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# The water footprint of sugar and sugar-based ethanol

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# Summary

The two most cultivated sugar crops are sugar cane and sugar beet. For centuries both crops have been used for the production of sucrose, generally known as table sugar. During the past decades, bio-ethanol production from sugar crops has become competitive with sugar production. In the USA High Fructose Maize Syrups (HFMS) and maize-based ethanol are two substitutes for sugar and sugar crop-based ethanol. Crop production in general, and sugar cane production in particular, requires a lot of water. The aim of this study is to calculate the water footprint of sugar, HFMS and bio-ethanol in the main producing countries, to identify favourable production areas and possibilities, and to assess the impact on the water system in certain production areas.

For sugar cane there are two major producers, Brazil and India, contributing respectively 29% and 21% to the global production. Sugar beet is mainly cultivated in the USA, which produces 11% of global production, and Europe, with France (13%), Germany (10%), the Russian Federation (7%), Ukraine (6%) and Turkey (6%) are the main producers. The USA is by far the largest maize producer, contributing 40% to global production. Sugar cane in Brazil is used for both sugar and bio-ethanol production. India's sugar cane is mainly used for the production of sugar. Worldwide, sugar beet is mainly used for sugar production and ethanol production is still limited. Maize from the USA is used for both HFMS and bio-ethanol production.

The water footprint is used here as indicator of water consumption in the full production chain of sugar or ethanol production. The water footprint consists of three components. The green water footprint is the amount of precipitation that is stored in the soil and consumed by crops during the growing season by evapotranspiration. The blue water footprint is the amount of fresh water that is extracted from ground- and surface water used for irrigation as well as the amount of water used in processing the crop. The grey water footprint is the amount of water needed to dilute pollutants to an acceptable level, conform exiting water quality standards.

There is a large variation in the water footprint of sweeteners and ethanol produced from sugar beet, sugar cane and maize between the main producing countries. The water footprint of sugar produced from sugar cane varies between 870 $m^3$ water /ton of sugar produced in Peru and 3340 $m^3$/ton in Cuba. The water footprint of cane sugar for the main producing countries is 1285 $m^3$/ton in Brazil and 1570 $m^3$/ton in India. The weighted global average is 1500 $m^3$/ton. The water footprint of beet-based sugar varies between 425 $m^3$/ton in Belgium and 1970 $m^3$/ton in Iran. The main producing countries show water footprints of 545 $m^3$/ton in France, 1025 $m^3$/ton in the USA, 580 $m^3$/ton in Germany, 1430 $m^3$/ton in the Russian Federation and 1900 $m^3$/ton in the Ukraine. The weighted global average is 935 $m^3$/ton. The water footprint of HFMS 55 produced in the USA, world's largest producer, is 740 $m^3$/ton. The global average water footprint of HFMS 55 is 1125 $m^3$/ton.

The water footprint of ethanol shows similar differences between countries. The water footprint of cane-based ethanol varies between 1670 litre of water/litre of ethanol produced in Peru and 6355 l/l in Cuba. The water footprint in Brazil is 2450 l/l, in India 2995 l/l and 2775 l/l in the USA. The weighted global average is 2855 l/l. The beet-based ethanol water footprint varies between 490 l/l and 2570 l/l in Belgium and Iran. The water footprint of the main producers is 615 l/l in France, 1173 l/l in the USA, 645 l/l in Germany, 1705 l/l in the

Russian Federation and 2370 l/l in the Ukraine. The weighted global average water footprint of beet-based ethanol is 1355 l/l. The water footprint of maize-based ethanol in the USA is 1220 l/l. The weighted global average water footprint of maize-based ethanol is 1910 l/l.

For the calculation of the grey water footprint international drinking water standards for nitrogen, used in the USA and Europe and by the WHO, have been applied. The contribution of the grey water footprint to the total water footprint is limited. A brief study is performed to the impact of the implementation of some national Dutch standards for a healthy ecosystem on the grey water footprint. The impact of those more strict standards, available for two nutrients and agrochemicals, on the grey and total water footprint is enormous. No international accepted standards for ecology however are available at present.

The impact of the water footprint of sugar crops is assessed for the Indo-Gangetic basin in India, where sugar cane is an extensively cultivated crop as well as for the area north of the Black and Caspian Sea, where a lot of sugar beet is cultivated. Water consumption by sugar cane contributes for a considerable part to the water stress in the Indus and Ganges basins. Future developments in demography and industry, as well as climate change, will stress the basins even more. Agriculture, and especially the cultivation of thirsty crops, will put even more pressure on water resources. Although water stress is increasing in the Black and Caspian Sea area, the main problem with the rivers feeding both seas, Dnieper, Don and Volga, is pollution. Many tributaries and reservoirs, as well as the Black Sea ecosystem, are heavily polluted by contaminants from industry and excessive fertilizer application. Sugar beet, as one of the major crops in the area, shows a relatively big grey water footprint and is one of the contributors of pollution.

## List of abbreviations

| | |
|---|---|
| CWR | Crop Water Requirements |
| DDGS | Distillers Dried Grains with Solubles |
| EWR | Environmental Water Requirement |
| EPA | Environmental Protection Agency |
| EU | European Union |
| $f_v[p]$ | Value fraction of product *p* |
| $f_p[p]$ | Product fraction of product *p* |
| HFMS | High Fructose Maize Syrup |
| HFMS 42 | High Fructose Maize Syrup with 42% fructose and 5% glucose |
| HFMS 55 | High Fructose Maize Syrup with 55% fructose and 45% glucose |
| HFS | High Fructose Syrup |
| HIS | High Intensity Sweeteners |
| IFA | International Fertilizer Industry Association |
| MCL | Maximum Contamination Level |
| PWU | Process Water Use |
| WCL | Water Competition Level |
| WF | Water Footprint |
| WSI | Water Scarcity Indicator |
| WtA-ratio | Withdrawal-to-availability ratio |

U.S. states

| | |
|---|---|
| IA | Iowa |
| IL | Illinois |
| IN | Indiana |
| MI | Michigan |
| MN | Minnesota |
| NC | North Carolina |
| NE | Nebraska |
| PA | Pennsylvania |
| WI | Wisconsin |

# 1 Introduction

Sugar is a frequently discussed commodity. One of the reasons is that sugar crops, along with cotton, rice and wheat, are some of the thirstiest crops (WWF, 2003); water intensive crops that consume a large amount of water during their growth period. Table sugar, or sucrose, is made out of sugar cane and sugar beet, neglecting the small part produced from sweet sorghum and sugar palm. However, there are many other sweeteners that are used for our food production. Two examples are High Fructose Maize Syrups (HFMS) and artificial or high intense sweeteners.

A useful indicator to express the water use for the production of commodities is the Water Footprint (WF) as introduced by Hoekstra (2002). The WF of a commodity is defined as the total volume of freshwater that is used during the production process. For agricultural commodities water use mainly consists of water consumption by crops during growing period and grey water which is the volume of water needed to dilute a certain amount of pollution such that it meets ambient water quality standards (Hoekstra and Chapagain, 2008). The water consumed during the growing season consists of a green and a blue component. Green water refers to evaporated rain water, while blue water refers to the amount of ground- or surface water used for irrigation. Another part of the blue water footprint is the amount of process water used which is generally limited compared to evapotranspiration and irrigation extractions. This study uses the WF to determine water consumption for the production of sugar from sugar cane and sugar beet.

Sugar crops are not only usable for the production of sugar but are a feedstock for ethanol production as well. With an increased demand of this bio-fuel an interesting agricultural point of friction has arisen. Another crop that offers opportunities for both sweetener and bio-ethanol production is maize. In the USA maize is widely used for both production of HFMS and bio-ethanol. Hoekstra and Hung (2002) made a first estimation of the water needed to produce crops in different countries of the world. In subsequent studies, like those to coffee and tea (Chapagain and Hoekstra, 2003), cotton (Chapagain et. al, 2006) and a MsC-thesis to rice (Mom, 2007), more specific data on growing locations and production methods have been taken into account in calculating the WF of crops and the derived commodities. Furthermore the WF is used in a global study by Gerbens-Leenes et al. (2008) to water use for the production of bio-energy. This study assesses the water use of sugar cane, sugar beet and maize that are all suitable for both sweetener and bio-ethanol production.

First, in chapter 2, this thesis will discuss sweeteners for human consumption. The sugar crops and maize are studied regarding share in global production and the production processes are explained. The production of bio-ethanol from sugar crops and maize is discussed in chapter 3. Chapter 4 is dedicated to the method of approach, used for the calculation of the water footprint of sugar and ethanol. Furthermore data sources used for those calculations are dealt with. In chapter 5 the WF of sugar and bio-ethanol is presented on the basis of the main production areas worldwide. Finally, in chapter 0, the impact of the WF of sugar beet and sugar cane on the natural water resources in two main production areas is assessed. Conclusions are drawn in chapter 7 and chapter 8 is used for discussion.

## 1.1 Objectives

Figure 1 represents a simplified system of global sweeteners and bio-ethanol production that will be assessed during this study. For the production of sweeteners and bio-ethanol several resources are available. Water is one of those resources and will form the basis of this study. There are three major ways to produce sweeteners for human consumption and two major ways of producing bio-ethanol. As mentioned, this study will focus on the cultivation of sugar crops for the production of sugar, taking into account opportunities of artificial sweeteners and high fructose maize syrups, as substitute for sugar. As can be seen in Figure 1, worldwide, sugar crops are by far the most important feedstock for sweeteners. The main feedstocks for ethanol are sugar crops as well. The water footprint is used as indicator for the suitability of the ‘production routes’ available in Figure 1

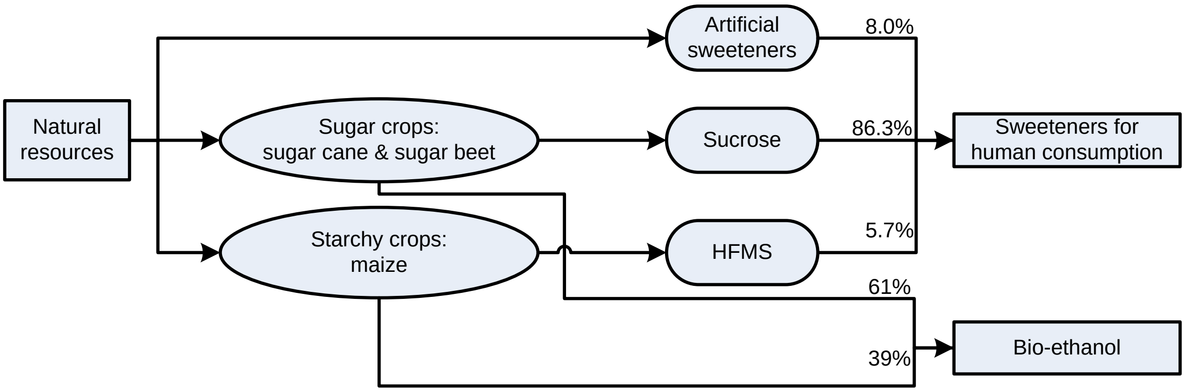

*Figure 1. Sweetener and energy crop system for food and bio-ethanol production (sources: Berg (s.a), ISO (2007), Van der Linde et. al (2000) and Campos (2006)).*

The study has three objectives:

1. To calculate the water footprint of sweeteners for human consumption and bio-ethanol produced from sugar crops and maize for the main producing countries and districts, divided by green, blue and gray water.
2. To assess which production lines, considering Figure 1, and locations to use.
3. To assess the impact of the water footprint of the production of sugar crops on the natural water resources at some of the main production areas.

In this report, unless mentioned else, ethanol refers to bio-ethanol, sugar to sucrose and sweeteners to the total of sucrose, high fructose maize syrups and artificial sweeteners.

# 2 Sweeteners for human consumption

The word sugar is used in many ways. In daily usage, sugar refers to sucrose, also called saccharose ($C_{12}H_{22}O_{11}$), a carbohydrate made up of a molecule of glucose and a molecule of fructose, which makes it a disaccharide. This kind of sugar is also referred to as table sugar. Scientifically, sugars (saccharides) are a family of naturally occurring carbohydrate compounds, produced by plants through the process of photosynthesis (Cheesman, 2004). Chemically all saccharides are principal components of the class of carbohydrates (Coultate, 1989). This study will restrict to those components that are used most for food and ethanol production.

Fructose ($C_6H_{12}O_6$) is a monosaccharide (hexose) and is found naturally in honey and fruits. Pure fructose is produced from sucrose. Furthermore fructose is found in high fructose syrups, mainly produced from maize. Glucose ($C_6H_{12}O_6$) is another monosaccharide and is commercially known as a mixture of glucose, dextrose and maltose. Although many other types of carbohydrates exist this study will focus on sucrose and combinations of glucose and fructose. Sucrose is referred to as sugar, while a combination of glucose and fructose is defined as high fructose (maize) syrup.

Sugar is made from sugar cane and sugar beet and to a very small extent from sweet sorghum and sugar palm. Chemically, sugar produced from cane and beet is the same. Approximately 70% of global sugar consumption is produced from sugar cane, and the remainder from sugar beet. High fructose syrups (HFS) are produced from starchy crops, mainly maize. The sweetness of HFS depends on the composition. HFS is a mixture of fructose and glucose of which glucose is less sweet than sucrose and fructose twice as sweet as sucrose. A blend of 55% fructose and 45% glucose (HFMS 55) most closely duplicates the flavour of sucrose (Ensymm, 2005). Another frequently used blend is HFMS 42. A third kind of sweeteners are (low or non-caloric) artificial sweeteners or High Intensity Sweeteners (HIS). These sweeteners are up to 8000 times as sweet as sugar. In paragraph 2.2 sugar and sugar crops are discussed, paragraph 2.3 discusses high fructose (maize) syrups and paragraph 2.4 deals with artificial sweeteners.

## *2.1 Global sweetener production and consumption*

Although the use of HFMS’ is increasing fast compared to sugar consumption, sugar is still the most used sweetener worldwide. In the USA, the calories consumed per capita from HFMS have almost equalled sugar consumption (USDA/ERS, 2007). In the rest of the world HFMS consumption is still limited, but yet increasing. Based on studies performed by the Netherlands Economic Institute (Van der Linde, 2000), Campos (2006) and the International Sugar Organisation (2007) an estimation of global consumption of sweeteners is made and presented in Figure 2.

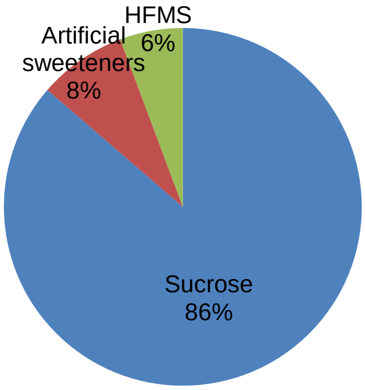

*Figure 2. Percentage of global sweetener consumption in sugar equivalent (Source: Van der Linde, 2000; Campos, 2006; ISO, 2007).*

The main sugar producing countries are Brazil, producing 20.8% of total global sugar, India (14.7%), the European Union (11.9%), China (7.0%), U.S.A. (4.6%), Thailand (3.7%), Mexico (3.6%) and Australia (3.1%) (ISO, 2007). Table 1 shows the production of sugar, divided by sugar cane and sugar beet.

*Table 1. Main sugar producing countries, divided by sugar cane and sugar beet, as percentage of global sugar production (Source: FAOSTAT, period: 2001 -2006)*

| **Cane sugar** | | **Beet sugar** | |
|---|---|---|---|
| **Country** | **Percentage** | **Country** | **Percentage** |
| Brazil | 23.5 | France | 12.1 |
| India | 16.9 | United States of America | 11.6 |
| China | 8.6 | Germany | 11.5 |
| Thailand | 5.6 | Russian Federation | 6.2 |
| Mexico | 4.7 | Turkey | 5.9 |
| Australia | 4.5 | Poland | 5.6 |
| Pakistan | 3.0 | Ukraine | 5.5 |
| United States of America | 3.0 | United Kingdom | 4.1 |
| Russian Federation | 2.9 | Italy | 3.6 |
| Cuba | 2.3 | Netherlands | 3.0 |

Asia is the largest sugar producer (Table 2) as well as the largest importer (Table 3). South and Central America and Oceania are the only net exporters. The import and export of sugar, or any other commodity, is directly related to the import and export of virtual water (Hoekstra, 2008). Therefore the international trade in sugar (and ethanol) is of interest for this study.

*Table 2. Main sugar producing continents as percentage of global sugar production (FAO, 2001-2006)*

| Continent | Percentage |
|---|---|
| Asia | 33 |
| Latin America & Caribbean | 32 |
| Europe | 19 |
| Africa | 7 |
| Northern and central America | 5 |
| Oceania | 4 |

*Table 3. Sugar imports and exports per continent in tons in 2006 (Source: ISO, 2007)*

| Continent | Imports | Exports | Export - Import |
|---|---|---|---|
| South America | 1126515 | 21659588 | 20533073 |
| Oceania | 286582 | 4428787 | 4142205 |
| Central America | 1351589 | 4266769 | 2915180 |
| Europe | 8298905 | 8054169 | -244736 |
| North America | 4173277 | 367669 | -3805608 |
| Africa | 7740579 | 3164973 | -4575606 |
| Adjustment for unknown trade | 4792200 | 0 | -4792200 |
| Asia | 21705578 | 7616886 | -14088692 |

## 2.2 Sugar

### 2.2.1 Sugar cane

Sugar cane is a tropical, C4 plant which belongs to the grass family. C4 plants have a more efficient photosynthesis pathway than C3 plants and are capable of generating carbohydrates at a higher rate. C4 plants grow well with sufficient sunlight and warm temperatures (25 -30˚C). Sugar cane, in contrast to other C4 plants, needs plentiful of water. The growth period of sugar cane is 12 months on average (Cheesman, 2004; Patzek et al., 2000). Brazil is the largest producer of sugar cane, covering 29% of yearly total global sugar cane production (Figure 3). Sugar cane in Brazil is used for both sugar and ethanol production. In India sugar cane is mainly used for the production of sugar.

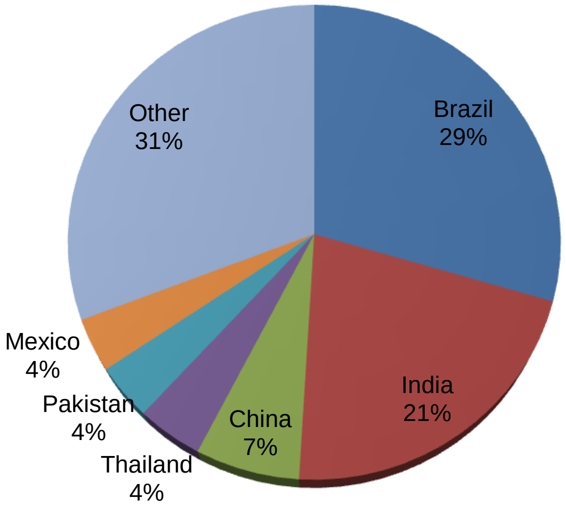

*Figure 3. Percentage of global sugar cane production (Source: FAOSTAT, 2008, period: 1998-2007)*

Table 4 presents the share in global production of sugar cane of the main producing countries, as well as their share in cane sugar and ethanol production. Brazil is obviously a large producer of both sugar and ethanol. India has a large share in global cane sugar production, but a very small share in global ethanol production. The USA is a large ethanol producer, but, as can be seen sugar cane is not a very common feedstock, since the U.S. share in global sugar cane production is limited. The main feedstock for U.S. ethanol production is maize.

*Table 4. Sugar cane, cane sugar (Source: FAO, 2001-2006) and ethanol (F.O. Licht, 2005) production as percentage of global production.*

| Country | Global sugar cane production (%) | Global raw cane sugar production (%) | Global ethanol production (%) |
|---|---|---|---|
| Brazil | 30 | 24 | 32 |
| India | 21 | 17 | 1 |
| China | 7 | 9 | 3 |
| Thailand | 4 | 6 | 1 |
| Pakistan | 4 | 3 | - |
| Mexico | 4 | 5 | - |
| Colombia | 3 | 2 | - |
| Australia | 3 | 5 | - |
| United States of America | 2 | 3 | 43 |
| Indonesia | 2 | 2 | - |

- : less than 1%

#### *2.2.1.1 Production process*

Figure 4 shows the production process of sugar and sugar-based ethanol. The process is based on several studies on sugar cane processing (Cornland, 2001; Moreira, 2007.; Shleser, 1994; Smeets, 2006; Silva, 2006). The dark blue ellipses are traded (by-) products for which value fraction are determined. The orange ellipse represents the harvested crops as delivered at the plant and on the basis of which the product fractions of the (by-) products are determined.

In many countries where sugar cane is grown, labour is cheap so cane is harvested manually. Before harvest, most leaves are removed by controlled burning. Removing tops and leaves on the field, decreases transportation costs and work at the mill. Some plantations use mechanical harvesting, which means tops and leaves have to be removed at the mill and are often brought back on the field as fertilizer, are burned for the generation of steam and electricity or are used as animal feed. The stems consist of cellulose and hemicelluloses. In those components the sugar is captured. Furthermore the stem consists of lignin which gives the plant its strength. At the plant the clean millable stalks are chopped into pieces and washed to remove trash. After washing, the cane pieces are crushed in a mill. The substance that is created is filtered, which results in juice and a fibrous residue, bagasse. The remainder in the filter is called filter cake or filter mud.

The bagasse is often burned in order to produce steam and electricity that is used for the production process. In modern equipped plants some 450 kWh of electricity can be produced per tonne of mill-run bagasse (Paturau, 1989). Although there is a wide range in energy generation due to different combustion methods, nowadays this is still a good average value of energy produced. The filter cake is often brought back to the land and serves as fertilizer. The juice that remains after filtering can be used for the production of ethanol or sugar.

Sugar is extracted by first evaporating the juice. Subsequently the syrup is then crystallized by either cooling or boiling crystallization. What remains are clear crystals (sugar) surrounded by molasses. Molasses is the residual syrup from which no crystalline sugar can be obtained by simple means. The molasses are removed by centrifugation and can be used for several purposes, after some treatment. More regular in mixed plants in Brazil, molasses is used for the production of ethanol. Otherwise molasses can be used to produce yeast, animal feed, fertilizer, rum, ethyl alcohol, acetic acid, butanol/acetone, citric acid, and monosodium glutamate (Paturau, 1989). For what purpose molasses are used varies per country and mill and so does the value of molasses.

By following the other production line, juice can be used for the production of ethanol. The juice is first fermented, often with molasses-based yeast or together with molasses, and subsequently cooled to maintain a fermented wine mixture. After fermentation the ethanol is distilled from another by-product, vinasse. This results in hydrous ethanol, approximately 95% pure and anhydrous ethanol that is nearly 100% pure.

Until now, the first-generation feedstocks sugar and starch are used worldwide to produce ethanol. Not common in commercial plants yet is the use of second-generation feedstocks. Second-generation feedstocks are lignocellulosic by-products (tops and leaves and bagasse) that can be converted into ethanol by hydrolysis. During this process the polysaccharides in the lignocellulosic biomass are converted to sugar by saccarification (hydrolysis) and subsequently fermented to ethanol.

#### *2.2.1.2 Process water use*

Macedo (2005) claims water use for a sugar cane mill with an annexed distillery to be 21 $m^3$ per ton of cane processed. Thanks to recycling and some changes in the production process water use has decreased enormous. In a survey conducted in 1997 at 34 mills in Brazil, water consumption was indicated at 0.92 $m^3$/t cane. The São Paolo State Plan on water resources estimated water use in 1990 at 1.8 $m^3$ per ton of cane. Since Process Water Use (PWU) is very small compared to water consumption during the growing period of sugar cane, it is not taken into account in the calculation of the WF. Waste water used to be a big problem with sugar cane processing (Cheesman, 2004). Although there are still big differences in waste water release per factory, treatment has improved enormously during the past decades. In Brazil regulations and standards for waste water release have aggravated and supervision is increased. Therefore waste water release is not taken into account in calculating the grey WF.

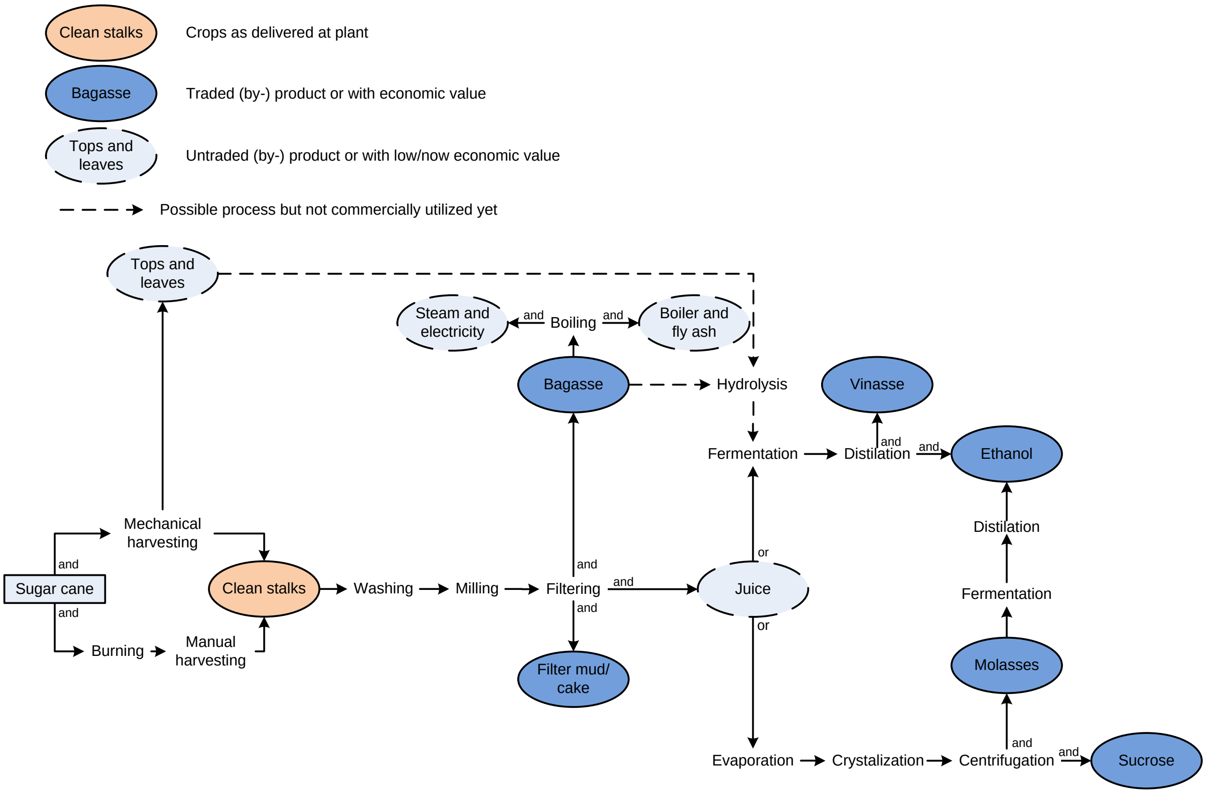

*Figure 4. Sugar cane production tree (source: Cheesman, 2004 and Quintero et. al., 2008).*

### 2.2.2 Sugar beet

Sugar beet is a root crop and cultivated mainly on the northern hemisphere in a temperate climate. It has a relatively long growing season for an annual plant. It is sown in spring and harvested in autumn. The time of harvest is of great influence on the sugar content. Main producers are the EU, the USA, the Russian Federation, Turkey, Ukraine and China (Figure 5). Although sugar beet has the highest yield of ethanol per hectare (Rajapogol, 2007), the use of sugar beet for ethanol is still limited compared to sugar cane. Sugar beet is mainly used for sugar production.

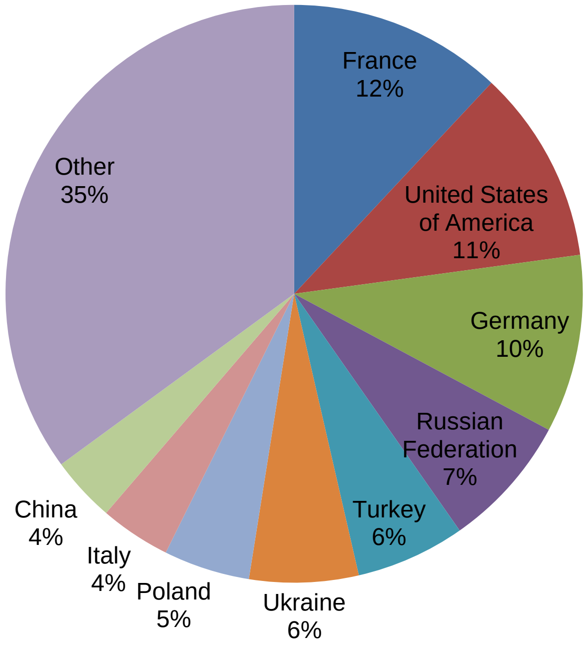

*Figure 5. Percentage of global sugar beet production (FAOSTAT, period: 1998-2007).*

#### 2.2.2.1 Production process

Although seemingly different crops, the production processes of sugar cane and sugar beet show many correspondences. Also by-products originate at the same moment in the production process and can be used for similar purposes. The production process as described below is a theoretical process based on several studies (Cheesman, 2004; Vaccari et al., 2005; Henk et al., 2006; CIBE & CEFS, 2003). Again, dark blue ellipses represent products with considerable economic value and the orange ellipse is the crop as delivered at the sugar beet factory for processing.

The bottom production line in this figure represents the main production phases for sugar production, where molasses is used for ethanol production. The top production line displays the direct production of ethanol from juice. The trash (i.e. leaves, sand en stones, from sugar beets) is to a large extent removed on the field and the leaves are used as natural fertilizer. The other part of trash is removed during the washing of the beets. After being cut into slices, warm water is added to the sugar beet shavings and the juice is extracted by filtering the beet diffusion juice. The juice can now be treated for the extraction of sugar or the production of ethanol

For the production of sugar, the juice is purified using lime and carbon dioxide. The juice is subsequently thickened by evaporating the water. The mixture is heated to approximately 80˚C to crystallize the sucrose. Finally the fill mass, which is the crystals with some liquor, is centrifuged to separate the crystals from the molasses. The crystals are dried to remain the pure sucrose.

In contrast to sugar cane, at present not many sugar beet plants are purely established as ethanol plant. For most factories sugar production is core business. If ethanol is produced it is extracted from beet molasses by a process of fermentation and distillation. Another way of ethanol production from sugar beet is by direct fermentation of sugar beet juice, just like with sugar cane. Figure 6 shows the two pathways of ethanol production.

### *2.2.2.2 Process water use*

Most water in sugar beet processing is involved in washing the beets. Like sugar cane, plants have invested in water recycling and waste water management. Vaccari et al. (2005) assumes water consumption in older sugar beet plants ranges from 2.5 up to 4.5 $m^3$/t beet processed. New, modern equipped plants with good waste water treatment are able to use water very efficiently en even eliminate fresh water intake. Cheesman (2004) refers to Fornalek (1995) who explains water use in a Polish plant reduced to 10 $m^3$/ton sugar (approximately 1.5 $m^3$/t beet) and to Polec and Kempnerska-Omielczenko who report water use has declined to 1.1 $m^3$/ton beet. Since those values are very small compared to water consumption of sugar beet during its growth period, it is not taken into account in calculating the WF.

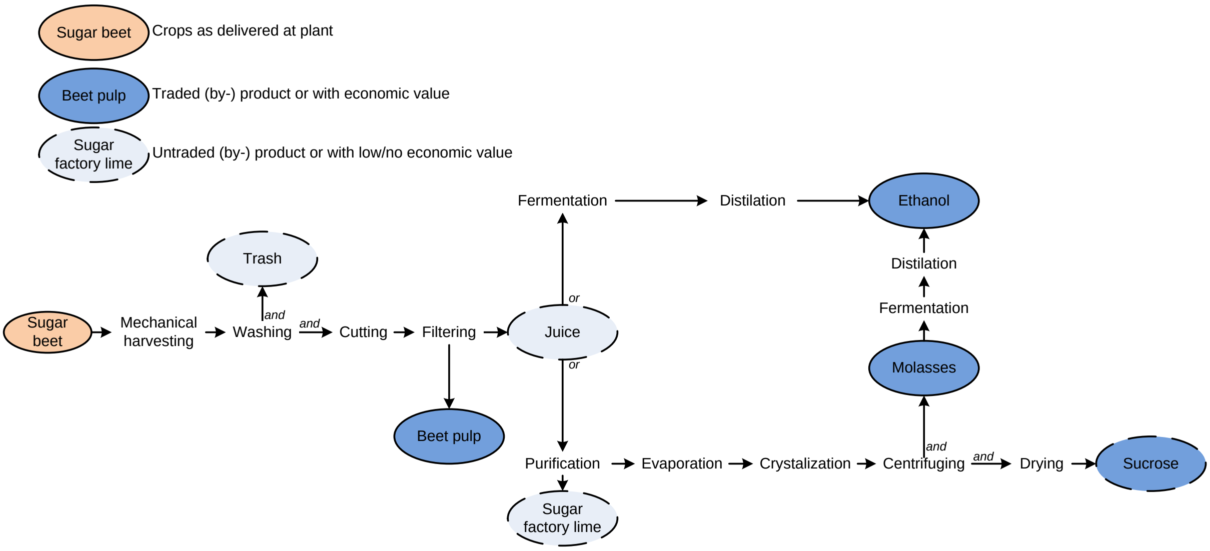

*Figure 6. Sugar beet production process (Source: CIBE and CEFS, 2003)*

## 2.3 High fructose syrups

Since the beginning of the seventies of the last century the consumption of High Fructose Maize Syrups (HFMS') has increased enormously in the USA. At the same time, cane and beet sugar consumption has decreased significantly. A smaller amount of yearly caloric sweetener consumption is ascribed to dextrose and glucose produced from maize. Figure 7 shows total maize sweetener consumption has surpassed cane and beet sugar consumption. Although European countries show similar developments, HFMS consumption has not shown such an explosive growth. In other parts of the world, sugar is also still by far the largest caloric sweetener.

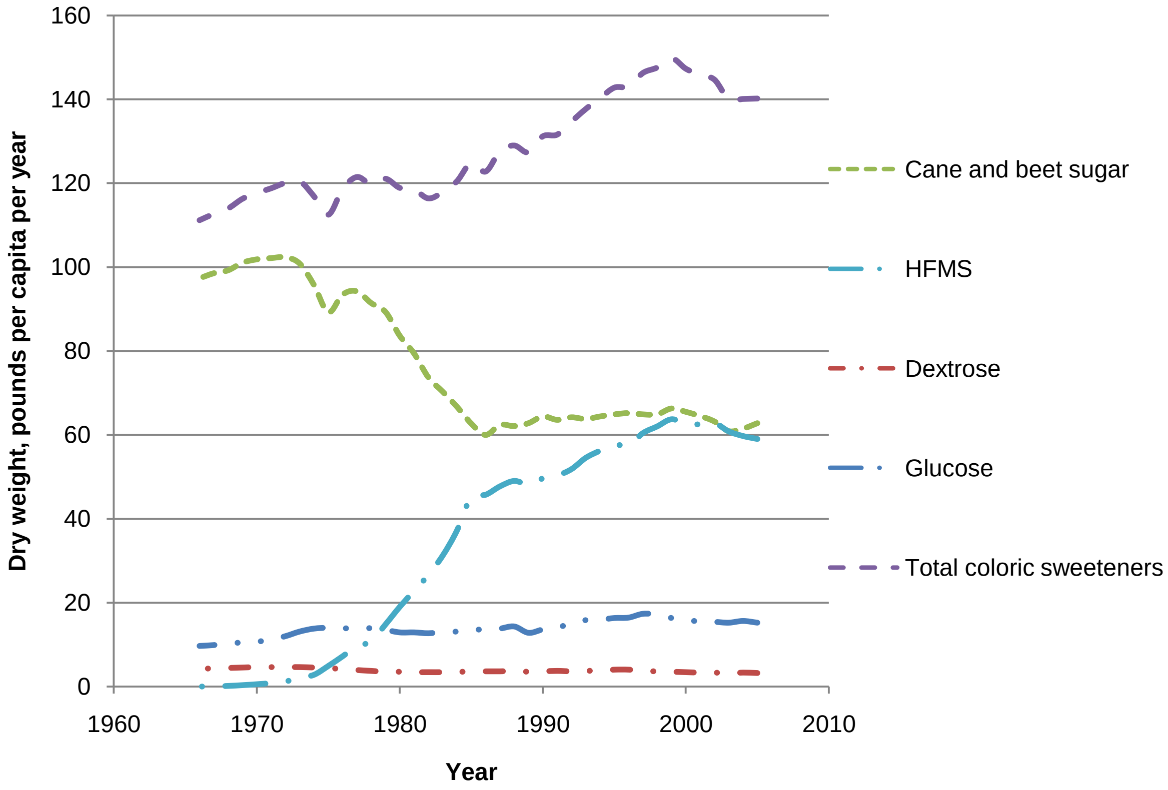

*Figure 7. USA per capita caloric sweetener consumption (Source: USDA, 2008)*

### *2.3.1 Maize*

Maize, like sugar cane, is a C4 plant and part of the grass family. Different kinds grow well in both moderate and sub-tropical climates. It is the most extensively grown crops in North and South America. Another important producer is China (Figure 8).

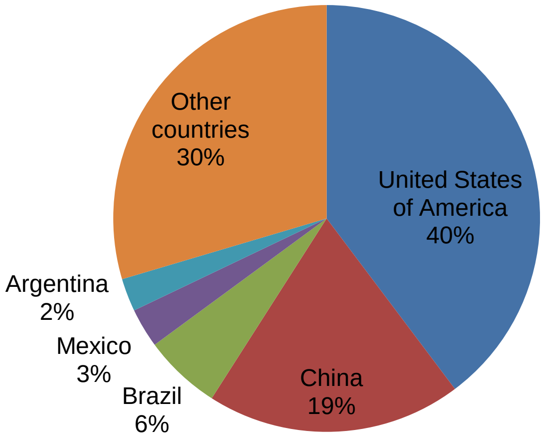

*Figure 8. Percentage of global maize production (Source: FAOSTAT, 2008, period: 1998-2007)*

Maize is utilized for many products. The starch in the grains is used for many purposes, of which one is the conversion into sweeteners. Although HFMS production and consumption has increased considerably during the last decades, its production has stabilized during the last years (Figure 9). On the other hand production of maize-based ethanol has increased enormously.

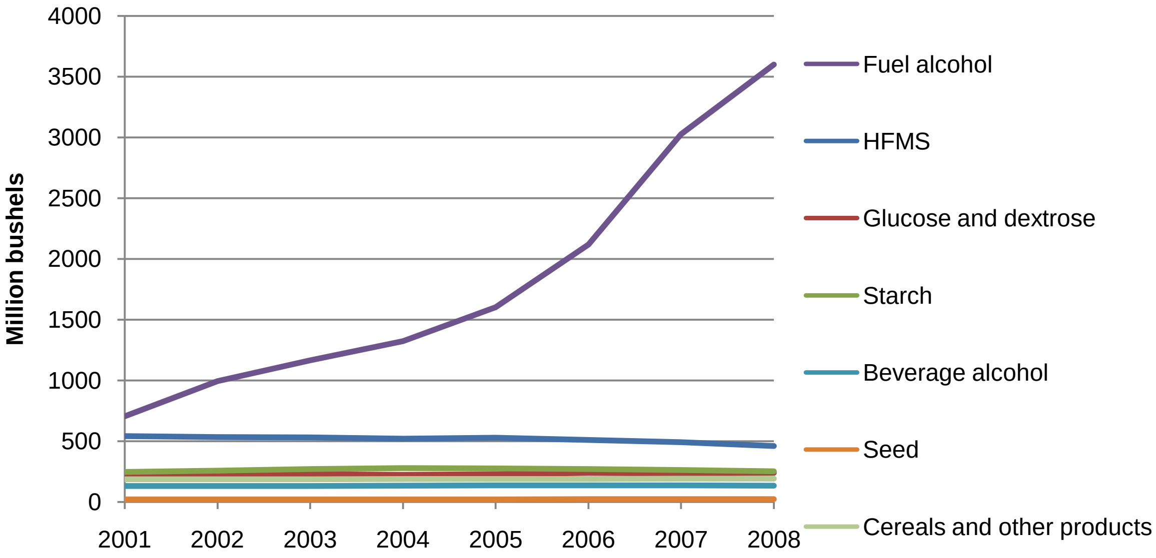

*Figure 9. Utilization of U.S. maize (source: USDA, ERS (2009), period: 2001-2008).*

The increase in ethanol production has resulted in a utilization degree for fuel alcohol of 73% of total maize production in 2008. In 2001 only 31% of all maize produced in the USA was used for the production of fuel alcohol. The utilization of maize for HFMS is still ranked second. Figure 10 presents the utilization degree of U.S. maize.

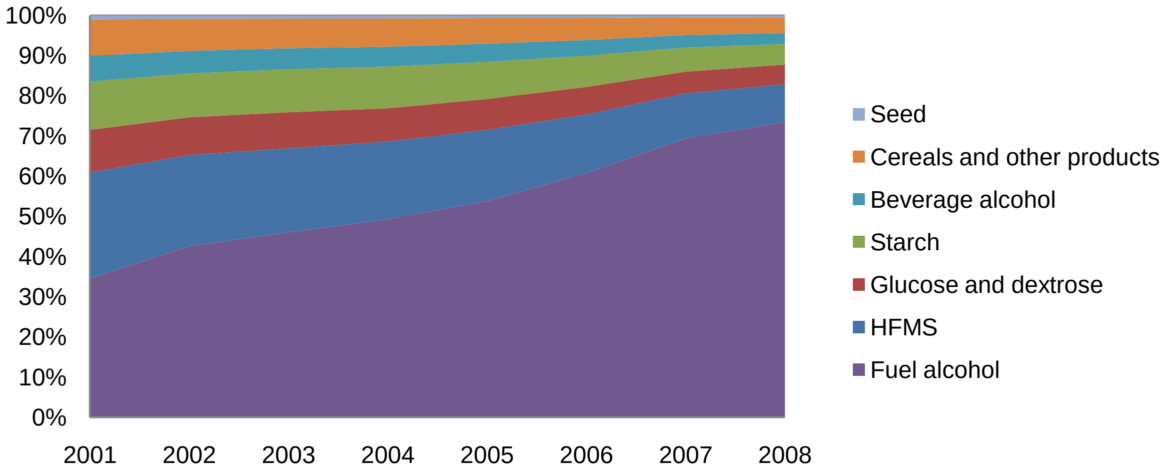

*Figure 10. Utilization degree of U.S. maize (source: USDA, ERS (2009), period: 2001-2008).*

### *2.3.1.1 Production process*

There are two maize production processes, wet and dry milling. The advantage of wet milling is that both ethanol and HFMS can be produced, while with dry milling only ethanol can be produced. Dry milling however is more cost and energy efficient. Currently, most maize-based ethanol in the USA is produced by dry milling. Morris (2005) describes a shift from wet milling in the 1970's and 1980's to dry milling, with currently 75% of all maize-based ethanol produced by the dry milling process. First, the maize wet milling process will be described and subsequently the dry milling process. Finally, the process water use is discussed. The production processes are based on the U.S. situation since the USA is by far the biggest producer of HFMS and maize-based ethanol. The production processes described are most common and are based on studies by EPA (1995), Lawrence (2003) and Szulczyk (2007) for wet milling and Jossetti (s.a.), the Clean Fuels Development Coalition (s.a.) and Szulczyk (2007) for the dry milling process. Both processes are graphically represented in the process diagram of Figure 11.

Maize harvesting in the USA nearly almost exists of separating the grains from the stover, leaving the stover on the field and collecting the grains. The grains are delivered at the plant and trash is removed in order to remain only grains. The grains are put into steeping tanks with a dilute sulfurous acid solution of 52˚C to soften the kernel. The steeped grains undergo degermination in order to separate the germ from the other components. The germ is washed, dewatered and dried and the oil is extracted and sold since it has a high economic value. The fibrous material that remains is also dried and mixed with steep liquor. Again, this is dried and sold as gluten feed for cattle and other animals.

The slurry that remains is again washed and finely grinded to remove starch and gluten from fibres. The fibres are added to the germs and the starch-gluten slurry passes to filters to the centrifuges in order to separate the starch from the gluten. The gluten can subsequently be dried in several ways. The maize gluten meal is also used as animal feed. The starch slurry that remains is used for many purposes. Approximately 80% of all U.S. starch slurry is converted into sweeteners and fuel alcohol. This study focuses on the production of HFMS and ethanol and refrains from other end-products that can be produced from starch. HFMS is derived by refining the starch slurry by hydrolyses using acids and enzymes. Ethanol is produced by fermenting and distilling the starch slurry.

The dry milling process mainly differs in the way the grain is treated in the early stage. Instead of soaking the kernels in acid water, the kernels are milled dry. The meal is subsequently mixed with water and enzymes and passes through cookers where the starch is liquefied. The slurry is cooled and other enzymes are added to convert starch into fermentable sugars (dextrose). The slurry is fermented and distilled to separate the ethanol from the fibrous residue. The residue is centrifuged and dried and leads to Distillers Dried Grains with Solubles (DDGS). Finally the ethanol passes through a dehydration system to remove the water and make the ethanol anhydrous.

#### *2.3.1.2 Process water use*

Although its name suggests little water is involved in dry milling, the difference in process water use between dry and wet milling is rather small. In wet milling water is added to the grain before grinding, while in dry milling the water is added after the grains are milled. Wu (2008) estimates water use at 3.45 litre of water per litre of (denatured) ethanol produced for dry milling and at 3.92 l water/l ethanol for wet milling. According to a study by Shapouri in 2005, 4.7 litre of water is needed to produce one litre of ethanol with wet milling. Using Wu's most recent 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 l /t maize for wet milling. Like with the processing of sugar cane and sugar beet this amount of water is very small compared to the amount of water involved in growing the maize. For that reason the PWU is not considered in the calculations.

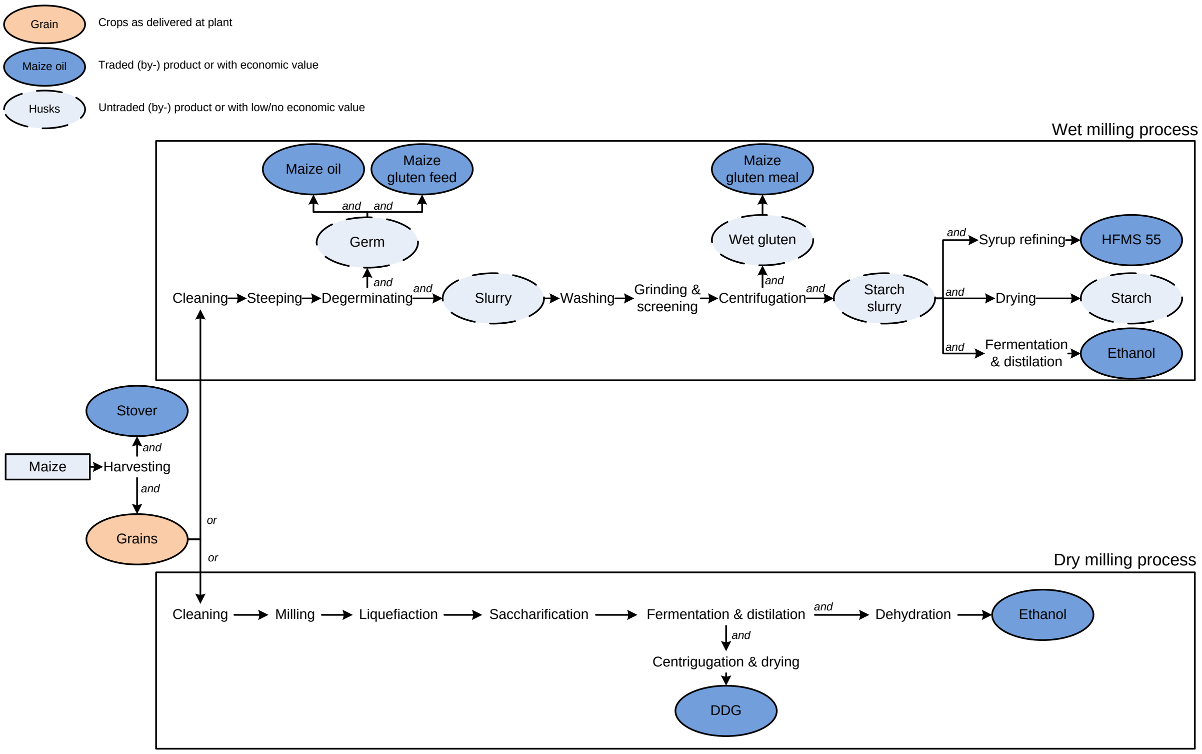

*Figure 11. Maize wet and dry milling process.*

### *2.4 Artificial sweeteners*

Artificial sweeteners are also known as low or non-caloric and high intensity sweetener (HIS). Several artificial sweeteners are available, varying in sugar equivalent which is the relative sweetness compared to sugar. Consumption of these sweeteners has increased during the last decades and has an expected annual growth rate of 4% (Campos, 2006). Much information about HIS production and consumption is not publically available. Aspartame is currently the largest artificial sweetener with a market share of approximately 55% of the global one thousands of millions U.S. dollars (US$ 1bn) market.

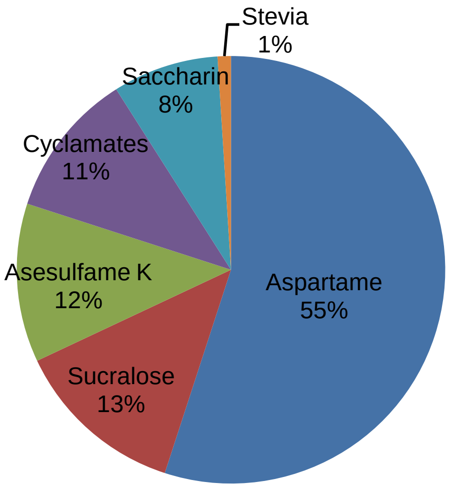

*Figure 12. Global artificial sweetener market share (Source: Campos, 2006).*

# 3 Bio-ethanol

Ethanol ($C_2H_5OH$) is the most used liquid bio-fuel, currently accounting for 86% of total liquid bio-fuel production. Of all ethanol produced, about 25% of global ethanol production is used for alcoholic beverages or for industrial purposes. The other 75% is fuel for transportation (Worldwatch Institue, 2007). Most ethanol (95%) is produced by fermentation of carbohydrates derived from agricultural crops, the remainder is synthetic ethanol. Both products are chemical identical. Another difference in ethanol that can be made is its purity. Anhydrous ethanol is at least 99% pure while hydrous ethanol contains some water and has a purity of 96%. Since gasoline and water do not mix, only anhydrous ethanol is suitable for blending. Hydrous ethanol is used as 100% gasoline substitute for cars with adapted engines (Berg, 2004).

## *3.1 Ethanol production*

Ethanol production has increased rapidly during the last three decades and has even doubled from 2001 to 2006 (Figure 13). The increase can partially be attributed to developments in the possibilities to blend ethanol with gasoline. In Brazil, the growth in ethanol production can largely be ascribed to an increase in motor vehicles that drive both on fossil fuels and ethanol.

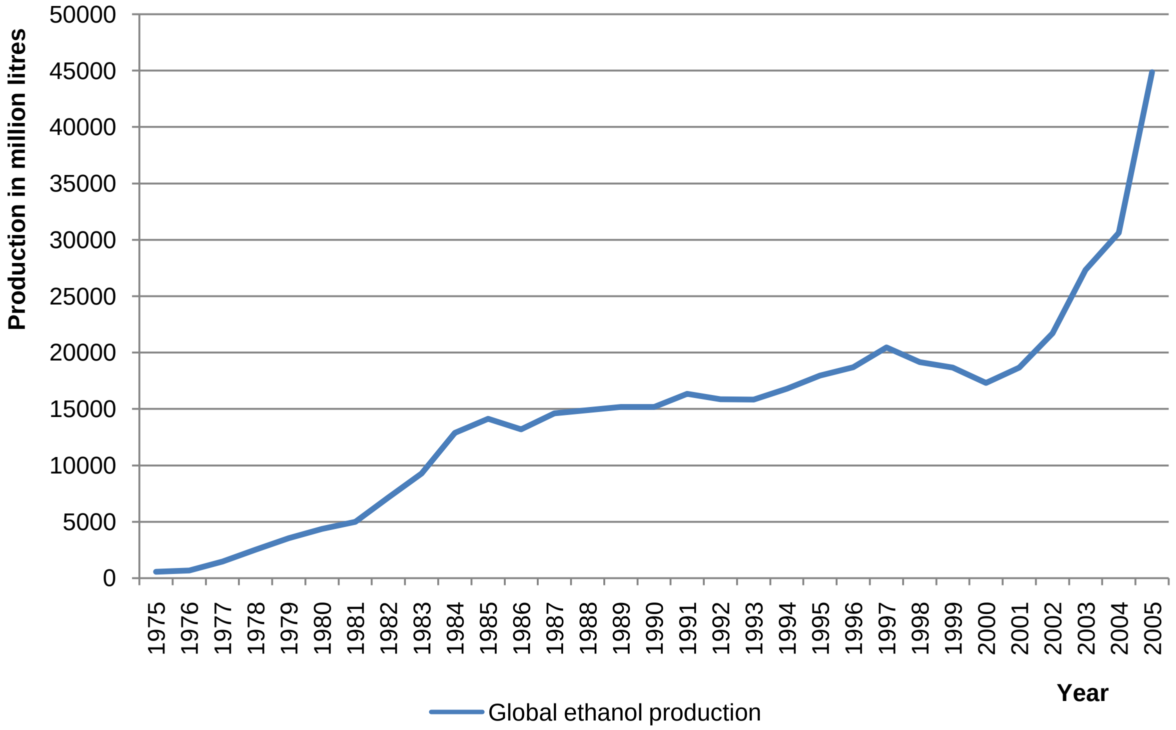

*Figure 13. Global ethanol production (Source: F.O. Licht; period 1975 - 2005).*

### 3.2 Ethanol production by feedstock

According to Berg (2004) there are two first-generation feedstocks for ethanol, sugar crops (61%) and starchy crops (39%). Sugar-based ethanol is produced from sugar cane and sugar beet, while the majority of starch-based ethanol is produced from maize. In 2005 the USA and Brazil were the largest producer of ethanol. U.S. ethanol production is to a very large extent based on maize while Brazilian ethanol is almost completely cane-based. Table 5 shows the main ethanol producing countries and their main feedstocks. 'Appendix I: World's main ethanol feedstock' shows the main producing countries and their feedstocks in 2003 and 2013. Information about the share of each feedstock regarding starch-based ethanol is studied by F.O. Licht but not publically available.

As can be seen in the table, the first-generation feedstocks are all important crops for food production. Worldwide discussion is continuing on the competition of ethanol with the food sector. Food prices seem to rise due to an increased demand for crops by the ethanol sector. The competition between the ethanol and food sector will be briefly discussed in paragraph 3.3. For this reason, what is called the next- or second-generation feedstocks are of interest. With this type of ethanol production, crops can be used for food production, while the residue is used for the production of ethanol. It is, however, more difficult to convert lignocellulosic biomass to ethanol. Although it is not commercially produced yet it can be profitable in future.

*Table 5. Total global production of ethanol (source: F.O. Licht, 2005)*

| **Country** | **Million litres** | **Percentage** | **Main feedstock** |
|---|---:|---:|---|
| United States of America | 16,214 | 36.1 | Maize |
| Brazil | 16,067 | 35.8 | Sugar cane |
| China | 3,800 | 8.5 | Maize, sugar crops, grains |
| India | 1,700 | 3.8 | Sugar cane |
| France | 910 | 2.0 | Sugar beet, grains[1] |
| Russia | 750 | 1.7 | Sugar beet, grains[1] |
| South Africa | 390 | 0.9 | Sugar cane |
| Spain | 376 | 0.8 | Grains[1] |
| Germany | 350 | 0.8 | Grains[1] |
| Thailand | 300 | 0.7 | Sugar cane |
| Others | 4,017 | 9.0 | |

1) Mainly wheat and barley

Table 6 gives an outline of the ethanol yield of the major feedstocks. A survey conducted by the Worldwatch Institute (2007) gives an indication of typical yields of main producing countries for the national most used feedstock. Rajopogal (2007) gives an indication of ethanol yields based on several, not mentioned sources. According to the Worldwatch Institute, Brazil has the highest productivity with a yield of 6500 litres per hectare with sugar cane cultivation. The production process that results in this yield is not known. Since in Brazilian ethanol plants conversion of molasses to ethanol is rather common it is probably included in this yield.

*Table 6. Typical ethanol yield per hectare of farmland by crop and region (Source: Worldwatch Institute, 2007; Rajapogal, 2007)*

| | Typical yield (litres per hectare of cropland) | | | | |
|---|---|---|---|---|---|
| **Crop** | **USA** | **EU** | **Brazil** | **India** | **Rajopogal** |
| Sugar cane | | | 6,500 | 5,300 | 4,550 |
| Sugar beet | | 5,500 | | | 5,060 |
| Maize | 3,100 | | | | 1,968 |
| Wheat | | 2,500 | | | 952 |
| Barley | | 1,100 | | | |

### 3.3 Sugar crops: competition between food and bio-ethanol

Questioning whether a crop should be used for food or ethanol production is not only restricted to that specific crop, but also to the natural resources it needs for production. With the present increase in food prices, the question rises whether the use of (food) crops for the production of bio-fuels is ethically acceptable.

Until now, both food and ethanol demands are rising. The way this will evolve is hard to predict. For food consumption the size of human population and its collective appetite is an important issue. For ethanol the energy conversion technologies are of interest. For both food and ethanol production, developments in agronomy, like agricultural efficiencies and development of crops that are able to grow on marginal lands, can contribute to a well-balanced organization of the agronomy sector (Worldwatch Institute, 2007).

According to FAO (2008d), on short term higher agricultural commodity prices will have a negative impact on household’s food security. Crop production for bio-fuels however is not the only cause of rising food prices. The increasing global population and growing demand for food as well as failed harvests due to climate change influence also push prices. On the long term however, growing demand for bio-fuels and an increase in agricultural commodities can be an opportunity for individual smallholders and rural communities in developing countries. Enabling them to expand production, to facilitate infrastructure and to offer access to markets are requirements to transform the short term negative influence to positive income-generating opportunities.

# 4 Methodology

## *4.1 Water footprint*

The water footprint (WF) of a product (commodity, good or service) is defined as the volume of freshwater used for the production of that product at the place where it was actually produced (Hoekstra and Chapagain, 2008). The WF of a product is the same as the virtual-water content of a product as first introduced by Allan (1998). For many products with agricultural feedstocks, the rain water evaporated during the growing season of the plant, along with the amount of irrigation water extracted from ground- or surface water, contributes most to the WF. The first term is referred to as the green WF. The latter is referred to as the blue WF. Another part of the blue WF is the amount of water used during crop processing. As discussed in chapter 2 this amount is relatively small and difficult to determine for each specific country not to mention production regions. For this reason process water use (PWU) is not taken into account in WF calculations in this study. The third component of the WF is the grey WF which is the volume of water required to dilute pollutants emitted to the natural water system during its production process to such an extent that the quality of the ambient water remains beyond agreed water quality standards (Hoekstra and Chapagain, 2008).

The calculation of the green and blue WF is based on CWR's computed with the CROPWAT model (FAO, 2008b). The program makes a distinction between the monthly available precipitation and the required irrigation water. The WF of unprocessed crops is calculated by dividing the required green and blue water over the crop yield. Yearly average crop yields for the twenty major production countries regarding total yearly production quantity are determined on the basis of the FAOSTAT-database (FAO, 2008c). Next, the WF of the (by-) products is calculated on the basis of the WF of the unprocessed crop. The distribution of the water needed to produce the root product (i.e. the crop) over the derived (by-) products, is based on the product fraction and the value fraction. The product fraction denotes the weight of a (by-) product in tons, obtained from one ton of root product. Since not all (by-) products have equal market values ($/ton of (by-) product) the value fractions are taken into account as well. Finally, the grey WF is added to the green and blue WF. The calculation of the grey WF is based on the amount of pollutants that is emitted to the surface water and the agreed water quality standard of that water body.

All data sources required for the calculation of the WF as described above are discussed in more detail in this chapter. The method of approach for the calculation of the WF is discussed in '

Appendix II: Water footprint calculation’. The method is based on Appendix I of ‘The Globalization of water’ (Hoekstra and Chapagain, 2008). In this explication, the term yield is expressed in ton/ha and the virtual-water content in $m^3$/ton. These quantities can be expressed in terms of litres (l), gigajoules (GJ) or any other unit to express a product (commodity or service) in.

## *4.2 Data sources*

### *4.2.1 Crop parameters and climate data*

The data used to perform the calculations is received from several sources. The CROPWAT model contains information about soils and data about various crops, like cropping seasons and crop parameters. The information about weather stations is partly received from the CLIMWAT database (FAO, 2008a) and missing climate data is gathered from the Global climate data atlas of Müller and Hennings (2000). The start of the cropping seasons for sugar beet and maize is based on the temperatures and precipitation of the considered area. The growing season of sugar beet and maize starts when the average temperature is above 10 ˚C, using a two-week interval. For sugar cane, in most cases, the start of the cropping dependents on the start of the rain season. Since temperatures are rather constant during the year in tropical regions, temperatures influence the start of the cropping season to a smaller extent. The WF of maize-based products for the twenty main producing countries, except the USA, is based on CWR's as computed by Gerbens-Leenes et al. (2008).

### *4.2.2 Sugar crop and maize yields*

Yields for sugar cane and sugar beet as well as for maize, with the exception of the USA, are taken from the FAOSTAT database (FAO, 2008c). An exact description of the composition of the product yield is missing. In many countries sugar cane is harvested manually after sometimes controlled burning. This means tops and leaves are partially removed on the field. When sugar cane is harvested mechanically the tops and leaves are still attached to the stalk at the mill. Whether the yield for a specific country is based on the yield of clean stalks or the yield with tops and leaves still attached is unclear. For most countries the yield will be given for clean stalks, since the data from the FAOSTAT database corresponds to yields given in several studies conducted in the same country that give more specific information. It is assumed that the correction applied by FAO results in comparable yields for all studied countries.

Sugar beets are harvested mechanically in the main producing countries. This means they are most probably measured at the beet factory with still some trash and leaves attached. Since the fraction of trash and leaves is very small compared to the beet (± 2%) (Kranjc, 2006) the yield is assumed to be of clean, processed beets.

The yield of maize in the USA is derived from the United States Department of Agriculture. For maize the yield is given for the harvested grains only. Since this study uses the product fraction of all economically valuable parts of a feedstock, comparing only the grains with sugar cane and sugar beet would give an unfair comparison. Since stover makes up a considerable part of the maize plant (56%) with an economic value, this part cannot be neglected. Here for, the amount of stover is added to the yield as given by the USDA. The yield for the other nineteen main producing countries is taken from FAOSTAT (FAO, 2008c) and the amount of stover is added as well. We use here the term 'unprocessed maize' to refer to the total biomass of stover plus grains.

### 4.2.3 Selected countries

The countries that are selected as main producing countries of sugar crops are based on total annual production of the crops per year according to the FAOSTAT-database. The important production areas within a country are based on data of the harvested area of a crop provided by Ramankutty (2008). This is displayed in Figure 15 and Figure 16. The location of the available weather stations is subsequently plotted on the GIS-image of the harvested area (Figure 14). The weather stations located in areas with a high percentage of land covered with the considered crop are used for calculations with CROPWAT.

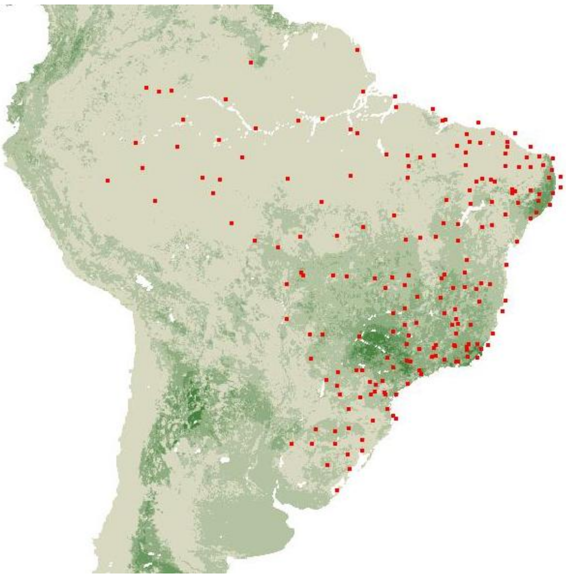

*Figure 14. Area of sugar cane harvested (Source: Ramankutty, 2008). Grey indicates no sugar cane is harvested, darker green means implies a larger area of sugar cane is harvested in the specific grid cell. The red points represent weather stations with available climate data (Source: CLIMWAT, FAO).*

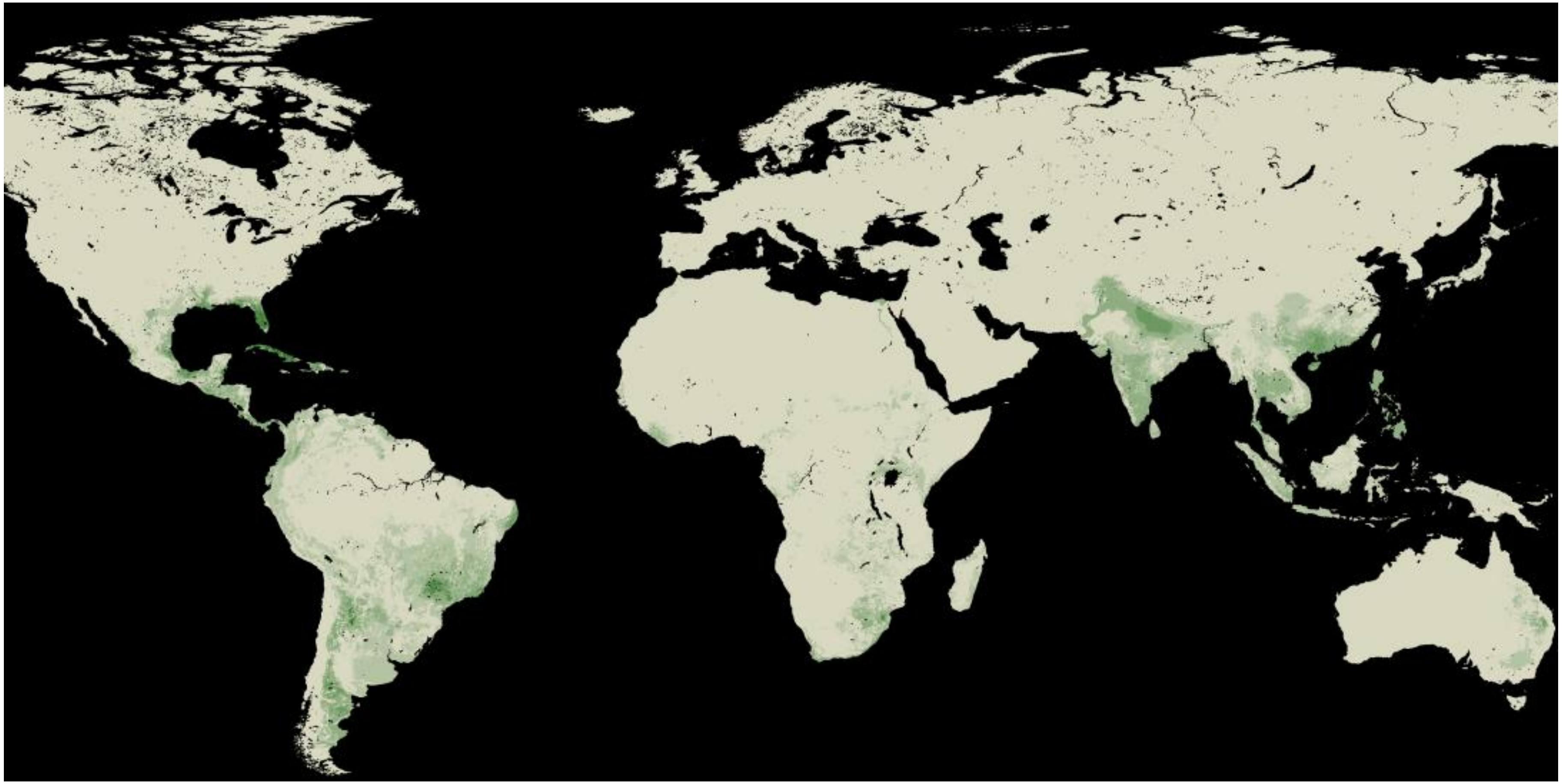

*Figure 15. Sugar cane production grid cell map. Grey inidcates no sugar cane is grown in the specific cell. Green indicates sugar cane is grown. Darker green represents a higher percentage of the grid cell is used for sugar cane cultivation (Source: Ramankutty, 2008).*

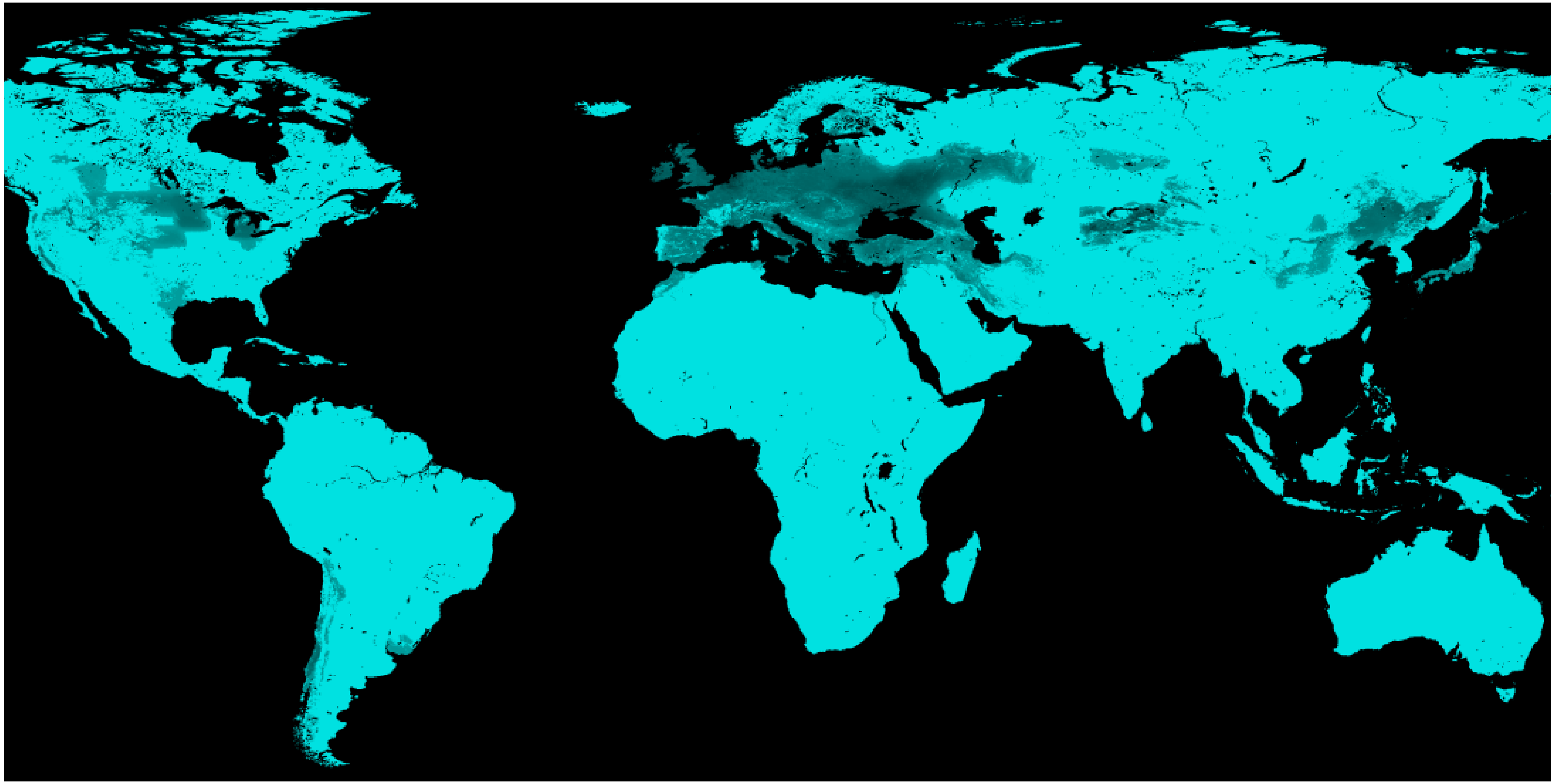

*Figure 16. Sugar beet production grid cell map. Blue indicates no sugar beet is grown in the specific cell. Grey indicates sugar beet is grown. Darker grey represents a higher percentage of the grid cell is used for sugar beet cultivation (Source: Ramankutty, 2008).*

### *4.2.4 Product fractions*

The product fractions are determined for traded (by-) products or products with an economic value. The product fractions of all the derived (by-) products in sugar cane, sugar beet and maize processing, are based on the production processes as described chapter 2. For each (by-) product the dry matter weight in tons per ton of fresh primary crop is determined. For each crop, several studies concerning the compositions of feedstocks and products derived during the productions process, in a number of countries, are used. The studies used for the calculation of the average global production fractions are summarized in Table 7 for sugar cane, Table 8 for sugar beet and Table 9 for maize.

*Table 7. Studies used for the calculation of average global production fractions for sugar cane (by-) products.*

| **Author (year)** | **County** |
|---|---|
| Thu Lan (2008) | Thailand |
| Macedo (2007) | Brazil |
| Patzek (2005) | Brazil |
| Cheesman (2004) | Several |
| Woods (2000) | Unknown |
| Cordoves Herera (1999) | Unknown |
| Allen et. al. (1997) | Unknown |
| Shleser (1994) | Hawaii |
| Thomas (1985) | Brazil |

*Table 8. Studies used for the calculation of average global production fractions for sugar beet (by-) products.*

| **Author (year)** | **County** |
|---|---|
| Kranjc (2006) | Slovenia |
| Henke et al. (2006) | Czech Republic |
| Vaccari et al. (2005) | Unknown |
| Cheesman (2004) | Several |
| CIBE & CEFS (2003) | European Union |
| FAO (1999) | Unknown |
| CIAA (s.a.) | European Union |

*Table 9. Studies used for the calculation of average global production fractions for maize (by-) products*

| **Author (year)** | **County** |
|---|---|
| Szulczyk (2007) | USA |
| WU (2007) | USA |
| Lawrence (2003) | USA |
| EPA (1995) | USA |
| Jossetti (s.a.) | USA |

### 4.2.5 Value fractions

For the market or economic value of the considered (by-) products version 1.1 of the SITA-database of the International Trade Centre (UNCTAD/WTO) among others is used. For the six main producing countries of the (by-) product of interest, the export prices for the period from 1996 to 2005 are determined. For each exporter the countries that together account for more than 80% of total export are used to calculate the value of a (by-) product. When less than three countries account for 80% of export, a minimum of three importing countries is used. The SITA-database shows quite some variance in prices between countries, as well as in time. Furthermore for some countries there is a lack of information for some years, which makes the data less reliable. For this reason the average value fractions are used in order to estimate a global value. Not all (by-) product export data are available in SITA. For this reason other sources are used as described in the paragraphs below.

#### 4.2.5.1 Cane sugar

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 U.S.$/kWh the value fraction of bagasse is calculated.

#### 4.2.5.2 Beet sugar

Sugar is by far the most valuable product of sugar beet processing. According to the Institute of Sugar beet Research (ISR, 2005), the total value of by-products (molasses, beet pulp and lime) is € 14 per ton of sugar beet. This corresponds to market values as reported by SITA on which value fractions calculation is based on.

#### 4.2.5.3 Sugar cane-based ethanol

Since ethanol is not included in the SITA-database and the ethanol price rather fluctuates, the average of current and expected prices, as determined by the U.S. Food and Agricultural Policy Research Institute (FAPRI, 2008), is used. The ethanol price is based on the average U.S. (US$ 0.51) and Brazilian price (US$ 0.37) which makes an average of US$ 0.44. Filter cake and vinasse can be used for many purposes and are often brought back to the land as fertilizer. Filter cake has relatively high values of nitrogen and phosphorous and vinasse a high value of potassium. According to Leal (2007) and Moreira (2007) fertilizer use can be reduced by approximately 50% when vinasse and filter cake is used as fertilizer.

#### *4.2.5.4 Sugar beet-based ethanol*

For the production of ethanol from sugar beets only one by-product is taken into account, beet pulp. Since the product fraction of vinasse in sugar beet processing for ethanol is very low (0.002) (IENICA, 2004) this by-product is not considered in calculating the water footprint of sugar beet-based ethanol. The value of ethanol is just as for sugar cane-based ethanol derived from FAPRI (2008). The value of sugar beet pulp is based on information from the USDA (2006) which reports a value of US$ 6 per ton of beet pulp and the Dutch Institute of Sugar Beet Research (ISR, 2005) that reports a total value of sugar beet by-products (molasses, beet pulp and lime) of € 14 per ton of beet pulp. Based on this information the value of beet pulp is estimated at US$ 10 per ton of beet pulp, which corresponds to the SITA-database.

#### *4.2.5.5 High fructose maize syrups and maize-based ethanol*

The value fractions of maize based-ethanol and HFMS's by-products are based on the USDA cost-of-production survey (Shapouri, 2005). The value of HFMS 55 is based on the average U.S. Midwest price as provided by the Economic Research Service of the USDA (www.ers.usda.gov, 2008). For prices of maize gluten meal, maize gluten feed, crude maize oil and distillers' dried grains as well as HFMS 55 prices from 2000 – 2003 are available for all (by-) products. Although stover is generally left on the field it is considered in this study since it represents an economic value for farmers. Just like the vinasse and filter cake in sugar cane processing, the nutrient value of stover reduces the amount of fertilizer that has to be applied. Like cane bagasse, stover is suitable for a fermentation-based biomass conversion process (Pordesimo, 2004), but it is not economically utilized yet. Less than 5% of all stover is harvested and used for animal bedding and feed. (ILSR, 2002). Most often it is left on the field, not solely as fertilizer, but also to prevent soil erosion and retain soil moisture. The ethanol prices are the same as described in paragraph 4.2.5.3.

### *4.2.6 Grey water footprint*

The amount of grey water is a component of the WF that is not easily determined. It is dependent on several variables which are all difficult to quantify. The background of those difficulties is diverse and will be explained in this paragraph. Further discussion on the grey WF can be found in 'Appendix V: The grey water footprint'. The grey WF is the volume of water that is needed to dilute the amount of pollutants that is emitted to a free flowing water body to an accepted water quality standard (Hoekstra and Chapagain, 2008). This definition contains three variables that have to be quantified in order to calculate the grey WF. The first is the *amount of pollutants* that are emitted, the second is *a free flowing water body* and the third is the *acceptable standard*.

#### *4.2.6.1 Acceptable standard*

First the *acceptable standard* will be considered. Worldwide many standards are dictated by many authorities and organizations. All standards serve a certain purpose and are sometimes specified by type of water body. In the USA the Environmental Protection Agency (EPA) draws up regulation as well as states do separately. In

Europe, the European Union issues directives for water quality and standards for some pollutants. Standards and directives are specified by type of water body and by purpose of the water destined for. Besides those regulatory agencies for the USA and the EU the guidelines from the World Health Organization (WHO) are considered. The WHO gives recommendations in its ‘Guidelines for Drinking-water Quality (2006). For this study three nutrients and agro-chemicals are examined. Of the three nutrients, nitrogen, phosphorous and potassium, no standards are given for potassium for any aim which implies it is not a major or hazardous pollutant. For phosphorous, none of the three regulatory organs has determined drinking water standards. For aquatic life the EPA has appointed standards for different types of water bodies. The EU only gives qualitative directives for a ‘good ecological status’. Based on those directives each member country is able to set standards for their characteristic situation. The Netherlands for example has introduced standards for both nitrogen and phosphorous for each type of water body as described by the European Water Framework Directive. For nitrogen, EPA, EU as well as WHO give standards for water intended for human consumption. EPA and WHO recommend a standard for nitrate of 10 mg/l (measured as nitrogen, $NO_3$-N). The EU recommends a standard with a maximum of 50 mg nitrate ($NO_3$) per litre, which equals 11.3 mg/l of nitrate-nitrogen ($NO_3$-N). Finally, for the total of all pesticides the EU gives a standard of 0.50 μg/l for drinking water. This very strict norm prevents farmers of using heavily polluting agrochemicals with a long time to half-life. By using agrochemicals that deactivate or degrade rather fast, pollution can be prevented. Since agrochemicals with a long time to half-life become more often prohibited in many countries, they will not be considered in this study. Which agrochemicals are used for each crop within a country is hard to discover. However, since most modern agrochemicals have a relatively short half-life they will be assumed to be deactivated before becoming hazardous for the environment. As explained above, only for nitrogen large-scale applicable standards (for drinking water) are available. This leads to the standards as recommended by EPA and WHO, almost equal to that of the EU, are used in this study.

#### *4.2.6.2 Free flowing water body*

The second term in the definition of grey water that is discussed is *free flowing water body*. The (drinking water) standard for nitrogen that just is accepted as standard for the grey WF is applicable for each fresh surface water. For this standard the term free flowing water body does not result in any problem. However, the aim of the EU and EPA for example is to give more water body specific standards in future, especially for aquatic life. Until now, some EU member countries, like The Netherlands, have already formulated standards for aquatic life. These standards are all specified by type of water body.

#### *4.2.6.3 Amount of emitted pollutants*

The third part of the grey WF that is discussed is *the amount of pollutants that is emitted*. Since nitrogen is the only considered pollutant the factors that influence the amount of nitrogen that reaches a water body are discussed briefly. The most important factors are listed below:

- Application rate of nitrogen
- Run-off

- Leaching
- Ammonia volatilization
- Biological denitrification
- Removal during harvest

Without going very deep into this matter, the complexity of quantifying nitrogen flows in an agricultural environment is explained. This will ground the relative conservative approach this study uses. There is wide variance in the amount of nitrogen applied worldwide (

Appendix IV: Fertilizer application rates). This is a result of, among other things, agricultural methods like application method and timing, soil characteristics and crop varieties. Run-off is often depending on the amount of plant residue left on the field after harvest, weeds control, precipitation and soil characteristics. Also leaching also is depending on soil characteristics as well as ground water levels and precipitation. Ammonia volatilization is the loss of nitrogen to the atmosphere as ammonia. This occurs under certain conditions, especially when daily rainfall is insufficient to transfer the nitrogen into the root zone of the plant. Of larger influence however is biological denitrification, which converts nitrate-N into gaseous forms using anaerobic bacteria present in soil. The last factor discussed, is the amount that is removed from the field during harvest. The amount taken up by the plant highly depends on the application method. In precision farming the amount absorbed by the plant will be much higher than in conventional agriculture. Furthermore the part of the plant in which the nitrogen is stored in relation to the part that is harvested and the part that remains on the field is of interest. Much of the nitrogen in plant residue is available in a subsequent cropping season or will ultimately leach or runoff to a water body.

Until now, in studies to the grey WF by Chapagain et al. (2006) and Van Oel et al. (2008) is assumed that 10% of the applied nitrogen reaches a free flowing water body, assuming a steady state balance at the root zone in the long run. This assumption is among other things based on a nitrogen uptake of 60%. According to IFA (Wichmann, 1992) nitrogen uptake for sugar cane is approximately one kg of nitrogen per ton of cane and four to five kg nitrogen per ton of sugar beet. Taking the application rates (

Appendix IV: Fertilizer application rates) and yields (FAOSTAT, 2008) into account, the uptake varies highly but generally reaches 60% for sugar cane and for sugar beet uptake hypothetically exceeds application. Barber, cited by Patzek (2004), estimates that the maize harvest of nine tons of grain, 150 kg/ha of nitrogen is removed. Currently U.S. farmers apply approximately 150 kg/ha and 80 kg/ha remains on the field by stover. So, of the 230 kg/ha that is available 150 kg/ha is removed. This means 65% of all nitrogen is removed. Values about uptake and removal given by Patzek nearly correspond to those given by IFA. Since no site specific information about soil characteristics and agricultural methods can be applied in a global study, this study uses the assumption as made by Chapagain et al. (2006).

# 5 Results

This chapter presents the results of the calculations of the WF of sweeteners and ethanol produced from the three researched crops, sugar cane, sugar beet and maize. The results are presented for the twenty main producing countries. For maize products, the WF is calculated with more detailed data for the USA, since maize is competitive with sugar crops in the USA for both sweetener and ethanol production. For the remaining nineteen countries CWR's as computed by Gerbens-Leenes et al. (2008) are used. First the product and value fractions, as they are determined on the basis of all literature studied, are presented. In the next paragraphs the WF of sugar and HFMS 55 is presented and compared. Subsequently the same is done for ethanol.

## 5.1 Product and value fractions

### 5.1.1 Sugar cane

The biomass of sugar cane consists of several materials that result in a number of (by)-products during the processing of sugar cane. The exact composition depends on regional conditions like weather and the cultivated variety, which is for example of influence on the sugar content. Sugar is the most valuable material, but other materials have economic value as well. In Table 10 and Table 11 the (by-) products of sugar cane are presented. Many studies in different countries have been conducted. Some of them are presented in the tables. The results of the study by Allen correspond best to many other studies that, however, do not include all by-products.

*Table 10. Composition of fresh sugar cane (product fraction of fresh sugar cane).*

| | Shleser (1994) | Patzek (2005) | Thu Lan (2008) | Cordoves Herera (1999) | Thomas (1985) |
|---|---|---|---|---|---|
| Tops and leaves | 0.4 | 0.23 | 0.2 | 0.41 | 0.3 |
| Clean stalks | 0.6 | 0.77 | 0.8 | 0.59 | 0.7 |

*Table 11. (By-) products of clean millable sugar cane stalks (product fraction of clean stalks).*

| | Shleser (1994) | Allen (1997) | Thu Lan (2008) | Cordoves Herera (1999) | Source | Country |
|---|---|---|---|---|---|---|
| Sugar | 0.10 | 0.14 | 0.10 | 0.14 | Shleser | Hawaii |
| Bagasse | 0.17 | 0.27 | 0.25 | 0.12[1] | Patzek | Brazil |
| Molasses | 0.03 | 0.03 | 0.05 | | Thu Lan | Thailand |
| Filter cake | | 0.05 | | | Cordoves Herera | Unknown |
| Water | 0.70 | 0.51 | | 0.71 | Thomas | Brazil |
| Other | | | | 0.03 | Allen et. al. | Unknown |

1) Based on dry matter

Table 12 shows the product and value fractions of the (by-) products of cane sugar processing. The distribution of the WF of unprocessed sugar cane over the derived (by-) products is given as well. The distribution is based on the ratio of value fraction divided by the product fraction. The value of sugar and molasses is based on the export value as recorded in the SITA-database. The value fraction of bagasse is calculated with the value of bagasse as it is used for the generation of electricity. The value of filter cake is determined on the basis of its value as fertilizer. The value fractions of the main exporting countries, where the average value fraction is based on, are displayed in Table 29 in ‘

Appendix VI: Value fractions'.

*Table 12. Product ($f_p[p]$) and value fractions ($f_v[p]$) of cane sugar and by-products.*

| **Product [p]** | **Product fraction ($f_p[p]$)** | **Value fraction ($f_v[p]$)** | **WF allocation fraction[1]** |
|---|---|---|---|
| Sugar, raw | 0.14 | 0.87 | 0.72 |
| Molasses | 0.03 | 0.05 | 0.19 |
| Bagasse | 0.14 | 0.07 | 0.06 |
| Filter cake | 0.04 | 0.01 | 0.03 |
| Water and residue | 0.65 | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left(f_p(p)/_{f_v(p)}\right)}{\Sigma_p\left(f_p(p)/_{f_v(p)}\right)}$

For the calculation of the value fractions of filter cake and vinasse, which is only derived in ethanol production, it is assumed that the total value of filter cake filter cake and vinasse together is divided on a 50/50 basis. The U.S. Department of Agriculture (USDA, 2006) estimated total fertilizer costs for sugar cane at approximately US$ 100 per hectare (period: 1996 – 2005). The FAO (2004) estimated fertilizer costs for Brazil at US$ 89 per hectare (1998 - 2002). Assuming the costs of fertilizers on US$ 100 per hectare, with the use of vinasse and filter cake this can be reduced to US$ 50. This results in a total value for filter cake and vinasse of US$ 50. Allocation on a 50/50 basis means a value of US$ 25 for filter cake and US$ 25 for vinasse per hectare are accredited. The application rate per hectare of both is the amount that is produced from one hectare of sugar cane, i.e. 2600 kg filter cake/ha and 1635 kg vinasse (dry matter)/ha.

Filter cake: $40\frac{kg\ filter\ cake}{ton\ cane}\times 65\frac{ton\ cane}{ha}=2600\frac{kg\ filter\ cake}{ha}$

Vinasse: $1\frac{m^3}{ton\ cane}\times 65\frac{ton\ cane}{ha}=65\frac{m^3}{ha}$

Vinasse (dry matter): $65\frac{m^3}{ha}\times 25.15\frac{kg}{m^3}=1635\frac{kg}{ha}$

These results in a value for filter cake of 25/2600 x 1000 ≈ US$ 10/ton and 25/1635 x 1000 ≈ US$ 15/ton for vinasse. This value of filter cake is used for the determination of the value fractions in sugar production as well.

For the calculation of the value fractions of the by-products derived by ethanol production the same economic values of the by-products are used. The product and value fractions and the water distribution for those (by-) products are shown in Table 13.

*Table 13. Product ($f_p[p]$) and value fractions ($f_v[p]$) of cane-based ethanol and by-products.*

| **Product [p]** | **Product fraction ($f_p[p]$)** | **Value fraction ($f_v[p]$)** | **WF allocation fraction[1]** |
|---|---|---|---|
| Ethanol | 0.06 | 0.89 | 0.92 |
| Bagasse | 0.14 | 0.09 | 0.04 |

| | | | |
|---|---|---|---|
| Vinasse | 0.03 | 0.01 | 0.02 |
| Filter cake | 0.04 | 0.01 | 0.02 |
| Water and residue | 0.63 | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left(f_p(p)/f_v(p)\right)}{\Sigma_p\left(f_p(p)/f_v(p)\right)}$

### *5.1.2 Sugar beet*

The most valuable component of the sugar beet is obviously the sugar. Like sugar cane, beets have some valuable by-products as well. Beet pulp for example is often used to produce animal feeding pellets or it is used for several other purposes, like paper production.

*Table 14. (By-) products of sugar beets (product fraction of beets without areal leaves).*

| | Kranjc (2006) | CIAA (s.a.) | FAO (1999) | Solarnavigator.net | Source | Country |
|---|---|---|---|---|---|---|
| Sugar | 0.12 | 0.16 | 0.14 | 0.15 | Kranjc | Slovenia |
| Molasses | 0.02 | 0.04 | 0.04 | 0.04 | CIAA | Unknown |
| Beet pulp | 0.04 | 0.05 | 0.05 | 0.05 | FAO | Unknown |
| Water | 0.46 | 0.75 | 0.77 | | Solarnavigator.net | Unknown |
| Other | 0.34 | | | | | |

Table 15 shows the product and value fractions of sugar beet (by-) products as well as the distribution of the WF of unprocessed sugar beet of the derived (by-) products. The value fractions of the main exporting countries are given in Table 30 in ‘

Appendix VI: Value fractions’.

*Table 15. Product ($f_p$[p]) and value fractions ($f_v$[p]) of sugar beet (by-) products (Source: SITA database, period: 1996-2005).*

| **Product [p]** | **Product fraction ($f_p$[p])** | **Value fraction ($f_v$[p])** | **WF allocation fraction**[1] |
|---|---|---|---|
| Sugar, raw | 0.16 | 0.89 | 0.69 |
| Beet pulp | 0.05 | 0.06 | 0.15 |
| Molasses | 0.04 | 0.05 | 0.16 |
| Water and residue | 0.75 | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left(f_p(p)/f_v(p)\right)}{\Sigma_p\left(f_p(p)/f_v(p)\right)}$

*Table 16. Product ($f_p$[p]) and value fractions ($f_v$[p]) of beet-based ethanol and by-products.*

| **Product [p]** | **Product fraction ($f_p$[p])** | **Value fraction ($f_v$[p])** | **WF allocation fraction**[1] |
|---|---|---|---|
| Ethanol | 0.09 | 0.92 | 0.86 |
| Beet pulp | 0.05 | 0.08 | 0.14 |
| Water and residue | 0.86 | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left(f_p(p)/f_v(p)\right)}{\Sigma_p\left(f_p(p)/f_v(p)\right)}$

### *5.1.3 Maize*

Maize (by-) products are used in many commodities. Mainly starch, extracted from the grain is often used as a primary product. The two main starch-based commodities are HFMS's and ethanol and are discussed in this study. Depending on the production process (paragraph 2.3.1.1) a number of valuable by-products are derived. Wet milling, which is used for producing both ethanol and HFMS yields in maize oil, maize gluten feed and maize gluten meal. With the dry milling process only ethanol can be produced and the only by-product is distillers' dried grains with solubles (DDGS). The product and value fractions of the (by-) products of both production processes are shown in Table 17, Table 18 and Table 19.

*Table 17. Product ($f_p$[p]) and value fractions ($f_v$[p]) of HFMS 55 and by-products in wet milling process (product fraction of total maize biomass).*

| **Products** | **Product fraction ($f_p$[p])** | **Value fraction ($f_v$[p])** | **WF allocation fraction**[1] |
|---|---|---|---|
| HFMS 55 | 0.36 | 0.73 | 0.23 |
| Stover | 0.54 | 0.15 | 0.03 |
| Maize gluten feed | 0.10 | 0.04 | 0.05 |
| Maize gluten meal | 0.02 | 0.04 | 0.23 |
| Maize oil | 0.01 | 0.04 | 0.46 |
| Water and residue | - | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left(f_p(p)/f_v(p)\right)}{\Sigma_p\left(f_p(p)/f_v(p)\right)}$

*Table 18. Product ($f_p$[p]) and value fractions ($f_v$[p]) of ethanol and by-products in maize wet milling process (product fraction of total maize biomass).*

| Products | Product fraction ($f_p$[p]) | Value fraction ($f_v$[p]) | WF allocation fraction[1] |
|---|---|---|---|
| Ethanol | 0.15 | 0.65 | 0.37 |
| Stover | 0.54 | 0.21 | 0.03 |
| Maize gluten feed | 0.10 | 0.05 | 0.04 |
| Maize gluten meal | 0.02 | 0.05 | 0.22 |
| Maize oil | 0.01 | 0.04 | 0.34 |
| Water and residue | 0.18 | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left({f_p(p)}/{f_v(p)}\right)}{\Sigma_p\left({f_p(p)}/{f_v(p)}\right)}$

*Table 19. Product ($f_p$[p]) and value fractions ($f_v$[p]) of ethanol and by-products in dry milling process (product fraction of total maize biomass).*

| Products | Product fraction ($f_p$[p]) | Value fraction ($f_v$[p]) | WF allocation fraction[1] |
|---|---|---|---|
| Ethanol | 0.15 | 0.66 | 0.78 |
| Stover | 0.54 | 0.22 | 0.15 |
| DDGS | 0.14 | 0.12 | 0.07 |
| Water and residue | 0.17 | 0.00 | 0.00 |

1) WF allocation fraction: $\frac{\left({f_p(p)}/{f_v(p)}\right)}{\Sigma_p\left({f_p(p)}/{f_v(p)}\right)}$

## 5.2 The water footprint of sweeteners

Appendix VII: Crop production' gives an overview of the twenty main producing countries of all three feedstocks. The WF of sweeteners produced in those countries is presented below. For sugar crops, the WF of sugar (and ethanol) is calculated on the basis of multiple weather stations in each country. The WF of maize-based products is based on one weather station within a country. However, for the more detailed study to the WF of maize-based products in the USA multiple weather stations are given. In this paragraph, first the WF of each unprocessed crops is presented followed by the WF for sugar and HFMS 55. The calculation of the ethanol WF is based on the same unprocessed crops WF's.

### *5.2.1 Sugar cane*

The WF of unprocessed sugar cane shows big differences between countries. This can partly be attributed to the range in CWR's, varying between 1233 and 2082 mm per cropping season. The range in reported crop yields however shows an even larger variance, 31.4 to 118.6 tons per hectare (Appendix VIII: Water footprint of unprocessed crops). Peru, Egypt, Colombia and Guatemala all report high yields resulting in low WF's, while China benefits from a low average CWR. Mexico and Brazil have rather favourable CWR's and yields above average that reduces the WF of sugar cane. Cuba and Pakistan report very low yields resulting in a very large WF. Figure 17 shows countries like Peru, Egypt Australia, India and Pakistan have a large blue WF component and are completely or highly dependent on irrigation. The grey WF contributes only to a small extent to the total WF.

Figure 18 presents the total WF of unprocessed sugar cane per country. Brazil and India are the largest producers and have a high national sugar cane WF's. Brazil needs 82 billion m$^3$ of water to produce its sugar cane, India 73 billion m$^3$ and although Pakistan is the fifth largest producer, it has the third largest notional WF for sugar cane of 23 billion m$^3$.

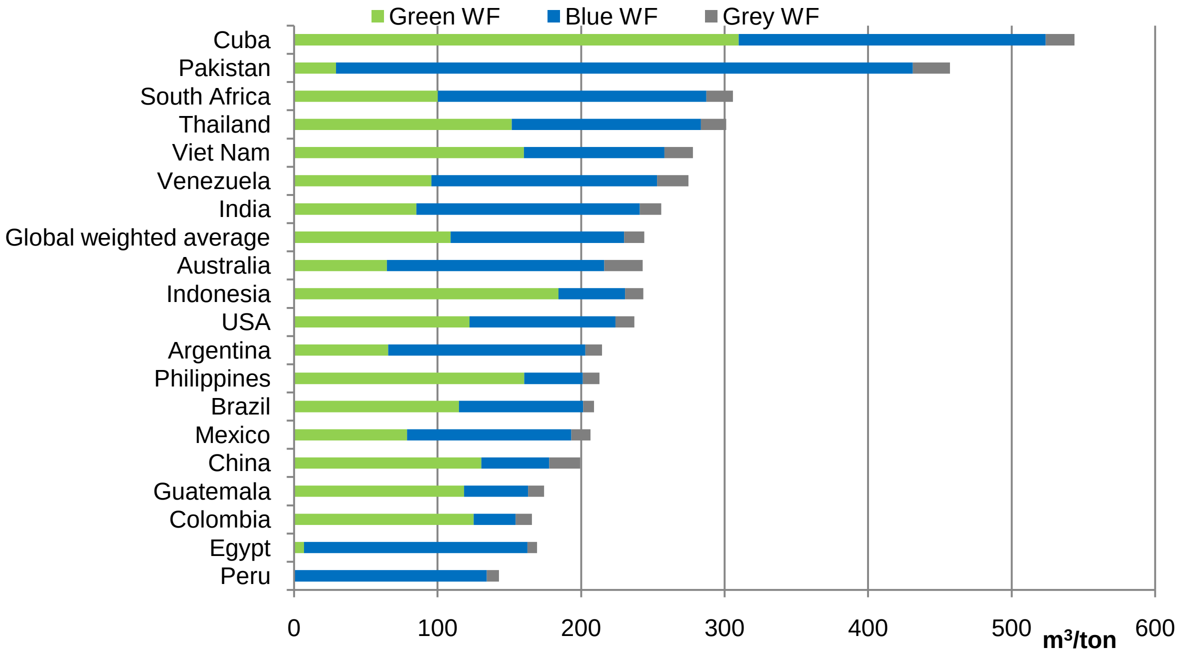

*Figure 17. Water footprint of unprocessed sugar cane, classified by green, blue and grey water footprint.*

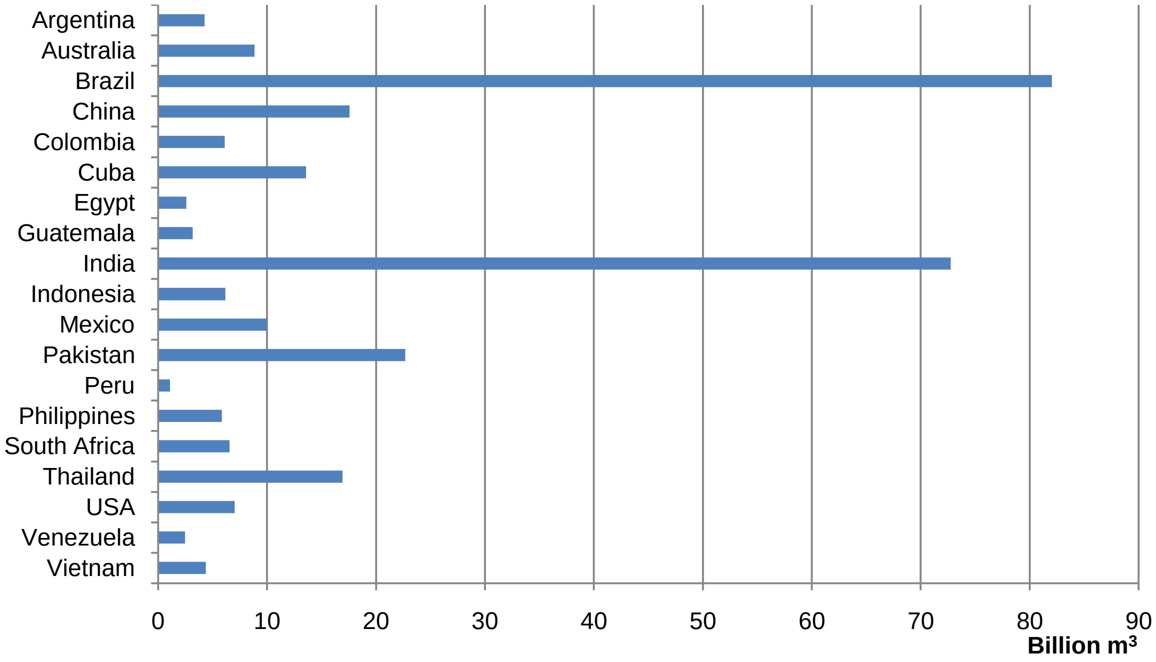

*Figure 18. The total national water footprint for sugar cane for the main producing countries.*

Figure 19 shows the WF of cane sugar for the selected countries. Since product and value fraction are assumed to be equal all over the world it is obvious that the countries with a high WF for unprocessed sugar cane, have a high WF for cane sugar as well.

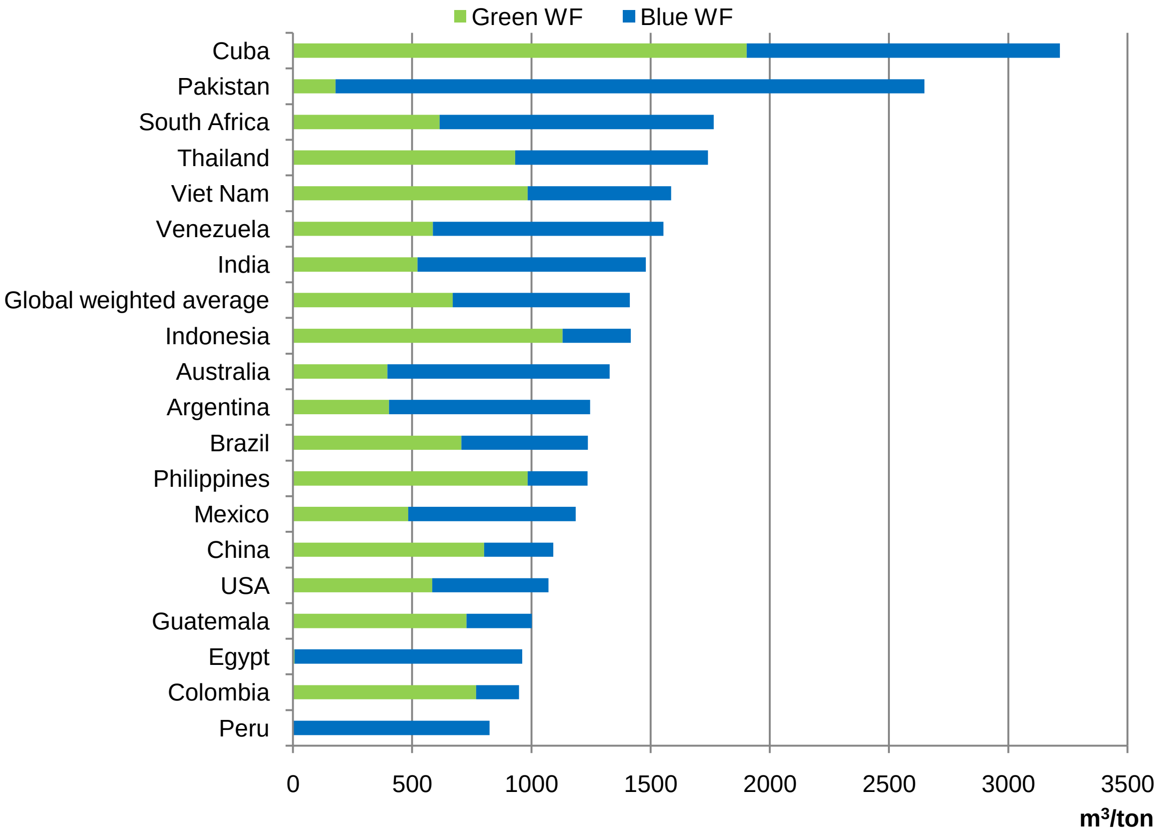

*Figure 19. Water footprint of cane sugar, classified by green and blue water footprint.*

Figure 20 presents the WF of cane sugar, adding the grey WF. It can be seen that the application rate of nitrogen, with the nitrogen standard used for grey WF calculation, does not result in big differences between the countries. The proportion of the grey WF varies between 4% and 11% of the total WF. Some minor differences occur between certain countries, resulting in a different order in the classification of countries from small to large WF's (compare Figure 19 and Figure 20). The total WF of cane sugar varies between 3340 $m^3$/ton (l/kg) in Cuba and 877 $m^3$/ton in Peru. The WF of cane sugar produced in Brazil, world's largest producer, is 1284 $m^3$/ton of sugar. The WF's of all sugar cane (by-) products, for all selected countries are presented in Appendix IX: Water footprint of sugar and crop by-products'. Process water use (PWU) is not included in the WF here. In some areas however, intake of process water from surface or groundwater is a problem for both plant and environment. Taking PWU into account approximately 5 $m^3$ per ton of sugar produced has to be added to the WF in case of process water recycling and 120 $m^3$ in case of no recycling. Most sugar factories do have some degree of recycling however. The amount of process water used, for both sweetener and ethanol from sugar crops and maize, is approximately the same. The extra amount that should be added to the WF due to PWU mentioned in this paragraph can be added to the ethanol WF as well.

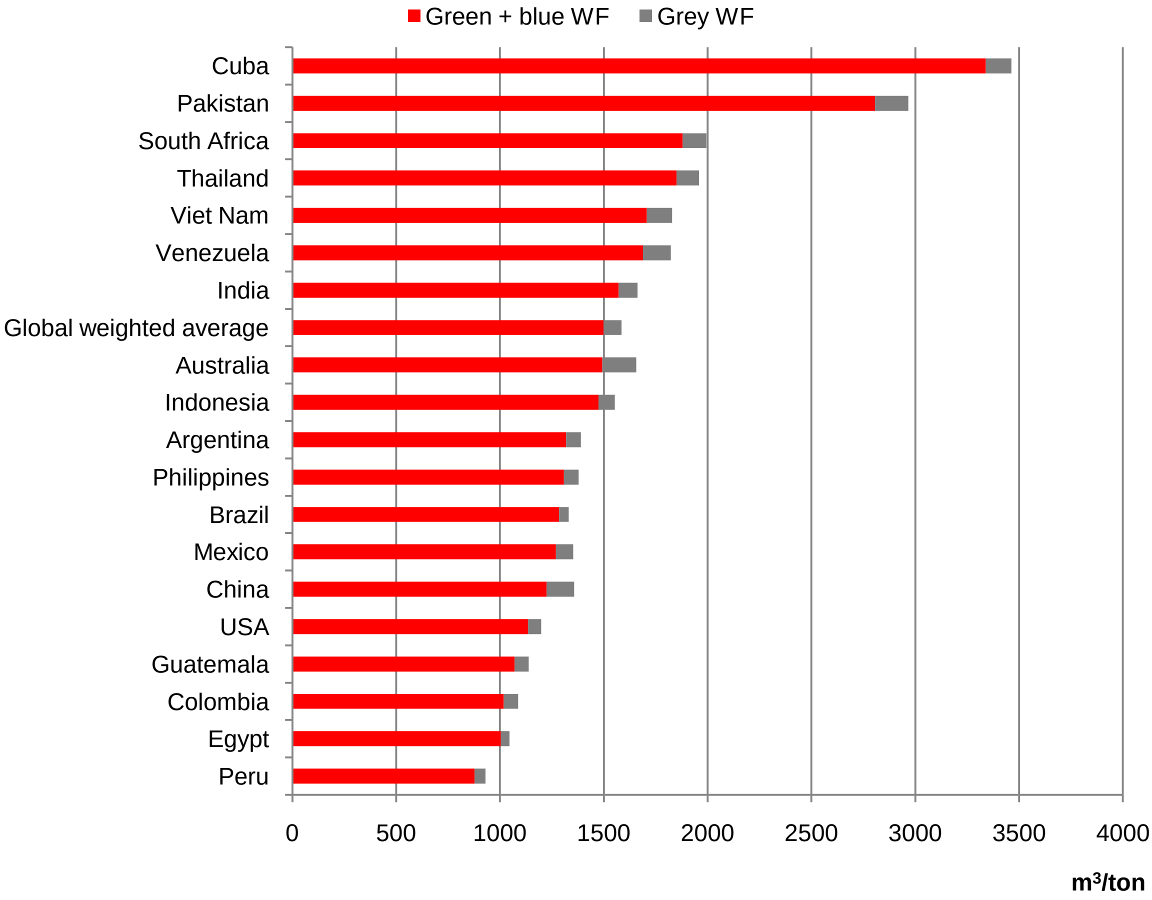

*Figure 20. The total (green + blue) water footprint of cane sugar adding the grey water footprint.*

### *5.2.2 Sugar beet*

In accordance with the WF of sugar cane and cane sugar, the results for sugar beet are presented in this paragraph. For all main producing countries the yearly production quantities and their share in total annual sugar beet production is presented in ‘

Appendix VII: Crop production’. The results for the WF for unprocessed sugar beet are found in ‘Appendix VIII: Water footprint of unprocessed crops’ and for beet sugar and sugar beet by-products the results are listed in ‘Appendix IX: Water footprint of sugar and crop by-products’.

A large part of world’s sugar beet is grown on the European continent, with France and Germany in Western Europe as main producers and the Russian Federation and Ukraine among others in Eastern Europe. Europe’s large production quantity is succeeded by the USA. In Asia, China, Iran and Japan are the main producers. Sugar beet cultivation in Africa is limited and concentrated in mainly Egypt and Morocco. The production in South America is limited as well.

Figure 21 presents the WF of unprocessed sugar beet for the twenty main producing countries. Iran has the largest WF and is almost completely dependent on irrigation. The large WF of Ukraine and the Russian Federation is imputed to a very low yield (21.2 ton/ha and 23.4 ton/ha) since the CWR of both countries are not extremely high (623 and 494 mm/cropping season). Countries like France (518 mm/cropping season) and Japan (519 mm/cropping season) have similar CWR’s but significantly lower WF’s. Low yields in Ukraine and the Russian Federation are, among other factors, most likely due to a short period with minimum temperatures necessary for sugar beet cultivation. All north-western European countries have relatively small WF due to favourable climate conditions and high yields.

The national sugar beet WF is a result of national annual production and the WF of sugar beet. Due to large production quantities and large sugar beet WF’s Ukraine and the Russian Federation have high national sugar beet WF’s. The USA, as world’s second largest producer needs 5.2 billion $m^3$ to produce its sugar beet. France’ sugar beet cultivation consumes only 3.0 billion $m^3$ to produce even more tons of sugar beet. The national WF for sugar beet for all countries is presented in Figure 22.

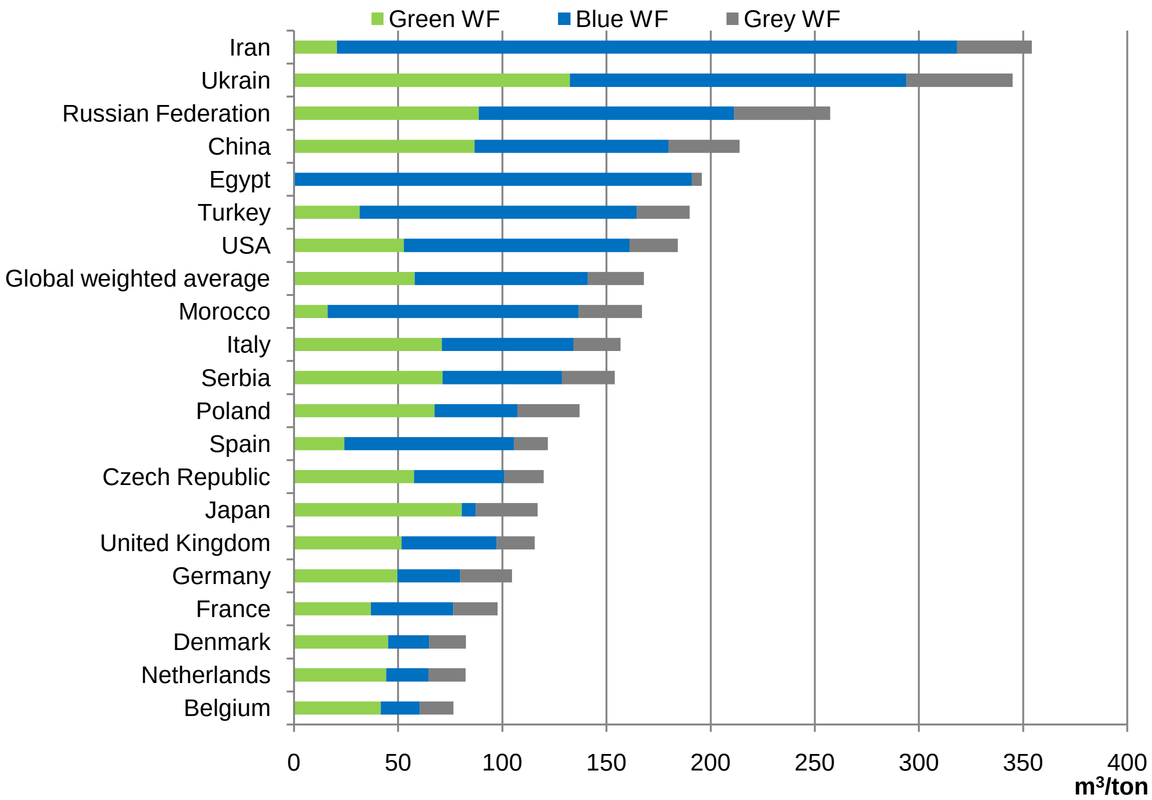

*Figure 21. Water footprint of unprocessed sugar beet, classified by green, blue and grey water footprint*

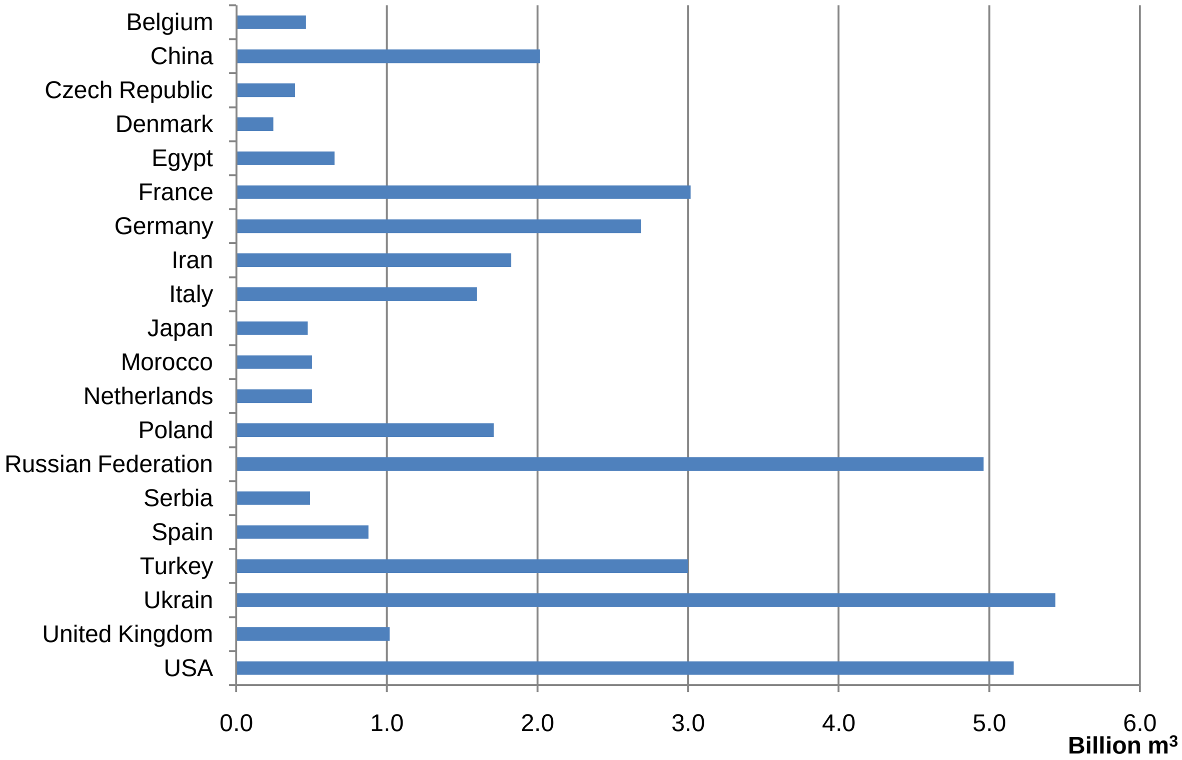

*Figure 22. The total national water footprint for sugar beet for the main producing country.*

Figure 23 presents the green and blue WF-components of beet sugar for the selected countries. In Figure 24 the grey WF is added to the green and blue WF which does not result in new large differences between countries. The grey WF varies between 26 $m^3$/ton of sugar produced (Egypt) and 280 $m^3$/ton (Ukraine). The countries with large WF's (Iran, Ukraine, Russian Federation and China) appear to have large grey WF's as well. Taking PWU into account, an extra 10 to 25 $m^3$ has to be added to the WF of beet sugar.

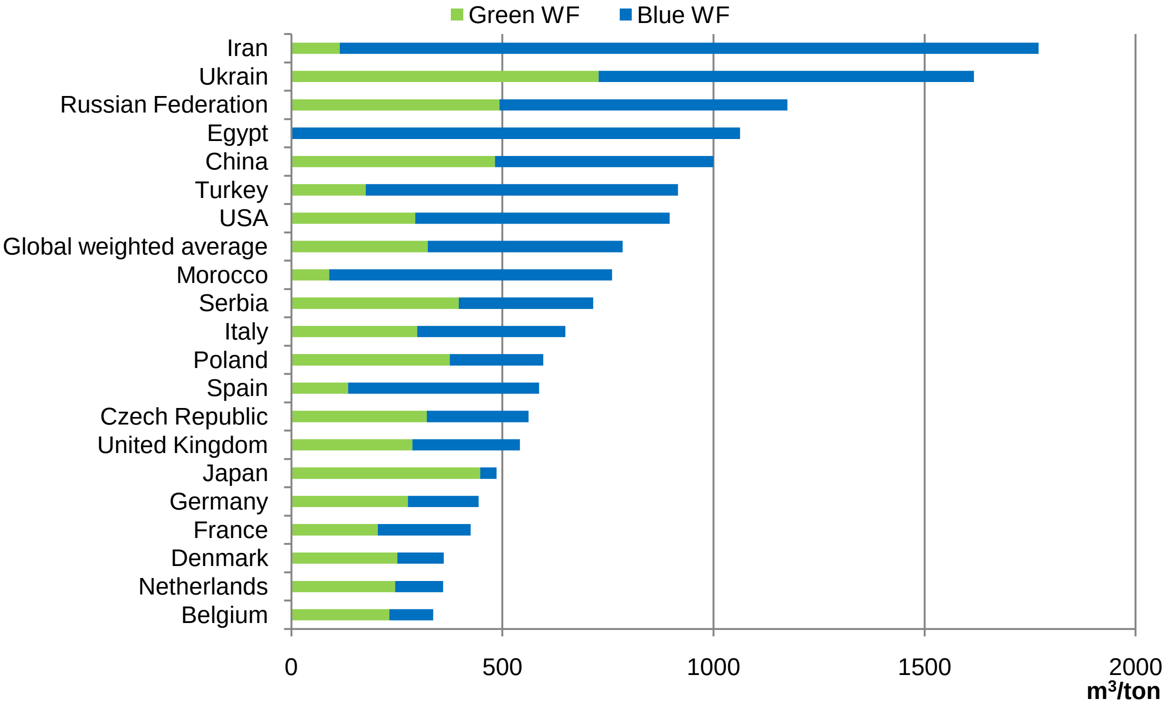

*Figure 23. Water footprint of beet sugar, classified by green and blue water footprint.*

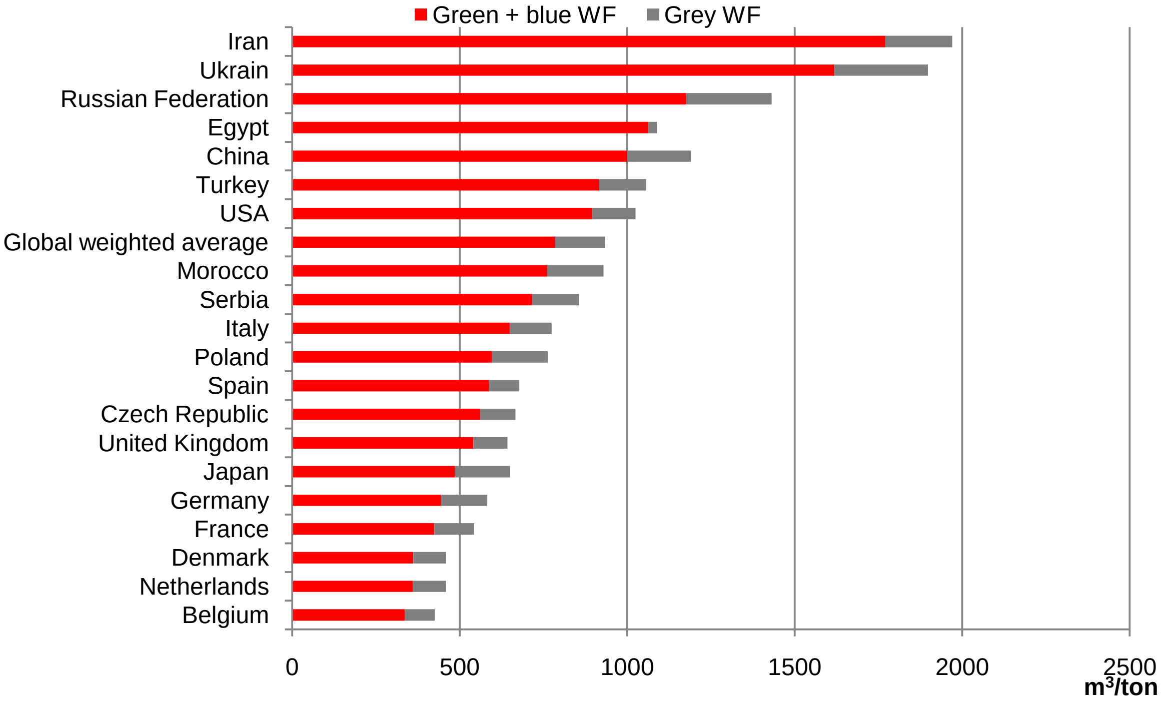

*Figure 24. The total (green + blue) water footprint of beet sugar adding the grey water footprint.*

### *5.2.3 Maize*

In order to compare the WF of sugar with the WF of HFMS, the relative sweetness of both sweeteners is compared. HFMS 55 has approximately the same sweetness equivalent as sugar, so WF calculations are performed for this composition of HFMS. Since maize is only competitive with sugar crops in the USA, for both sweetener and ethanol production, first a detailed study tot the WF of HFMS 55 and maize-based ethanol in the USA is performed. Subsequently the WF of those products in the nineteen other main maize producing countries is calculated. This calculation is based on CWR's as computed by Gerbens-Leenes et al. (2008). These CWR's are, in contrast to the WF calculations in the rest of this study, based on a single weather station located in one of the major production locations within a country.

#### *5.2.3.1 USA*

Figure 25 presents the total WF of unprocessed maize, determined with the information of sixteen weather stations in some of the main producing states. The CWR's vary between 492 mm/cropping season (Duluth, MN) and 694 mm/cropping season (Lincoln, NE) and yields between 14.1 ton/ha (Burlington, NC) and 23.5 ton/ha (Chicago and Moline, both IL). The WF varies between 291 $m^3$ per ton of maize in Duluth (MN) and 465 $m^3$/ton in Burlington (NC). The grey WF is lowest in Green Bay (WI), 48 $m^3$/ton and Madison (WI) and highest in Burlington, 103 $m^3$/ton. In general, states in the heart of the Corn Belt show lower WF's than the other states. The weighted U.S. average WF of unprocessed maize is 358 $m^3$/ton. A table with all WF's is found in 'Appendix VIII: Water footprint of unprocessed crops'.

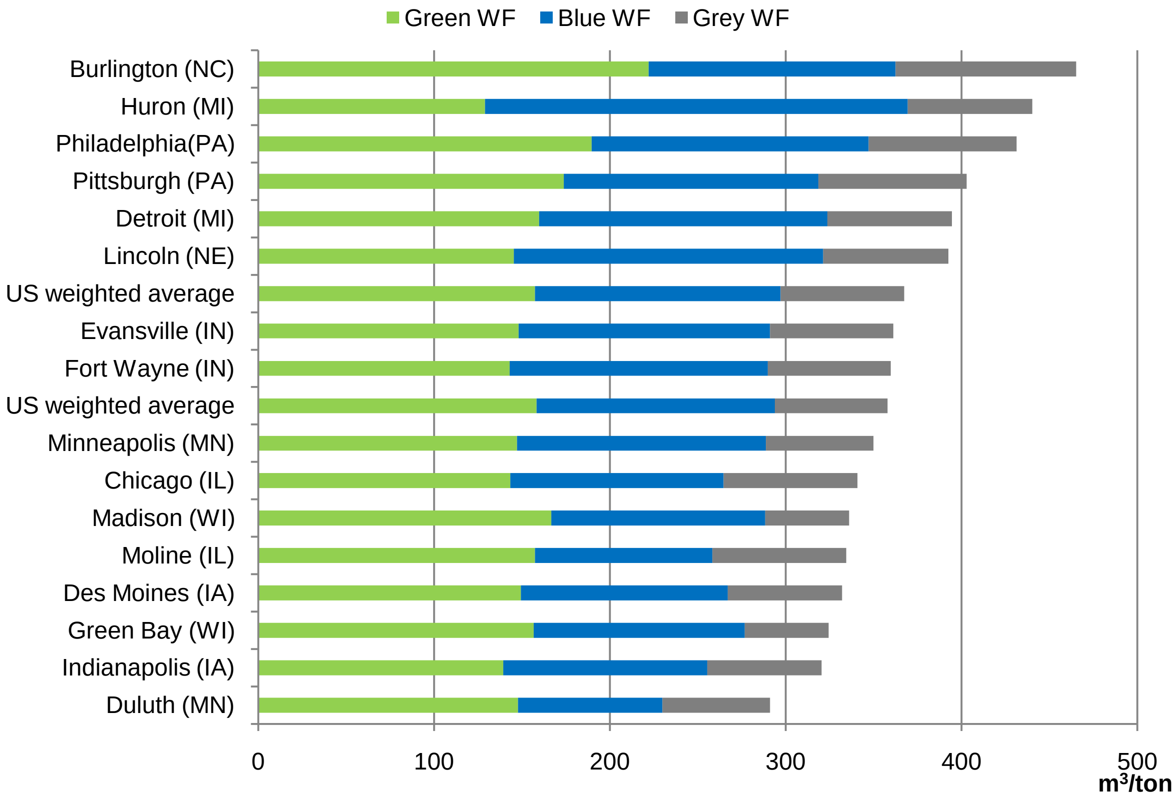

*Figure 25. Water footprint of unprocessed maize in the USA, classified by green, blue and grey water footprint.*

Figure 26 presents the WF of HFMS 55. The results obviously correspond to the values calculated for the WF of unprocessed maize. Compared to sugar produced from sugar cane and sugar beet, the grey component of HFMS 55 is relatively large. This is not a result of abundant fertilizer application in maize cultivation, but can be declared by the small amount of green and blue water compared to sugar production and the small yield of maize. The weighted U.S. average WF of HFMS 55 is 721 $m^3$/ton. The PWU in maize processing is also relatively small compared to the green, blue and grey WF of maize growing. Approximately 3 to 5 $m^3$ has to be added to the WF for PWU.

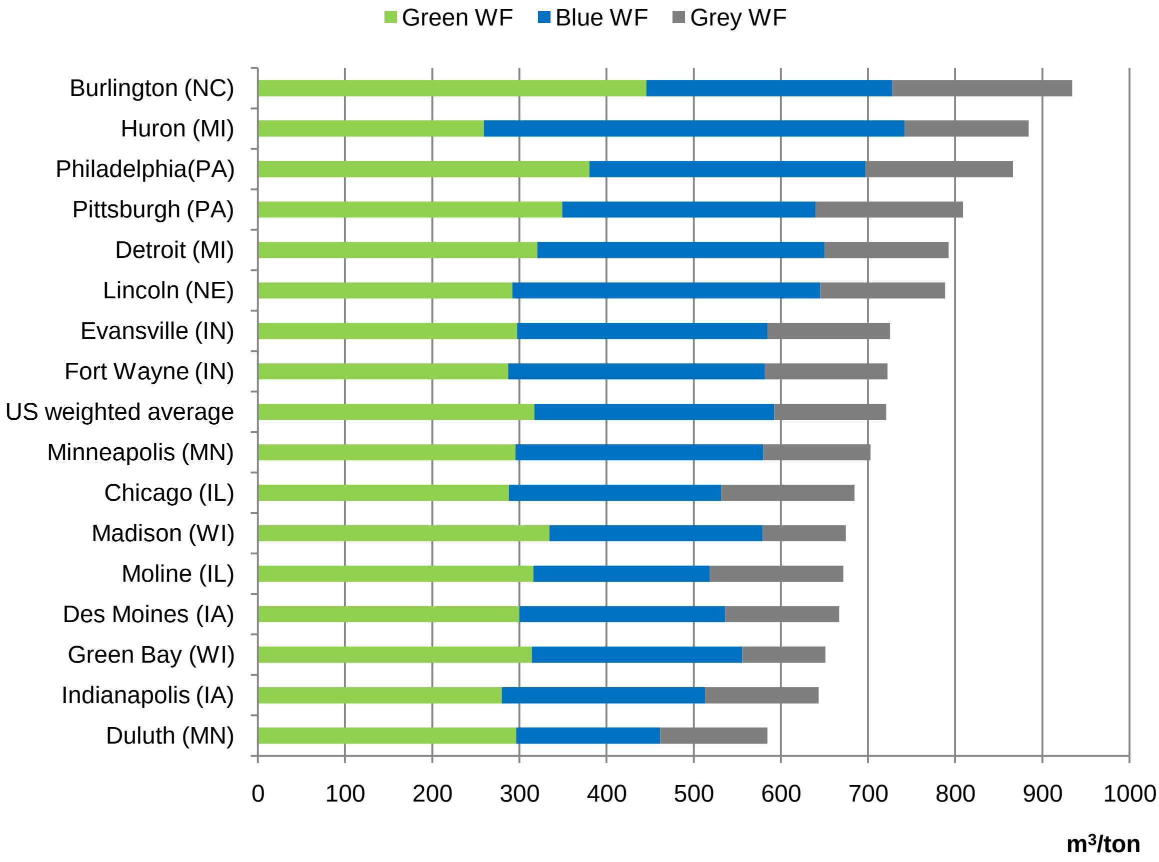

*Figure 26. Water footprint of HFMS 55 in the USA classified by green, blue and grey water footprint. The calculation of the water footprint of HFMS 55 is based on the total maize biomass, including stover.*

#### *5.2.3.2 Other countries*

The total WF of unprocessed for the twenty main producing countries is displayed in Figure 27. The WF varies between 1655 $m^3$/ton in India and 280 $m^3$/ton in Argentina. The WF in the USA, world's largest producer, is 367 $m^3$/ton and the weighted global average is 561 $m^3$/ton. Argentina profits from a favourable CWR. Countries like France, Spain, Germany and Italy report high yields resulting in relatively low WF's. Yields vary between 20.9 ton/ha in Spain and 3.3 ton/ha in Nigeria. The grey WF varies between 7 $m^3$/ton in Indonesia and 139 $m^3$/ton in Egypt. Countries like Ukraine, Romania, Nigeria and Egypt are highly dependent on irrigation, with less than 40% of the WF covered by green water. A table with the WF's of unprocessed maize in the twenty main producing countries is displayed in 'Appendix VIII: Water footprint of unprocessed crops'.

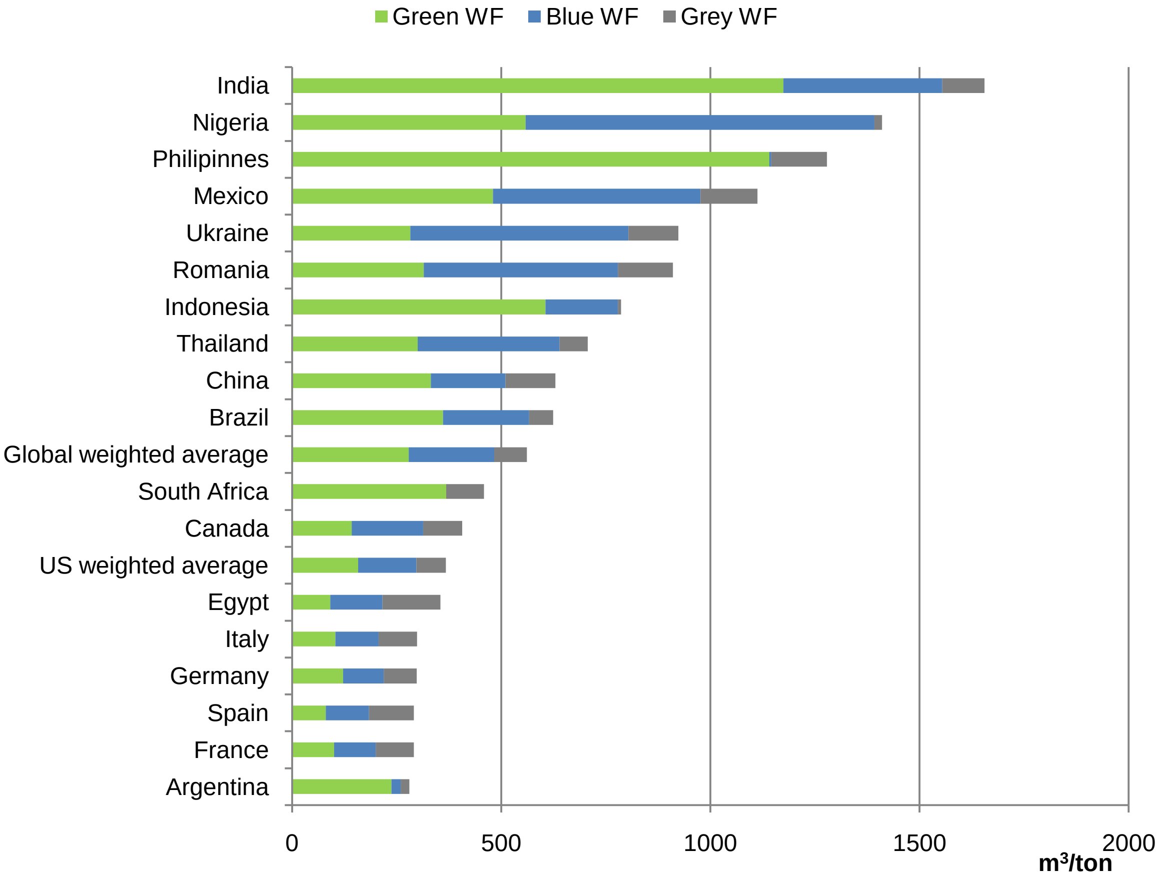

*Figure 27. Water footprint of unprocessed maize, classified by green, blue and grey water footprint. Calculations are based on CWR's as computed by Gerbens-Leenes et al. (2008), except for the weighted U.S. average water footprint. The calculation of the water footprint of HFMS 55 is based on the total maize biomass, including stover.*

Figure 28 presents the WF of HFMS 55 classified by green, blue and grey WF for the twenty main producing countries. HFMS produced in India has the highest WF (3324 m$^3$/ton) and Argentina appears to have the lowest WF (563 m$^3$/ton). The weighted global average WF of HFMS 55 is 1126 m$^3$/ton. The WF of HFMS 55 and all derived by-products in HFMS production for the displayed countries are summarized in Table 47 and Table 48 in 'Appendix IX: Water footprint of sugar and crop by-products'

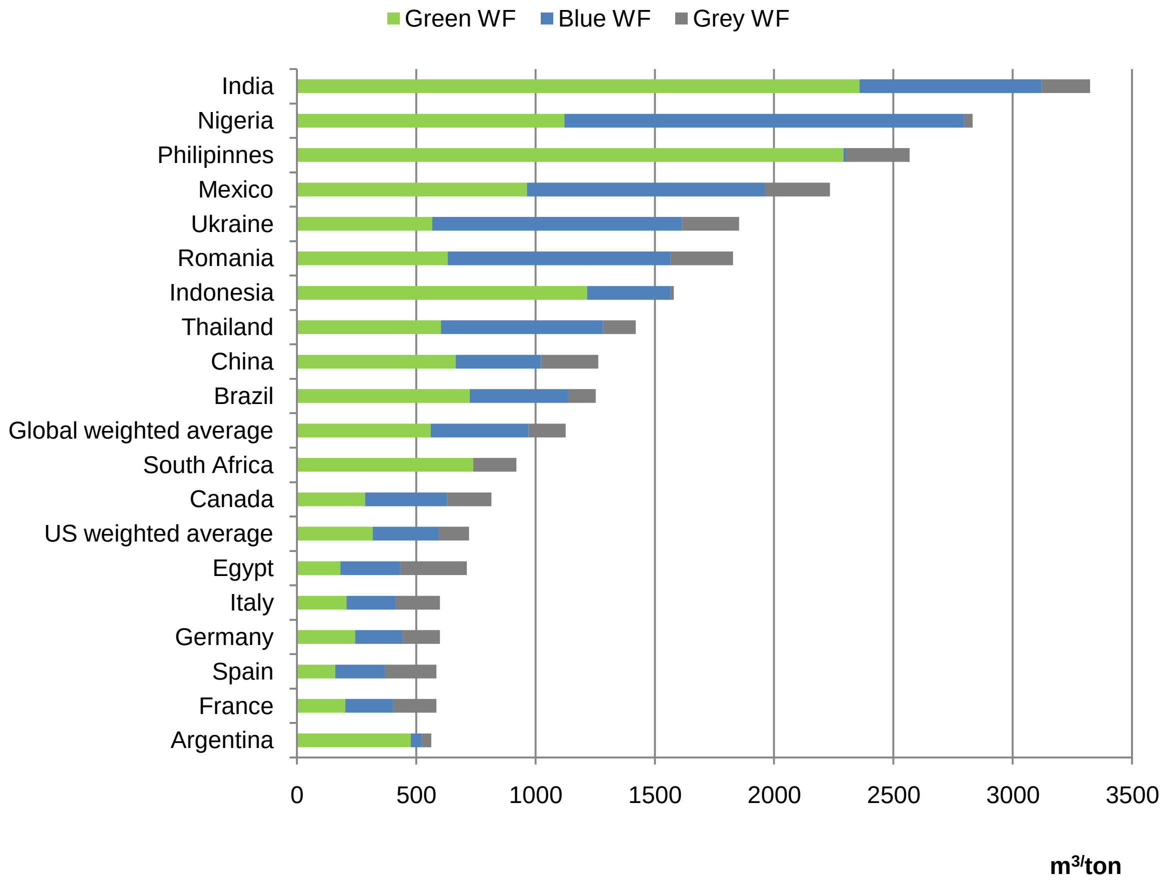

*Figure 28. Water footprint of HFMS 55, classified by green, blue and grey water footprint. Calculations are based on CWR's as computed by Gerbens-Leenes et al. (2008), except for the weighted U.S. average water footprint. The calculation of the water footprint of HFMS 55 is based on the total maize biomass, used for the production of several (by-) products, under which HFMS 55.*

### *5.2.4 Sweetener comparison*

Since the WF's of sugar, produced from sugar cane and sugar beet, and HFMS 55 are known the results can be compared. The sweetness of all commodities is equal, so HFMS 55 can be compared to both beet and cane sugar. Figure 30 once more presents the WF of all sweeteners and their feedstocks for the main producing countries. Obviously there is large variance between the WF of sugar from the same feedstock cultivated on different locations. The WF of cane sugar in Cuba is almost four times as large as the WF of cane sugar in Peru. For beet sugar the difference in WF is approximately factor 5 between Belgium and Iran.

Considering Figure 30, in general, the WF of cane sugar is larger than the WF of beet sugar. Peru, with the smallest cane sugar WF (877 $m^3$/ton), has a larger WF then most European countries. Brazil, world's largest cane sugar producer, has a WF of 1284 $m^3$/ton, which is comparable with the beet sugar WF's of China (1190 $m^3$/ton) and the Russian Federation (1432 $m^3$/ton). The weighted global average WF for beet sugar is 935 $m^3$/ton, 1499 $m^3$/ton for cane sugar and 1126 $m^3$/ton for HFMS 55.

Figure 29 shows the WF of beet sugar, cane sugar and HFMS 55 in the USA. The weighted U.S. average WF of HFMS 55 is 721 $m^3$/ton. Unlike the global averages, in the USA HFMS 55 has the smallest WF.

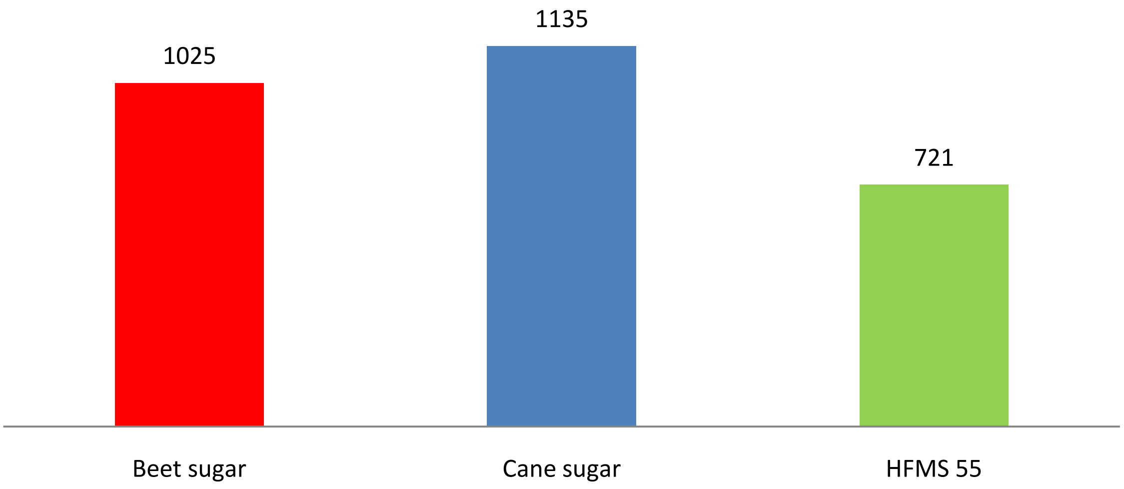

*Figure 29. The water footprint of three sweeteners in the USA: beet sugar, cane sugar and HFMS 55 ($m^3$ water/ton of sweetener)*

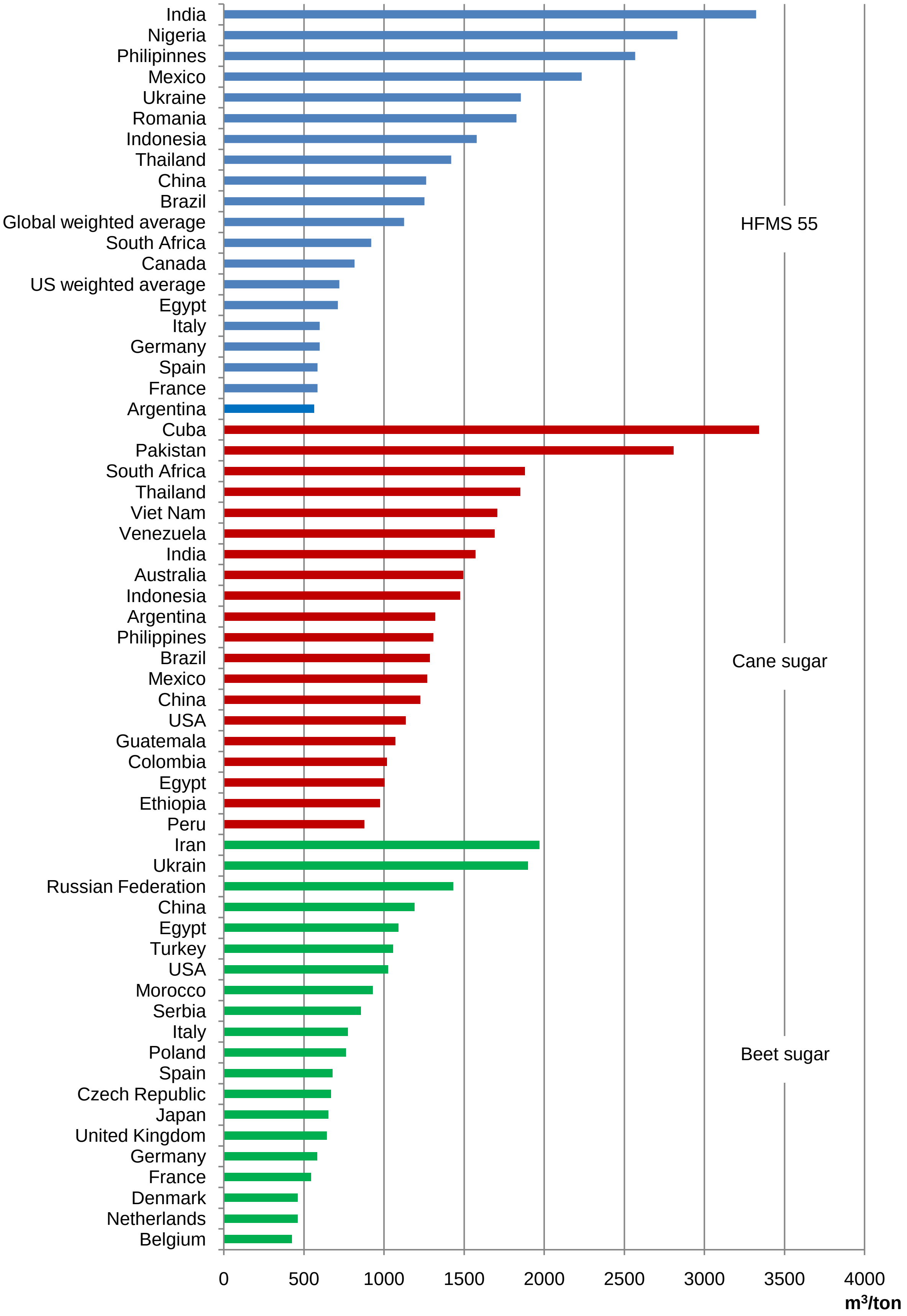

*Figure 30. Water footprint of cane and beet sugar and HFMS 55 for all selected locations, including the grey water footprint.*

## 5.3 The water footprint of ethanol

The calculation of the ethanol WF for all three feedstocks is based on the CWR's and yields as used for the calculation of the sweetener WF's. The WF of the unprocessed crops is listed in 'Appendix VIII: Water footprint of unprocessed crops'. In this paragraph, first the results of the ethanol WF calculations for the three crops are presented. Next the results are mutually compared. Finally the results will be compared to a study by Gerbens-Leenes et al. (2008).

### 5.3.1 Sugar cane

Since the WF of ethanol is based on the same WF's of unprocessed crops this study uses for the calculation of the sugar and HFMS 55 WF, there will be many similarities regarding the magnitudes of the sweetener and ethanol WF's for each country. Also the proportion of blue water, compared to that of green water, needed for the production of ethanol will correspond to the proportion of blue water needed for the production of sugar and HFMS 55. Figure 31 shows the WF's of cane-based ethanol for the twenty main producing countries. The WF of cane ethanol and its by-products is presented in Table 49 of '

Appendix X: Water footprint of ethanol and crop by-products’. Like sugar production, from a water point of view, production of ethanol is most favourable in Peru, Colombia and Egypt. Egypt and Peru however are highly dependent on irrigation, whereas Colombia, Guatemala and China have the favour of a lot more precipitation. Pakistan requires a large amount of water for the production of ethanol, of which over 90% is blue water.

The proportion of grey water required for the production of cane ethanol is limited, as can be seen in Figure 32. The grey WF varies between 62 l water/l ethanol produced (Egypt) and 246 l/l (Australia). On average the grey WF accounts for approximately 6% of the total WF. The weighted global average total WF of cane ethanol is 2855 l water/l ethanol produced.

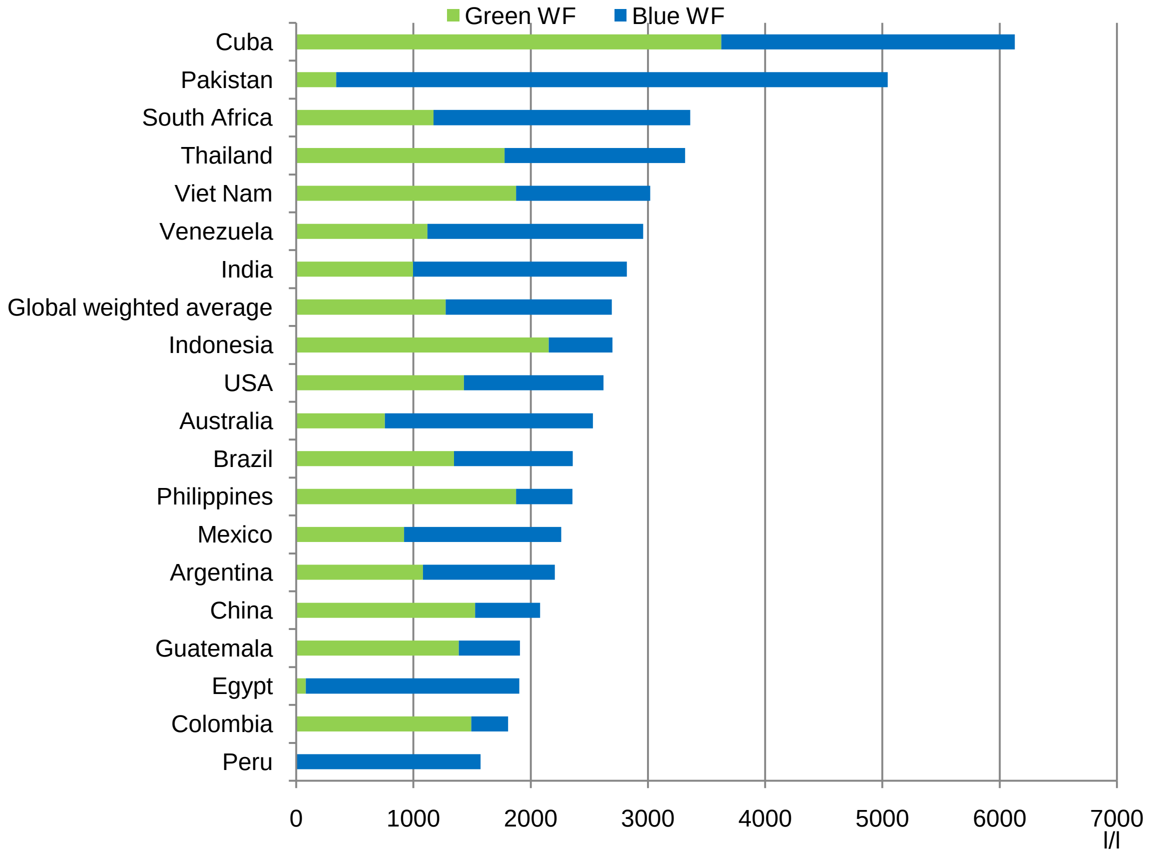

*Figure 31. Water footprint of cane-based ethanol, classified by green and blue water footprint.*

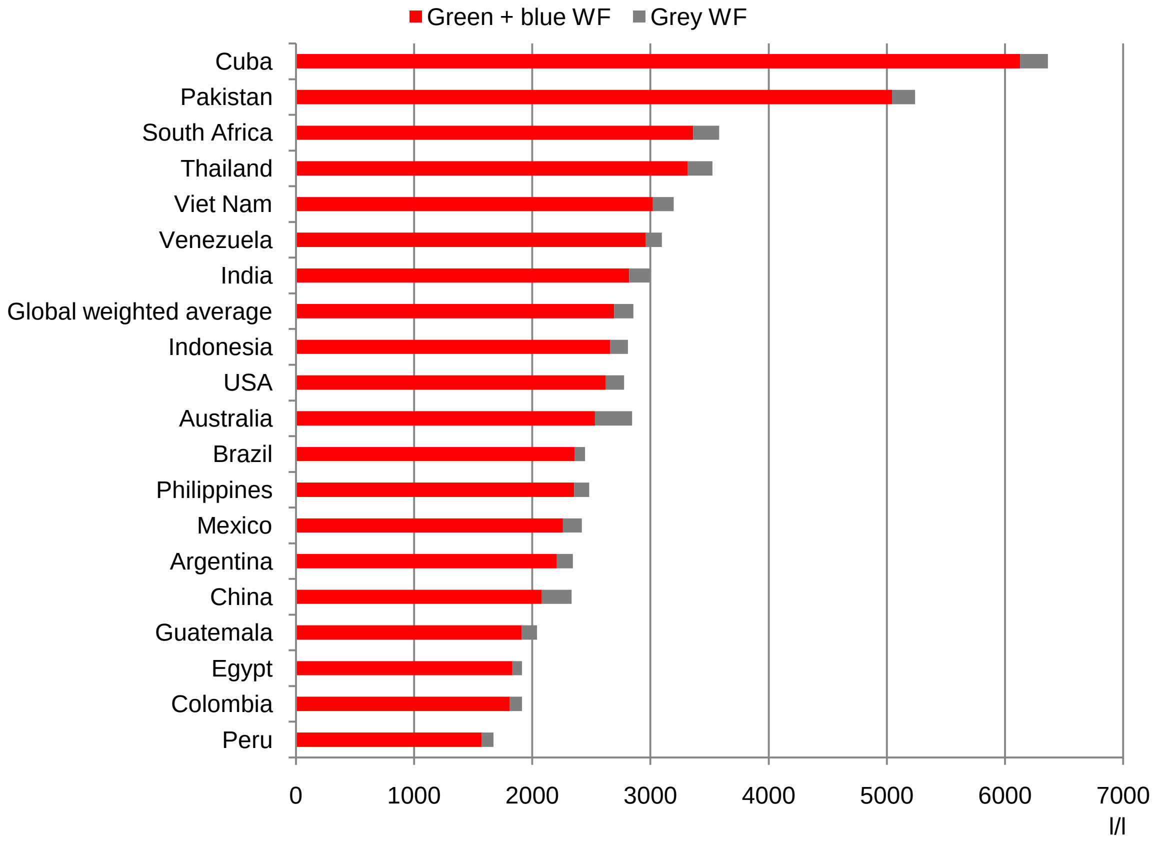

*Figure 32. The total (green + blue) water footprint of cane-based ethanol including the grey water footprint.*

### 5.3.2 Sugar beet

For the production of one litre of ethanol from sugar beet, far less water is required compared to the production with sugar cane as feedstock. The weighted global average of beet based ethanol is 1355 l water/ l ethanol produced. Figure 33 presents the green and blue WF of beet-based ethanol for the twenty main producing countries. For most countries in western and middle Europe and Japan, more than half of the WF is provided by green water. For Mediterranean countries, the Russian Federation, Ukraine and Iran as well as China, the USA and France, irrigation should meet more than half of the water requirement.

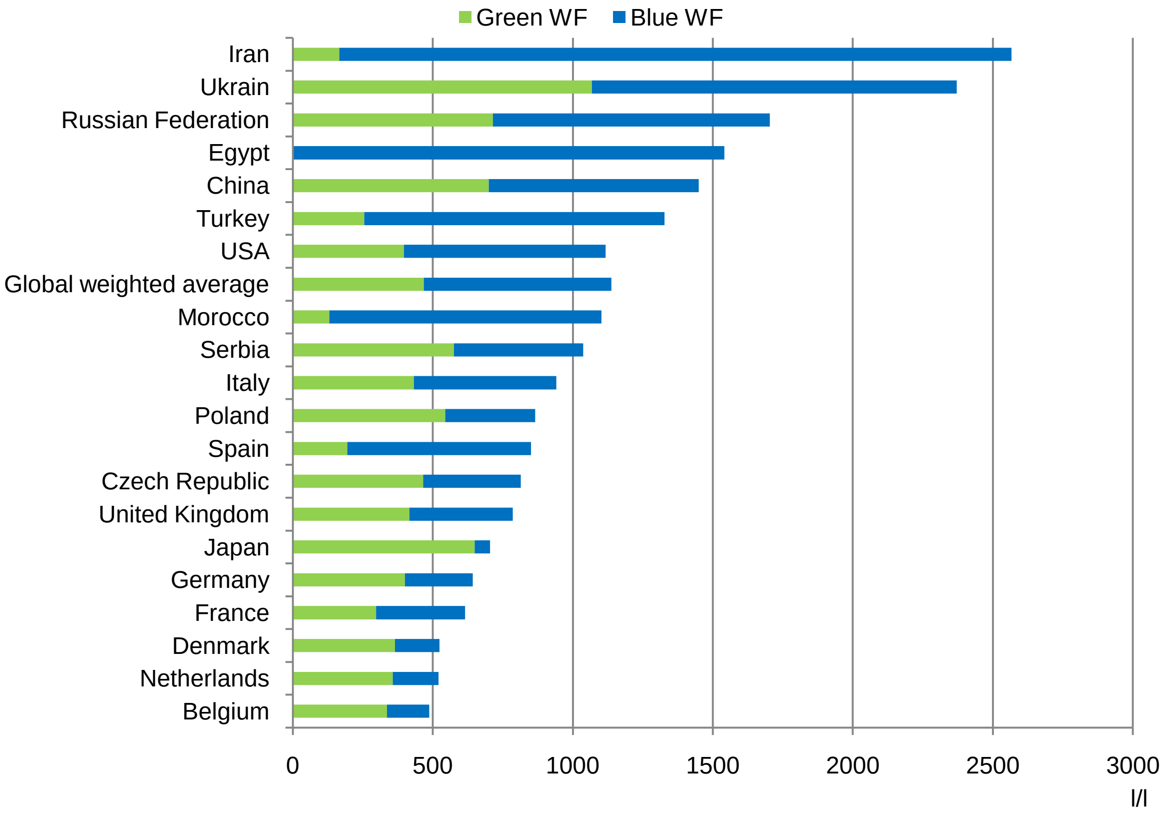

*Figure 33. Water footprint of beet-based ethanol, classified by green and blue water footprint.*

The grey WF of beet-based ethanol varies between 38 (Egypt) and 411 l water/l ethanol (Ukraine). Egypt is, like with sugar cane cultivation, again the country that needs least dilution water for nitrogen application. Figure 34 shows all grey water components compared to the total of green and blue WF.

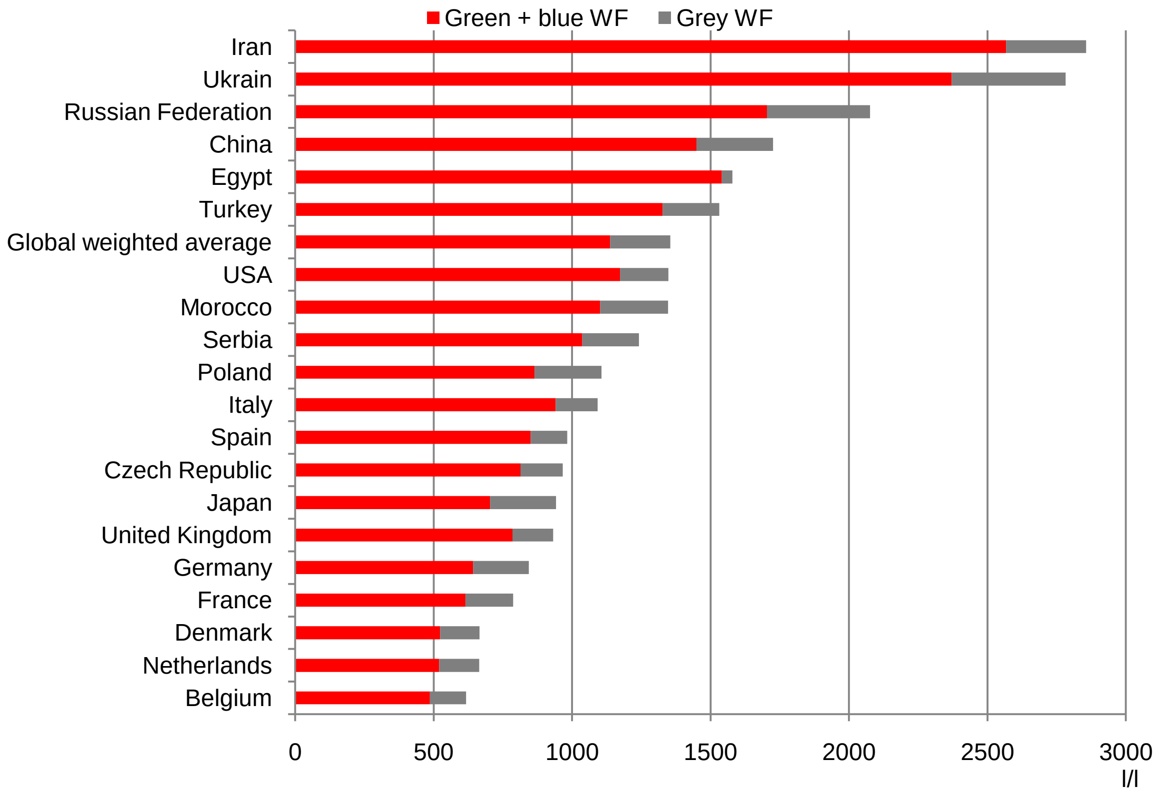

*Figure 34. The total (green + blue) water footprint of beet-based ethanol including the grey water footprint.*

### *5.3.3 Maize*

For the production of ethanol two production processes are evaluated, wet and dry milling. Most U.S. maize-based ethanol is produced by dry milling. By wet milling however it is possible to produce HFMS as well. For this study the WF for both production methods is calculated.

#### *5.3.3.1 USA*

Figure 35 presents the WF of maize-based ethanol in the USA produced by wet and dry milling. As can be seen the difference between both production methods is relatively small. Although the name of the production methods perhaps suggest the WF in a wet milling process is higher, the opposite is true. Due to the high values of wet milling by-products, the ethanol WF in a wet milling process is approximately 3% smaller than the ethanol WF in a dry milling process.

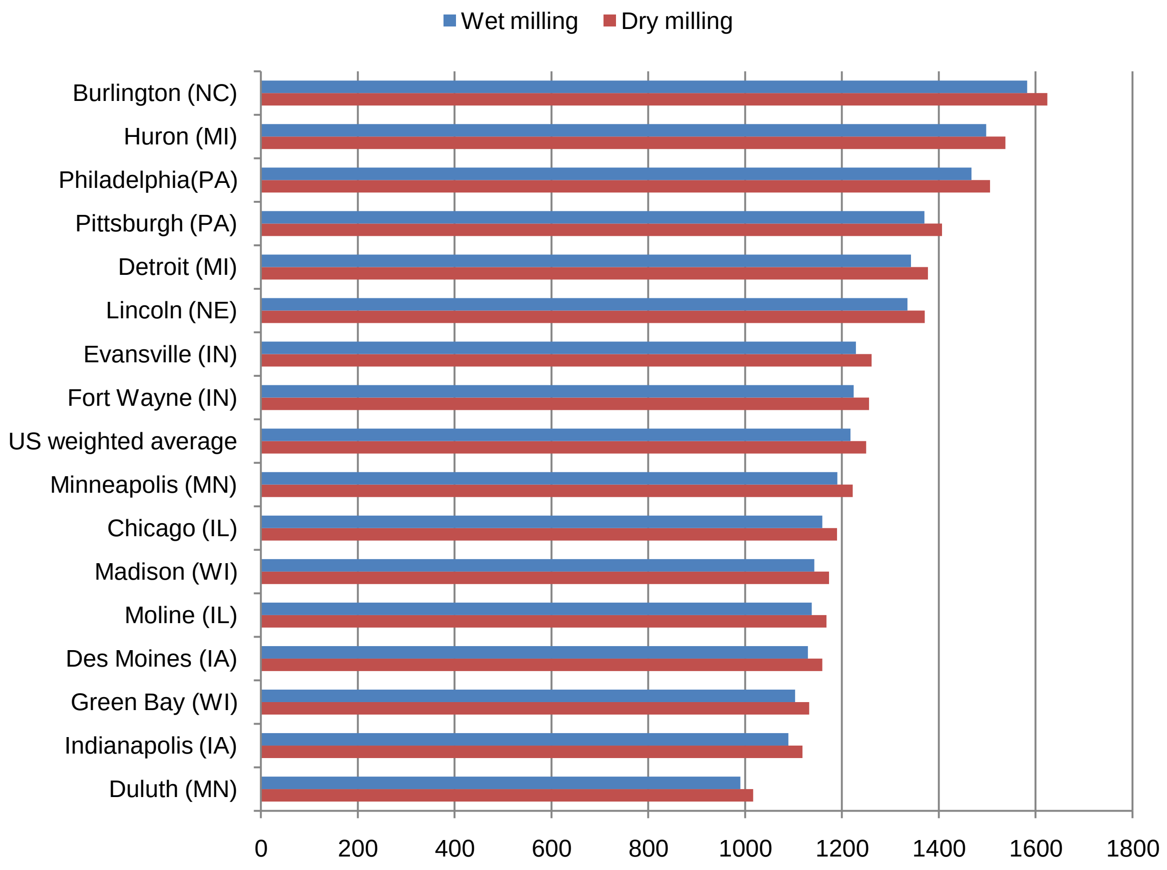

*Figure 35. The water footprint of maize-based ethnaol in the USA produced by wet and dry milling.*

Figure 36 presents the green and blue WF of maize-based ethanol produced by wet milling. On average half of the required water (green and blue) for the production of maize based ethanol is provided by precipitation. The weighted U.S. average green WF is 54% of the total WF of 1004 l water/l ethanol produced, excluded the grey WF. The low value for the WF of maize-based ethanol in the USA, compared to other studies, is remarkable. The background of this difference will be shown in paragraph 5.3.4 of this chapter and will be discussed in chapter 0.

The grey WF is a relatively large component of the total WF (Figure 37), approximately 18%. The grey WF varies between 162 l/l (Wisconsin) and 287 l/l (Philadelphia). Fertilizer application rates are lowest respectively highest in those states as well.

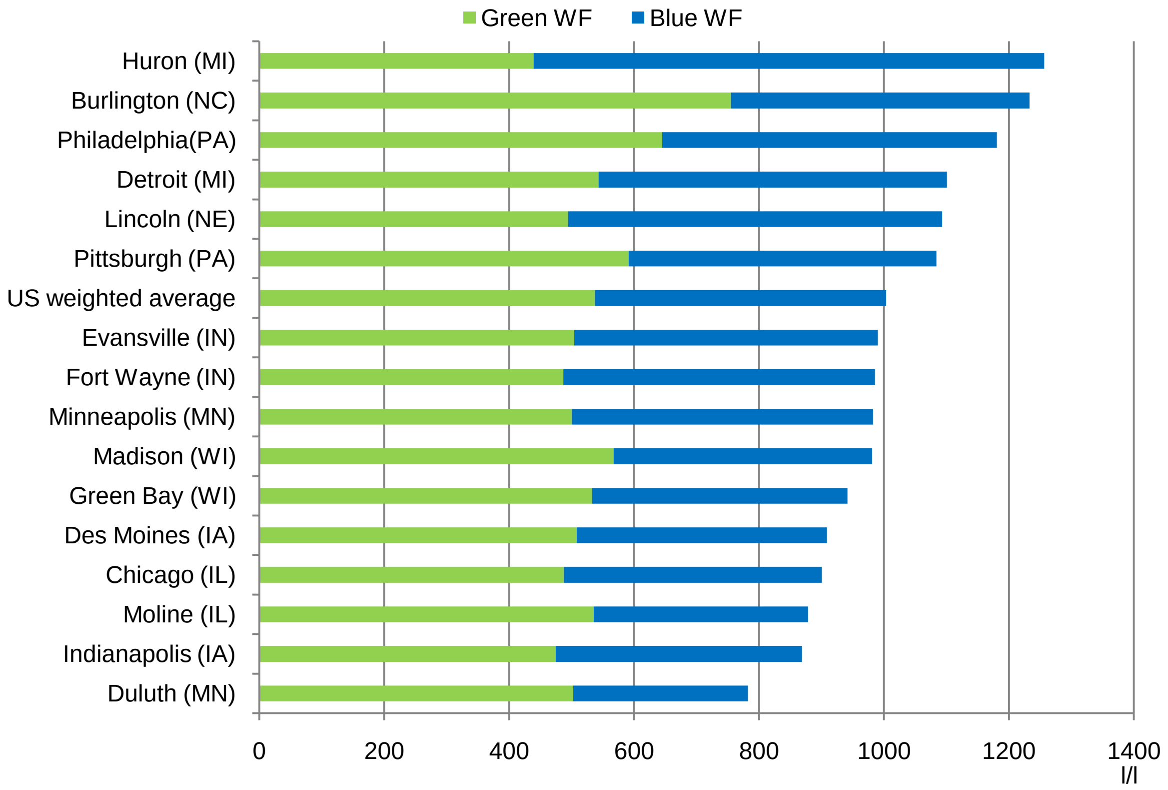

*Figure 36. Water footprint of maize-based ethanol in the USA produced by wet milling, classified by green and blue water footprint. The calculation of the water footprint of ethanol is based on the total maize biomass, including stover.*

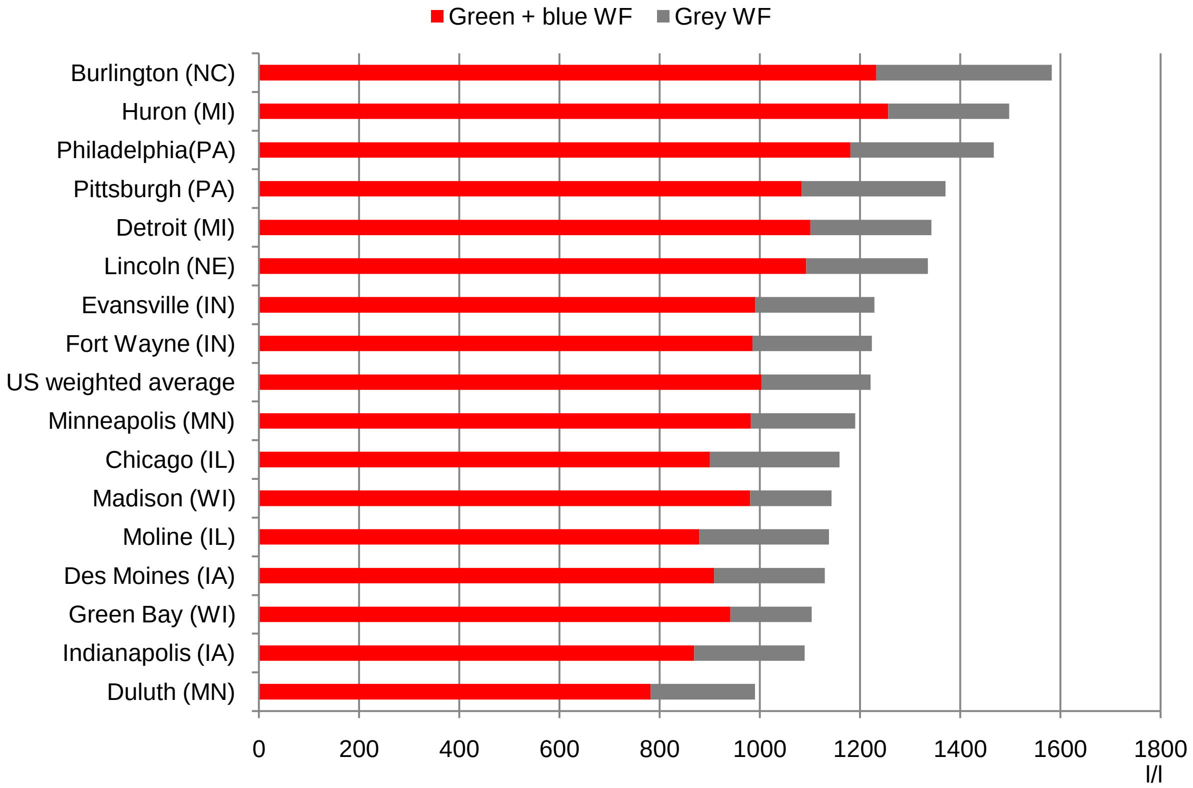

*Figure 37. The total (green + blue) water footprint of maize ethanol in the USA produced by wet milling adding the grey water footprint. The calculation of the water footprint of ethanol is based on the total maize biomass, including stover*

The total WF of maize-based ethanol produced by dry milling is shown in Figure 38. The WF is divided in a green, blue and grey component.

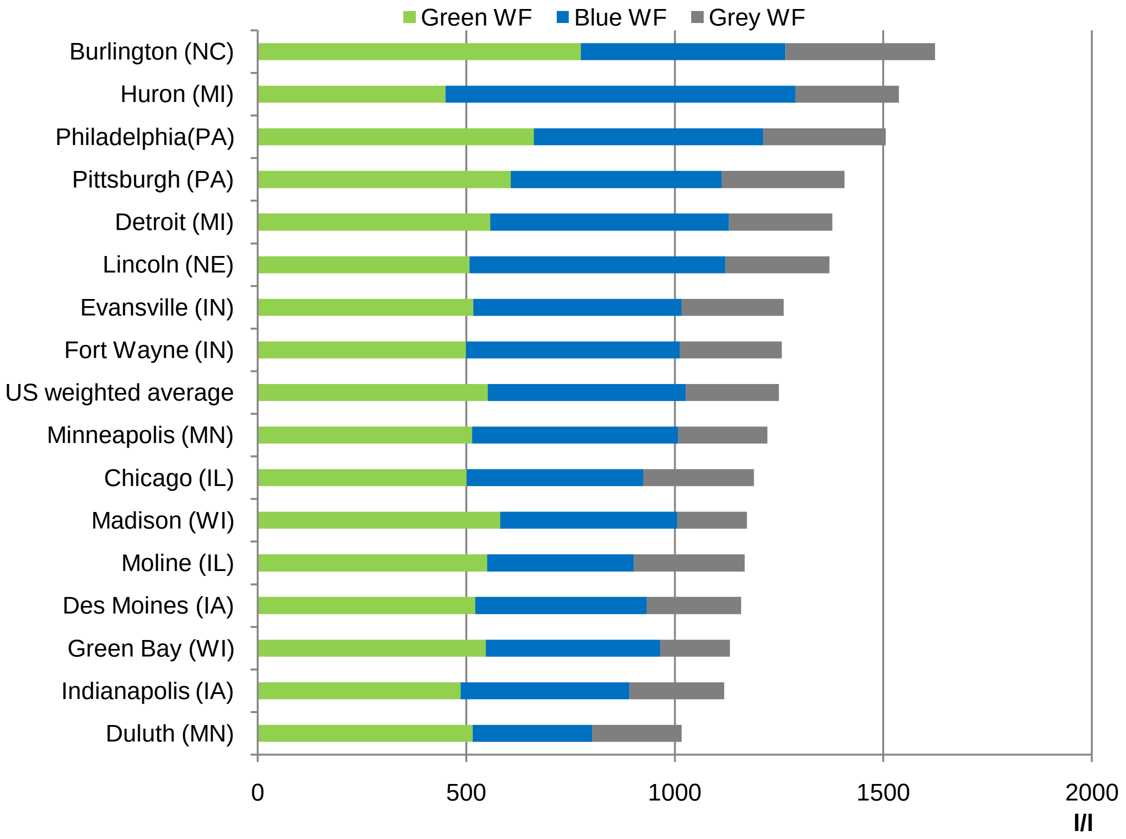

*Figure 38. The total water footprint of maize-based ethanol in the USA produced by dry milling classified by green, blue and grey water footprint. The calculation of the water footprint of ethanol is based on the total maize biomass, including stover*

### *5.3.3.2 Other countries*

The WF of maize-based ethanol produced by both wet and dry milling for the main producing countries is listed in tables in ‘

Appendix X: Water footprint of ethanol and crop by-products'. The total WF of both production methods is graphically presented in Figure 39. The three components of the WF for a wet milling production process are displayed in Figure 40. The order of magnitude of the three components for the dry milling process are the same as those presented in this figure.

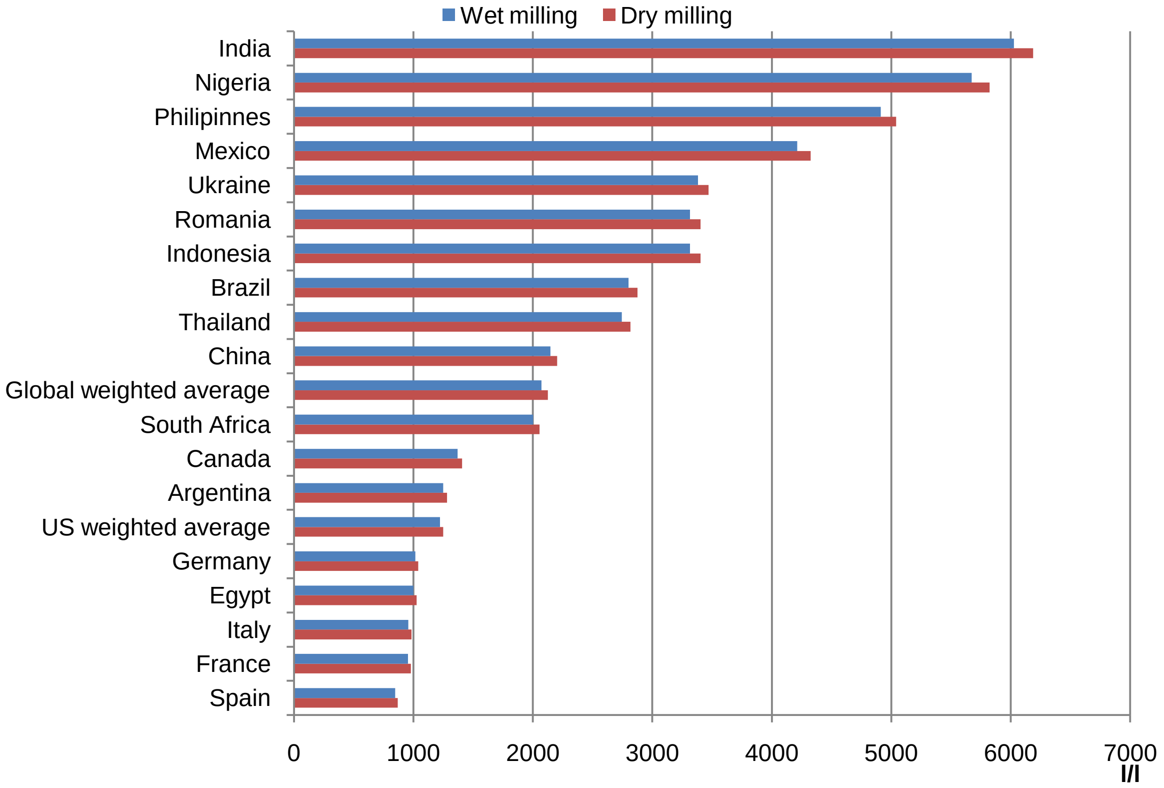

*Figure 39. The water footprint of maize-based ethnaol in the twenty main producing countries produced by wet and dry milling.*

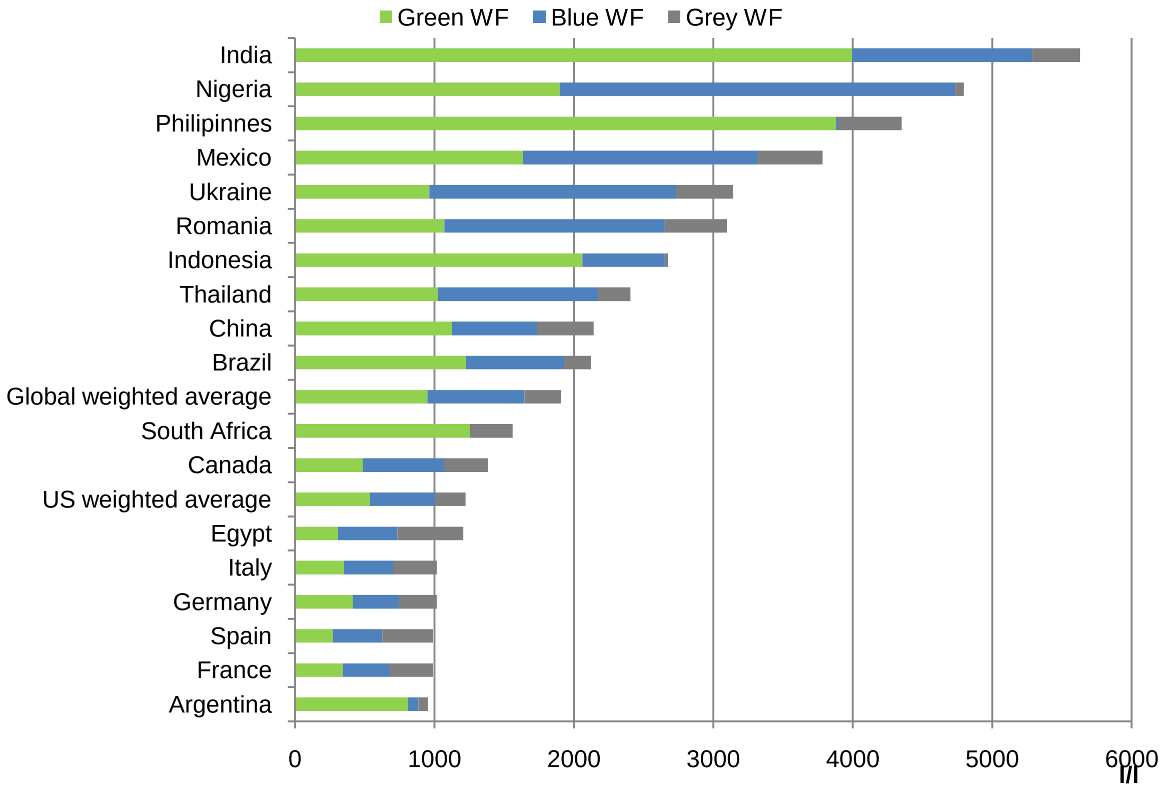

*Figure 40. Water footprint of maize-based ethanol produced by wet milling, classified by green and blue water footprint. Calculations are based on CWR's as computed by Gerbens-Leenes et al. (2008), except for the weighted U.S. average water footprint. The calculation of the water footprint of ethanol is based on the total maize biomass, including stover*

### 5.3.4 Ethanol comparison

Figure 42 presents the ethanol WF of the two sugar crops and maize (dry milling) for the main producing countries. Ethanol production from sugar beet is, considering water consumption, far more efficient than production from sugar cane. The weighted global average WF of cane-based ethanol (2856 l water/l ethanol) is 211% of the weighted global average beet-based ethanol WF (1355 l water/l ethanol). The weighted global average WF of maize-based ethanol is 2125 l/l, 156 % of the beet-based ethanol WF. In general, sugar cane cultivation is less dependent on irrigation than sugar beet. The proportion of the blue WF is 53% of the total WF for sugar cane and 59% for sugar beet. The impact of, mainly the blue component of, the WF on the environment will be assessed in chapter 0.

The production of maize-based ethanol in the USA is, from a water point of view, quite sufficient. The weighted average WF of maize-based ethanol in the USA is 1221 l/l, 1348 l/l for sugar beet and 2775 l/l for sugar cane. Other studies report a significantly higher WF for maize. Gerbens-Leenes et al. (2008) report a maize-based ethanol WF for the USA of 1825 l water/l ethanol (only the green and blue WF), 182% of the WF calculated in this study. The ground for this difference is dual. First, there are some differences in data used for the calculation of the WF. Gerbens-Leenes et al. use the climate data provided by Müller and Hennings (2000), while this study uses data provided by CLIMWAT 2.0 (FAO, 2006). Furthermore this study uses several weather stations in multiple states to calculate CWR's, whilst Gerbens-Leenes calculations are based on one single station for each country. Another difference in data sets is the yields used for the calculations. Gerbens-Leenes et al. use data provided by FAOSTAT, this study uses more recent data provided by the USDA (2009). The main difference regarding yield however, is the interpretation of yield and the calculation method. This is the second ground of the difference in WF.

This study makes a comparison between the two sugar crops and maize. The methodology is to divide the WF of the unprocessed crops over all products produced from the crop, by the ratio between value fraction and product fraction $\left(\frac{f_v[p]}{f_p[p]}\right)$ (

Appendix II: Water footprint calculation). Gerbens-Leenes et al. have a different approach of the WF. In their study, first the amount of energy in the form of ethanol provided by the sugar or starch content of a crop is calculated. Next, the WF of the unprocessed crop is divided by the energy delivered, resulting in the WF in amount of water per unit of energy ($m^3$/GJ). This approach does not take the value and fraction of by-products compared to ethanol into account.

In order to make a fair comparison between for example cane ethanol and maize ethanol, all by-products derived from the cultivation of both plants have to be considered. One major difference in ethanol processing is, that for cane based ethanol the whole plant is harvested and processed, while with maize only the grains are used. With sugar cane processing the sugar is extracted from the plant and the different kinds of residue are used for many purposes. All residues or by-products represent a certain proportion of the sugar cane plant and have an economic value. With maize processing only the grains are harvested and processed. This also results in several by-products with a certain value. The stover, approximately half of the mass of the maize plant, however is not harvested and is left on the land. It prevents soil erosion and serves the purpose of fertilizer, like vinasse and filter cake do for sugar cane growing. Although stover is not harvested, its economic value as fertilizer is not negligible. For this reason the stover is added to the harvested yield. Simply said, the amount of precipitation and irrigation water one hectare of land receives is not only attributed to the grains, but to the entire plant and the products derived from it. This results in a smaller WF for ethanol. All ethanol WF's calculated in this study, are listed in Table 20, Table 21 and Table 22and are compared to the Gerbens-Leenes et al. study.

Figure 41 shows the WF of three ethanol feedstocks in the USA. Maize-based ethanol has the smallest WF in the USA. The WF of maize-based ethanol in the USA is smaller than the weighted global average WF of sugar beet (1355 l/l) and sugar cane (2856 l/l) as well.

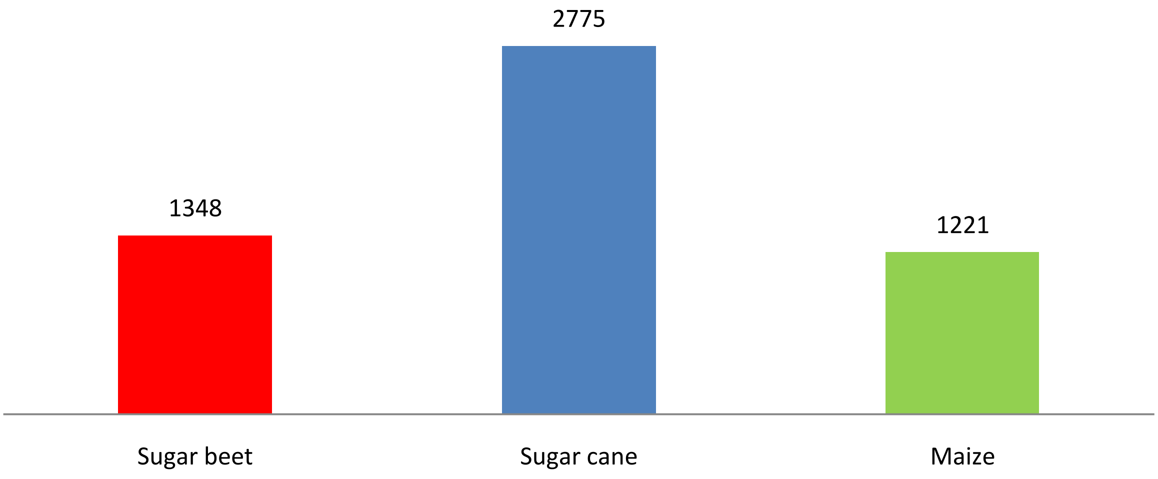

*Figure 41. The water footprint of ethanol for three different feedstocks in the USA (l water/l ethanol produced).*

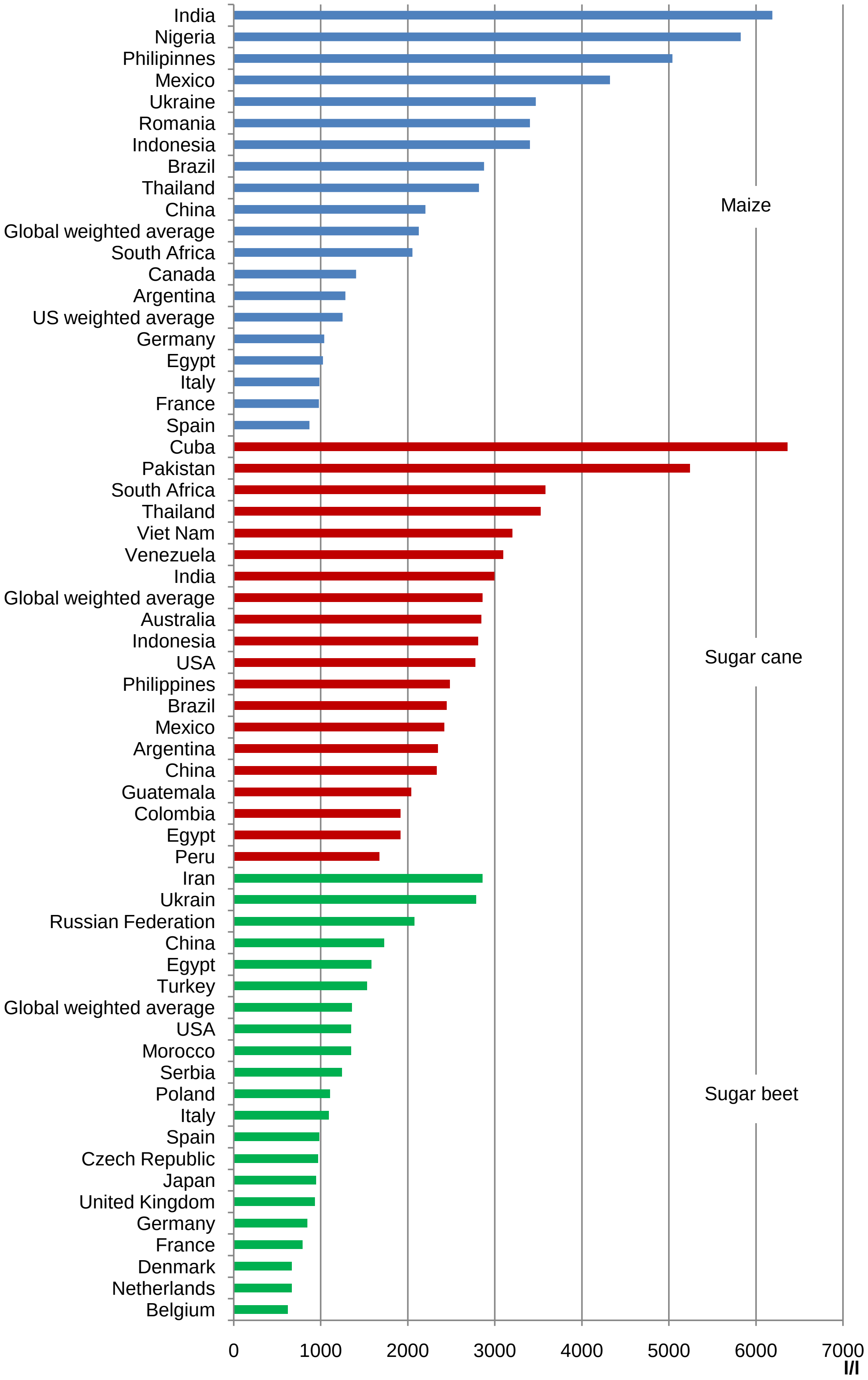

*Figure 42. Water footprint of ethanol produced from maize (dry milling), sugar cane and sugar beet (l water/l ethanol produced).*

*Table 20.Overview of ethanol water footprint for sugar beet for the selected countries, including comparison with a study by Gerbens-Leenes et al. (2008).*

| **Country** | **Green and blue** | **Green, blue and grey** | **Gerbens Leenes et al. Green and blue** | **Green and blue**[1] | **Green, blue and grey** | **Gerbens Leenes et al. Green and blue** [2] | **Difference between 1 and 2** |
|---|---|---|---|---|---|---|---|
| | l/l | l/l | l/l | $m^3$/GJ | $m^3$/GJ | $m^3$/GJ | % |
| Belgium | 487 | 617 | 1147 | 21 | 26 | 49 | 58 |
| China | 1450 | 1725 | 2270 | 62 | 74 | 97 | 36 |
| Czech Republic | 814 | 966 | 1006 | 35 | 41 | 43 | 19 |
| Denmark | 523 | 666 | 796 | 22 | 28 | 34 | 34 |
| Egypt | 1541 | 1579 | 866 | 66 | 67 | 37 | -78 |
| France | 615 | 788 | 608 | 26 | 34 | 26 | -1 |
| Germany | 643 | 844 | 842 | 27 | 36 | 36 | 24 |
| Iran | 2567 | 2857 | 3440 | 110 | 122 | 147 | 25 |
| Italy | 941 | 1092 | 1170 | 40 | 47 | 50 | 20 |
| Japan | 704 | 943 | 866 | 30 | 40 | 37 | 19 |
| Morocco | 1102 | 1347 | 515 | 47 | 58 | 22 | -114 |
| Poland | 865 | 1106 | 1427 | 37 | 47 | 61 | 39 |
| Russian Federation | 1704 | 2076 | 4072 | 73 | 89 | 174 | 58 |
| Spain | 851 | 982 | - | 36 | 42 | - | - |
| Netherlands | 521 | 665 | 819 | 22 | 28 | 35 | 36 |
| Turkey | 1328 | 1531 | 1123 | 57 | 65 | 48 | -18 |
| Ukrain | 2371 | 2782 | 3791 | 101 | 119 | 162 | 37 |
| United Kingdom | 785 | 932 | 866 | 34 | 40 | 37 | 9 |
| USA | 1173 | 1348 | 1264 | 50 | 58 | 54 | 7 |
| Serbia | 1037 | 1241 | 1919 | 44 | 53 | 82 | 46 |
| **Weighted global average** | **1137** | **1355** | **1381** | **49** | **58** | **59** | **18** |

*Table 21. Overview of ethanol water footprint for sugar cane for the selected countries, including comparison with a study by Gerbens-Leenes et al. (2008).*

| **Country** | **Green and blue** | **Green, blue and grey** | **Gerbens Leenes et al. Green and blue** | **Green and blue**[1] | **Green, blue and grey** | **Gerbens Leenes et al. Green and blue** [2] | **Difference between 1 and 2** |
|---|---|---|---|---|---|---|---|
| | l/l | l/l | l/l | $m^3$/GJ | $m^3$/GJ | $m^3$/GJ | % |
| Argentina | 2207 | 2343 | 2200 | 94 | 100 | 94 | 0 |
| Australia | 2531 | 2843 | 1638 | 108 | 122 | 70 | -55 |
| Brazil | 2358 | 2447 | 2317 | 101 | 105 | 99 | -2 |
| China | 2079 | 2332 | 1942 | 89 | 100 | 83 | -7 |
| Colombia | 1808 | 1914 | 1849 | 77 | 82 | 79 | 2 |
| Cuba | 6128 | 6363 | 5265 | 262 | 272 | 225 | -16 |
| Egypt | 1833 | 1912 | 1685 | 78 | 82 | 72 | -9 |
| Guatemala | 1909 | 2039 | 1966 | 82 | 87 | 84 | 3 |
| India | 2819 | 2993 | 2761 | 120 | 128 | 118 | -2 |
| Indonesia | 2660 | 2810 | 2597 | 114 | 120 | 111 | -2 |
| Mexico | 2261 | 2418 | 2036 | 97 | 103 | 87 | -11 |
| Peru | 1572 | 1671 | 1100 | 67 | 71 | 47 | -43 |
| Pakistan | 5045 | 5239 | 3042 | 216 | 224 | 130 | -66 |
| Philippines | 2355 | 2483 | 2340 | 101 | 106 | 100 | -1 |
| South Africa | 3362 | 3580 | 2293 | 144 | 153 | 98 | -47 |
| Thailand | 3317 | 3524 | 2761 | 142 | 151 | 118 | -20 |
| USA | 2620 | 2775 | 2434 | 112 | 119 | 104 | -8 |
| Venezuela | 2960 | 3097 | 3159 | 127 | 132 | 135 | 6 |
| Viet Nam | 3021 | 3197 | 3346 | 129 | 137 | 143 | 10 |
| **Weighted global average** | 2692 | 2856 | 2527 | 115 | 122 | 108 | **-7** |

*Table 22. Ethanol water footprint for maize in the USA, including comparison with a study by Gerbens-Leenes et al. (2008).*

| **Country** | **Green and blue** | **Green, blue and grey** | **Gerbens Leenes et al. Green and blue** | **Green and blue**[1] | **Green, blue and grey** | **Gerbens Leenes et al. Green and blue** [2] | **Difference between 1 and 2** |
|---|---|---|---|---|---|---|---|
| | l/l | l/l | l/l | $m^3$/GJ | $m^3$/GJ | $m^3$/GJ | % |
| Maize | 1003 | 1221 | 1825 | 43 | 52 | 78 | 45 |

Table 23 presents a comparison between the results of maize based ethanol received in this study and a study by Gerbens-Leenes et al. (2008). Some of the parameter values are compared in the table and used for calculating the WF of ethanol and by-products. The first column presents the values used for the calculation of the weighted U.S average WF in this study. The second column is partially split into two, of which the first column presents the original values as used by Gerbens-Leenes et al. and the second are the modified values, based on the yield of total maize biomass, including stover which represents 54% of total maize biomass. Gerbens-Leenes used the yield of only the grains (8.4 ton/ha). When the stover is added, the total yield is 18.3 ton/ha $(8.4\ /\ 46 \times 100)$. This is a 9.6% lower yield than used in this study. The CWR used in the calculation by Gerbens-Leenes et el. is 10.4% higher than the CWR computed in this study. Those differences result in a 22.2% higher WF of unprocessed maize.

Subsequently the influence of taking stover into account is calculated. The ratio of the value fraction divided by the product fraction is calculated for both scenario and the WF is calculated. Taking stover into account results in an ethanol WF of 1557 m$^3$ water per ton of ethanol produced. Without stover the WF of maize-based ethanol is 1908 m$^3$/ton, a difference of 23%. The differences in CWR, yield and distribution over the by-products declares the difference in WF between this study and the study by Gerbens-Leenes et al.

*Table 23. Comparison between the results of maize-based ethanol received in this study and a study by Gerbens-Leenes et al. (2008).*

| | **This study** | **Gerbens-Leenes et al.** | | **Difference (%)** |
|---|---|---|---|---|
| Weather station | Weighted U.S. average | Des Moines | | |
| CWR (mm/cropping season) | 594 | 656 | | 10.4 |
| Yield (ton/ha) | 20.2[1] | 8.4[2] | 18.3[3] | -9.6 |
| Green + blue WF unprocessed maize | 294 | 781 | 359 | 22.2 |
| Ratio of value and product fractions[4] | | | | |
| Ethanol | 4.3 | 2.4 | 4.3 | |
| Stover | 0.4 | - | 0.4 | |
| Maize gluten feed | 0.5 | 0.3 | 0.5 | |
| Maize gluten meal | 2.5 | 1.3 | 2.5 | |
| Maize oil | 4.0 | 2.4 | 4.0 | |
| WF of (m$^3$/ton): | | | | |
| Ethanol | 1274 | 1908 | 1557 | 22.5 |
| Stover | 114 | - | 140 | |
| Maize gluten feed | 147 | 243 | 180 | |
| Maize gluten meal | 735 | 1032 | 898 | |
| Maize oil | 1176 | 1911 | 1437 | |

1) Yield of total maize biomass, including stover

2) Yield of maize grains, exclusive stover

3) Yield of total maize biomass, including stover, based on the grain yield used by Gerbens-Leenes et al. (2008)

4) $\frac{f\quad[p]}{f_p[p]}$

# 6 Impact assessment

The human interference in a river basin can have enormous consequences for the natural environment and the human population. Both cause and effect are many-sided. This study focuses on the impact of the WF of sugar crops on some vulnerable river basins. The vulnerability of a river basin can be expressed in many ways. The WWF (2007) for example has made a top ten list of great rivers at risk. It is drawn up, based on the most menacing threats influencing water quality and the natural environment (invasive species, over-fishing and pollution) and water quantity (infrastructure, dams, navigation, climate change and water over-extraction). The green WF influences the natural water resources mainly if the cultivated crop has a higher WF than the natural vegetation. Over-extraction is correlated to the blue WF and will be researched for this impact assessment. Water extraction mainly consists of water use for irrigation, industry, livestock and human water consumption. The blue WF of sugar and ethanol is the amount of water extracted from the available freshwater resources for irrigation and the process water requirements. The process water requirements are determined to be nil, since modern equipped factories almost completely recycle their process water. Although the grey WF is related to water quality, the WF is first of all an indicator for water quantity.

The impact of the WF of a country, region or river basin on the considered area depends on the availability of freshwater in that area. The WF of an area consists of two components, the internal and external WF. The internal WF is the part that finds benefit by the area itself (e.g. agriculture for domestic consumption). The external WF is the appropriation of other areas on the water resources in the considered area (e.g. agriculture for foreign consumption). So, whether a river basin suffers under water stress depends on the availability of water and the total WF of the river basin.

There are multiple water scarcity indicators to reflect the water stress in a river basin. This impact assessment uses the withdrawal-to-availability ratio (WtA-ratio) (Alcamo et al., 2000) and the Water Stress Indicator (WSI) (Smakhtin et al., 2004), a modification of the WtA-ratio. The WtA-ratio divides the water withdrawal in a river basin by the total runoff in that basin. Smakhtin modified this ratio by subtracting the Environmental Water Requirements (EWR) from the Mean Annual Runoff (MAR). The EWR is the required volume of water planned for the maintenance of freshwater ecosystem functions and the services they provide to humans.

$$\mathrm{WSI}=\frac{\mathrm{Withdrawals}}{\mathrm{MAR\text{-}EWR}}$$

Table 24 gives the classifications for a river basin of the WtA-ratio and the WSI. Alcamo et al. (2002, 2003) have identified critical river basins based on several scenarios. Smakthin et al. also indicate water stressed regions where river basins are overexploited. In these regions the EWR cannot be satisfied while many other areas are marked as environmental water scarce. Some of those basins are about to move to the higher level of human water scarcity if EWR should be met. As water withdrawals increase, the number of basins where the EWR is not met is growing. The most common causes of increased withdrawal are population and economic growth. Besides, climate change may affect the availability of water.

*Table 24. Classification of water stress according the WtA-ratio and WSI (Sources: Alcamo (2003), Smakthin (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 |

‘Appendix XI: Water stress’ discusses water stress in some of the major river basins in the world, based on several water stress indicators. Two areas with water stressed basins, or foreseen stressed basin, are discussed in more detail below. The Dnieper, Don and Volga basin north of the Black and Caspian Sea, where a lot of sugar beet is grown is discussed first. Subsequently the Indus and Ganges basins in India and Pakistan are discussed.

## *6.1 Dnieper, Don and Volga*

Although the area north of the Black and Caspian Sea is not a very arid area, water stress in Ukraine, Kazakhstan, Belarus and the Russian Federation is already a fact and increasing. The biggest problem in the area however is water pollution. Pollution in the rivers Dnieper and Don, which drain to the Black Sea, has already caused considerable environmental damage to the Black Sea ecosystem. In 1992 the Russian Federation's Committee on Fishing reported 994 cases in which water bodies were completely contaminated by agricultural runoff. Of the 26 fish species formerly present in the Black Sea, only five remained after serious eutrophication. Fish catch dropped by more than 65% (http://www.country-data.com). Besides pollution by excessive use of fertilizers, irrigation has resulted in water scarcity in some areas as well. High intense agriculture, in combination with inefficient irrigation and poor management, accounts for more than 90% of total water consumption in Central Asia (Unece, 2002). Surface water is overexploited for irrigation and groundwater is overused for public consumption supply.

Besides poor agriculture practice, two other factors influence the water quality and quantity in the Dnieper, Don and Volga river basins. First, industrialization has grown rapidly during the past decades. Due to lack of treatment of waste water, pressure on the water system is eminent. A second future impact on the rivers is climate change and the construction of dams as studied by Palmer et al. (2008). This study implemented the A2 scenario of the Intergovernmental Panel on Climate Change (IPCC, 2000) for water use and river discharge, in the Watergap model. Besides the A2 scenario, that makes assumption for population and economic growth, and technology, the impact of dams is complied with as well. Results showed that a decrease in river discharge in both Don (-20.4%) and Dnieper (-15.2%) and an increase for the Volga (+5.2%), compared to the annual average discharge in the period 1960 – 1990, are to be expected in 2050,.

Although the countries occupying the Dnieper, Don and Volga river basins may experience water scarcity at present and in future, Ukraine and Kazakhstan for example are among the biggest net exporters of water with respectively 31.8 and 39.2 billion $km^3$ over the period 1995 – 1999 (Hoekstra and Hung, 2002). The Russian Federation is a net importer, but site specific data of the considered river basins however is not available.

As mentioned before, the biggest problem for the north part of the Black and Caspian Sea area is pollution. As can be seen in ‘

Appendix IV: Fertilizer application rates' rates for sugar beet are very high in the countries within the area. The amount of water needed to dilute the contaminants to an acceptable level is high as well. This study has used international drinking water standards for nitrogen to calculate the grey WF. When more strict standards for, for example, a healthy ecosystem would be used, the grey WF can even increase by approximately factor two for nitrogen. When also potassium and the total amount of agrochemicals would be taken into account in preserving a healthy ecosystem, the grey WF could increase with even factor 100. The ecosystem of the rivers Dnieper and Don, and especially their tributaries, is highly affected by human interference. This assumes there is not sufficient water to dilute the contaminants to an acceptable level to avoid the degradation of the ecosystem.

## 6.2 Indo-Gangetic basin

Some of the river basins with severe water stress are located in India. Two of those rivers are the Indus and Ganges, together forming the Indo-Gangetic plain or basin. The Indus originates on the Tibetan Plateau and finds its way through India and Pakistan to the Arabian Sea. The river basins area is over a million square kilometres, of which 321,289 square kilometres belong to India. The Indian part of the basin encompasses nearly 10 percent of the total geographical area of India. For Pakistan, the Indus is the largest river and considered as the life line of the country. Since the independency of the countries in 1947 they almost went to war over the Indus water. After a long struggle in 1960 finally the Indus Water Treaty was signed (Postel and Wolf, 2001). Already before the independency however, the allocation of the water of the Indus was a problem between the states of British India (Beach et al., 2000). And also at present the rivers water is a national point of discussion and civil commotion. In Pakistan the provinces of Punjab and Sind argue about an equitable allocation of water. A likewise situation is seen in Thailand, where the Chao Phraya's discharge is reducing in the south. As Bangkok's most important source of freshwater there is discussion about allocation of the rivers water resource between northern and southern regions (Postel and Wolf, 2001).

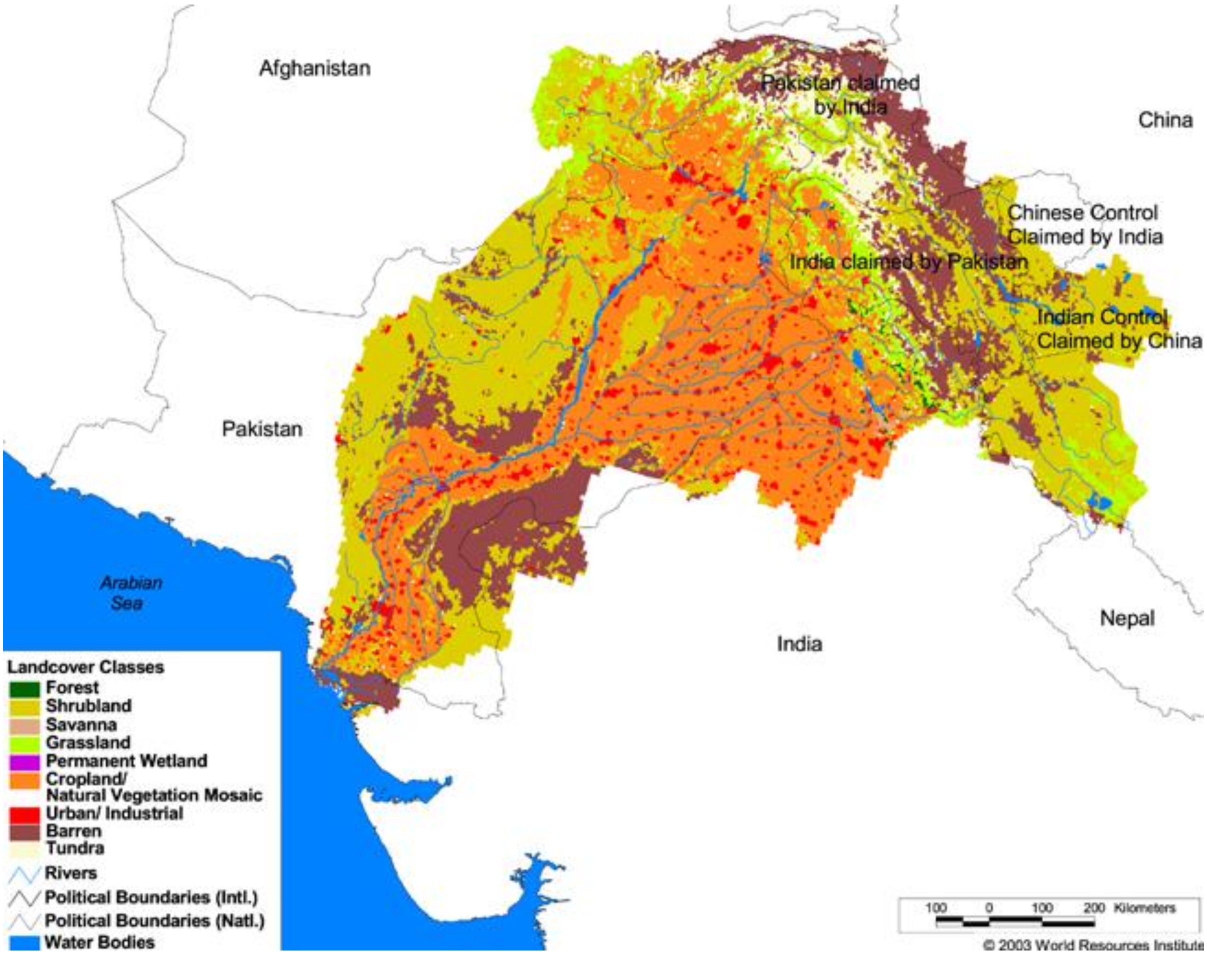

*Figure 43. Land cover in the Indus basin (Water Resource eAtlas ).*

Figure 43 is a map of the Indus basin. A large part of the Indian basin is cultivated cropland. It covers 5% of India's agricultural area and measures 9.6 million hectares. Besides sugar cane, another thirsty crop is extensively cultivated in the area, cotton (Van Oel et al., 2008 and Ramankutty, 2008). Of all crops cultivated, the thirsty crops wheat, rice, cotton and sugar cane are most extensively grown under irrigated areas (WWF, 2003). Table 25 presents the CWR's and total water consumption of those crops as determined by WWF.

*Table 25. Average global crop water requirements (CWR) and total water consumption by crop in the Indus Basin (Source: WWF, 2003 and WWF, 2004)*

| | **Average CWR (litres/kg of crop)** | **Total water consumption Indus Basin (million m$^3$)** |
|---|---:|---:|
| Wheat | 900 | 51 |
| Rice | 3000 – 5000 | 71 |
| Cotton | 7000 - 29000 | 51 |
| Sugar cane | 1500 - 3000 | 50 |

Agriculture is not the only pressure on natural resources. Population density is quite high already, with 165 people per square kilometre in 1995 and in some areas exceeding 500 people per square kilometre (Water Resources eAtlas, 2008), and population growth is high as well (Worldbank, 2006). From the total Indus discharge in Pakistan, at present, 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 over-exploited and groundwater quality is deteriorating and the linked problem is soil salinization. Besides the problem of the available resources the Worldbank (2006) observes problems regarding maintenance of water infrastructure, governance and trust, and productivity in the Pakistani part of the basin.

The other river of the Indo-Gangetic basin, the Ganges is the largest river of the Indian sub-continent. Although it is one of the most humid areas, with annual precipitation above 10 metres in some places, during some periods of the year the basin experiences severe water stress. Since distribution of rain fall over the year is very irregular, the discharge of some Indian rivers during the monsoon period represents 70% – 95% of total annual flow. Due to absence of flow regulation in some parts of the basin, severe water scarcity occurs mainly from January until April. 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, despite those forecasts are based on different scenarios. Most of these scenarios are based on factors like increasing water withdrawal for both domestic and industrial use, since both population and industrial growth is expected and a change in water availability due to climate change.

Figure 44 presents the land cover of the Ganges basin. Cropland accounts for 72% of the total land coverage. Sugar cane is one of the major crops cultivated in the area and deteriorates the water scarcity.

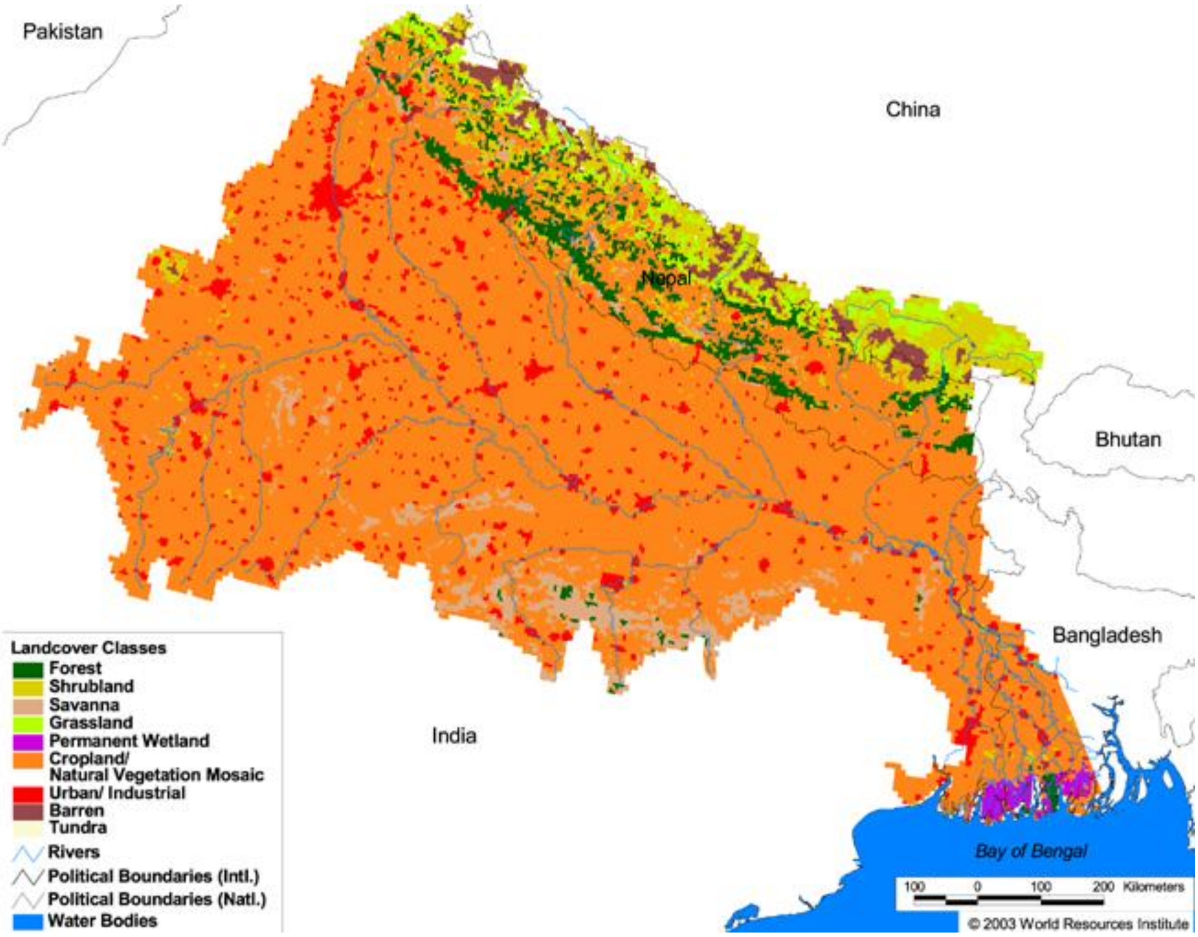

*Figure 44. Land cover in the Ganges basin (Water Resource eAtlas ).*

# 7 Conclusions

The weighted global average WF of cane sugar is 1500 $m^3$/ton, 935 $m^3$/ton for beet sugar and 1125 $m^3$/ton for HFMS 55. For the production of ethanol, the WF shows similar proportions between these crops. The weighted global average WF of ethanol is 3620 $m^3$/ton for sugar cane, 1720 $m^3$/ton for beet-based ethanol and 2420 $m^3$/ton for maize-based ethanol.

In the USA, until now the only country that uses maize on large scale as feedstock for both sweetener and ethanol production, the weighted average WF for HFMS 55 is 720 $m^3$/ton. The (unweighted) average WF for cane sugar in the USA is 1135 $m^3$/ton and 1025 $m^3$/ton for beet sugar. The weighted U.S. average maize-based ethanol WF is 1550 $m^3$/ton. The (unweighted) average WF of cane-based ethanol in the USA is 3520 $m^3$/ton and 1710 $m^3$/ton for beet-based ethanol and

The differences in WF of a commodity produced from a certain feedstock can be attributed to mainly two variables: CWR and yield. The FAOSTAT-database shows large variance in yield between countries, resulting in large variance in WF as well. The CWR of all crops show large variance between countries as well. Secondly there are large differences between countries in irrigation requirements. Egypt for example is completely dependent on irrigation for every crop it grows, while in Japan for sugar beet cultivation only 5% of the CWR has to be derived by irrigation.

With the use of drinking water standards of nitrogen, the grey WF does not contribute to the total WF in a very large extent for commodities produced from sugar crops. For maize-based products however, in some countries the grey WF contributes to over 20% to the total WF. When more strict water quality standards, for example for a healthy ecosystem, are used in calculating the WF, the grey component of the WF can increase by factor 100

Water stress is a problem in many parts of the world already and an expansion of water stressed areas is expected. Furthermore already stressed areas will suffer longer and more severe stress in future due to climate change, population and economic growth and expansion of irrigated agriculture. Mainly sugar cane is grown in some of the most water scarce river basins in the world. However, also sugar beet influences both quantity and quality in some of the major river basins of the world. The water footprint of sugar crops does not solely result in water stress in any area, but has a considerable contribution, together with other agricultural practices, to water scarcity in some river basins.

# 8 Discussion

Finally, some assumptions made in this study will be discussed. First, this study excluded process water requirements for both sweetener and ethanol production. Cheesman (2004) reports large variance in PWR, but a modern equipped factory is able to recycle process water and reduce water use to almost zero. For the grey WF the amount of contaminants released is of interest. This is correlated with the extent of recycling of process water and waste water treatment by a factory. Since total recycling in all production processes is assumed, waste water release is supposed to be zero.

The WF’s calculated in this study is the WF if the CWR should be met. In most countries irrigation is required to fulfill the CWR. It is assumed that all blue water requirements are met. This however, does not correspond to the actual situation in many countries. In some countries irrigation practice is not common for all farmers and for some regions irrigation might not be possible all year long due to water scarcity. In order to make a sincere comparison between countries, the required amount of blue water is based on CWR instead of the actual blue water applied.

Regarding the yield of the crops, some important assumptions are made. The yields for sugar beet and sugar cane, for all countries, are derived from the FAOSTAT-database. Both crops are almost completely harvested in most countries. Only some leaves are left on the field, which are only a small part of the entire plant. With maize in the USA however, only the grains are harvested, leaving the stover on the land. Like by-products derived by sugar cane and sugar beet processing, stover has an economic value as fertilizer as well. When for maize the yield of only the grains should be used, the CWR would not be distributed over all by-products. This results in a considerably higher WF of HFMS 55 and maize-based ethanol.

This study is based on the calculation method as described by Hoekstra and Chapagain (2008), using product and value fractions among others. Other studies to the WF of biofuels often use the (hypothetical) energy content of a crop instead of the ratio of the value fraction divided by the product fraction. How the energy is obtained from the crop as well as the use of the energy is not considered in that approach. A part of the crops energy will be converted to biofuels while others are used as fertilizer, animal feed or feedstock for lots of commodities, or for direct combustion of the crop. Not all crop energy is suitable for all purposes. To convert the crop energy into a usable energy for a specific purpose, sometimes a complex and energy devouring process is needed. An example is the conversion of lignocellulose, like corn stover, to what is called second generation ethanol. For that reason stover is not commercially used as ethanol feedstock yet, and instead used as fertilizer. An important lignocellulosic by-product of sugar cane processing is bagasse. This could be used for the production of ethanol. Until now however, it is more profitable to use bagasse for direct combustion for the generation of electricity and heat for steam. The possibilities of obtaining energy and the amount of energy derived from specific parts of a crop or by-product influences the value of the by-product. The calculation method of Hoekstra and Chapagain takes this into account by using the economic value of a by-product, instead of the energy content of the by-product.

The production of sweeteners and ethanol from sugar crops and maize is extensively discussed in this study. There are quite some differences between the three feedstocks as well as between countries in the amount of water required to produce sweeteners and ethanol. Both sweeteners and ethanol have substitutes. This study concentrates on cane sugar, beet sugar and sugar-based ethanol, taking into account maize-based ethanol and HFMS since these compete with sugar. Substitutes for ethanol like other bio-fuels are not discussed. Regarding sugar substitutes an important one is mentioned, artificial sweeteners. Not much information on the production of those sweeteners is publically available however. No indications of high water consumption during the production process are found. Furthermore the sugar equivalent of artificial sweeteners is very high. It can be assumed that the WF of artificial sweeteners is very small compared to that of sugar and HFMS. In order to reduce the total global WF of sweetener consumption, the usage of artificial sweeteners might be an effective measure. This means more sugar crops and maize are available as feedstock for ethanol production, remaining the global WF of cultivated sugar crops and maize unchanged. At present liquid biofuels, i.e. biodiesel and ethanol, account for 1.9% of total global energy consumption and 0.9% of total global transport fuel consumption (FAO, 2008).

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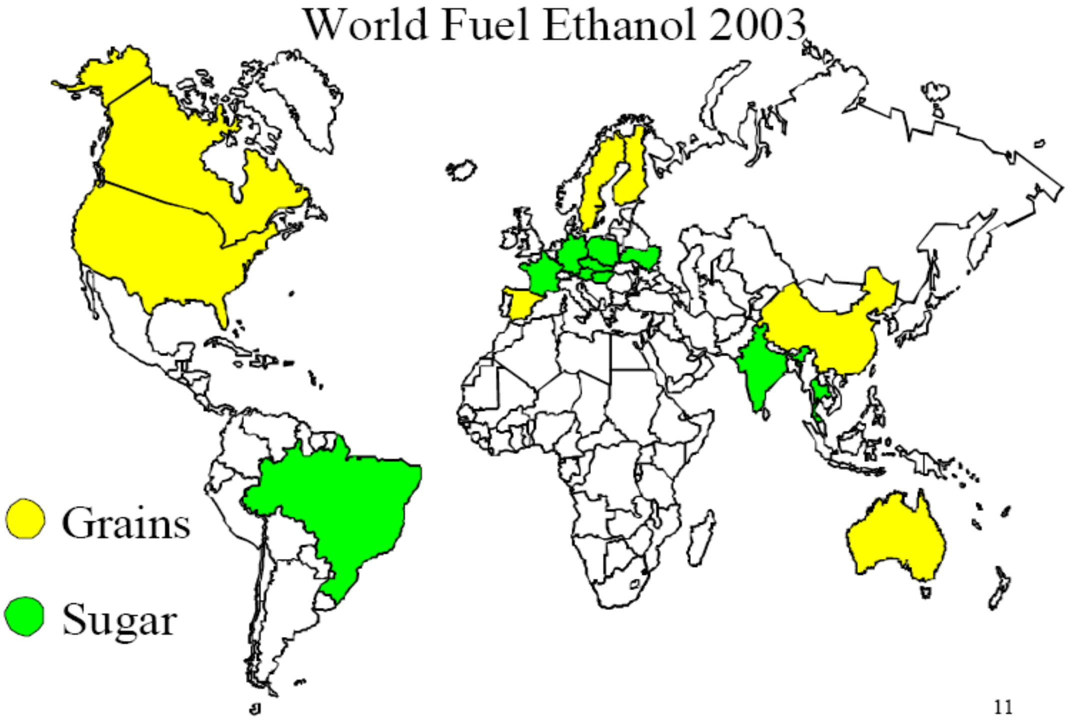
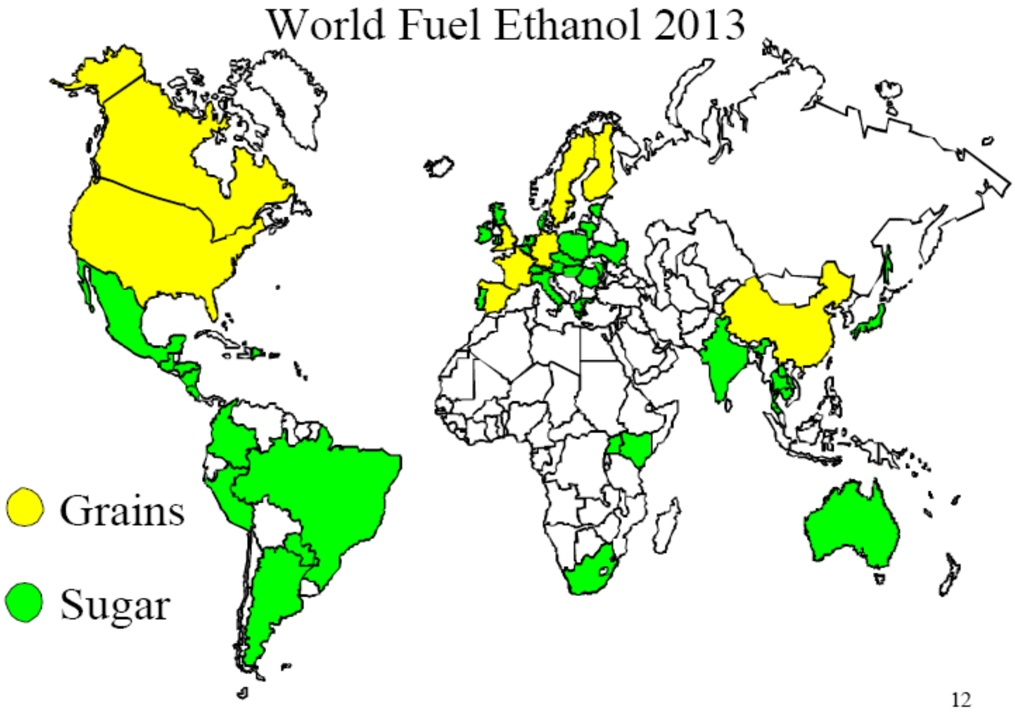
## Appendix I: World's main ethanol feedstocks





Source: Berg (2004)

# Appendix II: Water footprint calculation

## *Green, blue and grey water*

The water footprint (WF) is divided in three types of water use. The first is ‘green water’ which is defined as the rainwater that evapotranspirates from the field. The second is ‘blue water’ that represents the irrigation water extracted from ground or surface water that evapotranspirates on the field. Another part of the blue water component refers to the water that is extracted from ground or surface water and is used during the production process. The last component of the WF is ‘grey water’ that is defined as the required dilution volume for pollutants emitted to the natural water system. During both the agricultural and industrial stage water gets polluted. In crop production, fertilizers and agro-chemicals are applied on the field. For calculating the grey water one needs to account only the most critical pollutant, which is the pollutant with the highest volume of water used. During the processing of the product, a part of the process water is drained as waste water.

## *Calculation of the water footprint of a product*

First, the green water component is calculated. This is done by determining the crop water requirement (CWR) that is calculated by multiplying the crop coefficient ($K_c$) by the reference crop evapotranspiration $ET_0$ (mm/day).

$$CWR = K_c \times ET_0 \tag{1}$$

In this study, the CWR is calculated by applying the CROPWAT 4.3 model (FAO, 2007) that is based on the Penman-Monteith equation (Allen, 1998). This model requires information about the location (altitude, latitude and longitude), climate conditions (air temperature, humidity, radiation and wind speed) and the crop and can calculate the CWR for a crop on any location.

When rainfall is insufficient to compensate for the water lost by evapotranspiration irrigation is required. The irrigation requirement (IR) is zero when the effective rainfall ($P_{eff}$) exceeds the CWR and otherwise equal to the difference between the CWR and effective rainfall:

$$IR = max(0, CWR - P_{eff}) \tag{2}$$

CROPWAT calculates the irrigation requirement by subtracting the effective rainfall from the CWR.

The green water evapotranspiration is equal to the minimum of CWR and effective rainfall:

$$ET_g = min(CWR, P_{eff}) \tag{3}$$

In case no irrigation is applied blue water evapotranspiration is zero. Otherwise the blue water evapotranspiration is the minimum of the irrigation requirement and the amount of irrigation water that is available for plant uptake ($I_{eff}$):

$$ET_b = min(IR, I_{eff}) \quad (4)$$

Since CROPWAT does not take into account the effectiveness of irrigation in reservoirs and canals, the blue water evapotranspiration is assumed to equal the irrigation requirement.

The crop water use (CWU) as defined by Hoekstra (2008) consists of the green ($CWU_g$) and blue ($CWU_b$) component and is the accumulation of daily evapotranspiration over the complete growing period. The CWR in CROPWAT is given in mm and is multiplied by the factor 10 to convert into $m^3$/ha.

$$CWU_g = 10 \times \sum_{d=1}^{lp} ET_g \quad (5)$$

$$CWU_b = 10 \times \sum_{d=1}^{lp} ET_b \quad (6)$$

In CROPWAT the green water use is defined as $CWU_g = CWR - IR$ where IR is the blue water use.

To calculate the green component of the virtual-water content of a product ($v_g$, $m^3$/ton) , the crop water use is divided by the yield (Y, ton/ha):

$$WF_g = \frac{CWU_g}{Y} \quad (7)$$

The blue component of the WF ($v_b$, $m^3$/ton) is calculated by dividing the blue crop water use by the yield (Y, ton/ha). Because of evaporation in artificial storage reservoirs and transport canals an extra loss should be calculated ($E_{irr}$, $m^3$/yr ). This loss occurs during the entire year and should for that reason be divided over the total production received from the irrigated area.

$$WF_b = \frac{CWU_b}{Y} + \frac{E_{irr}}{Prod} \quad (8)$$

CROPWAT does not take this loss into account. Since this is a global study and there is no standard in irrigation schemes regarding storage reservoirs and transport canals, this factor will not be considered.

The third component of the WF is grey water ($v_{grey}$, $m^3$/ton) , that is calculated as the load of pollutants that enters the water system (L, kg/ha) divided by the maximum acceptable concentration for the pollutant considered ($c_{max}$, kg/$m^3$) and the crop yield for one cropping season ( Y, ton/ha).

$$v_{gray} = \frac{{}^{L}/_{c_{max}}}{Y} \quad (9)$$

The total WF of a product can now be calculated by accumulating the three components:

$$WF_{tot} = WF_g + WF_b + WF_{gray} \tag{10}$$

So far, the calculation of the water footprint was based on only one processed product $p$ obtained from a root product $r$. However, from one root product often several products can be obtained. Each product can be expressed as a fraction of the root product. The product fraction ($f_p$[p]) is calculated by dividing the quantity of a processed product (w[p], ton) by the quantity of the root product (w[r], ton):

$$f_p[p] = \frac{w[p]}{w[r]} \tag{11}$$

Each product (p) obtained from the root product has its own market price (P[p], US$/ton). The sum of all product prices is the total value of the root product. With a root product of which *n* processed products can be obtained the value fraction of a product $p$ ($f_v$[p], US$/US$) can be calculated by:

$$f_v[p] = \frac{P[p] \times w[p]}{\sum_{i-1}^{n}(p[i] \times w[i])} \tag{12}$$

Here, the numerator is the market value of the product and the denominator is the sum of the market value of the *n* processed products that originate from the root product.

During the industrial process of the root product, water is used in different production stages. Each (by-)product, originated at the end of a production stage, only consumes the water in the previous stages and not the water used in the subsequent stages. For this reason, only the process water use (PWU, $m^3$/ton) involved with the production of product $p$ is added to the WF of that product. Here for, the total of the WF as a result of the growing season of root product $r$ as well as the PWU during the production of the root product, is multiplied by the value fraction divided by the product fraction

$$WF[p] = (WF[r] + PWU[r]) \times \frac{f_v[p]}{f_p[p]} \tag{13}$$

## Appendix III: Water use in the cane sugar factory

Water use in a sugar cane plant producing sugar and ethanol on a 50/50 basis.

*Table 26. Water use (mean values) in mills having an annexed distillery (Source: Neto, 1996 (cited by Moreira, 2007).*

| **Sector** | **Process** | **Mean use (Total m$^3$/t cane)** | **%** |
|---|---|---|---|
| Feeding | Sugar cane washing | 5.33 | 25.4 |
| Extraction (grinding) | Inhibition | 0.25 | 1.2 |
| | Bearing cooling | 0.15 | 0.7 |
| Juice treatment | Preparation of lime mixture | 0.01 | 0.0 |
| | Cooling at sulphiting (1) | 0.05 | 0.2 |
| | Filter inhibition | 0.04 | 0.2 |
| | Filter condensers | 0.30 | 1.4 |
| Juice concentration | Condensers/multijets evaporation (1) | 2.00 | 9.5 |
| | Condensers/multijets heater (1) | 4.00 | 19.0 |
| | Molasses dilution | 0.03 | 0.1 |
| | Crystallizer cooling (1) | 0.05 | 0.2 |
| | Sugar washing (1) | 0.01 | 0.0 |
| Electrical power generation | Steam production | 0.50 | 2.4 |
| | Turbo-generator cooling | 0.20 | 1.0 |
| Fermentation | Juice cooling (2) | 1.00 | 4.8 |
| | Fermentation cooling (2) | 3.00 | 14.3 |
| Distillery | Condenser cooling (2) | 4.00 | 19.0 |
| Other | Floor & equipment cleaning | 0.05 | 0.2 |
| | Drinking | 0.03 | 0.1 |
| Total | | 21.00 | |

(1) in sugar production only

(2) in ethanol production only

## Appendix IV: Fertilizer application rates

Fertilizer use by crop per country (Source: www.fao.org/ag/agl/fertistat, 2008)

| **Application rate (kg/ha)** | **Sugar cane** | | | **Sugar beet** | | | **Maize** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Country** | **Rate N** | **Rate P** | **Rate K** | **Rate N** | **Rate P** | **Rate K** | **Rate N** | **Rate P** | **Rate K** |
| Argentina | 80 | 2 | 0 | | | | 28 | 19 | 0 |
| Australia | 229 | 66 | 164 | | | | | | |
| Austria | | | | 85 | 52 | 112 | 120 | 56 | 68 |
| Azerbijan | | | | 9 | 10 | 8 | 11 | 11 | 6 |
| Bangladesh | 85 | 69 | 72 | | | | 10 | 8 | |
| Belarus | | | | 90 | 40 | 122 | | | |
| Belgium | | | | 110 | 50 | 155 | 65 | 30 | 40 |
| Bolivia | 60 | 0 | 0 | | | | | | |
| Brazil | 55 | 51 | 110 | | | | 40 | 35 | 0 |
| Bulgaria | | | | | | | 1 | 0 | 33 |
| Canada | | | | | | | 156 | 52 | 95 |
| Chile | | | | 200 | 250 | 90 | 200 | 100 | 119 |
| China | 150 | 75 | 65 | 120 | 65 | 35 | 130 | 40 | 30 |
| Colombia | 100 | 150 | 100 | | | | 50 | 70 | 40 |
| Costa Rica | 100 | 40 | 60 | | | | 100 | 40 | 10 |
| Croatia | | | | 100 | 61 | 79 | 100 | 35 | 20 |
| Cuba | 63 | 50 | 87 | | | | | | |
| Czech Republic | | | | 90 | 29 | 56 | 83 | 22 | 24 |
| Denmark | | | | 100 | 35 | 70 | | | |
| Dominican Repiblic | 80 | 60 | 60 | | | | 100 | 60 | 60 |
| Democratic People's Republic of Korea | | | | | | | 58 | 12 | 90 |
| Ecuador | 70 | 20 | 100 | | | | 120 | 40 | 40 |
| Egypt | 80 | 20 | 0 | 23 | 8 | 114 | 233 | 36 | 0 |
| El Salvador | 133 | 49 | 15 | | | | 76 | 33 | 103 |
| Ethiopia | | | | | | | 7 | 14 | 0 |
| Fiji Islands | 100 | 40 | 81 | | | | | | |
| Finland | | | | 120 | 80 | 70 | | | |
| France | | | | 145 | 38 | 35 | 170 | 59 | 36 |
| Germany | | | | 145 | 70 | 155 | 150 | 50 | 40 |
| Greece | | | | 140 | 65 | 50 | 190 | 45 | 5 |
| Guatemala | 100 | 80 | 50 | | | | 100 | 60 | 60 |
| Guinea | | | | | | | 80 | 60 | 80 |
| Honduras | 150 | 40 | 100 | | | | 100 | 50 | 35 |
| Hungary | | | | 63 | 53 | 113 | 115 | 20 | 24 |
| India | 125 | 44 | 38 | | | | 42 | 15 | 8 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Indonesia | 90 | 35 | 30 | | | | 5 | 25 | 4 |
| Israel | | | | | | | 250 | 80 | 200 |
| Ireland | | | | 180 | 130 | 245 | | | |
| Italy | | | | 90 | 60 | 55 | 184 | 80 | 35 |
| Japan | 226 | 91 | 61 | 176 | 324 | 160 | 200 | 200 | 150 |
| Kenya | 60 | 40 | 40 | | | | 40 | 30 | 0 |
| Laos | 60 | 20 | 0 | | | | 50 | 25 | 0 |
| Latvia | | | | 176 | 82 | 112 | | | |
| Lebanon | | | | 25 | 100 | 450 | 80 | 50 | 40 |
| Lithuania | | | | 57 | 24 | 46 | 16 | 6 | 10 |
| Madagascar | 37 | 38 | 28 | | | | | | |
| Malawi | 60 | 40 | 15 | | | | 60 | 15 | 0 |
| Malaysia | | | | | | | 92 | 40 | 10 |
| Mexico | 100 | 45 | 40 | | | | 80 | 20 | 0 |
| Morocco | | | | 160 | 100 | 200 | | | |
| Myanmar | 35 | 15 | 10 | | | | 35 | 10 | 2 |
| Netherlands | | | | 108 | 50 | 70 | 44 | 30 | 8 |
| New Zealand | | | | | | | 120 | 136 | 0 |
| Nicaragua | 80 | 40 | 40 | | | | 50 | 20 | 20 |
| Nigeria | | | | | | | 6 | 1 | 20 |
| Pakistan | 125 | 56 | 0 | | | | | | |
| Paraguay | 60 | 40 | 40 | | | | 30 | 30 | 90 |
| Philipinnes | 85 | 55 | 30 | | | | 58 | 16 | 10 |
| Poland | | | | 121 | 43 | 53 | 82 | 29 | 36 |
| Portugal | | | | 150 | 90 | 120 | 160 | 60 | 11 |
| Republic of Moldova | | | | 15 | 0 | 0 | 1 | 0 | 55 |
| Slovakia | | | | 57 | 19 | 22 | 86 | 10 | 30 |
| South Africa | 92 | 57 | 133 | | | | 55 | 30 | 0 |
| Spain | | | | 178 | 100 | 108 | 225 | 110 | 9 |
| Sudan | 0 | 0 | 0 | | | | | | |
| Sweden | | | | 100 | 40 | 70 | | | |
| Switzerland | | | | 143 | 75 | 204 | 160 | 80 | 0 |
| Syrian Arab Republic | | | | 60 | 60 | 0 | 35 | 30 | 10 |
| Taiwan, Province of China | 0 | 0 | 0 | | | | | | |
| Togo | | | | | | | 35 | 15 | 5 |
| Thailand | 70 | 55 | 65 | | | | 56 | 32 | 48 |
| Turkey | 109 | 64 | 35 | | | | 129 | 32 | 5 |
| United Republic of Tanzania | | | | | | | 80 | 40 | 10 |
| United Kingdom | | | | 100 | 50 | 120 | | | |
| United States of America | 100 | 40 | 220 | 120 | 40 | 60 | 150 | 70 | 90 |
| Uruguay | 150 | 80 | 120 | | | | 40 | 60 | 30 |
| Venezuela | 150 | 100 | 100 | | | | 100 | 40 | 55 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Viet Nam | 105 | 50 | 55 | | | | 105 | 60 | 6 |
| Cambodia | | | | | | | 25 | 15 | 0 |
| Zimbabwe | 6 | 1 | 2 | | | | 153 | 22 | 21 |
| Zambia | | | | | | | 16 | 5 | 3 |
| **Weighted global average** | **91** | **47** | **56** | **108** | **69** | **102** | **88** | **40** | **33** |

## Appendix V: The grey water footprint

Many water quality standards with different aims and applications are available. In the USA, the United States Environmental Protection Agency (USEPA or EPA) sets criteria for both aquatic life and for domestic water supply and human health. The EPA is required to publish and periodically update water quality criteria. The last nation-wide valid publication is the 'Goldbook': Quality criteria for water (EPA, 1986). Since then, the latest criteria are determined for each state, type of water body and season separately. All criteria however, are an update of the Goldbook criteria and often not modified.

The maximum contamination level (MCL) for drinking water (kg/m$^3$) is only given for nitrate. The MCL for nitrate-nitrogen is 10 mg/l (EPA, 2005). For phosphate EPA gives no guidelines for drinking water, but it does for water quality with respect to ecology (EPA, 1986). In order to control algal growth, for streams and rivers phosphate should not exceed 0.1 mg/l, for streams entering lakes 0.05 mg/l and for lakes and reservoirs 0.025 mg/l. For nitrate-nitrogen EPA has published an update of the 1998 'Ambient water quality criteria for amonia' to protect aquatic life from acute and chronic effects of concentrations of un-ionized ammonia and total ammonia given in terms of nitrogen (mg N/l). The document provides several nitrogen guidelines, dependent on parameters like PH-content and temperature, for many fish species. No standard criteria are given for specific water bodies. Furthermore EPA does not provide any standards with respect to eutrophication.

In Europe, the European Union (EU) has set norms for drinking water and directives for aquatic life. In order to obtain a 'good chemical status' for some pollutants (priority substances) environmental quality standards (eqs) are appointed. To obtain a 'good ecological status' the physico-chemical quality elements '*temperature, oxygen balance, pH, acid neutralizing capacity and salinity do not reach levels outside the range established so as to ensure the functioning of the type specific co system and the achievement of the values specified above for the biological quality elements'* (Directive 2000/60/EC). No specific demands for nutrients concentrations are given: *'Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements'*. In The Netherlands, the STOWA (Dutch acronym for the Foundation for Applied Water Research) has carried out a research, under commission of the Ministry of Transport, Public Works and Water Management, to obtain numerical values for nutrients to achieve a 'good ecological status' for waters in natural conditions. The World Health Organization (WHO) has set drinking water norms as well. For aquatic life no standards are available.

*Table 27. Standards for drinking water and aquatic life.*

| | Drinking water | | | | Aquatic life | |
|---|---|---|---|---|---|---|
| | **Nitrate [$NO_3$]** | **Nitrite [$NO_2$]** | **Nitrate-nitrogen [$NO_3$-N]** | **Pesticides, total** | **Total Nitrogen [N]** | **Total phosphorous [P]** |
| Unit | mg/l | mg/l | mg/l | µg/l | mg/l | mg/l |
| EPA | 44.2 | | 10 | | | 0.025 - 0.10 |
| EU | 50 | 0.5 | 11.3 | 0.50 | | |
| WHO | 50 | | 10 | | | |
| The Netherlands | 50 | | | | 1.0 – 4.0 | 0.03 - 0.14 |

The criteria and guidelines as mentioned above are site specific, especially the criteria as formulated for The Netherlands. For that reason the criteria are compared to natural occurring levels of nutrients on a global scale.

A study by Meybeck and Helmer (1989) to the distribution of elements in 60 major rivers provides data on nitrogen and phosphorous levels in rivers (> 100,000 km$^2$). The nitrogen level is given in N-$NH_3^+$, N-$NO_3^-$ and N org and phosphorous is given in P-$PO_4^{3-}$. Table 28 provides the Most Common Natural Concentrations (MCNC) of nitrogen and phosphorous, corresponding to the median value obtained as well as minimum and maximum values representing 10% and 90% of the distribution.

*Table 28. Natural geographic distribution of dissolved elements in rivers (Most Common Natural Concentrations (MCNC); median value obtained) (Source: Meybeck and Helmer, 1989)*

| Element | Minimum (mg/l) | Maximum (mg/l) | MCNC (mg/l) |
|---|---|---|---|
| N-$NH_3^+$ | 0.005 | 0.04 | 0.015 |
| N-$NO_3^-$ | 0.05 | 0.2 | 0.10 |
| N organic | 0.05 | 1.0 | 0.26 |
| N total | 0.105 | 1.24 | 0.375 |
| P-$PO_4^{3-}$ | 0.002 | 0.025 | 0.010 |

From Table 27 and Table 28 can be seen that in no case the global natural occurring level of total nitrogen is higher than the Dutch criterion for large rivers (Dutch criterion > MCNC: 4.0 > 0.375). For phosphorous the Dutch criterion for large rivers (total N < 0.14 mg/l) is not naturally exceeded as well (0.14 > 0.010). Even the maximum obtained levels of nitrogen and phosphorous do not exceed the Dutch norms for large rivers. Since worldwide no large rivers are expected to exceed the Dutch norms in a natural way, the norms will be assumed applicable on a global scale. However, average natural occurring global levels of nitrogen and phosphorous are only known for large rivers. The more strict criteria for, for example, shallow pools (0.03 mg P/l) cannot be compared to global natural occurring values.

In order to provide a global standard for the calculation of the grey water footprint a norm has to be determined on the basis of available information. In this study the norm is based in the environmental demands for aquatic life instead of drink water demands for human health. Since little is known about natural occurring levels of nutrients in many water bodies, the criteria for large rivers will be set normative for grey water. Since those criteria are the less strict criteria compared to other water bodies, the norm can be entitled as conservative as general norm for aquatic life. Since for potassium no criteria are known, this nutrient is not taken into account when determining the grey water footprint. As criterion for the use of agrochemicals the standards of Annex I of Council Directive 98/83/EC of the EU are applied (Table 27).

The amount of nutrients applied for each crop is taken from the FERTISTAT database of the FAO (2007). When now data is available for a certain crop in a country, a weighted global average is used. The application rates are shown

Appendix IV: Fertilizer application rates. Pesticide application rates are given for sugar cane for the Brazilian situation by Moreira (2007) for sugar beet in the United Kingdom by Elsayed (2003) and for maize in the USA by Hill et al. (2006). Since national information on pesticides per crop for all countries is not available, the application rates of the mentioned studies are used as crop specific and not site-specific.

## Appendix VI: Value fractions

*Table 29. Value fractions ($f_v[p]$) of cane sugar and by-products (Source: UNCTAD/WTO (2007), SITA-database, period: 1996-2005).*

| | Brazil | India | China | Thailand | Australia | USA | Average |
|---|---|---|---|---|---|---|---|
| Sugar, raw | 0.76 | 0.87 | 0.90 | 0.83 | 0.90 | 0.88 | 0.86 |
| Molasses | 0.15 | 0.05 | 0.05 | 0.06 | 0.04 | 0.06 | 0.07 |
| Bagasse | 0.09 | 0.07 | 0.05 | 0.10 | 0.06 | 0.06 | 0.07 |
| Filter cake[1] | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |

1) Calculations based on USDA (2006) and FAO (2004)

*Table 30. Value fractions ($f_v[p]$) of beet sugar and by-products (Source: UNCTAD/WTO (2007), SITA-database, period: 1996-2005).*

| | France | Germany | USA | Russian Federation | Ukraine | Average |
|---|---|---|---|---|---|---|
| Sugar | 0.97 | 0.95 | 0.74 | 0.93 | 0.91 | 0.90 |
| Molasses | 0.02 | 0.02 | 0.17 | 0.02 | 0.04 | 0.05 |
| Beet pulp | 0.02 | 0.03 | 0.09 | 0.05 | 0.05 | 0.05 |

*Table 31. Value fractions ($f_v[p]$) of cane ethanol and by-products.*

| | Brazil | India | China | Thailand | Australia | USA | Average |
|---|---|---|---|---|---|---|---|
| Ethanol[1] | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 | 0.89 |
| Vinasse[2] | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Filter cake[2] | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Bagasse[3] | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |

Sources:
1) FAPRI (2008)
2) Calculations based on USDA (2006) and FAO (2004)
3) Calculations based on Paturau (1989)

*Table 32. Value fractions ($f_v[p]$) of beet ethanol and by-products (Source: UNCTAD/WTO (2007), SITA-database, period: 1996-2005).*

| | France | Germany | USA | Russian Federation | Ukraine | Average |
|---|---|---|---|---|---|---|
| Ethanol | 0.90 | 0.92 | 0.89 | 0.93 | 0.93 | 0.92 |
| Beet pulp | 0.10 | 0.08 | 0.11 | 0.07 | 0.07 | 0.08 |

Sources:
1) FAPRI (2008)
2) UNCTAD/WTO (2007), SITA-database

## Appendix VII: Crop production and yield

*Table 33. Average annual sugar cane production (FAOSTAT, period: 1998-2007)*

| | Country | Average annual production (ton/yr) | Percentage | Yield (ton/ha) |
|---|---|---|---|---|
| 1 | Brazil | 392264072 | 29.5 | 71.8 |
| 2 | India | 284523120 | 21.4 | 67.3 |
| 3 | China | 88195237 | 6.6 | 69.5 |
| 4 | Thailand | 56169787 | 4.2 | 56.4 |
| 5 | Pakistan | 49623460 | 3.7 | 48.3 |
| 6 | Mexico | 48190815 | 3.6 | 74.4 |
| 7 | Colombia | 36824924 | 2.8 | 88.5 |
| 8 | Australia | 36444733 | 2.7 | 85.8 |
| 9 | United States of America | 29585579 | 2.2 | 75.5 |
| 10 | Philippines | 27480319 | 2.1 | 73.4 |
| 11 | Indonesia | 25701900 | 1.9 | 70.3 |
| 12 | Cuba | 24966000 | 1.9 | 31.4 |
| 13 | South Africa | 21375280 | 1.6 | 53.7 |
| 14 | Argentina | 19807000 | 1.5 | 68.7 |
| 15 | Guatemala | 18283783 | 1.4 | 90.2 |
| 16 | Egypt | 15789368 | 1.2 | 118.6 |
| 17 | Vietnam | 15755630 | 1.2 | 53.0 |
| 18 | Venezuela | 8987375 | 0.7 | 68.5 |
| 19 | Peru | 7633668 | 0.6 | 118.2 |
| 20 | Bangladesh | 6574011 | 0.5 | 40.0 |

*Table 34. Average annual sugar beet production (FAOSTAT, period: 1998-2007)*

| | Country | Average annual production (ton/yr) | Percentage | Yield (ton/ha) |
|---|---|---|---|---|
| 1 | France | 30901364 | 12.0 | 75.4 |
| 2 | United States of America | 28024867 | 10.9 | 51.8 |
| 3 | Germany | 25682208 | 10.0 | 58.2 |
| 4 | Russian Federation | 19281213 | 7.5 | 23.5 |
| 5 | Turkey | 15793480 | 6.1 | 42.7 |
| 6 | Ukraine | 15767170 | 6.1 | 21.2 |
| 7 | Poland | 12458135 | 4.8 | 40.5 |
| 8 | Italy | 10206396 | 4.0 | 47.8 |
| 9 | China | 9427394 | 3.7 | 35.1 |
| 10 | United Kingdom | 8810400 | 3.4 | 54.9 |
| 11 | Spain | 7201389 | 2.8 | 66.3 |
| 12 | Belgium-Luxembourg | 6239111 | 2.4 | 63.3 |
| 13 | Netherlands | 6119180 | 2.4 | 60.5 |
| 14 | Iran | 5156272 | 2.0 | 30.1 |
| 15 | Japan | 4048400 | 1.6 | 59.5 |
| 16 | Egypt | 3330889 | 1.3 | 48.6 |
| 17 | Czech Republic | 3264770 | 1.3 | 47.7 |
| 18 | Serbia | 3197643 | 1.2 | 42.6 |
| 19 | Morocco | 3023697 | 1.2 | 52.7 |
| 20 | Denmark | 2992544 | 1.2 | 56.7 |

*Table 35. Average annual maize production (FAOSTAT, period: 1998-2007)*

| | Country | Average annual production (ton/yr) | Percentage | Yield (ton/ha) |
|---|---|---|---|---|
| 1 | United States of America | 264662163 | 39.7 | 8.9 |
| 2 | China | 128692514 | 19.3 | 5.0 |
| 3 | Brazil | 39088661 | 5.9 | 3.2 |
| 4 | Mexico | 19925360 | 3.0 | 2.7 |
| 5 | Argentina | 16639646 | 2.5 | 6.2 |
| 6 | France | 14748861 | 2.2 | 8.6 |
| 7 | India | 13463590 | 2.0 | 1.9 |
| 8 | Indonesia | 10661079 | 1.6 | 3.1 |
| 9 | Italy | 10035448 | 1.5 | 9.2 |
| 10 | South Africa | 9032300 | 1.4 | 2.8 |
| 11 | Canada | 8975600 | 1.3 | 7.7 |
| 12 | Romania | 8915305 | 1.3 | 3.1 |
| 13 | Hungary | 7085182 | 1.1 | 6.0 |
| 14 | Egypt | 6589772 | 1.0 | 7.7 |
| 15 | Nigeria | 5582300 | 0.8 | 1.5 |
| 16 | Serbia and Montenegro | 5413711 | 0.8 | 4.4 |
| 17 | Ukraine | 5174090 | 0.8 | 3.4 |
| 18 | Philippines | 4985745 | 0.7 | 2.0 |
| 19 | Spain | 4191487 | 0.6 | 9.6 |
| 20 | Thailand | 4176148 | 0.6 | 3.8 |

*Table 36. Nitrogen application rates and maize yields in the USA (USDA, 2008).*

| State | N application rate (kg/ha) | Grain yield (46 %) (ton/ha) | | | | Stover (54%) (ton/ha) | Total yield (ton/ha) |
|---|---|---|---|---|---|---|---|
| | | 2006 | 2007 | 2008 | Average | | |
| Illinois | 179 | 10.2 | 11.0 | 11.2 | 10.8 | 12.7 | 23.5 |
| Indiana | 150 | 9.9 | 9.7 | 10.0 | 9.9 | 11.6 | 21.4 |
| Iowa | 143 | 10.4 | 10.7 | 10.7 | 10.6 | 12.5 | 23.1 |
| Michigan | 132 | 9.2 | 7.7 | 8.7 | 8.5 | 10.0 | 18.6 |
| Minnesota | 131 | 10.1 | 9.2 | 10.3 | 9.9 | 11.6 | 21.4 |
| Nebraska | 154 | 9.5 | 10.0 | 10.2 | 9.9 | 11.7 | 21.6 |
| North Carolina | 145* | 8.3 | 6.3 | 4.9 | 6.5 | 7.6 | 14.1 |
| Pennsylvania | 145* | 7.7 | 7.8 | 8.3 | 7.9 | 9.3 | 17.2 |
| Wisconsin | 90 | 9.0 | 8.5 | 8.6 | 8.7 | 10.2 | 18.9 |
| Weighted U.S. average | 145* | 9.4 | 9.5 | 9.7 | 9.5 | 11.1 | 20.6 |

* Weighted nine state average

## Appendix VIII: Water footprint of unprocessed crops

*Table 37. Water footprint of unprocessed sugar cane for the main producing countries (m3/ton).*

| Country | Green WF | Blue WF | Grey WF | Total WF |
|---|---|---|---|---|
| Argentina | 65 | 137 | 12 | 215 |
| Australia | 65 | 152 | 27 | 243 |
| Belize | 206 | 51 | 20 | 277 |
| Brazil | 115 | 87 | 8 | 209 |
| China | 130 | 47 | 22 | 199 |
| Colombia | 125 | 29 | 11 | 166 |
| Cuba | 310 | 214 | 20 | 544 |
| Egypt | 7 | 156 | 7 | 163 |
| Ethiopia | 55 | 94 | 10 | 159 |
| Guatemala | 118 | 45 | 11 | 174 |
| India | 85 | 156 | 15 | 256 |
| Indonesia | 184 | 46 | 13 | 240 |
| Morocco | 56 | 147 | 14 | 218 |
| Pakistan | 29 | 402 | 26 | 457 |
| Peru | 0 | 134 | 8 | 143 |
| Philippines | 160 | 41 | 12 | 213 |
| South Africa | 100 | 187 | 19 | 306 |
| Thailand | 152 | 132 | 18 | 301 |
| USA | 122 | 102 | 13 | 237 |
| Venezuela | 96 | 157 | 22 | 275 |
| Viet Nam | 160 | 98 | 20 | 278 |
| **Weighted global average** | **109** | **121** | **14** | **243** |

*Table 38. Water footprint of unprocessed sugar beet for the main producing countries ($m^3$/ton).*

| **Country** | **Green WF** | **Blue WF** | **Grey WF** | **Total WF** |
|---|---|---|---|---|
| Belgium | 42 | 19 | 16 | 77 |
| China | 87 | 93 | 34 | 214 |
| Czech Republic | 58 | 43 | 19 | 120 |
| Denmark | 45 | 20 | 18 | 83 |
| Egypt | 0 | 191 | 5 | 196 |
| France | 37 | 39 | 21 | 98 |
| Germany | 50 | 30 | 25 | 105 |
| Iran | 21 | 298 | 36 | 354 |
| Italy | 71 | 63 | 23 | 157 |
| Japan | 80 | 7 | 30 | 117 |
| Morocco | 16 | 121 | 30 | 167 |
| Netherlands | 44 | 20 | 18 | 82 |
| Poland | 67 | 40 | 30 | 137 |
| Russian Federation | 89 | 123 | 46 | 257 |
| Serbia | 71 | 57 | 25 | 154 |
| Spain | 24 | 81 | 16 | 122 |
| Turkey | 32 | 133 | 25 | 190 |
| Ukrain | 132 | 162 | 51 | 345 |
| United Kingdom | 52 | 46 | 18 | 116 |
| USA | 53 | 108 | 23 | 184 |
| **Weighted global average** | **58** | **83** | **27** | **168** |

*Table 39. Water footprint of unprocessed maize for the main producing regions in the USA (m3/ton).*

| Place | Green WF | Blue WF | Grey WF | Total WF |
|---|---|---|---|---|
| Burlington (NC) | 222 | 140 | 103 | 465 |
| Chicago (IL) | 143 | 121 | 76 | 341 |
| Des Moines (IA) | 149 | 118 | 65 | 332 |
| Detroit (MI) | 160 | 164 | 71 | 395 |
| Duluth (MN) | 148 | 82 | 61 | 291 |
| Evansville (IN) | 148 | 143 | 70 | 361 |
| Fort Wayne (IN) | 143 | 147 | 70 | 360 |
| Green Bay (WI) | 157 | 120 | 48 | 324 |
| Huron (MI) | 129 | 240 | 71 | 440 |
| Indianapolis (IA) | 139 | 116 | 65 | 320 |
| Lincoln (NE) | 145 | 176 | 71 | 393 |
| Madison (WI) | 167 | 122 | 48 | 336 |
| Minneapolis (MN) | 147 | 142 | 61 | 350 |
| Moline (IL) | 157 | 101 | 76 | 334 |
| Philadelphia(PA) | 190 | 158 | 84 | 431 |
| Pittsburgh (PA) | 174 | 145 | 84 | 403 |
| **Weighted U.S. average** | **158** | **136** | **64** | **358** |

*Table 40. Water footprint of unprocessed maize for the twenty main producing countries ($m^3$/ton).*

| Country | Green WF | Blue WF | Grey WF | Total WF |
|---|---|---|---|---|
| Argentina | 237 | 22 | 21 | 280 |
| Brazil | 361 | 206 | 58 | 624 |
| Canada | 142 | 171 | 93 | 406 |
| China | 331 | 178 | 120 | 629 |
| Egypt | 91 | 125 | 139 | 355 |
| France | 101 | 99 | 91 | 291 |
| Germany | 122 | 97 | 79 | 298 |
| India | 1174 | 380 | 101 | 1655 |
| Indonesia | 605 | 174 | 7 | 786 |
| Italy | 104 | 103 | 92 | 299 |
| Mexico | 480 | 496 | 136 | 1113 |
| Nigeria | 558 | 834 | 18 | 1410 |
| Philipinnes | 1141 | 5 | 133 | 1279 |
| Romania | 315 | 464 | 131 | 910 |
| South Africa | 368 | 0 | 90 | 458 |
| Spain | 80 | 104 | 108 | 291 |
| Thailand | 300 | 339 | 68 | 707 |
| Ukraine | 283 | 521 | 120 | 923 |
| Weighted U.S. average | 158 | 136 | 64 | 358 |
| **Weighted global average** | **279** | **204** | **78** | **561** |

## Appendix IX: Water footprint of sugar and crop by-products

*Table 41. Water footprint of cane sugar and sugar cane by-products, excluding the grey water footprint (m$^3$/ton).*

| Country | Bagasse | Filter cake | Molasses | Cane sugar | | |
|---|---|---|---|---|---|---|
| | | | | Green WF | Blue WF | Green + blue WF |
| Argentina | 101 | 51 | 338 | 402 | 844 | 1246 |
| Australia | 121 | 54 | 360 | 397 | 932 | 1328 |
| Brazil | 101 | 50 | 403 | 706 | 532 | 1237 |
| China | 89 | 44 | 355 | 801 | 290 | 1091 |
| Colombia | 77 | 39 | 257 | 769 | 180 | 949 |
| Cuba | 262 | 131 | 1047 | 1904 | 1313 | 3217 |
| Egypt | 78 | 39 | 313 | 7 | 955 | 962 |
| Ethiopia | 74 | 37 | 298 | 335 | 579 | 914 |
| Guatemala | 82 | 41 | 326 | 728 | 274 | 1002 |
| India | 120 | 60 | 482 | 523 | 957 | 1480 |
| Indonesia | 114 | 57 | 455 | 1131 | 285 | 1396 |
| Morocco | 102 | 51 | 407 | 346 | 905 | 1251 |
| Pakistan | 216 | 108 | 718 | 179 | 2469 | 2648 |
| Peru | 67 | 34 | 269 | 0 | 825 | 825 |
| Philippines | 101 | 50 | 335 | 985 | 251 | 1236 |
| South Africa | 144 | 72 | 575 | 615 | 1149 | 1765 |
| Thailand | 142 | 71 | 567 | 932 | 809 | 1741 |
| USA | 112 | 56 | 448 | 585 | 487 | 1071 |
| Venezuela | 126 | 63 | 422 | 587 | 966 | 1554 |
| Vietnam | 129 | 65 | 430 | 984 | 601 | 1586 |
| **Weighted global average** | **115** | **58** | **383** | **670** | **743** | **1413** |

*Table 42. Water footprint of cane sugar and sugar cane by-products, including the grey water footprint ($m^3$/ton).*

| **Country** | **Bagasse** | **Filter cake** | **Molasses** | **Cane sugar** | |
|---|---|---|---|---|---|
| | | | | **Grey WF** | **Total WF** |
| Argentina | 107 | 54 | 358 | 72 | 1318 |
| Australia | 121 | 61 | 405 | 164 | 1492 |
| Brazil | 105 | 52 | 418 | 47 | 1284 |
| China | 100 | 50 | 399 | 133 | 1224 |
| Colombia | 83 | 41 | 276 | 69 | 1018 |
| Cuba | 272 | 136 | 1087 | 123 | 3340 |
| Egypt | 82 | 41 | 327 | 41 | 1003 |
| Ethiopia | 79 | 40 | 317 | 61 | 975 |
| Guatemala | 87 | 44 | 348 | 68 | 1070 |
| India | 128 | 64 | 511 | 91 | 1571 |
| Indonesia | 120 | 60 | 480 | 79 | 1475 |
| Morocco | 109 | 54 | 436 | 88 | 1339 |
| Pakistan | 228 | 114 | 762 | 159 | 2807 |
| Peru | 71 | 36 | 286 | 52 | 877 |
| Philippines | 106 | 53 | 355 | 71 | 1307 |
| South Africa | 153 | 76 | 612 | 114 | 1879 |
| Thailand | 151 | 75 | 602 | 109 | 1850 |
| USA | 119 | 59 | 474 | 63 | 1135 |
| Venezuela | 137 | 69 | 458 | 135 | 1688 |
| Vietnam | 139 | 69 | 463 | 122 | 1707 |
| **Weighted global average** | **122** | **61** | **407** | **86** | **1499** |

*Table 43. Water footprint of beet sugar and sugar beet by-products, excluding the grey water footprint ($m^3$/ton).*

| **Country** | **Beet pulp** | **Molasses** | **Beet sugar** | | |
|---|---|---|---|---|---|
| | | | **Green WF** | **Blue WF** | **Green + blue WF** |
| Belgium | 72 | 75 | 232 | 104 | 336 |
| China | 216 | 225 | 482 | 517 | 1000 |
| Czech Republic | 121 | 126 | 321 | 241 | 561 |
| Denmark | 78 | 81 | 251 | 110 | 361 |
| Egypt | 229 | 239 | 0 | 1063 | 1063 |
| France | 92 | 95 | 205 | 219 | 424 |
| Germany | 96 | 100 | 276 | 167 | 443 |
| Iran | 382 | 398 | 114 | 1656 | 1771 |
| Italy | 140 | 146 | 298 | 351 | 649 |
| Japan | 105 | 109 | 448 | 38 | 486 |
| Morocco | 164 | 171 | 90 | 670 | 760 |
| Poland | 129 | 134 | 375 | 222 | 597 |
| Russian Federation | 253 | 264 | 493 | 682 | 1175 |
| Spain | 127 | 132 | 134 | 453 | 587 |
| Netherlands | 77 | 81 | 246 | 113 | 359 |
| Turkey | 198 | 206 | 176 | 740 | 916 |
| Ukraine | 353 | 368 | 728 | 889 | 1617 |
| United Kingdom | 117 | 122 | 287 | 255 | 541 |
| USA | 193 | 201 | 293 | 603 | 896 |
| Serbia | 154 | 161 | 397 | 318 | 715 |
| **Weighted global average** | **169** | **176** | **323** | **462** | **784** |

*Table 44. Water footprint of beet sugar and sugar beet by-products, including the grey water footprint ($m^3$/ton).*

| **Country** | **Beet pulp** | **Molasses** | **Beet sugar** | |
|---|---|---|---|---|
| | | | **Grey WF** | **Total WF** |
| Belgium | 92 | 92 | 90 | 426 |
| China | 257 | 257 | 190 | 1190 |
| Czech Republic | 144 | 144 | 105 | 666 |
| Denmark | 99 | 99 | 98 | 459 |
| Egypt | 235 | 235 | 26 | 1089 |
| France | 117 | 117 | 119 | 543 |
| Germany | 126 | 126 | 139 | 582 |
| Iran | 425 | 425 | 200 | 1970 |
| Italy | 167 | 167 | 126 | 774 |
| Japan | 140 | 140 | 165 | 650 |
| Morocco | 200 | 200 | 169 | 929 |
| Poland | 165 | 165 | 166 | 763 |
| Russian Federation | 309 | 309 | 257 | 1432 |
| Spain | 146 | 146 | 91 | 678 |
| Netherlands | 99 | 99 | 99 | 458 |
| Turkey | 228 | 228 | 141 | 1056 |
| Ukraine | 414 | 414 | 280 | 1897 |
| United Kingdom | 139 | 139 | 101 | 643 |
| USA | 221 | 221 | 129 | 1025 |
| Serbia | 185 | 185 | 141 | 856 |
| **Weighted global average** | **202** | **202** | **150** | **935** |

*Table 45. Water footprint of HFMS 55 and maize by-products in the USA, excluding the grey water footprint (m$^3$/ton).*

| **Place** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **HFMS 55** | | |
|---|---|---|---|---|---|---|
| | | | | **Green WF** | **Blue WF** | **Green + blue WF** |
| Burlington (NC) | 1156 | 624 | 624 | 446 | 282 | 728 |
| Chicago (IL) | 844 | 456 | 456 | 288 | 244 | 531 |
| Des Moines (IA) | 852 | 460 | 460 | 300 | 236 | 536 |
| Detroit (MI) | 1032 | 558 | 558 | 321 | 329 | 650 |
| Duluth (MN) | 733 | 396 | 396 | 297 | 165 | 462 |
| Evansville (IN) | 928 | 502 | 502 | 297 | 287 | 585 |
| Fort Wayne (IN) | 924 | 499 | 499 | 287 | 295 | 582 |
| Green Bay (WI) | 882 | 477 | 477 | 314 | 241 | 556 |
| Huron (MI) | 1178 | 636 | 636 | 259 | 483 | 742 |
| Indianapolis (IA) | 814 | 440 | 440 | 280 | 233 | 513 |
| Lincoln (NE) | 1025 | 554 | 554 | 292 | 353 | 645 |
| Madison (WI) | 920 | 497 | 497 | 335 | 244 | 579 |
| Minneapolis (MN) | 921 | 498 | 498 | 296 | 284 | 580 |
| Moline (IL) | 824 | 445 | 445 | 316 | 203 | 519 |
| Philadelphia(PA) | 1107 | 598 | 598 | 381 | 316 | 697 |
| Pittsburgh (PA) | 1016 | 549 | 549 | 349 | 291 | 640 |
| **Weighted U.S. average** | **941** | **508** | **508** | **317** | **275** | **592** |

*Table 46. Water footprint of HFMS 55 and maize by-products in the USA, including the grey water footprint ($m^3$/ton).*

| Place | Maize oil | Maize gluten feed | Maize gluten meal | HFMS 55 | |
|---|---|---|---|---|---|
| | | | | Grey WF | Total WF |
| Burlington (NC) | 1484 | 188 | 802 | 206 | 934 |
| Chicago (IL) | 1087 | 138 | 587 | 153 | 684 |
| Des Moines (IA) | 1059 | 134 | 572 | 130 | 667 |
| Detroit (MI) | 1258 | 160 | 680 | 143 | 792 |
| Duluth (MN) | 928 | 118 | 502 | 123 | 585 |
| Evansville (IN) | 1152 | 146 | 622 | 141 | 725 |
| Fort Wayne (IN) | 1147 | 146 | 620 | 141 | 723 |
| Green Bay (WI) | 1034 | 131 | 559 | 96 | 651 |
| Huron (MI) | 1404 | 178 | 759 | 143 | 884 |
| Indianapolis (IA) | 1022 | 130 | 552 | 130 | 643 |
| Lincoln (NE) | 1252 | 159 | 676 | 143 | 788 |
| Madison (WI) | 1071 | 136 | 579 | 96 | 675 |
| Minneapolis (MN) | 1116 | 142 | 603 | 123 | 703 |
| Moline (IL) | 1067 | 135 | 576 | 153 | 672 |
| Philadelphia(PA) | 1376 | 175 | 743 | 169 | 866 |
| Pittsburgh (PA) | 1285 | 163 | 694 | 169 | 809 |
| **Weighted U.S. average** | **1145** | **145** | **618** | **129** | **721** |

*Table 47. Water footprint of HFMS 55 and maize by-products for the twenty main producing countries, excluding the grey water footprint (m$^3$/ton).*

| **Country** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **HFMS 55** | | |
|---|---|---|---|---|---|---|
| | | | | **Green WF** | **Blue WF** | **Green + blue WF** |
| Argentina | 828 | 447 | 447 | 477 | 45 | 521 |
| Brazil | 1806 | 976 | 976 | 725 | 413 | 1137 |
| Canada | 998 | 539 | 539 | 286 | 343 | 629 |
| China | 1625 | 878 | 878 | 665 | 358 | 1023 |
| Egypt | 688 | 372 | 372 | 182 | 251 | 433 |
| France | 638 | 345 | 345 | 202 | 200 | 402 |
| Germany | 698 | 377 | 377 | 244 | 195 | 440 |
| India | 4957 | 2678 | 2678 | 2358 | 763 | 3121 |
| Indonesia | 2484 | 1342 | 1342 | 1216 | 349 | 1564 |
| Italy | 659 | 356 | 356 | 208 | 207 | 415 |
| Mexico | 3113 | 1682 | 1682 | 965 | 996 | 1960 |
| Nigeria | 4440 | 2399 | 2399 | 1121 | 1675 | 2796 |
| Philipinnes | 3653 | 1973 | 1973 | 2291 | 9 | 2300 |
| Romania | 2484 | 1342 | 1342 | 632 | 933 | 1564 |
| South Africa | 1174 | 634 | 634 | 739 | 0 | 739 |
| Spain | 585 | 316 | 316 | 161 | 208 | 369 |
| Thailand | 2038 | 1101 | 1101 | 603 | 681 | 1283 |
| Ukraine | 2563 | 1385 | 1385 | 568 | 1046 | 1614 |
| Weighted U.S. average | 941 | 508 | 508 | 317 | 275 | 592 |
| **Weighted global avg** | **1541** | **833** | **833** | **560** | **410** | **971** |

*Table 48. Water footprint of HFMS 55 and maize by-products for the twenty main producing countries, including the grey water footprint (m$^3$/ton).*

| **Country** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **HFMS 55** | |
|---|---|---|---|---|---|
| | | | | **Grey WF** | **Total WF** |
| Argentina | 894 | 114 | 483 | 42 | 563 |
| Brazil | 1989 | 253 | 1075 | 115 | 1253 |
| Canada | 1295 | 165 | 700 | 187 | 816 |
| China | 2007 | 255 | 1084 | 240 | 1264 |
| Egypt | 1132 | 144 | 611 | 280 | 713 |
| France | 928 | 118 | 501 | 183 | 584 |
| Germany | 951 | 121 | 514 | 159 | 599 |
| India | 5278 | 670 | 2852 | 203 | 3324 |
| Indonesia | 2508 | 319 | 1355 | 15 | 1579 |
| Italy | 952 | 121 | 514 | 185 | 599 |
| Mexico | 3548 | 451 | 1917 | 274 | 2234 |
| Nigeria | 4497 | 571 | 2430 | 36 | 2832 |
| Philipinnes | 4078 | 518 | 2203 | 268 | 2568 |
| Romania | 2903 | 369 | 1568 | 263 | 1828 |
| South Africa | 1462 | 186 | 790 | 181 | 920 |
| Spain | 929 | 118 | 502 | 216 | 585 |
| Thailand | 2254 | 286 | 1218 | 136 | 1420 |
| Ukraine | 2944 | 374 | 1591 | 240 | 1854 |
| Weighted U.S. average | 1145 | 145 | 618 | 129 | 721 |
| **Weighted global avg** | **1789** | **227** | **966** | **156** | **1126** |

## Appendix X: Water footprint of ethanol and crop by-products

*Table 49. Water footprint of cane-based ethanol and sugar cane by-products, excluding the grey water footprint ($m^3$/ton).*

| Country | Bagasse | Filter cake | Vinasse | Ethanol | | |
|---|---|---|---|---|---|---|
| | | | | Green WF | Blue WF | Green + blue WF |
| Argentina | 121 | 47 | 63 | 1372 | 1426 | 2797 |
| Australia | 139 | 54 | 72 | 958 | 2249 | 3208 |
| Brazil | 129 | 50 | 67 | 1704 | 1284 | 2988 |
| China | 114 | 44 | 59 | 1935 | 701 | 2636 |
| Colombia | 99 | 39 | 51 | 1893 | 398 | 2291 |
| Cuba | 337 | 131 | 175 | 4596 | 3171 | 7767 |
| Egypt | 101 | 39 | 52 | 104 | 2307 | 2323 |
| Guatemala | 105 | 41 | 54 | 1757 | 662 | 2419 |
| India | 155 | 60 | 80 | 1263 | 2311 | 3573 |
| Indonesia | 146 | 57 | 76 | 2732 | 688 | 3371 |
| Mexico | 124 | 48 | 64 | 1167 | 1698 | 2865 |
| Peru | 86 | 34 | 45 | 0 | 1992 | 1992 |
| Pakistan | 277 | 108 | 144 | 432 | 5963 | 6395 |
| Philippines | 129 | 50 | 67 | 2378 | 607 | 2985 |
| South Africa | 185 | 72 | 96 | 1486 | 2775 | 4261 |
| Thailand | 182 | 71 | 94 | 2251 | 1953 | 4204 |
| USA | 144 | 56 | 75 | 1812 | 1509 | 3321 |
| Venezuela | 163 | 63 | 84 | 1419 | 2333 | 3752 |
| Viet Nam | 166 | 65 | 86 | 2376 | 1452 | 3829 |
| **Weighted global average** | **148** | **58** | **77** | **1617** | **1795** | **3412** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

*Table 50. Water footprint of cane-based ethanol and sugar cane by-products, including the grey water footprint ($m^3$/ton).*

| Country | Bagasse | Filter cake | Vinasse | Ethanol | |
|---|---|---|---|---|---|
| | | | | Grey WF | Total WF |
| Argentina | 129 | 50 | 67 | 173 | 2970 |
| Australia | 156 | 61 | 81 | 396 | 3604 |
| Brazil | 134 | 52 | 70 | 114 | 3102 |
| China | 128 | 50 | 66 | 321 | 2956 |
| Colombia | 105 | 41 | 55 | 134 | 2425 |
| Cuba | 350 | 136 | 181 | 298 | 8065 |
| Egypt | 105 | 41 | 54 | 100 | 2423 |
| Guatemala | 112 | 44 | 58 | 164 | 2584 |
| India | 164 | 64 | 85 | 220 | 3793 |
| Indonesia | 154 | 60 | 80 | 190 | 3561 |
| Mexico | 133 | 52 | 69 | 199 | 3064 |
| Peru | 92 | 36 | 48 | 126 | 2118 |
| Pakistan | 288 | 112 | 149 | 246 | 6640 |
| Philippines | 136 | 53 | 71 | 162 | 3147 |
| South Africa | 197 | 76 | 102 | 276 | 4537 |
| Thailand | 194 | 75 | 100 | 263 | 4467 |
| USA | 152 | 59 | 79 | 196 | 3518 |
| Venezuela | 170 | 66 | 88 | 173 | 3925 |
| Viet Nam | 176 | 68 | 91 | 224 | 4053 |
| **Weighted global average** | **157** | **61** | **81** | **208** | **3619** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

*Table 51. Water footprint of beet-based ethanol and sugar beet by-products, excluding the grey water footprint ($m^3$/ton).*

| Country | Beet pulp | Ethanol | | |
|---|---|---|---|---|
| | | Green WF | Blue WF | Green + blue WF |
| Belgium | 97 | 426 | 190 | 617 |
| China | 288 | 887 | 951 | 1837 |
| Czech Republic | 162 | 589 | 443 | 1032 |
| Denmark | 104 | 462 | 202 | 663 |
| Egypt | 306 | 0 | 1953 | 1953 |
| France | 122 | 377 | 403 | 780 |
| Germany | 128 | 508 | 307 | 815 |
| Iran | 509 | 210 | 3043 | 3254 |
| Italy | 187 | 547 | 645 | 1192 |
| Japan | 140 | 823 | 70 | 892 |
| Morocco | 219 | 164 | 1232 | 1397 |
| Poland | 172 | 689 | 407 | 1096 |
| Russian Federation | 338 | 906 | 1253 | 2159 |
| Spain | 169 | 246 | 832 | 1079 |
| Netherlands | 103 | 452 | 208 | 660 |
| Turkey | 263 | 323 | 1360 | 1683 |
| Ukraine | 470 | 1353 | 1652 | 3006 |
| United Kingdom | 156 | 527 | 468 | 995 |
| USA | 293 | 502 | 913 | 1487 |
| Serbia | 206 | 729 | 585 | 1314 |
| **Weighted global average** | **226** | **593** | **848** | **1441** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

*Table 52. Water footprint of beet-based ethanol and sugar beet by-products, including the grey water footprint (m$^3$/ton).*

| **Country** | **Beet pulp** | **Ethanol** | |
|---|---|---|---|
| | | **Grey WF** | **Total WF** |
| Belgium | 122 | 166 | 782 |
| China | 342 | 349 | 2187 |
| Czech Republic | 192 | 193 | 1225 |
| Denmark | 132 | 180 | 844 |
| Egypt | 313 | 48 | 2001 |
| France | 156 | 218 | 998 |
| Germany | 167 | 255 | 1069 |
| Iran | 567 | 367 | 3620 |
| Italy | 217 | 192 | 1385 |
| Japan | 187 | 302 | 1195 |
| Morocco | 267 | 310 | 1707 |
| Poland | 219 | 305 | 1402 |
| Russian Federation | 412 | 472 | 2631 |
| Spain | 195 | 167 | 1245 |
| Netherlands | 132 | 182 | 843 |
| Turkey | 304 | 259 | 1941 |
| Ukrain | 552 | 521 | 3526 |
| United Kingdom | 185 | 186 | 1181 |
| USA | 336 | 222 | 1708 |
| Serbia | 246 | 259 | 1573 |
| **Weighted global average** | **269** | **276** | **1717** |

To convert the WF from m$^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from m$^3$/ton to m$^3$/GJ multiply by 0.034.

*Table 53. Water footprint of maize-based ethanol and maize by-products by wet milling in the USA, excluding the grey water footprint ($m^3$/ton).*

| **Country** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **Ethanol** | | |
|---|---|---|---|---|---|---|
| | | | | **Green WF** | **Blue WF** | **Green + blue WF** |
| Burlington (NC) | 1565 | 846 | 846 | 957 | 605 | 1562 |
| Chicago (IL) | 1143 | 618 | 618 | 618 | 523 | 1141 |
| Des Moines (IA) | 1154 | 623 | 623 | 644 | 508 | 1152 |
| Detroit (MI) | 1398 | 755 | 755 | 688 | 707 | 1395 |
| Duluth (MN) | 993 | 536 | 536 | 637 | 355 | 991 |
| Evansville (IN) | 1257 | 679 | 679 | 639 | 616 | 1255 |
| Fort Wayne (IN) | 1251 | 676 | 676 | 616 | 633 | 1249 |
| Green Bay (WI) | 1195 | 646 | 646 | 675 | 518 | 1193 |
| Huron (MI) | 1595 | 862 | 862 | 556 | 1036 | 1592 |
| Indianapolis (IA) | 1103 | 596 | 596 | 601 | 500 | 1101 |
| Lincoln (NE) | 1388 | 750 | 750 | 627 | 758 | 1385 |
| Madison (WI) | 1245 | 673 | 673 | 719 | 525 | 1243 |
| Minneapolis (MN) | 1247 | 674 | 674 | 635 | 610 | 1245 |
| Moline (IL) | 1116 | 603 | 603 | 679 | 435 | 1114 |
| Philadelphia(PA) | 1499 | 810 | 810 | 817 | 679 | 1496 |
| Pittsburgh (PA) | 1376 | 743 | 743 | 749 | 624 | 1374 |
| **Weighted U.S. average** | **1274** | **688** | **688** | **681** | **591** | **1272** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

*Table 54. Water footprint of maize-based ethanol and maize by-products by wet milling in the USA, including the grey water footprint ($m^3$/ton).*

| **Country** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **Ethanol** | |
|---|---|---|---|---|---|
| | | | | **Grey WF** | **Total WF** |
| Burlington (NC) | 2009 | 255 | 1086 | 443 | 2006 |
| Chicago (IL) | 1472 | 187 | 795 | 328 | 1469 |
| Des Moines (IA) | 1434 | 182 | 775 | 280 | 1431 |
| Detroit (MI) | 1704 | 216 | 921 | 306 | 1701 |
| Duluth (MN) | 1257 | 160 | 679 | 264 | 1255 |
| Evansville (IN) | 1560 | 198 | 843 | 302 | 1557 |
| Fort Wayne (IN) | 1554 | 197 | 840 | 302 | 1551 |
| Green Bay (WI) | 1401 | 178 | 757 | 205 | 1398 |
| Huron (MI) | 1902 | 242 | 1027 | 306 | 1898 |
| Indianapolis (IA) | 1384 | 176 | 747 | 280 | 1381 |
| Lincoln (NE) | 1696 | 215 | 916 | 307 | 1693 |
| Madison (WI) | 1451 | 184 | 784 | 205 | 1448 |
| Minneapolis (MN) | 1512 | 192 | 817 | 264 | 1509 |
| Moline (IL) | 1445 | 183 | 780 | 328 | 1442 |
| Philadelphia(PA) | 1863 | 237 | 1007 | 363 | 1860 |
| Pittsburgh (PA) | 1740 | 221 | 940 | 363 | 1737 |
| **Weighted U.S. average** | **1550** | **197** | **838** | **276** | **1543** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

*Table 55. Water footprint of maize-based ethanol and maize by-products by dry milling in the USA, including the grey water footprint (m$^3$/ton).*

| **Country** | **Stover** | **DDGS** | **Ethanol** | | | |
|---|---|---|---|---|---|---|
| | | | **Green WF** | **Blue WF** | **Grey WF** | **Total WF** |
| Burlington (NC) | 144 | 148 | 982 | 621 | 455 | 2059 |
| Chicago (IL) | 105 | 108 | 635 | 537 | 337 | 1508 |
| Des Moines (IA) | 106 | 109 | 661 | 521 | 287 | 1469 |
| Detroit (MI) | 128 | 132 | 707 | 726 | 314 | 1746 |
| Duluth (MN) | 91 | 94 | 653 | 364 | 271 | 1288 |
| Evansville (IN) | 115 | 119 | 655 | 633 | 310 | 1598 |
| Fort Wayne (IN) | 115 | 118 | 633 | 649 | 310 | 1592 |
| Green Bay (WI) | 110 | 113 | 693 | 531 | 211 | 1435 |
| Huron (MI) | 146 | 150 | 571 | 1063 | 314 | 1948 |
| Indianapolis (IA) | 101 | 104 | 617 | 513 | 287 | 1418 |
| Lincoln (NE) | 127 | 131 | 643 | 778 | 315 | 1737 |
| Madison (WI) | 114 | 117 | 738 | 538 | 211 | 1487 |
| Minneapolis (MN) | 115 | 118 | 651 | 627 | 271 | 1549 |
| Moline (IL) | 102 | 105 | 697 | 446 | 337 | 1480 |
| Philadelphia(PA) | 138 | 141 | 839 | 697 | 373 | 1909 |
| Pittsburgh (PA) | 126 | 130 | 769 | 641 | 373 | 1783 |
| **Weighted U.S. average** | **117** | **3590** | **699** | **602** | **283** | **1584** |

*Table 56. Water footprint of maize-based ethanol and maize by-products by wet milling for the main producing countries, excluding the grey water footprint ($m^3$/ton).*

| **Country** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **Ethanol** | | |
|---|---|---|---|---|---|---|
| | | | | **Green WF** | **Blue WF** | **Green + blue WF** |
| Argentina | 1122 | 606 | 606 | 1024 | 96 | 1120 |
| Brazil | 2446 | 1322 | 1322 | 1556 | 886 | 2442 |
| Canada | 1352 | 730 | 730 | 613 | 737 | 1350 |
| China | 2201 | 1189 | 1189 | 1428 | 769 | 2197 |
| Egypt | 931 | 503 | 503 | 391 | 538 | 930 |
| France | 864 | 467 | 467 | 434 | 429 | 862 |
| Germany | 945 | 511 | 511 | 524 | 419 | 944 |
| India | 6713 | 3627 | 3627 | 5062 | 1639 | 6701 |
| Indonesia | 3365 | 1818 | 1818 | 2610 | 748 | 3359 |
| Italy | 892 | 482 | 482 | 446 | 444 | 890 |
| Mexico | 4216 | 2278 | 2278 | 2071 | 2137 | 4209 |
| Nigeria | 6013 | 3249 | 3249 | 2406 | 3596 | 6002 |
| Philipinnes | 4947 | 2673 | 2673 | 4918 | 20 | 4938 |
| Romania | 3365 | 1818 | 1818 | 1356 | 2002 | 3359 |
| South Africa | 1589 | 859 | 859 | 1587 | 0 | 1587 |
| Spain | 793 | 428 | 428 | 345 | 446 | 791 |
| Thailand | 2760 | 1491 | 1491 | 1294 | 1461 | 2756 |
| Ukraine | 3471 | 1875 | 1875 | 1219 | 2246 | 3465 |
| **Weighted global avg** | **2087** | **1128** | **1128** | **1203** | **881** | **2084** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

*Table 57. Water footprint of maize-based ethanol and maize by-products by wet milling for the main producing countries, including the grey water footprint ($m^3$/ton).*

| **Country** | **Maize oil** | **Maize gluten feed** | **Maize gluten meal** | **Ethanol** | |
|---|---|---|---|---|---|
| | | | | **Grey WF** | **Total WF** |
| Argentina | 1211 | 154 | 654 | 90 | 1209 |
| Brazil | 2694 | 342 | 1456 | 248 | 2690 |
| Canada | 1754 | 223 | 948 | 402 | 1751 |
| China | 2718 | 345 | 1468 | 516 | 2713 |
| Egypt | 1533 | 195 | 828 | 600 | 1530 |
| France | 1257 | 160 | 679 | 392 | 1254 |
| Germany | 1288 | 164 | 696 | 342 | 1286 |
| India | 7149 | 908 | 3862 | 435 | 7136 |
| Indonesia | 3397 | 431 | 1835 | 32 | 3391 |
| Italy | 1289 | 164 | 696 | 397 | 1287 |
| Mexico | 4805 | 610 | 2596 | 588 | 4796 |
| Nigeria | 6091 | 774 | 3291 | 78 | 6080 |
| Philipinnes | 5523 | 701 | 2984 | 575 | 5513 |
| Romania | 3931 | 499 | 2124 | 566 | 3924 |
| South Africa | 1980 | 251 | 1069 | 390 | 1976 |
| Spain | 1258 | 160 | 680 | 465 | 1256 |
| Thailand | 3053 | 388 | 1650 | 292 | 3048 |
| Ukraine | 3987 | 506 | 2154 | 516 | 3980 |
| Weighted U.S. average | 1546 | 196 | 835 | 276 | 1548 |
| **Weighted global average** | **2422** | **308** | **1309** | **334** | **2418** |

*Table 58. Water footprint of maize-based ethanol and maize by-products by dry milling for the main producing countries ($m^3$/ton).*

| **Country** | **Stover** | **DDGS** | **Ethanol** | | | |
|---|---|---|---|---|---|---|
| | | | **Green WF** | **Blue WF** | **Grey WF** | **Total WF** |
| Argentina | 146 | 150 | 1051 | 98 | 476 | 1625 |
| Brazil | 327 | 335 | 1597 | 910 | 1139 | 3645 |
| Canada | 160 | 164 | 629 | 756 | 397 | 1782 |
| China | 250 | 257 | 1466 | 790 | 537 | 2793 |
| Egypt | 117 | 120 | 402 | 553 | 346 | 1301 |
| France | 111 | 114 | 445 | 440 | 355 | 1240 |
| Germany | 118 | 121 | 538 | 431 | 351 | 1320 |
| India | 703 | 721 | 5196 | 1682 | 964 | 7842 |
| Indonesia | 387 | 397 | 2679 | 768 | 867 | 4314 |
| Italy | 112 | 115 | 458 | 456 | 332 | 1246 |
| Mexico | 491 | 504 | 2126 | 2194 | 1161 | 5481 |
| Nigeria | 661 | 679 | 2470 | 3691 | 1221 | 7382 |
| Philipinnes | 573 | 588 | 5048 | 20 | 1321 | 6390 |
| Romania | 387 | 397 | 1392 | 2055 | 867 | 4314 |
| South Africa | 233 | 240 | 1628 | 0 | 976 | 2604 |
| Spain | 99 | 101 | 354 | 458 | 289 | 1101 |
| Thailand | 320 | 328 | 1328 | 1500 | 742 | 3571 |
| Ukraine | 394 | 405 | 1251 | 2305 | 843 | 4399 |
| **Global weighted average** | **241** | **248** | **1234** | **904** | **555** | **2694** |

To convert the WF from $m^3$/ton (= l/kg) to l/l multiply by 0.789 (kg/l). To convert the WF from $m^3$/ton to $m^3$/GJ multiply by 0.034.

## Appendix XI: Water stress

Figure 45 presents the WtA-ratio calculated with the Watergap 2.1 model for the year 1995, based on climate normal period, 1961 – 1990. Furthermore it presents the change in water withdrawals in 2025 for a business-as-usual scenario (Cosgrove and Rijsberman, 2000). Overlaying the water stress map with the vegetation maps of sugar cane and sugar beet (Ramankutty, 2008) results in a map with sugar crops grown in water stressed areas. Besides the business-as-usual scenario, Alcamo et al. (2002) have determined critical regions regarding water stress with four other scenarios. Some of the main producing regions of sugar beet and sugar cane are located in areas with severe water stress. Brazil, the largest sugar cane producer does not suffer any water stress under a business-as-usual scenario. Other scenarios, analyzed by Alcamo et al (2002) and Palmer et al. (2008) however, show water stress in the downstream part of the São Francisco River in the north-eastern of Brazil where one of major sugar cane production areas is located. Especially the impact of dams does result in severe water stress in the area.

India, as worlds seconds producer of sugar cane, suffers a lot more under water stress. At this time large parts of the country already have high or severe water stress. Due to an increasing population, economic growth and irrigation expansion, water withdrawals will only increase (Figure 45). Mainly the Ganges and Indus, although mainly flowing through Pakistan, will be severely stressed in future. Other severely stressed areas with significant production are the state of Florida in the USA, parts of Mexico, the Murray-Darling basin in Australia and the downstream part of the Nile. Due to increasing withdrawals, the Chao Phraya basin in Thailand will become severely stressed as well. This means that from the top ten producers in the world, only China, Colombia and the Philippines produce their sugar cane in areas with no or only little water stress.

Comparing the WtA-ratio map with the areas of extensive sugar beet cultivation results in overlapping in north-western Europe (lower Seine and Rhine), Ukraine and the Russian Federation (Dnieper, Don and Volga), parts of Turkey (Kizilirmak and Tigris & Euphrates) and China (Yellow River). In the USA the basin with most concern is the Rio Grande, flowing into the Gulf of Mexico. Another basin in Texas with severe water stress is the Brazos River. In both river basins sugar cane, sugar beet, as well as maize, is grown. In the large Mississippi basin sugar beet and maize is grown in the north and sugar cane near its mouth. Although for some tributaries water stress is reported, water scarcity in the Mississippi basin is not a central issue.

Table 59 presents an overview of some river basins dealing with water stress and where a significant area is used for sugar crop cultivation. The water competition level (WCL) (Falkenmark, 1989) is the total runoff in an area by the total population of that area. Areas with more than 1700 m$^3$/cap/yr are considered water sufficient, between 1000 – 1700 m$^3$/cap/yr an area is considered water stressed, areas with 500 – 1000 m$^3$/cap/yr indicate chronic water scarcity and below 500 m$^3$/cap/yr an area is absolutely water scarce. The WtA-ratio presented in Table 59, unlike the WSI, does not take into account the EWR. Since the EWR is about 30% - 40% the WtA-ratio should not exceed 60% - 70% to maintain the river basins ecosystem. Regarding the WCL and WtA-ratio not all basins suffer water scarcity at present. Several studies to future water scarcity, which are based on coequal and different scenarios, expect severe water stress in those basins as well. In the next paragraphs some of those basin and their underlying problems will be discussed. The Dnieper, Don and Volga, between Eastern Europe and Central Asia will be considered as basins with a major sugar beet industry. The Ganges and Indus in India and Pakistan are dealt with since India is world's second largest sugar cane producer and are forecasted to become very water scarce basins.

*Table 59. Water competition level (WCL) and withdrawal-to-availability ratio (WtA-ratio) for some river basins and the main crops cultivated in per basin.*

| **River basin** | **Main countries** | **WCL in 1995 ($m^3$/cap)[a]** | **WtA-ratio (%)** | **Production area for** |
|---|---|---|---|---|
| Dnieper | Ukraine, Belarus, Russian Fed. | 1552 | 95[c] | Sugar beet |
| Don | Russian Fed. Ukraine | 1422 | 65[c] | Sugar beet |
| Kizilirmak | Turkey | 1171 | 55 - 100[c] | Sugar beet |
| Rhine-Meuse | Germany, France, Belgium, Netherlands | 1396 | 75[c] | Sugar beet |
| Seine | France | 965 | 55[c] | Sugar beet |
| Yellow River | China | 361 | 89[b] | Sugar beet |
| Rio Grande | USA | 621 | 139[b] | Sugar cane and beet |
| Brazos | USA | 1288 | >100[c] | Sugar cane and beet |
| Nile | Egypt | 2207 | 99[b] | Sugar cane and beet |
| Ganges | India | 1700 | 50[b] | Sugar cane |
| Indus | India, Pakistan | 830 | 72[b] | Sugar cane |
| Chao Phraya | Thailand | 1237 | 55[c] | Sugar cane |

Sources:

a) Watersheds of the world cd, online version (2008)

b) Rosegrant et al. (2002)

c) determined on the basis of the 'Watersheds of the World : Global Maps' (World Resources Map, 2003)

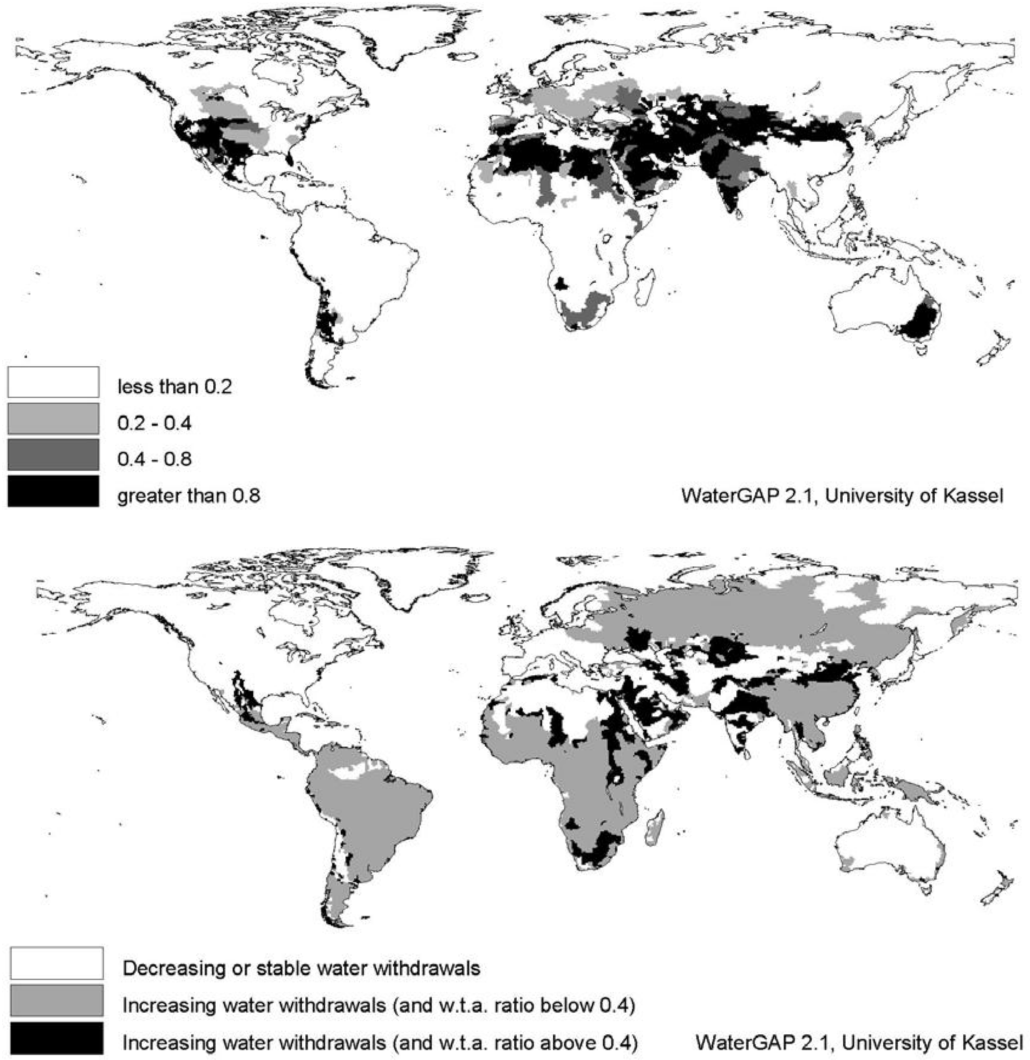


*Figure 45. Water stress conditions for the year 2000, using the withdrawal-to-availability ratio*