

Article

Avocado Water Footprint for Two Municipalities in Michoacán, Mexico: A Research of the Blue and Green WF

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Abstract: The Water Footprint (WF) is an indicator used to determine good practices for efficiently using water in human activities. This work evaluates the green (rainfed) and blue (irrigation) water footprint of avocado cultivation in the municipalities of Acuitzio (2012–2016) and Morelia (2016–2020) in Michoacán, Mexico. Likewise, the water stress of irrigation water use is analyzed, linking the blue WF with the volumes of concessions for agricultural use. The results revealed that the mean green WF for Acuitzio is 1292.49 m³/ton, and the mean blue WF is 689.23 m³/ton. In Morelia, the mean green WF is 582.97 m³/ton, and the mean blue WF is 711.74 m³/ton. The mean production of irrigated avocado in Acuitzio is 7963.62 (ton/year), and in Morelia, 8547.76 (ton/year), which allows us to project that, in Acuitzio, the avocado crop requires an annual mean of 5,046,610.69 m³, while the mean requirement in Morelia is 6,029,920.59 m³. The average volume of water for agricultural use in Acuitzio is 3,357,782.93 m³, while the average water demand is 149.27%. This situation shows water stress in this municipality since water consumption exceeds available water resources. For Morelia, the water available for agricultural use is 11,418,745.40 m³, and the average consumption of avocado as a crop is 53.18%, which can put the supply of this resource for other agricultural crops at risk.

Keywords: blue and green water footprint; water stress in agriculture; Acuitzio and Morelia



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1. Introduction

Water is a key natural resource that fulfills the social and ecosystem functions necessary to sustain life. Currently, this resource is depleted. Among the causes are rapid population growth and increasing production activities and consumption, making freshwater resources scarcer [1,2]. Among the economic activities that demand the largest water amounts, according to Huang et al. [3] and Kang et al. [4], agricultural irrigation is the largest consumer of water, with a demand for 70% of available fresh water. The discrepancies in its distribution for different uses can limit water availability and put human well-being, economic growth, ecosystem functions, and biodiversity at risk [5]. This situation makes it necessary to carry out assessments of the sustainability of water use, for which some indicators used are ISO 14046 [6,7] and the water footprint (WF) methodology. The latter serves as a guide for the present study.

Water footprint accounting (WF) is an emerging approach developed by the Water Footprint Network (WFN) in 2002 [8,9]. Its objective is to evaluate the use of water resources in producing an item [8,10,11]. In an agricultural context, in this research, WF is understood as the volume of water needed to produce a given mass of agricultural yield [9]. The WF is divided into three components for study: green WF, blue WF, and grey WF. Green WF

is water that arrives through precipitation and is retained in the soil in the unsaturated zone [12]. Blue WF is defined as the volume of fresh water extracted from a surface or underground source and consumed in the production of an item; in the context of agricultural produce, it includes irrigation water, whatever the source [13,14]. Finally, grey WF is defined as the volume of freshwater required to assimilate the pollutant load, given natural baseline concentrations and environmental quality standards [8,12,15,16]. The scope of this study does not consider the determination of the gray water footprint due to the lack of data on agrochemical use and agricultural returns in the study area.

This indicator has been widely used in the agriculture sector using different scales of data aggregation for analysis. In this context, the study by Chapagain and Hoekstra [17] uses a product scale when estimating the water requirement of a standard cup of coffee or tea in the Netherlands. On a global scale, Mekonnen and Hoekstra [18] estimated the WF of 126 agricultural crops. For their part, Dumont et al. [19] and De Migue et al. [20] conducted their studies at the basin level in Spain. At the municipal level, the studies by Manzardo et al. [21] developed a method to take into account the water footprint at the urban level to support water management in Vicenza, northern Italy, while Arrien et al. [22] adopted the municipal scale to quantify the water footprint of corn in the Province of Buenos Aires, Argentina. The aforementioned studies are examples of how the water footprint approach is a valuable tool to explore water use and determine its sustainability, mainly in the agriculture sector [23], at different scales, and how this tool helps in the management of sustainable water resources in the medium and long term [24].

Even though the water footprint indicator allows us to know the volume of water required for producing a commodity, it was considered necessary to add the study of water stress to the research. This indicator measures the proportion of water use relative to the water resources available in a region. That is, water stress is generated by the increase in the use and consumption of water [9,25,26]. Evaluating water resources is not new; authors such as [8,17,26–29] have studied this topic. In this context, the challenge of the study is to establish the relationship between the blue water footprint and the availability of concessioned water for agricultural use at a municipal scale. This relationship allows for determining an agricultural crop's water stress on local water resources, assuming that the rest of the water demands remain constant.

For this research, water concessions are those that are granted to a private concessionaire to supply water and/or wastewater services to customers in a city or defined service area [29].

Studying the water footprint of avocado cultivation is key, since this fruit has become one of Mexico's main crops due to its high economic value in international markets. The beginnings of avocado exports date back to the 1980s, with their introduction to the European Market [30], and continued into the 1990s, when France was the main importer of Michoacan avocados [31]. However, Michoacan avocado exports changed destination when, in 1997, phyto-sanitary barriers were eliminated with respect to the pit borer pest, which had been the main non-tariff barrier to the commercialization of avocados in the United States of America [32]. Cultivation of the crop expanded in this period, generating US \$411 million. By 2020, this figure had increased by more than 82%, reaching US \$2297.78 million [33]. This situation has changed agricultural land use [31], with the country becoming the world's leading fruit producer. Michoacán is now the main avocado producer in Mexico, contributing 70% [34].

Among the factors that have favored the development and expansion of avocado cultivation in Michoacán is the biophysical characteristics and agri-environmental conditions of the region [35], as well as Mexico's emergence in global markets since the signing of international agreements [36]. However, the expansion of avocado cultivation has generated negative effects, both social and environmental. These include land use deprivation in various indigenous and peasant communities, mainly in the Purépecha plateau region [37], and a rise in deforestation, which generated a decrease of up to eight thousand hectares of temperate forest in Michoacán in the period 1975–1993 [38]. It has also impacted biodiversity and soil degradation, causing a decrease in water retention and

altering hydrological systems [35,39]. In addition to the above, there are incidences related to organized crime [40], the displacement of subsistence agricultural crops [41] and the human health and environmental problems caused by the use of pesticides in agricultural practices of avocado cultivation [42].

The area of study of this research, as a first stage of work between 2020–2021, focuses on the municipalities of Acuitzio and Morelia in the state of Michoacán, as they are an important source of information for subsequent studies in municipalities with higher production, such as Uruapan [43].

Avocado production in Acuitzio and Morelia has increased since 2008, when the crop covered 788 ha between the two municipalities, increasing by 2020 to 3376 ha, i.e., a growth of 77% [34]. Although these municipalities are not among the main avocado producers in Michoacán, they represent a benchmark for evaluating the water consumption of avocado cultivation in places where the incorporation of avocado production is recent. According to some authors [31,44], municipalities such as Uruapan have been involved in the avocado sector for over 50 years. The question then arises about the green and blue water footprint in municipalities recently incorporated into avocado production. Given this situation, the objective of this study is to evaluate the green and blue WF and analyze the sustainability of using irrigation water for avocado production in the municipalities of Acuitzio and Morelia.

1.1. Area of Study

The municipalities of Acuitzio and Morelia are located in Michoacán in Mexico (Figure 1). They are located between 19°23' and 19°33' N and 101°15' and 101°27' W, at an altitude ranging from 2100 to 3400 m.a.s.l. with a total area of 18,013 ha [45]. In 2020, an area of 2007 ha (11.14%) was reportedly dedicated to avocado cultivation [15]. The municipality of Morelia, capital of the state of Michoacán, is located between 19°26' and 19°52' N and 101°02' and 101°31' W, at an altitude ranging from 1500 to 3000 m.a.s.l., and has a total area of 119,349 ha [45]. This municipality had 1369 ha (1.14%) dedicated to avocados in 2020 [34].

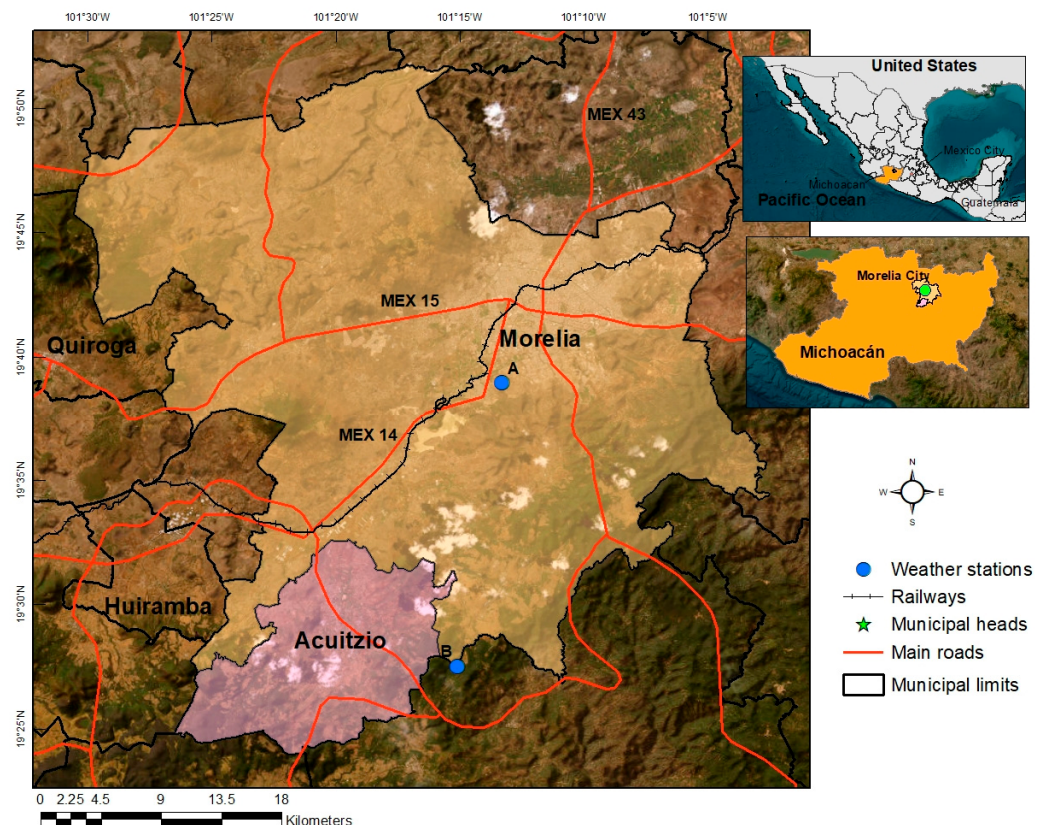


Figure 1. Geographical location of the municipalities and meteorological stations of Acuitzio and Morelia.

Regarding the altitude of the orchards in Acuitzio, they are located at an average of 2310 m.a.s.l, with a maximum of 2763 m.a.s.l and a minimum of 2068 m.a.s.l. Some 55% of the orchards are located between 2154 and 2326 m.a.s.l. In the municipality of Morelia, the orchards are located at an average altitude of 2351 m.a.s.l, with a maximum of 2697 m.a.s.l. and a minimum of 2219 m.a.s.l. A majority of the orchards (82%) are located between 2219 and 2407 m.a.s.l (Figure 2) [46].

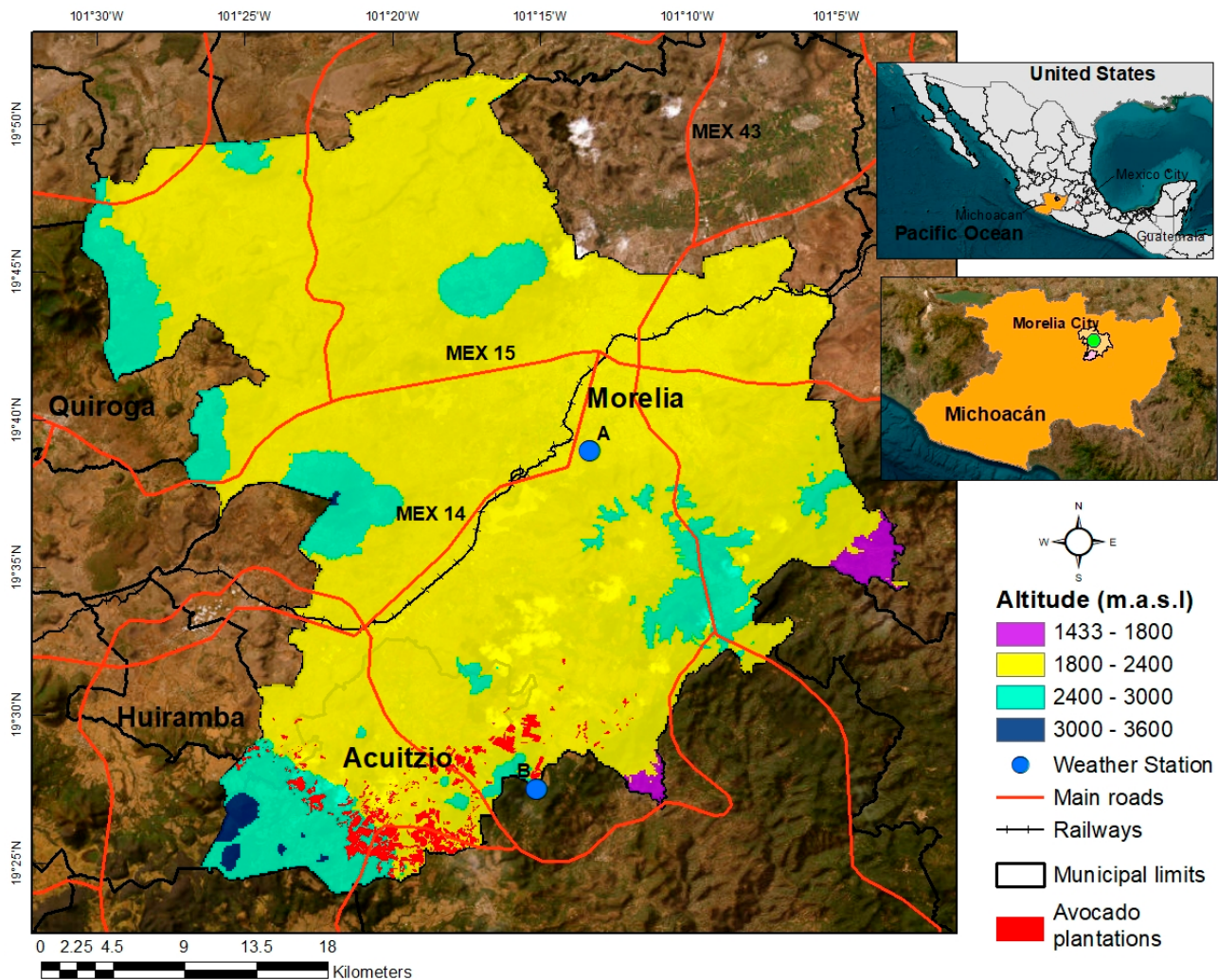


Figure 2. Altitude of avocado orchards according to the Morales–Manilla polygon [46].

Climatic Conditions of the Study Area

According to the Köppen system modified by García [47], Acuitzio has a temperate subhumid climate with cool and long summers, the temperature ranging between 5.8 °C and 24.7 °C, with an average annual temperature of 16.15 °C. The hottest month is May with a maximum (28 °C) and a minimum (9.2 °C), and the coldest month is January with a minimum (2.6 °C). The long-term total annual precipitation (1951–2010) is 901.5 mm; The months with the largest precipitation are concentrated in the summer, and July is the wettest month (205.5 mm) (Figure 3) [48].

Morelia, according to the Köppen system modified by García [47], has a semi-warm subhumid climate with rainy season during the summer; the average annual temperature range is between 9.8 °C and 26.7 °C with an average annual temperature of 18.4 °C, the hottest month is May with a maximum (30.7 °C) and a minimum (12.7 °C) and the coldest month is January with a minimum (6.6 °C). The total annual precipitation is 770.5 mm, and the wettest month is July (174.5 mm) (Figure 3) [49].

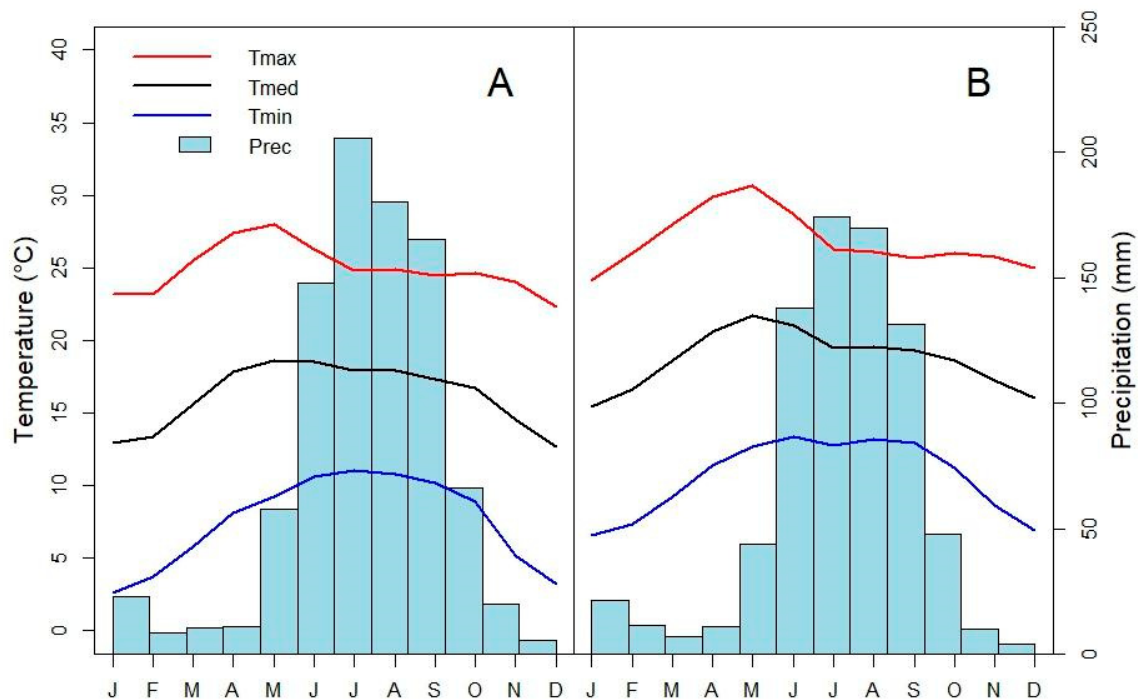


Figure 3. Climo-graphs for the period 1981–2010 for the municipalities of: (A) Acuitzio, weather station 16001 [48], and (B) Morelia, weather station 16082 [49].

2. Materials and Methods

2.1. Information Sources

We obtained the information used in the analysis from the following sources. For weather data, we consulted two sources. For Morelia municipality we used weather data of the UNAM campus Morelia weather station which is part of the University Network of Atmospheric Observatories (RUOA) of the Institute of Atmosphere and Climate Change of the Autonomous University of Mexico (UNAM) <https://ruoa.unam.mx/> (accessed on 28 November 2021) [50]. For Acuitzio, we used weather data from El Castillo weather station, located at 10 km South-East of Acuitzio's capital town, which is a node of the meteorological monitoring network of the Association of Avocado Producers and Packers Exporters of Mexico (APEAM) <http://www.apeamclima.org/> (accessed on 10 November 2021) [51]. For crop production, cultivated surface and crop yield, we considered data from the Agri-Food and Fisheries Information Service (SIAP) of Mexico's federal government <https://www.gob.mx/siap> (accessed on 9 October 2021) [34], as well as the Food and Agriculture Organization of the United Nations <https://www.fao.org/faostat/es/#data/QV> (FAO) (accessed on 22 November 2021) [33]. We obtained the soil characteristics and information data from 1:50,000 and 1:250,000 scale digital soil maps of the National Institute of Statistics and Geographic <https://www.inegi.org.mx> (INEGI) (accessed on 10 December 2021) [52]. The specific crop characteristics data (height, phenology) were obtained directly from field observations at the orchards and from plantation managers. Finally, we used the data of records of water availability through water rights concessioned for agricultural use from the Public Registry of Water Rights (REPD) of Mexico's Federal Government Comisión Nacional del Agua (CONAGUA) <https://app.conagua.gob.mx/consultarepda.aspx> (accessed on 20 December 2021) [53].

2.2. Water Footprint Method for Estimating Water Consumption

Considering the data from the aforementioned sources, the workflow diagram of the analytical procedure for calculating the green and blue water footprint and water stress of avocado cultivation in the municipalities of Acuitzio and Morelia is described graphically in Figure 4.

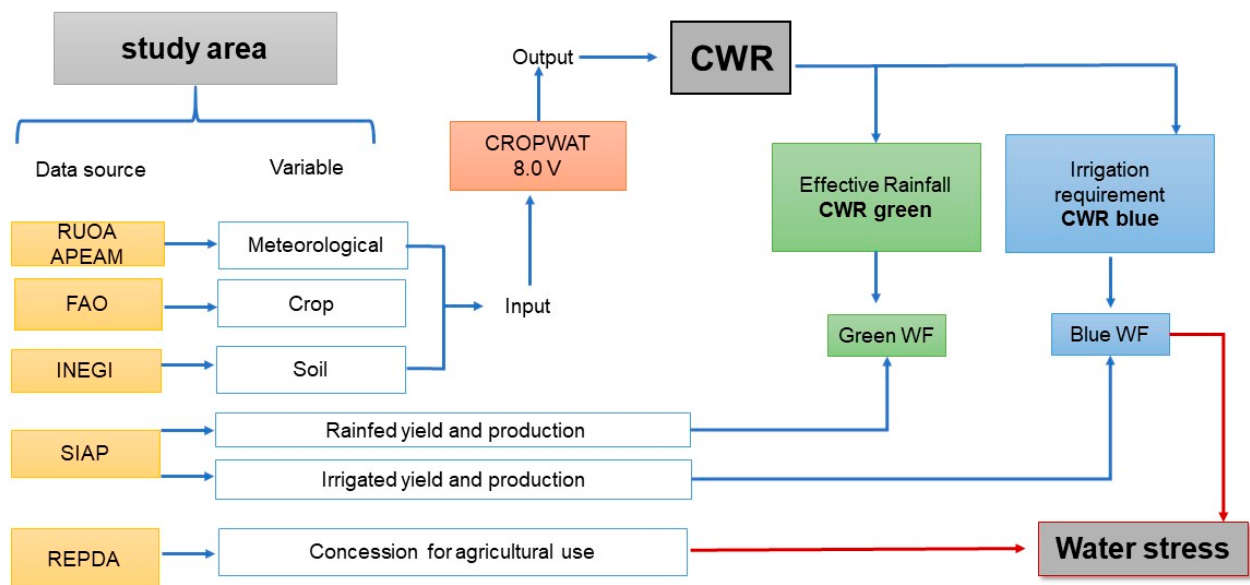


Figure 4. Workflow diagram of the procedure for the analysis of green and blue WF (G–B WF) and water stress. CWR (crop water requirement), WF (water footprint), CWR green (green crop water requirement), CWR blue (blue crop water requirement).

2.2.1. Crop Water Requirement (CWR)

The first step is to estimate the CWR (crop water requirement), which corresponds to the volume of water a crop needs to develop its metabolic functions and to grow [54]. To estimate the CWR, the CROPWAT v 8.0 software was used, a program that feeds meteorological data (minimum and maximum temperature, humidity, wind speed, and precipitation), crop characteristics (crop Coefficient-Kc, root depth, critical depletion, yield response, and crop growth initiation), and soil data (soil moisture and maximum infiltration rate). Meteorological data were obtained from two stations: (A) Morelia (Figure 1) is located in the municipality of Morelia at coordinates 19°64′ latitude and 101°22′ longitude at 1936 m.a.s.l. [50]. The second meteorological station, (B) El Castillo Acuitzio-Villa Madero (Figure 1), is located in the municipality of Madero at coordinates 19°26′ N latitude and 101° 17′ W longitude, 10 km from Acuitzio and at an altitude of 2308 m.a.s.l. [51]. The values established in FAO Manual 56 were used [54] with regard to avocado cultivation data (Table 1). For the soil data, the soil textures were determined by on-site cartographic analysis, concluding that they are fine and medium [52], inputs for the CROPWAT v 8.0 program (Table 1) [54,55].

Table 1. Input data on crop characteristics and soil values. Source: [54,55].

Avocado Crop Characteristics	
Kc-Initial Kc/Development Kc/Final	0.6–0.85–0.75
Root depth (m)	0.60–0.80
Critical Exhaustion (Fraction)	0.50
Performance Response	1.10–1.30
Height (m)	6.5
Onset of flowering	March
Soil Data	
Available soil moisture (CC–PMP) (mm/meter)	290
Maximum infiltration rate (mm/day)	40

The CWR will be equal to the crop evapotranspiration (ET_c) expressed in mm per unit time [55,56]. The calculation of the initial reference evapotranspiration (ET_0) was performed using the Penman–Monteith equation, which considers the atmospheric and physiological factors (stomatal resistance) that govern the processes of direct evaporation from the soil and the transpiration of vegetation. In this case, the existence of ideal conditions without water limitations for the growth of the studied crop is assumed [54,55].

$$CWR_c^p = ET_0^p \times K_c \quad (1)$$

$$CWR_c^p = ET_c^p \quad (2)$$

where CWR_c^p is the crop water requirement in (mm/day), for a crop c , in a region p ; ET_0^p is the initial reference evapotranspiration (mm/day) in a region p ; and K_c is the coefficient of a crop c , which describes the variations in the amount of water that plants extract from the soil as they grow.

The results of the CWR calculation include: the effective precipitation $ET_{c\text{green}} = P_{\text{eff}}$, which represents the part of the precipitation retained by the soil and is available for the use of the crop, and the evapotranspiration of the blue crop ($ET_{c\text{blue}} = IR$), which is the irrigation requirement (IR); this turns out to be the amount of additional water resource that the crop demands, because the effective precipitation did not cover all the water needs [55,57].

2.2.2. Calculation of Green and Blue Water Requirement

$$CWR_{\text{green}}_c^p = 10 \times \sum_D^{lg} ET_{c\text{green}} \quad (3)$$

$$CWR_{\text{blue}}_c^p = 10 \times \sum_D^{lg} ET_{c\text{blue}} \quad (4)$$

where $\sum_D^{lg} ET_{c\text{green}}$ Equation (3) is the sum of the evapotranspiration of the effective precipitation of water (green water) over the growing period of the crop from the day of planting (day 1) (D) to the day of harvest, and where lg is the length of the processing time. According to [11], the factor for converting water depth (mm) to the volume of water per land area (m^3/ha) is 10. In Equation (4), we have $\sum_D^{lg} ET_{c\text{blue}}$, the sum of the blue water [55].

2.2.3. Green and Blue Water Footprint Calculation

$$WF_{\text{green}}_c^p = \frac{CWR_{\text{green}}_c^p}{R_c} \quad (5)$$

$$WF_{\text{blue}}_c^p = \frac{CWR_{\text{blue}}_c^p}{R_c} \quad (6)$$

Equations (5) and (6), which will be in m^3/ton , consider the results of Equations (2) and (3), as well as the yield R_c in units of mass per area of crop c (ton/ha). Yield data were obtained from the Agri-Food and Fisheries Information Service [34].

2.2.4. Calculation of Annual Green and Blue Water Consumption

In the annual calculation of water consumption Equations (7) and (8), Equations (5) and (6) results are used and multiplied by annual production $Prod_c^p$, with data from the Agri-Food and Fisheries Information Service [34] of a crop c for a region p .

$$\text{Green water consumption}_c^p = WF_{\text{green}}_c^p \times Prod_c^p \quad (7)$$

$$\text{Blue water consumption}_c^p = WF_{\text{blue}}_c^p \times Prod_c^p \quad (8)$$

2.2.5. Calculating the WATER stress of Irrigation Water Use

The water stress of irrigation water use (WSIW) was determined Equation (9) from the ratio of *Blue water consumption*_c^p and the volumes of surface and groundwater granted for agricultural use *VC*, which were obtained from the Public Registry of Water Rights (REPDA) for the period and sites of the study [53].

$$WSIW = \frac{\text{Blue water consumption}_c^p}{VC} \quad (9)$$

3. Results

3.1. Crop Water Requirement (CWR)

From the analysis of the meteorological information (Appendix A, Figure A1), the municipality of Acuitzio was determined as having an annual mean water depth (ETc) of 1299.98 mm/year (± 33.68), mean annual rainfall of 1508.17 mm/year (± 618.16), mean blue water requirement of 567.43 mm/year (± 30.77) and effective precipitation (green water) mean of 863.65 mm/year (± 95.65). In the case of Morelia, a mean annual depth (ETc) of 1382.46 mm/year (± 46.91), mean annual rainfall of 714.38 mm (± 223.81), mean irrigation requirement of 841.78 mm/year (± 148.44) and a mean effective rainfall of 554.80 mm/year (± 133.11) were estimated (Table 2).

Table 2. Water Requirement of Avocado Cultivation.

Municipality	Year	Total Rainfall (mm/year)	ETc (mm/year)	Effective Rainfall (Green Water) (mm/year)	Irrigation Requirement (Blue Water) (mm/year)
Acuitzio	2012	964.00	1295.9	765.1	595.6
	2013	1395.00	1261.3	892.5	517.2
	2014	1059.00	1292.6	797.7	579
	2015	1083.00	1273.7	790.5	598
	2016	2426.00	1322.5	1011.1	548.8
	2017	2122.00	1353.9	925	566
	Mean	1508.17 (± 618.16)	1299.98 (± 33.68)	863.65 (± 95.65)	567.43 (± 30.77)
Morelia	2016	560.80	1400.50	483.20	917.30
	2017	594.31	1446.60	457.20	996.20
	2018	1081.30	1322.90	773.90	606.10
	2019	559.60	1354.40	470.80	883.60
	2020	775.90	1387.90	588.90	805.70
	Mean	714.38 (± 223.81)	1382.46 (± 46.91)	554.80 (± 133.11)	841.78 (± 148.44)

The average values for each municipality are presented, and the standard deviation is presented in parentheses.

The analysis showed that, in Acuitzio, avocado cultivation requires 39.65% blue water and 60.34% green water. For Morelia, the proportions are 60.27% for the irrigation requirement and 39.79% for the effective precipitation. The difference between both municipalities is due to the climatic conditions (Figure 3). In Acuitzio, the average annual precipitation is 901.50 mm, and the temperature is 16.5 °C. In Morelia, the precipitation is 770.50 mm, and the average temperature is 18 °C. This difference causes evapotranspiration to be higher in Morelia. This means that the lower the precipitation and the higher the temperature, the higher the evapotranspiration depth, which increases the blue water requirement.

3.2. Green and Blue Water Footprint of Avocado Cultivation

The municipality of Acuitzio was estimated to have an average green WF for rainfed plantations of 1292.49 m³/ton (± 178.97) for a mean yield of 6.82 (ton/ha) (Appendix A, Table A1), with the maximum in 2012 (1391.09 m³/ton) and the minimum in 2015 (1097.92 m³/ton). Regarding irrigated plantations, a mean total WF of 1714.65 m³/ton (± 394.51) was determined for a mean yield of 8.67 (ton/ha), with a maximum in the blue WF in 2012 (1082.91 m³/ton), the driest year of the study period, and minimums in 2013 (517.20 m³/ton), 2016 (596.52 m³/ton) and 2017 (547.92 m³/ton), all years with higher rainfall (Appendix A, Table 3. For Morelia, a mean green WF for rainfed plantations was estimated at 582.97 m³/ton (± 109.86) for a mean yield of 9.50 (ton/ha), with a maximum in 2018 (744.13 m³/ton) and a minimum in 2019 (448.38 m³/ton). For irrigated plantations, a mean total WF of 1179.70 m³/ton (± 102.63) was estimated for a mean yield of 11.91 (ton/ton). The maximum in the blue WF was in 2019 (810.64 m³/ton), the driest year of the study period, and the minimum in 2018 (474.63 m³/ton), the wettest year (Table 3) (Table A1).

Table 3. Water footprint for rainfed production and irrigation.

Municipality	Year	Rainfed Plantations	Irrigation Production			Mean WF for Rainfed and Irrigated Plantations (m ³ /ton)
		Green WF (m ³ /ton)	Green WF (m ³ /ton)	Blue WF (m ³ /ton)	G+B WF (m ³ /ton)	
Acuitzio	2012	1391.09	1391.09	1082.91	2474.00	1932.55
	2013	1275.00	892.50	517.20	1409.70	1342.35
	2014	1595.40	886.33	643.33	1529.67	1562.53
	2015	1097.92	988.13	747.50	1735.63	1416.77
	2016	1162.18	1099.02	596.52	1695.54	1428.86
	2017	1233.33	895.45	547.92	1443.37	1338.35
	Mean	1292.49 (± 178.97)	1025.42 (± 197.19)	689.23 (± 209.11)	1714.65 (± 394.51)	1503.57 (± 225.34)
Morelia	2016	530.99	386.56	733.84	1120.40	825.69
	2017	571.50	354.42	772.25	1126.67	849.08
	2018	744.13	606.03	474.63	1080.66	912.40
	2019	448.38	431.93	810.64	1242.57	845.47
	2020	619.89	560.86	767.33	1328.19	974.04
	Mean	582.97 (± 109.86)	467.96 (± 110.12)	711.74 (± 135.31)	1179.70 (± 102.63)	881.34 (± 61.20)

The estimates showed that, in Acuitzio, the green and blue water footprint was 41.39% larger than in Morelia, even though evapotranspiration in the latter was higher. The lower water requirement is because, in Morelia, the average yield of avocado cultivation is 27% higher than in Acuitzio (Table A1).

3.3. Annual Green and Blue Water Consumption of Avocado Cultivation

The municipality of Acuitzio was estimated to have an average annual water consumption for rainfed production of 1,405,722.89 m³ ($\pm 802,455.50$) for an average production of 1139.62 (ton/year) (Appendix A, Table A1), with a maximum in 2017 (2,220,000.00 m³) and a minimum in 2013 (196,350.00 m³). With regard to irrigation production, a total mean annual consumption of 15,241,145.00 m³ ($\pm 4,860,371.00$) was determined for an average production of 7963.62 (ton/year). The maximum was reached in 2017 (20,534,629.50 m³), the year with the highest volume of avocado production, 11,528.20 (ton/year), and the minimum in 2012 (6,980,391.00 m³), the period of lowest avocado production at 2821.50 (ton/year). For the municipality of Morelia, the mean annual consumption for rainfed production was estimated at 1,627,716.40 m³ ($\pm 721,804.40$) for a mean production of 2755.52 (ton/year), with a maximum in 2020 (2,167,152.00 m³) and a minimum in 2016 (579,840.00 m³). Regarding irrigated production at this site, a total mean annual consumption of 11,072,488.91 m³ ($\pm 1,728,986.00$) was estimated for an average production of 8547.76 (ton/year), with a maximum in 2017 (12,515,400.70 m³), the year with the highest volume of avocado production 9708.00 (ton/year) and a minimum in 2016 (8,221,388.57 m³), the period with the lowest avocado production at 6500.00 (ton/year) (Table 4; Table A1).

Table 4. Annual consumption of rainfed and irrigated production.

Municipality	Year	Rainfed Production		Irrigated Production		Total Water Consumption for Rainfed and Irrigated Production (m ³)
		Rainfall (m ³)	Rainfall (m ³)	Irrigation (m ³)	Total (m ³)	
Acuitzio	2012	1,365,703.50	3,924,963.00	3,055,428.00	6,980,391.00	8,346,094.50
	2013	196,350.00	9,945,000.00	4,034,160.00	13,979,160.00	14,175,510.00
	2014	788,526.45	13,956,559.20	5,627,880.00	19,584,439.20	20,372,965.65
	2015	1,650,959.25	8,537,400.00	5,812,560.00	14,349,960.00	16,000,919.25
	2016	2,212,798.16	10,585,171.03	5,433,120.00	16,018,291.03	18,231,089.19
	2017	2,220,000.00	14,218,113.33	6,316,516.17	20,534,629.50	22,754,629.50
	Mean	1,405,722.89 (±802,455.50)	10,194,534.43 (±3,810,787.00)	5,046,610.69 (±1,239,070.00)	15,241,145.00 (±4,860,371.00)	16,646,868.02 (±5,081,850.00)
Morelia	2016	579,840.00	3,451,428.57	4,769,960.00	8,221,388.57	8,801,228.57
	2017	1,417,320.00	5,322,836.70	7,192,564.00	12,515,400.70	13,932,720.70
	2018	2,430,046.00	7,224,058.85	4,607,688.96	11,831,747.80	14,261,793.80
	2019	1,544,224.00	3,812,134.86	6,892,080.00	10,704,214.90	12,248,438.86
	2020	2,167,152.00	5,402,382.63	6,687,310.00	12,089,692.60	14,256,844.63
	Mean	1,627,716.40 (±721,804.40)	5,042,568.32 (±1,501,050.00)	6,029,920.59 (±1,238,695.00)	11,072,488.91 (±1,728,986.00)	12,700,205.31 (±2,333,822.00)

The average values for each municipality are presented, and the standard deviation is presented in parentheses.

3.4. Analysis of the Water Stress of Irrigation Water Use

For the municipality of Acuitzio, the mean total volume of water granted for agricultural use was estimated at 3,357,782.93 m³ (±135,982.50), with a maximum in 2017 (3,545,001.60 m³) and a minimum in 2012 (3,156,689.60 m³). Likewise, a mean annual water consumption of 5,046,610.69 m³ (±1,239,070.00) was determined for irrigated production, and the mean water consumption granted for avocado cultivation was 149.27% (±31.91), with a minimum annual production of the crop in 2012 (96.79%) and a maximum in 2017 (178.18%). The analysis of the water stress of irrigation water use in the municipality of Acuitzio suggests that avocado cultivation requires not only all of the water granted but also an additional 49.27% situation that causes greater pressure on the water resource (Table 5).

Table 5. Water stress of agricultural irrigation water use in Acuitzio.

Year	Annual Irrigation Water Consumption (m ³)	Surface Water Concession (m ³)	Groundwater Concession (m ³)	Total Concession (m ³)	Consumption of Granted Water %
2012	3,055,428.00	1,681,715.60	1,474,974.00	3,156,689.60	96.79
2013	4,034,160.00	1,681,715.60	1,568,286.00	3,250,001.60	124.12
2014	5,627,880.00	1,681,715.60	1,708,286.00	3,390,001.60	166.01
2015	5,812,560.00	1,681,715.60	1,708,286.00	3,390,001.60	171.46
2016	5,433,120.00	1,681,715.60	1,733,286.00	3,415,001.60	159.09
2017	6,316,516.17	1,681,715.60	1,863,286.00	3,545,001.60	178.18
Mean	5,046,610.69 (±1,239,070.00)	1,681,715.60 (±0)	1,676,067.33 (±135,982.50)	3,357,782.93 (±135,982.50)	149.27 (±31.91)

For the municipality of Morelia, the mean total volume of water granted for agricultural use was estimated at 11,418,745.40 m³ (±1,212,152.00), with a maximum in 2020 (12,391,049.30 m³) and a minimum in 2016 (9,942,349.12 m³). The mean annual irrigation water consumption was 6,029,920.59 m³ (±1,238,695.00), while the mean percentage of granted water consumption was 53.18% (±11.88), with a maximum in 2017 (70.15%), and a minimum (37.66%) in 2018 (Table 6). In this municipality, the analysis did not show a larger volume of water consumption than that the water volume available for the avocado crop. This situation does not demonstrate water stress for the study period. However, by demanding more than 50% of the available water volume, the supply of this resource for other agricultural crops can be put at risk.

Table 6. Water stress of agricultural irrigation water use in Morelia.

Year	Annual Irrigation Water Consumption (m ³)	Surface Water Concession (m ³)	Groundwater Concession (m ³)	Total Concession (m ³)	Consumption of Granted Water %
2016	4,769,960.00	6,310,219.52	3,632,129.60	9,942,349.12	47.99
2017	7,192,564.00	6,310,219.52	3,943,236.76	10,253,456.30	70.15
2018	4,607,688.96	7,956,111.52	4,277,140.76	12,233,252.30	37.66
2019	6,892,080.00	7,956,111.52	4,317,508.76	12,273,620.30	56.11
2020	6,687,310.00	7,956,111.52	4,434,937.76	12,391,049.30	54.00
Mean	6,029,920.59 (±1,238,695.00)	7,297,754.72 (±901,492.20)	4,120,990.72 (±328,689.30)	11,418,745.40 (±1,212,152.00)	53.18 (±11.88)

4. Discussion

The analysis of avocado cultivation in the municipalities of Acuitzio and Morelia revealed how the increase in rainfall has a significant impact on the results of the water footprint, a situation similar to that reported by Novoa et al. [58] in the Valle de Guadalupe, Mexico, where it was shown that in the driest years there is a greater consumption of water in the vine and olive crops and lower consumption in years with higher humidity. Another study is that of Reyes and Naranjo [59] in Quindío, Colombia, which demonstrated that the precipitation contribution is enough to cope with the water needs of the avocado crop at that study site. This condition caused the green water footprint component to be 3630.00 m³/ton, while the blue water requirement was 0 m³/ton.

Furthermore, Cruz-Pérez et al. [60] in his studio on the Canary Islands in Spain determined the water footprint for avocado cultivation of 1741.94 m³/ton; at the same time, they obtained evidence that the WF at this site is mainly affected by irrigation with a blue WF greater than the green WF, a situation similar to that of Acuitzio (Table 7).

Table 7. Green and/or blue water footprints of different regions and in the present study.

Reference	Location, Country	Green Water Footprint m ³ /ton	Blue Water Footprint m ³ /ton
[59]	Quindío, Colombia	3630.00	0
[60]	Canary Islands	651.30	1090.61
[18]	Global mean water footprint	849.00	283.00
[18]	Mean water footprint of Mexico	746.00	266.00
[43]	Uruapan, Michoacan	417.10	----
[43]	Uruapan Michoacán	----	1071.40
Present study Rainfed plantations	Acuitzio, Michoacan	1292.97	----
Present study Irrigation plantations	Acuitzio, Michoacan	----	1714.65
Present study Rainfed plantations	Morelia, Michoacan	582.97	----
Present study Irrigation plantations	Morelia, Michoacan	----	1179.70

At the local level, variations were also found in the estimates of water consumption. For example, Burgos [61] reported a water requirement for avocado cultivation in the region of Michoacán of 180 to 652 m³/ton, while Gómez-Tagle et al. [43] estimated a WF for rainfed plantations of 417.10 m³/ton for the municipality of Uruapan in Michoacán, and of 1071.4 m³/ton for irrigated plantations. In the latter case, the difference between the present research on water consumption and the study sites of Acuitzio and Morelia is due to the fact that the air is drier and the winds are stronger, which causes lower relative humidity and greater evapotranspiration [55].

In addition to climatic differences, yield is another factor that influences water consumption since, with a low crop yield, the value of the blue and green water footprint will be higher [59]. This situation takes place in Acuitzio. Hoekstra and Mekonnen [62] stated that water consumption in agricultural products depends on the climate, irrigation and fertilization practices, and on crop yields.

This scenario makes reducing the blue and green water footprint necessary since this would relieve pressure on the available water resources. Chukalla et al. [63] report that changing and combining irrigation management practices is the way forward. Esteve-Llorens et al. [64] emphasize the importance of technical irrigation systems to make the use of surface and groundwater more efficient. Additionally, Mekonnen and Hoekstra [2] note that the strategy should also tend towards improving the productivity of rainfed agriculture because it can help reduce irrigation water consumption and the associated environmental impacts.

Regarding the water stress of irrigation water use, Jiang et al. [11] report that dependence on blue water in the Tarim River Basin in China has caused imbalances in water use; another similar study is that of Novoa et al. [58] where, in the words of the author, they detected unsustainability in the upper basin of the Cachapoal River in Chile, based on the blue water footprint indicator and caused mainly by climatic variations. In the case of Wedaa et al. [65], research shows how irrigated agricultural crops in Iraq have had to switch to seasonal crops due to the scarcity of blue water.

In addition, Ma et al. [66] found that, in the arid region of Aksu located in the Tarim Basin, the water consumption of the 15 main agricultural crops has increased by almost 3.13 times from 1990 to 2020; at the same time, the calculation of the blue water footprint allowed us to estimate water use up to 1.30 times greater than that reported by the corresponding authorities.

At the local level, the study by Gómez-Tagle et al. [43] shows that avocado production can generate stress and a scarcity of blue water, as this fruit can consume up to 120% of the volume of concession water in the municipality of Uruapan. These studies reach conclusions, similar to ours, where it is evident that, in the short or medium term, there will be scenarios of overexploitation of water resources.

5. Conclusions

The blue and green water footprint analysis reveals how climate variables exert significant pressure on avocado crop water consumption. Thus, the contribution of this research is key, considering that Michoacán is the main avocado growing region at the national level. Therefore, if this trend in water consumption continues, there is a risk that irrigation water will decrease due to overexploitation and in turn other subsistence agricultural crops will be marginalized.

Finally, it is important to note that, although the WF indicator is a valuable tool for assessing the water use of a product, this methodology has its limitations, such as the uncertainty of the data and the assumption that the regional crop has optimal and homogenous soil, water, crop and climatic conditions.

Because of the above, it is necessary to reflect on the fact that the calculation of the water footprint demonstrated in this research is only an approximation of water use and that onsite measurements are necessary for greater accuracy regarding the real water consumption of avocado cultivation at the orchard level.

Despite the limitations, this study is a benchmark to support managers and decision-makers in adopting an environmental perspective, which seeks both transparency and monitoring of the water footprint and the implementation and validation of water-saving initiatives so that water resources are sustainable over time.

In addition to the above, the present study, which is part of a doctoral thesis [67], opened a line of work that allows research on the water footprint and stress in other avocado-producing municipalities in Michoacán and other states of Mexico. At the same time, it is also influencing future works on this topic to add to their studies the mapping of virtual water exports and the estimation of the gray water footprint in future research.

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H.G.-G.-R.; Validation, L.S.-A. and H.G.-G.-R.; Visualization, L.S.-A. and H.G.-G.-R.; Writing—original draft, D.J.F.-V., L.S.-A., A.G.-T. and H.G.-G.-R.; Writing—review and editing, D.J.F.-V., L.S.-A., A.G.-T. and H.G.-G.-R. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Appendix A.1. Meteorological Variables for WF

For the municipality of Acuitzio, an average maximum temperature of 25.35 °C (± 1.51) and average minimum temperature of 7.65 °C (± 2.89) were estimated; it was also established that the hottest month is May, with 27.10 °C (2012) and 29 °C (2017), and the coldest is January, with 1.90 °C (2012) and 3.60 °C (2017). The mean relative humidity (RH) was 76.50% (± 12.53), with April the driest month for this region with a 2012 value of 45.77% and 47.85% in 2017. The mean wind run was 161.24 km/day (± 25.88); the month with the strongest winds is January, with 187.96 km/day (2012) and the maximum recorded was 181.08 km/day (2017) (Figure A1).

Likewise, a mean monthly evapotranspiration (ET_o) of 139.13 mm (± 24.43) was estimated, with a maximum in April of 177.60 mm (2012) and a minimum of 115.01 mm in January (2012) (Figure A1). In this municipality, there was an average monthly rainfall of 176.81 (mm) (± 137.43) for the study period. The rainy season runs from July to October with mean rainfall of 291.78 (mm); the highest rainfall was in 2017 (2229.60 mm) and the year with the lowest rainfall was 2012 (1106.60 mm).

For Morelia (Figure A1), a mean maximum temperature of 26.93 °C (± 2.23), and a minimum temperature of 6.89 °C (± 4.58) was determined. May is the hottest month, with 31.57 °C (2012) and 29.48 °C (2017), and the coldest is January with 1.06 °C (2016) and 2.98 °C (2017). The average RH was 59.86% (± 15.19) and the driest month is April with 35.67% (2016) and 38.85%. The mean wind run was 145.32 km/day (± 35.67), the lightest winds occurring in November: 50.31 km/day (2016) and 51.86 km/day (2017).

Finally, for Morelia, a mean monthly ET_o of 149.05 mm (± 33.81) was estimated, with a maximum in April of 190.50 mm (2016) and a minimum in November of 96.30 mm (2016) (Figure 4). The average rainfall for this region was 59.53 mm (± 69.63), the year with the highest rainfall was 2018 (1081.3 mm) and the lowest rainfall was in 2019 (559.90 mm) (Figure A1). Taking into account the above estimates, the municipality of Morelia has higher evapotranspiration (ET_o) than Acuitzio, due to the fact that the air is drier, which causes lower relative humidity and greater evapotranspiration [55].

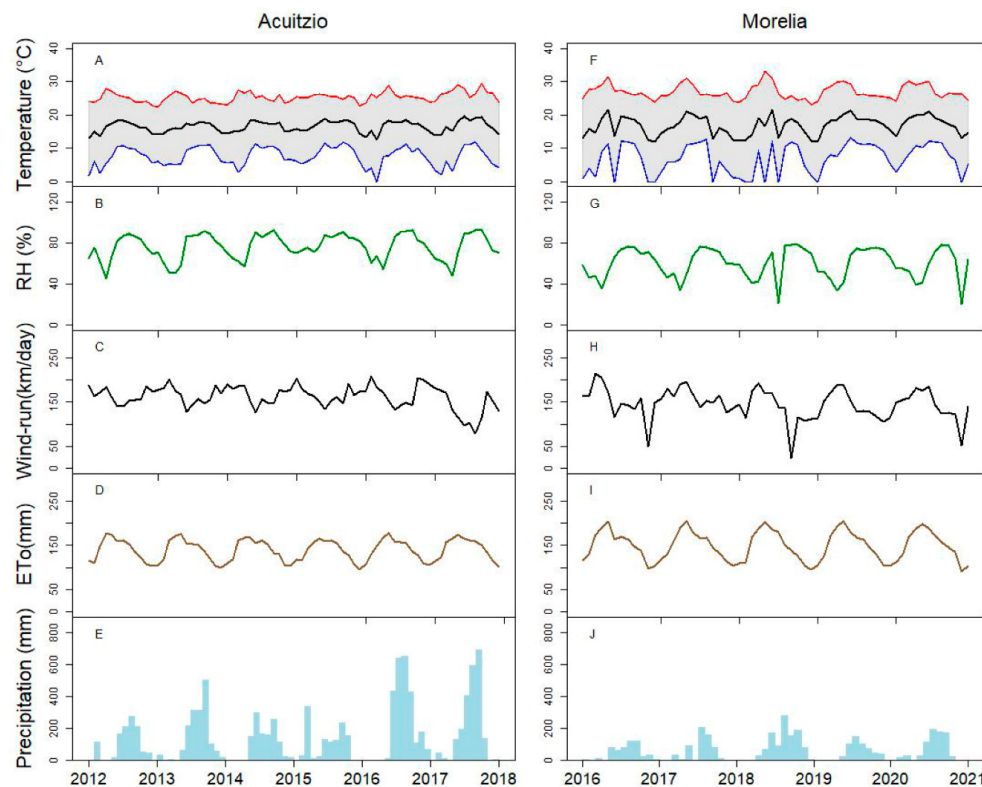


Figure A1. Monthly series of meteorological variables of the municipalities of Acuitzio (A–E) and Morelia (F–J). In the first panel of the graph, we have mean maximum temperature red line, mean temperature black line and mean minimum temperature blue line.

Appendix A.2. Characterization of Avocado Production

The panorama of avocado cultivation in the studied municipalities has a progressive behaviour that is shown in Table A1, both for rainfed and irrigated production. In Acuitzio, according to official data, the average planted area for rainfed production was estimated at 228.90 ha (± 38.37), which rose from 178.85 ha in 2012 to 294 ha in 2017. This means an increase of 64% in total, which corresponds to 10.7% per year. As for the production volume, a mean of 1139.62 (ton/year) (± 716.35) was determined, which rose from 981.75 (ton/year) in 2012 to 1800 (ton/year) in 2017, an increase of 83% 818.25 (ton/year). For avocado cultivation under irrigated conditions in this municipality, the SIAP (2021) reports a planted area of 1250 ha in 2012, which grew to 1562 ha in 2017, an increase of 312 ha. In addition, the volume of production increased from 2821.50 (ton/year) in 2012 to 11,528 (ton/year) in 2017, which represents a growth of 308%.

Table A1. Avocado production in the studied municipalities.

Municipality	Year	Rainfed Production			Irrigated Production		
		Planted Surface (ha)	Production Volume (ton/year)	Crop Yield (ton/ha)	Planted Surface (ha)	Production Volume (ton/year)	Crop Yield (ton/ha)
Acuitzio	2012	178.85	981.75	5.50	1250.00	2821.50	5.50
	2013	209.00	154.00	7.00	1257.00	7800.00	10.00
	2014	218.85	494.25	5.00	1420.00	8748.00	9.00
	2015	233.85	1503.72	7.20	1430.00	7776.00	8.00
	2016	238.85	1904.00	8.70	1499.00	9108.00	9.20
	2017	294.00	1800.00	7.50	1562.00	11,528.20	10.33
	Mean	228.90 (± 38.37)	1139.62 (± 716.35)	6.82 (± 1.35)	1403.00 (± 126.68)	7963.62 (± 2868.25)	8.67 (± 1.75)
Morelia	2016	330.00	1092.00	9.10	590.00	6500.00	12.50
	2017	398.00	2480.00	8.00	887.00	9313.80	12.90
	2018	418.00	3265.60	10.40	967.00	9708.00	12.77
	2019	426.00	3444.00	10.50	909.00	8502.00	10.90
	2020	451.00	3496.00	9.50	918.00	8715.00	10.50
	Mean	404.60 (± 45.82)	2755.52 (± 1015.59)	9.50 (± 1.02)	854.20 (± 150.56)	8547.76 (± 1240.60)	11.91 (± 1.12)

Continuing with Table A1, a mean planted area of 404.60 ha (± 45.82) was estimated for the rainfed modality in Morelia, going from 330 ha in 2016 to 451 ha in 2020, an increase of 121 ha. This represents a total increase of 36.6%, which corresponds to 6.11% annually. Regarding the production volume, an average of 2755.52 (ton/year) (± 1015.59) was estimated, rising from 1092 (ton/year) in 2016 to 3496 (ton/year) in 2020, an increase of 220%. For irrigated production, an average planted area of 854 ha (± 150.56) was estimated, going from 590 ha in 2016 to 918 ha in 2020, an increase of 328 ha. In addition, the volume of production grew from 6500 (ton/year) in 2016 to 8715 (ton/year) in 2020.

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