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Sugarcane water footprint in the province of Tucumán, Argentina. Comparison between different management practices

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ABSTRACT

The sugar-alcohol industry plays a key role in the economics of the province of Tucumán (Argentina). For that reason, the quantification of water volumes consumed during sugarcane growing as well as the water used in the sugar and bioethanol production and in the manufacturing of associated by-products, is highly important for the development of policies that ensure the sugar and alcohol sustainability. The water footprint is the most widespread and up-to-date indicator used to assess water use and consumption associated to a product, activity or watershed. In this work, the green, blue and grey water footprint of the sugarcane production in Tucumán (Argentina), considering different technology levels, has been assessed. All data used in calculations are mostly taken from local sources, from campaigns 2012 to 2016, with the further goal of building a regional water footprint map of such an important crop as sugarcane is. Results are roughly distributed in green water footprint 12% and grey water footprint 88%. Green water footprint exhibits a counterposed behavior with respect to the technology levels. Blue water footprint is very low, under rainfed farming conditions, because it is only associated to dilution and application water for agrochemicals. Grey water footprint exhibits high values for higher technology level due to the use of triazine-based herbicides, which are not present in the agrochemical recipe of the low technology level. This situation raises an interesting trade-off showing that not always higher technology levels would be the more sustainable ones.

1. Introduction

Sugarcane industry generates lot of labor and many essential products, such as sugar, ethanol and bagasse (lignocellulosic by-product of the sugarcane milling). Sugarcane has a global importance, contributing to 29% of the total world crop production (Gerbens-Leenes and Hoekstra, 2012). Over the period 2005–2014, Brazil produced 39% of the global sugarcane, followed by India (19%), China (7%), and Thailand and Pakistan (4% each) (FAO, 2017).

In Argentina (1.4% of the global sugarcane production), sugarcane processing is the second most important economic and social activity in the north-west region of the country (INTA informa, 2013), playing a key role in the economics of the province of Tucumán, which hosts 64% of the sugarcane grown in Argentina (MHFP, 2016): 274,180 ha (Fandos et al., 2016). The region's economy has been strongly influenced by mandatory incorporation of bioethanol and biodiesel —defined by Argentine law 26,093— in gasoline and gasoil blends, respectively. Since 2010, the bioethanol percentage in gasoline has been gradually augmented from 5 to 12% in volume, causing an increase of 700,000 m^3 in the ethanol production between 2010 and 2016 (MHFP, 2016).

Sugar and bioethanol production may be considered as constituted by two key stages: agriculture and manufacturing, whose water consumption and wastewater generation is significant with respect to all agroindustrial activities in the province of Tucumán (DPSE & DPN, 2017).

The quantification of the water consumed during sugarcane growing (absorption and evaporation), as well as the water used in both sugar and bioethanol production and the manufacturing of some associated by-products, is highly important for stakeholders. It is particularly interesting to use this information to develop public policies that ensure the sugar and alcohol sustainability.

Nowadays, one of the most widespread indicators of water use and consumption in the world is the water footprint (WF), defined as the total freshwater volume consumed (evaporated or

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incorporated) and contaminated to produce a product in a specified place and moment (Hoekstra et al., 2011). The WF is the result of three contributions: the green WF, related to rain water consumption; the blue WF, related to surface and underground water usage; and the grey WF that represents a virtual water volume required to assimilate the pollutants load of effluents under the existing water quality standards. The WF not only gives information on the consumption/degradation of the resource but it also represents a business tool for those companies that include it into their management system.

Mekonnen and Hoekstra (2011) have estimated the total global WF in 7404 Gm^3 $year^{-1}$, distributed in 5771 Gm^3 $year^{-1}$ for green WF, 899 Gm^3 $year^{-1}$ for blue WF and 733 Gm^3 $year^{-1}$ for grey WF, considering data from 1996 to 2005. The same authors report for Argentina a total WF of 166.9 Gm^3 $year^{-1}$, divided into 157.6, 4.3 and 5.0 for green WF, blue WF, grey WF, respectively.

According to Gerbens-Leenes and Hoekstra (2012), the weighted global average WF of sugarcane is 209 m^3 t^{-1}, ranging between 120 m^3 t^{-1} and 410 m^3 t^{-1}.

Several researchers have published results on WF related to sugarcane growing around the world. Su et al. (2015), for instance, present a WF of 187–251 m^3t^{-1}, in different regions in Taiwan. In Tamazula (Mexico), the average WF of irrigated sugarcane is estimated by Haro et al. (2014); they obtain an annual average WF of 104.9 m^3 t^{-1}, only for blue WF. This value cannot be compared with the results presented by Gerbens-Leenes and Hoekstra (2012) for Mexico as the last authors estimate the total WF average by country. Nevertheless, the relevance of the work by Haro et al. (2014) is the consideration of local condition in their estimation.

A separate paragraph may be devoted to Brazil due to the importance of sugarcane in this country. Scarpare et al. (2016) first show a global revision —in which Argentina is not included—, and then, they estimate an average WF for rainfed sugarcane of 161.2 m^3 t^{-1} under green management, taking into account the plantation age (new plants and ratoons). Da Silva et al. (2015) estimate a 139 m^3 t^{-1} green WF, 57 m^3 t^{-1} blue WF and 13 m^3 t^{-1} grey WF for Paraíba state under rainfed conditions. Agnellos Barbosa et al. (2017) carry out a research on WF in small experimental plots in Campinas, modifying variables such as irrigation with treated domestic sewage, freshwater and complementary fertilization. Pezzi Fachinelli and Pereira (2015) evaluate the green, blue and grey WF indicators of sugarcane cultivation in the watershed of Paranaíba considering also the impact of the water demand for different scenarios on the context of water availability. In this case, WF is estimated to be around 142 m^3 t^{-1} (full irrigation) and 151 m^3 t^{-1} (rainfed).

In recent years, many studies present the results of WF for a bunch of crops in Argentina, such as corn (Álvarez et al., 2016), potato (Rodríguez et al., 2015), rice (Marano and Filippi, 2015), soybean (Piastrellini, 2015), vineyard (Civit et al., 2012), peanut (Anschau et al., 2015), and cotton (Anschau and Bongiovanni, 2016). Nevertheless, for the case of Argentinean sugarcane production, published studies on WF are scarce. Despite the fact that Gerbens-Leenes and Hoekstra (2012) present results of sugarcane WF for Argentina, among some selected countries, those results seem to be derived from FAO statistics instead of from specific local studies. It would be advisable to perform WF calculations case-by-case for all sugarcane producing regions to reach more accurate and worthful values to make decisions.

Particularly, this work takes as a starting point a previous one in which a Life Cycle Assessment study had been performed over the sugar-alcohol industry in Tucumán (Nishihara Hun et al., 2017), and belongs to a bigger project that seeks to evaluate the WF of the sugar-alcohol value chain in Tucumán (taking into consideration the whole agricultural, manufacturing and logistics complex with local information).

In the agricultural practice of sugarcane production in Tucumán, the access to technological resources is often heterogeneous (Giancola et al., 2012). This diversity causes significant variation in consumption and use of water resources, and generation of liquid effluents. Therefore, the consideration of different technology levels (TL) applied in the usual agricultural practices results unavoidable.

This work explores the agricultural stage (sugarcane production) considering three TLs in order to have a deeper insight of the activities involved and to detect critical points and improvement opportunities. As in every agroindustry, WF of the agricultural stage is expected to have a high share in the WF of the entire system, i.e. considering all the stages. Moreover, a great deal of effort is required to proceed with calculations due to multiple and complex factors that affect biomass production. Results of this precursory WF assessment linked to agriculture tasks will constitute a baseline scenario to later progress towards the WF calculation of the other stages as future research.

2. Material and methods

Tucumán is the smallest province of Argentina (22,524 km^2). Located in the NW region of the country, it hosts 1.5 million inhabitants (Fig. 1). The province shows two main geographic areas: a western mountainous one (with peaks up to 5500 m above sea level), and an oriental plain with a gentle slope to the east, which exhibits an average altitude of 400 m above sea level. The mountains intercept wet winds coming from the Atlantic Ocean, promoting orographic rainfalls of about 1000 mm per year in the sugarcane cultivation area.

The system boundary was set according to the habitual scheme of production in Tucumán (see Fig. 2), but only the agriculture subsystem is considered in this study.

As mentioned before, agricultural practices in sugarcane production vary according to the growers' access to the productive factors, defining different TLs. In this specific case, it has been taken the classification of the current growing practices into three TL: high (HTL), medium (MTL) and low (LTL), representing 40, 50 and 10% of the cultivated area, respectively (Giancola et al., 2012). Table 1 shows the main features of each TL. Even though HTL would represent the optimal growing and harvesting labors for sugarcane, the socio-economic reality of the region makes the expansion of these practices unfeasible so far.

WF calculations must be conducted through four steps (Hoekstra et al., 2011); two of them are developed in this work: (i) goals and scope definition of the WF assessment, and (ii) WF accounting. The geographic area under study is located in the west-center plains in the province of Tucumán (65.3° W, 27.0° S), in the Salí-Dulce river basin. The weather is subtropical with dry season in winter, and the soil is predominantly silty or silty-loam in the surface and silty-clay-loam in deeper layers (Romero et al., 2009).

The WF estimation encompasses a one-year time window, using five-year average data (2012–2016). The water provision for sugarcane growing comes from rain, exclusively (rainfed). Finally, the three components of the WF are assessed.

2.1. Green water footprint

At this point it is important to introduce the concept of crop cycle in sugarcane: firstly, sugarcane is seeded initiating the crop cycle and then, after harvest (cane plant), different successive regrowth are allowed (cane ratoon) with the same root system, in accordance with each TL. In order to calculate the green WF, a five-

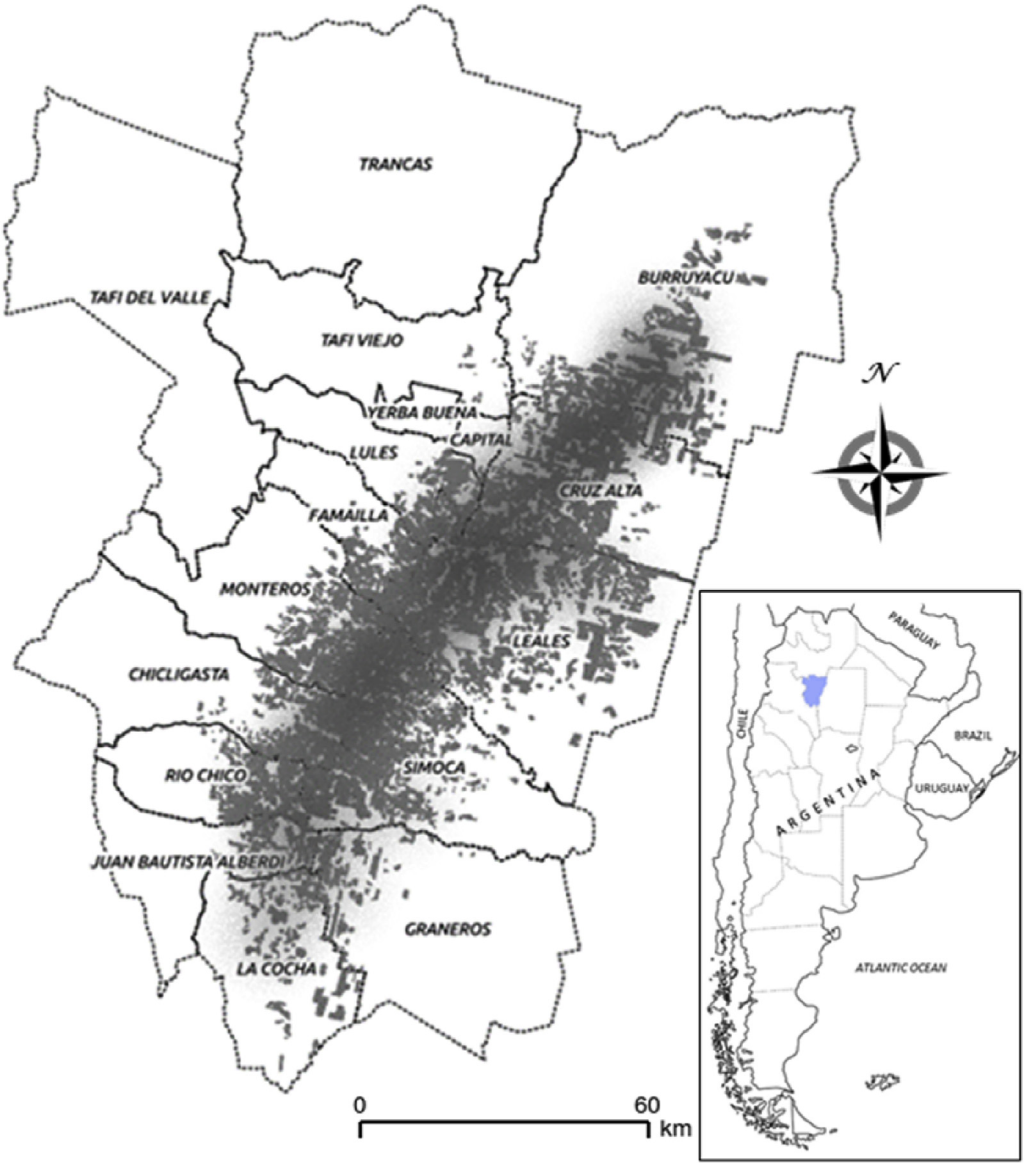

Fig. 1. The province of Tucumán showing the sugarcane cultivated area (modified from INTA News, 2017). Inset: location of Tucumán within Argentina.

year crop cycle is taken into account for HTL, as well as a six-year crop cycle for MTL and a seven-year cycle for LTL, with harvest every 12 months, for every TL.

Only for HTL, it is a common practice to leave the crop residues (sugarcane tops and leaves) after harvesting as a covering layer on the harvested fields. The WF estimation is carried out considering three cases: (i) all the generated residues remain on the soil, (ii) 50% of the residues are removed from the soil, and (iii) the crop residues are removed thoroughly. For MTL and LTL, all sugarcane top and leaves are burned before harvesting (see Table 1).

According to Hoekstra et al. (2011), the green WF during the growing period (WF_{green}, $m^3\ t^{-1}$) is the ratio between the green component of the crop water use (CWU_{green}, $m^3\ ha^{-1}$) and the crop yield (Y, $t\ ha^{-1}$) (Eq. (1)).

$$WF_{green} = \frac{CWU_{green}}{Y} \tag{1}$$

CWU_{green} is calculated by accumulating daily green evapotranspiration ($ET_{green,d}$, mm day^{-1}) over the complete growing period (Eq. (2)).

$$CWU_{green} = 10\sum_{d=1}^{T} ET_{green,d}, \tag{2}$$

where $ET_{green,d}$ is the daily green water evapotranspiration and the factor 10 converts water depths in millimeters into water volume per land surface in $m^3\ ha^{-1}$. $ET_{green,d}$ is the minimum between the daily effective evapotranspiration ($ET_{c,d}$, mm day^{-1}) and the daily effective precipitation ($P_{eff,d}$, mm day^{-1}) (Eq. (3)). The summation is done over the period from the day of planting ($d = 1$) to the day of harvest ($d = T$).

$$ET_{green,d} = \min\left(ET_{c,d}, P_{eff,d}\right) \tag{3}$$

$ET_{c,d}$ is obtained using the method described by Allen et al. (2006), which consists in evaluating the crop reference evapotranspiration (ET_0, mm day^{-1}) and the crop coefficient K_c.

ET_0 is estimated using the software CROPWAT 8.0® (FAO, 2009),

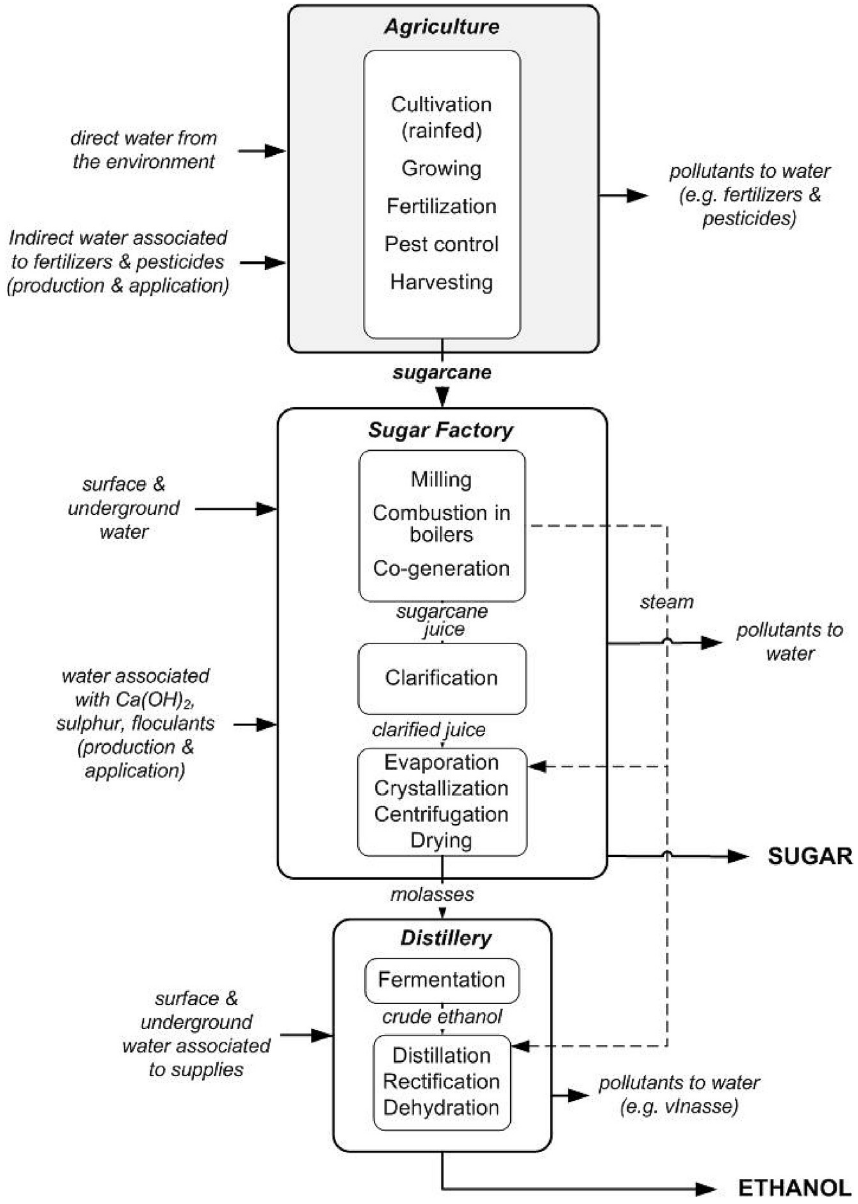

Fig. 2. Schematic of the overall system of sugar and bioethanol production.

Table 1
Main features of the three TLs considered for the agricultural labors (Nishihara et al., 2017).

Main differential aspects	High (HTL)	Medium (MTL)	Low (LTL)
Crop yield [t ha^{-1}]	75	62	55
Harvest system	Mechanized	Semi-mechanized	Semi-mechanized + manual
Trash burning	Scarce	Total	Total
Agrochemicals use	Intensive	Moderate	Scarce

which implements the Penman-Monteith equation, adopting local geographical coordinates —Lules (La Bomba) in Table 2— and using also local meteorological data: minimum and maximum temperature (°C), wind speed (m s^{-1}), relative humidity (%) and daylight hours (%).

For K_c calculation, this parameter is considered to be split into two separate coefficients, one for crop transpiration —the basal crop coefficient (K_{cb})—, and one for soil evaporation (K_e) (Eq. (4)). For K_{cb} and K_e estimation, climatic data mentioned before are used

Table 2
Geographical coordinates of four of the meteorological stations of Tucumán considered in the case study.

Meteo station	Latitude	Longitude	Elevation (m)
El Colmenar	−26.7875	−65.1953	482
Monte Redondo	−26.8192	−64.8503	393
Santa Ana	−27.4747	−65.6764	389
Lules (La Bomba)	−26.9095	−65.3518	382

together with data on precipitation (mm) and crop height (h, cm).

$$K_c = K_{cb} + K_e \tag{4}$$

Data of eight meteo stations located in the sugarcane area are retrieved from the EEAOC online database, with daily information from January 1st, 2012, to December 31st, 2016 (Sección Agrometeorología EEAOC, 2017). Daylight hours were taken from AQUASTAT 2017 using geographical coordinates of El Colmenar, Monte Redondo and Santa Ana (Ceballos et al., 2011); only these three stations are considered since this parameter does not significantly change in the crop area (Table 2).

The crop height evolution (h) along the different phenological stages for five sugarcane varieties, as they develop in Tucumán, are adjusted using a logistical function (Eq. (5)) for both cane plant and ratoon following Saez (2017).

$$h = a\frac{1 + m \cdot e^{-t/\tau}}{1 + n \cdot e^{-t/\tau}}, \tag{5}$$

In Eq. (5), t is the time in days, and a, m, n and τ are parameters depending on whether sugarcane considered is one-year old (plant) or older (ratoon). Data related to crop features such as seeding date, growth stages duration and harvest date are taken from personal communications with EEA Famaillá (INTA) experts. Table 3 shows the average values of the parameters for the five sugarcane varieties analyzed.

Alternatively, it is possible to perform the WF estimation by using data coming from CROPWAT 8.0® and CLIMWAT databases. This last procedure has been used in this work for comparison purposes. In this case, the only two available meteorological datasets, located in Tucumán, have been considered: La Cocha and Tucumán-Observatory.

2.2. Blue water footprint

Due to the rainfed conditions adopted in this case study, the blue component in crop water use (CWU_{blue}) is zero. In consequence, the blue WF (WF_{blue}, m^3 t^{-1}) is estimated considering the water incorporated with fertilizers and herbicides only, which depends on the TL.

$$WF_{blue} = \frac{dilution\ water + application\ \ water}{Y} \tag{6}$$

The incorporated water is classified as dilution water (m^3), representing the water existing in the commercial presentation of the product, and application water (m^3), which is the water used to apply each substance to the fields (Eq. (6)). For cane plant and ratoon, 0.30 m^3 ha^{-1}, 0.15 m^3 ha^{-1} and 0.60 m^3 ha^{-1} are used as application water, for LTL, MTL and LTL, respectively. Agrochemicals doses and formulations are taken from Nishihara Hun et al. (2017).

2.3. Grey water footprint

The grey WF is assessed according to Franke et al. (2013) (Eq. (7)). The local agricultural practice is classified as "good", according to the survey proposed by these authors.

$$WF_{grey} = \frac{\alpha \cdot AR / (C_{\max} - C_{nat})}{Y} \tag{7}$$

In Eq (7), the factor α is the leaching-runoff fraction, AR is the agrochemical application rate to the field (kg ha^{-1}), and $C_{\max}$ is the maximum acceptable concentration (kg m^{-3}). The limits defined by local legislation for nitrogen (N) and phosphorus (P) (SEMA, 2009) are taken into account, following the criteria established by Franke et al. (2013) for agrochemicals. C_{nat} is the natural concentration of the pollutant in the receiving water body (kg m^{-3}), considered as zero in this case study for all the contaminants.

It is worth noting that Eq. (7) is applied for all agrochemicals, taking as grey WF final result the highest among all the results obtained. Table 4 shows the amount of each substance applied for HTL, MTL and LTL, for both cane plant and cane ratoon.

Table 3
Parameters for the estimation, by means of Eq. (5), of the crop height during the different growth stages for cane plant and ratoon.

Parameters	Cane plant	Cane ratoon
a	268,16016	330,7968
m	−1,0000	−1.0000
n	43,3644	50,0663
τ	31,0173	32,7242

3. Results and discussion

The local climate is classified as humid subtropical with an average annual temperature of 19 °C, and about 1076 mm of annual rainfall. The driest month usually has less than 9 mm of precipitation. Annual precipitation and temperature profiles are shown in Fig. 3.

The results obtained for ET_0, estimated using CROPWAT 8.0®, and $ET_{green,d}$ are shown in Fig. 4.

The gap between $ET_{green,m}$ and ET_0 occurs from June to October agreement with the dry season in the studied area (see Fig. 4). These results are in accordance with the water stress conditions of the crop.

The results of WF obtained for the agricultural stage, per metric ton of raw sugarcane, are shown in Tables 5 and 6.

Green WF exhibits a counterposed behavior with respect to the TL: the higher the green WF values, the lower the TL (see Table 5). This is because crop yields increase with technification, which decreases the green WF (see Eq. (1)). Although the rotation scheme between sugarcane plant and ratoons is different in each TL, green WF values are not affected by this issue since green WF has similar values for sugar plant and ratoon.

If considering HTL with different percentages of crop residues remaining on the soil after harvesting, variation in green WF values cannot be regarded as significant nor showing a clear trend. However, it would be reasonable to expect a green WF drop as the covering percentage increases, due to higher water availability for the crop.

The small values for blue WF obey to the consideration of rainfed farming. The irrigated surface in Tucumán is exiguous and there is no evidence of a clear correspondence between irrigated areas and cultural yields. Furthermore, no statistical study of the irrigated area associated with the crop was found. Data is uncertain and strongly depends on rainfall and the availability of surface water resource. Irrigation is eventual and is not integrated into the productive cycle, showing an irregular management of the resource.

Unlike green WF, blue WF values increase as the TL increases. Despite of the fact that yields increase as TLs increase —which would produce a WF reduction—, the increase of the blue WF with TL can be explained by the more intensive water use associated to agrochemicals applications in higher TLs.

Table 6 shows results for grey WF according to different critical pollutants found for cane plant and ratoon at different TLs. Most studies report that the application of nitrogenate fertilizers is the main cause of grey WF (Franke et al., 2013). However, in this case, the use of N is far exceeded as a grey WF generator by atrazine —a

Table 4
Agrochemicals used in cane plant and ratoon for HTL, MTL and LTL.

Cane Plant	Formulation[a]	Dose			Active principle		
		HTL	MTL	LTL	HTL	MTL	LTL
Urea [kg ha^{-1}]	46%	210	210	180	96.2	96.2	82.8
Atrazine [kg ha^{-1}]	50%	4[b]	4[b]	–	2.5	2.5	–
Acetochlor [kg ha^{-1}]	80%	2[b]	–	–	1.8	–	–
Diammonium phosphate [kg ha^{-1}]	18% as N content	60	–	–	10.8	–	–
	42% as P content				25.2		
Cane Ratoon							
	Formulation	Dose			Active principle		
		HTL	MTL	LTL	HTL	MTL	LTL
Urea [kg ha^{-1}]	46%	210	210	180	96.6	96.6	82.8
Atrazine [kg ha^{-1}]	90%	4[b]	–	–	2.5	–	–
Ametryn [kg ha^{-1}]	80%	2	–	–	1.6	–	–
2,4-D [kg ha^{-1}]	50%	0.8[b]	0.8[b]	2[b]	0.6	0.6	1.6
MSMA [kg ha^{-1}]	69%	0.8[b]	0.8[b]	1[b]	0.7	0.7	0.9
Metolachlor [kg ha^{-1}]	90%	1[b]	–	–	1.0	–	–
Paraquat [kg ha^{-1}]	90%	0.2[b]	–	–	0.3	–	–
Diammonium phosphate [kg ha^{-1}]	18% as N content	60	–	–	10.8	–	–
	42% as P content				25.2		

[a] Formulation stands for the mass of active principle per mass of the commercial form.
[b] Expressed in [L ha^{-1}].

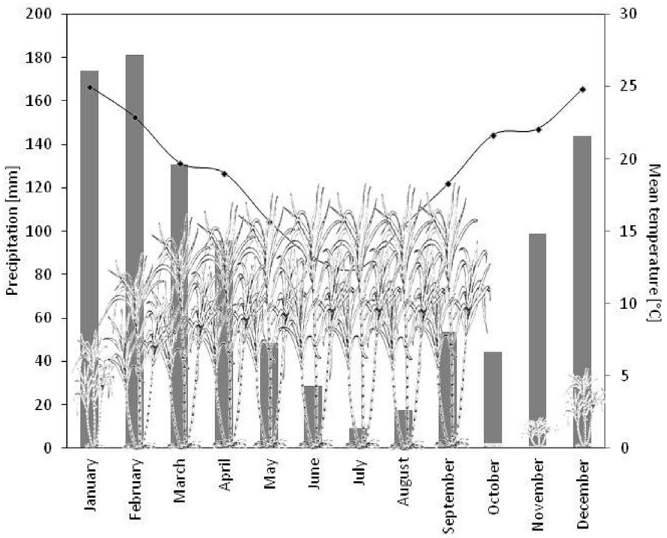

Fig. 3. Average annual distribution of precipitation and mean air temperature. The height of the sugarcane plants illustrates, schematically, the crop growth periods. Bars account for precipitation and line/dots, for mean temperature.

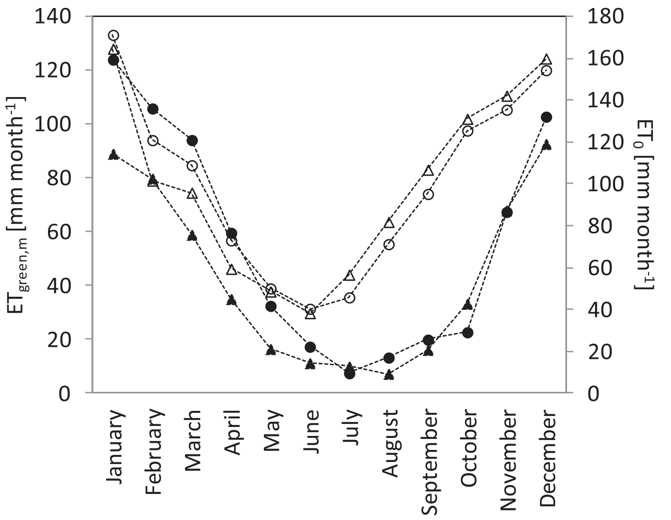

Fig. 4. Cumulative monthly evapotranspiration ($ET_{green,m}$) for sugarcane plant (–●–) and ratoon (–▲–). Cumulative monthly reference evapotranspiration ($ET_{0,m}$) for sugarcane plant (–○–) and ratoon (–Δ–). Data corresponding to HTL with 100% of crop residues coverage.

post-emergency herbicide— in HTL and MTL, that happens to be the critical pollutant, over the other agrochemicals. The case in which some specific agrochemical leads to highly disproportionate values is not common but there is some antecedents as the one in the work by Safaya et al. (2016), in which cypermethrin —a pyrethroid compound— is the critical pollutant. In those practices in which atrazine is not applied (MTL/ratoon and LTL), the highest grey WF is generated by urea (see Table 6). Grey WF values strongly depend on two parameters: maximum admissible concentrations and leaching-runoff fractions of the agrochemicals used in sugarcane cultivation. In this study, the first values are taken from current legislation whereas the second ones are recommended values from literature (local on-field measurements are not used).

It is worth noting that the current TL distribution is not easy to alter. The production system in Tucumán includes many actors, most of them with small crop fields and a low degree of cooperation among them. Therefore, there are socio-economic limitations for one of these cane growers to achieve a higher TL.

Table 5
WF_{green} and WF_{blue} of cane plant and cane ratoon for HTL, MTL and LTL. Values in m^3 t^{-1}.

Technology level	WF_{green} 0% cover	WF_{green} 50% cover	WF_{green} 100% cover	WF_{blue}
HTL	93	91	89	0.0072
MTL	113	–	–	0.0045
LTL	127	–	–	0.0042

Table 6
Critical chemical and WF_{grey} of cane plant and cane ratoon for HTL, MTL and LTL.

Technology level	Critical pollutant: plant	Critical pollutant: ratoon	Plant:ratoon cycle [years]	WF_{grey} per year: plant [m^3 t^{-1}]	WF_{grey} per year: ratoon [m^3 t^{-1}]	WF_{grey} (weighted) [m^3 t^{-1}]
HTL	Atrazine	Atrazine	1:4	703	706	705
MTL	Atrazine	Urea	1:5	850	16	155
LTL	Urea	Urea	1:6	16	16	16

Even though WF values cannot be compared because, by definition, the WF is a time-space specific indicator; the green WF obtained is of the same order as results reached by other authors (see Table 7). In general, the variation in the results of blue and grey WF are due to two regional features as mentioned before: (i) rainfed practices are considered and (ii) nitrogen-based fertilizers are not always the critical pollutants. Some remarks about the works in Table 7 follow.

Gerbens-Leenes and Hoekstra (2012) present results for different countries based on statistics. For Argentina, the green WF is similar to the value obtained in this work but the blue and grey WF differ significantly, probably due to the two features mentioned in the previous paragraph. In addition, they provide a global weighted average WF for sugarcane, 205 m^3t^{-1}, which puts Argentina in a good position with a total WF of 125 m^3t^{-1}. Table 7 also shows results obtained by using CROPWAT®. Figures obtained are consistent to those achieved in this work.

Results by Da Silva et al. (2015) are surprisingly low if compared to the work here presented and even to other works from Brazil. As they do not report the crop yield value, if their results are converted to m^3 t^{-1} by using the crop yield from Tucumán, their green WF would be only 10% of the value for Tucumán.

In the case of works by Haro et al. (2014) and Su et al. (2015), the order of magnitude of the values reported for blue WF are much higher than the one from Tucumán because these authors consider growing under irrigation. Those authors having values of blue WF equal to zero consider rainfed, neglecting water associated to agrochemicals dilution and application.

All contributions that calculate grey WF consider N as the critical pollutant.

At this point, and despite the fact that the third step of the WF calculation (WF assessment) is not considered in this work, it is important to make some remarks on the pressure on water resources in the region. This can be done through the analysis of water availability and other water withdrawals which could compete with sugarcane production. Unfortunately, this analysis can only be addressed knowing the lack of studies on WF in other activities of the region.

A rough idea on the water availability of the region can be found in the FAO statistics (AQUASTAT, 2015). In Argentina, the ratio of withdrawn renewable water over all the renewable water resources is less than 10%, of which, the proportion of this extraction for agricultural purposes is 5%. Water for agriculture in Argentina ranges between 50 and 75% of the national water withdrawal. In addition, the Water Stress Index (WSI) defined by Pfister et al. (2009) can also be used to characterize somehow the regional water availability. This index is related to the water consumed that deprives other users of water in the same watershed and it ranges from 0 (no water stress) to 1 (extreme water stress). Through Google Earth it is possible to access a layer on the WSI by Pfister et al. (2009), which shows that, for our region, WSI presents two values, 0.0106 and 0.2311. All these figures represent a relatively high level of water availability. This availability becomes clear by the following fact. As shown in Fig. 3 in the article, the growing period of the crop occurs in the rainy season (November to March), which has two main implications. On the one hand, this water eliminates the need for irrigation, therefore, sugarcane can be grown in rainfed conditions, but on the other hand, it is water that sugarcane absorbs being no longer available to other crops and for the recovery of blue water reservoirs.

Being the area under study an essentially agro-based region, there exist some competition for land and water use with other crops in the province, without considering the water used associated to the industrial activities. The apportion of the cultivated area for different crops is as follows: sugarcane 39%, soybean 28%, wheat 16%, corn 9%, and citrus fruits (lemon) 6% (Soria et al., 2016). Soybean, which rotates with wheat and corn, is a crop with low water requirements. Although it represents a low share of the cultivated area, lemon is one of the most highly valued crops of the province that tends to expand over the sugarcane area, competing both in the use of soil and water.

4. Conclusions

In this work, it was evaluated the appropriation of water by addressing, for the first time, the sugarcane WF in Tucumán, Argentina, taking into account specific characteristics of the crop (cycle duration, phenological stages, climate conditions, etc.). The green, blue and grey WF was estimated by applying and adapting the methodology proposed by Hoekstra et al. (2011). Different TLs are considered for the agricultural practices.

Green WF decreases as the degree of technification increases,

Table 7
Sugarcane *WF* comparison from several authors.

Location	This work	Gerbens-Leenes and Hoekstra (2012)	Haro et al. (2014)	Da Silva et al. (2015)	Pezzi Fachinelli and Pereira (2015)	Su et al. (2015)	Scarpare et al. (2016)	Agnellos Barbosa et al. (2017)	CROPWAT
	Tucumán (Argentina)	Argentina	Tamazula, Mexico	Paraiba (Brazil)	Paranaiba Brazil	Taiwan (farmers)	Tietê/Jacaré, (Brazil)	Southeast Brazil	La Cocha Tucumán (Argentina)
WFgreen [m^3 t^{-1}]	89	95	–	83[a]	151	119	140	52	81
WFblue [m^3 t^{-1}]	0.0072	25	105	0[a]	0	93	0	0	0
WFgrey [m^3 t^{-1}]	703	5	–	21[a]	–	17	22	7	–

[a] Expressed in [m^3 ha^{-1}].

showing similar values to the ones obtained by other authors for the same crop, under rainfed conditions. Blue WF is very low due to rainfed farming practices. Grey WF exhibits higher values for higher TL due to the use of triazine-based herbicides, which are not present in the agrochemical recipe of the LTL. The sometimes direct and sometimes inverse relationship of the WF with the TLs poses interesting trade-offs showing that not always the HTL could be the more sustainable one.

Some recommendations emerge to achieve a more sustainable sugarcane production. (a) It is necessary to further study fluctuations in water availability, including potential irrigation or fertigation, to improve the blue WF estimation to bring cane growers technical advice. (b) As the modification on the application of urea does not produce a significant effect on the grey WF, the attention should be paid on the herbicides. This assessment should include both the type of chemical and the application efficiency (to decrease losses by run-off, leaching and volatilization). (c) It is essential to reinforce the degree of cooperation among the small cane growers in order to achieve a more sustainable sugarcane production.

Additional recommendations will likely appear from a more comprehensive analysis of the local agro-industrial activity, i.e. including agricultural, industrial and transportation stages.

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