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Original article

Determination of the Water Footprint of Quinoa Under Nevşehir Conditions

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Abstract

Quinoa is an annual crop known for its resistance to various stress factors such as drought, frost, salinity and high radiation. However, its high protein content and antioxidant properties make quinoa an important human food. Nevşehir does not have a very high potential considering its climate and water resources. The region receives an average annual rainfall of 300-400 mm. This makes it impossible to grow the majority of crops with rainfall alone. Irrigation is necessary in most cases. However, insufficient water resources and low water quality limit irrigation. The main crops grown in Nevsehir (wheat, potatoes, dry beans, dried beans, and pumpkin) are crops that need irrigation. The agricultural production potential of the region can be increased with an efficient irrigation and plant diversity planning. In this sense, quinoa is a plant with high potential for Nevşehir. Quinoa cultivation can be beneficial in irrigated or marginal agricultural areas of Nevşehir. The amount of land suitable for agriculture but not used in Nevşehir is 234 455 decares. In this study, it was investigated how much water footprint the cultivation of quinoa in Nevşehir conditions would cause. For this purpose, the amount of land that is suitable for agriculture and cannot be used in Nevşehir was considered as quinoa cultivation area. In the study, the green and blue water footprint of quinoa was calculated. The amount of water required to produce 1 ton of quinoa in Nevşehir was found to be 1575 m3 ton-1. As a result, the total water footprint of quinoa was determined as 110 900 m3. The fact that quinoa has a low water requirement and water footprint in Nevşehir compared to other crops suggests that its cultivation in the region would be beneficial. Currently, there are no studies on the cultivation of quinoa in Nevsehir and it is not produced by producers. This study has shown that the production of quinoa in Nevsehir would be very productive for marginal and arid fields in the region. Quinoa cultivation is recommended for producers in the region.

Keywords: Green Water Footprint, Blue Water Footprint, Effective Rain, Virtual Water Content, Cropwat.

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INTRODUCTION

Nowadays, factors such as globalisation, rapid population growth, urbanisation and climate change create significant problems regarding the quantity and sharing of freshwater resources. Therefore, measuring the quantity and quality of water has become critical, especially in terms of water use within the country and at the global level. Efficient inter-sectoral economic linkages and planning will support environmental, economic and social sustainability. Protecting Türkiye's water resources is vital for economic sustainability. Water efficiency, especially the rational use of water, is important to reduce water consumption per unit of individual, community, production and consumption to determine water footprints. Calculation of water footprint for Turkey is of great importance in terms of planning, increasing water saving awareness and making changes in national policies (Turan, 2017).

The water footprint of a crop refers to all the water used directly and indirectly to produce that crop (Hoekstra et al., 2011; Muratoglu and Avanoz, 2021). Therefore, knowing the water footprint of all kinds of crops is very important for sustainable water management. Especially considering that the agricultural sector consumes the most water of all sectors, the importance of knowing the water footprint of agricultural products will be realised. Knowing the water footprint of agricultural products enables cultivation according to the plant pattern suitable for the climate and soil conditions of the region. In this way, water resources can be used more sustainably as regions focus on the production of certain plants.

Yerli et al. (2019) calculated the blue and green water footprints of silage maize, potato, sugar beet and alfalfa plants under Van conditions. Winter precipitation, vegetation period precipitation and evapotranspiration were used in the calculation. The results showed that the total amount of water required per ton for each plant species was 147.4 m^3 ton^{-1} for silage maize, 230.3 m^3 ton^{-1} for potato, 120.0 m^3 ton^{-1} for sugar beet and 287.5 m^3 ton^{-1} for alfalfa. The total water footprints of the crops were calculated as 786.674 m^3, 1.537.022 m^3, 6.909.240 m^3 and 638.827.875 m^3, respectively.

In order to make sustainable agricultural production in arid, saline and unfavourable areas, it is necessary to produce plants that can be cultivated under these unfavourable conditions. Quinoa (*Chenopodium quinoa* Willd.) stands out with its tolerance to various abiotic stress factors and adaptability to unfavourable environmental conditions. Quinoa originated from South America and spread all over the world (Yazar and İnce Kaya, 2014). Quinoa protects itself against the negative effects of drought thanks to its deeply branched root system, special vesicular glands, small and thick-walled cells, leaf area reduction and dynamic stomatal behaviour (Jensen et al., 2000; Yazar et al., 2014). Quinoa is resistant to salt stress as it can accumulate salt ions in its tissues and adjust leaf water potential to maintain cell turgor and transpiration (Jacobsen 2003; Gómez-Pando et al., 2010; Yazar et al., 2014). Quinoa is also less affected by frost than many other crops. Depending on the phenological stage and variety, it can withstand up to 4 hours at -8 °C (Jacobsen et al., 2003; Yazar et al., 2014). The remaining parts of the plant, which has been grown for grain by the people of this region since ancient times, have also been used in ruminant nutrition (Bazile and Baudron, 2015). In some countries, quinoa is also used as hay, green fodder (Kakabouki et al., 2014) and silage plant (Schooten and Pinxterhuis, 2003). Although quinoa is not a cereal in the true sense, it is considered as a cereal group worldwide. Its seeds are rich in essential amino acids such as lysine and high protein content and are highly nutritious in terms of vitamins and minerals (Comai et al., 2007; Geren et al., 2014). The protein content of quinoa seeds varies between 13% and 21%, while the oil content varies between 10% and 18% (Bhargava et al., 2007; Geren et al., 2014). Quinoa plant, which is not originally a cereal but is considered as a cereal, can play an important role in meeting the protein and carbohydrate needs of celiac patients and vegans since its seeds do not contain gluten (Geren and Güre, 2017).

Kır and Temel (2017) investigated the growth and yield characteristics of different quinoa varieties (Cherry Vanilla, French Vanilla, Mint Vanilla, Moqu-Arrochilla, Oro de Valle, Population-China, Q-52, Rainbow, Read Head, Sandoval Mix and Titicaca) under irrigated conditions in Iğdır. As a result of their study, crude protein content in the stem was found to be 5%. Titicaca stood out with the highest seed yield (412.03 kg da^{-1}), harvest index (43.88%) and thousand grain weight (2.65 g), while Q-52 stood out with earliness (140.75 days), Sandoval Mix with biological yield (1750.23 kg da^{-1}) and Population-China with crude protein content in seed (14.75%). In general, all varieties were found to be suitable for seed production under irrigated conditions. Samutuğlu et al (2021) investigated water-yield relations, plant water consumption and plant coefficients (Kc) of quinoa cultivar Titicaca (Q-52) grown under Mediterranean climatic conditions. The plants were subjected to full irrigation (TS) and deficit irrigation (SZ) with 75, 50 and 25 per cent, respectively (KS75, KS50, KS25). In the TS treatment, the soil water content was brought to field capacity every 7 days, while water was applied according to the curtailed irrigation rates. Kc was determined using plant water consumption (ET) and comparative plant water consumption (ETo) calculated by FAO56-Penman-Monteith method. ET values ranged from 302.0 mm (TS) to 198.2 mm (SZ) and quinoa grain yields were 295.2 and 243.0 kg da^{-1}, respectively. Statistically significant decreases in yield were observed with restricted irrigation compared to TS application. Under Antalya conditions, the developmental periods of quinoa plants were 31, 36, 15 and 26 days, respectively, and the total developmental period was 108 days. Kc values were 0.54, 1.13 and 0.79 for early, middle and late growth periods, respectively, and seasonal plant yield response factor (ky) was 0.54.

Nevşehir is a region with an annual rainfall of approximately 300-400 mm. Summers are hot and dry and winters are cold. Nevsehir's climate unfortunately limits a wide variety of crop production in the region. Wheat, barley, pumpkin seeds, potatoes, dry beans, grapes and sugar beet are the main crops grown in the region. Most of the above-mentioned crops are realised by irrigation. The climate of the region allows the cultivation of plants resistant to drought and unfavourable environmental conditions such as lavender, capers, sorghum and quinoa. However, the cultivation of these plants is almost non-existent. Considering the climate and the availability of water resources in Nevşehir, it is thought that increasing the production of these plants will enable the region's water resources to be used more accurately. Since quinoa is a plant resistant to drought, it is important to investigate its cultivation in this region. In particular, it may be important for the correct use of water resources that quinoa plant replaces the main crops grown. The amount of land suitable for agriculture but not used in Nevşehir is 234,455 decares. In particular, the evaluation of the possibility of growing quinoa plant in this area can provide important contributions to the region in terms of agriculture. The aim of this study is to estimate the water footprint of quinoa cultivation under irrigated and non-irrigated conditions in Nevşehir conditions. Due to the lack of any statistical data on quinoa cultivation in Nevşehir, the yield values of dry and non-irrigated conditions were obtained from other studies in the literature. For this purpose, yield values obtained under dry and irrigated conditions for the climates representing the region were used.

MATERIALS and METHODS

Distribution of Agricultural Land in Nevşehir

The total agricultural land of Nevşehir is 3.522.178 decares. 83% of the total agricultural land is used for dry farming and 17% for irrigated farming. Plants such as wheat, barley, chickpea, rye, etc. are generally cultivated in dry agricultural areas, while in irrigated agricultural areas, crops such as pumpkin, wheat, potato, dry beans, sugar beet are cultivated. Grain cultivation is the most common in Nevşehir. The remaining largest part of the land is reserved fallow. The 3rd largest part of the land is suitable for agriculture and is in the unusable land class. The remaining areas consist of vegetables, vineyards, honeylots, fodder crops, tuber crops, industrial crops, orchards and oilseeds. Figure 1 shows the distribution of vegetable crops in Nevşehir agricultural areas. Distribution of vegetation pattern according to agricultural areas of Nevşehir was obtained from the brief of Nevşehir Provincial Directorate of Agriculture in 2020 (Anonymous, 2024).

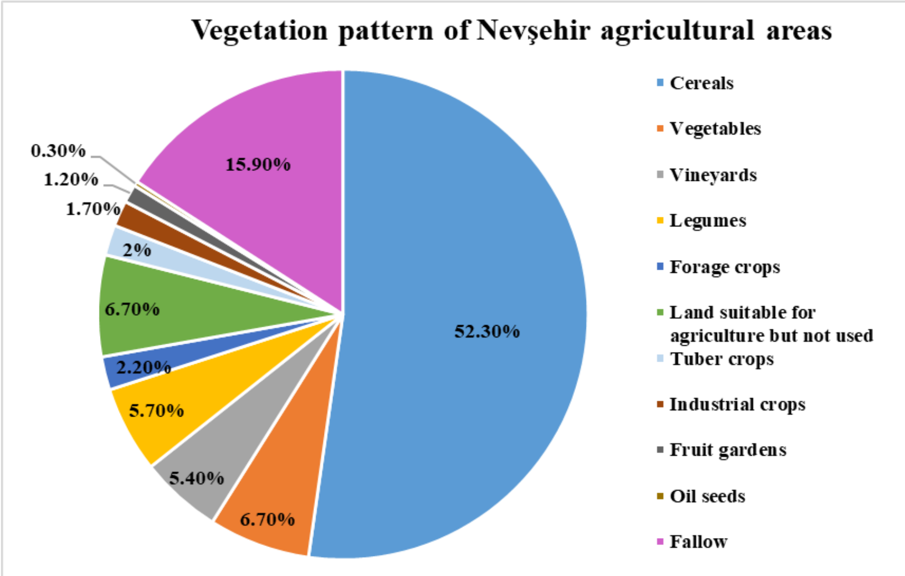


Figure 1. Vegetation pattern of Nevsehir Agricultural Areas

Irrigation Possibilities of Nevşehir

While 80% of the irrigated areas are provided from water wells, 20% are provided from dams and ponds operated by irrigation unions in Nevşehir in 2020. While a total area of 387.922 decares is irrigated from water wells, a total area of 94.078 decares is irrigated from dams and ponds. The district with the highest number of water wells is Derinkuyu (1900) and the lowest number is Kozaklı (58). The dam where the most area in the region is irrigated is Ayhanlar Dam with 15.000 decares. The information on the areas irrigated by water wells, dams and ponds in Nevşehir is taken from the briefing published by Nevşehir Provincial Directorate of Agriculture in 2020 (Anonymous, 2024).

Determination of green and blue water footprint

The amount of evapotranspiration is of great importance in the calculation of water footprint. Therefore, it is very important to measure the amount of evapotranspiration accurately and precisely. In this study, evapotranspiration was determined by Cropwat program developed by FAO. Maximum temperature, minimum temperature, humidity, wind speed and sunshine duration data of Nevsehir during the growing periods of quinoa were used for evapotranspiration. Apart from these, the number of days and plant coefficients (Kc) of the quinoa were determined according to Samutoğlu et al. (2021). As a result, the evaptranspiration value of quinoa was determined. Another important indicator used in water footprint calculation is effective precipitation (Pe). Effective precipitation data were obtained by entering the coordinate and climate data of Nevşehir into the Cropwat program.

The green and blue water footprints of quinoa were determined by the methods developed by Chapagain and Hoekstra (2004). Accordingly, green and blue plant water consumption is determined according to Equation 1 and Equation 2.

ETgreen: min (ETc, Pe) Equation 1

ETblue: max (0, ETc-Pe) Equation 2

ETgreen (mm) in Equation 1 represents green evapotranspiration; ETblue (mm) represents blue evapotranspiration; ETc (mm) represents crop water consumption and Pe (mm) represents effective rainfall. Plant water consumption formula are given in Equation 3 and Equation 4. Where BSTgreen (m^3 ha^{-1}) is the green water consumption of the plant and BSTblue (m^3 ha^{-1}) is the blue water consumption of the plant. After the results obtained, green virtual water content, blue virtual water content and total virtual water content are calculated according to Equation 5, Equation 6 and Equation 7.

SSMgreen: BSTgreen V^{-1}
Equation 5

SSMblue: BSTblue V^{-1}
Equation 6

SSMtotally: SSMgreen+SSMblue
Equation 7

Where V (tons ha^{-1}) is the yield. The formula for the total water footprint (SA) of each plant is given in Equation 8.

SAtotally: $\Sigma SSM_i x P_i$
Equation 8

P (tonnes) in the equation refers to the production quantity.

RESULTS and DISCUSSION

Nevşehir coordinates and climate data were entered into the Cropwat programme and effective precipitation values for Nevşehir were determined according to months. The effective precipitation values of Nevşehir obtained as a result of Cropwat programme are given in Figure 2.

Monthly rain - C:\Users\Nevu\Desktop\CROPWATT\mmmmm\NEVSEHIR.cli

Station NEVSEHIR **Eff. rain method** USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	45.0	41.8
February	39.0	36.6
March	46.0	42.6
April	53.0	48.5
May	57.0	51.8
June	33.0	31.3
July	11.0	10.8
August	6.0	5.9
September	12.0	11.8
October	31.0	29.5
November	35.0	33.0
December	51.0	46.8
Total	**419.0**	**390.4**

Figure 2. Effective precipitation (Pe) values of Nevşehir Province by months

The maximum temperature, minimum temperature, humidity, wind speed, and sunshine duration values for Nevşehir were entered into the Cropwat program, which then determined the Reference Evapotranspiration (ET0) for Nevşehir. Then, quinoa plant coefficients (Kc) values of 0.5 (initial), 1.00 (development) and 0.7 (final period) were entered into the Cropwat programme. The development periods of quinoa were entered as 30, 35, 25 and 27 days for initial, development, mid-season and late season, respectively. Plant root depths were entered as 0.3 and 0.6 m in the initial and developmental periods, respectively. Evapotranspiration value was then determined. Figure 3 shows the Kc coefficients and root depth of quinoa plants during the growth periods. Figure 4 shows the crop evapotranspiration (ETc) value of quinoa grown under Nevsehir conditions.

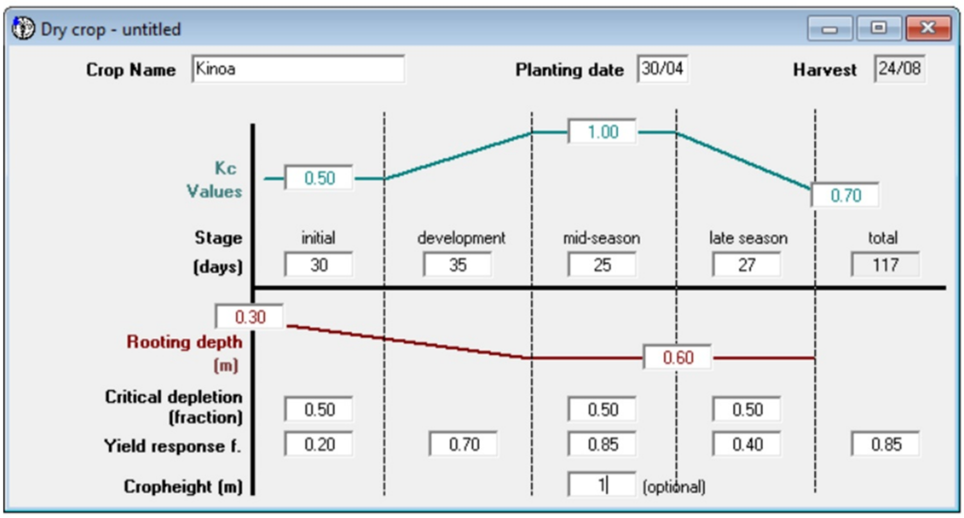
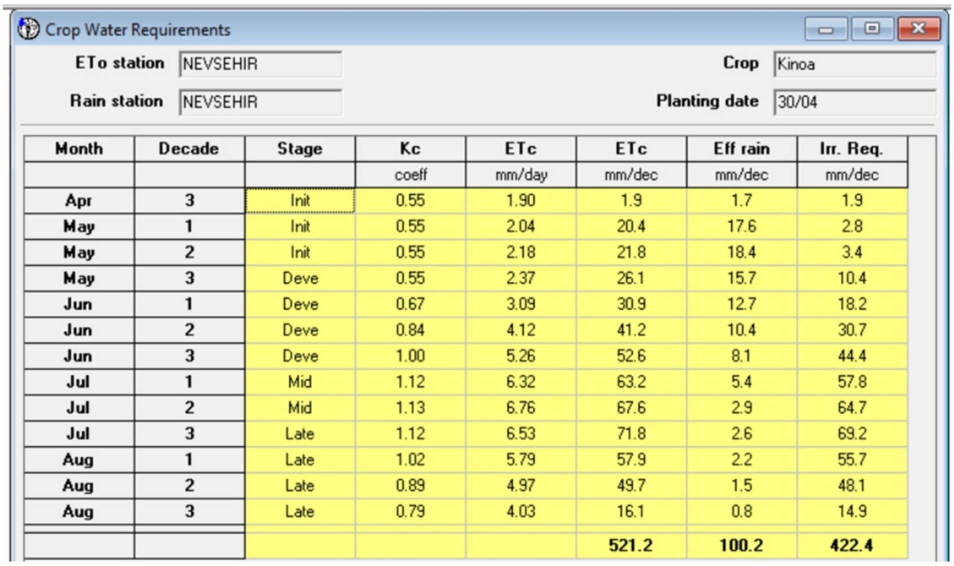


Figure 3. Vegetative parameters of quinoa grown under Nevsehir conditions



Crop Water Requirements

ETo station NEVSEHIR Crop Kinoa

Rain station NEVSEHIR Planting date 30/04

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	3	Init	0.55	1.90	1.9	1.7	1.9
May	1	Init	0.55	2.04	20.4	17.6	2.8
May	2	Init	0.55	2.18	21.8	18.4	3.4
May	3	Deve	0.55	2.37	26.1	15.7	10.4
Jun	1	Deve	0.67	3.09	30.9	12.7	18.2
Jun	2	Deve	0.84	4.12	41.2	10.4	30.7
Jun	3	Deve	1.00	5.26	52.6	8.1	44.4
Jul	1	Mid	1.12	6.32	63.2	5.4	57.8
Jul	2	Mid	1.13	6.76	67.6	2.9	64.7
Jul	3	Late	1.12	6.53	71.8	2.6	69.2
Aug	1	Late	1.02	5.79	57.9	2.2	55.7
Aug	2	Late	0.89	4.97	49.7	1.5	48.1
Aug	3	Late	0.79	4.03	16.1	0.8	14.9
					521.2	100.2	422.4

Figure 4. Evapotranspiration (ETc) value of quinoa grown under Nevsehir conditions

Studies on quinoa have shown that quinoa yields vary between 2-3 ton ha^{-1} (Martínez et al., 2009; Pulvento et al., 2010; Lavini et al., 2014; Yazar et al., 2014). Therefore, the quinoa that can be grown under irrigated and dry conditions in Nevşehir was designed to have a yield between 2-3 tons ha^{-1}. For quinoa production in Nevşehir, an area of 23.45 ha, which is suitable for agriculture but not used, was considered. Samutoğlu et al. (2021) cultivated quinoa under different irrigation levels under Antalya conditions. They applied full irrigation, rainfed, 25% water deficit, 50% water deficit and 75% water deficit to quinoa plants. As a result of their study, they obtained a yield of 2.95 t ha^{-1} in fully irrigated subjects and 2.43 t ha^{-1} in rainfed subjects. The authors reported that 25% water restriction in full irrigation made no statistical difference in quinoa yield (2.84 t ha^{-1}). Table 1 shows the estimated planting area and yield values of quinoa in irrigated and dry conditions.

Table 1. Estimated planting area and yield values of quinoa in irrigated and dry conditions

Production method	Planted area (hectar)	Product quantity (ton)	Yield (ton ha^{-1})
Quinoa (rainfed)	23.455	46.91	2
Quinoa (irrigated)	23.455	70.365	3

Studies have explained that the most suitable sowing period for quinoa in Turkey is March-April in regions close to sea level and April-May in high regions (Yazar and Kaya 2014; Samutoğlu et al. 2021). According to the above explanations, Nevşehir can be considered among the high regions with 1100 m. For this reason, the planting date of quinoa in Nevşehir is estimated towards the end of May and the harvest date towards the end of August. According to these data, ET and Pe obtained were taken into account and ETblue and ETgreen were calculated. ETgreen and ETblue of quinoa is given in Table 2. According to Table 2, ETgreen and ETblue were obtained as approximately 473 mm in total. ETblue accounts for about 73 per cent of the total total evapotranspiration. ET green is considerably lower than ETblue. This may be due to the low rainfall in Nevsehir.

Table 2. Green and blue evapotranspiration of Quinoa

Months	ETc (mm)	Pe (mm)	ETgreen (mm)	ETblue (mm)
May	62.1	51.7	51.7	10.4
June	113.2	31.2	31.2	82
July	183.9	10.9	10.9	173
August	113.7	4.5	4.5	109.2
Totally	472.9	98.3	98.3	374.6

The water footprint was calculated from quinoa yields estimated from irrigated and non-irrigated conditions. The total water footprint per ton was 2365 m^3 under rainfed conditions and 1575 m^3 under irrigated conditions. These values are lower than many plant varieties commonly grown in Nevşehir. For example dry beans, which has a high virtual water content and a large cultivation area, was calculated as 6851 m^3 ton^{-1} in Denizli. On the other hand, the average of dry beans in Turkey is 2580 m^3 ton^{-1}. Although dry beans are among the first crops cultivated in Nevşehir, it was higher than the quinoa water footprint calculated in the study. The main products of Nevşehir and their average water footprint in Turkey are as follows: wheat 1981 m^3 per ton, potatoes 197 m^3 per ton, rye 2185 m^3 per ton, barley 1782 m^3 per ton, grapes 988 m^3 per ton, and sugar beet 148 m^3 per ton (Anonymous, 2014; Avanoz, 2020). Although wheat, barley and rye benefit from winter precipitation in Turkey, they have a higher water footprint than quinoa and water-demanding crops such as potato sugar beet. The reason for this is thought to be due to the long growing period of the cereals mentioned above. Because both sugar beet and potato have a shorter growing period than cereals. Apart from these, the water footprint of quinoa calculated in the study was higher than that of potato and sugar beet. This is thought to be due to the fact that the mass produced by sugar beet and potato is more than the amount of water they consume per unit amount.

Table 3. Water footprint of Quinoa under irrigated and rainfed conditions

Production method	BSTgreen (m^3 ha^{-1})	BSTblue (m^3 ha^{-1})	SSMgreen ($m^3 ton^{-1}$)	SSMblue (m^3 ton^{-1})	Total water footprint (m^3 ton^{-1})	Product quantity (ton)	SA (m^3)
Quinoa (rainfed)	983	3746	492	1873	2365	46.91	110942
Quinoa (irrigated)	983	3746	327	1248	1575	70.36	110817

Conclusions

The results obtained from the study showed that the water footprint per ton of quinoa is lower than wheat, barley, rye and dry beans, which are frequently grown in Nevşehir, but higher than potatoes and sugar beets. Considering the growing seasons, it is thought that this is due to the fact that the planting-harvesting time and growing period of wheat, barley and rye are different from those of quinoa. However, it is thought that the reason why potato and sugar beet have a lower water footprint than quinoa may be due to the fact that potato and sugar beet are heavier in mass compared to the water consumed per unit. Although dry beans have an important place in terms of cultivation in the region, dry bean water footprint was found to be higher than that of quinoa. This situation suggests that quinoa cultivation can be grown instead of dry beans in regions where water resources are limited in Nevşehir. In addition, there is a 23.45 hectare area in Nevşehir that is suitable for agricultural production but not cultivated. It was thought that this area would be allocated to quinoa cultivation in Nevşehir, which currently has limited agricultural production, and that this area would increase the agricultural product diversity of Nevşehir. As a result, it was suggested that quinoa cultivation should be carried out in these areas, which are suitable for agricultural production but not cultivated.

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