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The water footprint of olives and olive oil in Spain

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Abstract

This paper evaluates the water footprint of Spanish olives and olive oil over the period 1997-2008. In particular, it analyses the three colour components of the water footprint: green (rainwater stored in the soil), blue (surface and groundwater) and grey (freshwater required to assimilate load of pollutants). Apparent water productivity and virtual water embedded in olive oil exports have also been studied. Results show more than 99.5% of the water footprint of one liter of bottled olive oil is related to the olive production, whereas less than 0.5% is due to the other components such as bottle, cap and label. Over the studied period, the green water footprint in absolute terms of Spanish olive oil production represents about 72% in rainfed systems and just 12% in irrigated olive orchards. Blue and grey water footprints represent 6% and 10% of the national water footprint, respectively. It is shown that olive production is concentrated in regions with the smallest water footprint per unit of product. However, the increase of groundwater consumption in the main olive producing region (Andalusia), from 98 to 378 Mm^3 between 1997 and 2008, has added significant pressure in the upstream Guadalquivir basin. This raises questions about the sustainability of irrigated olive orchards for export from the region. Finally, the virtual water related to olive oil exports illustrate the importance of green water footprint of rainfed olives amounting to about 77% of the total virtual water exports.

Additional key words: apparent water productivity; groundwater; irrigation; sustainability; virtual water trade.

Resumen

La huella hídrica de las aceitunas y aceite de oliva en España

Este artículo evalúa la huella hídrica de las aceitunas y aceite de oliva en España para el período 1997-2008. En concreto, analiza los tres componentes de color de la huella hídrica: verde (lluvia almacenada en el suelo), azul (aguas superficiales y subterráneas) y gris (agua dulce requerida para asimilar una determinada carga de contaminantes). La productividad aparente del aceite de oliva y el agua contenida en las exportaciones de aceite de oliva también han sido estudiadas. Los resultados muestran que más del 99,5% de la huella hídrica de un litro de aceite de oliva embotellado está relacionada con la producción de la aceituna, mientras que menos del 0,5% es a causa de otros componentes (botella, tapón y etiqueta). La huella hídrica verde en términos absolutos de la producción española de aceite de oliva representa un 72% en sistemas de secano y tan sólo 12% en olivares en regadío. Las huellas hídricas azul y gris suponen un 6% y 10% de la huella hídrica nacional, respectivamente. Se muestra que la mayor producción de aceituna se concentra en las regiones con la menor huella hídrica por unidad de producto. Sin embargo, el incremento del riego con aguas subterráneas en Andalucía, de 98 a 378 Mm^3 entre 1997 y 2008, ha añadido una presión significativa a la zona alta de la cuenca del Guadalquivir. Esto pone en debate la sostenibilidad del olivar en regadío para exportaciones desde la región. Finalmente, el agua virtual relacionada con las exportaciones de aceite de oliva indica la importancia de la huella hídrica verde del olivar en secano contando con el 77% del total de agua virtual exportada.

Palabras clave adicionales: agua subterránea; comercio de agua virtual; productividad aparente del agua; riego; sostenibilidad.

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Abbreviations used: AWP (apparent water productivity; ET (evapotranspiration); HDPE (high-density polyethylene); PET (polyethylene terephthalate); PP (polypropylene); WF (water footprint).

Introduction

In a context where water resources are unevenly distributed and, in regions where flood and drought risks are increasing, improved water management is urgently needed in Spain. In this country, about 85% of all water is used to grow food (Garrido *et al.*, 2010). Spain is the largest producer and exporter of olive oil and table olives. In the 2007/2008 agricultural season, 43% of the estimated olive oil world production was produced in Spain, amounting to 1.2 million tones and almost 2 billion euro (MARM, 2010a,b). The Europe Union comprises the first olive oil consumer in the world with 68% of the total. In addition, olive oil is a basic product of the Mediterranean diet and its moderate consumption contributes to a healthy diet (IOC, 2010).

The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution (Hoekstra *et al.*, 2009). The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. The green water footprint refers to consumption of green water resources (rainwater stored in the soil as soil moisture). The grey water footprint is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. Previous to this study, Garrido *et al.* (2010) calculated a total water footprint for crop production (blue and green) in Spain of 27,620 and 23,590 Mm^3 for a humid (1997) and dry (2005) year type, respectively. The green and blue water footprint of olives represented 35% of the total water consumed for crop production in Spain for the period 1997-2006.

Authors have claimed that drought effects can be mitigated and water savings achieved through global virtual trade in water stress regions (Allan, 1999; Chapagain *et al.*, 2006; Hoekstra and Chapagain, 2008). The unequal spatial distribution of global water resources can be compensated by virtual water trading (Islam *et al.*, 2007). Other authors indicate that virtual water trade is a misleading concept, which cannot be used to alleviate water scarcity (Ansink, 2010) and neither to be used alone as a criterion for selecting optimal trading strategies (Wichelns, 2010).

Garrido *et al.* (2010) found that Spain is a net exporter of virtual water embedded in crops, where Andalusia stands out as the largest and most unstable exporter owing mostly to olive oil production. Spain exports high value crops (*e.g.* vegetables and fruits) and imports lower value crops (*e.g.* grain) (*ibid*; Novo *et al.*, 2008). Within their study, Garrido *et al.* (2010) also showed that virtual water imports and exports grew significantly during the period 1997-2006. Most of the exports originate in the Southern and Southeast Regions, which include the most water-stressed basins. Dietzenbacher and Velázquez (2007) also evaluated virtual water trade in the region of Andalusia. Since Andalusia is a net virtual water exporter under semi-arid climatic conditions, questions have been raised about the expansion of irrigated olive orchards in the region. However, to assess the sustainability of the sector's growth, a detailed geographical and temporal analysis of the water use by the different sectors considering the social, economic and environmental aspects is required in the region.

The present study analyses geographically the explicit green, blue and grey water footprints of olives and one litre of olive oil, the apparent water productivities and the related virtual water exports of olive oil over the period 1997-2008 in Spain. The aim of this study is to provide an overview of the three colour components during the supply chain of olive oil, but not to directly be applied on decisions making of future olive oil sustainability, which require studies at local scale considering social, economic and environmental indicators.

Method and data

The green, blue and grey water footprints of olives and 1 litre of bottled olive oil are calculated following and refining the method described by Hoekstra *et al.* (2009). The water footprint is determined for a region (*i.e.* province and country) in absolute terms (volume) and relative terms (volume per unit of product). First, the water footprint of olive orchards is calculated as a whole including both oil and table varieties. Two types of olive production systems are analysed: irrigated *vs.* rainfed. Then, the analysis focuses on the production chain of 1 litre of olive oil, indicating the water consumptive volume along the value chain. Apparent water productivities and virtual water exports calculations are also provided based on Garrido *et al.* (2010).

The water footprint of olive oil includes both a supply chain and an operational part:

$$WF_{product} = WF_{supply\ chain} + WF_{operational} \qquad [1]$$

where $WF_{product}$ = the water footprint of a product; $WF_{supply\ chain}$ = the water footprint of the supply chain; $WF_{operational}$ = the operational water footprint (all of them in Mm^3 or L product^{-1}).

The $WF_{supply\ chain}$ is defined as the amount of freshwater used to produce all the goods and services that form the product inputs at a specific business unit:

$$WF_{supply\ chain} = WF_{supply\ chain\ [ingredients]} + WF_{supply\ chain\ [other\ parts]} \qquad [2]$$

The $WF_{supply\ chain\ [ingredients]}$ refers to the water footprint directly associated to ingredients (*e.g.* olives) and the $WF_{supply\ chain\ [other\ parts]}$ includes the water footprint of other components (*e.g.* bottle, cap, labelling materials and packing materials).

The $WF_{operational}$ is defined as the amount of freshwater used at a specific business unit. The operational water footprint of olive oil includes the water associated to the production of virgin olive oil. Life cycle assessment studies (Avraamides and Fatta, 2008) of olive oil production calculated that the blue water consumed during the olive oil processing stage only accounts for 1.4% of the overall water consumption. In addition, it can be assumed that all wastewater is treated with 100% treatment performance and effluent characteristics of the treated wastewater are within the legal limits. With these assumptions, the operational water footprint for olive oil production is considered to be negligible.

Supply chain water footprint related to the product ingredients

The supply chain water footprint of olives (in Mm^3 or m^3 ton^{-1}) in Spain has been calculated distinguishing the green ($WF_{supply\ chain\ [ingredients]\ green}$), blue ($WF_{supply\ chain\ [ingredients]\ blue}$) and grey water components ($WF_{supply\ chain\ [ingredients]\ grey}$):

$$WF_{supply\ chain\ [ingredients]} = WF_{supply\ chain\ [ingredients]\ green} + WF_{supply\ chain\ [ingredients]\ blue} + WF_{supply\ chain\ [ingredients]\ grey} \qquad [3]$$

Green and blue water footprint of olives

— CROPWAT model configuration

The green and blue water consumption of olives has been estimated as the actual evapotranspiration of olive orchards using the CROPWAT model (FAO, 2009). Two scenarios were distinguished for rainfed and irrigated conditions. Calculations were done by each province and year. For irrigation scenario we did not assume that plant water requirements were met, since this is not practical for olive agricultural practices (see section *CROPWAT scenarios*).

CROPWAT requires soil characteristics, climatic data and crop parameters. The olive orchards area on each soil textural type was obtained for each of the provinces using ArcGIS 9.3 software. The olive orchard cropping pattern is outlined using the Corine Land Cover 2000 (CLC2000) (EEA, 2009) and the Inventory and Characterisation of Irrigated Land in Andalusia 2002 (Regional Government of Andalusia, 2003) (Figure 1). The first layer presents a 1:100,000 scale (Bossard *et al.*, 2000) and the latter is obtained at 1:50,000 scale. CLC2000 illustrates the rainfed and irrigated olive orchards distribution for all provinces, except for the distribution of irrigated olive groves in Andalusia, which is taken from the Inventory. Both layers provide a reliable distribution of this perennial crop and indicate the most probable locations where olive orchards are grown. Nevertheless, both the CLC2000 and the Inventory and Characterisation of Irrigated Land in Andalusia 2002 present some limitations as they have not been updated since their creation. In addition, CLC2000 does not include the six provinces where olive groves have been developed after the year 2000 (Álava, Guipúzcoa, Lugo, Las Palmas, Santa Cruz de Tenerife and Valladolid), but these provinces

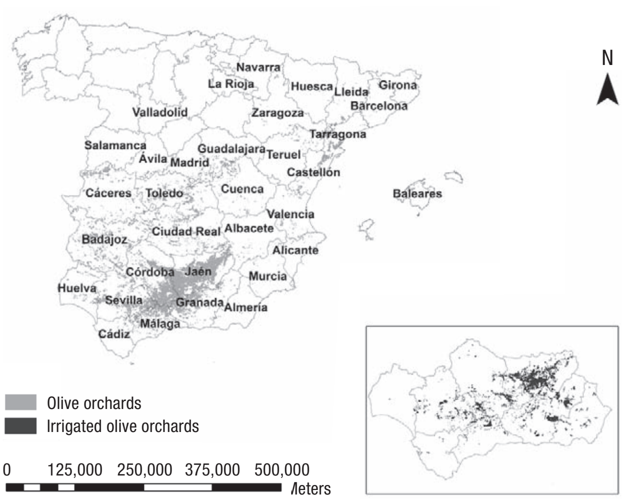

Figure 1. Olive orchards distribution in Spain and irrigated olive orchards distribution in Andalusia. Source: Own elaboration based on EEA (2009) and Regional Government of Andalusia (2003).

comprised only 852 ha in 2008 out of 2,450,447 ha in Spain as a whole (MARM, 2010a).

Soil type data have been taken from European Soil Data Base version V2.0 (EC, 2003) at 1: 1,000,000 scale. Four textural classes were identified: coarse, medium, medium-fine and fine. Reference values of physical soil characteristics depending on its texture are taken from Israelsen and Hansen (1965). The initial soil moisture content of each year is estimated using a ratio between the total available water content to the sum of the precipitation of November and December from the previous year.

Representative meteorological stations located in the major crop-producing regions are selected depending on data availability. Monthly reference evapotranspiration (ET_o) and precipitation for each of the provinces are obtained from the National Meteorological Agency (AEMET, 2010). These databases have been completed with the Integral Service Farmer Advice for the years 2007 and 2008 (MARM, 2010c).

Required crop parameters have been obtained from the literature (Lorite *et al.*, 2004; Orgaz *et al.*, 2005; Allen *et al.*, 2006), making a distinction between rainfed and irrigated olives. Constant tree densities and crown volume are assumed for rainfed (100 trees ha^{-1} and 9,000 m^3 ha^{-1}) and irrigated orchards (200 trees ha^{-1} and 9,000 m^3 ha^{-1}). Root depth is assumed to be 0.6 m, since most of the roots are located at this depth (Connel and Catlin, 1994). Once climate data, crop parameters and dominant soil texture class per province were determined CROPWAT calculations were performed.

— CROPWAT scenarios

Rainfed production is simulated in the model by choosing to apply no irrigation. In the rainfed scenario (indexed with *irr = 0*), the green water evapotranspiration is equal to the actual evapotranspiration as simulated by the model and the blue water evapotranspiration is zero:

$$ET_{green\ ij}(irr=0)=ET_{a\ ij}(irr=0) \quad [4]$$

$$ET_{blue\ ij}(irr=0)=0 \quad [5]$$

where $ET_{green\ ij}$ $(irr = 0)$ = Green water evapotranspiration (mm) in the rainfed scenario in province *i* and year *j*; $ET_{blue\ ij}$ $(irr = 0)$ = Blue water evapotranspiration (mm) in the rainfed scenario in province *i* and year *j*; $ET_{a\ ij}$ $(irr = 0)$ = Actual water evapotranspiration (mm) in the rainfed scenario in province *i* and year *j*.

For the irrigation scenario (*irr = 1*) the irrigation water volume to apply was estimated according to the Guadalquivir river basin situation, since the Guadalquivir basin comprised approximately 88% of the irrigated olive area in Spain in 2004 (AQUAVIR, 2005; MARM, 2010a). For a normal climatic year Guadalquivir basin has a net water allowance of 2,281 m^3 ha^{-1} for olive orchards (CHG, 2007). This water allowance includes transport and distribution losses except for large irrigated areas, which can have their own channel, but they could not be identified in the present study. Reduction of irrigation water according to drought level was incorporated based on indications of the Special Action Plans for Alert and Temporary Drought in the Guadalquivir Basin (*ibid*). To establish the level of drought, the management system "General Regulation" of the Guadalquivir basin was analysed since it included nearly 70% of irrigated water use for agriculture in the Guadalquivir basin (MARM, 2008a). Each year of the period 1997-2008 was classified in relation to the volume of water stored in reservoirs and drought level, which indicates what saving in agricultural water use is required. As a result, estimated water allowances over the period 1997-2008 depend on the drought level and are calculated based on the net water allowance of a normal climatic year when no drought occurs (Table 1).

The CROPWAT irrigation option selected was "irrigation at fixed interval per stage" with "fixed application depth". It was assumed a field efficiency of 0.9 for drip systems (Strosser *et al.*, 2007) since most olives areas in Spain are irrigated with this system. From 2003

Table 1. Estimated water allowances for the period 1997-2008 based on the level of drought

Year	Level of drought	Water saving in agriculture (%)	Estimated water allowances (m^3 ha^{-1})
1997	No drought		2280
1998	No drought		2280
1999	Prealert	5	2170
2000	Alert	30	1600
2001	No drought		2280
2002	No drought		2280
2003	No drought		2280
2004	No drought		2280
2005	Prealert	5	2170
2006	Alert	30	1600
2007	Alert	30	1600
2008	Alert	30	1600

to 2009 drip irrigated systems of olives have grown from 90 to 94% of the total irrigated systems (MARM, 2009). CROPWAT does not provide flexibility to apply variable application depth and frequency of irrigation water. As a result, schedule irrigation depended to some extent to the software capability. In addition, irrigation schedule required to be representative for the whole olive extension, so it was necessary to generalize the irrigation schedule for the entire area. In the end irrigation schedule was determined distributing the whole net water allowance along the irrigation period. Though the frequency and application depth of a same irrigation volume will affect the final green water, since the crop does not meet the water requirements, irrigation losses owing to the designed programme schedule will tend to be minimal.

In order to facilitate calculations with CROPWAT only two irrigation schedules were established based on the estimated net water allowances. The first one applies 2,200 $m^3\,ha^{-1}$ for normal years (years 1997-1998 and 2001-2004) and pre-alert situations (years 1999 and 2005). Depth application is 3 mm one day out of four days between 1st March and 31th October. This period provide 24 mm $month^{-1}$ irrigation water for the mentioned period. The second irrigation schedule applies 1,600 $m^3\,ha^{-1}$ for alert level of drought (years 2000 and 2006-2008). The same application depth of 2 mm is used but irrigation timing is limited to one out of four days, between 1st March-31st May and one out of three days between 1st in June-31th October. Over the first period 16 mm $month^{-1}$ were applied, whereas 20 mm $month^{-1}$ over the second one. The origin of blue water could only be taken into account for provinces of Andalusia based on the Inventories of Irrigated Land in Andalusia (Regional Government of Andalusia, 1999, 2003, 2008; J. Corominas, 2010, pers. comm., 29 June).

Under irrigated conditions the actual evapotranspiration is equal to the actual water use by crop over the growing period. The blue water evapotranspiration refers to the 'total net irrigation' minus irrigation losses. The former includes irrigation losses owing to type of irrigation system; the latter refers to water losses because of no adequate irrigation schedule. The green water evapotranspiration is equal to the actual evapotranspiration minus the blue water evapotranspiration, as simulated in the irrigation scenario:

$$ET_{blue\ ij}(irr=1) = Total\ net\ irrigation - irrigation\ losses \quad [6]$$

$$ET_{green\ ij}(irr=1) = ET_{a\ ij}(irr=i) - ET_{blue\ ij}(irr=1) \quad [7]$$

where $ET_{blue\ ij}(irr = 1)$ = Blue water evapotranspiration (mm) in the irrigated scenario in province i and year j; $ET_{green\ ij}(irr = 1)$ = Green water evapotranspiration (mm) in the irrigated scenario in province i and year j; $ET_{a\ ij}$ = Actual water evapotranspiration (mm) in province i and year j.

The green water footprint of the crop per unit has been estimated as the ratio of the green water consumption to the crop yield. The green water consumption is obtained by summing up separately the green water evapotranspiration over the growing period of rainfed and irrigated systems. The green water footprint in m^3 is calculated multiplying the final green water consumption over the growing period and the crop area. Similar calculations were applied to obtain the blue water footprint per unit and total. The inclusion of water consumption depending on the textural class is a refinement of the method of Hoekstra *et al.* (2009):

$$WF_{green\ jkl}\ (m^3\ ton^{-1}) = \frac{10 \quad \sum\left(ET_{green\ i} * R_i\right)_{jkl}}{Y_{jkl}} \quad [8]$$

$$WF_{green\ jkl}(m^3) = 10 * \sum(ET_{green\ i} * R_i)_{jkl} * A_{jk\,l} \quad [9]$$

$$WF_{blue\ jk}(m^3\ ton^{-1}) = \frac{10 \quad \sum\left(ET_{blue\ i} * R_i\right)_{jk}}{Y_{jk}} \quad [10]$$

$$WF_{blue\ jk}\left(m^3\right) = 10 * \sum(ET_{blue\ i} * R_i)_{jk} * A_{jk} \quad [11]$$

where $WF_{green\ jkl}$ = Green water footprint ($m^3\ ton^{-1}$ or m^3) of the province j, in year k and under production system l; $\sum (ET_{green\ i}*R_i)_{jkl}$ = Green water evapotranspiration (ET_{green} in mm) of province j, in year k and under production system l according to the proportion R of each textural class I; Y_{jkl} = Crop yield (ton ha^{-1}) in province, j in year k and under production system l; A_{jkl} = Crop area (ha) in province j, in year k and under production system l; $WF_{blue\ jk}$ = Blue water footprint ($m^3\ ton^{-1}$ or m^3) of province j, in year k under irrigation conditions; $\sum (ET_{blue\ i}*R_i)_{jk}$ = Blue water evapotranspiration (mm) of province j, in year k under irrigated conditions according to the proportion R of each textural class I; Y_{jk} = Crop yield (ton ha^{-1}) in province j, in year k under irrigated conditions; A_{jk} = Crop area (ha) in province j, in year k under irrigated conditions.

Area and yield data were obtained from the Agricultural Statistics Yearbooks (MARM, 2010a), except for the area of irrigated olive orchards in Andalusia that has been interpolated using the Inventories of Irrigated

Land in Andalusia of 1997, 2002 and 2008 (Regional Government of Andalusia, 1999, 2003, 2008).

Grey water footprint of olives

The 'grey' water footprint of a primary crop is an indicator of the degree of freshwater pollution associated with the production of the crop (Hoekstra *et al.*, 2009). As it is generally the case, the production of olives concerns more than one form of pollution. The grey water footprint has been estimated for nitrogen since it is a very dynamic element which can be the source of surface and ground water pollution caused by leaching (Fernández-Escobar, 2007). The grey water footprint can be expressed as following:

$$WF_{grey\ ijk}(m^3\ ton^{-1}) = \frac{WF_{grey\ ijk}(million\ m^3)*10^{\wedge 6}}{Pr_{ijk}} \quad [12]$$

$$WF_{grey\ ijk}(million\ m^3) = \frac{N_{surp} * A_{ijk} * 10^{-3}}{(C_{max} - C_{nat})} \quad [13]$$

where $WF_{grey\ ijk}$ = grey water footprint (Mm^3 or $m^3\ ton^{-1}$) of province *i*, in year *j* under production system *k; Pr* $_{ijk}$ = crop production (tons) of province *i*, in year *j* under production system *k;* N_{surp} = nitrogen surplus (kg ha^{-1}); C_{max} = the maximum acceptable concentration (50 mg $NO_3\ L^{-1}$); C_{nat} = natural concentration in the receiving water body (mg $NO_3\ L^{-1}$); A_{ijk} = crop area (ha) in province *i*, in year *j* under production system *k*.

Modifications of the method of Hoekstra *et al.* (2009) were made since the grey water footprint is calculated based on nitrogen surplus instead of the chemical application rate per hectare times the leaching fraction. Nitrogen surplus —the difference between nitrogen inputs and outputs in agriculture— can be a good indicator of potential losses to the environment at global, local or farm scale (EC, 2002). Nitrogen balances of 2006 have been used to determine the nitrogen surplus in olive orchards for each province as calculated by the Ministry of the Environment and Rural and Marine Affairs of Spain (MARM, 2008b). Nitrogen surplus is constant throughout the years for each province and does not differentiate between rainfed and irrigated olives. Thus, the nitrogen balance provides an approximate measure of nitrogen surplus for both olive production systems.

An ambient water quality standard of 50 mg $NO_3\ L^{-1}$ of water is used to calculate the water volume necessary to assimilate the load of pollutants following the nitrates and groundwater directives (EC, 1991; 2006). The natural concentration of pollutants in the receiving water body has been assumed negligible.

Supply chain water footprint related to other product components

The water footprint of the supply chain of 1 litre of bottled olive oil is not only made up of ingredients but also of other components that form the final product. Other main components of the product are presented in Table 2. For the calculation of the water footprint related to other components, raw material and process water requirements are taken into account separately.

The water footprint of crop products

The water footprint of crop products (*i.e.* olive oil) is calculated by dividing the water footprint of the input product (*i.e.* olives) by the product fraction (Hoekstra *et al.*, 2009; Garrido *et al.*, 2010). The latter is defined as the quantity of the output product obtained per quantity of raw material. In the present study the product fraction calculation is based on the industrial olive oil yield (Ruiz, 2001), which is known as the olive oil obtained per kilogram of milled olives. We have assumed an olive yield content of 22% for normal climate year according

Table 2. Water footprint of raw material and process water use (in $m^3\ ton^{-1}$) of other product components

Components	Raw material	Weight (g)[1]	Water footprint raw material[2]			Process water use[2]		
			Green	Blue	Grey	Green	Blue	Grey
Bottle – PET[3]	Oil	39	0	10	0	0	0	225
Cap – HDPE[4]	Oil	3	0	10	0	0	0	225
Label – PP[5]	Oil	0.3	0	10	0	0	0	225

[1] Source: Weight estimated for 1 liter bottle from Ercin *et al*. (2009). [2] Source: Van der Leeden *et al*. (1990). [3] PET: polyethylene terephthalate. [4] HDPE: high-density polyethylene. [5] PP: polypropylene.

to Pastor *et al.* (1999) with 50% olive moisture content. A product fraction of 19.6% is obtained.

As a result, the water footprint of 1 litre olive oil can be expressed as follows:

$$WF_{olive\ oil\ ijk} = \underbrace{\left(\frac{WF_{olives\ ijk}}{p_f} \quad d \right)}_{WF_{supply\text{-}chain\ [ingredients]}} + WF_{sup.\ chain\ [other\ parts]} + WF_{operational} \qquad [14]$$

where $WF_{olive\ oil\ ijk}$ = water footprint olive oil (L L^{-1}) in province i, year j and under production system k; $WF_{olives\ ijk}$ = water footprint olives (L kg^{-1}) in province i, year j and under production system k; p_f = product fraction (%); d = density of olive oil (0.918 kg L^{-1}); $WF_{sup.\ chain\ [other\ parts]}$ = water footprint supply chain of other parts (L L^{-1}).

Apparent water productivity (AWP) of olive oil

The concept of apparent water productivity is used to assess the economic efficiency of the water consumed per ton of olive oil produced. Market prices for each province are determined based on the production and price of the three types of virgin olive oil: extra, fine and normal virgin olive oil (MARM, 2010a).

$$AWP_{jkl} = \frac{\sum (Pr_i * P_i)_{jk}}{WF_{jkl}} \qquad [15]$$

where AWP_{jkl} = Apparent water productivity (€ m^{-3}) of province j, in year k and under production system l; $\sum (Pr_i * P_i)_{jk}$ = market price (Pr in € ton^{-1}) of province j, in year k according to the proportion Pr of the type of virgin olive oil production I; WF_{jkl} = water footprint olive oil (m^3 ton^{-1}) of province j, in year k and under production system l.

Virtual water exports of olive oil

The olive oil virtual water exports indicate the water embedded in exports. The green and blue virtual water exports have been analysed as follows:

$$WF_{green\ exp\ ij} = WF_{green\ ij}\ (m^3\ ton^{-1}) * E_{ij} * 10^{-6} \qquad [16]$$

$$WF_{blue\ exp\ ij} = WF_{blue\ ij}\ (m^3\ ton^{-1}) * E_{ij} * 10^{-6} \qquad [17]$$

where $WF_{green\ exp\ ij}$ = Green virtual water exports (Mm^3 $year^{-1}$) of province i in year j; $WF_{blue\ exp\ ij}$ = Blue virtual water exports (Mm^3 $year^{-1}$) of province i in year j; E_{ij} = Exports (ton $year^{-1}$) of province i in year j.

Main olive oil-producing provinces do not match with the major olive oil internationally exporting provinces, because of internal trade within Spain. Virtual water exports of olive oil are based on the production of each province to the national olive oil production in order to take into account where the olive oil production comes from.

Results

Water footprint of olives orchards

For the studied period, Spain shows the following average water footprint: 7,890 Mm^3 green water footprint (rainfed), 1,400 Mm^3 green water footprint (irrigated), 710 Mm^3 blue water footprint and 1,070 Mm^3 grey water footprint. The main factors influencing the water footprint in absolute terms (Mm^3) are crop area, rainfall and irrigation volume.

As shown in Figure 2, in the analysed period there is a clear upward trend of total water footprint. This trend is due to the growth of olive orchards from 2,157,600 ha in 1997 to 2,450,500 ha in 2008, since the volume of precipitation at the end of the period is lower than one in 1997. It is noteworthy to mention than 70% of the olive orchards expansion during the period belong to irrigated olive systems. The green water footprint of rainfed olives is significantly larger than the irrigated one, because the former comprises from 7.4 to 3.5 times the irrigated area, at the beginning and end of the period of study. In the case of the grey water footprint, variations rely uniquely on the area expansion because the same value of nitrogen surplus has been used for each year. There seems to be a correlation between the total annual water footprint and yearly rainfall, but the effective precipitation is higher in rainfed orchards than in irrigated ones. The lowest annual rainfall in 2005 (with 430 mm) is clearly reflected in the decrease of the green water footprint both under rainfed and irrigated conditions. The blue water footprint dropped in 2000 and 2006-2008 owing to the estimated water allowance of 1,600 m^3 ha^{-1} for the mentioned years due to the drought situation prevailing in the Guadalquivir basin.

Within the study period Andalusia comprises 87% of the national blue water footprint of olive production in Spain, with a blue water footprint of 761 Mm^3 in 2008. However, only 13% of national blue water footprint of

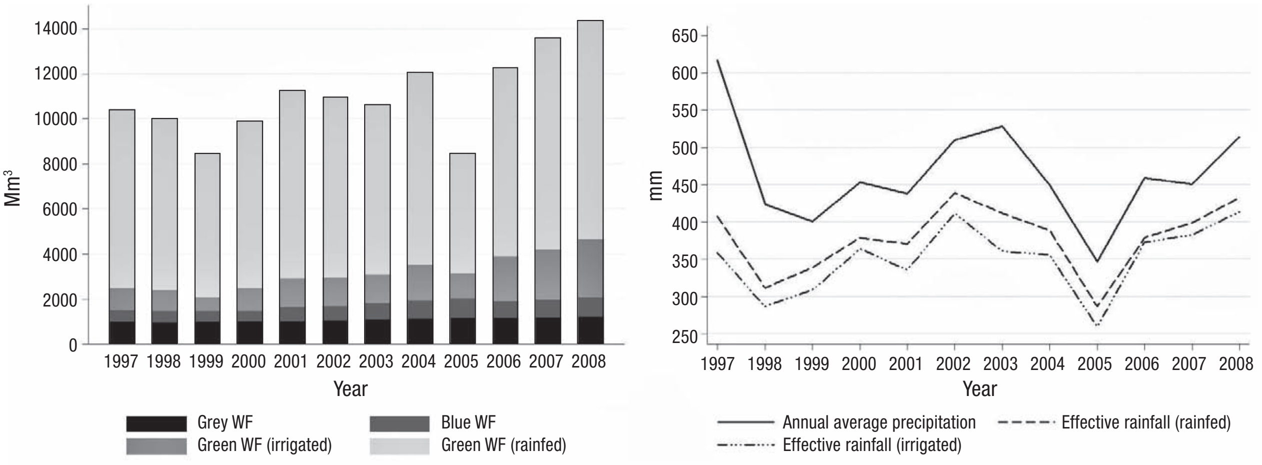

Figure 2. Total green, blue and grey water footprint of olive production in Spain in Mm^3 (left) and annual average rainfall and effective rainfall in mm (right) for the period 1997-2008.

olives was allocated to olive table production in that year. Seville is by far the most important table olives producing province, consuming 82 Mm^3 of blue water, 64% of the blue water footprint of olive production within the province. Surface water irrigation for olive orchards decreased in Andalusia from 66 to 43% in relation to the national blue water footprint over the study period. In contrast, groundwater resources have been increasingly consumed from 19 to 43%, growing groundwater abstractions from 106 Mm^3 (1997) to 378 Mm^3 (2008). Jaén is the first blue water consumer in Andalusia, and also in Spain with 401 Mm^3 in 2008, of which 99% belongs to olives for olive oil production. Between 1997 and 2008 surface water consumption moderately decreased and groundwater resources consumption more than doubled in the province (Figure 3). As a matter of fact, in 2008 most provinces increased groundwater consumption for olive production with the exception of Almería.

The water footprint in m^3 ton^{-1} is an indicator of the crop's blue and green water efficiency per unit of crop produced. In addition the grey water footprint in relative terms illustrate the estimated volume of water contaminated by nitrates per unit of crop produced, which can indicate the nitrate pollution potential. Higher crop water efficiency and less nitrates pollution potential are associated with lower footprints. For the

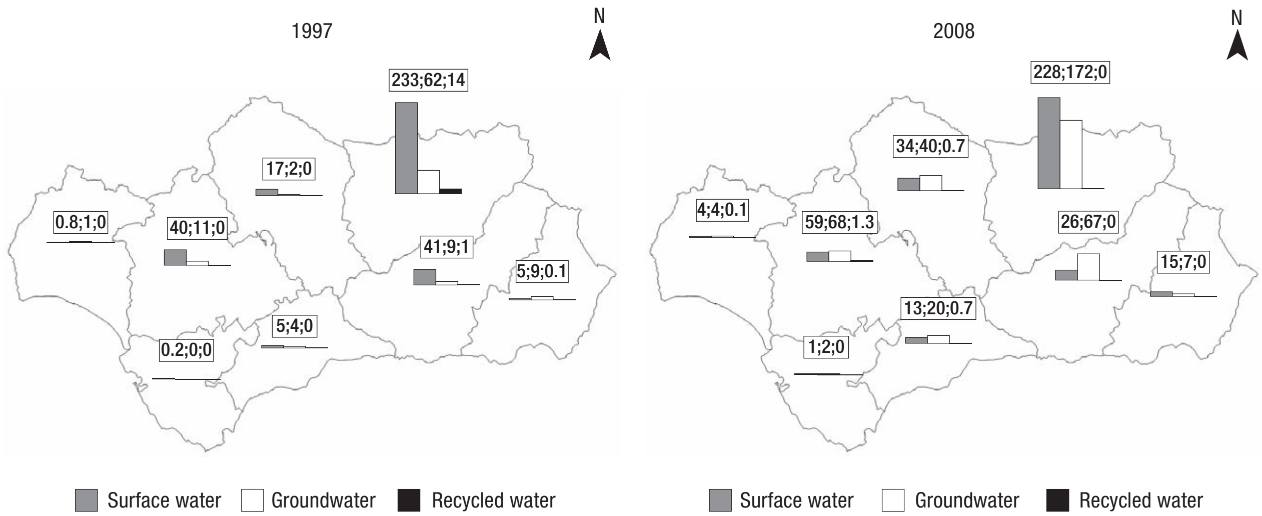

Figure 3. Origin of blue water footprint: surface, groundwater and recycled in Mm^3 for 1997 (left) and 2008 (right) in Andalusia. Source: Own elaboration based on the Inventory and Characterisation of Irrigated Land in Andalusia of 1997, 2002 and 2008 (Regional Government of Andalusia, 1999, 2003, 2008).

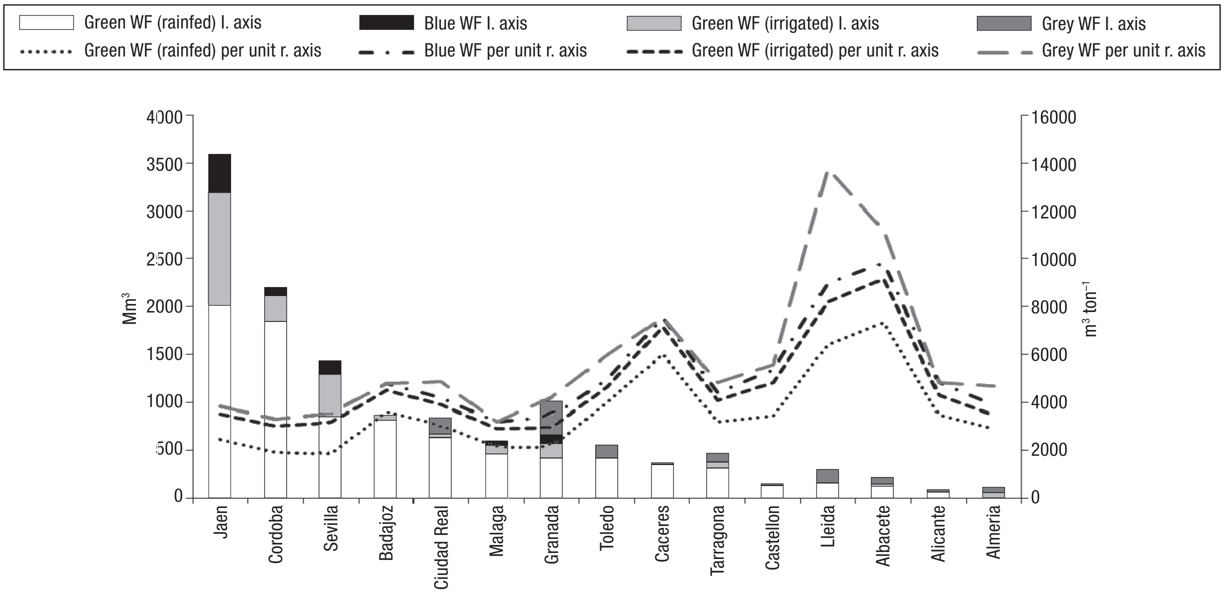

Figure 4. Green, blue and grey water footprint in Mm^3 and m^3 ton^{-1} of the main Spanish olive producing provinces in 2001.

studied period, Spain presents the following average water footprint per unit: 1,971 m^3 ton^{-1} green water footprint (rainfed), 856 m^3 ton^{-1} green water footprint (irrigated), 408 m^3 ton^{-1} blue water footprint and 190 m^3 ton^{-1} grey water footprint.

Figure 4 compares the total water footprint and the water footprint per unit of crop for the main olive producing provinces for an average rainfall year (2001). Only provinces that comprise ≥1% of the national olive production in 2001 are illustrated. In 2001, Jaén, Córdoba and Seville jointly represent 69% of the national olive production and 52 % of the national water footprint of olive production with 3,199; 1,457 and 874 Mm^3 respectively. While their total water footprints in Mm^3 are the largest, they are very efficient in terms of green and blue water use (m^3 ton^{-1}). Based on the nitrogen balances, olive production in Jaén, Córdoba and Seville does not generate any grey water footprint. In absolute terms Granada presents the largest grey water footprint with 273 Mm^3. However, the provinces showing the highest nitrogen pollution per ton of crop produced are minor olive producers such as Lleida, Albacete and Toledo.

Water footprint of olive oil

The water footprint of olive oil includes the sum of the water footprint of the ingredients and other components, that is to say, the supply chain water footprint. The water footprint related to other components for olive oil production does not represent more than 0.5% of the total supply chain for each year and province of study. In conclusion, most of the water used (consumed and polluted) to produce olive oil can be directly associated to olive production in the field. Table 3 presents the water footprint of olive oil in Mm^3 during the period of study. In colour terms, the components of the water footprint can be summarised as follows: 72% green water footprint from rainfed systems, 12% green water footprint from irrigated ones, 6% blue water footprint and 10% grey water footprint.

Spain has the following annual ranges of the water footprint per liter of olive oil produced: 8,250-13,470 L L^{-1} green water footprint (rainfed); 2,770-4,640 L L^{-1} green water footprint (irrigated); 1,410-2,760 L L^{-1} blue water footprint (irrigated); and 710-1,510 L L^{-1} grey water footprint (rainfed & irrigated). These ranges are weighted averages according to the share of each province to the national production. The blue water footprint of other components in rainfed olives has a negligible value of 0.4 L L^{-1}.

The water footprint in L L^{-1} is summarized for four typical olive oil producing provinces in Spain (Figure 5). In this figure the blue and grey water footprints of other components are not included in their respective colour components. The greater variation of the green water footprint in L L^{-1} of rainfed olives over the study pe-

Table 3. National water footprint of olive oil in Mm^3 during the period of study

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Ingredients												
Green WF (R)	7560	7207	5942	6903	7824	7535	7092	8016	5046	7836	8852	9119
Green WF (I)	909	851	553	905	1175	1140	1133	1395	992	1722	1929	2204
Blue WF (I)	470	463	404	413	574	596	652	712	788	651	703	770
Grey WF (R & I)	967	943	978	993	1010	1024	1078	1115	1130	1151	1159	1207
Other components												
Blue WF (R)	0.4	0.3	0.2	0.3	0.5	0.3	0.5	0.3	0.2	0.3	0.4	0.3
Blue WF (I)	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2
Grey WF (R)	9.7	6.6	4.8	7.7	10.5	6.1	10.7	7	5.2	7.6	8.3	7.6
Grey WF (I)	2.1	1.9	1.4	2.2	2.9	2.3	3.9	3	2.7	4.1	4.7	4.6
Total	9918	9473	7883	9225	10597	10305	9970	11248	7964	11373	12657	13313

R: rainfed. I: irrigated.

riod is remarkable, ranging from 4100 L L^{-1} in Cordoba in 2003 up to 29760 L L^{-1} in Toledo in 2004. This large variation of the water footprint in rainfed olive oil also occurs for the total of the provinces, as shown in Table 4. Among provinces with rainfed olive oil, Jaén and Córdoba are more efficient in terms of water consumption than Badajoz and Toledo. The green water footprint of olive oil produced from irrigated orchards exhibits less variation, with a minimum of 1,861 (Badajoz in 2005) and a maximum of 8,688 L L^{-1} (Toledo in 2004), probably because crop production is not so strongly affected by rainfall. From the selected provinces, Toledo is the only one that presents a grey water footprint ranging from 2,573 in 1997 to 7,484 L L^{-1}.

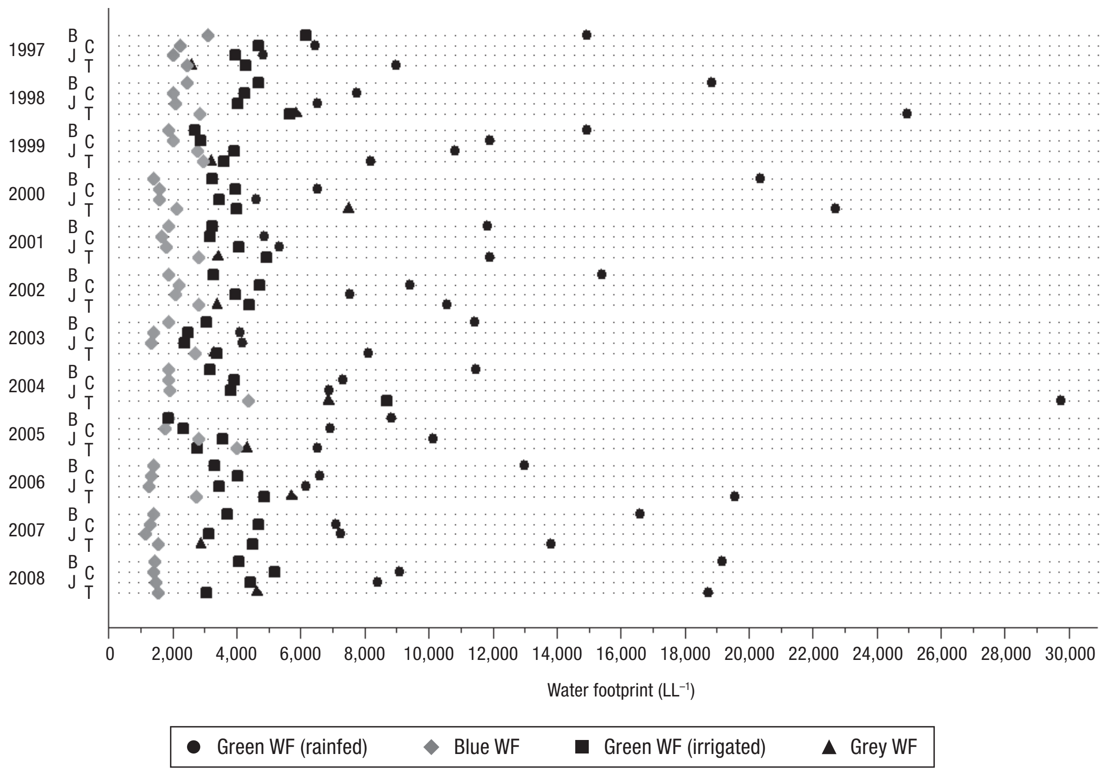

Figure 5. The water footprint of olive oil in L L^{-1} for four typical producing provinces. Provinces are coded as follow: B = Badajoz, C = Córdoba, J = Jaén and T = Toledo.

Table 4. Weighted average water footprint in L L^{-1}, according to the share of each province to the national production, and standard deviation (SD) of total water footprint (green + blue + grey components) for rainfed and irrigated olive oil.

Year	Total WF rainfed ($L\ L^{-1}$)		Total WF irrigated ($L\ L^{-1}$)	
	Mean	SD	Mean	SD
1997	8253	36467	6730	7331
1998	11711	56243	6845	10253
1999	13468	49429	7338	6198
2000	9661	69656	6219	10804
2001	7881	74503	6234	5903
2002	13064	91961	7651	59839
2003	7129	52331	4751	20973
2004	12144	26204	7133	9810
2005	10937	29474	6862	11193
2006	10985	17937	5939	5151
2007	11273	30293	5742	5548
2008	12702	20636	6690	6248

Apparent water productivity of olive oil

To analyze the AWP (€ m^{-3}) of olive oil two typical producing provinces, Jaén and Toledo, were compared (Figure 6). The AWP seems to be inversely related to the water footprint per unit of olive oil and varies in a similar way over the period in both production systems, due to the variation of olive oil market prices. Nevertheless, the frequent variations from year to year of the green water footprint under rainfed conditions cause a staggered AWP trend. In rainfed systems the AWP of olive oil ranges from 0.20 to 0.62 € m^{-3} in Jaén and from 0.07 to 0.36 € m^{-3} in Toledo. The AWP of irrigated systems has a relatively stable trend between 1997 and 2005 with values below 2.4 and 1.7 € m^{-3} in Jaén and Toledo respectively. The peaks of AWPs in 2006 and 2007 are related to highest olive oil prices of 4,119 (2006) and 4,868 (2007) € ton^{-1} in Jaén and 5,525 (2006) and 5,436 (2007) € ton^{-1} in Toledo. Greater olive oil prices in Toledo are caused by its relatively larger production of virgin olive oil of premium quality.

Virtual water exports of olive oil

According to the information from the Olive Oil Agency (OOA, 2010) exports comprise 55% of the total

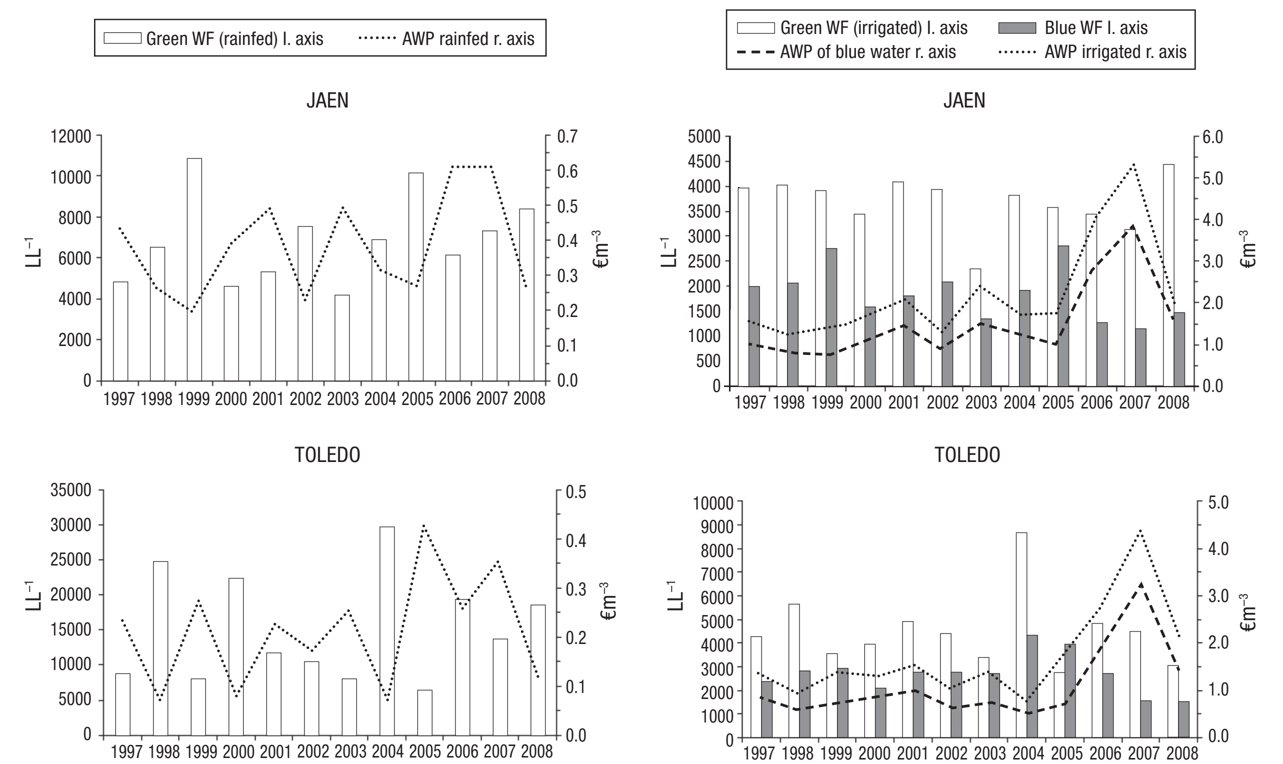

Figure 6. Olive oil water footprint and apparent water productivities for rainfed (left) and irrigated (right) production systems in Jaén (top) and Toledo (bottom) over the period 1997-2008.

national olive oil production between 2005/2006 and 2007/2008 agricultural seasons. Differences between production and exports of olive oil are based on the final stocks of each agricultural season. For instance, in 2002 olive oil production was not significantly large but final stocks of the olive oil produced in 2001 were exported. Then the fall of olive oil production in 2002 is reflected in the decline of exports in the following year (Figure 7).

As shown in Figure 7 the green water is the main component in most virtual water exports, amounting to 79% of the total virtual water exports between 1997 and 2008. Differences among years are very significant, green water being the most unstable component and closely dependent on precipitation. Note that blue virtual water exports are much more stable. Rainfed olives therefore have an important role in virtual water exports, even if both the area of irrigated olive trees and the related blue water component have increased during the period of study.

Discussion

For the studied period Spain has an average national water footprint, without including the grey component, of 9,960 Mm^3 which is in contrast to that estimated by Garrido *et al.* (2010) of approximately 2,800 Mm^3. In the present study the green water footprint is larger since soil is taken into account applying a soil water balance. In addition, we have not assumed that water requirements are met, which reduces the blue water evapotranspiration. The green component of the rainfed olives constitutes the largest proportion of the water footprint of olive orchards due to the greater harvested area of this production system. In addition, according to our CROPWAT results effective rainfall is higher in rainfed orchards than in irrigated ones since the irrigation water application lowers the green water evaporated.

In our study has been estimated that in 2008 Andalusia consumed 761 Mm^3 of blue water resources which comprises the 86% of the national blue water footprint of olive production in Spain. Groundwater abstractions have grown from 98 Mm^3 in 1997 to 378 Mm^3 in 2008 in Andalusia. In any case, improvements on the blue water consumption of olives can be achieved since the estimated water allowances of olives vary among systems of exploitation and also depending on regulated, un-regulated and groundwater sources. Moreover, the scale of our study does not enable to take into account farmers' decisions that consider the precipitation during irrigation management, assuming that rainfall is sufficient and reducing their irrigation schedules (García-Vila *et al.*, 2008).

On the other hand, the water footprint per unit of fruit produced can illustrate the efficiency of water consumption in relation to crop production. In our study the water footprint per unit of rainfed olive orchards (green) is usually higher (about 1,971 m^3 ton^{-1}) than the irrigated one (green plus blue) (around 1,264 m^3 ton^{-1}) due to lower crop yields. In rainfed olive trees, the rainfall and temperature patterns contribute to the fruit production, whereas irrigated olive orchard pro-

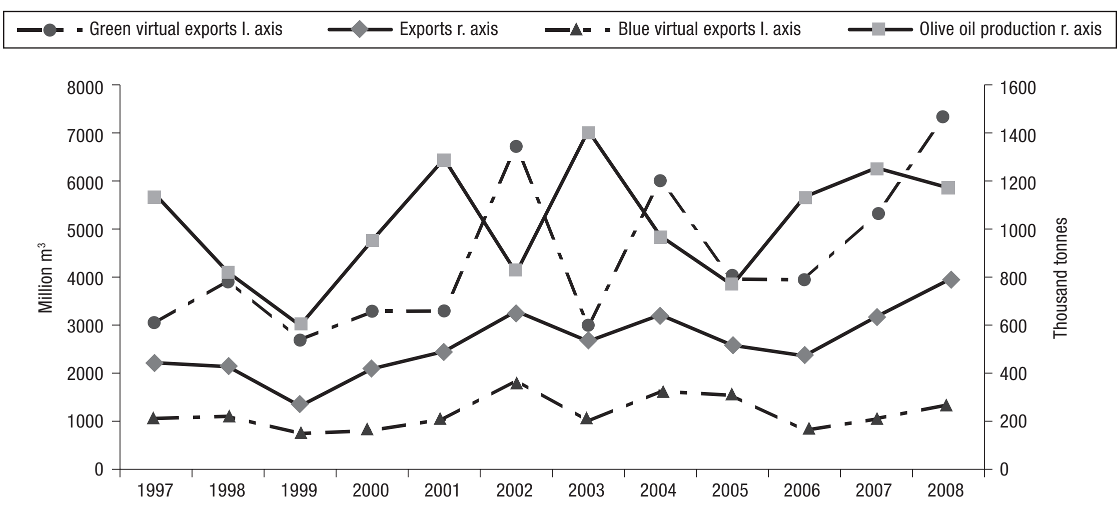

Figure 7. Green and blue virtual water exports (in Mm^3), exports (million tons), and olive oil production (million tons) over the period 1997-2008.

duction depends mainly on temperature since water stress is usually avoided by the irrigation water supply (Lavee, 2007). Despite the fact that rainfed olive systems depends only on precipitation, low yields per hectare of rainfed olives seem to point to a transition towards more productive olive orchards. However, problems related to diversity losses and environmental pressures arise with more intensive agricultural systems of olive orchards (MARM, 2007; Scheidel and Krausmann, 2011) and rainfed olive production does not use scarce blue water resources.

Aldaya and Llamas (2009) estimated the green and blue water footprint per unit of olive trees in the Guadiana river basin. In line with their study, in 2001 the green water footprint has a value of 600 m^3 ton^{-1} and 210 m^3 ton^{-1} for rainfed and irrigated systems respectively, and a value of 750 m^3 ton^{-1} of blue water footprint in the Middle Guadiana basin, which contains Badajoz and Caceres provinces. The present study shows under rainfed conditions significantly greater green water footprints (2,280 and 3,500 m^3 ton^{-1} for Badajoz and Cáceres). Irrigated systems indicate higher green water footprints (700 and 900 m^3 ton^{-1} for Badajoz and Cáceres) and lower blue water footprints (430 and 540 m^3 ton^{-1} for Badajoz and Cáceres) in 2001, in spite of using the same crop yields in both studies. These differences in the results could be due to methodological improvements: the present study takes into account different soil textures and does not assume optimal irrigation conditions. In any case, we should also bear in mind that the scale of our study is larger than in the case of Aldaya and Llamas (2009), which could lead to greater dispersion of the results.

The lion's share of the water footprint of one liter of bottled olive oil is in the supply chain, and in particular in the olive production process. In fact the water footprint of the supply chain of other components (bottle, cap and label) comprises less than 0.5% of the product's water footprint; which is in line with previous studies (Ercin *et al.*, 2009). Over the studied period Spanish olive oil production presents the following average percentage of components of water footprints: 72% green water footprint from rainfed systems, 12% green water footprint from irrigated ones, 6% blue water footprint and 10% grey water footprint.

The variability of the water footprint of olive oil per unit among provinces depends mainly on the type of production system and year, being the supply chain water footprint of the olives key to improve water management. The value of 15,831 m^3 ton^{-1} provided in Chapagain and Hoesktra (2004) during the period 1997-2001for virgin olive oil in Spain, which is equivalent to 14,533 L L^{-1}, is significantly larger than those obtained in this study, particularly in irrigated conditions. This is probably due to the fact that they assumed that the crop water requirements are met in olives trees.

To establish the crop coefficients, we have assumed constant tree densities and crown volumes for rainfed and irrigated systems. Outlier values of green water footprint of rainfed olive oil such as in Toledo, which reaches 29,760 L L^{-1} in 2004, are mainly caused by very low crop yields. However, rainfed olive trees in Toledo probably present lower tree densities than the assumed 100 trees ha^{-1}. The water evaporation differs depending on the olive crown volumes and planting pattern. More accurate values could be obtained using site-specific crop parameters.

Based on the grey water footprint results, the main olive oil producing provinces do not seem to represent significant sources of nitrate pollution with the exception of Granada. For instance, within the Guadalquivir basin, the Guadajoz and Jaen catchments show the lowest nitrogen surplus per hectare in basin due to olive orchards land use (Berbel and Gutiérrez, 2004). Jaén, the first olive oil producing province in Spain, presents a negative nitrogen balance (MARM, 2008b), suggesting that applications (mostly as mineral and organic fertilization) do not compensate the losses. In practice, nitrogen inputs of irrigated olives are nearly three times higher than rainfed ones (IDAE, 2007). Consequently, a nitrogen balance that differentiates between these two olive production systems would yield more accurate evaluations of the grey water footprint. Further research of grey water footprint also needs to focus both on spatial and temporal variation of pollutants since higher concentrations of nitrates in water bodies would be expected after fertilization application followed by rainfall gages (Rodríguez-Liziana *et al.*, 2005) and in the dry season than in the wet one (Angelopoulos *et al.*, 2009).

AWPs under rainfed conditions fluctuate in a greater extent than under irrigated ones because of their large crop yield variations from year to year. To assess the economic performance of a product, both the water footprint and market price variations, as occurred in years 2006 and 2007, are relevant.

Finally, the olive oil virtual water exports vary across years, and mostly depend on the green water, which denotes the importance of the green water in the virtual water trade, as reported in previous studies

(Aldaya *et al.*, 2010). Only 23% of virtual water exports of olive oil correspond to irrigation water. Andalusia is the largest blue water consuming Spanish region for olive production and 2008 groundwater resources reached a value of 42% of the national blue water consumption for olive production. The increasing groundwater use is in a way related to the blue virtual water exports of olive oil. Consequently, if the blue virtual water exports related to olive oil tend to grow in the following years, the Guadalquivir basin may face further water stress, particularly from groundwater resources. In an irrigated district of Córdoba 18% of farmers consider olive trees as an alternative to current cropping patterns (García-Vila *et al.*, 2008). As a result, further development of this crop in irrigated systems may be expected in the coming years.

In our study the water footprint of olive oil has been estimated taking into account variables such as soil type, production system and variation over the time of climate conditions and water allowances. It is not possible to provide a unique value in relative terms of water footprint for olives and consequently for olive oil in Spain since there are widely different production systems, productivity levels and irrigation management. All these aspects can be put into context with further local olive production studies.

Evaluations change significantly from year to year because most production is obtained in rainfed systems whose production depends on a greater extent on precipitation, than irrigated system does.

The operational water footprint of the product has been considered negligible. As a result, the supply chain water footprint comprises the total water footprint of the olive oil. More than 99.5% of the water footprint of the supply chain of one litre of olive oil takes place during the olive growing process. In contrast, only less than 0.5% of the supply chain water footprint is related to other, mainly to the plastic based bottle, cap and label production. The results of this study confirm the importance of a detailed water footprint supply chain assessment of ingredients in the case of agriculture based products.

The average water footprints of olive oil ranges in Spain are: 8,250-13,470 L L^{-1} green water footprint (rainfed), 2,770-4,640 L L^{-1} green water footprint (irrigated), 1,410-2,760 L L^{-1} blue water footprint (irrigated) and 710-1,510 L L^{-1} grey water footprint. The different components of the total water footprint in Mm^3 in the study period are as follows: 72% green water footprint from rainfed systems, 12% green water footprint from irrigated ones, 6% blue water footprint and 10% grey water footprint.

Virtual water exports of olive oil vary across years, and are mainly related to the green water footprints. Only 23% of virtual water exports originate from surface and groundwater blue resources. However, recent trends in the Guadalquivir basin (provinces of Jaén, Córdoba and Granada) indicate alarming growth in groundwater use, most of it used by olive growers. Our results suggest that virtual groundwater exports related to olive oil exports may add further pressure to the already stressed basin.

Finally, there are other factors such as plantation density of trees, volume of crown and volume and timing of irrigation water that could not be taken into account in the present analysis. Further studies at local scale considering these elements could make improvements in this area. In addition, further assessment of the economic, social and environmental aspects related to the olive oil water footprint could provide additional information for decision-making.

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