall in the ranges found earlier. For the US, Dominguez-Faus arrived at a water requirement for bio-ethanol between 500 and 4000 l per litre bio-ethanol. Chiu et al. (2009) indicated that bio-ethanol's water requirements range from 5 to 2140 l irrigation water per litre bio-ethanol.

7. Conclusions

The weighted global average WF of sugar cane is 209 m^3/tonne, and ranges between 120 and 410 m^3/tonne, of sugar beet 133 m^3/tonne (ranges between 37 and 446 m^3/tonne) and of maize 1222 m^3/tonne, (ranges between 566 and 2537 m^3/tonne). The large ranges in WFs indicate that there is ample room to improve WFs of crops for sugar and bio-ethanol and use water more efficiently. In general, it is more favourable to use maize as a feedstock for sweeteners or bio-ethanol than sugar beet or sugar cane. This is expressed in the WF multiplication ratio, the factor applied to convert crop WFs to product WFs. For sugar, the multiplication ratio is 2.0 for maize and 5.6 and 6.2 for sugar beet and sugar cane. For bio-ethanol, the ratio is 4.3 (maize), 10.2 (sugar beet) and 14.8 (sugar cane).

Differences in WFs are mainly caused by two variables, crop water requirements and yields. Crop water requirements show variation and depend on factors such as crop type, climate and soil characteristics. Some countries, for example Egypt, depend on irrigation, whilst other countries, for example Japan growing sugar beet, have small irrigation requirements. The yield levels differ between countries because of growing conditions and agricultural practises. All WF estimates are based on current conditions, so they do not reflect what is technologically possible. Many of the large WFs can probably be reduced with better practises.

In general, grey WFs are about ten percent of total WFs and contribute to water pollution. In some countries, however, grey WFs of maize-based products contribute to twenty percent of total WFs. At present, water stress is a problem in many parts of the world. 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 quality in major river basins, such as the basins of the Dnieper, where especially the grey WF contributes to water pollution. In some western European countries, blue water requirements for sugar beet and maize are large compared to available blue water. This is caused by large industrial and environmental water requirements. The globe's water resources are limited and allocation of water to bio-ethanol on a large scale will be at the cost of water allocation to food and nature. In the light of increased interest for biofuels, the availability of sufficient water to produce sweeteners and bio-ethanol forms a great challenge.

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Appendix A. Allocation of WF over economically valuable crop parts

For sugar cane, beet and maize, the FAOSTAT database provides annual yields. For maize, the FAO (2011) gives grain yields. We calculated WFs based on economically valuable crop parts. Stover forms 56% of the total maize crop and has economic value. We therefore included stover and estimated total maize yields by: $Y(c) = y(c) + stover$, where $y(c)$ is the maize yield (FAO, 2011) and $stover$ is $56/44 * y(c)$. Yield data $y(c)$ were derived from the FAO (2011) and data on US maize yields from the USDA/Agricultural Statistics Service (2008). Sugar cane, beet and maize provide sugar, bio-ethanol and byproducts, e.g. stover and bagasse. For sugar cane, information is available from Allen et al. (1997), for sugar beet from Kranjc et al. (2006). Each product or byproduct has a market price (US$/tonne) and contributes to market prices of root products. To calculate average value fractions, we derived data from UNCTAD/WTO (2007).

Filter cake and vinasse are often used as fertiliser, reducing other fertiliser use by 50% (Leal, 2005; Moreira, 2007). We determined filter cake and fertiliser values. For the calculation of the WF of bio-ethanol from sugar cane, the study assumed similar values for filter cake and vinasse. The US Department of Agriculture (USDA/Economic Research Service, 2006) estimated total fertiliser costs for sugar cane at US$100 per hectare for 1996–2005. With vinasse and filter cake application, this is US$50, giving a value for filter cake and vinasse of US$50 ($25 per hectare for filter cake and $25 for vinasse). Application rates of 2600 kg filter cake/ha and 1635 kg vinasse (dry matter)/ha give filter cake values of US$10/tonne and US$15/tonne for vinasse. We also used filter cake values for assessing value fractions in sugar production. For bio-ethanol by-products from sugar cane, the study used similar values.

We derived price data from the SITA-database of the International Trade Centre (UNCTAD/WTO, 2007). For the six main producing countries, we calculated average export prices for 1996–2005. For each exporter the countries that together account for more than 80% of total export were used to calculate (by) product values. When less than three countries account for 80% of the export, a minimum of three importing countries was used. When for a country no data were available, the study estimated an average value fraction to estimate a global value. When SITA data were unavailable, the study used other sources. For cane sugar and molasses, prices derive from SITA export prices. The study assessed bagasse values from amounts of energy produced by burning to generate electricity and steam. Several studies (Leal, 2005; Mohee and Beeharry, 1999; Paturau, 1989) indicate energy production between 360 and 510 kWh per tonne bagasse. Using average prices of 0.04 US$/kWh, the study calculated the bagasse value fraction.

SITA excludes bio-ethanol. We used averages of current and expected prices from FAPRI (2008). The study based bio-ethanol prices on average US (US$ 0.51) and Brazilian prices (US$ 0.37), giving an average of US$0.44. Sugar is the most valuable product of beet processing. According to ISR (2005), total values of by-products (molasses, beet pulp and lime) are €14 per tonne beet, corresponding to SITA market values on which we based value fraction calculations. For bio-ethanol production from beet, we included one by-product, beet pulp. Data on bio-ethanol values from sugar beet and cane came from FAPRI (2008). Sugar beet pulp values derived from the USDA (2006) (US$6 per tonne) and ISR (2005) (molasses, beet pulp and lime €14 per tonne). We estimated beet pulp values at US$10 per tonne. Value fractions of maize based bio-ethanol and HFMS's by-products derived from the USDA cost of production survey (Shapouri and Gallagher, 2005). The HFMS 55 value derived from average US Midwest prices from the Economic Research Service/USDA (2009). Prices of maize gluten meal, maize gluten feed, crude maize oil, DDGS and HFMS 55 are available for 2000–2003. This study took stover into account because it represents an economic value for farmers reducing fertiliser application. 5% of the stover is used for animal bedding and feed (ILSR, 2002).

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