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FOOD SECURITY IN A WATER-SCARCE WORLD: MAKING VIRTUAL WATER COMPATIBLE WITH CROP WATER USE AND FOOD TRADE

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Abstract

Virtual water has been proposed as a mechanism with potential to reduce the effects of water scarcity on food security. To evaluate the role of virtual water in reducing the effect of water scarcity on food security, all components of the available water resource in agricultural areas must be quantified to provide a basis for evaluating food imports driven by water scarcity. We refer to this situation as 'agri-compatible connections' among water scarcity, virtual water, and food security. To date, this has not been captured in the literature on water scarcity, virtual water flows and food security. The lack of agri-compatibility has rendered the virtual water concept seemingly inconsistent with trade theories and water-food security policy needs. We propose two requirements for achieving agri-compatible connections: (i) the limit of crop production imposed by water scarcity should be captured by quantifying all components of the water available to satisfy specific crop water requirement in the importing economy, and (ii) food import should satisfy 'water-dependent food security' need, which is the actual or potential food security gap created by insufficient available water from all sources for crop production (all other things being equal). Further, we propose that agri-compatible water scarcity should capture three key elements: (i) a reflection of aridity or drought potential, (ii) quantification of all the components of water resource available to a given crop at a given locality and time, and (iii) use of crop- and catchment-specific water scarcity factors to evaluate the effect of crop production and virtual water on water scarcity. In this paper, we show the conceptual outlines for the proposed agri-compatible connections. Achieving agri-compatible connections among water scarcity, virtual water and food security will enhance the analysis and understanding of the role of virtual water for food security in the importing economy and water scarcity in the exporting economy. We suggest that achieving agri-compatibility will improve the use of virtual water as a mechanism to reduce existing and future pressures on global food security.

Key words: *agri-compatibility, crop water use, food security, virtual water, water scarcity*

INTRODUCTION

Access to water and food is essential to human survival and is recognized as a fundamental human right (UN, 1948; Dubreuil, 2006). Water scarcity is however projected to be a key limiting factor to food production and development in the 21st century (WRI, 2003; UNDP, 2007). Many reports highlight the precariousness of global water security as water scarcity increases in scale and scope due to increasing demand for water (e.g. de Fraiture and Wichelns, 2010; Falkenmark et al. 2009; Falkenmark and Molden, 2008; Oki and Kanae, 2006). Projected changes in the global population, climate, economic growth and urbanization are expected to exacerbate water scarcity and further destabilize food security (Gregory et al. 2005). The economic theory of efficient allocation of resources tells us that as water becomes scarce, its allocation increasingly shifts from low economic-value activities (agriculture and other primary sectors) to relatively high-value activities (industrial and service sectors) (Ohlsson and Turton, 1999). This potential shift of water away from crop production raises concerns over the destabilizing effect of water scarcity on food security.

Food security is fundamentally linked to water availability for crop use as it is known that, on a global average, crop production is the largest water use sector (Thenkabail et al. 2010). Globally, the volume of water loss through crop evapotranspiration (ET) ranges from 6,685 to 7,500 km^3 yr^{-1} (Thenkabail et al. 2010), accounting for over 70% of global water abstraction (e.g. de Fraiture and Wilchens, 2010; Hamdy et al. 2003; Yang et al. 2006). For example, in 2000, the global crop water abstraction amounted to 7,130 km^3 (of which irrigation accounted for 2,630 km^3) and total abstraction for domestic and industrial use was 877 km^3 (de Fraiture and Wilchens, 2010). However, soil water deficit experienced under drought conditions during crop growing season is one of the major threats to achieving high and stable crop yields (Boyer, 1982; Rockstrom et al. 2009), making food security overly vulnerable to water scarcity (Liu, 2009). Water scarcity will, however, never be globally homogenous; it will always be geographically differentiated due to differences in climate and the management of different stocks and flows of water in the local hydrological system and differences in usage of water in economic activities.

To address the uneven distribution of global water reserves and increasing demand of water for food production, the movement of water through the trade of food commodities has been rationalised into the concept of virtual water. Virtual water refers to the volume of water used in the production of a unit crop commodity traded (Allan, 1998a, 1998b; 2003). The virtual water concept hypothesises that, by importing water-intensive food products from water-rich areas, water-scarce communities can offset local water scarcity and maintain food security (Allan, 1998a; 1998b; 2003; Yang et al., 2006; Liu et al., 2007; Aldaya, 2010a). It is this hypothesis that gives virtual water the potential to link water scarcity and food security through trade. Thus, importing food products saves the volume of water equivalent to the crop water requirement under the local conditions of production while augmenting domestic food security. Contrasted to engineering solutions, which move water to people, virtual water is an agro-economic mechanism that moves water embedded in traded food commodities from production sites to people in a water-scarce economy (Allan, 1998a). A large body of literature exists on virtual water, highlighting the utility of the concept as a potentially useful policy instrument for addressing the coupled problem of food-water insecurity (see e.g. Allan, 1998a; Hoekstra and Hung, 2005; Chapagain et al. 2006; Chapagain and Orr, 2009; Yang et al. 2006; de Fraiture and Wilchens, 2010). Virtual water is, therefore, now regarded as a key component of the options available to economies actually or potentially exposed to food insecurity as a result of water scarcity (Roth and Warner, 2008; Allan, 1998a).

Some studies (e.g. Ansink, 2010; Ramirez-Vallejo and Rogers, 2010) have, however, shown that some water-abundant countries import water-intensive crop commodities from water-scarce countries. Based on this evidence, these authors argue that food commodity trade is not motivated by water endowment and, therefore, the virtual water concept is insufficient for addressing policy requirements for improved food and water security. Wilchens (2010) also argued that virtual water does not offer sufficient insight for important policy questions regarding water security as it suffers conceptual limitations regarding relative water endowments and opportunity costs of production among trading countries. This paradox emanates from a lack of agri-compatible connections (or agri-compatibility) among water scarcity, the virtual water concept and food security (Figure 1). Specifically, the water scarcity considered excludes some components of the water resource (mainly soil water) in crop producing areas and its evaluation is entirely from an economic perspective.

Virtual water is a dual concept that has a crop-water use component and a trade component. The two parts, however, require detailed examination so that the ability to match sustainable water use to food security can be evaluated accurately. In this paper, we concentrate on the crop specific elements of

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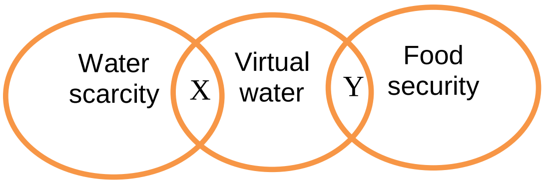
virtual water. We promote the concept that agri-compatibility is required to understand the link between water scarcity and food security through the movement of virtual water and to render virtual water more amenable to water and food security policy. To date, this has not been attempted and this paper proposes to show the requirements for agri-compatible connections by (i) demonstrating the need for such agri-compatible connection, (ii) providing a formula for calculating crop- and catchment-specific water scarcity (iii) showing the use of agri-compatible water scarcity in the evaluation of the effects of virtual water movements on water and food security.

Definition of Terms

Agri-compatibility: refers to the condition in which food is imported to fill the food security gap created by insufficient aggregate water supply from all relevant sources to satisfy the water requirements of crop production in the importing economy. The idea of agri-compatible connections is illustrated below.



X = agri-compatible water scarcity   Y = water-dependent food import

Agri-compatible water scarcity: insufficient water availability from all relevant sources (blue, green, grey) to satisfy the water requirement of a crop or crops at a particular area.

Water-dependent food import: import of food to fill potential or actual food security gap resulting from insufficient water from all relevant sources to meet the water requirement of crops.

Figure 1. Definition of terms

MATERIALS AND METHODS

The paper purpose was to present the ‘agri-compatible connections’ among water scarcity, virtual water, and food security, a field where literature is poor of information.
The second goal of the paper was to identify the requirements for achieving agri-compatible connections as follows:
a)the quantification of all components of the water available to satisfy specific crop water requirement in the importing economy;
b)food import should satisfy ‘water-dependent food security’ need.
Based on the main results in the field regarding food security and water scarcity, the final purpose was to identify and present proposals concerning the key elements for agri-compatible water scarcity.
From a methodological point of view the paper is based on the main research results in the field, presenting the conceptual outlines for the proposed agri-compatible connections.

RESULTS AND DISCUSSIONS

Food Security

Food security must necessarily refer to a state in which the food system is secured. Food systems include production and related supply chains of commodities and foods in the production-consumption nexus (Gerbens-Leenes et al. 2010; Gregory et al. 2005). Food security is complex as a number of biophysical and socio-economic factors interact in dynamic and complex ways to affect food systems that underpin food security (Gregory et al. 2005). Food security is generally defined as “availability of and assured access to sufficient food that is nutritionally adequate, culturally acceptable, safe and which is obtained in socially acceptable ways” (Gorton et al. 2009). The most widely used definition of food security emerged from the World Food Summit (1996): *"food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life".* The components of food security are availability, accessibility, utilization and stability of access (FAO, 2006).

The preceding definitions of food security reveal little of the issue of food crop production, but the ability to supply food relies on the availability of harvested food crops produced domestically or imported. In this paper, food security is equated to food availability in sufficient quantity to satisfy the dietary requirements of a given population and is understood to have a specific spatio-temporal context. Water is a key factor that links crop system productivity with food availability. Consequently, domestic food production to satisfy food security is subject to the constraint of water availability but food security is achievable through domestic production or import.

Water Scarcity

Water used in crop production is classified into three main colours: blue, green and grey (Chapagain and Orr, 2009). Blue water refers to groundwater and surface water (streams, lakes, rivers, dams) available for human use that is introduced into crop production systems through irrigation. There is greater competition for blue water from all water use sectors compared with the other water colours. Green water refers the fraction of precipitation that infiltrates and remains in the unsaturated zone of the soil after drainage and is available for crop evapotranspiration. Grey water represents recycled water that is used in crop production after treatment. In assessing the effect of crop production on water availability, grey water is defined as the water required for diluting pollutants from agro-chemical inputs in crop production (Chapagain and Orr, 2009). These definitions, however, leave out or mask the use of rainfall harvesting by collecting runoff or by direct interception from roof for crop production (but the latter is also used to augment domestic water use in developing countries) and desalinated water that can potentially be used in agriculture. Perhaps, these can be referred to as 'yellow water' and 'red water' respectively. We label the former 'yellow' water because, in terms of crop production, it is considered to be at the interface between blue and green water (Wisser et al. 2010; Hoff et al. 2010); and the latter 'red water' because it is expensive and difficult to obtain, particularly in terms of energy consumption.

Types of Water Scarcity

According to Rijsberman (2006), an individual who is unable to access safe and affordable water to meet personal basic requirements is said to be "water insecure". An area is "water scarce" when a significant proportion of the population become water insecure for a prolonged period. In the European Environment Outlook (2005), water scarcity is defined as the incidence of insufficient water resources (as a result of low availability or demand exceeding the supply capacity of the natural system) to satisfy long-term average requirements. Rockstrom et al. (2009) state that 'water scarcity is a general collective term used when water is scarce for whatever reason'. In this paper, water scarcity is defined as insufficient water availability from all sources to satisfy long-term average crop water requirement.

A distinction exists between economic and physical water scarcity. Physical water scarcity refers to inadequate quantity of available water to satisfy demand or water requirement. Economic scarcity or social water scarcity relates to constrained access to water as a result of limited investment in water infrastructure or socio-economic constraint (Rijsberman, 2006). A third type of water scarcity, hybrid water scarcity, relates to a combination of physical and economic scarcity where over-abstraction combines with limited socio-economic adaptive capacity. Ohlsson and Turton (1999) argue, however, that these are not distinctive types of water scarcity, but progressive orders or levels which are emergent from immediately lower orders. Thus, physical scarcity is first order scarcity. An effort to resolve this scarcity, through engineered systems to augment supply, leads to the emergence of a second order economic type scarcity. Addressing a second order scarcity through enhanced water conservation and use efficiency leads to the possibility of a third order scarcity which is a combination of physical and economic scarcities and signals a shift in water allocation from low-value to high-value use. It can also be argued, however, that economic scarcity can be first order scarcity which, when resolved, can lead to the second order physical scarcity.

Rijsberman (2006) provided a comprehensive overview of water scarcity indicators, discussing their merits, demerits and potential uses. On the basis of computational approaches and inherent assumptions, three broad types of water scarcity indicators can be distinguished: withdrawal to availability ratio, per capita water availability, and hybrid water scarcity indicators.

a)Withdrawal to Availability Ratio

This indicator compares water withdrawal with the renewal capacity of a watershed or natural system of a given geographic area. A widely used method for calculating scarcity is the Water Resources Vulnerability Index (WRVI) developed by Raskin et al. (1997). This technique computes scarcity as the proportion of total annual withdrawal to total available water resources. When annual withdrawal is 20-40% of renewable water supply, the region suffers water scarcity. When the value is above 40%, the region suffers severe water scarcity. Other approaches include the criticality ratio (Alcamo et al. 1997) which is the quotient of water withdrawal to total renewable water supply. A value of 0.4 indicates high water scarcity. Similar methods of calculating water scarcity can be found in Vorosmarty et al. (2000), Alcamo et al. (2003), and Oki and Kanae (2006). Another variant is the Water Exploitation Index (WEI) which is used to gauge water scarcity in Europe (European Environment Outlook, 2005). The WEI is the quotient of total water abstraction and the long term annual average water resources. A WEI value of 0.2 is the threshold that indicates water scarcity. A value higher than 0.40 indicates severe water scarcity.

b)Per Capita Water Availability

This category of indicators presents the amount of water potentially available to an individual in a given population that depends on a given amount of water resources in a particular geographic area (Rockstrom et al. 2009). An example of such a method is the Falkenmark indicator (Falkenmark et al. 1989). The Falkenmark indicator is commonly used because it is easy to measure and is readily understandable and meaningful, even though it also has certain limitations such as masking variability across spatial-temporal scales, infrastructural capacity and demand due to differences in socio-economic contexts (Rijsberman, 2006). According to the Falkenmark indicator, a country is suggested to suffer water stress if its per capita annual renewable water supply (surface water and groundwater) is less than 1700 m^3, water scarcity if its per capita available water is 1000 m^3 or less, and absolute scarcity when its per capita water availability is less than 500 m^3. It is easy to deduce from this indicator that an increase in population automatically increases water scarcity as the same amount of water circulates within the local hydrological cycle.

c)Hybrid Water Scarcity Indicators

Hybrid indicators combine physical and economic water scarcity into a single value. Examples include the water poverty index (Sullivan, 2002) and the social water stress index (SWSI) (Ohlsson, 1999). Ohlsson (1999), for example, generated the SWSI by weighting the Falkenmark indicator using the United Nations Development Program (UNDP) human development index and, thereby, incorporated social adaptive capacity (Rijsberman, 2006). Seckler et al. (1998) incorporated social adaptive capacity into their analysis to distinguish physical water scarce countries from economic water scarce countries.

Towards agri-compatible virtual water

a)Scope for Agri-compatibility

Currently, any reference to water scarcity is arbitrarily linked to food insecurity and any food import qualifies as virtual water. This limits the utility of virtual water for addressing specific water and food security policy. We therefore present and elaborate a framework for agri-compatible virtual water (Figure 2).

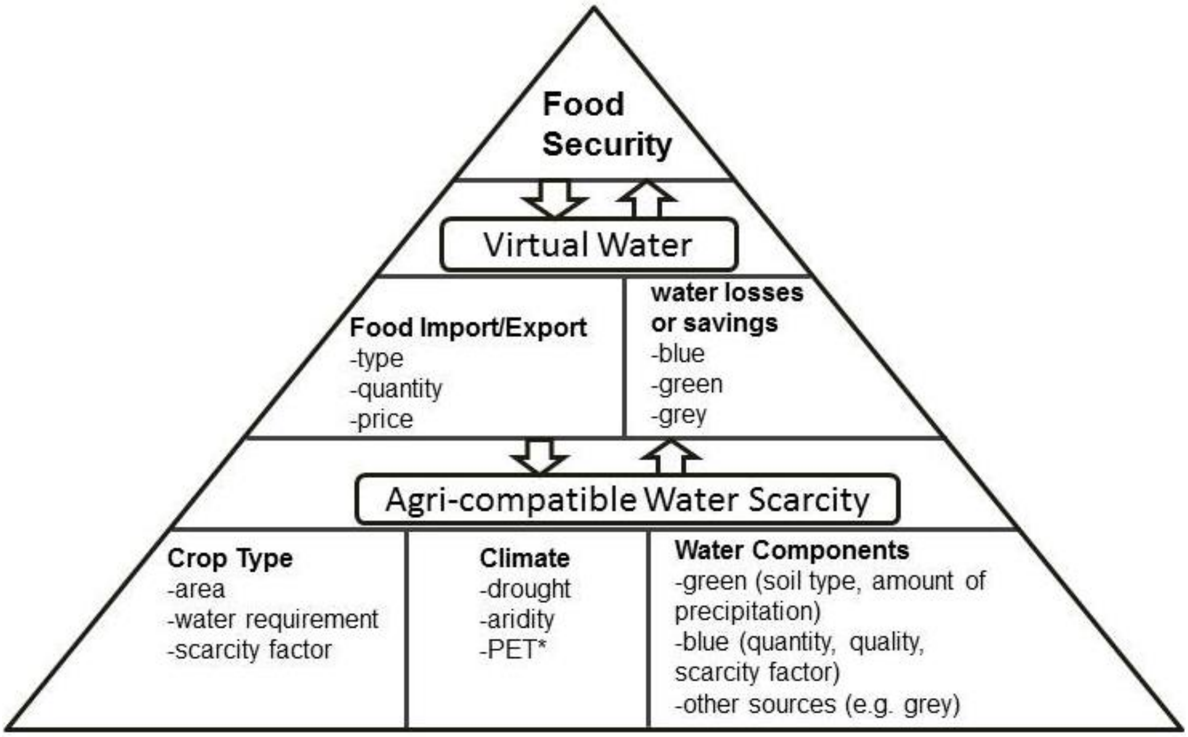


Figure 2. Agri-compatible framework for understanding the role of virtual water in achieving food security in a water-scarce community. The base of the triangle captures the elements of agri-compatible water scarcity which limits crop production and necessitates food import (virtual water). The apex of the triangle shows food security achieved through virtual water. Conversely, food security, achieved through virtual water, also affects water scarcity in the crop production area from which food crops are imported.
* Potential Evapotranspiration

Current methods of calculating water scarcity are not compatible with environmental water availability for crop production and therefore do not reflect crop water scarcity. These methods are limited by the following factors: i) current water scarcity indicators are based on blue water and socio-economics but do not capture green water availability and use, as well as yellow water or the possibility of red water use. The potential of deep groundwater as a buffer has received scant attention (Koehler, 2008); ii) increasing water scarcity in a certain area may have a high potential to cause a shift in water allocation from agriculture to non-agricultural uses even though the contribution of actual crop water use to overall water scarcity is rarely considered; iii) it is rare to include climatic variables such as temporal changes in precipitation which is critical for crop performance; iv) not all water scarcities are of significance for crop production, e.g. economic water scarcity has little relevance for rain-fed agricultural systems; (v) the scale of analysis is often too coarse to reveal important spatial, temporal and socio-economic differences within a given country, region or catchment.

Figure 2 shows that virtual water can be used as a mechanism to bolster food security while offsetting water scarcity in an importing economy, but can also affect water scarcity in the exporting economy. Figure 2 shows the two requirements for evaluating agri-compatible virtual water estimates. One, water scarcity must be agri-compatible, the other, food importation should serve *“water-dependent”* food security requirement

(Aldaya et al., 2010b). Water-dependent food security refers to actual or potential food security gap created by insufficient available water from all relevant sources for crop production (all other things being equal) to meet food security requirement.

b)Agri-compatible water scarcity

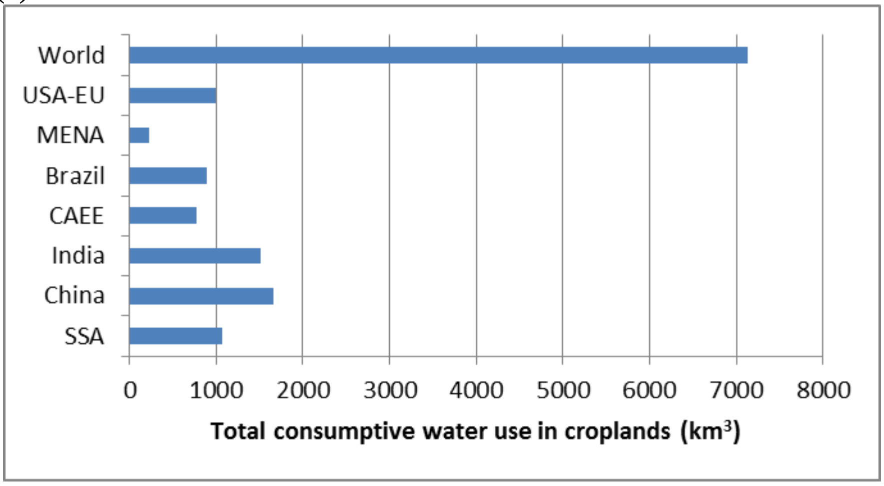
Agri-compatible water scarcity refers to insufficient water availability from all relevant sources to satisfy crop water requirement to the extent that food security is undermined. The components of agri-compatible water scarcity (crop type, climate and water components) are shown at the base of Figure 2. Existing water scarcity indicators give useful information on water availability for use by human populations. There is, however, relatively scant information on the link between water scarcity for food production and security. For water scarcity to be meaningful for virtual water and food security, the concept must be agri-compatible. In other words, water scarcity should be analysed through agricultural systems and expressed in terms of normal water balance concepts and the role of imported food commodities in the food balance sheet and water consumption in the importing economy. Agri-compatible water scarcity, therefore, accounts for the totality of environmental water availability (green, blue and other sources) and consumption in relation to specific crop water requirement (CWR) at a particular place and time. CWR, usually equated to crop evapotranspiration, is a function of climatic and weather conditions, soil properties, agronomic practices and crop factors. As a result and due partly to differences in crop water use efficiency (amount of water used per unit yield), crops can suffer genotype-specific water scarcity under the same production conditions. Agri-compatible water scarcity should capture three elements as discussed in the next sub-sections.

Aridity and Drought

Aridity describes the extent of dryness of the atmosphere, in terms of the relationship between precipitation and potential evapotranspiration (PET), of a given agro-ecosystem (Rockstrom et al. 2010). In arid agro-ecosystems, PET exceeds effective rainfall, spatial-temporal variability of rainfall is high and drought and dry spells are frequent (Rockstrom et al. 2010). The occurrence of seasonal and intra-seasonal water deficit for crops is therefore high and frequent, underscoring a high potential for physical water scarcity. Drought is a temporary shortage of water, over periods of months to few years, due to below-normal precipitation (Dai, 2011). The occurrence of drought during the growing season of crops can ultimately impair crop growth and yield if not addressed. While aridity is a permanent climatic feature of certain geographic regions, periodic and seasonal drought is common in many crop production areas of the world. Drought is a complex abiotic stress and difficult to predict because of the interaction of multiple factors related to crop, climate, soil and agronomic practices (Richards, 2006). Assessment of the effects of drought on yield is further complicated by the varying effectiveness of different crop response and adaptive mechanisms, the time of incidence in the crop cycle and the severity of the drought. Under rain-fed systems, drought can seriously decrease yield and can necessitate food import even though some crops have a physiological capacity to maintain high plant water status and minimize yield loss under short term water stress conditions (Blum, 2005). Aridity and drought increase CWR and increases the need for irrigation. These features make virtual water particularly relevant for regions with arid and semi-arid agro-ecosystems due to the high potential for agri-compatible water scarcity. Thus, in evaluating virtual water flows, it is important to consider the contribution of aridity and drought to water scarcity for crop production and, consequently, food import.

Allan (2000) argues that virtual water is particularly effective and efficient in addressing *progressive and occasional local agricultural drought*. Drought can compel a relatively water-secure economy to restrict food export and increase food import in order to maintain food security. Consequently, agri-compatible water scarcity estimates should reflect the effectiveness of the climate and weather in relation to the specific water requirement and phenology of a particular crop in a given area and time. Understanding the environmental effects of periodic and seasonal drought on crop yield response constitutes a more rigorous basis for evaluating the significance of virtual water for food security and water savings.

(a)



(b)

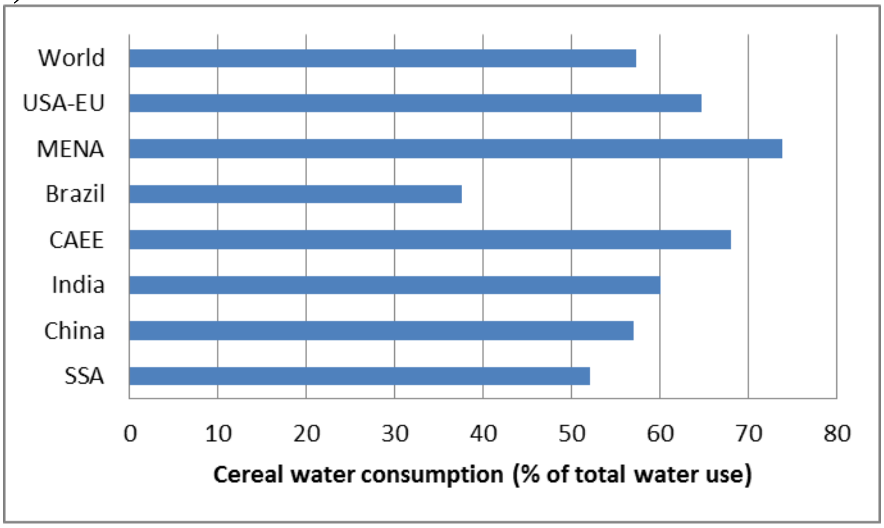


Figure 3. (a) Total crop water use in the world and selected major crop production regions in the year 2000 and (b) water used by cereals as a percentage of total crop water use in the world and selected major crop production areas in 2000 (de Fraiture and Wilchens, 2010).
MENA, CAEE and SSA denote Middle East and North Africa, Central Asia and Eastern Europe, and Sub-Saharan Africa respectively.

Cereal grains have the largest water use in global crop production, can fail due to seasonal drought and are the most traded crop commodity (Yang et al. 2006). World crop water use was over 7000 km^3 in 2000 (Figure 3a), of which cereals accounted for 57% (Figure 3b). Cereals also accounted for over 70% of total crop water use in the Middle East and North Africa (MENA) region in 2000 (Figure 3b). The higher aridity of the MENA region largely accounts for the high irrigation water requirement of cereal production (de Fraiture and Wilchens, 2010; Allan, 1998a; 1998b), giving rise to agri-compatible water scarcity. Not surprisingly, cereals constitute the largest food import to the MENA region. According to de Fraiture and Wilchens (2010), in 2000, Egypt alone imported 8 million tonnes of grains from the USA. As a result of the grain import, Egypt saved 8.5 billion m^3 blue water which could have been used to produce the imported grains (de Fraiture and Wilchens, 2010). Evaluations of virtual water show that the higher import of cereals and grains to the MENA region serves the purpose of water-dependent food security (Allan, 1998a; 1998b) as water availability is limited substantially by aridity. Therefore, it is important that the analysis of agri-compatible water scarcity incorporates a 'climate' factor that reflects the effect of aridity or drought potential.

Green and Blue Water Availability

Green and blue water are the main components of water resource that serves specific crop water requirements in crop producing areas, even though other components may exist in some other crop producing areas. A number of studies highlight the dominance of green water in global crop production by indicating that green water consumption is about 4-5 times higher than blue water consumption (Hoff et al. 2010; Aldaya et al. 2010b), yet green water volumes and consumption are rarely estimated (Hess, 2010). Hoff et al. (2010) suggest that two-thirds of global precipitation is stored as green water while the remaining third is blue water. Even the MENA region, which depends largely on irrigation, meets 50% of their total crop water requirement from green water, either in rain-fed agriculture or from precipitation over irrigated land (Hoff et al. 2010).

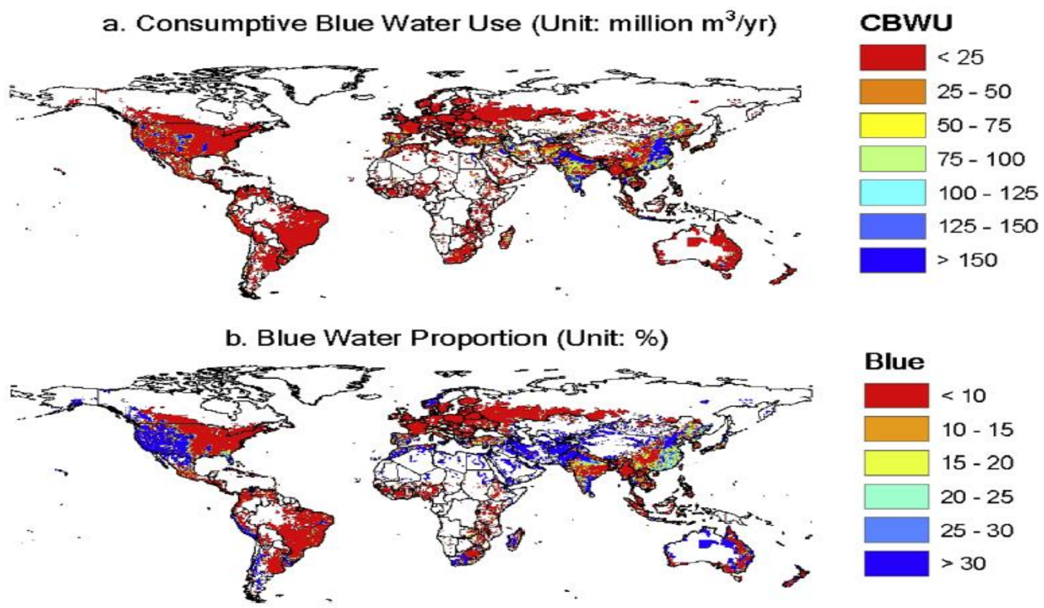


Figure 4. Global pattern of (a) blue water use in crop production (b) blue water use as a proportion of total water use in crop season (Liu and Yang, 2010).

Rockstrom et al. (2009) showed that global water scarcity for crop production can be significantly diminished when green water is properly sourced and managed. Liu and Yang (2010) undertook a spatially-explicit assessment of global green and blue water use on croplands and pasture fields. Their work demonstrated that high water use occurs in China and India, the southern part of West Africa, the mid-belt of USA and parts of South America. However, while blue water use could be substantial in global crop production (figure 4a), its proportional contribution to total water use is small (figure 4b). Green water therefore significantly moderates water scarcity and should be reflected in agri-compatible water scarcity.

Calculation of Crop and Catchment Water Scarcity Indicators

Allan (2000) asserted that analysis of drought must be specific to a given crop type or land use. Similarly, agri-compatible water scarcity must be specific to a particular crop and catchment at a particular area and time in order to be meaningful and purposeful. The work of Ridoutt and Pfister (2010) is significant as it creates opportunity for quantifying the specific contribution of each product to water scarcity, through its life cycle, and the location of water scarcity. Nevertheless, it does not fully capture agri-compatible water scarcity. We propose a calculation scheme for agri-compatible water scarcity factors at crop and catchment levels (Table 1).

Table 1. A scheme for calculating agri-compatible water scarcity at crop and catchment scales.

(i) CROP FIELD	(ii) CATCHMENT
Per unit time (t): $BWRi[t]\ (m^3) = (ETc[t] - P_{eff}[t]) \times A$ [where $ETc \geq P_{eff}$] Per season: $BWRi[season] = \sum_{t=1}^{l} BWRi[t]$ Scarcity factor (Cfi) = $\frac{BWRi[season]}{BWfi}$	$BWR_c[t] = \sum_{i=1}^{n} BWRi[t]$ $BWR_c[season] = \sum_{i=1}^{n} BWRi[season] =$ TBWR Scarcity factor (Cfc) = $\frac{TBWR}{\sum_{i=1}^{n} BWfi}$

Note:
(i) BWRi denotes blue water requirement of crop *i* per unit time (*t*) (m^3); P_{eff} denotes effective rainfall (mm) (effective rainfall is the proportion of rainfall that remains in the root zone after runoff and deep percolation); *ETc* denotes crop evapotranspiration (mm); *A* denotes areal coverage of crop *i* (m^2); *BWf* denotes the fractional amount of blue water in the catchment available for to crop *i* (m^3); *l* denotes length of crop growing period (days).
(ii) *TBWR* denotes total blue water requirement of all crops considered in the catchment (m^3);
n denotes number of crops considered; and *c* denotes catchment.

Scarcity factor (Cf) < 1 implies no scarcity; Cf > 1 implies water scarcity.
Thus, taking Cf = 1 as the threshold for water scarcity, it implies water scarcity increases as Cf increases from 1 and vice versa.
The development or use of these crop and catchment specific scarcity factors is important for the following reasons:
i) not all the catchments in a country might have agricultural withdrawals or abstractions of blue water
ii) different catchments will have different scarcity factors with respect to agriculture and overall withdrawal; and for different crops grown in the catchment
iii) there can be water scarcity in a particular area without there being water scarcity for a particular crop in the same area. Thus, green water availability could be sufficient to support the production of some crop(s) in a catchment that might be suffering blue water scarcity.
iv) intra-seasonal dry spells might adversely affect crop yield in a country or an area that is not considered as water-scarce in the conventional sense.
v) knowing the crop and catchment water scarcity factors will help match crops to catchments in order to save water or reduce the effect of the production of a particular crop on a given catchment. This will, in turn, aid the analysis of the effect of land cover change on water scarcity in a given catchment.
vi) the equations also have operational significance as they can be used to monitor temporal water scarcity (for only green water, blue water or both) at crop, field and catchment scales.
vii) the crop- and catchment-specific scarcity factors can be used in calculating crop water footprints and related effects on humans and ecosystems at both sites of production and consumption.

CONCLUSIONS

Virtual water has been proposed as an essential component of the policy toolkit available to water-scarce communities to reduce the effect of water scarcity on food security. As water scarcity becomes more widespread and crop production becomes increasingly constrained, interest in virtual water is growing in the water research and policy community. However, the connection and the mechanism by which virtual water can reduce the effect of water scarcity on food security remains unclear and contested. We attribute this situation to a lack of agri-compatibility, which should provide a basis for evaluating the role of virtual water in reducing the effect of water scarcity on food security. To evaluate the role of virtual water in the global issue of water scarcity and food security, all components of the available water in crop producing areas need to be quantified to provide a basis for evaluating food imports necessitated by water scarcity. This makes virtual water agri-compatible.

The agri-compatibility framework improves understanding of the connections among water scarcity, virtual water and food security; and shows the relevance of virtual water as a mechanism for reducing the effect of water scarcity on food security. This paper shows scope for agri-compatibility and has argued, that, to ensure agri-compatibility, two key requirements must be met. First, water scarcity should be agri-compatible and, second, food importation should serve "water-dependent" food security requirement. Addressing the former significantly improves overall agri-compatibility. Agri-compatible water scarcity must capture three elements: i) It should account for the totality of water availability and consumption from all relevant sources in crop production. This requires further research effort in the accurate measurement and monitoring of the dynamics of green water availability and consumption in croplands; ii) The analysis of water scarcity for food production should incorporate a 'climate' factor that reflects aridity and drought potential; iii) Water scarcity factors should be specific to crops and catchments to show the scale of crop and land use effect on local hydrological system and, therefore, water scarcity. A conceptual framework for analysing agri-compatible connections among water scarcity, virtual water and food security has been presented and a scheme for calculating agri-compatible water scarcity at crop and catchment scales has been proposed. Making virtual water agri-compatible will require a multi-disciplinary research effort that spans socio-economics, hydrology, soil-water-crop-atmosphere dynamics, spatially-explicit modelling and policy analysis. Nevertheless, achieving such agri-compatibility will significantly advance the utility of virtual water for policy in addressing the effect of water scarcity on food security.

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