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Analysis

# Strategic importance of green water in international crop trade

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ABSTRACT

Virtual water is the volume of water used to produce a commodity or service. Hitherto, most virtual water 'trade' studies have focused on its potential contribution to saving water, especially in water short regions. Very little, however, has been said about the opportunity cost of the associated water. The present research critically evaluates the strategic importance of green water (soil water originating from rainfall) in relation to international commodity trade. Besides having a lower opportunity cost, the use of green water for the production of crops has generally less negative environmental externalities than the use of blue water (irrigation with water abstracted from ground or surface water systems). Although it is widely known that major grain exporters – the USA, Canada, France, Australia and Argentina – produce grain in highly productive rain-fed conditions, green water volumes in exports have rarely been estimated. The present study corroborates that green water is by far the largest share of virtual water in maize, soybean and wheat exports from its main exporting countries (USA, Canada, Australia and Argentina) during the period 2000–2004. Insofar virtual water is 'traded' towards water-scarce nations that heavily depend on their blue water resources, green virtual-water 'trade' related to these commodities plays a role in ensuring water and water-dependent food security and avoiding further potential damage to the water environments in both importing and exporting countries. This potential of international green virtual-water 'trade', however, is constrained by factors such as technology, the potential for further increases in the productivity of soil and irrigation water, the level of socio-economic development, national food policies and international trade agreements.

## 1. Introduction

There is a growing body of literature focusing on the concept of virtual water and on its potential contribution to saving water, especially in water-short nations (Hoekstra and Hung, 2002; Hoekstra, 2003; Hoekstra and Chapagain, 2008). Few of them, however, focus on the relevance of green water (soil water originating from rain) in international commodity trade (De Fraiture et al., 2004; Allan, 2006; Chapagain et al., 2006b; CAWMA, 2007). The present research critically evaluates the strategic importance and implications of green water in international commodity trade.

The virtual-water content of a product (a commodity, good or service) refers to the volume of water used in its production (Allan, 1997, 1999). Building on this concept, virtual-water 'trade' represents the amount of water embedded in products traded internationally. International trade can save water globally if a water-intensive commodity is traded from an area where it is produced with high water productivity (ton/m$^3$) to an area with lower water productivity (De Fraiture et al., 2004; Oki and Kanae, 2004; Chapagain et al., 2006a; Yang et al., 2006). But apart from stressing its potential contribution to water savings, it is also important to establish whether the water used proceeds from rainwater evaporated during the production process (green water) or surface water and/or groundwater evaporated as a result of the production of the product (blue water). Traditionally, emphasis has been given to the concept of blue water through the "miracle" of irrigation systems. However, an increasing number of authors highlight the importance of green water on ensuring water and water-dependent food security through sustaining rain-fed crop production (Falkenmark and Rockström, 2004; CAWMA, 2007; Rockström et al., 2007). Green water generally has a lower opportunity cost than blue water (Hoekstra et al., 2001; Albersen et al., 2003). Even if it is more and more upheld that green water represents the largest share of virtual water in the international trade of agricultural commodities, with exports going from green water rich countries towards generally blue water based economies, hitherto, green water volumes have rarely been estimated.

The present research, framed within a more extensive study (Aldaya et al., 2008), focuses on the current importance of green water within international agricultural commodity trade. This research builds on earlier studies, which roughly estimated the share of green water in global agricultural production (Rockström et al., 1999; Chapagain and Hoekstra, 2004; De Fraiture et al., 2004). Chapagain

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et al. (2006b) carried out detailed calculations of the green water volumes for cotton production. More recently, Chapagain and Orr (2009) showed the importance of green water in the production of tomatoes in Spain. The present work complements these studies estimating the green and blue virtual-water content of maize, soybean and wheat exports from the USA, Canada, Argentina and Australia, which are the main exporting countries of these crops.

## 2. Method and Data

The selected crops are staple food crops with low economic value in the world market (125–240 US$/ton) and use the most water globally after rice (rice 21%, wheat 12, maize 9 and soybean 4) (Chapagain and Hoekstra, 2004; Hoekstra and Chapagain, 2008). Major exporting countries were chosen for the study: USA, Argentina and Canada, contributing 69% to the global exported maize, 63% to exported soybeans and, together with Australia, 58% to exported wheat (Table 1).

The virtual-water content of a product is calculated using the methodology developed by Hoekstra and Hung (2002, 2005), Chapagain and Hoekstra (2004) and Hoekstra and Chapagain (2007, 2008). The virtual-water content of primary crops ($m^3$/ton) has been calculated as the ratio of the water volume used during the entire period of crop growth (crop water requirement, $m^3$/ha) to the corresponding crop yield (ton/ha) in the producing country. The volume of water used to grow crops in the field has two components: effective rainfall (green water) and irrigation water (blue water).

The total crop water requirement, together with the effective rainfall and irrigation requirements per country have been estimated using the CROPWAT model (Allen et al., 1998; FAO, 2003a). The calculation is done using climate data for the major crop-producing states or provinces and a specific cropping pattern for each crop according to the type of climate (Tables 1 and 2). The climate data have been taken from the CLIMWAT model (FAO, 2003b) for the most appropriate climatic stations located in the major crop producing regions of each state or province (Table 2). For states or provinces with more than one climate station, the data for the relevant stations have been equally weighed assuming that the stations represent equally sized crop-producing areas. The actual irrigation water use (FAO, 2007a) is taken equal to the irrigation requirements as estimated with the CROPWAT model for those countries where the whole harvesting area is reportedly irrigated. In the countries where only a certain fraction of the harvesting area is irrigated, the actual irrigation water use is taken equal to this fraction times the irrigation water requirements. Concerning crop parameters, crop coefficients for different crops are taken from FAO (Allen et al., 1998; FAO, 2003a) and crop lengths from the work of Chapagain and Hoekstra (2004). In the case of the USA, the planting dates and cropping calendar are taken from USDA (2006).

**Table 1**
Crop calendar, yield and production by country.

| Commodity | Country | Planting period[a] | Yield[b] (ton/ha) | Average exports[c] ($10^6$ton/year) | % contribution to global exports |
|---|---|---|---|---|---|
| Maize | Argentina | Sept/ Oct/Nov | 5.99 | 10.76 | 12.69 |
| | Canada | May/ June | 7.22 | 0.26 | 0.30 |
| | USA | April/ May | 8.88 | 47.14 | 55.56 |
| Soybean | Argentina | Nov/ Dec/Jan | 2.51 | 6.58 | 11.69 |
| | Canada | May/ June | 2.22 | 0.75 | 1.34 |
| | USA | May/ June | 2.58 | 28.03 | 49.83 |
| Wheat (Spring) | Argentina | May/ June/ July | 2.37 | 9.40 | 8.24 |
| | Australia | May/ June/ July | 1.70 | 15.18 | 13.31 |
| | Canada | May | 2.22 | 15.09 | 13.23 |
| Wheat (Spring) | USA | April/ May | 2.76 | 26.95 | 23.63 |
| Wheat (Winter) | USA | Sept/Oct | | | |

Period 2000–2004.

[a] Source: USDA (2006).

[b] Sources: Statistics Canada (2007), USDA (2007), SAGPyA (2007) and USDA–FAS (2007).

[c] Source: FAO (2007b).

The 'green' virtual-water content of the crop has been estimated as the ratio of the green water use to the crop yield (Chapagain et al., 2006b). The 'blue' virtual-water content of the crop has been taken equal to the ratio of the volume of irrigation water used to the crop yield (ibid.). Both green and blue virtual-water contents have been estimated separately by state or province. Then, national average green and blue virtual-water contents have been calculated on the basis of the respective share of each state or province to the national production. The major crop producing states or provinces combined accounted for about 90% of the total national production (Table 2). Data on average crop yield and production by state or province are taken from Statistics Canada (2007), USDA (2007), SAGPyA (2007) and USDA-FAS (2007), and data on international trade from the FAOSTAT database (FAO, 2007b). In the case of the USA, winter and spring wheat were separately calculated and weighted according to the share of each to the national production. The total virtual-water content of primary crops is the sum of the green and blue components.

In order to assess the virtual-water 'flows' between nations, the basic approach has been to multiply international trade volumes (ton/year) by their associated virtual-water content ($m^3$/ton) for the 2000–2004 period. It is thus assumed that states or provinces within a country contribute to the national export in proportion to their total production.

## 3. Proportion of Green Water in International Crop Trade

### *3.1. Virtual-Water Content of Maize, Soybeans and Wheat in the Major Exporting Countries*

Table 3 summarises the virtual-water content ($m^3$/ton) of maize, soybean and wheat for the USA, Canada, Argentina and Australia over the period 2000–2004 as estimated by the present study against the results of Chapagain and Hoekstra (2004) for the same countries and crops during 1997–2001. No other analogous study was found in the literature. According to expectations, since both studies use the same methodology, similar outcomes have been obtained except for USA wheat. Its higher virtual-water content is probably due to the fact that the present research uses longer winter wheat growing periods according to USDA (2006).

The average virtual-water content of these crops in the selected countries gives a first rough indication of the relative impacts of the various production systems on water resources. In this sense, local data on productivities can tell where water use per unit of product is relatively large and where small. The water need per unit of product depends on both climate and water-use efficiency. Apart from reducing water use through adjusting consumption patterns or using water more efficiently, the reduction of water use by producing where the climate is most suitable is one of the options in order to save water at a national or global level (Hoekstra and Chapagain, 2008). The water use for crop production thus differs considerably among countries. In principle, and coinciding with the results of Chapagain and Hoekstra (2004), soybean and wheat production is most attractive in Argentina due to its higher water productivity (Table 3). That is, products are water-extensive because they require less water in their production and therefore have low virtual-water content. Maize

**Table 2**
Main maize, soybean and wheat producing regions and climate stations by country.

| Commodity | Country | Major maize, soybean and wheat producing regions by country | Climate stations[a] |
|---|---|---|---|
| Maize | Argentina | Cordoba (33%), Buenos Aires (31%), Santa Fe (15%), Entre Rios (8%), La Pampa (4%), Chaco (2%), Santiago del Estero (2%) | Anatuya, Azul, Balcarce, Campo Gallo, Concordia, Dolores, Mar de Plata, Marcos Juarez, Presidencia Roque Saenz Peña, Rosario, Santa Rosa, Santiago del Estero, Villa María de Río Seco |
| | Canada | Ontario (61%), Quebec (35%) | London, Quebec |
| | USA | Iowa (19%), Illinois (17%), Nebraska (11%), Minnesota (10%), Indiana (8%), Ohio (4%), South Dakota (4%), Kansas (4%), Wisconsin (4%), Missouri (4%), Michigan (2%), Texas (2%), North Dakota (1%) | Alpena, Austin, Bismarck, Brownsville, Chicago, Cincinnati, Columbia, Columbus, Concordia, Corpus Christi, Dayton, des moines, Dodge city, Evanville, Fargo, Fort Wayne, Grand rapids, Green bay, Huron, Indianapolis, Kansas city, Lincoln, Madison dane, Minneapolis st paul, Moline, North Plattee, Peoria, San Antonio, Sioux city, Springfield, Toledo, Topeka, Wichita, Wilkes barre |
| Soybean | Argentina | Santa Fé (30%), Cordoba (29%), Buenos Aires (21%), Entre Rios (7%), Santiago del Estero (4%), Chaco (4%) | Anatuya, Bell Ville, Buenos Aires, Campo Gallo, Concordia, Gualeguay, Junin, Marcos Juarez, Pilar Observatorio, Presidencia Roque Saenz Peña, Rosario, Santiago del Estero, Villa María de Río Seco |
| | Canada | Ontario (81%), Quebec (16%) | London, Maniwaki, North bay, Quebec |
| | USA | Iowa (16%), Illinois (16%), Minnesota (10%), Indiana (9%), Nebraska (7%), Missouri (6%), Ohio (6%), South Dakota (5%), North Dakota (3%), Kansas (3%), Michigan (2%), Wisconsin (2%), North Carolina (2%), Tennessee (1%) | Chicago, Cincinnati, Columbia, Columbus, Concordia, Dayton, des moines, Dodge city, Evansville, Fargo, Fort Wayne, Grand rapids, Green bay, Greensboro, Huron, Indianapolis, Kansas city, Lincoln, Madison dane, Memphis, Minneapolis, Moline, North Plattee, Peoria, Raleigh, Sioux city, Springfield, Toledo, Topeka, Wichita |
| Wheat (Spring) | Argentina | Buenos Aires (59%), Cordoba (14%), Santa Fé (14%), La Pampa (5%), Entre Rios (4%) | Balcarce, Barrow, Bell Ville, Concordia, Gualeguay, Macachín, Marcos Juarez, Pilar Observatorio, Rafaela, Rosario, Santa Rosa |
| | Australia | New South Wales (31%), Western Australia (29%), South Australia (20%), Victoria (14%) | Adelaide, Adelaide airport, Bencubbin, Carnamah, Ceduna airport, Clare post office, Coonabarabran, Cootamundra, Cowra, Dalwallinu, Deniliquin, Deniliquin Falkiner memo, Dubbo, Elliston, Esperance, Griffith-aws, Hay, Kadina, Kyabram, Lake Grace, Loxton, Maitland, Merredin, Mildura airport, Minnipa, Nuriootpa, Nyngan, Ongerup, Parkes, Peak hill, Port Lincoln, Port pirie, Revensthorpe, Roseworthy, Rutherglen research, Salmon gums, Snowtown, Streaky bay, Tatura inst sutainable, Wagga airport, Walgett, Wongan-Hills, Yongala |
| | Canada | Saskatchewan (44%), Alberta (32%), Manitoba (21%) | Calgary, Dauphin, Edmonton int, Edmonton municipal, Medicine, Moose, Regina, Swift, Winnipeg, Yorkton |
| | USA | North Dakota (44%), Montana (14%), South Dakota (11%), Idaho (7%), Washington (5%), Oregon (1%) | Billings, Bismarck, Fargo, Great falls, Helena, Huron, Pocatello, Portland, Rapid city, Spokane, Williston |
| Wheat (Winter) | USA | Kansas (24%), Oklahoma (10%), Washington (8%), Texas (6%), Ohio (4%), Nebraska (4%), Colorado (4%), Idaho (4%), Illinois (3%), Missouri (3%), Montana (3%), South Dakota (3%), Oregon (3%), Michigan (3%), Indiana (2%), California (2%), North Carolina (1%), Tennessee (1%) | Abilene, Alpena, Amarillo, Austin, Billings, Boise, Charlotte, Columbia, Columbus port, Concordia, Dallas fort, Dayton, Dodge city, Evansville, Fort Wayne, Fresno, Grand junction, Grand rapids, Great falls, Greensboro, Huron, Kansas city, Lincoln, Lubbock, Memphis, North Plattee, Oklahoma, Peoria, Pocatello, Portland, Raleigh, Rapid city, Sacramento, San Antonio, Spokane, Springfield, Toledo, Topeka, Tulsa, Wichita |

Period: 2000–2004.

[a] Source: CLIMWAT (2003b), climate stations chosen according to USDA (2006).

from Argentina, soybeans from Canada and wheat from the USA are the most water-intensive. When comparing crop varieties, maize appears to be the most water-extensive in all the selected countries, in line with the results of Chapagain and Hoekstra (2004).

**Table 3**
Virtual-water content (VWC) by crop and country (m$^3$/ton).

| | | Chapagain and Hoekstra (2004)[a] | Present study[b] | | | | |
|---|---|---|---|---|---|---|---|
| Commodity | Country | VWC | VWC | Green VWC | Blue VWC | Ratio Green/Blue[c] | Virtual water 'export' |
| Maize | Argentina | 469 | 595 | 515 | 80 | 6.4 | 6.41 |
| | Canada | 353 | 474 | 470 | 4 | 105.9 | 0.12 |
| | USA | 489 | 466 | 367 | 99 | 3.7 | 21.98 |
| Soybean | Argentina | 1107 | 1321 | 1298 | 23 | 56.5 | 9.86 |
| | Canada | 1203 | 1668 | 1640 | 28 | 58.5 | 1.26 |
| | USA | 1869 | 1413 | 1175 | 239 | 4.9 | 39.62 |
| Wheat | Argentina | 738 | 725 | 699 | 26 | 26.8 | 6.82 |
| | Australia | 1588 | 1502 | 1097 | 405 | 2.7 | 22.81 |
| | Canada | 1491 | 1057 | 963 | 95 | 10.2 | 15.95 |
| | USA | 849 | 1707 | 1028 | 679 | 1.5 | 45.99 |

[a] Period: 1997–2001.

[b] Period: 2000–2004.

[c] Ratio of green to blue virtual-water content.

No comparable results were found for green and blue water content in the literature. Since green water generally has a lower opportunity cost than blue water, it is useful to look at the ratio of green to blue water content for the selected crops and countries (Table 3). In all the studied countries green water is by far the dominant use, displaying in all cases ratios larger than one. For maize, the largest ratio of green to blue water content is found in Canada, which thus has the lowest impact per unit of crop. This is probably due to the reasonable yields under largely rain-fed conditions (Table 1). For soybean, Canada and Argentina have comparable green to blue water ratios, considerably higher than the USA. Concerning wheat production, Argentina has the highest ratio. When comparing neighbouring countries from a water resources perspective, all the studied crops from Canada are preferable over those from the USA due to better growing conditions (smaller irrigation requirements). Although Canada achieves lower crop yields per hectare than the USA its blue water requirements per ton of product are lower (Tables 1 and 3).

### 3.2. Water Use in the Major Exporting Countries

The nations with the largest water use in relation to export of maize, soybean and wheat during the period 2000–2004 are the USA (108 km$^3$/year), Argentina (23 km$^3$/year), Australia (just accounting for wheat — 23 km$^3$/year) and Canada (17 km$^3$/year) (Table 3). Following Chapagain et al. (2006a) we speak here about 'national water losses', referring to the fact that water used for producing commodities exported to other countries is not available anymore for domestic purposes. Export of agricultural products entails that national water resources are lost whereas import of agricultural products saves national water resources. Even if there is a net global water loss from an exchange, there might be a saving of blue water at the cost of a greater loss of green water or vice versa (ibid.).

Fig. 1 shows the proportion of green and blue virtual-water losses by crop and country. Noticeably, virtual-water 'exports' are overwhelmingly green in all the studied countries and crops because crop production in the selected countries is dominantly rain-fed. Even though there is an interconnectivity between the green and blue water resources, unlike blue water, green water cannot be automatically reallocated to other uses besides natural vegetation or alternative rain-fed crops (De Fraiture et al., 2004). Since blue water resources are generally scarcer, when exporting countries use green water resources they incur a lower opportunity cost in water use, holding other factors constant (Hoekstra et al., 2001; Albersen et al., 2003; Chapagain et al., 2006a; Yang et al., 2006). Furthermore, green water use has relatively few negative environmental externalities, because there is generally only a relatively small difference between the evapotranspiration from the crop field and the evapotranspiration that would take place in presence of natural vegetative cover. Although the hydrological impact is thus often small, there is a loss of natural environments (Rosegrant et al., 2002; De Fraiture et al., 2004). In contrast to green water, blue water use in irrigated agriculture has the potential for causing severe environmental problems such as water depletion, salinisation, water logging or soil degradation (FAO, 1997; Clay, 2004). A negative externality associated to both rain-fed and irrigated farming is the water quality degradation due to nonpoint pollution loads from fertilizers and pesticides.

In the cases of Canada and Argentina, the proportion of the blue virtual-water 'exports' is relatively small (Fig. 1). Wheat exports constitute the main source of water loss for Canada, which is almost entirely rain-fed since it can be grown in cool seasons, with low water

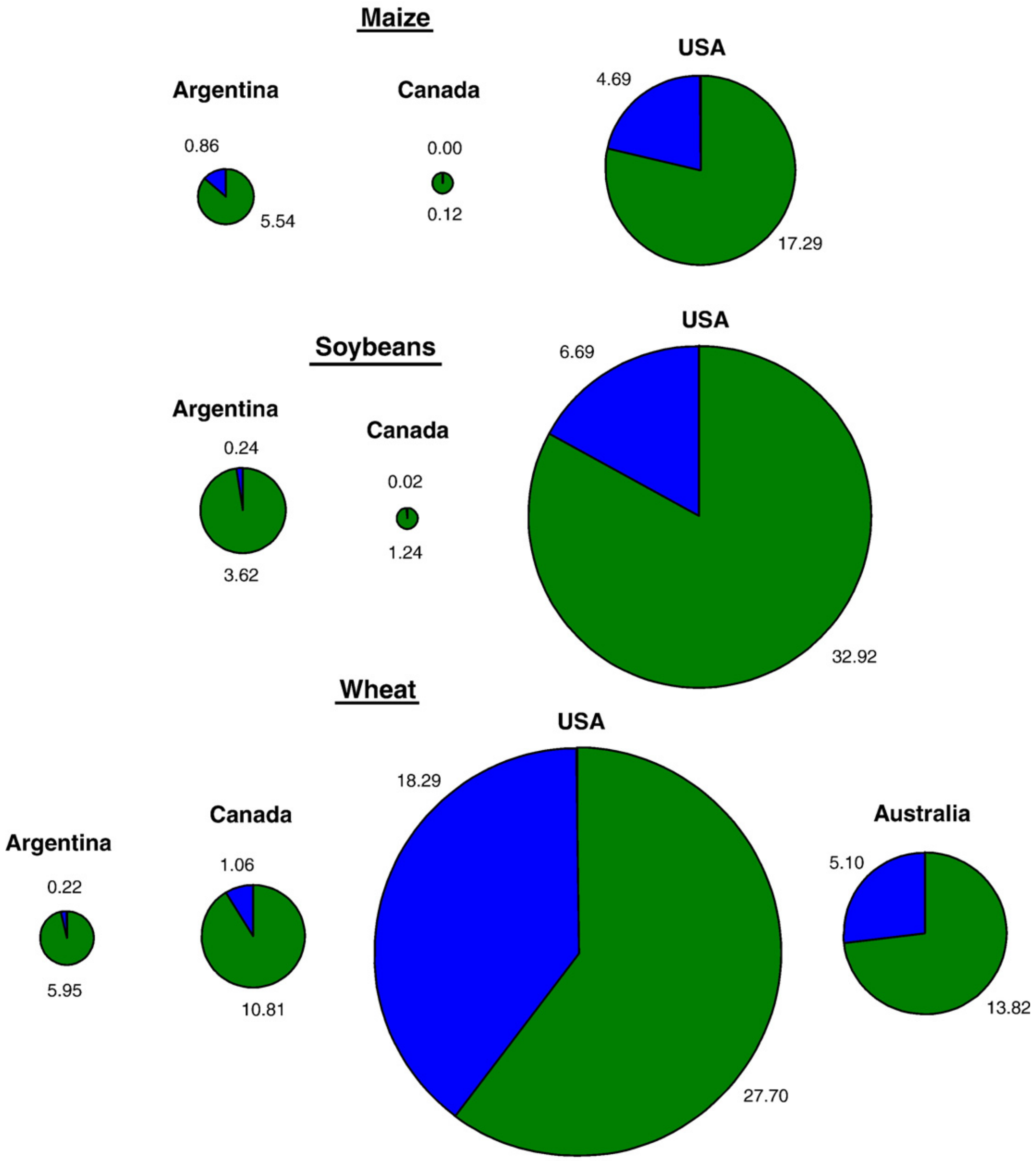

**Fig. 1.** Green and blue water proportion in the virtual-water embedded in maize, soybean and wheat exports of main exporting countries (km$^3$/year). The size of the pie is determined by the 'exported' amount of virtual water. Period 2000–2004.

requirements (Chapagain et al., 2006a). The national water loss for Argentina is mainly the result of soybeans exports, which is also almost entirely rain-fed. In the case of Australia, almost one third of total wheat exports are blue water resources (surface and ground water). The USA accounts for more than three quarters of all studied water losses related to maize and soybean exports and over a half of the water loss related to wheat export, making the country by far the biggest water user for export (Fig. 1).

As a whole, maize, soybean and wheat production in the USA like the rest of the largest exporting countries, is mainly based on green water resources. Maize and soybeans are grown without irrigation due to the exceptionally favourable agroclimatic conditions of the "corn belt" and exported in large quantities. The "corn belt" refers to the region of Midwest of the USA, primarily including the States of Iowa, Indiana, Illinois, and Ohio, where maize and soybeans are the predominant crop. In this region, both maize and soybeans present a large green to blue water use ratio (Figs. 2 and 3). The use of green water has no major competition with other uses. This type of loss of the national water resources is unlikely to be questionable from an economic perspective, due to its low opportunity cost (Chapagain et al., 2006a).

### 3.3. Blue Water Use in Exporting Countries — The USA Case

Although crop production in the USA is mainly rain-fed, irrigation has notably increased in recent years (FAO, 2007a). Currently, the blue water fractions in the three most important export crops in the USA are 39.8 % (wheat), 21.2% (maize) and 16.9% (soybean). Overexploitation of water resources has occurred in many regions. In the central and western part of the country many open access common pool resources such as rivers and aquifers have been overexploited causing water resource depletion and environmental degradation (Postel, 2000) (Figs. 4 and 5). For instance, the heavy use of the Colorado river as an irrigation source for the Imperial Valley (region of South-eastern California) has desiccated the lower course of the river in Mexico (Gleick, 1993). Another example is the groundwater pumping in excess of recharge, which has caused significant groundwater depletion in the Western United States (Rosegrant et al., 2002), such as the mining of the Ogallala Aquifer. The Ogallala Aquifer is one of the world's largest aquifers, lying under about 450,000 km² in portions of the eight states of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. The regions overlying the Ogallala aquifer are some of the most productive regions for growing corn, wheat and soybeans in the United States (often called the "breadbasket of America"). Indeed, the water use in this area to grow wheat, corn and other grains is significant (Opie, 2000; Clay, 2004). Unfortunately, the Ogallala Aquifer that supplies all the water for this irrigation is fossilized water (ibid.). This means that the water being drawn from it is not being replaced.

### 3.4. Water Saving in the Importing Countries

Importing countries are more diverse than exporting countries: 37 countries account for 90% of maize imports, 22 of soybean and 55 of wheat. The top 10 importing countries include Japan, China, Korea, Egypt, Netherlands, Spain and Mexico. The map presented in Fig. 6 shows the virtual-water 'flows' to the five major importing countries for wheat for the period 2000–2004.

By 'importing' virtual water embodied in agricultural commodities, a nation "saves" the amount of water it would have required to produce those commodities domestically. Though from an importing country perspective it is not relevant whether products have been produced using green or blue water in the country of origin, from a global point of view it has important implications (Chapagain et al., 2006a). For instance, Egypt is the largest importer of wheat, with the USA providing about 45% of the country's imports. Wheat from Egypt has an average virtual-water content of 930 $m^3$/ton of which 100% is blue water (Chapagain et al., 2006a), while the USA has a virtual-water content for wheat of 1707 $m^3$/ton of which 39.8% is blue water (Table 3). By importing wheat, Egypt saves 930 $m^3$ of water per ton of wheat. Globally, when imported from the USA, there is not a total water saving because wheat production in the USA requires more water than in Egypt. Exports to Egypt from this country result in a considerable net global water loss of 777 $m^3$ per ton. However, if we just look at blue water only, importing wheat from the USA to Egypt saves 251 $m^3$/ton (since USA production requires 679 $m^3$/ton of blue water and wheat production in Egypt 930 $m^3$/ton). Along these lines, Egypt, as some other water-scarce importing countries, has formulated policies to import low value but high water consuming food like cereals (Van Hofwegen, 2005). Nevertheless, even if the potential of trade to "save" water at national level is substantial, most international food trade occurs for reasons not related to water resources (CAWMA, 2007).

During droughts, nations that rely on green-water based grain imports seem to be at greater risk of food shortages than other

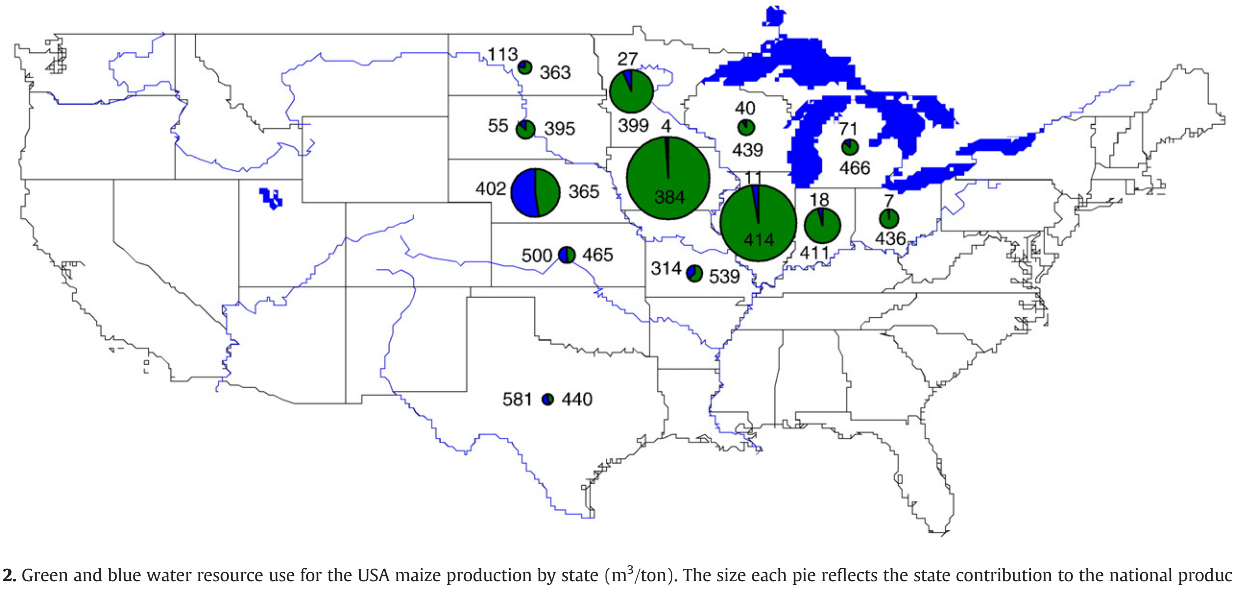

**Fig. 2.** Green and blue water resource use for the USA maize production by state ($m^3$/ton). The size each pie reflects the state contribution to the national production.

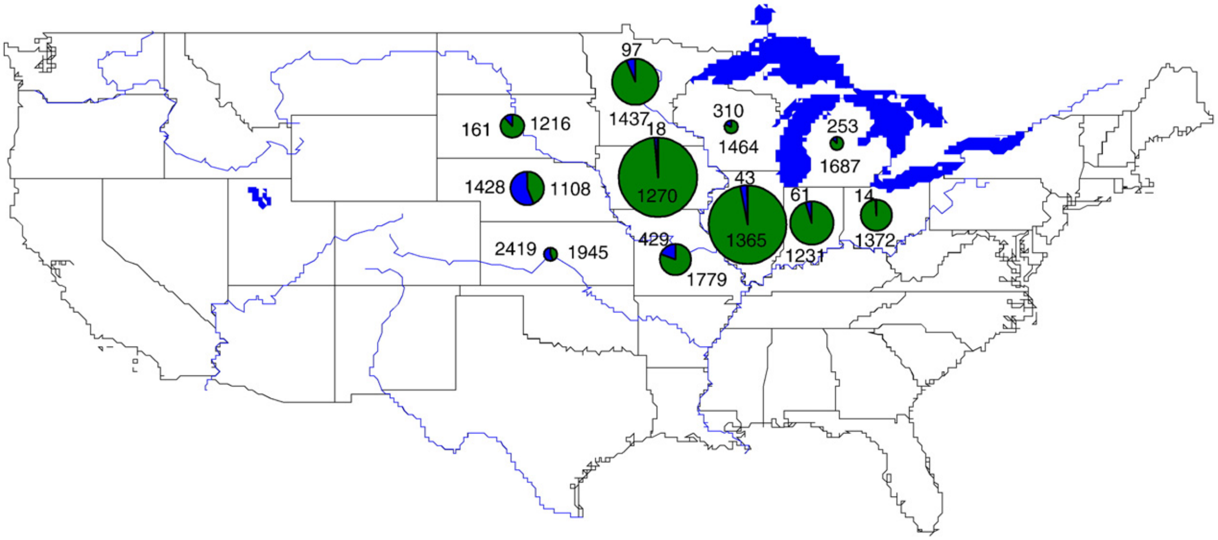

**Fig. 3.** Green and blue water resource use for the USA soybean production by state ($m^3$/ton). The size each pie reflects the state contribution to the national production.

nations. Due to climate variability rainfall-based crop production is less reliable than surface or groundwater based production. However, since global commodity markets are well integrated, imports from other countries have the potential to replace green water-dependent crops during dry periods and reduce the risk of famine in importing countries.

## 4. Conclusion

The present study quantitatively corroborates that international trade in wheat, maize and soybeans is based on green water. Major exporters produce under relatively favourable productive rain-fed conditions while most importers would have relied (at least partially) on their blue water resources. Virtual-water 'trade', thus, can reduce irrigation water demand and play a role in ensuring water and water-dependent food security in water-short countries.

At present, however, this option is far from being fully exploited due to the absence of a more water friendly international trade regime with equal access to global markets, which takes into account both water productivity and blue/green water ratio in products. Other obstacles are formed by the inadequacy of water pricing structures worldwide and the agricultural subsidies in the EU and USA. For instance, this study reveals that USA wheat exports, particularly from certain semiarid states, are increasingly based on their blue water resources for irrigation. This is probably due to USA policy of subsidies to irrigated agriculture. USA and EU support to their agricultural sectors, often encouraging non-sustainable water use. The current global virtual-water 'trade' is primarily among the countries above the low-income level in the World Bank country classification (Yang et al., 2006). Countries with low-income levels are minor participants. As Allan (2006) points out, socio-economic development is a prerequisite to access virtual water in the global system. Besides, other factors are also interrelated with global green water 'trade' such as availability of land, labour, technology, the costs of engaging in trade, the potential for further increases in the productivity of soil water and irrigation water, national food policies and international trade agreements. There are factors that can also contribute to increased food demand and to increased water use for food production, such as population growth, changes in diets and the use of cereals and oilseeds for biofuel production (De Fraiture et al., 2007; Gerbens-Leenes et al., 2008).

In the future, in a context of greater water scarcity and demand, green virtual-water 'trade' will probably become increasingly important from a global perspective. Rain-fed agriculture, with some of the

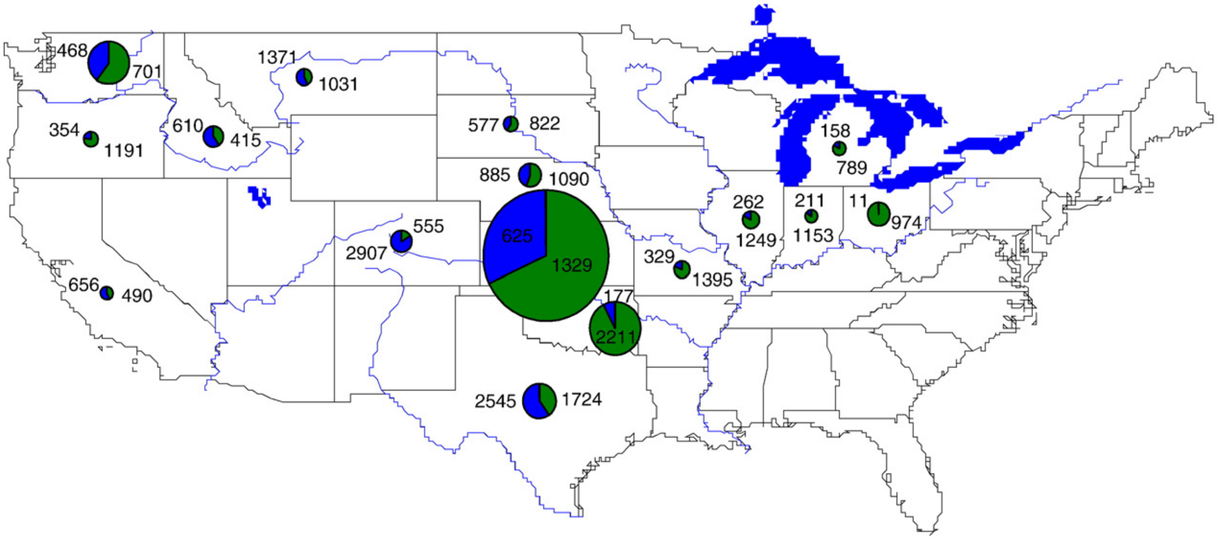

**Fig. 4.** Green and blue water resource use for the USA winter wheat production by state ($m^3$/ton). The size each pie reflects the state contribution to the national production.

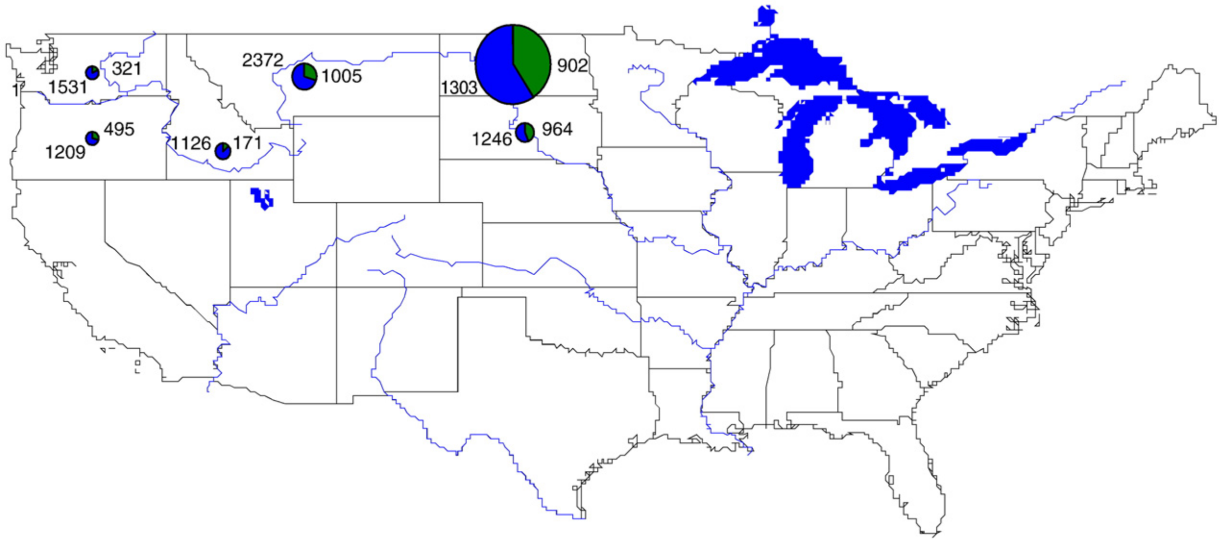

**Fig. 5.** Green and blue water resource use for the USA spring wheat production by state ($m^3$/ton). The size each pie reflects the state contribution to the national production.

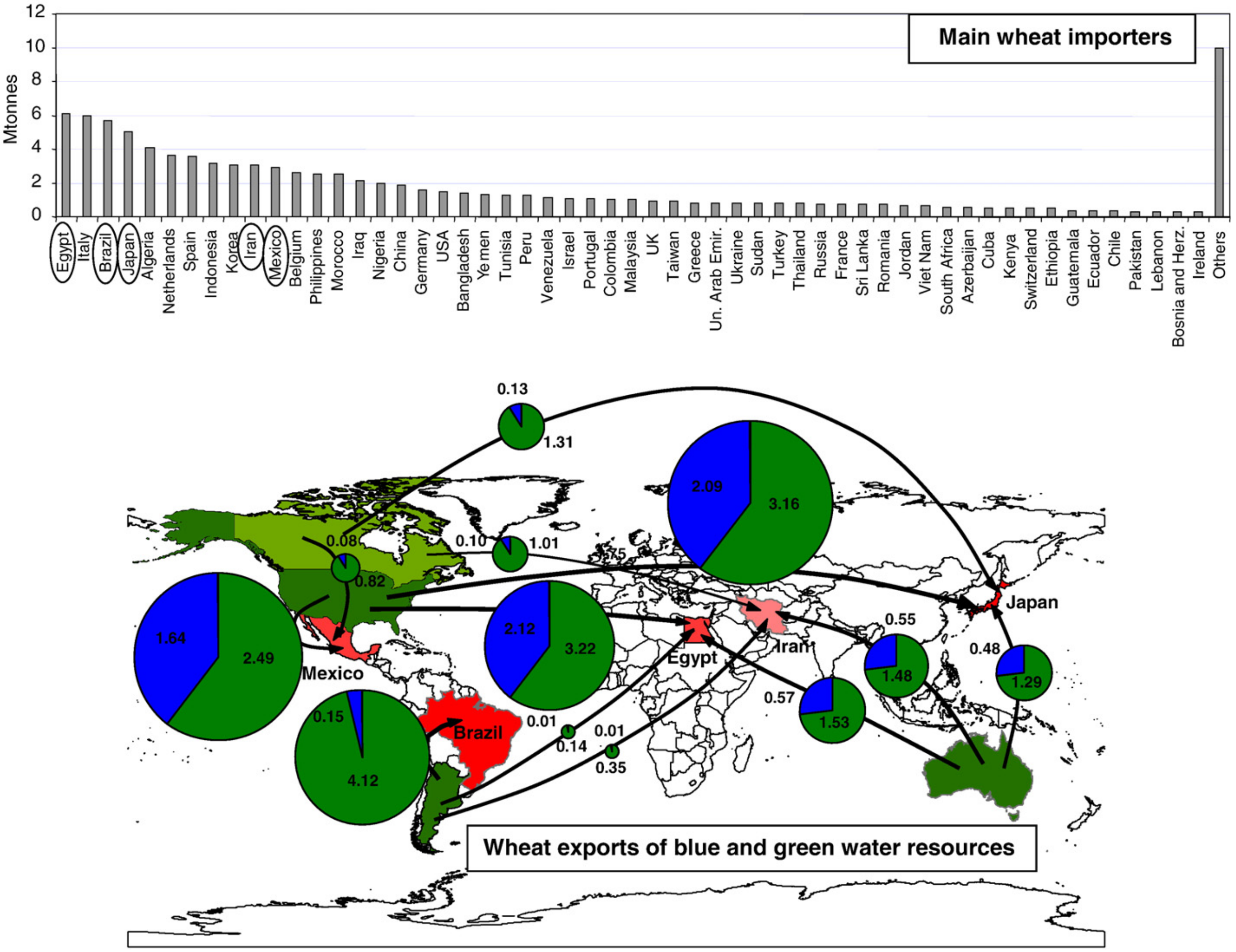

**Fig. 6.** Green and blue virtual-water 'flows' related to wheat trade by major exporting and importing nations ($km^3$/year). The size of each pie is determined by the amount of virtual water 'traded'. Countries with virtual-water 'exports' are depicted in green and countries with virtual-water 'import' in red; the colour shade depends on the quantity of virtual water 'traded'. Period 2000–2004.

highest yields in several regions, hold great underexploited potential for increasing water productivity through better water management practices — gaining more yield and value from water. In this context, the socio-economic development of poor economies in humid regions, such as the case of Sub-Saharian Africa, could drive these economies enter the international market and promote the virtual-water 'trade' solution, as Argentina did earlier. The importance of international green virtual-water 'trade' and its contribution to water and food security in the future will, though, depend on factors such as the productivity of blue and green water, international trade agreements, the costs of engaging in trade, and the nature of domestic economic objectives and political considerations.

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## References

Aldaya, M.M., Hoekstra, A.Y., Allan, J.A., 2008. Strategic importance of green water in international crop trade. Value of Water Research Report Series No. 25. UNESCO - IHE Delft, The Netherlands.

Allan, J.A., 1997. 'Virtual water': a long term solution for water short Middle Eastern economies? Water Issues Group, School of Oriental and African Studies. University of London. Available from: www.soas.ac.uk/research/our_research/projects/waterissues/papers/38347.PDF [Accessed 16 January 2008.

Allan, J.A., 1999. Water stress and global mitigation: water food and trade. Arid Lands Newsletter. Available from: http://ag.arizona.edu/OALS/ALN/aln45/allan.html [Accessed 16 January 2008].

Allan, J.A., 2006. Virtual water, part of an invisible synergy that ameliorates water scarcity. In: Rogers, Llamas, Martinez-Cortina (Eds.), Water Crisis: Myth or Reality? Balkema Publishers.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration – guidelines for computing crop water requirements – FAO irrigation and drainage paper 56. Food and Agriculture Organization, Rome, Italy.

Albersen, P.J., Houba, H.E.D., Keyzer, M.A., 2003. Pricing a raindrop in a process-based model: general methodology and a case study of the Upper-Zambezi. Physics and Chemistry of the Earth 28, 183–192.

CAWMA, 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan, London.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. Value of Water Research Report Series No. 16, UNESCO- IHE. Delft, The Netherlands. Available from: www.waterfootprint.org/Reports/Report16Vol1.pdf [Accessed 16 January 2008].

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., 2006a. Water saving through international trade of agricultural products. Hydrology and Earth System Sciences 10, 455–468.

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

Chapagain, A.K., Orr, S., 2009. An improved water footprint methodology linking global consumption to local water resources: a case of Spanish tomatoes. Journal of Environmental Management 90 (2), 1219–1228.

Clay, J.W., 2004. World Agriculture and the Environment: A Commodity-by-commodity Guide to Impacts and Practices. Island Press.

De Fraiture, C., Cai, X., Amarasinghe, U., Rosegrant, M., Molden, D., 2004. Does International Cereal Trade Save Water? The Impact of Virtual Water Trade on Global Water Use. Comprehensive Assessment Research Report 4. Comprehensive Assessment Secretariat. Colombo, Sri Lanka. Available from: www.iwmi.cgiar.org/Assessment/FILES/pdf/publications/ResearchReports/CARR4.pdf [Accessed 16 January 2008].

De Fraiture, C., Giordano, M., Yongsong, L., 2007. Biofuels and implications for agricultural water use: blue impacts of green energy. International Water Management Institute, Colombo, Sri Lanka. Available from: www.iwmi.cgiar.org/EWMA/files/papers/Biofuels%20-%20Charlotte.pdf [Accessed 16 January 2008].

Falkenmark, M., Rockström, J., 2004. Balancing water for humans and nature: the new approach in ecohydrology. Earthscan, London, UK.

FAO, 1997. Environmental considerations in irrigation development. In: Irrigation potential in Africa: A basin approach. FAO Land and Water Bulletin 4. Food and Agriculture Organization. Rome, Italy. Available from: http://www.fao.org/docrep/W4347E/w4347e10.htm [Accessed 10 January 2009].

FAO, 2003a. CROPWAT Model. Food and Agriculture Organization. Rome, Italy. Available from: www.fao.org/nr/water/infores_databases_cropwat.html [Accessed 16 January 2008].

FAO, 2003b. CLIMWAT Database. Food and Agriculture Organization. Rome, Italy. Available from: www.fao.org/nr/water/infores_databases_climwat.html [Accessed 16 January 2008].

FAO, 2007a. AQUASTAT - FAO's Information System on Water and Agriculture. Food and Agriculture Organization. Rome, Italy. Available from: www.fao.org/nr/water/aquastat/main/index.stm [Accessed 16 January 2008].

FAO, 2007b. FAOSTAT Database. Food and Agriculture Organization. Rome, Italy. Available from: http://faostat.fao.org [Accessed 16 January 2008].

Gerbens-Leenes, P.W., Hoekstra, A.Y., Van der Meer, T.H., 2008. Water footprint of bio-energy and other primary energy carriers. Value of Water Research Report Series No.29. UNESCO-IHE, Delft, The Netherlands.

Gleick, P.H., 1993. Water in crisis. A guide to the world's fresh water resources. Oxford University Press, New York. 473 pp.

Hoekstra, A.Y. (Ed.), 2003. Virtual water trade: proceedings of the international expert meeting on virtual water trade. In: Hoekstra, A.Y. (Ed.), Value of Water Research Report Series No.12. UNESCO-IHE, Delft, The Netherlands. Available from: www.waterfootprint.org/Reports/Report12.pdf [Accessed 16 January 2008].

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resources Management 21 (1), 35–48.

Hoekstra, A.Y., Chapagain, A.K., 2008. Globalization of water: sharing the planet's freshwater resources. Blackwell Publishing, Oxford, UK.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No. 11. UNESCO-IHE, Delft, The Netherlands. Available from: www.waterfootprint.org/Reports/Report11.pdf [Accessed 16 January 2008].

Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environmental Change 15 (1), 45–56.

Hoekstra, A.Y., Savenije, H.H.G., Chapagain, A.K., 2001. An integrated approach towards assessing the value of water: a case study on the Zambezi basin. Integrated Assessment. 2, 199–208.

Oki, T., Kanae, S., 2004. Virtual water trade and world water resources. Water Science and Technology 49 (7), 203–209.

Opie, J., 2000. Ogallala: water for a dry land. University of Nebraska Press, Lincoln, Nebraska. 478 pp.

Postel, S., 2000. Entering an era of water scarcity: the challenges ahead. Ecological Applications 10 (4), 941–948.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M., Engwall, M., 1999. Linkages among water vapor flows, food production and terrestrial ecosystem services. Conservation ecology 3 (2), 1–5.

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. PNAS 104 (15), 6253–6260.

Rosegrant, M., Cai, X., Cline, S., 2002. World water and food to 2025. International Food Policy Research Institute (IFPRI, Washington D.C.

SAGPyA, 2007. Secretaría de Agricultura, Ganadería, Pesca y Alimentos — Estimaciones agrícolas. Buenos Aires. Available from: www.sagpya.mecon.gov.ar/ [Accessed 16 January 2008].

Statistics Canada, 2007. Canada's National Statistical Agency. Ottawa, Ontario. Available from: www.statcan.ca/ [Accessed 16 January 2008].

USDA, 2006. Major World Crop Areas and Climatic Profiles. United States Department of Agriculture. Washington, D.C., United States. Available from: www.usda.gov/oce/weather/pubs/Other/MWCACP/index.htm [Accessed 16 January 2008].

USDA, 2007. USDA National Agricultural Statistics Service – Quick Stats – U.S. & All States Data – Crops. Washington DC. Available from: www.nass.usda.gov/QuickStats/Create_Federal_All.jsp [Accessed 16 January 2008].

USDA-FAS, 2007. Australia Wheat. United States Department of Agriculture - Foreign Agricultural Service Washington DC. Available from: www.fas.usda.gov/pecad2/highlights/2000/12/aswheat/as_wht0012.htm#DATABASE%20STATISTICS [Accessed 16 January 2008].

Van Hofwegen, P., 2005. Virtual water: Conscious choices. Voices on Virtual Water. World Water Council. Available from: www.worldwatercouncil.org/fileadmin/wwc/Programs/Virtual_Water/Virtual_Water_voices.pdf [Accessed 16 January 2008].

Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrology and Earth System Sciences 10, 443–454.