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Water footprint of representative agricultural crops on volcanic islands: the case of the Canary Islands

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Research Paper

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Abstract

The Canary Islands are a Spanish archipelago, where the greatest water demand comes from agriculture. Being an outermost European region that receives a large number of tourists per year, the need for greater food sovereignty becomes more important. It is vital to undertake studies on the water footprint (WF) of the main crops, in order to identify the irrigation practices of local farmers and establish recommendations for water saving through improvement of these practices. The results of this study show that the average WF for bananas in the Canary Islands is 340.80 $m^3\,t^{-1} \pm 34.07$ and for avocadoes is 1741.94 $m^3\,t^{-1} \pm 286.16$. The WF models proposed can explain 92 and 86% of the total variance of the WF for banana and avocado crops, respectively. The WF of both crops can be reduced, and this work can be a starting point for improvement. Farmers will face a change in temperature and water availability due to climate change; useful water saving strategies for local farmers can now be made based on estimation of the WF with yield and net needs data.

Introduction

Deterioration of the quality of life for human beings is mainly the result of deterioration of nature. The effects associated with climate change, such as rising sea levels, changes in the ocean environment, extreme weather events or increased soil erosion, can be crucial for the islands (Nurse et al., 2014). Precisely because climate change is very noticeable and threatens the island population, islands can play a pioneering role in the transition to sustainable energy sources, by taking advantage of specific natural conditions (Frydrychowicz-Jastrzebska, 2018). These specific natural conditions consist mainly of favorable wind and solar conditions (Blechinger et al., 2016), but it is also possible to utilize other site-specific possibilities, such as the potential for utilization of hydropower, biomass, geothermal, or ocean energy (Veigas and Iglesias, 2013). However, energy dependence is not the only problem facing the islands. The natural lack of water on the islands has been an obstacle for all civilizations that have inhabited them—in this particular case, the Canary Islands—and water management has always been a critical issue (Ruiz-Rosa et al., 2019). The islands try to reduce their water stress through careful water management and development of modern technologies such as desalination (Santamarta et al., 2021) or obtaining water from fog (Ritter, Regalado and Guerra, 2015).

About 1.2 billion people worldwide live in conditions of water scarcity, which is defined as the imbalance between supply and demand of freshwater resources (FAO, 2020). Water scarcity can be caused by poor water management or unfavorable geographical conditions, as may be the case in the Canary Islands. Thus, climate change is a major challenge for these islands. The increase in average global temperature, which is estimated to rise by 2–3°C by 2050, will reduce water resources by 30% (García-García et al., 2020). A further reduction in water resources is therefore not only an economic loss, but also a risk for populated areas, local agriculture, and nature itself. This is why water abstraction for agriculture should be minimized by rationalizing irrigation, in the form of controlling the actual water use of crops (Karandish and Šimůnek, 2016). In this regard, the reuse of wastewater is an effective method of alleviating water scarcity (Hortelano et al., 2020).

Modern technologies in agriculture have enabled human progress in other sectors, which has significantly improved the quality of human life. However, some of the unsustainable modern approaches in agriculture such as tillage, increasing the area of fields, or the use of fertilizers create stress for nature (Arevalo et al., 2011). These practices lead to increased erosion, loss of biodiversity, eutrophication of surface and groundwater, and reduction of the soil's capacity to retain water. This can cause a loss of natural balance and, in extreme cases, the collapse of local ecosystems. In this context, climate change in the form of storms, droughts, or floods represents an additional stress to nature and thus accelerates its degradation (Bijlsma et al., 1995).

Agriculture in the Canary Islands faces various challenges, all of which are linked to climate change (Schmitz et al., 2018). In particular, rising temperatures, which will strongly affect tropical crops such as avocado and bananas, as well as rising sea levels (banana cultivation in the Canary Islands is mainly on the coast), put the sector in a vulnerable position (Álvarez-Méndez et al., 2021). Of course, the decrease in rainfall will also have a direct relationship with irrigation and the water footprint (WF) of crops (Santamarta et al., 2022).

Although the main crops such as bananas and avocados are exported and contribute enormously to the Canarian economy (Vidueira et al., 2015), the sustainability of this model is questioned, both in terms of the carbon footprint of transporting the products and the irrigation needed in an island region sensitive to climate change (Hernandez et al., 2018). Furthermore, the food sovereignty of the islands is compromised if most of the agricultural land is devoted to export crops, where monocultures are favored and crop variety is limited, making the Canary Islands highly dependent on the import of products (Godenau et al., 2022).

Most of the water resources produced in the Canary Islands are used for agriculture, in some cases using more than 80% of the available water (Cruz-Pérez and Santamarta, 2021). Agriculture in the Canary Islands must overcome various obstacles inherent in the orography of the terrain, which is steep and rugged in most of the islands. This has resulted in more than 60% of the crops in the Canary Islands (Pestana et al., 2015) being located in areas near the coast (due to the existence of flatter land than on the peaks). This is also due to the fact that the main crop cultivated (*Musa acuminata*) has high temperature requirements, and the temperature near the coast is higher. This has contributed significantly to the development of irrigated agriculture in the archipelago.

Agriculture in the Canary Islands is limited by the market. Although there is domestic consumption, a large percentage is exported, with 97% of the crop land destined for export, being concentrated on the islands of Tenerife, Gran Canaria, and La Palma (Pestana et al., 2015).

Undoubtedly, the Canary Islands banana is one of the most recognized agricultural products of the archipelago. It is recognized under the Protected Geographical Indication (PGI) and is produced throughout the Canary Islands. Bananas are one of the crops with the highest water demand, with a consumption of up to 15,000 $m^3 ha^{-1}$ per year (Rodríguez Gómez, 2006). Although avocado (*Persea americana*) has been grown in the Canary Islands and Andalusia for many years, in recent years, it is spreading rapidly in these areas. It is a booming agricultural product, due to high market demand (Sommaruga and Eldridge, 2021). Avocado trees require between 6000 and 9000 $m^3 ha^{-1}$ per year.

Pollution accounting tools have emerged, in order to measure the environmental impact of an activity and/or the manufacture of a product. Among these tools is the concept of the WF, which measures the amount of drinking water required to carry out an activity, as well as the volume of water polluted in the process (Hoekstra et al., 2012).

The objective of this paper is to study the WF of banana and avocado crops in the three most important islands of the Canary archipelago (Fig. 1). In terms of agriculture, Tenerife, Gran Canaria, and La Palma are the most important islands; we aim to establish the water demands of the two most important crops in the Canary Islands, in terms of area and economic profit. These studies are still to be conducted in the Canary Islands and are considered a key element in decision making regarding future water improvements for agriculture in the archipelago, specifically in the context of climate change.

Methodology

Regarding WF, it is important to consider the use of water, differentiating between consumptive and non-consumptive use. Consumptive use is characterized by the fact that water, once used, is not returned to the environment or is not returned in the same condition in which it was obtained (Sultana et al., 2015). Non-consumptive use is that in which the water is returned to the medium from which it was extracted (Li et al., 2017). Whatever the case, both direct and indirect use of water and the impacts resulting from its use are considered. Direct water is defined as the amount of water required only in the production process or provision of a service (WFN, 2002). However, obtaining a product generally requires the input of several raw materials, intermediate products, and a series of services in the different stages of production. The provision of a service requires work tools; thus, in the production of these intermediate inputs or means of work, water that has not been considered in the final product or service provision (WFN, 2011) is also consumed. The water associated with these intermediate inputs is indirect water.

In both direct and indirect use, the origin of the water is distinguished (Jeswani and Azapagic, 2011). Green water corresponds to water from rainfall that is not lost through runoff and is incorporated into the soil or vegetation (UNDP, 2002). It is water that is available for free use by plants and constitutes the unique water support for rainfed crops, spontaneous vegetation, and forests. This source of water is particularly important in crop production. Blue water corresponds to the fraction of the hydrological cycle that is transformed into surface or underground runoff and is consumed by incorporation or evaporation in the process being evaluated (Zhuo et al., 2016). It feeds the flow of rivers and aquifer reserves, while it is susceptible to being dammed, naturally in the form of lakes or artificially by means of the construction of reservoirs. Except for the desalination of seawater and other non-conventional water sources, domestic, industrial, and irrigated cultivation are always supplied by blue water sources. Finally, grey water is a theoretical concept that refers to the pollution of the resource.

The WF of agricultural products is generally high, as this sector requires large volumes of water to grow crops. The WF of agriculture is particularly influenced by its green and blue components. Given that the blue WF indicates the amount of potable water contributed to a process and/or product, it is evident that it will be high in agriculture; as seen in previous sections, agriculture is one of the sectors with the highest water demand worldwide (Navalpotro et al., 2012). The green WF is of great importance in agriculture as well, since it is one of the few sectors where rainwater is directly incorporated into the final product which, in this case, is the agricultural crop (destined for humans and livestock).

Calculation of the WF is based on the methodology proposed by the Water Footprint Network (WFN), especially for agricultural and/or livestock products (Ercin, Aldaya and Hoekstra, 2011). The blue, green, and grey WF is calculated separately, and their sum is then calculated to obtain the WFN WF of the product under study.

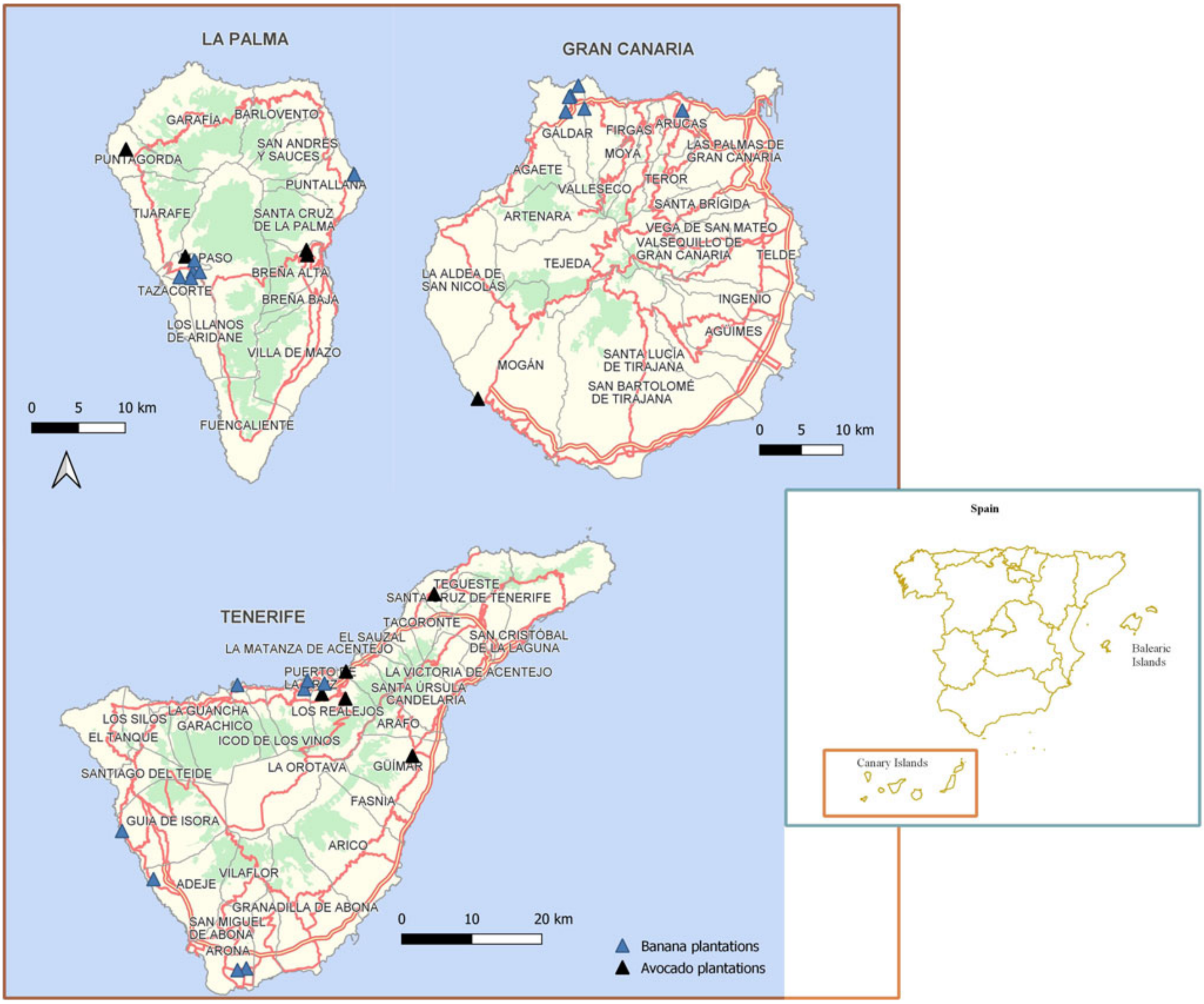

Figure 1. Situation of banana and avocado farms on the three islands selected for the study in the Canary Islands, Spain.

Blue and green water footprint

When calculating the green WF of a crop, the ratio of the consumption of green water (rainwater) used in the crop/farm is considered, between the crop yields. For this, it is necessary to know the net crop needs under study, considering the following factors: (i) crop plot location; (ii) crop height; (iii) effective precipitation of the area where the crop is located; (iv) hours of sunshine; (v) wind speed; (vi) crop temperature; (vii) crop production; (viii) irrigation uniformity coefficient; and (ix) electrical conductivity of irrigation water.

This information can be obtained from several sources: (i) from the farmers who participated in the study; (ii) from the Food and Agriculture Organization of the United Nations (FAO); and (iii) from the Spanish Agroclimatic Information System for Irrigation (*Red SiAR*).

Grey water footprint

In order to calculate the grey WF of a crop, we need the data related to annual tons of fertilizer applied. Knowing the average fertilizer application rate and the maximum concentration of fertilizers allowed by current regulations, the grey WF of a crop can be determined.

R version 4.1.3 was used for data analysis. Pearson's *r* correlation coefficient was computed to assess the linear relationship between variables. A correlation plot was made using the 'corrplot' package (Wei and Simko, 2021). A generalized linear model (GLM) using the 'fitdistrplus' package (Delignette-Muller and Dutang, 2015) set to the Gaussian distribution was used to create the model to test the effect of Total WF (log transformed) on Yield and Net Needs (as fixed factors). Collinearity of variables was checked with the package 'car' (Weisberg, 2019). The χ^2 test was used to test for the significance of the fixed factors on the variation of Total WF. When presenting the WF results obtained for each of the plots studied, these considerations have been followed:

- The production WF is presented as the sum of the blue WF and the green WF. This is because the blue WF represents the volume of water consumed by the plant from a potable water source, i.e., irrigation by the farmer. This consumption should vary according to the green WF, i.e., the volume of water incorporated into the plant through rainfall. For this, it is also necessary to calculate evapotranspiration, which represents the combination of two distinct processes, where water is lost through two different mechanisms. First, water evaporates from the soil surface and second, it is released from the crop through a process known as transpiration (Allen et al., 1998).

- The results of the grey WF are presented separately, as this concept expresses the volume of potable water necessary to dilute the pollutants present in the water after incorporating agricultural fertilizers into the water.
- The annual results are shown for each plot; however, in the process of calculating the three dimensions of the WF (blue, green, and grey), monthly calculations are made since the evapotranspiration and, therefore, the green and blue WF change daily. However, for clarity and because it is the usual procedure, the blue, green, and grey WF results are presented as cubic meters per ton produced in each plot.
- In the WF tables, the following concepts represent the following values:

ETgreen (Equation 1) contemplates the minimum value between effective precipitation and total evapotranspiration of a crop (ETc) for each month. The resulting value for each month is then added, and we obtain the annual ETgreen value.

$$\mathrm{ETgreen} = \min(\mathrm{ETc}, \mathrm{Eprec.}) \tag{1}$$

ETblue (Equation 2) is the minimum value between the total net irrigation and the actual irrigation requirement, according to the FAO.

$$\mathrm{ETblue} = \max(0,\ \mathrm{ETc{-}Eprec.}) \tag{2}$$

Eta is the sum of the ETblue and ETgreen values.
UACgreen is the green water use of the crop, in $m^3\,ha^{-1}$.
UACblue is the blue water use of the crop, in $m^3\,ha^{-1}$.
UACtotal is the sum of UACgreen and UACblue.
Production is the number of tons produced, per hectare, in each of the farms studied.
WFgreen is the value of UACgreen divided by the production of the farm (Equation 3).

$$\mathrm{WFgreen} = \mathrm{UACgreen}/\mathrm{Production} \tag{3}$$

WFblue is the value of UACblue divided by the production of the farm (Equation 4).

$$\mathrm{WFblue} = \mathrm{UACblue}/\mathrm{Production} \tag{4}$$

WFproduction is the sum of the WFgreen and WFblue values (Equation 5).

$$\mathrm{WFproduction} = \mathrm{WFgreenF} + \mathrm{WFblue} \tag{5}$$

WFgrey contemplates the load of pollutants that is introduced into the water system and must be divided by the difference between the environmental quality standard for that pollutant (verify with the regulations of each country the maximum concentration) and its natural concentration in the receiving water body. The average fertilizer application rate must be calculated, divided by the previously mentioned subtraction and then, from the production of the farm, the grey WF is obtained.

Results and discussion

For calculation of the WF of banana production, a total of 20 plots were analyzed, located on the islands of Tenerife, La Palma, and Gran Canaria. The results of the banana production footprint are presented as the sum of the blue and green WF, because it is the theoretical water used in its entirety for irrigation. The data correspond to 2020/2021 production and the meteorological values used are those for the year 2021 (Table 1).

The WF is the sum of the three components of the footprint, i.e., green, blue, and grey. The sum of the green and blue components is presented as the water required to obtain the crop production. The grey WF is presented as a theoretical concept that helps to know the amount of water that would be necessary to neutralize the water pollution caused by the fertilizers used in production.

Regarding the grey WF, the average values are shown in Table 2, by island, and they are calculated on the basis of average nitrate usage.

For calculation of the WF of avocado, a total of 13 plots were analyzed, also located on the islands of Tenerife, La Palma, and Gran Canaria. The data correspond to 2020/2021 production and the meteorological values taken are those of the year 2021 (Table 3). The average values for the grey WF are presented in Table 4 and have also been calculated based on nitrates, which are the most important pollutant in the cases studied.

It is observed that the values of the WF for banana production are very similar to each other and lower than those of avocado, due to the fact that production per unit area is much higher in the case of banana. As expected, the blue WF in both banana and avocado crops was much higher in every plot compared to the green WF. Both crops have high water demands, and rainfall is low in the places where these crops are cultivated in the Canary Islands.

Total WF was positively correlated (see Fig. 2) with green and blue WF, especially blue WF with a strong correlation r (18) = 0.99, $P < 0.001$. This indicates that irrigation water showed an important correlation with the total WF.

A positive, moderate-in-strength correlation was determined between yield and blue WF as well as total WF r (18) = 0.6 and 0.53 respectively, $P < 0.01$ and 0.017 respectively. Higher yields would lower WFs for a constant amount of water demanded by the plant, as higher yield usually implies higher water use (this was not demonstrated with our data due to variations in the water needs). If the increase in water demands is higher than the increase of yield, the WF will also increase with yield.

There was a negative relationship (see Fig. 2), moderate in strength and statistically significant between net need of the banana crop and green WF, blue WF, and total WF, r (18) = −0.61, −0.59, and −0.65 respectively, $P < 0.001$. This means that the higher the water demand (net needs) of the banana crop, the lower the different WF will be. This can be explained, as banana crops with higher water demands are located in warmer locations where yields are higher, lowering the WF (Luan et al., 2018).

A GLM was set using a log-transformation as the dependent (response) variable (total WF), and yield as independent (predictor) variable. There was evidence that yields of banana crops were significant predictors of the total WF ($F = 9.276$ [18 DF]

Table 1. Green and blue water footprint values of 20 banana farms in Tenerife, La Palma, and Gran Canaria

	Etgreen	Etblue	Et$_a$	UACgreen	UACblue	UACtotal	Production	WFgreen	WFblue	WFproduction
Island	mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	m^3 ha^{-1}	m^3 ha^{-1}	m^3 ha^{-1}	t ha^{-1}	m^3 t^{-1}	m^3 t^{-1}	m^3 t^{-1}
La Palma1	104.82	1219.53	1324.35	1048.20	12,195.30	13,243.50	30.43	34.44	400.7	435.14
La Palma2	27.81	1309.87	1337.68	278.1	13,098.75	13,376.85	43.33	6.42	302.28	308.7
La Palma3	27.81	1238.50	1266.31	278.1	12,384.96	12,663.06	38.46	7.23	322.01	329.24
La Palma4	179.86	1307.68	1487.53	1798.55	13,076.75	14,875.31	45.11	39.87	289.87	329.74
La Palma5	27.81	1288.34	1316.15	278.1	12,883.44	13,161.54	41.67	6.67	309.2	315.88
La Palma6	27.81	1341.52	1369.33	278.1	13,415.23	13,693.33	70.99	3.92	188.98	192.9
Tenerife1	66.6	1417.22	1483.81	665.95	14,172.16	14,838.11	53.54	12.44	264.7	277.14
Tenerife2	198.1	1552.64	1750.74	1981.00	15,526.45	17,507.45	38.98	50.82	398.29	449.1
Tenerife3	198.1	1022.92	1221.02	1981.00	10,229.19	12,210.19	19.04	104.02	537.12	641.13
Tenerife4	41.96	1792.69	1834.64	419.55	17,926.87	18,346.42	64.88	6.47	276.31	282.78
Tenerife5	5.83	1684.60	1690.43	58.3	16,846.00	16,904.30	49.9	1.17	337.61	338.78
Tenerife6	14.56	660.23	674.79	145.6	6602.29	6747.89	46.34	3.14	142.47	145.61
Tenerife7	198.1	908.29	1106.39	1981.00	9082.87	11,063.87	41.52	47.71	218.74	266.44
Tenerife8	14.56	907.99	922.55	145.6	9079.95	9225.55	45.71	3.19	198.62	201.81
Gran Canaria1	34.82	2486.06	2520.88	348.2	24,860.56	25,208.76	58.98	5.9	421.51	427.41
Gran Canaria2	34.82	2242.75	2277.57	348.2	22,427.50	22,775.70	29	12.01	773.36	785.37
Gran Canaria3	82.98	1163.83	1246.81	829.8	11,638.25	12,468.05	47.88	17.33	243.07	260.4
Gran Canaria4	34.82	1515.23	1550.05	348.2	15,152.33	15,500.53	50.16	6.94	302.11	309.05
Gran Canaria5	34.82	1466.00	1500.82	348.2	14,660.04	15,008.24	79.94	4.36	183.39	187.75
Gran Canaria6	34.82	1914.41	1949.23	348.2	19,144.07	19,492.27	58.76	5.93	325.81	331.73

Production year: 2020/2021.

Table 2. Average value (±standard error) of the grey water footprint in the 22 banana farms studied in Tenerife, La Palma, and Gran Canaria

Island	Average fertilizer application rate kg ha^{-1}	Area ha	Total fertilizer applied t yr^{-1}	Nitrogen leaching into bodies of water 10% t yr^{-1}	Maximum conc. mg l^{-1}	Hhproc, grey (10^6 m^{-3} yr^{-1}) m^3 yr^{-1}	Production t	WFgrey m^3 t^{-1}
La Palma	620.35	0.94 ± 0.28	0.12 ± 0.04	0.01 ± 0	10	0.001 ± 0.00036	46.17 ± 17.06	30.81 ± 3.22
Tenerife		7.15 ± 2.51	0.93 ± 0.33	0.09 ± 0.03		0.002 ± 0.00044	355.98 ± 141.98	32.47 ± 5.31
Gran Canaria		1.16 ± 0.51	0.15 ± 0.07	0.02 ± 0.01		0.002 ± 0.00041	61.56 ± 24.23	26.39 ± 4

Production year: 2020/2021.

$P < 0.01$) with an adjusted R^2 of 0.30 and a standard error of 0.3355.

The predictive model (Equation 6) of total WF for banana was:

$$\text{Total WF} = 139.81[[\exp]]\hat{(}0.00054 \times \text{Yield}) \tag{6}$$

The χ^2 goodness of fit test showed a P-value of 0.99, which is greater than the significance level $\alpha = 0.05$. We can conclude that the observed values are not significantly different from the predicted values of the model, meaning the model is a good predictor.

Avocado orchards showed similar correlations to bananas. There was a negative relationship (see Fig. 3), moderate and strong in strength and statistically significant between net need of the banana crop and blue WF, green WF, and total WF r $(10) = -0.68$, -0.78, and -0.7 respectively, $P < 0.016$ in all three cases. The higher the water need of the avocado, the lower the WF will be. Avocado trees in areas with warmer climates tend to have higher yields and higher water demands, lowering the total WF.

A positive strong correlation was found between yield and net needs r $(10) = 0.76$, $P = 0.004$. As expected, a higher yield increases water demand, maybe due to the fruit production itself, or maybe because higher yields are usually in warmer areas. As expected, there was a strong positive correlation between all WFs.

The same procedure for the bananas was used for the avocado data—GLM using a log-transformed response variable (total WF of avocado) and net needs as predictors without interaction. According to BIC criteria, the Gaussian distribution was the best fit. There was evidence that the net needs of the avocado were significant predictors of the total WF ($F = 12.56$ [10 DF], $P < 0.01$), with an adjusted R^2 of 0.55 and a standard error of 0.4092.

The predictive model (Equation 7) of total WF for avocado was:

$$\text{Total WF} = 2623.59[[\exp]]\hat{(}-0.092 \times \text{NetNeeds}) \tag{7}$$

The model showed good predictions in estimating the total WF, as the χ^2 goodness of fit test showed a P-value of 0.998, which is greater than the significance level $\alpha = 0.05$.

If avocado net needs increase by 1 mm yr^{-1}, total WF would increase to 2393.7 m^3 t^{-1}.

According to a recent study (Sommaruga and Eldridge, 2021), a database covering the period from 1996 to 2005 shows that the average blue WF of the avocado in the world is 237 m^3 t^{-1}. However, there are regions of the world where these values differ significantly from the average, as is the case in some areas of Guatemala (2295 m^3 t^{-1}). In our case, it is observed that the theoretical values of the blue WF in the Canary Islands differ significantly from the world average value. However, it is important to remember that calculation of the blue WF is derived from calculation of the green WF and, due to the fact that rainfall in the Canary Islands is not as abundant as in tropical areas of the world, it is expected that the farmers' irrigation input should be high. It is also important to consider that the calculation of the footprint assumes that irrigation and rainfall cover all the evapotranspirative demand of the crop, and this may not be real depending on how well the crop is irrigated. Indeed, this was verified in a recent study in Mexico, where the WF was significantly lower for crops grown under rainfed conditions than those grown under irrigated conditions (Gómez-Tagle et al., 2022).

Avocado production in 2020/2021 was low due to wind events during the flowering season that considerably affected some areas of the islands. However, it is noteworthy that, in the plots where there were volumetric meters, it was possible to make the calculation with real water expenses for those productions, and the values showed a much lower consumption, specifically 900.07 m^3 t^{-1} ± 367.88. This suggests that this study must be repeated for a few years to understand the real WF of the banana and avocado crops in the Canary Islands.

The average WF for bananas in Canary Islands in our study was 340.80 m^3 t^{-1} ± 34.07, and for avocado it was 1741.94 m^3 t^{-1} ± 286.16. As expected, the WF is lower for bananas due to higher yield per unit area. Nevertheless, the WF of avocado will be lower when compared with higher yield years. The great dispersion of data between avocado orchards is also notable.

Research conducted in a semi-arid area showed WF values for banana of approximately 500 m^3 t^{-1} (Ramachandran et al., 2022). In our case, this decrease in WF for the same crop may be justified by the fact that banana yield in the Canary Islands is higher than in India (on average 12,500 t ha^{-1} higher between 2015 and 2020, according to data obtained from FAO) and the irrigation systems used in the islands are mostly efficient drip irrigation.

Analyzing the WF is crucial to be able to predict how climate change will affect major crops, especially given the strong external dependence of Europe on the world's semi-arid agricultural imports (Alexoaei, Cojanu and Coman, 2021). Indeed, in a context of climate change and generalized reduced water availability,

Table 3. Green and blue water footprint values of 13 avocado farms in Tenerife, La Palma, and Gran Canaria

Island	Etgreen mm yr^{-1}	Etblue mm yr^{-1}	Et$_a$ mm yr^{-1}	UACgreen m^3 ha^{-1}	UACblue m^3 ha^{-1}	UACtotal m^3 ha^{-1}	Production t ha^{-1}	WFgreen m^3 t^{-1}	WFblue m^3 t^{-1}	WFproduction m^3 t^{-1}
La Palma1	94.94	572.53	667.47	949.36	5725.31	6674.67	2.27	417.72	2519.14	2936.85
La Palma2	107.71	670.51	778.22	1077.15	6705.07	7782.22	5.17	208.25	1296.31	1504.56
La Palma3	94.94	579.51	674.45	949.36	5795.13	6744.49	5.36	177.21	1081.76	1258.97
La Palma4	20.72	473.16	493.88	207.19	4731.64	4938.83	11.5	18.02	411.45	429.46
La Palma5	63.75	634.22	697.97	637.46	6342.24	6979.70	6.73	94.71	942.28	1036.98
Tenerife1	98.78	587.07	685.85	987.84	5870.66	6858.50	1.88	524.47	3116.90	3641.37
Tenerife2	98.78	509.71	608.5	987.84	5097.11	6084.95	2	493.92	2548.56	3042.48
Tenerife3	136.47	639.44	775.91	1364.69	6394.37	7759.06	4.95	275.67	1291.66	1567.33
Tenerife4	98.78	538.4	637.19	987.84	5384.01	6371.85	2.97	332.57	1812.62	2145.19
Tenerife5	57.37	761.52	818.89	573.69	7615.22	8188.91	6	95.62	1269.20	1364.82
Tenerife6	128.56	520.03	648.6	1285.62	5200.35	6485.96	5.36	239.98	970.73	1210.71
Gran Canaria1	14.21	1527.10	1541.31	142.1	15,271.02	15,413.12	20.16	7.05	757.44	764.49

Production year: 2020/2021.

Table 4. Average value (±standard error) of the grey water footprint in the 13 avocado farms studied in Tenerife, La Palma, and Gran Canaria

Island	Average fertilizer application rate	Area	Total fertilizer applied	Nitrogen leaching into bodies of water 10%	Maximum conc.	Hhproc, gray (10^6 m^{-3} yr^{-1})	Production	WFgrey
	kg ha^{-1}	ha	t yr^{-1}	t yr^{-1}	mg l^{-1}	m^3 yr^{-1}	t	m^3 t^{-1}
La Palma	130	0.9 ± 0.36	0.12 ± 0.05	0.01 ± 0.005	10	0.0012 ± 0.0005	5.9 ± 2.43	274.44 ± 78.34
Tenerife		0.82 ± 0.1	0.11 ± 0.01	0.01 ± 0.004		0.0013 ± 0.0004	2.92 ± 0.48	416.63 ± 86.36
Gran Canaria		1.67 ± 0.43	0.22 ± 0.06	0.02 ± 0.006		0.0015 ± 0.0004	14.75 ± 10.25	334.13 ± 269.65

Production year: 2020/2021.

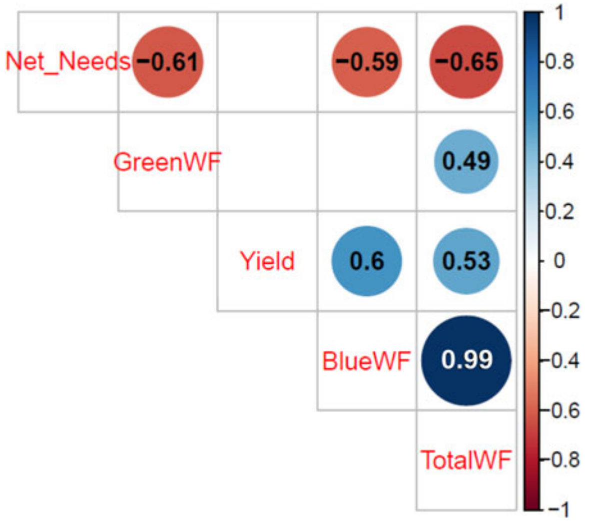

Figure 2. Correlation matrix for banana crop. The number inside the circles corresponds to the Pearson's *r* statistic. The size and the color of the circle indicate that the relationship is significant and if it is direct or inverse.

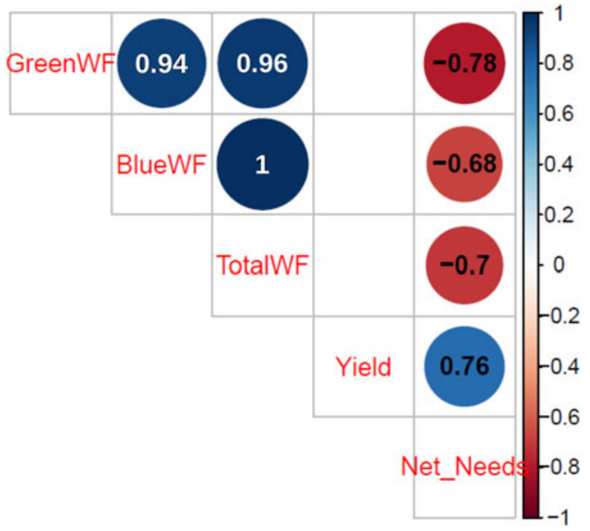

Figure 3. Correlation matrix for avocado crop. The number inside the circles corresponds to the Pearson's *r* statistic. The size and the color of the circle indicate that the relationship is significant and if it is direct or inverse.

it is vital to involve reused water as a source of irrigation (Biswas, Mailapalli and Raghuwanshi, 2021; Kaewmai et al., 2021).

For its part, grey WF values for banana are much lower than for avocado. However, avocado values are lower than others found in similar studies in Chile (Novoa et al., 2019). This is mainly due to the way fertilizers are applied, both in quantity and type of compound, although this is usually done in reference to nitrates (Chukalla, Krol and Hoekstra, 2018). It is observed that the quantities of fertilizers applied are higher on the island of Tenerife for both avocado and banana, and in the rest of the islands a lower quantity is used. This is also due to the lower production in Gran Canaria and La Palma in both cases.

Conclusions

Total WF in the Canary Islands is mainly affected by irrigation with a higher blue WF compared to green WF. WF models proposed can explain 30 and 55% of the total variance of WF on banana and avocado crops, respectively, in our study. WF values can now be estimated for banana and avocado crops with yield and net need of the plant, which could lead to an improvement in water usage in both crops. WFs should not be used as a tool to compare different regions, as evapotranspiration and rainfall in different zones change drastically. It can be used to improve the use of water and reduce water use-specific areas where it has been calculated. These values can serve as an indication of the sector, as a tool to reduce water use in the future through the improvement of irrigation systems and the use of technologies that allow for more efficient use of water.

Further studies are needed to improve the model's predictions, with more data from different years and more orchards, especially in avocado crops.

Data availability statement. The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Competing interests. None.

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