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An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes

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ABSTRACT

A water footprint (WF) measures the total water consumed by a nation, business or individual by calculating the total water used during the production of goods and services. This paper extends the existing methods for WF to more localised levels for crops grown partly in open systems and partly in plastic-covered houses with multi-seasonal harvesting, such as the horticulture industry in Spain. This improvement makes it possible to visualise the links of EU tomato consumption to precise production sites in Spain and opens a debate to the usefulness of such findings. This paper also compares existing ecological methodologies with WF and argues that both life cycle analysis (LCA) and ecological footprint (EF) models could benefit from WF methods. Our results show that the EU consumes 957,000 tons of Spanish fresh tomatoes annually, which evaporates 71 Mm^3/yr of water and would require 7 Mm^3/yr of water to dilute leached nitrates in Spain. In Spain, tomato production alone evaporates 297 Mm^3/yr and pollutes 29 Mm^3/yr of freshwater. Depending upon the local agro-climatic character, status of water resources, total tomato production volumes and production system, the impact of EU consumption of fresh tomatoes on Spanish freshwater is very location specific. The authors suggest that business now seek to report and address negative impacts on the environment. WF opens the door to complex water relationships and provides vital information for policy actors, business leaders, regulators and managers to their draw, dependence and responsibilities on this increasingly scarce resource.

1. Introduction

The necessary increase in water consumption to meet future agricultural demands while balancing any associated social and environmental impacts, poses one of the leading environment and sustainability challenges facing the planet. Although it can be argued that there is enough water to provide for present and future generations if properly managed (IWMI, 2007), trade-offs between environmental protection and development are inevitable (Rockström et al., 2007). A failure to manage many water systems optimally is pushing too many areas beyond their sustainable limits. This is particularly the case where decisions and activities that cause the degradation of hydrological habitats have political and financial rather than hydrological related underpinnings.

In the Mediterranean region for example, there are significant environmental and social pressures already impacting the water supply; namely drought and water quality, but also increased population, tourism and intensive agricultural activity. Water resources currently deliver to this multitude of stakeholders with very little regard placed toward the management of existing water supplies. The agricultural sector in particular relies heavily on traditionally non-agricultural land and on groundwater resources for intensively grown export crop production. This reliance, linked to rising demands, means that accommodating water needs will depend upon a better understanding of impacts vis-à-vis the consumption base. In order to link production site impacts with the consumption base and begin to explore the limits of production systems from a water perspective, we have drawn on the concept of virtual water and water footprint (hereafter WF).

This study links EU tomato consumption to production sites in Spain with the main objective of improving WF methods to account for more specific growing conditions at localised scales and to explore wider questions of responsibility and measurement of water resources. There is a brief comparison between WF and existing methods of measuring production impacts. For key stakeholders such as retailers and farmers to understand impacts of their draw on water resources, feedback needs to be specific and accurate. With business now acknowledging that their license to operate hinges on their ability to measure, report and address negative impacts on the environment, the bar is being

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raised for all interested parties to be better informed on water dynamics.

2. Background

2.1. Virtual water

Virtual water refers to the amount of water that is required to produce a certain product. Virtual water content can be evaluated at the field or processing level, depending upon the specific item or scope of study. In this paper we focus on the water content of tomatoes at field level. Water is termed as 'virtual' because the amount of water physically contained in the final product is negligible compared to the amount that went into its production. The virtual water concept was introduced by Allan (1998a, 1998b, 2001), and was inspired by his investigation into the suitability of virtual water imports as a partial solution to problems of water scarcity in the Middle East. He argued that trade of water intensive products to the Middle East region relieved the need for those import countries to use their own water to produce the same product. The concept of virtual water took on more precise and practical applications once Hoekstra and Hung (2002), Chapagain and Hoekstra (2003), Zimmer and Renault (2003), Oki et al. (2003), Yang et al. (2006) and de Fraiture et al. (2004) began to quantify and calculate global virtual water flows.

Virtual water content can also be expressed as a water footprint (WF). A total WF of a nation show the water used within a country, and the water used outside a country's borders to produce all products consumed. More importantly, it evaluates where water originates, and can meaningfully explore the suitability of production sites to 'export' water. The first preliminary assessment of the WF of nations was carried out by Hoekstra and Hung (2002). This study used the volume of blue water withdrawal (e.g. water from lakes, rivers, reservoirs) in a nation as a measure of water use from domestic resources, added to the net virtual water import related to the international trade of a limited number of primary crops to calculate an average WF of a nation. A more extensive assessment was later carried out by Chapagain and Hoekstra (2003) which included the international trade of livestock and livestock products.

However, neither study accounted for the volume of green water (effective rainfall) used to produce crops consumed domestically, a situation later rectified by Chapagain and Hoekstra (2004). While numerous studies on various WF scenarios exist (Hoekstra and Hung, 2002, 2005; Chapagain and Hoekstra, 2003, 2004; Chapagain and Orr, 2008), the nature of their scope has detracted from their potential to speak meaningfully about specific growing sites. Firstly, they use average climate data to calculate the virtual water content of a product. For a country with greater spatial variation of climate, such as the USA, China or India, the average virtual water content of a product varies significantly over time and space. Secondly, they assume that in all cases the potential crop evaporation is met. This means that deficit crop water requirements are always fulfilled by supplementary irrigation, which is far from reality, as only 20% of global arable land is irrigated. Therefore there is an overestimation of the virtual water content of crops and livestock products in these studies. Lastly, these studies do not account for any pollution effect of production on local freshwater bodies.

Chapagain et al. (2006) extended the WF concept by quantifying the impacts of pollution related to the consumption of cotton products. This required establishing the water volumes needed to dilute waste flows to such an extent that the quality of water would remain at least equal to agreed water quality standards. The authors further refined existing studies by using climate data from climate stations effectively covering production regions. This accounted for more specific climatic variations within countries. The cotton study also used local crop characteristics together with the water availability during crop production (the volume of supplementary irrigation available). Chapagain (2006) and later Hoekstra and Chapagain (2008) presented the evolution of the concept of virtual water and water footprint into one coherent framework. Though this provides a useful methodology to calculate the WF related to the consumption of crop products from open systems, it does not address the different conditions of production under covered systems. Also, in these studies the crop water requirements calculated for one dominant season is assumed to be valid for crops grown at different seasons in a year. Thus they ignore the inter-seasonal variability of virtual water content of crops in countries where there may be more than one major growing seasons.

2.2. Comparison with LCA and EF

The most common way to assess environmental impacts from a product perspective is the life cycle analysis (LCA). The most commonly known and used indicator for understanding ecological impacts is the ecological footprint (EF). Both of these tools are briefly discussed here as they relate to their inclusion of water resources.

LCA studies the (eco)efficiency of products and assesses the environmental impacts of resource use in a production system with the aim of recommending improvements to that system. As noted by Andersson et al. (1998), an ideal LCA study should include agricultural production, industrial refining, storage and distribution, packaging, consumption and waste management. There are a few studies covering the entire life cycle of food products such as the tomato (Antón et al., 2005), tomato ketchup (Andersson and Ohlsson, 1999), rye bread and ham (Weidema et al., 1995), and Greek beer production (Koroneos et al., 2005). With regard to water resources, Foster et al. (2006, p. 54) carried out a comprehensive DEFRA-commissioned study to inform UK government policy in reducing the environmental impacts of food consumed in the UK. In their review of existing LCA studies they concluded that '…there is no standard approach in evaluating these impacts [water use] in LCA, and they receive limited attention in such studies'. There is also a failure to discern spatial differences in growing systems in the majority of studies, and when water is included, it is done so rather simplistically.

A recent study by Antón et al. (2005) highlights water as a major impact category and argues that the production stage has by far the larger impact (22 l per kg of tomato) on water compared to waste disposal (0.5 l) and fabrication (0.005 l). Their study is focused on assessing impacts on individual categories and thus does not take into account the inherent cross category impact. For example, the waste generated, *i.e.* polluted return flows, if discharged untreated, can render a larger volume of water resources unusable than predicted by the analysis pointing to a mere 0.005 l, which is perhaps only valid if drainage water is re-used. The input variables used in that model are unclear, whereas improvements to the WF model provide a fully explained calculation scheme together with the different input variables. The results by Antón et al. (2005), are for a closed system, which in cases where production is under hybrid (first grown in an open system and then under a covered system), the 'green water use' is not obvious.

The WF is conceptually similar to the EF concept (Hoekstra, 2007), the latter being introduced in the second half of the 1990s (Wackernagel and Rees, 1996; Wackernagel et al., 1997; Wackernagel and Jonathan, 2001). The EF measures how much land and water area (ha) a human population requires to produce the resources it consumes and to absorb its wastes under prevailing technology. One of the main criticisms of the EF concept has been the problem of data aggregation (van den Bergh and Verbruggen, 1999; Cornelis and Erwin, 2000; Opschoor, 2000; Lenzen and

Murray, 2001; Senbel et al., 2003) which may be its weakest measure of sustainability. Studies show that if global consumption was equal to current UK living styles then the resources of three planets would be required (WWF, 2006), a ratio consistent with most Western lifestyle nations. The current global EF is estimated to be over 23% larger than the planet's regenerative capacity. An EF provides information to a region's dependence at the global level and highlights the reliance and impact we have on often distant locations (Herendeen, 2000). Studies have shown the Netherlands and Japan, often held up as economic success stories and examples for the developing world to follow, enjoy high material standards at the cost of unaccounted ecological deficits in many other parts of the world (Rees, 1996).

From a freshwater perspective, current EF models do not adequately capture freshwater use. An EF shows the area needed to sustain people's living; the WF indicates the annual water volume required to sustain a population. A nation's or individuals water impacts under EF are calculated by equating the energy required to process freshwater for human consumption and the land area required to support those water-processing industries. These measures are somewhat irrelevant in terms of major threats to the world's freshwater ecosystems, where the key issues are water abstraction, water pollution, and the physical modification of water bodies (*e.g.* dams, draining of wetlands).

2.3. Tomato production and Spain

The tomato is the single most important horticultural crop in terms of world production and trade. According to FAO figures, world production of tomatoes is around 100 million tonnes per year (about 15% of total vegetable production, excluding potatoes). Tomatoes are valuable to the EU in terms of production and consumption and while only a small percentage of overall horticulture exports and production, are nonetheless representative of the myriad issues which surround horticulture trade as a whole. Fresh tomatoes have been chosen for this study as opposed to processed (sauces, purees, juice, ketchups, etc.) as the un-transformed crop picked on-site can be more easily traced through the supply-chain and trade statistic databases.

Covered growing systems, also referred to as greenhouses[1] or poly-tunnels, dominate the Spanish tomato sector. This type of covered production system is chosen by farmers to extend the harvest season and help maintain a controlled environment suitable for optimal crop production, and to maximise profits. These systems also raise additional environmental concerns of waste disposal of plastics and landscape degradation. Most covers are moveable plastic tunnels, erected and dismantled at the end of each growing season. The types of protected systems differ considerably across the country depending on climatic conditions, construction style and materials, equipment required inside the structures and the knowledge available to manage these systems most effectively (Peet and Welles, 2005). Spain originally targeted high priced and out-of-season (for northern EU) crops, but is now able to meet the demand from retailers for high quality food throughout the year.

The majority of fresh tomato imports to the EU originate from the southern Spanish mainland and the Canary Islands. Tomato cultivation covers over 60,000 ha, or equivalent to 14% of the total land area under horticulture and 20% of the total production value of Spanish horticulture. This makes the tomato one of the most important horticultural crops in Spain in terms of land area covered and production value (Lawrence, 2004). The main tomato producing regions in Spain are in the Ebro valley (Navarra, Rioja, and Zaragoza) and Guadiana valley (Extremadura) for industrial tomatoes, and in the south-east catchments of the Júcar, Segura and Sur (Valencia, Alicante, Murcia, Almeria) and Canary Islands for fresh tomatoes (Beaufoy, 2005) (see Table 1). According to Beaufoy (2005) these sites are among the most significant in Spain in terms of conflicts between agriculture and the conservation of rivers and water resources.

In Spain, the main environmental issues associated with tomato cultivation other than water consumption, are water pollution, soil pollution and erosion, with habitat loss from expanding cultivation in some areas. The over-exploitation of aquifers from horticulture exports has affected water quantity and quality, including water salinity and declining water tables, with additional loss of biodiversity, ecological value and landscape amenity across the Mediterranean area (Martínez-Fernández and Selma, 2004). Current water use, in Almeria for example, is around 4–5 times more than annual rainfall and is mainly obtained from deep wells with high salinity of water, limiting the possibilities for water re-use. Almeria also has the largest poly-tunnel concentration in the world, with around 40,000 ha of greenhouse crops grown predominantly under flat-roof greenhouses (Cantliffe and Vansickle, 2000).

A response to the excessive water abstraction from aquifers from the new Spanish Government has been the implementation of the national water plan 'Programa Agua', which calls for, among other things, an increase in de-salination plants (Downward and Taylor, 2007). De-salination plants also contribute to many other significant environmental impacts (*i.e.* high carbon footprint, marine impacts, waste flows) but remain an increasingly favoured response to water scarcity, especially in southern Europe where climate change, irrigation, urbanisation and increasing demands from tourism have combined to create water scarcity.

3. Methodology

The consumption of goods and services often creates stress on the water resources of production sites. However, the dynamic between use and stress can be entirely different per location. The effect of local consumption on the water resources of other countries can be quantitatively analysed in two ways. First one can look at the absolute volume of water imported (the size of the external WF) and the kind of virtual water imported (the quality of the WF). Second one can consider the relative volume of water imported compared to the available resources in exporting countries. Though the size of the external WF can be large, it will

Table 1
Major tomato producing regions in Spain and their relevant climate stations

Regions	Representative climate stations[a]	Production (t/yr)	Area under covered production system (%)
Andalucía	Almeria	807,000	55
	Granada	165,000	55
	Málaga	165,000	55
	Cádiz	148,000	55
Murcia	Murcia	310,000	75
Cataluña	Tarragona, Barcelona, Gerona, Lérida	124,300	0
Castille La Manche	Guadalajara, Cuenca, Toledo, Cuadad Real, Albacete	111,300	0
Extremadura	Badajoz, Cáceres	1,250,000	0
Navarra	Pamplona	127,000	0
Canary Islands	Santa Cruz, La-Luz, Aprecife	252,000	100
Others	–	550,000	0
Total production[b]	–	4,009,600	–

[a] Source: CLIMWAT (FAO, 1993).
[b] Total average production of tomatoes in Spain is 4,009,600 t/yr with an average yield of 63 t/ha during the period 2000–2004 (FAOSTAT data, 2006).

[1] Plastic and glass covered walk-in structures are considered greenhouses.

exert less pressure in exporting countries if the kind of water used is abundantly available in those countries (*e.g.* export of rain-fed maize from the USA). Thus, before quantifying the WF of a product, we need to analyse the virtual water content of that product which distinguishes the kind of water used in the production process.

The virtual water content of a primary crop VWC_c (m^3/t) is calculated as the ratio of the volume of water used for crop production WU_c (m^3/ha), to the volume of crop produced, Y_c (t/ha).

$$VWC_c = \frac{WU_c}{Y_c} \quad (1)$$

The volume of water used for crop production (WU_c, m^3/ha) is composed of two components

$$WU_c = WU_{evaporative} + WU_{non-evaporative} \quad (2)$$

where $WU_{evaporative}$ is the volume of water evaporated and $WU_{non-evaporative}$ is the volume of water unavailable for further use as a result of pollution which is calculated as

$$WU_{evaporative} = WU_g + WU_b \quad (3)$$

$$WU_{non-evaporative} = WU_p \quad (4)$$

Here WU_g (m^3/ha) is the evaporation of rainfall from crop land (green water use), WU_b (m^3/ha) is the evaporation of irrigation water from crop land (blue water use), and WU_p (m^3/ha) is the polluted volume of water resources resulting from leached fertilisers, chemicals or pesticides from agricultural land. The first two components, WU_g and WU_b, are evaporative and are no longer available immediately in the local hydrological cycle. The concept of green water flow was first introduced by Falkenmark at an FAO seminar in 1993 (Falkenmark, 1995) as the total volume of water evaporated from soil moisture. Subsequently, Falkenmark and Lannerstad (2005) elaborated how blue water flow transforms into green water flow as a result of evaporation from irrigated fields, wetlands and evaporating surfaces. With this definition, it is difficult to separate the part of the evaporative demand of a crop met by direct rainfall (effectively stored in soil moisture and available at the root zone of the plant) and the part of the demand met by irrigation water supply replenishing the deficit soil moisture. A more clear distinction of green and blue water is made by Savenije (1998) and Döll (2002) by defining green water as the evaporation from rain-fed land. Later Chapagain et al. (2006) used this distinction as the basis for calculating the green virtual water content of cotton products and green water footprints related to cotton consumption. The term green water use in the present paper follows Chapagain et al. (2006). The term 'green water flow' in Falkenmark's (1995) paper corresponds to the total evaporative water use ($WU_{evaporative}$) in this paper.

The required dilution volume, WU_p, is theoretically available further downstream from the point of use. This water may or may not be economically re-usable depending on the absolute position of the return flows or its desired use. For example, return flows from coastal areas are not useful for drinking, industrial use or for irrigation. However, this water may be usable for other important uses such as to balance the effect of salt intrusion or to support saline water ecosystems in coastal areas.

Therefore, the virtual water content of a primary crop is made of evaporative and non-evaporative components expressed as

$$VWC_c = \frac{WU_{evaporative}}{Y_c} + \frac{WU_{non-evaporative}}{Y_c} = VWC_e + VWC_{ne} \quad (5)$$

where the evaporative virtual water content of a crop, VWC_e, is calculated as

$$VWC_e = \frac{WU_{evaporative}}{Y_c} = \frac{WU_g}{Y_c} + \frac{WU_b}{Y_c} = VWC_g + VWC_b \quad (6)$$

and the non-evaporative virtual water content of a crop, VWC_{ne}, is calculated as

$$VWC_{ne} = \frac{WU_{non-evaporative}}{Y_c} = \frac{WU_p}{Y_c} = VWC_p \quad (7)$$

where VWC_p is the pollution component of virtual water content of the crop. The components WU_g and WU_b depend on the specific crop evaporation requirement and soil moisture availability in the field. The crop evaporation requirement for a crop (ET_c [t] mm/day) is calculated using the crop coefficient (K_c [t]) for the respective growth period and reference crop evaporation (ET_0 [t] mm/day) at that particular location and time.

$$ET_c[t] = K_c[t] \times ET_0[t] \quad (8)$$

Depth of water (mm/day) can be expressed in terms of volume per hectare ($m^3/ha/day$) by multiplying with a factor of 10. We have used the CROPWAT model (FAO, 1992) which employs the classic Penman–Monteith equation to estimate evaporation ET_0 following the methodology recommended by FAO (Allen et al., 1998). The ET_0 is only affected by climatic parameters. It expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider crop characteristics and soil factors. The crop evaporation (ET_c) differs distinctly from the reference evaporation (ET_0), as ground cover, canopy properties and aerodynamic resistance of the crop are different from grass (this is the reference crop in the methodology recommended by Allen et al., 1998). The effects of the characteristics that distinguish field crops from grass are integrated into the crop coefficient (K_c). The major factors determining K_c are crop variety, climate and the crop growth stage. Due to differences in evaporation during the various growth stages, the K_c for a given crop will vary over the growing period (from planting to harvesting). For perennial crops, the planting dates can be assumed to be the green-up date for the calculation of crop water requirements.

Soil moisture is maintained either by effective rainfall or by irrigation water supply. The CROPWAT model has a few inbuilt options to estimate effective rainfall. We have chosen the USDA SCS (USDA Soil Conservation Service) method, as it is one of the most widely used in estimating effective rainfall in agricultural water management (Cuenca, 1989; Jensen et al., 1990).

The green water use, u_g [t], is equal to the minimum effective rainfall, p_{eff} [t], and the crop evaporation requirement at that time-step.

$$u_g[t] = \min\left(ET_c[t], p_{eff}[t]\right) \quad (9)$$

Total green water use (WU_g) in crop production is calculated by summing-up green water use for each time-step over the entire length of crop period, l (day).

$$WU_g = \sum_{t=0}^{l} u_g[t] \quad (10)$$

Green water use is independent of irrigation water supply and solely depends on the effective rainfall and crop evaporation requirements, whereas blue water use depends on crop evaporation requirement, green water availability and irrigation water supply. The first two variables ET_c [t] and u_g [t] define the irrigation requirement (I_r [t]) which is calculated as

$$I_r[t] = ET_c[t] - u_g[t] \tag{11}$$

The blue water use, u_b [t] is the minimum irrigation requirement, I_r [t], and the effective irrigation water supply, I_{eff} [t]. The effective irrigation supply is the part of the irrigation water supply that is stored as soil moisture and available for crop evaporation. Blue water use is zero if the entire crop evaporation requirement is met by the effective rainfall.

$$u_b[t] = \min\left(I_r[t], I_{eff}[t]\right) \tag{12}$$

Total blue water use (WU_b) in crop production is calculated by summing-up blue water use for each time-step over the entire length of crop period, l (day).

$$WU_b = \sum_{t=0}^{l} u_b[t] \tag{13}$$

The dilution volume of water is a theoretical amount of water that would be required to dilute pollutants emitted during the production process to such an extent that the quality of the ambient water would remain below agreed water quality standards. The translation of the pollution effect into an equivalent volume of water necessary for dilution per unit of production is difficult to quantify, as the agreed standard can always be debated. The standard can differ widely based on the use value of the water resources further downstream.

$$u_p[t] = \max\left(\frac{L[i,t]}{L_a[i,t]}\right) \tag{14}$$

Where $L[i,t]$ is the weight of a pollutant i (ton) emitted into the water system from crop production and $L_a[i,t]$ is the permissible limit of that particular pollutant (t/m^3) in ground or surface water bodies. Total dilution water use in crop production is thus

$$WU_p = \sum_{t=0}^{l} u_p[t] = WU_{non\text{-}evaporative} \tag{15}$$

The evaporation demand can be calculated on a daily time-step, whereas effective rainfall should be calculated on a larger time-step to account for the role of the water holding capacity of soil and agriculture practices. The moisture from previous time-steps can be stored and used for crop evaporation before the soil becomes saturated and percolation or runoff occurs. The mean monthly rainfall is also assumed to occur at six different events at 5-day intervals with rainfall uniformly distributed over the entire month as recommended in the CROPWAT model (1992). In this study we have taken 10-day intervals to calculate effective rainfall and irrigation requirements.

A schematic of estimating the blue, green and non-evaporative water use and the respective components of the virtual water content of primary crops is presented in Fig. 1.

The above method is applicable for open production systems where the use of effective rainfall (WU_g) fulfils part of the crop

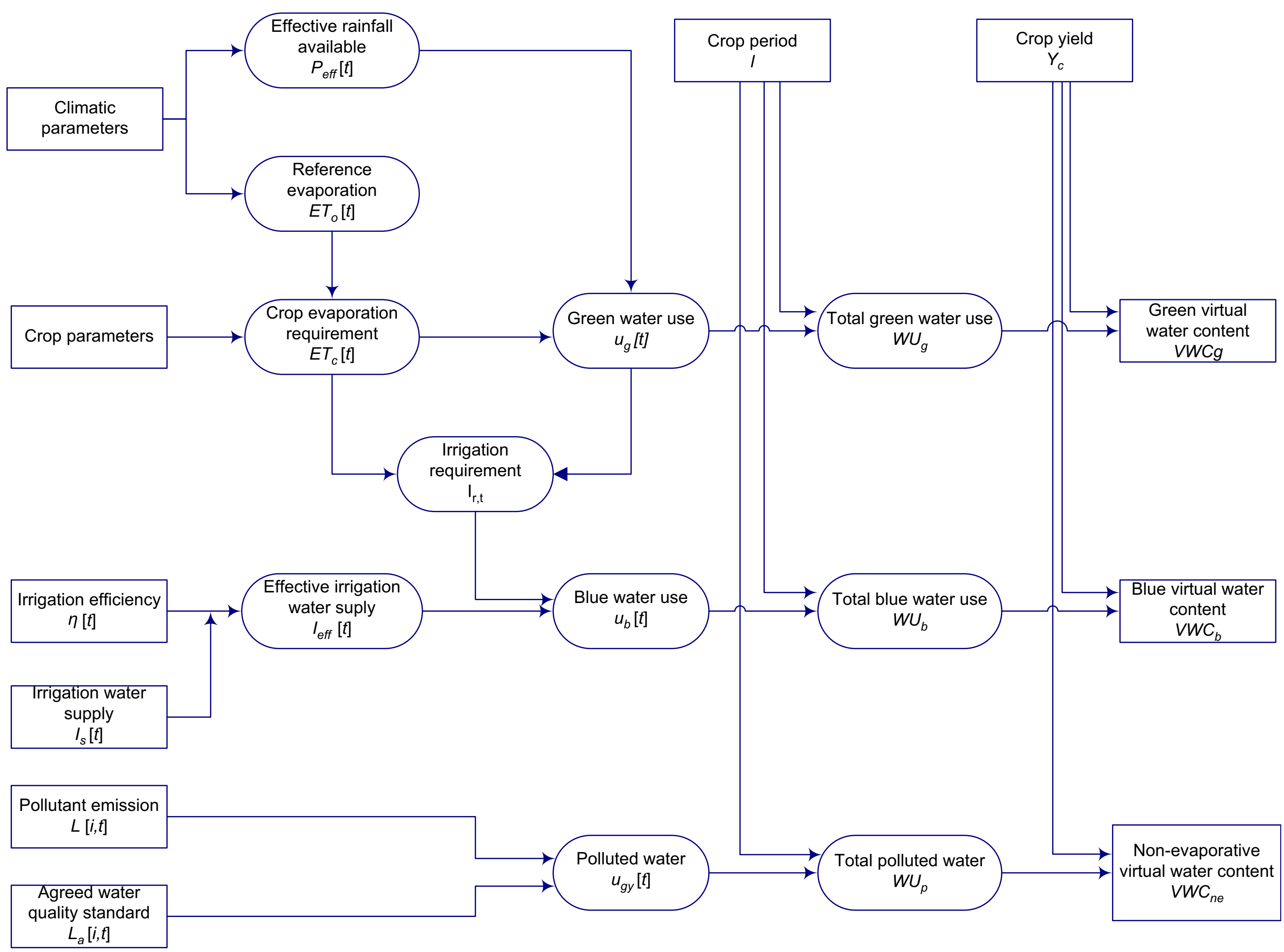

Fig. 1. Diagram to calculate the virtual water content of a primary crop grown without cover.

evaporation demand, thus reducing irrigation water use (WU_b). The green water component is zero in covered systems. Greenhouses have different dynamics of crop evaporation which the CROPWAT model cannot directly use to estimate real crop evaporation. Compared to irrigated crops outdoors, the seasonal ET of greenhouse horticultural crops is relatively low due to a lower evaporative demand inside greenhouses (Orgaz et al., 2005). Based on the observed climatic data inside the greenhouse, the calculated ET_c matched 70–80% of the ET_c computed with climatic parameters observed in the open environment (Fernàndez, 2000; Fernandes et al., 2003; Harmato et al., 2004). Fig. 2 presents the modified schematic to estimate the virtual water content of tomatoes grown under covered systems.

Spanish tomatoes are usually planted in the first week of August and harvested from the third week of April until the last week of December. Tomatoes are grown in an open environment until the third week of November and are then covered. For tomatoes grown in mixed (partly open and partly covered) systems, we used a combination of both schemes (Figs. 1 and 2). The initial period when the crop is grown uncovered uses the first scheme (Fig. 1) and for the remaining period when under cover, we use the second scheme (Fig. 2). By adding respective water use (blue, green and non-evaporative) from these two schemes, results in the total water use for the entire crop period. This total water use (m^3/ha) is then divided by crop yield (t/ha) to obtain respective virtual water contents. Table 1 presents the location of all tomatoes grown in Spain, however, our main results in Tables 4–6 are for fresh tomatoes only.

Since this is a crop with a continuous harvest, attaining crop water requirement, effective rainfall and irrigation requirements from one single run of the CROPWAT model, as is the case for common crops such as wheat and maize, is not possible. We have therefore assumed two sets of crop; first with a crop length of 150 days and the second at 270 days. The K_c values of crops are taken as 0.60 (initial), 1.15 (mid) and 0.80 (late). The crop development stages are assumed to be 30 days (initial stage), 45 days (development stage), 45 days (mid-stage) and 30 days for first set of crops at the harvesting stage (and 150 days for the second set of crop).

We have assumed the yield of fresh tomatoes from Extremadura as representative of open production systems (1,250,000/20,400 = 61 t/ha). According to FAOSTAT data (2006), the average yield of fresh tomatoes in Spain is 63 t/ha. The average tomato yields in different production areas do not differ much in Spain which is also noted by Antón et al. (2005). In our analysis, we have assumed a constant average yield of 60 t/ha for open systems and 80 t/ha for covered systems across different regions in Spain. We have assumed irrigation efficiencies of 80% and 90% in open and covered systems, respectively.

The use of fertiliser and other agro-chemicals is common in tomato production. While we can analyse the fate of individual fertilisers on a detailed basis, this process is quite time and data demanding. One of the objectives of this paper is to show the relationship between chemical fertiliser use and consequent pollution of the local environment to the consumption of these products. For this example we have chosen nitrogen as the indicator of impact of fertiliser and pesticides used in production systems and have taken NO_3 leaching to be 25 kg/ha from open and 15 kg/ha from covered systems (Mema et al., 2005). Since 1991, European Union (EU) member states have had to comply with the Nitrates Directive which aims to sustainably protect ground and surface waters from nitrogen (nitrates) pollution originating from agriculture. The permissible limit of nitrates in surface and groundwater bodies is set by the EU as 50 mg nitrate-NO_3 per litre. The standard recommendation by the EPA (2005) is 10 mg per litre (measured as nitrogen), equivalent to 45 mg nitrate-NO_3

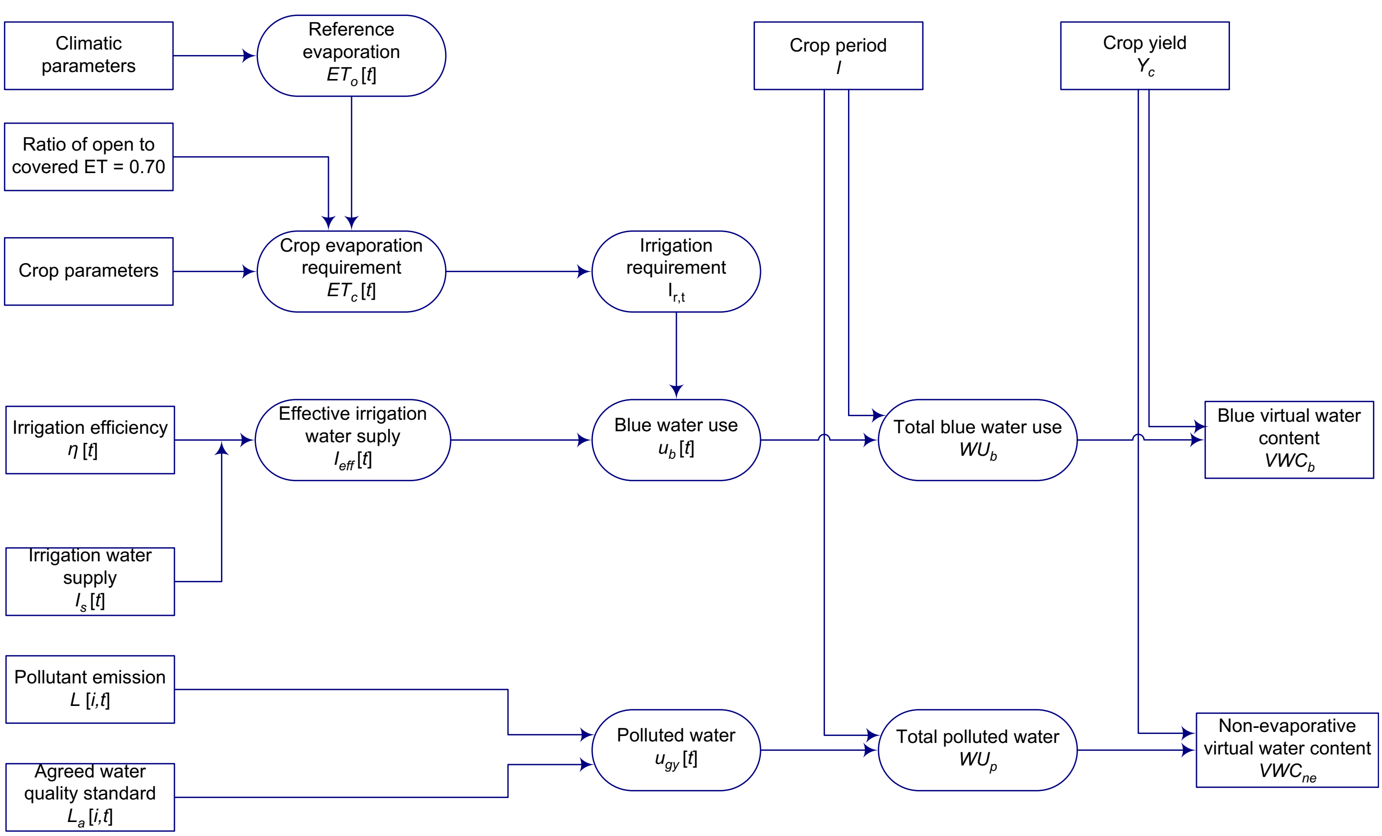

Fig. 2. Diagram to calculate the virtual water content of tomatoes grown under covered systems.

per litre. We have used the EU directive of 50 mg nitrate-NO_3 per litre to estimate the volume of water necessary to dilute polluted return flows to permissible limits.

The virtual water flow, Q, between two nations or regions is the volume of virtual water transferred from one place to another as a result of a particular product trade. The virtual water flows between nations are calculated by multiplying commodity trade flows (T_c, t/yr) by the associated virtual water content from origin (VWC, m^3/t).

$$Q = \sum_{c=1}^{C} T_c \times VWC_c \quad (16)$$

The WF of an individual, business or nation related to the consumption of a particular product is calculated by adding the volume of water used in production processes. Based on the origin of a product, the WF of a particular product can either be internal (consumption of domestic products) or external (consumption of imported products). This is estimated by multiplying the volume of product consumed in any given period of time with its respective virtual water content. Since the virtual water content of a product has two components, evaporative (VWC_e) and non-evaporative (VWC_{ne}), the resulting WF can also be expressed in terms of methods of water use.

$$\begin{aligned} WF &= WF_{internal} + WF_{external} \\ &= \sum_{i=1}^{m} C_i \times VWC_{internal} + \sum_{e=1}^{n} C_e \times VWC_{external} \\ &= \left(\sum_{i=1}^{m} C_i \times VWC_{e,\,internal} + \sum_{i=1}^{m} C_i \times VWC_{ne,\,internal}\right) \\ &\quad + \left(\sum_{e=1}^{n} C_e \times VWC_{e,\,external} + \sum_{e=1}^{n} C_e \times VWC_{ne,\,external}\right) \\ &= \left(WF_{internal,\,evaporative} + WF_{internal,\,non-evaporative}\right) \\ &\quad + \left(WF_{external,\,evaporative} + WF_{external,\,non-evaporative}\right) \quad (17) \end{aligned}$$

where C_i is the quantity of product consumed from domestic resources with virtual water content $VWC_{internal}$ (virtual water content of the domestic products), C_e is the quantity of imported product consumed with virtual water content $VWC_{external}$ (virtual water content of imported product), and m and n are the number of products consumed from domestic production and import, respectively.

The water footprint can also be expressed in terms of sources of water use as

$$\begin{aligned} WF &= WF_{evaporative} + WF_{non-evaporative} \\ &= WF_{blue} + WF_{green} + WF_{non-evaporative} \quad (18) \end{aligned}$$

The total water footprint is an aggregated number and tells us little about the sources of water use. We have kept the distinction between evaporative (separating the blue and green) and non-evaporative (separating the irrigation loss and polluted volumes) components at each level in assessing the virtual water content of a product and the WF of the product consumption.

4. Results

The crop water requirement, use of effective rainfall and irrigation water requirement are presented as per Spanish climate station in Table 2. As there is no deficit crop water requirement due to supplementary irrigation in tomato production in Spain, total crop water use is always equal to the crop water requirement.

Table 2
Crop water evaporation and the evaporative virtual water content of tomatoes per regions in Spain

Regions	Crop evaporation (mm/yr)		Virtual water content in open system (m^3/t)			Virtual water content in covered system (m^3/t)		
	Green	Blue	Green	Blue	Total	Green	Blue	Total
Almeria	56	473	9.4	78.8	88.1	4.9	41.4	46.3
Granada	98	349	16.3	58.1	74.5	8.6	30.5	39.1
Málaga	120	403	20.1	67.2	87.3	10.5	35.3	45.8
Cádiz	117	448	19.5	74.7	94.3	10.2	39.2	49.5
Murcia	88	374	14.6	62.3	76.9	7.7	32.7	40.4
Tarragona	200	244	33.4	40.7	74.1	17.5	21.4	38.9
Barcelona	199	233	33.2	38.9	72.1	17.4	20.4	37.8
Gerona	207	162	34.6	27.0	61.6	18.2	14.2	32.3
Lérida	103	526	17.1	87.7	104.8	9.0	46.0	55.0
Guadalajara	96	347	15.9	57.8	73.7	8.4	30.4	38.7
Cuenca	135	251	22.6	41.8	64.4	11.8	22.0	33.8
Toledo	90	401	14.9	66.8	81.7	7.8	35.1	42.9
Cuadad Real	88	373	14.7	62.2	76.9	7.7	32.7	40.4
Badajoz	106	407	17.7	67.9	85.6	9.3	35.6	44.9
Cáceres	97	492	16.1	82.0	98.1	8.5	43.0	51.5
Pamplona	222	148	37.1	24.6	61.7	19.5	12.9	32.4
Santa Cruz	56	691	9.3	115.1	124.4	4.9	60.4	65.3
La-luz	22	544	3.7	90.7	94.4	1.9	47.6	49.6
Aprecife	74	706	12.3	117.7	129.9	6.4	61.8	68.2
Others[a]			11.4	52.4	63.7	6.0	27.5	33.5

[a] The crop evaporation is weighted based on the share of individual regions to national production (Table 1).

Dividing the volume of water necessary to dilute polluted return flows to permissible limits by tomato yield per hectare, we obtain the volume of water required to dilute return flows to the agreed standard per ton of tomatoes; equal to 8 m^3/t for open production systems and 4 m^3/t for covered systems. The national average pollution component of virtual water content of Spanish tomatoes is 7.2 m^3/t. As the combined effect of a set of different pollutants at different levels of production can always be higher than that of an individual pollutant, the number estimated here using nitrates is rather an underestimation of the reality. The volume of water use for major tomato producing regions is presented in Table 3.

Extremadura province uses the largest amount of water for tomato production. Tomatoes from this region are primarily used for the industrial tomato sector, whereas in Andalucía, the second largest user, tomatoes are grown for export without industrial processing.

By dividing the volume of blue and green water uses by the gross national production, we obtain the blue (60.5 m^3/t) and green (13.6 m^3/t) virtual water contents of Spanish tomatoes as a national

Table 3
Total volume of water used (evaporated, polluted or lost) as a result of tomato production in major tomato regions in Spain

Regions	Evaporative water use (1000 m^3/yr)			Non-evaporative water use (1000 m^3/yr)	Total water use (1000 m^3/yr)
	Green water evaporated	Blue water evaporated	Total evaporated		
Andalucía	12,162	70,406	82,568	7469	90,037
Murcia	2920	12,427	15,347	1518	16,864
Cataluña	3674	6038	9713	1036	10,748
Castille La Manche	1894	6362	8256	928	9184
Extremadura	21,140	93,685	114,823	10,417	125,240
Navarra	4708	3128	7837	1058	8895
Canary Islands	1750	22,580	24,331	1715	26,046
Others	6101	28,097	34,198	4583	38,781
Total	54,350	242,723	297,072	28,723	325,796

Period: 2000–2004.

average. The non-evaporative virtual water content of Spanish fresh tomatoes is 7.2 m^3/t (Table 4).

Assuming that one tomato is equal to 100 gm, we can then estimate that 1.4 l of green water and 6.1 l of blue water were evaporated for its production, or 7.5 l in total. The total water per tomato when added with the volume of water effectively polluted (0.7 l) is averaged at 8.2 l per 100 gm. Compared to Antón et al. (2005), this is nearly 4 times larger and includes the use of green, blue and impacts on blue water as a result of polluted return flows. Chapagain and Hoekstra (2004) estimate this number to be 18.5 l per 100 gm of tomato. This is very high as the study by Chapagain and Hoekstra (2004) overestimates the green water use in the covered/partially covered systems of crop production and also uses national average climate data to estimate the average virtual water content of the crop.

The major market for Spanish fresh tomatoes is the EU25 which accounted for 96% of the total Spanish export of fresh tomatoes from 2000 to 2004 (ITC, 2006). The largest importers within the EU25 are Germany (25%), the UK (19%), France (17%) and the Netherlands (16%). The gross national imports of Spanish fresh tomatoes for selected countries are presented in Table 5.

The impact of consumption of Spanish fresh tomatoes is mainly on blue water resources which either evaporate or become polluted to some degree during the production process. Table 6 shows the main destinations of Spanish tomato consumption and their associated draw on certain water sources. The virtual water import related to the trade of fresh tomatoes from Spain is calculated by multiplying the volumes of tomato export from Spain by the virtual water content of the crop. Spanish fresh tomato production evaporates approximately 71 Mm^3/yr of water and would require a further 7 Mm^3/yr of blue water to dilute the leached nitrates as a result of EU consumption. The country with the largest WF related to the consumption of Spanish tomato consumption is Germany with19.7 Mm^3/yr, while the UK is 15 Mm^3/yr.

Table 6 shows that annually, Spanish fresh tomato exports evaporate 74 Mm^3/yr of green and blue water from Spanish water resources. In this process, the return flows pollute 7 Mm^3/yr of Spanish freshwater. We found that tomato production in Spain evaporates 54.4 Mm^3/yr of green water (green water footprint of global consumption of Spanish tomatoes), 242.7 Mm^3/yr of blue water (blue water footprint of global consumption of Spanish tomatoes) and pollutes 28.7 Mm3/yr of blue water (non-evaporative water footprint of global consumption of Spanish tomatoes). With the existing irrigation efficiencies in tomato production in Spain, the irrigation losses (55.1 Mm^3/yr) are nearly double than the total dilution water required (28.7 Mm^3/yr). Here, we can reduce the local water use in tomato production by increasing the irrigation efficiencies so that the losses are no more than necessary for diluting polluted return flows. Reducing non-evaporative water losses beyond this point should be done in appropriate combination of increased irrigation efficiencies and reduced pollution load in the return flows. However, we should bear in mind that such gains in water use efficiency will eventually reduce the water availability for other uses further downstream.

Table 4
The virtual water content (VWC) of fresh tomatoes per regions in Spain (m^3/t)

Regions	Evaporative VWC			Non-evaporative VWC	Total VWC
	Green VWC	Blue VWC	Total evaporative VWC		
Andalucía	9.5	54.8	64.3	5.8	70.1
Murcia	9.4	40.1	49.5	4.9	54.4
Cataluña	29.6	48.6	78.1	8.3	86.5
Castille La Manche	17.0	57.2	74.2	8.3	82.5
Extremadura	16.9	74.9	91.9	8.3	100.2
Navarra	37.1	24.6	61.7	8.3	70.0
Canary Islands	6.9	89.6	96.6	6.8	103.4
Others	11.1	51.1	62.2	8.3	70.5
National average	13.6	60.5	74.1	7.2	81.3

Table 5
Export of fresh tomatoes from Spain (t/yr)

	2000	2001	2002	2003	2004	Average
Germany	226,059	276,269	247,995	223,559	236,091	241,995
UK	167,984	193,158	181,946	173,719	183,016	179,965
France	163,912	163,370	160,363	159,616	161,867	161,826
The Netherlands	217,840	229,991	2889	189,022	137,273	155,403
EU25	954,337	1,103,296	811,466	967,114	949,801	957,203
World	984,337	1,147,890	854,982	1,015,330	1,003,741	1,001,256

Period: 2000–2004.
Source: PC-TAS (ITC, 2006).

5. Discussion

The methods used here are an improvement on earlier studies, and better account for impacts made through covered production with extended harvesting seasons. The inclusion of local climatic information and adjusted data for covered systems, combined with yields, specific crop lengths and greenhouse efficiencies, improves this global aggregate measure toward a reflection of local impacts. The specific virtual water contents of each region (Table 4) give more detailed information than aggregate water estimations as found in LCA and more relevant information than equivalent EF results. Unlike the emission of gases and their global mixing effect, polluted water is more localised in its impact, while the consequence of having a larger or smaller WF created by an individual or a nation can be felt directly at locations from where those imports originate.

The information a WF generates, however, much like in LCA and EF studies, may not alone tell us the sustainable water limits of any given system. The key information necessary in addition to the WF is that it does not factor in the relative abundance of water at the point of use. Because of the unequal distribution of water and the relative specificity with which water interacts with the environment, global water impacts are not homogeneous. Therefore a thorough comprehension of localised impacts cannot rely on WF alone. Hydrological data determine the specific recharge of areas, but only when combined with VW and WF information can the sustainable limits of systems be more thoroughly estimated and discussed.

Technical solutions to improve a WF could involve buying and sourcing products from regions of higher water abundance or from areas of higher water efficiency. Similarly, sourcing from areas where the WF is made-up with a majority of green water could reduce the need to mobilise water from freshwater bodies. In this sense, the opportunity costs of blue and green water need to be factored in. Green water is considered to have a low opportunity

Table 6
Virtual water import related to the global import of fresh tomatoes from Spain (Mm^3/yr)

	Evaporative virtual water import (Mm^3/yr)			Non-evaporative virtual water import (Mm^3/yr)	Total virtual water import (Mm^3/yr)
	Blue	Green	Total		
Germany	14.6	3.3	17.9	1.7	19.7
France	9.8	2.2	12.0	1.2	13.2
UK	10.9	2.4	13.3	1.3	14.6
The Netherlands	9.4	2.1	11.5	1.1	12.6
EU25	57.9	13.0	70.9	6.9	77.8
World	60.6	13.6	74.2	7.2	81.4

Period: 2000–2004.

cost, as water is used where it falls and is then held in the soil. If transpired through crop production, this water could be considered a 'gift'. If, however, water used in production is blue, then the opportunity costs of the water used are generally higher, because blue water has a number of alternative uses. It also has a supply cost as it has to be mobilised through pipes, pumps, or irrigation equipment before applied to the crop. If a farmer is paying the full and correct price for water, then their choice of crop would need to reflect a higher added-value to cover the costs of using that water. If water is under-priced or not priced at all, a situation which too often exists, then the externalities of trade ought to be accounted for.

A WF could most simply be minimised through a reduction of consumption levels, but perhaps only if consumers and retailers can be appealed to in ways which might help alter consumption patterns. Consumers in today's food economy are largely unaware of the impacts of food production on water resources and the wider environment, yet they are a force with enormous potential for bringing necessary change. The impact on water resources at different levels of production can be useful in attributing levels of responsibility.

Ultimately a WF becomes more or less sustainable if the system on which the water is drawn is from well-managed systems. If water is properly allocated and accounted for and water rights are well administered, then any economic benefits leaving the catchment would be within the limits of the water that is set aside for economic activity. In this sense the relative efficiencies of farms and practices would be incentivised to farmers through the water made available to them by allocation.

Both supermarkets and manufacturers could play a key role in reversing inappropriate water resource management and environmental harm. Businesses can be guided toward practical solutions where water use has exceeded sustainable limits and will have to become more attuned to the benefits of understanding, measuring and improving water impacts beyond their factory door. The great strength of virtual water and WF is making direct links between water abstracted for productive purposes and the products on retailer's shelves. Ironically, it is 'virtual' water that represents a real and quantifiable amount of water which can be measured against for improvement. Future water scarcity and stress implications will eventually force businesses to be far more accountable for the water they rely on, as they seek to diminish their reputational and economic risks.

6. Conclusions

By focusing on specific sites within the wider intensive tomato growing practices of Spain, we can speak more meaningfully about impacts and the necessary changes that might need to occur. However, the areas under tomato production are relatively small, and other irrigated crops such as cereals, olives, vines and fruit trees, cover far larger areas. In terms of larger-scale concerns, it is Mediterranean and Spanish irrigated agriculture in general that needs to be addressed, rather than any single crop. In this paper we have used one product from one area to highlight our methodology. The case of consumption of tomatoes shows us the dependence of global consumers on the scarce local resources of other places.

Water used for producing export commodities significantly contributes to changes in local water systems. The local character of a product's virtual water content must be made more transparent through the supply-chain in order to better understand the impacts of distant consumption on local water resources. This point is missing in both the conceptual framework of EF models and also in the majority of WF studies. EU consumption of fresh tomatoes from Spain shows that both EF and LCA models can be enhanced by considering water as an additional indicator of resource use. Site-specific data add to the usefulness of this indicator. Regional studies show exactly how much water is taken from local water systems, under what conditions, and how much water would be required to counter polluted flows. More importantly, we can see where that water came from in the hydrological cycle, while relating traded products to production sites. WF models are better designed to effectively represent major threats to the world's freshwater ecosystems, especially with regard to water abstraction and water pollution, and should be seen as complimentary to EF and LCA studies.

The information from virtual water, EF, LCA and WF is designed to account for the resources on which consumption and therefore trade depends. If certain trade exacts too heavy a toll on the environment, any balancing act must allow for long-term consideration of the multiple users and uses of a nation's water resource over time. An understanding of water impacts is one criterion among many when making decisions, but is a crucial element in determining how we can adapt to the challenges of facing our growing populations' demand on limited water resources.

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