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Agricultural Water Footprint of Southern Highbush Blueberry Produced Commercially with Drip Irrigation and Sprinkler Frost Protection

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Abstract

A study was conducted from 2010 to 2017 to determine the water footprint for producing blueberries in the Entre Ríos province of Argentina. Three cultivars of southern highbush blueberry (hybrid cross of *Vaccinium* sp.) were evaluated in the study, including "Star", "Emerald", and "Snowchaser". In each case, the plants were irrigated by drip and protected from frost using overhead sprinklers. Water requirements for irrigation and frost protection varied among the cultivars due to differences in the timing of flowering and fruit development. The annual water footprint for fruit production in each cultivar is expressed in units of cubic meters of water used to produce one ton of fresh fruit and ranged from 212 - 578 $m^3 \cdot t^{-1}$ for "Star", 296 - 985 $m^3 \cdot t^{-1}$ for "Emerald", and 536 - 4066 $m^3 \cdot t^{-1}$ for "Snowchaser". "Snowchaser" flowered earlier than the other cultivars and, therefore, needed more water for frost protection. "Star", on the other hand, ripened the latest among the cultivars and required little to no water for frost protection. Frost protection required a minimum of 30 $m^3 \cdot h^{-1}$ of water per hectare and in addition to drip irrigation was a major component of the water footprint.

Keywords

Blue, Green, and Grey Water, Freeze Damage, Irrigation Efficiency, Microirrigation

1. Introduction

The United Nations consider water security as the "capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN-Water 2013) [1]. However, the definition is broad and does not define the parameters for its application. For that reason, Hoekstra and Hung (2002) [2] proposed the concept of the "water footprint" as a means to evaluate utilization of freshwater resources for human activities, including agriculture. The concept addresses both water use and water source and is defined as the amount of water necessary to produce a unit of a particular product (Hoekstra *et al.* 2011 [3]; Lovarelli *et al.* 2016 [4]).

In irrigated agriculture, the water footprint is expressed as the volume of fresh water utilized for production of a crop and for diluting any pollutants produced during the production process. Water may include irrigation from surface and underground water sources, referred to as blue water; rainfall that infiltrates into the unsaturated soil layer and is available for crop growth, defined as effective precipitation and referred to as green water; and any water contaminated during the production process, referred to as grey water. When a crop receives full irrigation, green water is calculated first and is equal to the effective precipitation during the growing season, and blue water is subsequently derived using green water. Unlike blue and green water, grey water is difficult to measure and has not been well studied in most cropping systems.

Most blueberry (*Vaccinium* sp.) fields in Argentina are irrigated by drip, and a large number are equipped with sprinkler systems for frost protection during flowering and fruit development (Pannunzio 2010) [5]. The need for a blueberry crop to produce during the months of September, October, and November, against the fruiting season in the northern hemisphere, implies that blooming occurs during periods of high risk for freeze damage. Freezes in the region are primarily due to radiation frosts, which occur during thermal inversions, and in some cases from advective freezes or a mix of both. Typically, overhead sprinklers are used in Argentina to protect blueberries from damage during a frost or freeze. For the purposes of calculating the water footprint, we considered any water used for frost protection as grey water.

Knowledge of the water footprint is useful for developing irrigation management practices for blueberry and for improving water productivity, sustainability, and competitiveness in production of this crop (Holzapfel *et al.* 2009) [6]. The concept has been applied to numerous agricultural commodities, including farm animals and their byproducts (Mekonnen and Hoekstra 2011) [7], mangoes (*Mangifera indica* L.) (Ridoutt *et al.* 2010) [8], kiwifruit (*Actinidia deliciosa* L.) (Deurer *et al.* 2011) [9], and potatoes (*Solanum tuberosum* L.) (Herath *et al.* 2014) [10]. In Argentina, the subject was approached by Morábito (2012) [11] for grapevines (*Vitis vinifera* L.) produced in the Mendoza region and by Marano and Filippi (2015) [12] for rice (*Oryza sativa* L.) produced in the Entre Ríos region. In 2014, the Water Authority of Buenos Aires [13], Argentina incorporated the water footprint concept into their management plans to establish the cost of irrigation water for all farmers.

The objective of the present study was to determine the water footprint for producing various cultivars of southern highbush blueberry (hybrid cross of *Vaccinium* sp.) in Concordia in the Argentine Republic. Each cultivar was irrigated by drip and protected from frost damage using overhead sprinklers.

2. Material and Methods

2.1. Description of Study Site

The study was conducted from 2008 to 2017 at a commercial farm located in the province of Entre Ríos, Argentina (**Figure 1**). The cultivars selected for study included "Star" and "Emerald", which were planted in lot 7 at the farm in 2008, and "Snowchaser", which was planted in lot 13 in 2009. Plants were grown on raised beds (0.3 m high × 0.80 m wide) and spaced 0.9, 1.0, and 0.85 m apart within rows of "Star", "Emerald", and "Snowchaser", respectively. "Emerald" is a

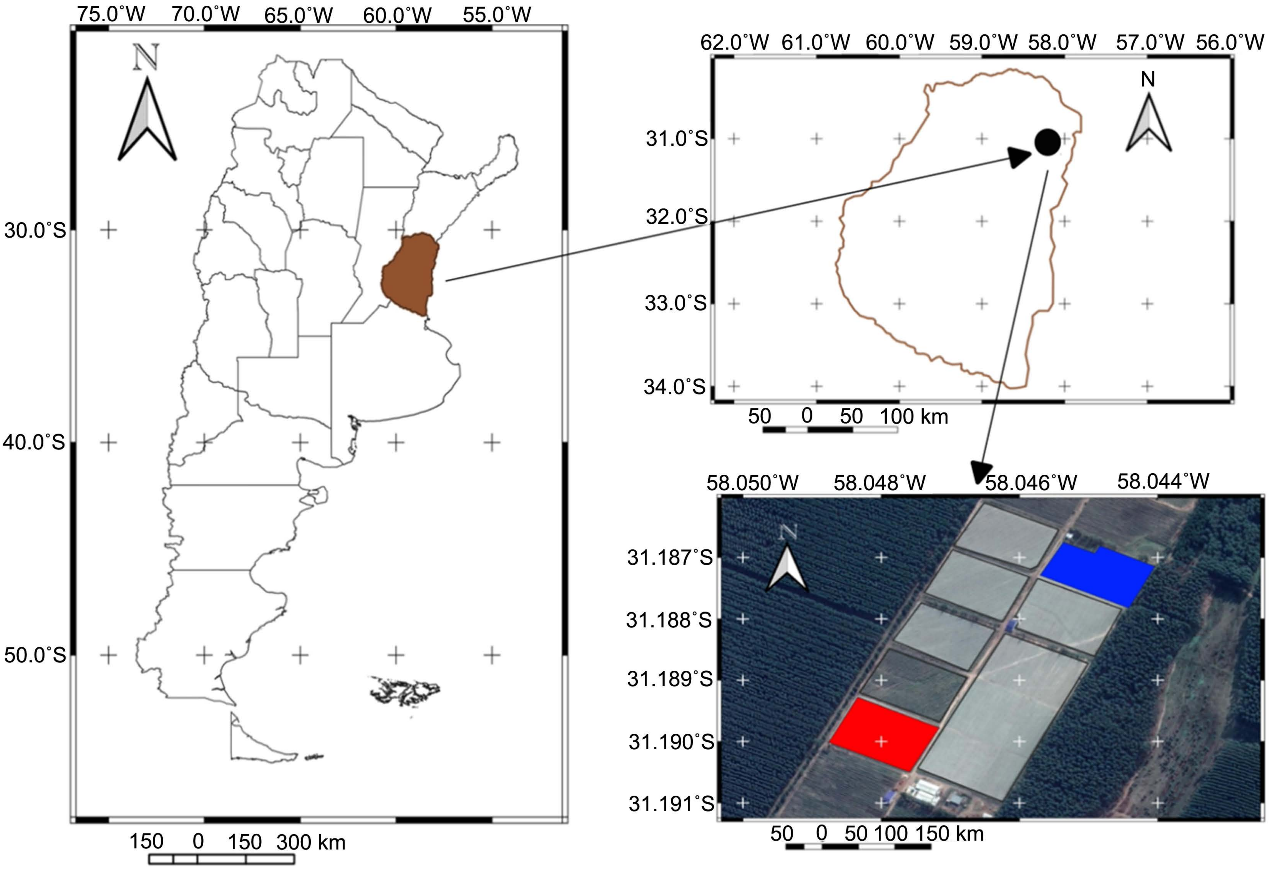

Figure 1. Geographical location of the study site in the Entre Ríos province of Argentina. The areas highlighted in blue and red represent lot 7 and 13, respectively.

vigorous cultivar and, therefore, requires more distance between plants than "Star" and "Snowchaser". Rows were centered 3.5 m apart. Each cultivar was managed using an evergreen system, which included avoiding defoliation of the plants during the winter and maintaining fertigation with liquid sources of N throughout the year. The raised beds were mulched with 300 $m^3 \cdot ha^{-1}$ of slash pine (*Pinus elliotii* Engelm.) bark and a layer of 30-µm polyethylene plastic. Canopy cover varied throughout the year due to post-harvest pruning and reached up to 80% of the total field area during harvest in "Emerald" and "Snowchaser" and 65% of the total field area during harvest in "Star".

Both fields at the site contained quartz-oxic, ancient alluvial, reddish sandy soils, which overlaid more clayey materials. Texture was finer at deeper depths and ranged from loamy sand to loam in the top 0.6 m of the soil profile (**Table 1**). Electrical conductivity (EC) of the soil was low and averaged 0.2 and 0.3 $dS \cdot m^{-1}$ in lot 7 and 13, respectively.

2.2. Irrigation and Frost Protection

Each cultivar was irrigated using two laterals of drip tubing per row. The tubing had in-line 1 $L \cdot h^{-1}$ emitters (labyrinthine type, turbulent flow) every 0.3 m. The system generated a continuous band of wet soil on the beds, with a maximum width of 0.80 and 0.85 m at a depth of 0.1 m in lot 7 and 13, respectively. Irrigation was scheduled based on soil matric potential, which was measured daily using tensiometers.

Mini-sprinkler systems were installed on the farm for frost protection. The sprinklers (225 $L \cdot h^{-1}$ flow rate) were staggered at a distance of 9.5 m within every third row in each cultivar. Once fully pressurized, the system provided full coverage and applied 2.25 mm of water per hour, which under calm conditions prevented freeze damage at temperatures as low as −2.9˚C (Burgos 1963 [14], Cline and Fernández 1998 [15], Conlan *et al.*, 2018, [16] Smith, 2019 [17], Kunwar and Fonsah, 2022 [18]). The average flow rate applied for freeze protection in each plot was 30 $m^3 \cdot h^{-1}$ per hectare. Prior to 2016, the sprinkler systems were initiated for frost protection at temperatures of 1.5˚C, which often resulted in

Table 1. Composition and texture of the soils at the study site in the Entre Ríos province of Argentina.

Lot	Depth (m)	Sand (%)	Silt (%)	Clay (%)	Texture
7	0 - 0.2	82.5	11.0	6.5	Loamy sand
7	0.2 - 0.4	76.0	12.5	11.5	Sandy loam
7	0.4 - 0.6	57.5	13.5	29.0	Sandy loam
13	0 - 0.2	64.5	19.0	16.5	Sandy loam
13	0.2 - 0.4	57.0	16.5	26.5	Sandy loam
13	0.4 - 0.6	49.0	19.5	31.5	Loam

unnecessary water use for many hours. Later, 0.5˚C was used as the threshold temperature for frost protection in each cultivar, starting at 10% bloom. The sprinklers were run continuously during each frost event and were operated until the sun was shining and ambient temperature was >1˚C. Otherwise, damage to the plants would have been considerable and, in some cases, could have resulted in complete loss of the crop.

Water used for irrigation and frost protection was pumped from five wells on the farm. The volume delivered by each well was measured daily using volumetric water meters. Electrical conductivity of the water averaged 0.3 $dS \cdot m^{-1}$.

2.3. Fruit Harvest

Each cultivar was harvested by hand in 2010-2017. "Star" and "Emerald" rarely exceeded 14 weeks of harvest, whereas "Snowchaser" took about 25 weeks to harvest. Harvest began in July for "Snowchaser", in early September for "Emerald", and in late September for "Star". Fruit was weighed on each harvest date to determine the total yield in each cultivar.

2.4. Water Footprint

The water footprint for each cultivar was calculated following methods proposed by Hoekstra *et al.* (2009) [19]. The water footprint indicator for product, in this case blueberries, is the sum of three components, including the blue, green, and grey water footprints. Each was calculated annually by dividing crop water use ($m^3 \cdot ha^{-1}$) for each respective component by total crop yield ($t \cdot ha^{-1}$) in a given year. Green water use (*i.e.*, evapotranspiration of rainfall) was equated to the amount of total crop evapotranspiration (ET_c) provided by effective rainfall (P_{eff}), while blue water use was equal to the difference between ET_c and P_{eff}. For each cultivar, ET_c was calculated daily by multiplying potential evapotranspiration (ET_o) by a single crop coefficient (K_c) for blueberry and adjusted for canopy size as needed (Bryla 2011 [20]; **Table 2**). ET_o was determined by the FAO Penman-Monteith method (Allen *et al.* 1998 [21]) using data downloaded from an agricultural weather station located 5 km away from the site in Salto Grande (http://www.inia.uy/gras/Clima/Banco-datos-agroclimatico [22]). P_{eff} was estimated using the U.S. Department of Agriculture Soil Conservation Service method (USDA Soil Conservation Service 1993 [23]) and adjusted for water storage capacity based on an average rooting depth of 0.4 m for each cultivar (Dastane 1974 [24]). Grey water use was determined by measuring the amount water used for frost protection. Usually, grey water also includes the volume of irrigation water needed to wash salts and other contaminants from the soil profile (Hoekstra *et al.* 2009 [19]); however, precipitation was more than adequate to leach the soil at the site and maintain EC well below the threshold for salinity damage in highbush blueberry (<1.5 $dS \cdot m^{-1}$; Machado *et al.* 2014 [25]; Patten *et al.* 1989 [26]).

Table 2. Average monthly potential evapotranspiration (ET_o), crop coefficients (K_c), and crop evapotranspiration (ET_c) of "Star", "Emerald", and "Snowchaser" blueberry in the Entre Ríos province of Argentina (2009-2017).

Month	ET_o	Star		Emerald		Snowchaser	
		K_c	ET_c	K_c	ET_c	K_c	ET_c
January	179	0.9	161	0.8	143	1.1	197
February	148	0.9	133	0.8	118	1.1	162
March	117	0.8	93	0.7	84	0.9	105
April	74	0.7	52	0.7	52	0.8	55
May	41	0.4	17	0.7	29	0.8	33
June	31	0.1	3	0.7	22	0.8	25
July	36	0.1	4	0.7	25	0.6	21
August	57	0.1	6	0.7	40	0.8	45
September	85	1.1	94	1.0	82	1.2	102
October	117	1.2	141	1.0	113	1.2	141
November	151	1.0	151	0.8	121	1.1	166
December	174	0.9	157	0.8	139	1.1	192
Total	1210	-	1012	-	968	-	1244

3. Results and Discussion

3.1. Water Contributions by Rainfall

Total precipitation at the study site ranged from 604 to 1545 mm·year^{-1} in 2010-2017 (**Figure 2**). Effective use of precipitation was considerably less and ranged from 246 to 512 mm·year^{-1} in "Star", 259 to 590 mm·year^{-1} in "Emerald", and 303 to 787 mm·year^{-1} in "Snowchaser". "Star" had no leaves in August and, therefore, used little to no rainwater during the winter. "Emerald", on the other hand, was in bloom in late July to early August, while "Snowchaser" had a full canopy in August and was ready for harvest. Consequently, these latter two cultivars utilized an average of 26% and 46% more rainwater, respectively, than "Star".

3.2. Frost Protection

Star' required less frost protection each year than "Emerald" and "Snowchaser" (**Figure 3**). That was because "Star" flowered in late August to September and only required frost protection in colder years. Regardless of whether the critical temperature was set at 1.5˚C or 0.5˚C, frost protection was only needed for 8 days or less each year in "Star" and was unnecessary in this cultivar during the third year and final 3 years of the study. In contrast, frost protection was needed for 1 - 15 days per year in "Emerald" and 2 - 18 days per year in "Snowchaser".

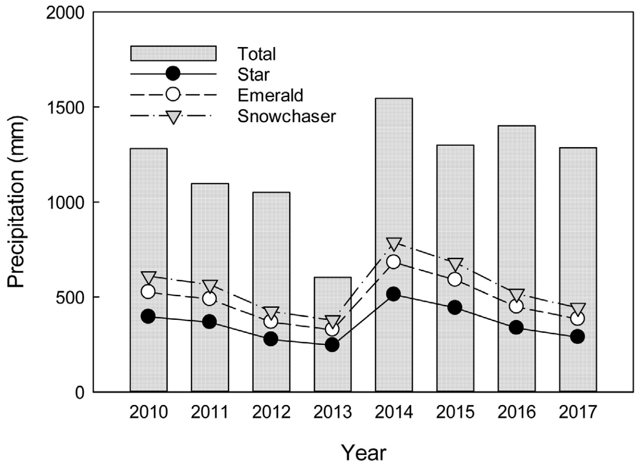

Figure 2. Total and effective amount of precipitation used by "Star", "Emerald", and "Snowchaser" blueberry in the Entre Ríos province of Argentina.

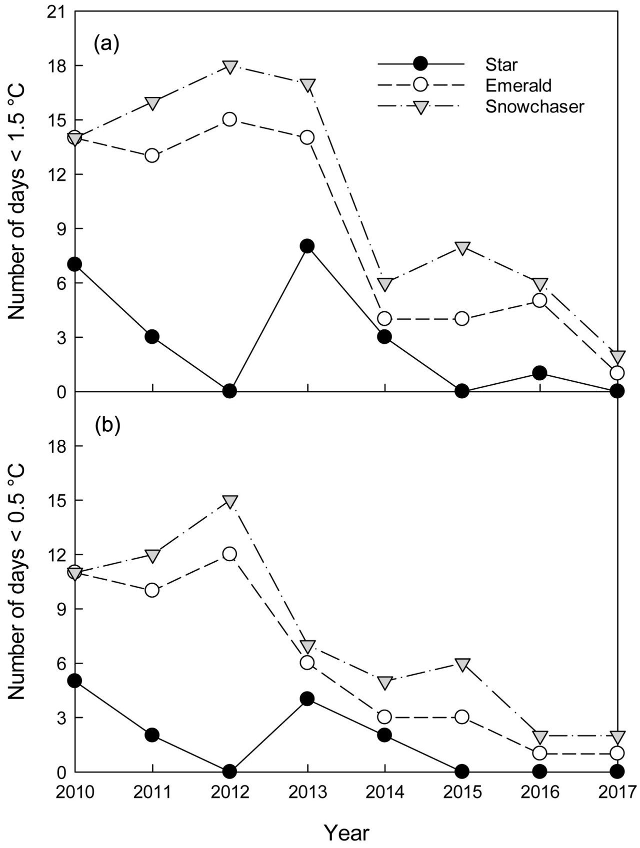

Figure 3. Number of days in which ambient air temperature was below a critical threshold of 1.5˚C (a) and 0.5˚C (b) during flowering and fruit set in "Star", "Emerald", and "Snowchaser" blueberry in the Entre Ríos province of Argentina.

"Snowchaser" flowered in June and July each year and required frost protection during the entire blooming period. "Emerald" flowered in late July to early August and also required frost protection during blooming.

3.3. Water Use

Blue water use was similar among the cultivars and ranged from average of 844 to 1639 m^3 ha^{-1} of water per year (**Figure 4(a)**). In contrast, green water use differed considerably among the cultivars due primarily to differences in P_{eff} (**Figure 4(b)**). In this case, values ranged from 2455 to 7869 $m^3 \cdot ha^{-1}$ of water and, on average, were 15% higher in "Snowchaser" than in "Emerald" and 34% higher in "Emerald" than in "Star". Grey water use also varied considerably among the cultivars, which in this case was due to differences in frost protection (**Figure 4(c)**). On average, grey water use accounted for 17%, 36%, and 44% of total water use in "Star", "Emerald" and "Snowchaser", respectively.

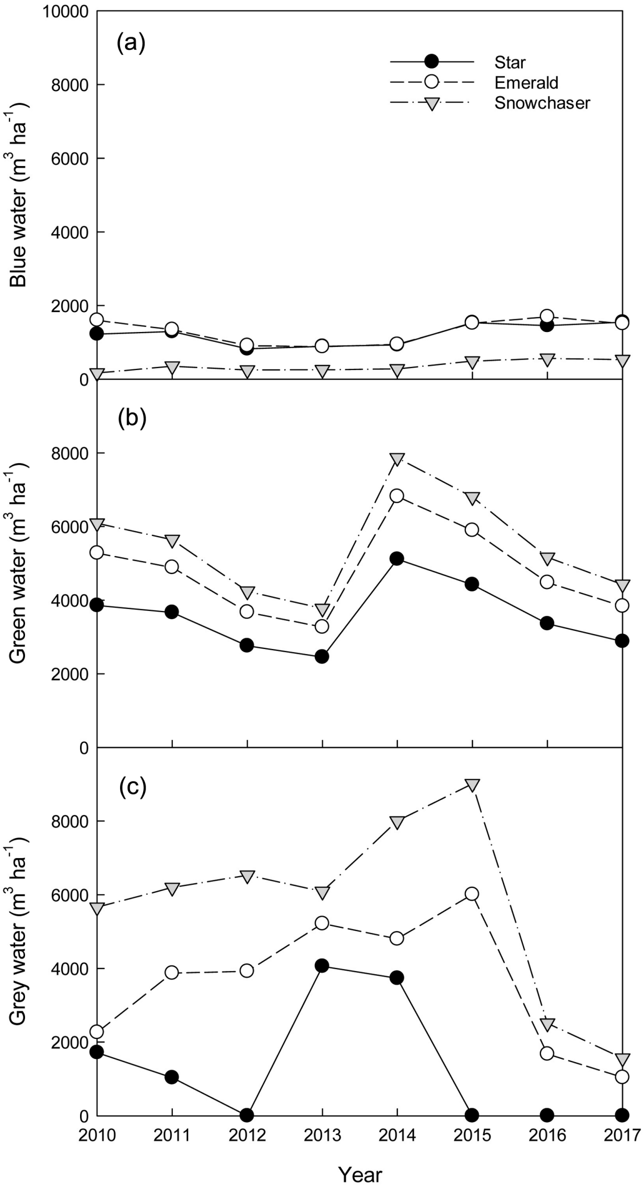

Figure 4. Total amount of blue (a), green (b), and grey (c) water required per year by "Star", "Emerald", and "Snowchaser" blueberry in the Entre Ríos province of Argentina.

Initially, total consumptive water use was higher in "Emerald" and "Star" than in "Snowchaser", which was planted a year later than the other cultivars. However, "Star" lost most of its leaves during the winter and, therefore, once mature, had lower total water use than "Emerald" and "Snowchaser". Dourte *et al.* (2010) [27] likewise found that water use declined sharply after summer pruning of "Star" blueberry in Florida, USA. Overall, "Star" used the least amount of water per year among the cultivars, ranging from a low of 3587 $m^3 \cdot ha^{-1}$ in 2012 to a high of 9786 $m^3 \cdot ha^{-1}$ in 2014. "Snowchaser", on the other hand, used the most amount of water among the cultivars, ranging from a low of 7655 $m^3 \cdot ha^{-1}$ in 2017 to a high of 17,369 $m^3 \cdot ha^{-1}$ in 2015. High water use in this latter case was due to frequent applications of water for frost protection (**Figure 4(c)**); however, frost protection was only needed for 6 - 8 days in 2015 (**Figure 2**), indicating that water use would have been less that year had the sprinklers been managed properly. On average, total water use in "Snowchaser" was 104% higher than in "Star" and 28% higher than in "Emerald".

3.4. Yield

Yield varied over time in each cultivar and averaged 10.3 - 21.2 $t \cdot ha^{-1}$ per year in "Star", 8.8 - 22.2 $t \cdot ha^{-1}$ per year in "Emerald", and 3.5 - 21.5 $t \cdot ha^{-1}$ per year in "Snowchaser" (**Figure 5(a)**). Initially, yield was low in "Snowchaser" but was

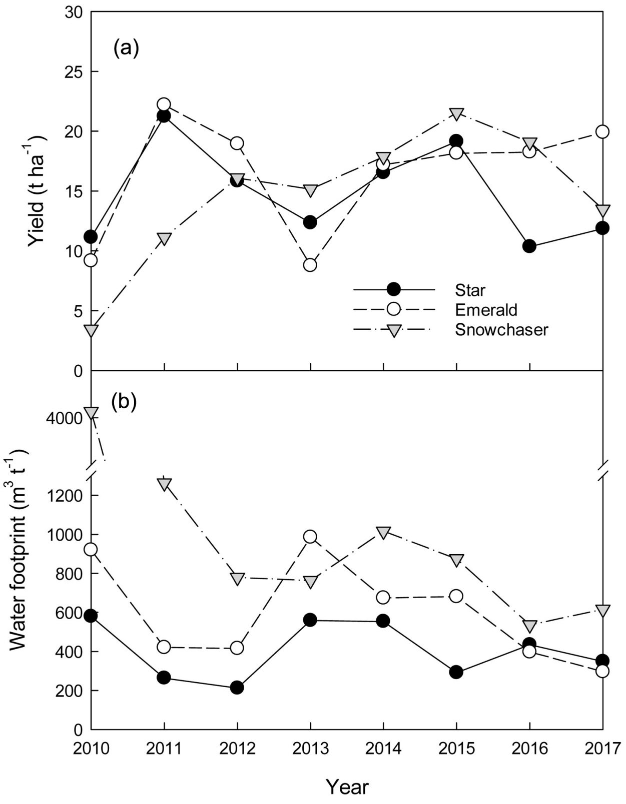

Figure 5. Yield (a) and the water footprint (b) of "Star", "Emerald", and "Snowchaser" blueberry in the Entre Ríos province of Argentina.

similar to the other cultivars once each of the plantings reached full production in 2012. Yield was also low in "Emerald" in 2012 due to frost damage and was low in "Star" in 2016 due to problems with the irrigation pump during fruit ripening. On a single plant basis, yield averaged 3.1 - 7.8 kg·plant^{-1} in "Emerald", which was similar to production of this same cultivar in Florida, USA (4.6 - 7.2 kg·plant^{-1}; Williamson *et al.* 2015) [28].

3.5. Water Footprint

The water footprint varied considerably among the cultivars and ranged from a total of 212 to 579 m^3·t^{-1} in "Star", 296 to 985 m^3·t^{-1} in "Emerald", and 536 to 4066 m^3·t^{-1} in "Snowchaser" (**Figure 5(b)**). The value was initially high in "Snowchaser" due to the young age of the planting, which was 2 years old in 2010. At that point, the plants produced only 3.5 t·ha^{-1} of fruit but required a considerable amount of water for irrigation and frost protection (**Figure 4(b)** and **Figure 4(c)**). Mekonnen and Hoekstra (2011) [7] estimated the global water footprint for blueberry was 845 m^3·t^{-1}, which was similar to "Snowchaser" (886 m^3·t^{-1} in 2011-2017) but 41% and 109% higher than the 8-year averages in "Emerald" (599 m^3·t^{-1}) and "Star" (405 m^3·t^{-1}), respectively. However, in their case, they calculated that 170 m^3·t^{-1} was allocated to grey water use due to leaching of NO_3-N from the root zone. In our case, we assumed that NO_3 leaching was minimal at the site because the plants were fertigated with NH_4 sources of N (*i.e.*, ammonium sulfate and urea), the primary form of N acquired by ericaceous plants, such as southern highbush blueberry (Merhaut and Darnell 1995) [29]. Ammonium-N is immobile in soil and not readily leached; however, even under low pH conditions, NH_4-N is readily converted to NO_3-N in blueberry fields (Hanson *et al.* 2002 [30]; Bañados *et al.* 2012 [31]). In a study in Oregon, USA, NO_3-reached levels as high as 157 mg·L^{-1} in the soil solution when northern highbush blueberry (*V. corymbosum* L.) plants were fertigated weekly with liquid urea (Bryla *et al.* 2010) [32]. Presumably, most NO_3-N in a blueberry field is leached from the soil during periods of heavy precipitation, which in the present study occurred primarily during November through April (**Table 3**). Therefore, the contribution of grey water to the water footprint was likely higher than estimated in the present study and warrants further investigation into NO_3 leaching in highbush blueberry.

Mekonnen and Hoekstra (2011) [7] also calculated the global water footprints for blue and green water in blueberry and estimated that 334 and 341 m^3·t^{-1} was allocated to these components of water use, respectively. The blue water footprint was much lower in the present study, averaging only 94 m^3·t^{-1} over each year and cultivar. In the Entre Ríos province of Argentina, most crops, including blueberry, require very little irrigation during the summer, which reduces blue water use in the region considerably. The green water footprint, on the other hand, was similar to the global average for blueberry and averaged 362 m^3·t^{-1} over each year and cultivar. Based on a theoretical analysis, Cifuentes and Merino

Table 3. Monthly precipitation measured at the study site in Concordia, Entre Ríos province of Argentina.

Month	Precipitation (mm)								
	2009	2010	2011	2012	2013	2014	2015	2016	2017
January	52	189	76	22	50	150	171	68	98
February	130	492	156	351	138	247	51	170	292
March	55	102	86	130	90	152	27	68	232
April	67	70	173	0	47	258	22	610	196
May	10	83	90	32	94	49	80	36	199
June	43	24	71	0	0	60	44	74	40
July	30	49	73	21	28	32	0	101	73
August	60	27	99	215	20	8	271	55	0
September	180	80	80	0	25	39	55	0	0
October	0	31	66	0	50	108	50	98	155
November	424	17	59	0	62	141	174	44	63
December	108	117	68	279	0	301	354	76	102
Total	1159	1281	1097	1050	604	1545	1299	1400	1450

(2013) [33] estimated that blueberry requires 400 - 800 m^3 of water to produce a tonne of fruit in different regions of Chile. In their case, estimated water use was much higher in northern regions of the country due to the arid climate.

The data obtained from each cultivar reflect the difficulties and benefits they have with regards to water use. For example, "Snowchaser" had the highest water footprint among the cultivars due to early flowering and its extended harvest season. "Star", on the other hand, which bloomed later in the season, required much less water than the other cultivars for frost protection. In fact, this cultivar required no frost protection in 4 out of 8 years in the study. "Star" was introduced into Argentina more than 15 years ago. Berries from this cultivar are softer than those from the other cultivars, but its high productivity and the date in which it produces fruit are strengths that continue to make it a popular choice for many plantations in the country. "Emerald" is also a highly productive cultivar but requires more water for frost protection than "Star". Currently, "Emerald" is one of the most widespread cultivars in Argentina due to the fact that it produces the majority of its fruit during highly profitable market windows.

Aside from cultivar selection, other means could be used to reduce the water footprint in blueberry. One option is to avoid early cropping and eliminate the need for frost protection during the first year or two after planting. In addition to reducing water use, delayed cropping increases vegetative growth during establishment and can result in higher cumulative yields over time in certain cultivars (Strik and Buller 2005) [34]. Growers could also use alternative methods of frost protection, such as heaters or wind machines (Snyder and Melo-Abreu 2005) [35]. Such methods eliminate any need of water for frost protection but are usually more expensive to set up and operate than sprinkler systems. A third option is to use best management practices for frost protection, including good site selection, proper pruning and irrigation, and use of frost alarms and models (Snyder and Melo-Abreu 2005) [35]. Typically, lower areas in the local topography have colder temperatures and hence are at more risk for freeze damage than higher areas. Removal of trees and brush from around the field to improve air circulation will allow gentle breezes to penetrate the planting, displacing colder air with warmer air from higher locations during a frost. In highbush blueberry, flower buds on short, small-diameter shoots will open and become susceptible to freeze damage sooner than flower buds on larger diameter shoots (Cline and Fernandez 1998) [15]. Pruning to a balanced mix of early blooming and later blooming shoots will help ensure a crop if a frost or freeze occurs. Dry soils inhibit heat transfer and storage and, therefore, frost protection is improved by wetting the soil in days prior to a predicted frost event (Monteith and Unsworth 2013) [36]. Finally, both frost alarms and models are useful for determining when to operate sprinkler systems during a frost or freeze, using water only as needed. Cold hardiness models were recently developed for frost protection of northern highbush blueberry in Washington, USA (https://weather.wsu.edu/) [37]. Each practice listed above can help reduce the volume of water used for frost protection and hence diminish the water footprint in regions prone to freeze damage.

4. Conclusion

The water footprint differed considerably among three cultivars of southern highbush blueberry in the present study, including "Star", "Emerald", and "Snowchaser". These cultivars are commonly grown in the Entre Ríos province of Argentina. Blue water use was similar among the cultivars, while green and grey-water use varied due to differences in leaf senescence and flowering. "Snowchaser" bloomed at the beginning of winter and required more grey water for frost protection than "Emerald" and "Star", which bloomed later. "Star", on the other hand, lost most of its leaves during the winter and used the least amount of water among the cultivars. Irrigation designers could use this information to quantify water requirements for each cultivar and allocate water for irrigation and frost protection, accordingly. For example, "Star" could be planted at sites where availability of water is limited for irrigation and frost protection. Alternatively, growers could reduce their water footprint by substituting other methods of frost protection for preventing freeze damage (e.g., heaters or wind machines).

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Conflicts of Interest

On behalf of all authors, the corresponding author states that there are no conflicts of interest.

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