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Case study

The water consumed in the production of grapes for vinification (*Vitis vinifera*). Mapping the blue and green water footprint

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ABSTRACT

The aim of this study is to provide information about the green and blue water footprint for the production of the most relevant varieties of grapes, in the five wine-growing regions of the province of Mendoza, and for different irrigation systems. The outcomes show that Bonarda and Syrah are the red varieties that require less water per quintal produced in Mendoza. For the case of white varieties, the one that consumes less water is Pedro Giménez. The greatest values of green water footprint correspond to General Alvear and San Rafael in South region and San Carlos in Uco Valley region, while the lowest values are found in Junín and San Martín in East region. The adoption of pressurized irrigation systems implies savings of 14% water consumed per quintal of grape produced when compared to the surface irrigation system. In addition, the results obtained allow to infer the optimal districts for the production of the different grape varieties from the point of view of the water footprint. This information can assist the decision making process of the winemaking industry in the region, thus contributing to the sector's environmental sustainability related to the use of water.

1. Introduction

The most important environmental problem of this century is climate change and the biggest challenge for humans is to face the related impacts and negative effects derived from it. The KPMG Survey of Corporate Responsibility Reporting states ten global sustainability megaforces that will affect the future of every business (KPMG International, 2012). The first one in the list is climate change, but there are also two more top ten relevant forces in themselves: food security and water scarcity.

Water scarcity is understood as the lack of enough and safe water to develop human activities. The term highlights areas where water resources are under pressure. There are two types of water scarcity: physical and economic. Physical water scarcity occurs when there is not enough water to meet demand, while economic water scarcity is a consequence of the lack of investment or insufficient capability to provide water in areas where the population does not have the monetary means to utilize an adequate source of safe water (White, 2012). In addition, water scarcity can occur even in areas where there is plenty of rainfall or freshwater (WHO, 2010).

Water is required to irrigate crops, and so, to ensure food security. Agriculture is the biggest anthropogenic freshwater consumer activity in the globe. Water that comes either from surface and underground sources, or directly from precipitations, is used to irrigate crops required to feed the growing world population. Water is needed not only to meet the food demand of people and livestock, but also to provide fibers and energy. Clearly, the availability and distribution of freshwater is not homogeneous worldwide: there are abundant water resources in some countries such as Brazil in Latin America, and shortages in others like Ethiopia, Haiti, and Niger, with the least amount of water available (The World Bank, 2010). According to the World Organization of Health (WHO, 2015) by 2025 half of the world's population will be living in water-stressed areas. This is one of the main reasons why, during the last decade, water has become a central issue to evaluate in environmental studies and sustainability assessments.

The use of water in drylands[1] is even more critical than in other type of land. According to the United Nations, "41% of the world's land is occupied by drylands where 2 billion people live. Between 10% and 20% of these lands—more than 4000 million hectares—are degraded or unproductive" (Millennium Ecosystem Assessment, 2005). In

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[1] Drylands are characterized by the aridity index (AI), that is the ratio between precipitation and potential evapotranspiration ((P/ETP) in a definite site (UNEP, 1997). Drylands are divided in: (a) hyper-arid lands, $P/ETP < 0.05$; (b) arid lands, P/PET between 0.05 and 0.20; (c) semiarid lands, P/PET between 0.20 and 0.50; and (d) dry–subhumid lands, P/PET between 0.50 and 0.65 (Civit et al., 2013).

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Argentina, 75% of its territory corresponds to arid, semiarid and dry-subhumid lands (Abraham, 2002). The western provinces of the country have drylands in their whole extension. Particularly, the province of Mendoza has between 96%–97.5% of its total area as dryland. The main agro-economic activities in Mendoza are viticulture and wine production. There are a few studies on the consumption of water in the production chain of the wine sector in Mendoza (such as Dueck and Comellas 2015; Hernández et al., 2013; Civit et al., 2012). However, these studies do not examined variations in the water requirement between different grape varieties or only analyze one region of the province.

The aim of this study is to provide information about the green and blue water footprint for the production of the most relevant varieties of grapes, in the five wine-growing regions of the province of Mendoza, and for different irrigation systems.

There are two main methodologies for accounting and assessing the water footprint of a product. The first one was introduced by Professors Hoekstra and Hung, 2002 A. Hoesktra and P. Hung in 2002 and accounts for the volumes of water used and consumed when making a product (Hoekstra, 2008), considering the water involved in all the production stages. According to this approach, the water footprint of a product is an indicator of the freshwater appropriation considering the direct and indirect water use (Hoekstra et al., 2011). In the case of agriculture products, it represents the amount of water involved in the process of growing crop, which is useful for the allocation of water budgets to different activities. This procedure can also include a sustainability assessment, in which the water footprint is evaluated from an environmental, social and economic perspective. On the other hand, it doesn't assess the impacts associated with the water consumption on availability or degradation.

The second one, was developed within the Life Cycle Assessment framework, designed for understanding the impact derived from water use and water consumption along the lifecycle of a product or a process. It translates the water withdrawals and pollution along a product system into impacts not only on water availability but also on water degradation, such as eutrophication or water toxicity (Ridoutt and Pfister, 2013; Margni et al., 2012). A water footprint profile considers the scarcity index of the region or site where the use of water is taking place (ISO 14046, 2014; Boulay et al., 2013).

In this paper the Hoekstra's approach will be followed for the calculation of the grape's water footprint. The calculation of the water scarcity footprint for the wine production in Mendoza is the next step of this work, together with the development of a loss factor in the upstream processes for the modelling of water footprint in irrigated zones.

2. Materials and methods

Both, the intrinsic characteristics and the specific methodological issues of the system under study, are described.

2.1. Water footprint

The water footprint distinguishes among green, blue and grey water footprint. Green water footprint (WF_{green}) is related to water coming from precipitation temporally stored in soil; blue water footprint (WF_{blue}) indicates the consumption of surface or underground water, and grey water footprint (WF_{grey}) expresses the volume of water needed to dilute pollutants to achieve allowed values in the receiving water bodies (Hoekstra et al., 2011). The sum of WF_{green} and WF_{blue} indicate the total consumption of freshwater (hereinafter referred to as "total water consumption"), while WF_{grey} shows the degradation of water quality. WF_{green} is calculated as the green component in crop water use (CWU_{green}) divided by the crop yield (Y) (Eq. (1)). In a similar way, the WF_{blue} is calculated as the blue component in crop water use (CWU_{blue}) divided by Y (Eq. (2)). CWU_{green} and CWU_{blue} represent the appropriation of freshwater, and are calculated by accumulation of daily evapotranspiration throughout the complete growing period of the crop (see Section 2.5: Water footprint associated to grape production).

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

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

The methodology proposed by Hoekstra et al. (2011) includes four phases: i) setting goals and scope; ii) water footprint accounting; iii) water footprint sustainability assessment; and iv) water footprint response formulation. Not all of this phases are mandatory. In this study considers only up to the water accounting step.

Another useful parameter for the assessment of the water use is the *water productivity* of the crop, defined as the ratio between the amount harvested and the water consumed to produce it, expressed in units of mass/m^3 of water (Hoekstra, 2013).

2.2. Grapes production for winemaking in Mendoza, Argentina

Mendoza is a province located on the Middle West side of Argentina, with drylands over its whole extension (Abraham, 2002). The forecast of surface water runoff for 2016/2017 predicts that the rivers of the province will have a hydrological year between "moderately poor" and "dry", causing the sixth consecutive year of water emergency (DGI, 2016).

Mendoza is one of the Great Wine Capitals together with Adelaide, South Australia (Australia); Bilbao, Rioja (Spain); Bordeaux (France); Cape Town, Cape Winelands (South Africa); Mainz, Rheinhessen (Germany); Porto (Portugal); San Francisco, Napa Valley (United States of America); Valparaíso, Casablanca Valley (Chile); and Verona (Italy) with a growing wine tourism activity related to many wineries. The most recent data available establish that in 2015, Mendoza had 159,649 ha cultivated with vines (*Vitis vinifera*) for making wine, fresh consumption and raisins. The crop cultivation can only occur within the three irrigated oasis, there is not rainfed production at all in Mendoza (Fig. 1). The annual production in 2015 was 16,884,089 Qq[2] (INV, 2016) being Mendoza the main wine producer (around 70%) in Argentina, exporting more than USD 1200 million per year. According to the Cuyo's Observatory Net, viticulture, is responsible of the half of exportations of the agro-industrial products. Agroindustry contributes around 9% of the Geographical Gross Product (GGP) (Pasteris de Solavallone, 2012).

The clear dependency between the economy, wine production, water and climate change in Mendoza has raising a growing concern, from which stemmed the need to know the water footprint of the agricultural stage of wine production, aiming at the sustainable management of this critical natural resource.

2.3. Definition of the study regions and system boundaries

The study follows the regions classification proposed by the National Institute of Viticulture (Fig. 1). In each region we consider only the districts where grapes for vinification have an annual production over 1.5% with respect to the total of Mendoza.

The system boundaries consider only the agricultural stage where grapes are obtained (see Supplementary information, Figure A). A cut-off rule of 0.5% by volume of water was used. That is, the processes such as evaporation, transpiration, irrigation, product integration, in-stream use that consumes less than 0.5% of the total water consumption of the product-system, are excluded from the studý s system boundaries. According to this criterion, the water volume required for application of fertilizers and pesticides and for washing machinery and the harvest boxes is excluded from the blue water calculation. The information

[2] 1 Qq (quintals) = 100 kg = 0,1 t

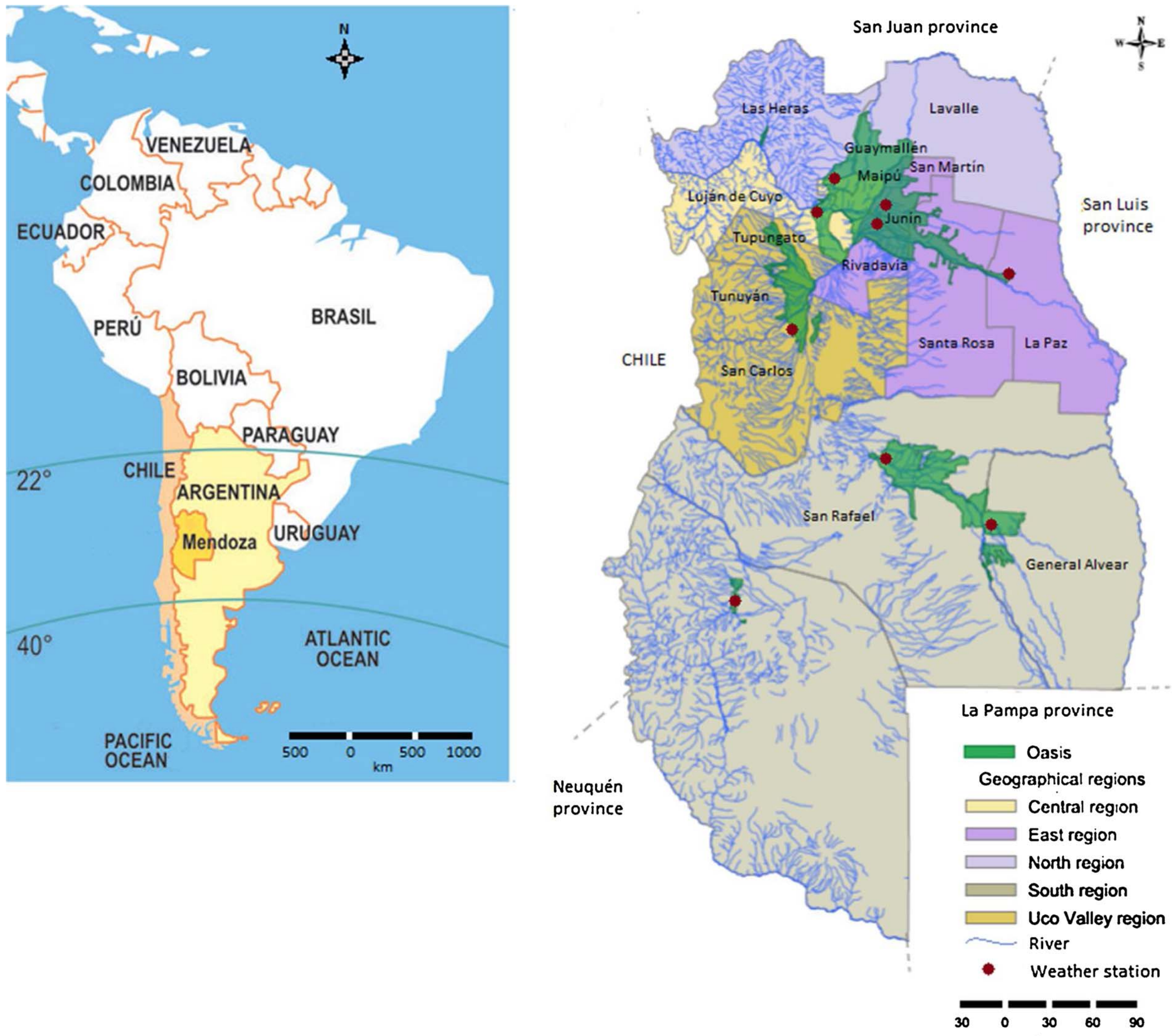

Fig. 1. Location of Mendoza regions and considered weather stations.
Source: Author's elaboration using cartography from IADIZA-CONICET (2014).

regarding to the water consumption associated to these processes was extracted from Cucchi and Becerra (1995); Yaciófano (2016, personal communication).

2.4. Selection of the grape varieties

Based on the extension of the cultivated areas, their yield and their market, the most significant wine varieties cultivated in Mendoza are Malbec, Bonarda, Cabernet Sauvignon and Syrah for red wines; Chardonnay and Pedro Giménez for the white ones. Malbec is most famous grape variety produced in Argentina, and has become so popular that there is even a Malbec Day celebrated every year on April 17th. A threefold increase of the cultivated area of Malbec has been registered between 1993 and 2013, and about 240% increment in production in the same period (INV, 2014). Bonarda is a traditional varietal in the province and the second in importance for amount of quintals produced. The other two red varieties, Cabernet Sauvignon and Syrah are also relevant for their market share. Chardonnay is the highest quality grape that is produced among the white ones, while Pedro Giménez is the one that occupies the first place among the common grapes.

The total production of each variety during the 2001–2010 crop seasons for the all districts and regions considered is shown in Table A of supplementary information (Observatorio Vitivinícola Argentino, 2013).

Grapes destined to produce very high quality wines require special agricultural practices, which lead to a reduction in the skin-pulp ratio and an increase of the concentration of phenols. The most common are thinning of clusters or canopy (about 50%) and regulated deficit irrigation in the last phenological stage of the fruits. These activities can modify the result of the water footprint accounting per unit produced. The production data of all varieties and regions considered in this study take into account these special agricultural practices.

2.5. Water footprint associated to grape production

For determining the crop water use, some specific factors must be calculated, such as *Reference Evapotranspiration (ETo),* defined as the evaporating power of the atmosphere in a specific locality and time of the year corresponding to a hypothetical crop of grass in active growth, with a uniform height of 12 cm, adequately watered, with a surface resistance of 70 s/m and 0.23 albedo (Allen et al., 1998); *Crop Water Requirement (CWR),* defined as “the amount of water required to compensate the evapotranspiration loss from the cropped field” (Allen et al., 1998, p. 9) or in other words “the water needed for evapotranspiration under ideal growth conditions, measured from planting to harvest" (Hoekstra et al., 2011, p131); *Crop Evapotranspiration under standard conditions (ETc)* "is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions" (Allen et al., 1998, p.8). The ratio between ETc/ETo is known as *Crop Coefficient* (Kc), which are experimentally determined and is used to estimate ETc (Eq. (3)).

$$ETc = Kc \times ETo \tag{3}$$

When some agricultural practices are needed to be performed during the crop growth, such as irrigation, the *Crop Evapotranspiration under non-standard conditions* (ETc_{adj}), defined as "the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions" (Allen et al., 1998, p. 9), must to be considered. This is the case of grape cultivation in Mendoza, where the only way to perform agricultural activities is through irrigation. The surface irrigation system is used in 88% of the area planted with grapes (INV, 2012). In this irrigation system the water is applied and distributed over the soil surface by gravity. The remaining area planted with grapes is irrigated by pressurized systems, mostly dripping (INV, 2012). Pressurized systems are used mainly to give different qualities to the grape that will be used for winemaking. Therefore, we consider two irrigation systems in this case study: gravity and dripping. It is necessary to adjust the volume of water consumed by type of the irrigation system used. For surface system, the values of Kc from Allen et al. (1998) are adopted (Kc_{si}). For pressurized system, the crop coefficient is adjusted for irrigated crops under non-standard conditions (Kc_{pi}) as reported by Allen et al. (1998), following the recommendations of Aldaya (2012, personal communications). These adjusted crop coefficients (Kc_{pi}) are needed to calculate the crop evapotranspiration considering the decrease of the soil moisture by evaporation. With the value of evapotranspiration, the real contribution of irrigation water is calculated.

The estimation of ETc and ETc_{adj} requires knowledge of different parameters, as length of crop growth stages, sprouting and harvesting dates, radical depth and crop mean height. In this study, the crop growth cycle is divided into four stages taking 160 days: initial stage with 18 days, crop development stage with 38 days, mid-season stage with 62 days and late season stage lasting 42 days for East and North regions. For Central, South and, Uco Valley regions, 210 days distributed in initial stage (23 days), crop development stage (50 days), mid-season stage (82 days) and late season stage (55 days) (Catania et al., 2007). The sprouting and harvesting dates for each region are specified in Table B of supplementary information. The maximum radical depth reached is 0.8 m and the crop mean height is 1.20 m. This information is assumed to be common to every grape variety produced and regions considered (Allen et al., 1998).

We determine the crop water requirement by means of CROPWAT version 8.0 (FAO, 2000). Climate information was obtained from different weather stations (Fig. 1) belonging to the Direction of Climate Contingencies of Mendoza Government and to the Argentine Air Force, corresponding to the 2001–2010 period. All the calculations were made for that decade, which, on one hand, enables to capture the fluctuations in the local weather that can modify the production. On the other hand, because the maps resulting from this study will be upload on the internet (CCT Mendoza digital repository), so that producers and decision makers can consult them, and they will be updated according to data and projections for the next decade 2011–2020.

The soil parameters were estimated with the Soil Water Characteristics software (USDA, 2009) according to the average soil textures for each district identified by the Soil Laboratory of INTA EEA Mendoza (Hudson and Masotta, 1993). The irrigation calculations were adjusted taking into account application efficiencies of 45% for surface irrigation and 95% for pressurized irrigation, as suggested by Chambouleyron (1999).

Then, we calculated the CWU_{green} and CWU_{blue} by Eqs. (4) and (5) in which ET_{green} and ET_{blue} represent daily green water evapotranspiration and daily blue water evapotranspiration, respectively. We calculated ET_{green} by adopting the minimum value between the ETc and the effective precipitation, and ET_{blue} by the difference between the ETc and the effective precipitation; both for each day of the crop growth period. The sum is made during the period between the day of sprouting (day 1) and the day of harvest (lgc represents the length of the crop growth cycle in days).

$$CWU_{blue} = \sum_{d=1}^{lgc} ET_{blue} \tag{4}$$

$$CWU_{blue} = \sum_{d=1}^{lgc} ET_{blue} \tag{5}$$

With the values of CWU_{green} and CWU_{blue}, we estimate the WF_{green} and WF_{blue} by equations 1 and 2, for each grape variety associated with each region under study, considering the two types of irrigation systems. We express the WF_{green} and WF_{blue} in cubic meters per quintals (m3/Qq), where 1Qq = 100 kg. We chose quintal as mass unit because is the unit commonly used in the wine sector of Mendoza. With the values obtained for WF_{green} and WF_{blue}, maps for each grape variety were carried out. For this, the software gvSIG 2.3 (gvSIG3 Association, 2016) was used.

3. Results

The obtained values of Kc for surface irrigation (Kc_{si}) and the crop coefficient adjusted for drip irrigation (Kc_{pi}) are presented in Table 1. In all cases is observed a decrease of Kc_{pi} with respect to Kc_{si} for all stages of the crop growth. This decrease in Kc_{pi} values is associated with a reduction of the soil moisture evaporation, because the drip irrigation system wets only a fraction of the exposed soil surface and also most of the moistened soil is shadowed by vegetation. The variations in Kc values are transferred to ETc results, and thus to the crop water requirements. Therefore, the water requirement of grapes irrigated by gravity is greater than that of grapes irrigated by drip system. For instance, the water requirement of Malbec irrigated by gravity in Luján de Cuyo is in average 23.6% higher for the initial stage, 17% for the development stage, 12.6% for the middle stage, and 16% for the final stage of crop growth, with respect to Malbec irrigated by dripping (supplementary information, Table C). This example demonstrates the benefits in terms of water savings of drip irrigation.

The maximum values of green water footprint are found in La Paz, San Rafael and General Alvear for Cabernet Sauvignon, Bonarda y Chardonnay; in San Carlos and San Rafael for Malbec and Pedro Gimenez; and in La Paz and San Carlos for Syrah. The lowest values of green water footprint obtained are in Junín and Lavalle, for all grape varieties studied. Figs. 2 and 3 show the results obtained for Malbec and Chardonnay as maps to make easier the interpretation of the results for the general public. The maps of the remaining varieties are presented in the supplementary information (Figures B–D). The values for drawing all the maps are presented in Tables D and E of supplementary information.

In agreement with the variations in the values of Kc for both types of irrigation studied, the blue water footprint results associated to irrigation requirements show less water consumption for the crop under

Table 1
Crop coefficient (Kc) for grapes for vinification, according to the irrigation system.

Crop development stage	Kc_{si} for surface irrigation	Kc_{pi} for pressurized irrigation
Initial stage	0.34	0.26
Mid-season stage	0.79	0.69
Late season stage	0.70	0.56

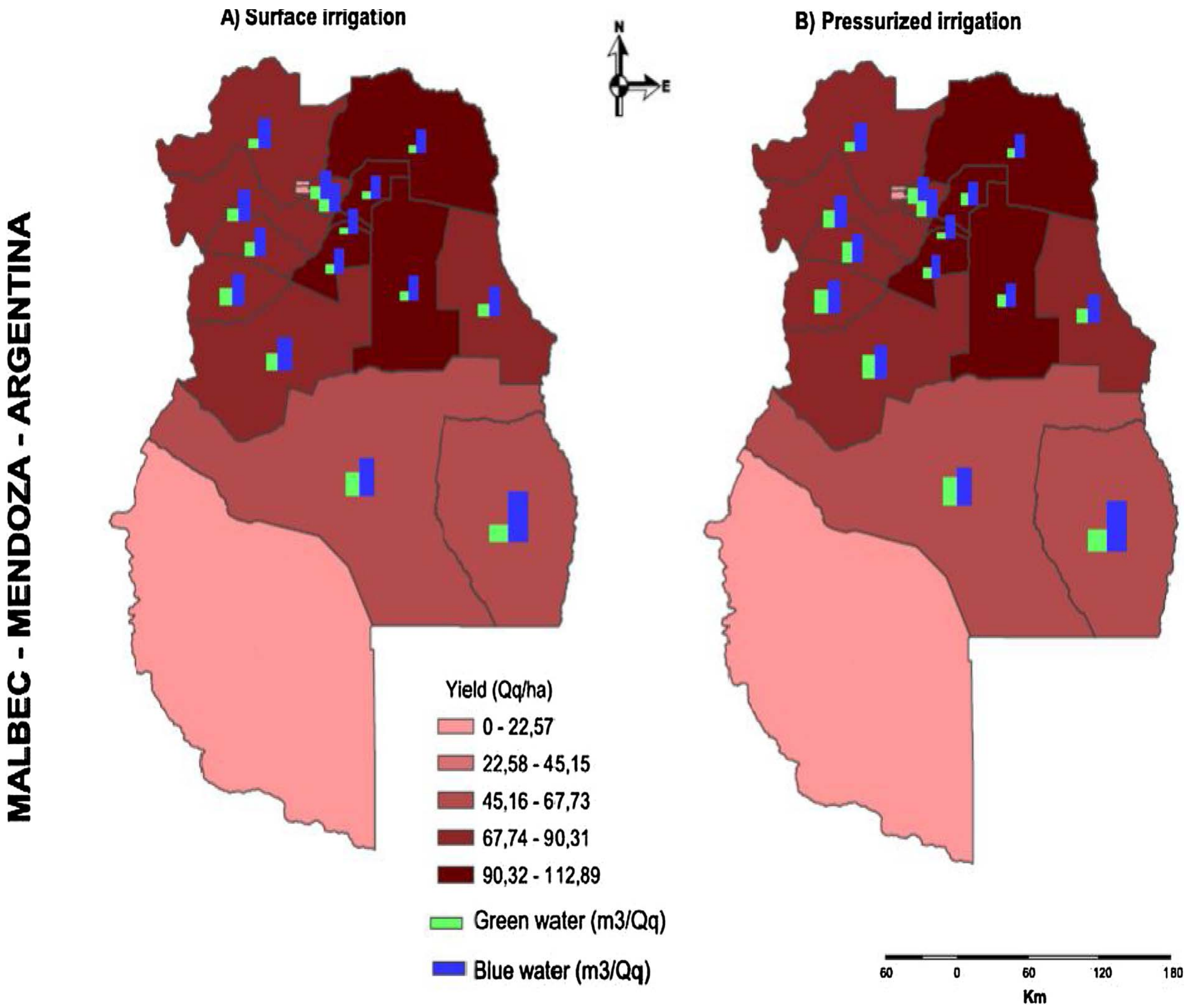

Fig. 2. Water footprint accounting for Malbec under surface and pressurized irrigation, in Mendoza, Argentina.

irrigation by drip than for grapes irrigated by gravity. These reductions in the volume of blue water consumption go from 17% in Junín and Las Heras to 23.7% in all departments of the Uco Valley region. Table 2 shows the reduction of the blue water footprint associated with the implementation of pressurized irrigation instead of surface irrigation, for the variety Malbec. The other grape varieties studied have a similar trend as Malbec.

Of the water consumed during the growing period, green water footprint represents 28% when surface irrigation is applied, and 34% when applying pressurized irrigation, independently from the variety of grapes. That can be explained because the pressurized irrigation system has higher efficiency that surface irrigation system, therefore less blue water is consumed, whereby the proportion of green water footprint increases in relation to the total water consumed.

The white variety with the lowest water consumption per quintal produced is Pedro Giménez. Although this advantage of Pedro Giménez versus Chardonnay occurs in all departments studied, it is most notable when the grape is produced in La Paz, Las Heras, Tupungato and Lavalle, which is manifested in reductions of the blue water footprint of 64.5%, 55.4%, 33.8% and 32.5%, respectively.

For the red varieties, the lowest total water consumption corresponds to Bonarda, except in San Rafael and Guaymallén, where the lowest consumption corresponds to Syrah. The blue water footprint values for Cabernet Sauvignon and Malbec are, on average for all departments, 37% and 26% higher than Bonarda's.

Bonarda, Malbec, Pedro Giménez and Chardonnay varieties require more water when they are produced in General Alvear than when they are grown in other localities of the province. Syrah and Cabernet Sauvignon consume more water when are produced in La Paz, General Alvear and San Carlos than when they are grown in the rest of the localities of Mendoza.

The lowest volumes of total water consumption of Cabernet and Chardonnay varieties were found in San Martín, Rivadavia and Junín. For Pedro Giménez and Malbec, the lowest water consumption was detected in San Martin and Lavalle. Bonarda and Syrah consume less total water when they are grown in the district of Maipú. These values per unit of product are associated with higher crop yields obtained in these districts.

4. Discussion

The water footprint of the grape in Mendoza range between 54.53 m3/Qq and 102.03 m3/Qq, being the crop yield the aspect that mainly affect to the results. The crop yield is largely conditioned by edaphic, climatic and natural factors. For example, there are districts and regions, such as San Rafael, General Alvear, and Uco Valley region, where natural factors such as frost and strong winds cause a decrease in crop yield. In other districts like La Paz, the crop yield is also affected by the salinity of the soils. This reduction in the crop yields increases the water footprint.

The crop yields used in this study are real average values for each department, since at the moment there is no detailed information at the

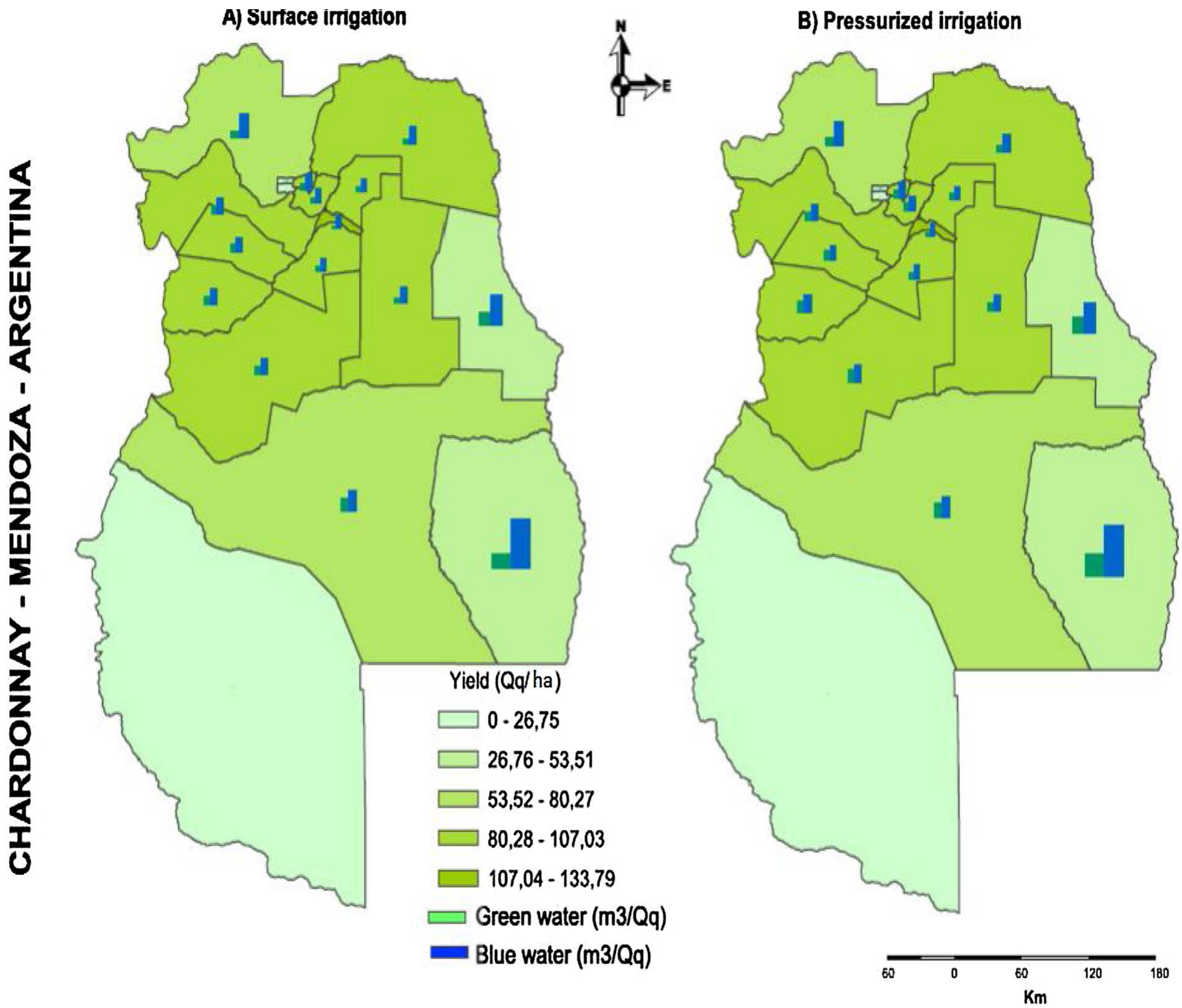

Fig. 3. Water footprint accounting for Chardonnay under surface and pressurized irrigation, in Mendoza, Argentina.

Table 2
Blue water footprint (m^3/Qq) for Malbec in Mendoza, Argentina.

Geographic region	Locations	Surface irrigation	Pressurized irrigation
North	Las Heras	63.97	53.05
	Lavalle	48.39	39.26
Central	Maipú	53.53	42.17
	Luján de Cuyo	62.57	49.29
	Guaymallén	55.51	43.73
East	Santa Rosa	48.56	38.21
	San Martín	46.00	36.20
	Rivadavia	49.15	39.10
	Junín	53.93	44.79
	La Paz	58.18	46.45
South	San Rafael	70.33	57.10
	General Alvear	120.67	95.56
Uco Valley	Tupungato	50.97	38.90
	San Carlos	61.87	47.22
	Tunuyán	61.14	46.67

parcel level. Therefore, the found values of water footprint represent an average for several practices of crop management, including practices that increase wine quality. Consulted experts coincide that, depending on the region, variety and expertise of the agronomist, are the agricultural practices carried out. They also assert that thinning of clusters or canopy could be done in any grape variety, but in Mendoza is more common in Malbec and Cabernet Sauvignon (Puelles, 2016; Yaciófano, 2016; Pérez Peña, 2016; Grassin, 2016, personal communications). On average, a thinning of clusters of 50% when the grapes turn red implies reductions in yield of 35–45% (Dayer et al., 2012). It is evident that this reduction in grape productivity has negative effects on water footprint values. For example, the water footprint per quintal produced of Malbec is between 53.8% and 81.8% higher when thinning of clusters is applied, compared to the value obtained when this practice is not adopted.

The adoption of pressurized irrigation systems provides important water savings compared with the gravity irrigation. Even though only 11.95% of the total area of vines is irrigated by drip systems (INV, 2012), a 14.3% water saving is achieved, representing as much as 17.55 m^3 of fresh water per Qq of grape produced. Taking the Malbec as an example, these savings represent 28,501,260 m^3/year. Civit et al. (2012) show that when drip irrigation is applied instead of surface irrigation, the water savings can reach up to 50%. This extra water consumed when using surface irrigation returns to the water cycle, but is no longer available for other agricultural, industrial and even residential uses.

The weighted average of water footprint of grapes for Mendoza is 582 m^3/t, similar to the results found in other regions. For instance, Lamastra et al. (2014) found, for six grape varieties produced in Palermo (Italy), an average of total water footprint of 580 m^3/t. Pina et al. (2011) obtained a water footprint of 513 m^3/t in Portugal. Herath et al. (2013) found an average of water consumption (green and blue) of 643 m3/t for two regions of New Zeland. The global average presented by Mekonnen and Hoekstra (2011); Mekonnen and Hoekstra (2010) is 608 m^3/t. While Ene et al. (2013) found higher values of total water (1189 m3/t) for grape produced in Romania. The difference between the results of Ene et al. and those found in this study are mainly due to the low levels of crop yields in Romania. Romanian yields are low mainly because the agricultural technology implemented is old, in addition to the influence of natural factors, such as droughts, floods, attacks of pests and diseases. In Mendoza, the adopted agricultural technology is very advanced, reason why this factor does not condition the yield of the crops. In all those studies more than 70% of the water involved corresponds to green water while in Mendoza the green water is the smallest portion. The highest values of green water footprint for all varieties of grape studied are recorded in districts where annual average rainfall is higher. This shows that rainfall occurs during periods of crop growth that require more water. The values of green, blue and the total water consumption found in this study for Malbec in Luján de Cuyo are similar to those published by Hernández et al. (2013) in the same region.

Different variables and aspects influence the choice of the best place to produce grapes for vinification, but not always water efficiency and water productivity are considered among them. Efficient use of water is essential for understanding the sustainability of the wine production, thus it is important to reduce the amount of water per produced unit. The most recommended districts to cultivate grapes in Mendoza, from this point of view, are:

- San Martín, Rivadavia, Junín and Las Heras for Cabernet;
- Lavalle and San Martín for Malbec;
- Maipú and San Martín for Bonarda;
- Maipú and Guaymallén for Syrah;
- San Martín, Rivadavia and Junín for Pedro Giménez and Chardonay.

It is remarkable the great aptitude of San Martín to produce all the grape varieties considered in this study, while General Alvear is the least suitable for that purpose.

Lavalle presents also good conditions for the production of Pedro Giménez, from the water productivity point of view, Known as the "National Capital of Homemade Wine", they give added value to these wines, with the label and the brand, valuing the origin, the family tradition and sustainability practices.

While these results could be used to give recommendations for the production of a given grape variety, the water productivity is clearly not the main issue for making decisions on this regard. For example, from the obtained results it is inferred that Malbec produced in the North region of Mendoza would be more "water use efficient" than in other regions. However, the best Malbec is elaborated in the Uco Valley, Luján de Cuyo and Maipú, where the better terroir conditions give the characteristic taste of this variety. The water footprint indicator is then useful to identify strategies to improve the water productivity.

5. Conclusions

The main contribution of this paper is to provide detailed information with scientific support on the consumption of water in each of the districts of Mendoza of the more important varieties of grapes to vinificate. The results provide useful information for winemakers and eventually for consumers, allowing them to choose the most benign options from the water use point of view, in accordance with the objectives of sustainable development.

As derived from results, the edaphoclimatic characteristics of each region as well as the natural factors such as frosts and winds are the aspects that mainly affect the water footprint of grapes, since they condition the performance of each variety. We also found that the implementation of pressurized systems causes reductions of the water footprint of up to 23.7% in relation to the surface systems.

The terroir conditions of certain areas of Mendoza determine the high quality of its wines, and are the main drivers for this industry. Besides, the identification of the districts and the irrigation technologies that determine lower water footprint for each variety is another relevant issue of the location of the grape production. A sustainable decision making process should consider both the quality of the wines and the preservation of the environment. The adoption of pressurized irrigation systems in high terroir quality districts can help providing such combination of wines with high quality and low water footprint.

A similar analysis could be extended to all the wine producer regions in Argentina, in order to obtain a water footprint map of the Argentine viticulture.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.10.037.

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