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Articles

Water footprint of onion (*Allium cepa* L.) and husk tomato (*Physalis ixocarpa* Brot.) crops in the region of Atlixco, Puebla, Mexico

Huella hídrica de los cultivos de cebolla (*Allium cepa* L.) y tomate de cáscara (*Physalis ixocarpa* Brot.) en la región de Atlixco, Puebla, México

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Abstract

The production of vegetables and flowers under irrigation in the region of Atlixco, Puebla, requires large quantities of water. An indicator of these water requirements is found in their water footprint. This study aimed to estimate the water footprint of husk or green tomato (*Physalis ixocarpa* Brot.) and onion (*Allium cepa* L.) crops in the region. The water footprint for onion in spring-summer (SP-SU) and autumn-winter (A-W) and husk tomato crops for the A-W cycle were estimated for the year of 2017. Green and blue Water Footprints were calculated from evapotranspiration estimated using the CROPWAT version 8 program; together with climate and yield information, management practices and crop development inferred from interviews with regional producers. The gray water footprint was estimated based on the use of nitrogen and phosphoric fertilizers. The water footprint of the (SP-SU) onion crop was greater than that of the (A-W) onion and (A-W) husk tomato, which can be explained considering seasonal climatic changes and yields. It was concluded that onion and tomato crops result in a high level of water consumption in the region, as the water incorporated into their production processes in 2017 was 4 876 710.3 m^3, which represents 5.2% of the water allocated to total water consumption and 6.8% of the water allocated to agriculture in the region.

Keywords: Atlixco, water footprint, onion, husk tomato.

Resumen

La producción de hortalizas y flores bajo riego en la región de Atlixco, Puebla, demanda altas cantidades de agua; un indicador es su huella hídrica. El objetivo de este estudio fue estimar la huella hídrica de los cultivos de tomate de cáscara, tomatillo o tomate verde (*Physalis ixocarpa* Brot.) y cebolla (*Allium cepa* L.) en la región. Se estimó la huella hídrica de cebolla de primavera-verano (P-V) y otoño-invierno (O-I), y de tomate de cáscara para el ciclo O-I para el año 2017. Las huellas hídricas verde y azul se calcularon con la evapotranspiración estimada con el programa *CROPWAT* versión 8, con información climática e información de rendimiento, prácticas de manejo y desarrollo de los cultivos obtenidos en una encuesta a productores de la región. La huella hídrica gris se estimó con base en el uso de fertilizantes nitrogenados y fosfóricos. La huella hídrica del cultivo de cebolla de P-V fue mayor que la de cebolla de O-I y del tomate de cáscara de O-I, lo que se explica por los cambios climáticos estacionales y los rendimientos. Se concluyó que los cultivos de cebolla y tomate de cáscara tienen un uso consuntivo de agua alto en la región, ya que el agua incorporada en sus procesos de producción en 2017 fue de 4 876 710.3 m^3, lo que representa 5.2% del agua concesionada para todos los usos consuntivos de agua y 6.8% del agua concesionada para la agricultura en la región.

Palabras clave: Atlixco, huella hídrica, cebolla, tomate de cáscara.

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Introduction

Water is a natural resource that suffers from high demand, due to domestic requirements and for the production of various goods and services in different economic sectors. There is a tendency towards increased competition for water resources, particularly between agricultural activities and domestic and industrial uses (Meinzen-Dick & Appasamy, 2002). In government public policy, the priority in water management focuses on human supply, particularly in large cities. Population growth and industrial developments, coupled with the impacts of climate change accentuate the problem of water shortages for the urban population (McDonald *et al*., 2011). In contrast, agriculture is seen as a user that hinders supply to large cities, because it is the sector that demands the most water worldwide, as it uses approximately 80% to 90% of world water consumption (Shiklomanov, 2000; Morison, Baker, Mullineaux, & Davies, 2008). The solution is not to stop allocating water to agriculture, as this fulfills the function of providing food and raw materials. Greater efficiency is required in the use of water for irrigation, in order to generate transferable surpluses for other economic uses or ecological purposes (Chukalla, Krol, & Hoekstra, 2015).

It is important to identify water indicators of demand for crop irrigation and efficiency in water use for the planning and management of water in a river basin. A common parameter related to the demand for water resources in a basin consists of consumptive use, which refers to water that after its use is no longer available for other purposes, because it evaporates or is lost in the production process (Perry, 2007). According to Burman and Pochop (1994), the term consumptive use originated in the Western United States and includes evapotranspiration by crops and the water necessary for the formation of plant tissue. Because consumptive use does not take into account all water used in the production process of a good or service, other indicators that are applicable at local, regional, national and international levels have been proposed. Among these indicators, one of the most current and recently applied is the water footprint (WF) (Vanham & Bidoglio, 2013).

The water footprint has been proposed as an indicator of the sustainability of the water resource (Pellicer-Martínez & Martínez-Paz, 2016). It makes it possible to identify the cause-effect relationships at a socio-environmental level and the impacts on the water resource, by referring to the consumption habits of population groups. The water footprint refers to the use of water and must be compared with availability. This is useful for a more general comparison and evaluation, leading to improved planning and better use of water resources, especially in regions where competition is high.

The general concept of footprint refers to a quantitative measure that describes the human appropriation of natural resources (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011). A footprint describes how, in relation to human activities, an impact or burden on global sustainability is generated (Valdivia, Ugaya, & Hildenbrand, 2013). In particular, the water footprint of a product is defined as the total volume of fresh water that is used directly or indirectly for its production. It can be applied at different scales, from the level of a plot of land to countries or regions, to compare water footprints of products or to plan reduction in water consumption (Mekonnen & Hoekstra, 2014). The water footprint of a geographically delimited area (province, nation, catchment area, basin), is equal to the sum of the water footprints of all the processes that are carried out in that specific area (Hoekstra *et al*., 2011).

To quantify the water footprint, the volume of fresh and contaminated fresh water is assessed throughout the supply chain, in terms of an analysis of the life cycle. This can be calculated for a product or a process related to either agriculture, industry or the service sector. The water footprint has three components: the blue water footprint (blue water), the green water footprint (green water) and the gray water footprint (gray water).

The blue water footprint refers to the volume of surface and groundwater consumed (evaporated) as a result of producing a commodity. The green water footprint refers to the consumption of rainwater that has not been converted into surface runoff or groundwater. The gray water footprint of a product refers to the volume of fresh water that is required to dilute the pollutant load according to concentrations in the natural environment and the maximum permissible limits by law (Hoekstra *et al*., 2011). In relation to the gray water footprint, nitrogen (N) and phosphorus (P) are essential minerals for life and in agriculture they are essential for production (Sutton *et al*., 2013). However, excessive use of fertilizers has also increased the amount of N and P going into natural ecosystems (Bennet, Carpenter, & Caraco, 2001; Vitousek *et al*., 2009). All this has caused a loss of nutrients in farmland and consequent environmental problems, such as alteration in water quality, pollution of groundwater, loss of biodiversity and eutrophication (Obersteiner, Penuelas, Ciais, Van der Velde, & Janssens, 2013). Therefore, there is a need to evaluate these impacts on the quantity and quality of water.

An estimate of the water footprint for irrigated areas of the country is useful to assess the rationality of agricultural production in a basin or region (Sadras, Grassini, & Steduto, 2011) and compare this to the availability of the water resource. The water footprint must be estimated by crop and production cycle for each basin, where irrigated agriculture demands significant amounts of water and competes with other sectoral uses. In the state of Puebla, the Atlixco region has the previously mentioned characteristics, as it represents an area of horticultural and flower production directed towards the national and international market, uses underground and surface water and faces competition for water resources, used in domestic, industrial and service contexts.

The aim of this study was to compare the water footprint of the husk tomato and onion crops, produced under irrigation during the spring-summer and autumn-winter cycles in the Atlixco region, Puebla, as well as to compare this with the reported water footprint for these crops in other locations. This study area was selected because of the strong competition between water uses, particularly concerning agricultural activity, where the production of vegetables and flowers predominates. For each of the two crops, the components of the water footprint were quantified: green footprint, blue footprint and gray footprint. The estimate for evapotranspiration to calculate the green and blue water footprints was made using the CROPWAT version 8.0 software designed by FAO. The results from this study provide a contribution to the regional analysis of the water resource and for comparing water use efficiency of the crops studied, with that of other crops in the region.

Materials and methods

Study area

The study was carried out in the area of irrigated annual crop agriculture in the municipalities of Atlixco and Huaquechula, in the Huaquechula sub-basin (Figure 1). The area is located on the Atlixco - Izúcar de Matamoros aquifer, which mostly underlies Phaoezem, Leptosol and Planosol soils. The climate is semi-dry, with summer rains and an average annual temperature of 14 °C to 19 °C (Conagua, 2016).

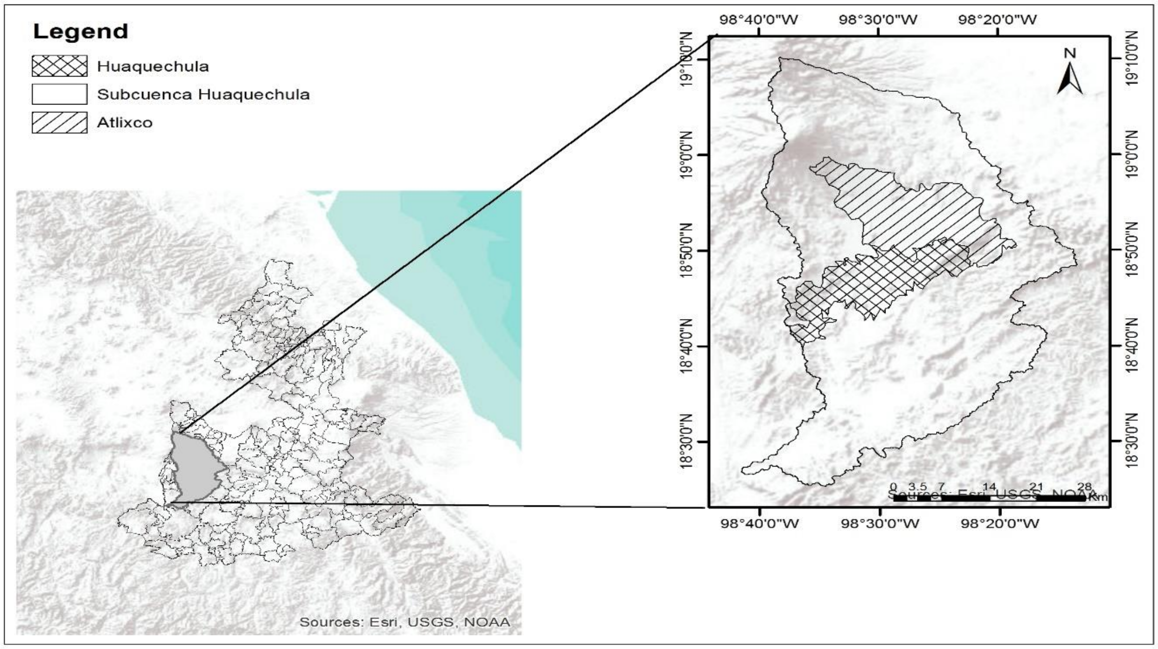

Figure 1. Location of study area.

Estimate of water footprint

We estimated the water footprint for husk tomato and onion crops. Firstly, the autumn-winter cycle was considered, because its production is mostly during this period. The spring-summer and autumn-winter cycle was estimated for the onion crop. In the agricultural year of 2017, 234.3

hectares of onion were sown for the spring-summer cycle; for the autumn-winter cycle, 460 hectares of onion and 290 hectares of husk tomato were sown (SIAP, 2017). The water footprint was estimated using the method proposed by Hoekstra *et al*. (2011):

$$WF = WF_{\text{green}} + WF_{\text{blue}} + WF_{\text{gray}} \tag{1}$$

Where *WF* is the total water footprint of the crop, WF_{green} the green water footprint, WF_{blue} the blue water footprint and WF_{gray} the gray water footprint, all in m^3 t^{-1}.

The green water footprint was estimated as:

$$WF_{green} = \frac{CWU_{green}}{Y} \tag{2}$$

$$CWU_{green} = 10\ x \sum_{d=1}^{lgp} ET_{c\ green} \tag{3}$$

$$ET_{c\,\text{green}} = Kc \cdot ET_o \tag{4}$$

Where CWU_{green}, Crop Water Use, represents use of water for cultivation that is associated with precipitation in m^3 hectare^{-1}; Y represents the crop yield, in t hectare^{-1}; $ET_{c\ \text{green}}$ represents the evapotranspiration on the part of the crop associated with effective precipitation; ET_o is the evapotranspiration reference; K_c is a coefficient associated with crop growth; $\sum$ represents the crop growth cycle, from planting (day 1) to harvest (lgp), and 10 is a unit conversion factor.

The blue water footprint was estimated as:

$$WF_{blue} = \frac{CWU_{blue}}{Y} \tag{5}$$

$$CWU_{blue} = 10\ x \sum_{d=1}^{lgp} ETc_{blue} \tag{6}$$

CWU_{blue} represents the use of water for cultivation from surface or underground sources (irrigation) and $ET_{c\ \text{blue}}$ the evapotranspiration of the crop that is associated with the availability of irrigation water.

In order to estimate $\text{CWU}_{\text{green}}$ and CWU_{blue}, ETc and effective precipitation (EP) were estimated using the CROPWAT version 8.0 program (FAO, 1996). The ET_o is estimated by applying the Penmam-Monteith method, whereas the EP was estimated using the USDA-SC method, at 10-day intervals. $ET_{c\ \mathrm{green}}$ was estimated from the values obtained using CROPWAT, as established by Renderos (2014):

$$ET_{c\,green} = \min(ET_c, EP) \tag{7}$$

For the cultivation period, the $\mathrm{ET_c}$ or EP values for periods of 10 days were added together, depending on which of these was lower.

ET_{blue} was obtained from CROPWAT estimates, as in (Renderos, 2014; Novoa, Rojas, Arumí, Ulloa, & Urrutia, 2016):

$$ET_{blue}\ (mm\ 10\ days^{-1})\ =\ Irrigation\ requirement\ (mm\ 10\ days^{-1}) \tag{8}$$

Irrigation requirement (mm 10 $\mathrm{days^{-1}}$) = ET_c (mm 10 $\mathrm{days^{-1}}$) – EP (mm 10 $\mathrm{days^{-1}}$)

$$ET_{blue}\ =\ max\ (ET_C - EP) \tag{9}$$

Therefore, the differences in ET_c - EP that had positive values were added together.

We used maximum and minimum temperature, relative humidity and wind speed information from the weather station in Puebla City, from the CLIMWAT database; this station was selected because it was the closest CLIMWAT station to the study area. Information concerning crop phenology, crop cycle duration and management practices was obtained from a survey applied to 31 producers in the study area. For onion cultivation, the spring-summer cultivation cycle was 97 days (April 7 to July 30) and the autumn-winter cycle was 97 days (August 2 to November 24). The autumn-winter husk tomato crop cycle was 95 days (July 20 to October 30).

The Gray Water Footprint was estimated based on the use of fertilizers in the study area, applying the following equation (Renderos, 2004):

$$WF_{\text{gray}} = \frac{AR \cdot \alpha}{(C_{max} - C_{nat}) \cdot Y} \tag{10}$$

Where WF_{gray} is the gray water footprint, in m^3 hectare^{-1}; AR is the fertilizer application rate, in kg hectare^{-1}; α is the fraction of fertilizer that infiltrates (is exported) to the bodies of water; C_{max} is the maximum acceptable concentration in units of mass per volume; C_{nat} is the natural concentration in units of mass per volume; Y is the crop yield, in t ha^{-1}.

Fertilizer application rate was obtained with on-farm interviews, by means of questionnaires applied to the 31 producers surveyed. The average doses of nitrogen fertilization used for the estimate were 137.4 kg per hectare^{-1} for onion and 105 kg hectare^{-1} for husk tomato crops; while the average phosphorus doses applied were 77.9 and 36 kg ha^{-1} respectively. These values were altered to show their N and P content. The fraction of fertilizer exported (α) to water reserves was 0.1 for nitrogen, assuming that on average 10% of the amount of nitrogen fertilizer applied is lost by leaching (Mekonnen & Hoekstra, 2010; Franke, Boyacioglu, & Hoekstra, 2013). For phosphorus, an α value of 0.3 was applied, considering the average leaching value reported by Franke *et al*. (2013). A C_{max} value of 0.006 for nitrogen and 0.03 for phosphorus was applied, in compliance with the Official Mexican Standard NOM-001-SEMARNAT-1996 (DOF, 1996). Due to lack of information, the concentration of natural nitrogen and natural phosphorus in these water reserves (C_{nat}) was assumed to be zero (Mekonnen & Hoekstra, 2010; Renderos, 2014).

Results

Characteristics of systems of cultivation

Onion and husk tomato producers own land areas of less than 1 hectare. An average harvest for the autumn-winter cycle of husk tomato was recorded at 16.2 t hectare^{-1}. For the onion crop, an average harvest for the spring-summer cycle of 7.7 t hectare^{-1} was registered and 20.4 t hectare^{-1} for the autumn-winter cycle. Water for irrigation comes from surface currents and consists mainly of groundwater extracted from wells. The predominant irrigation system is by gravity, using irrigation channels. Most producers believe that the quality of the water they use for irrigation is good. The average cost for irrigating a plot is $171 pesos per hour of irrigation. Irrigation flow was determined as 44 290 l s^{-1}, with an average irrigation frequency of 7 days per month during each crop cycle of 96 days. Each irrigation session lasts for approximately four hours.

Effective Precipitation and Evapotranspiration (ET_o)

The average ET_o obtained using CROPWAT for the year of 2017, applying the Penman-Monteith method, was 4.1 mm day^{-1}. The greatest ET_o

occurred during the hottest months, corresponding to the period from March to May. The period with greatest effective rainfall was the summer cycle, during the months of June to September (124.7 to 110 mm). This means that the quantity of water used by the plants was greater during the summer months, giving an impression of benign conditions in the region for agricultural production during the period from May to October, when EP is greater than ET_o (Figure 2).

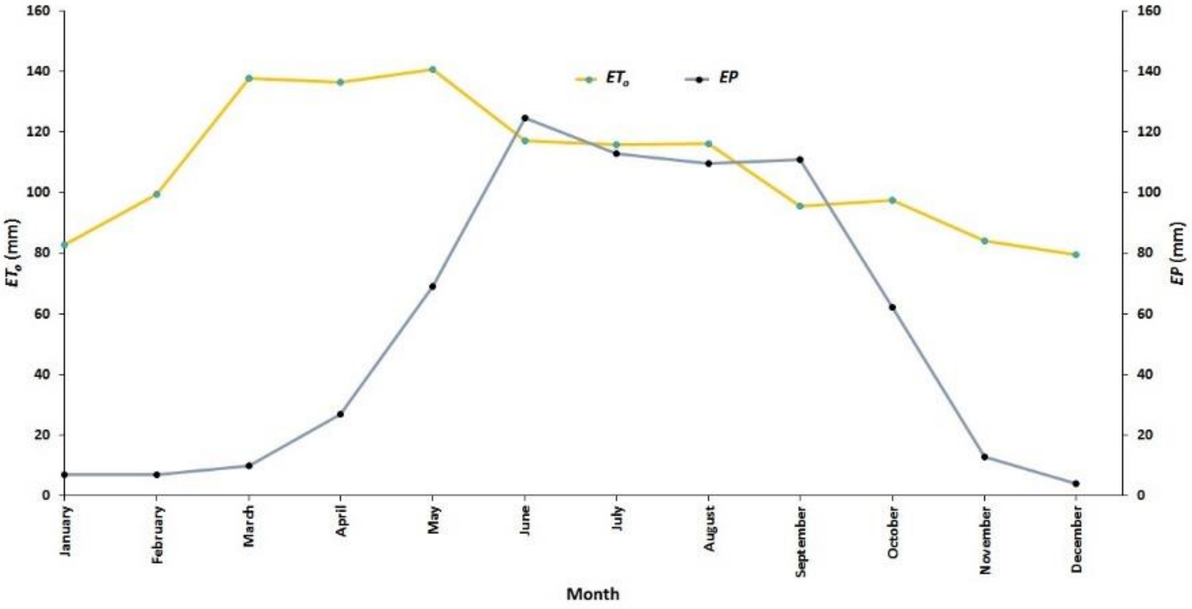

Figure 2. Effective precipitation (*EP*) and related evapotranspiration (ET_o).

Water footprint of onion and husk tomato crops

The green water footprint for the autumn-winter onion crop was 176.4 m^3 t^{-1}, the blue water footprint 53 m^3 t^{-1} and the gray water footprint 20.1 m^3 t^{-1}. The total water footprint was 249.7 m^3 t^{-1}.

For the onion crop of the spring-summer cycle, the green water footprint was 293.3 m^3 t^{-1}, the blue water footprint of 263 m^3 t^{-1} and the gray water footprint of 22.9 m^3 t^{-1}. The total water footprint was 578.7 m^3 t^{-1}.

For the husk tomato crop, a green footprint of 165.8 m^3 t^{-1}, a blue water footprint of 21.9 m^3 t^{-1} and a gray water footprint of 8.6 m^3 t^{-1} were estimated; the total water footprint was 196.3 m^3 t^{-1}.

According to the estimated water footprints, the husk tomato crop has the lowest total water footprint (Figure 3). The spring-summer onion crop was the one which absorbed most water during its production process, whereas the autumn-winter onion crop had a total water footprint of medium capacity.

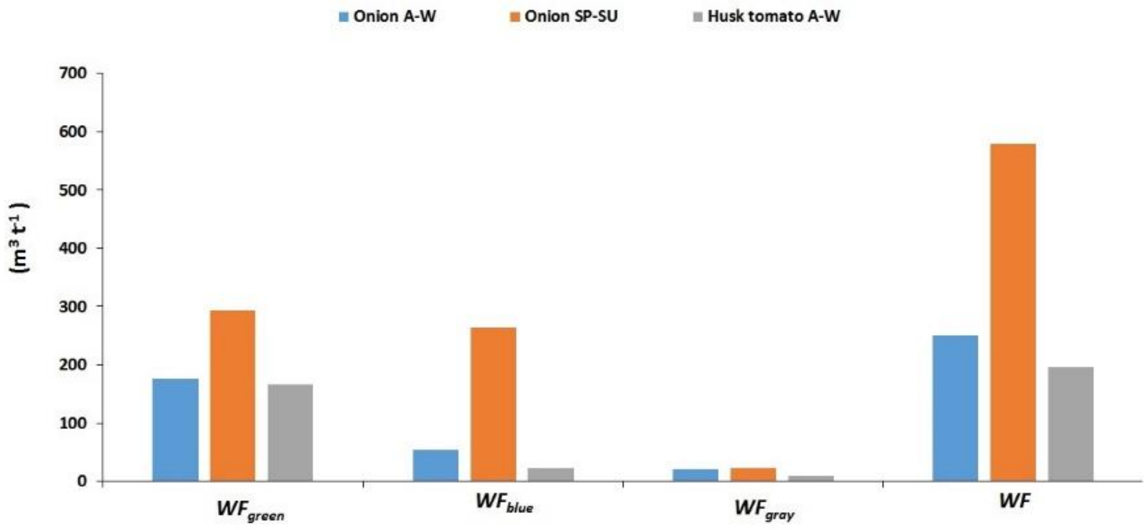

Figure 3. Water footprint of onion and husk tomato crops in the Atlixco region, Puebla.

Regional implications of estimated water footprints on water resources

Considering regional production of onion and husk tomato crops and results concerning their water footprints, these crops have an important impact on the use of regional water resources (Table 1).

Table 1. Impact of the water footprint of onion and husk tomato crops on the regional water resource.

	Onion SP-SU	**Onion AU-WI**	**Husk tomato AU-WI**	**Total**
Production (t)*	3 584.8	8 418.0	3 567.0	
Area harvested (hectare)*	234.3	460.0	290.0	
WF total (m^3 t^{-1})	578.7	249.7	196.3	
Total water absorbed** (m^3)	2 074 336.4	2 102 104.9	700 269.0	
Total water absorbed (hm^3)	2.1	2.1	0.7	

% of total volume allocated***	2.2	2.2	0.8	5.2
% of total volume allocated to agriculture	2.9	2.9	1.0	6.8

* Final agricultural data for 2017 from the Agrifood and Fisheries Information Service (SIAP, 2017).

** Total water absorbed by regional production of onion and husk tomato.

*** Considering a total volume allocated of 93.4 hm^3 and 76.4 % (71.4 hm^3) assigned to agricultural purposes (REPDA, 2016).

Discussion

Estimated green and blue water footprints contributed the most to the total water footprint for onion cultivation. These values were higher than the international averages reported by Mekonnen and Hoekstra (2010), whereas that of the gray footprint was less. We consider that the water footprint was underestimated, because only the use of fertilizers was considered and not the use of pesticides.

The total water footprint of the onion crop in the spring-summer cycle was high (578.65 m^3 t^{-1}) compared to the total water footprint obtained for the autumn-winter cycle (249.7 m^3 t^{-1}). It also exceeds that reported by Ríos-Flores, Jacinto-Soto, Torres-Moreno and Torres-Moreno (2017) for this crop (115 m^3 t^{-1}) in the autumn-winter cycle for the Delicias region, Chihuahua, Mexico. Compared to data reported internationally, our estimates for the spring-summer cycle are similar to those reported by Castañeda and Ramírez (2016) for Colombia (505.1 m^3 t^{-1}). The estimates for the autumn-winter cycle are comparable to the total water footprint reported by Mallma and Mejía (2015) for Peru and the international averages reported by Mekonnen and Hoekstra (2010) (272 m^3 t^{-1}). No state or regional benchmark exists for comparison. The differences between production cycles and between regions can mainly be linked to differences in climate and yields, because low crop yields and high evapotranspiration result in a higher water footprint (Hoekstra & Chapagain, 2007).

Estimated ET_o (4.1 mm día^{-1}) is typical of temperate climate regions (Allen et al., 2006). Reference evapotranspiration (ET_o) and effective precipitation (*EP*) data for the study region indicate conditions of green water availability for crop production during the period from June to September, because EP is greater than ET_o. Onion cultivation in the region uses a large quantity of green water, both in the spring-summer and autumn-winter cycles. However, the blue water requirement is much greater in spring-summer; explained by the higher temperatures during this period of crop growth. The notable difference in the water footprint of the onion crop for the two crop cycles —for which temperature and precipitation are climatic variables that determine the difference in crop growth conditions— gives an idea of how changing climate conditions, with higher temperatures and lower rainfall will lead to a lower green water footprint on the part of the crop, thus increasing the need for irrigation water and augmenting its blue water footprint.

Crop yield affects the efficiency of water use and therefore the water footprint. The estimated onion crop yield for spring-summer (7.69 t hectare^{-1}) is low compared to the estimate for this cycle in the state of Puebla (21.2 t hectare^{-1}) and the national average (33.6 t hectare^{-1}) (SIAP, 2018). We believe that this is a key factor in terms of the efficiency of water use and explains the estimated high water footprint. In contrast, the onion crop yield for the autumn-winter cycle (20.4 t hectare^{-1}) exceeds the average state yield (16.0 t hectare^{-1}) and similar to the national average yield (21.2 t hectare^{-1}) (SIAP, 2019). These results indicate greater efficiency in the use of water during this cycle, with a lower water footprint.

The husk tomato crop for the autumn-winter cycle had a total water footprint (196.32 m^3 t^{-1}), less than the total water footprint of the onion crop, both for spring-summer and for autumn-winter, indicating greater efficiency in the use of water, for this alternative crop. There is little information about the water footprint of the husk tomato crop. An indirect comparison can be made between the ET_c obtained in this study with that reported for a study that was conducted in Chapingo, Mexico, by López, Arteaga, Vázquez, López, and Sánchez (2010). In this study, an ET_c value of 300.2 mm was obtained for the cultivation period, whereas the authors referred to report an ET_c value of 243 mm for husk tomatoes. We should take into account the fact that in this study, the estimate was made using climatic data, whereas the authors estimated the ET_c using data from the soil matric potential. Another possible comparison is with the values reported for horticultural crops by Mekonnen and Hoekstra (2010). They report values of 194, 43, 85 and 322 m^3 t^{-1} for the green, blue, gray and total water footprints, respectively, for horticultural crops. In this study, values of 165.75 m^3 t^{-1}, 21.95 m^3 t^{-1}, 8.63 m^3 t^{-1} and 196.32 m^3 t^{-1} were obtained for the green, blue, gray and total water footprints, respectively. The partial and total water footprints are lower than the average values reported by the authors cited. This is explained because in the present study, the use of nitrogen and phosphoric fertilizer was calculated, but the use of pesticides was not included.

The water assimilated during the production process of onion and husk tomato crops is important in terms of the use of regional water, as it represents 5.22% of the volume allocated for all uses and 6.83% of that allocated for agricultural use. The biggest impact is caused by the onion crop. For a region with increasing water demand for domestic, industrial and recreational use, improving the efficiency of irrigation for agriculture more is necessary to reduce pressure on the water resource, principally concerning water extracted from the Atlixco-Izúcar de Matamoros aquifer.

Conclusions

The onion crop (*Allium cepa* L.) from the spring-summer cycle manifested an elevated water footprint in the region of Atlixco, Puebla, compared to the values estimated for other regions in Mexico and the world, which is associated with a high requirement of blue water, due to temperature and precipitation conditions. The onion crop (*Allium cepa* L.) from the autumn-winter cycle had a lower water footprint than the spring-summer cycle and was similar to that reported as the world average for the crop. The temperature in the region during the months of the crop cycle relates to evapotranspiration and determines the value of the total water footprint. The tomato crop (*Physalis ixocarpa Brot.)* from the autumn-winter cycle had a lower water footprint than the onion crop, both for spring-summer and autumn-winter, which is less than the average value reported for horticultural crops.

Onion (*Allium cepa* L.) and husk tomato (*Physalis ixocarpa* Brot.) in the region of Atlixco, Puebla, incorporates 5.5 hm^3 per agricultural year for its production process, representing 5.22% of the water allocated to all consumptive uses and 6.83% of that allocated to agricultural use.

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