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Future Prediction of Net Irrigation Requirements for Coffee Trees under Different Production Scenarios

Predicción a futuro de las normas netas de riego del cafeto en diferentes escenarios productivos

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ABSTRACT: This study aimed to estimate the future net irrigation requirements of coffee trees based on climate variability across different coffee-growing regions in Cuba. Representative sites were selected in the four main mountainous regions of the country where coffee is cultivated. Climate data from the PRECIS model under the RCP 4.5 climate scenario-recommended by the Cuban Institute of Meteorology-were used to evaluate water management needs in each region and crop. The CROPWAT 8.0 modeling program was applied to estimate irrigation requirements for the medium term (2050), based on forecasted climate variability. The obtained results were then compared to the values established in Resolution 17/2020 of the National Institute of Hydraulic Resources. The total net irrigation requirements estimated for coffee trees under future climate conditions indicate an increase ranging from 8.8% in La Palma (equivalent to 8,447.0 $m^3 \cdot ha^{-1}$) to 40.5% in Palenque de Yateras (8,793.0 $m^3 \cdot ha^{-1}$). The largest differences between total net and reduced irrigation requirements under the RCP 4.5 scenario were found in the western and central regions (48% to 78%), while smaller differences were observed in the eastern region (17% to 51%). A comparison with the values from Resolution 17/2020 shows that future irrigation requirements are between 8.8% and 40.5% higher, indicating increased pressure on water resources in the studied coffee-growing areas.
Keywords: Climate Change, Estimation, Water Requirements, PRECIS Model.

RESUMEN: El trabajo se desarrolló con el objetivo de estimar a futuro las normas netas totales de riego del cafeto según la variabilidad climática en diferentes zonas productoras del grano en Cuba. Para ello fueron seleccionados sitios representativos donde se cultiva el cafeto en los cuatro macizos montañosos de Cuba. Se tomaron los datos climáticos del modelo PRECIS en el escenario climático RCPs 4.5, recomendado por el Instituto de Meteorología de Cuba para evaluar el manejo del agua en función de las regiones climáticas y cultivos como el cafeto. Para la estimación de las normas de riego a mediano plazo (2050), en función de los pronósticos de variabilidad climática se utilizó el programa de modelación CROPWAT 8.0. Por último, se compararon las normas de riego obtenidas con las que aparecen en la *Resolución 17/2020* del Instituto Nacional de Recursos Hidráulicos. Las estimaciones de las normas netas totales de riego para el cafeto según la variabilidad climática en los próximos años para los sitios de estudio indican que habrá un incremento de las mismas entre un 8,8 % en La Palma, que equivalen a 8 447,0 $m^3 \cdot ha^{-1}$ y un 40,5 % en Palenque de Yateras (8 793,0 $m^3 \cdot ha^{-1}$). Las mayores diferencias entre las normas netas totales y las normas netas reducidas para el escenario RCP 4.5 se tienen en la región occidental y central las que varían entre 48 % y 78 %, siendo menores para la región oriental donde están en el rango de 17 % a 51 %. Al comparar las obtenidas con las de la resolución 17/2020, estas son superiores entre un 8,8 % y 40,5 % lo que indica que habrá una fuerte presión sobre los recursos hídricos en las zonas cafetaleras estudiadas.
Palabras clave: cambio climático, estimación, necesidades hídricas, modelo PRECIS.

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INTRODUCTION

Coffee cultivation is widespread in several tropical countries and it supports economically part of the world's population. This is considered one of the agricultural products with the greatest weight in the world market Vasallo *et al.* (2020), being also the most traded beverage in the world and the second most consumed beverage after water and for these reasons it has become a staple product for many people around the planet (Rojas, 2018).

In the case of Cuba, coffee production is concentrated in the provinces of Cienfuegos, Villa Clara and Sancti Spíritus and with a marked development in the eastern region of the country, with the most representative volumes in the provinces of Santiago de Cuba, Guantánamo, Granma and Holguín. (García *et al.,* 2013).

Irrigation is a decisive factor in agriculture to obtain an adequate yield and, therefore, it is necessary to have an impact on good production in order to contribute to food security and sovereignty of the population (Baltazar & Chipana, 2016).

According to Nelson *et al.* (2009) agriculture is extremely vulnerable to climate change and the increase in temperatures reduces crop production. This, linked with changes in rainfall patterns, increase the likelihood of crop failure, and on that sense is expected that the impacts of climate change will be negative for agriculture, threatening global food security.

To analyze the different impacts of climate change and due to the high uncertainty regarding future climate conditions, the Intergovernmental Panel on Climate Change IPCC (2023) advises to work with “scenarios”, which are coherent and consistent descriptions of how the Earth's climate system may change in the future.

Among the various publications about IPCC, the scenarios are defined as Representative Concentration Pathways (RCPs) that provide a range of Greenhouse Gas (GHG) emissions and concentrations that allow exploration of the possible future climatic parameters in a broader way than those used in the past.

It should be reiterated that the RCPs are not predictions or policy recommendations; however, they have been chosen to describe possible future scenarios. They are defined taking as reference the intensity of the radiation in 2100, where the estimates for radiation are based on GHG emissions. These “possible future climate scenarios” are derived from the scenarios of possible future GHG emissions, used in climatic models as input for the calculation of climate projections (Cortés *et al.*, 2013).

All simulations are carried out globally on a 0.5° grid, covering the period 1850-2100 and the results are evaluated as a function of transient atmospheric CO_2. Temporally, constant management assumptions are made, focusing on the isolated effect of the climatic change on current crop production systems (Jägermeyr *et al*., 2021).

With the development and popularization of computers, tools are provided to store large volumes of data and perform numerous calculations in agricultural production systems under different management scenarios and contrasting climatic conditions (Flores *et al.*, 2013).

In recent studies, Camejo *et al.* (2016) and Díaz *et al.* (2016) used the CropWat model for the calculation of water requirements and irrigation schedules with feasible results. In this context, CropWat is presented as a tool with potentialities to determine irrigation requirements, so it is intended with the present work to estimate in the future the total net irrigation requirements of the coffee plants according to climatic variability in the different areas producing this grain in Cuba.

MATERIALS AND METHODS

For the selection of the sites of coffee cropping in the mountainous massifs of Cuba where the coffee plantations are developed, (Sierra de los Órganos, Guamuhaya, Sagua-Nipe-Baracoa and Sierra Maestra), (Figure 1), representatives for the definition of future irrigation needs, was consulted the general director the Coffee, Cocoa and Coconut, of the Agroforestry Group (GAF) of the Cuba Ministry of Agriculture (Minag) (Legrá, 2022).

Figure 1. Location of the study areas.

In the processing of the climatic variables involved in the adjustment of climatic scenarios recommended by INSMET, each system was evaluated to verify which of them will be more restrictive for water management and according to the different climatic regions for coffee plantations and finally in the completion of the necessary information for the entry of data in each of the windows of the CROPWAT version 8.0 program, for its subsequent running for the prediction of future of the water needs of the crop.

Within the mountainous massifs, the following sites were selected (Table 1):

Table 1. Sites selected for the study of future water needs of the coffee trees.

Province	Place	Coordinates		Height (m.o.s.l)
		North	West	
Pinar del Río	La Palma	22° 74' 89"	-83° 55' 36"	150.0
Villa Clara	Jibacoa	22° 01' 94"	-79° 99' 19"	388.0
Guantánamo	Palenque de Yateras	20° 36' 94"	-74° 97' 00"	423.0
Granma	Guisa	20° 26' 14"	-76° 54' 97"	255.0
Santiago de Cuba	Cruce de los Baños	20° 13' 02"	-76° 32' 41"	189.0
Guantánamo	El Salvador	20° 15' 39"	-75° 13' 43"	102.0

For the study, a 36-year series from 2015 to 2050 was taken from the PRESIS regional model, for the RCP 4.5 scenario, which has a resolution of 125 x 125 km. The variables taken were maximum and minimum temperature, relative humidity, wind speed and rainfalls, which represent the future climatic parameters for the study sites. The water needs of the coffee plants were calculated with emphasis on wet, medium and dry hydrological years. For the selection of the years, the empirical probability was determined from the expression:

$$P = \left(\frac{m - 0,3}{n + 0,4}\right) \cdot 100$$

Where: m: order number, n: number of members of the series.

Each of the years of the series was classified according to its probability. The scenarios of probability are 25 % wet, 50 % medium and 75 % dry, according to Pérez & Álvarez (2005).

The soils in the mountainous regions of Cuba where are the coffee plantations were classified according to the latest Soil Classification established in our country Hernández-Jiménez *et al.* (1999), and their correlation Hernández *et al.* (2005) with the Genetic Classification of Cuban Soils (IS-Cuba, 1980). Once identified, their hydro physical properties were taken from those reported by Cid *et al.* (2012) (See Table 2).

Table 2. Correspondence between the soils of coffee plantations and those proposed by Cid *et al.* (2012) from its hydrophysical functioning

Province	Place	Soils
Pinar del Río	La Palma	Yellowish alithic with typical high clay activity
Villa Clara	Jibacoa	Typical low clay activity yellowish alithic with low clay activity
Granma	Guisa	Fersialithic reddish-brown pulverized soil
Stgo. de Cuba	Cruce de los Baños	Typical yellowish alithic with high clay activity
Guantánamo	El Salvador	Fersialithic reddish-brown pulverized soil
Guantánamo	Palenque de Yateras	Fersialithic reddish-brown pulverized soil

Once the information was processed, Table 3 was prepared with the data inputted in the CropWat program.

The development phases were taken from Cisneros-Zayas *et al.* (2015) (See Table 4).

Table 4. Average duration of the phases of development of coffee trees, for San Andrés Region.

No	Phases	Durations	Average days
I	Flowering-fruiting	February up to April	89
II	Fructification-fruit development	May up to August	123
III	Ripen-harvest	September - 1st decade December	101
IV	Harvest-recovery	2nd decade December-January	52

Crop Coefficients (*Kc*): Initial: 1,01 Mid-season: 1,04 Late season: 0,49 Cisneros-Zayas *et al.* (2015)
Sensitivity factor (Ky): 0,52. (González-Robaina et al., 2017).

Table 3. Soil data inputted in CropWat program.

Place	Field capacity (cm3·cm-3)	Wilting point (cm3·cm-3)	ATD (mm/m)	Infiltration Rate (m·day-1)	Root depth (m)
La Palma	0.235	0.127	108.0	2.6	0.40
Jibacoa	0.168	0.091	77.2	6.2	
Guisa	0.333	0.180	153.0	4.9	
Cruce de los Baños	0.290	0.157	133.2	2.6	
El Salvador	0.332	0.179	152.5	1.15	
Palenque de Yateras	0.333	0.180	153.0	4.9	

Criteria for total irrigation requirements

The criteria for total irrigation requirements are the following: Irrigation timing: Irrigated at critical depletion. Irrigation Application: Refill soil to field capacity. Irrigation efficiency (Field efficiency) 85 %.

Drip Irrigation. Allowable Depletion Fraction; p=40 %.

Criteria for reduced irrigation requirements

The criteria for reduced irrigation requirements are the following: Irrigation timing: Irrigated when the *ET* is reduced for the stage. Development stage; 4 %. Mid-season: 4 %. Late season: 10 %. Irrigation application: Refill soil to field capacity. Irrigation efficiency (Field efficiency) 85 %. Irrigation system: Drip Irrigation. (See Figure 2).

For the reduction of irrigation requirements, was considered the work carried out in Cuba by Valdés & Vento (1984) and Valdés et al. (1995), who offer elements to affirm that the coffee trees can be considered as an intermediate species between C3 and C4 due to anatomical changes in the foliar photosynthetic apparatus, as well as the assimilation of CO_2. In addition, based on the agronomic management of the coffee trees where is provoked a water stress in the flowering phase for induce and grouping the flowering, it was decided to make reductions in the initial stage of flowering - fruiting and harvest - recovery. It was considered that these reductions did not affect the yield in more than 3 %.

The program CROPWAT, version 8.0, was used to estimate the water requirements of the coffee plants, according to the evapotranspiration of the crop by stages of development year by year from 2015 to 2050. This software allows managing irrigation programs both in unirrigated and in irrigated conditions and it was used to determine the reference evapotranspiration by the FAO Penman-Monteith method starting from the use of the main climatic variables: relative humidity, temperature, wind speed and insolation, as well as the incidence of the effective rainfalls, being processed the new RCP (Representative Concentration Path) scenarios for the coffee growing areas of Cuba (Centella, 2017).

The estimated irrigation requirements obtained were compared with those approved by the National Institute of Hydraulic Resources (INRH. Resolution 17/2020) (GOC-Cuba, 2020).

RESULTS AND DISCUSSION

Behavior of the climatic variables of the RCP 4.5 scenario (2020 - 2050) for the study sites

Table 5 shows the average values of the variables maximum and minimum temperature, relative humidity, wind speed and precipitation for the 2020-2050 series studied for each work site. As can be seen, the maximum temperature (T_{max}) varied between 26.5 and 33.8 ºC, the minimum temperature (T_{min}) between 18.7 and 22,8 ºC, and relative humidity (HR) ranged between 73.6 and 84.6 %. Wind speed (V_v) was between 0,76 and 2.48 m·s^{-1}. Finally, precipitation reached a maximum of 2156,0 mm in Jibacoa, Villa Clara and a minimum of 1 040.94 mm in Cruce de los Baños, Santiago de Cuba.

When analyzing the behavior of the reference rainfalls and evapotranspiration (ET_0) variables for the study sites, for the western and central zones represented by the sites La Palma and Jibacoa (Figures 3a, 3b) for most of the years the rainfalls exceeds the ET_0, so it could be expected that in the irrigation schedule the total net irrigation requirements will be lower than in other coffee growing sites. In the case of the eastern region represented by the sites Guisa, Cruce de los Baños, El Salvador and Palenque de Yateras (Figures 3c, 3d. 3e. 3f) the ET_0 exceeds the rainfalls, which indicates that in this zone the total irrigation norms may be higher.

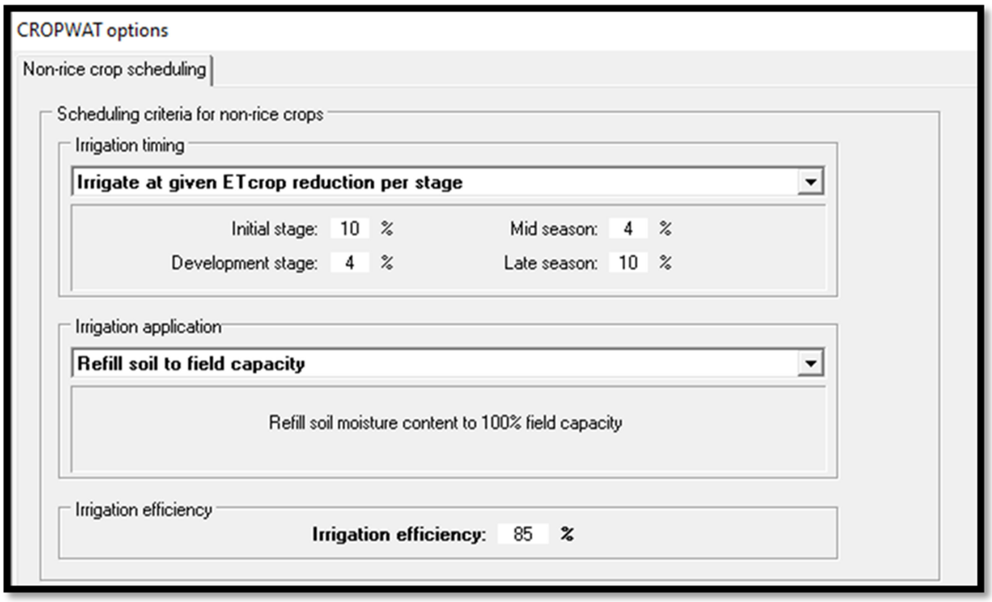
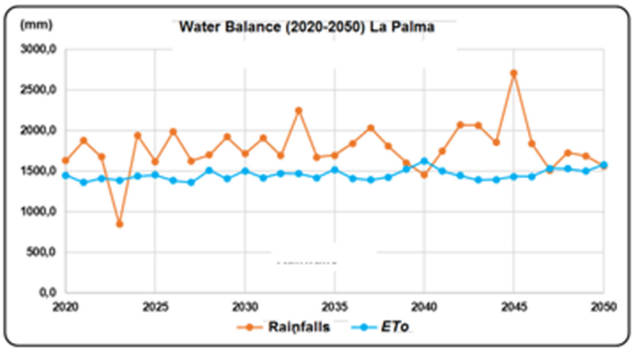
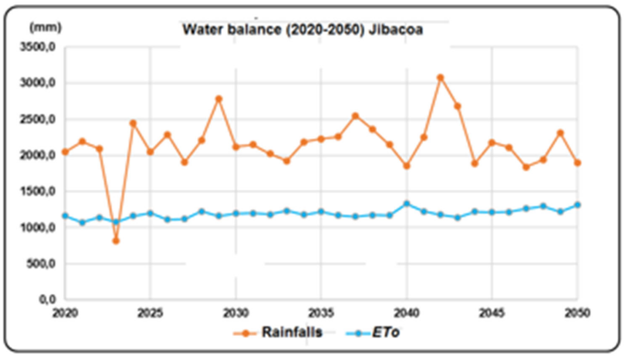


Figure 2. Irrigation criteria for reduced irrigation requirements.

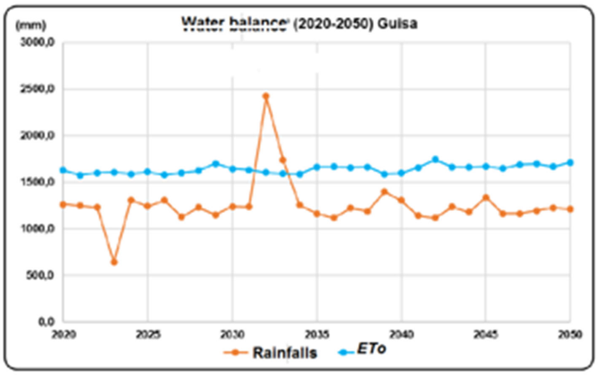
Table 5. Average values of the climatic variables in the 2020-2050 series of the different meteorological stations associated with the study sites

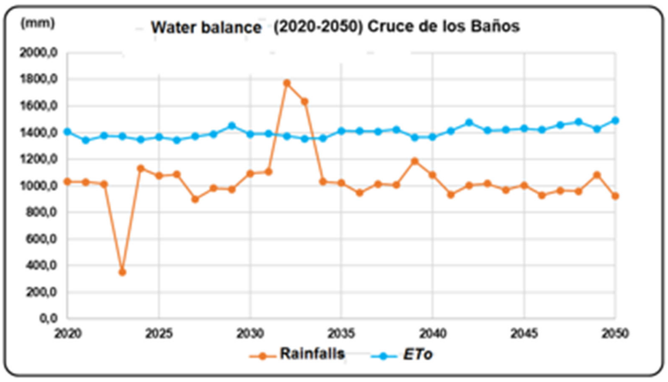
Place	T máx. (º C)	T mín. (º C)	HR (%)	Vv (m s-1)	Rainfall (mm)
La Palma	31.17	22.30	75.7	1.49	1 784.92
Jibacoa	26.57	18.71	84.6	2.48	2 156.00
Palenque de Yateras	33.19	22.88	73.6	1.51	1 256.94
Guisa	33.80	21.23	78.0	1.72	1 040.94
Cruce de los Baños	32.82	20.94	76.5	0.76	1 060.45
El Salvador	33.16	22.98	73.6	1.49	1 093.86



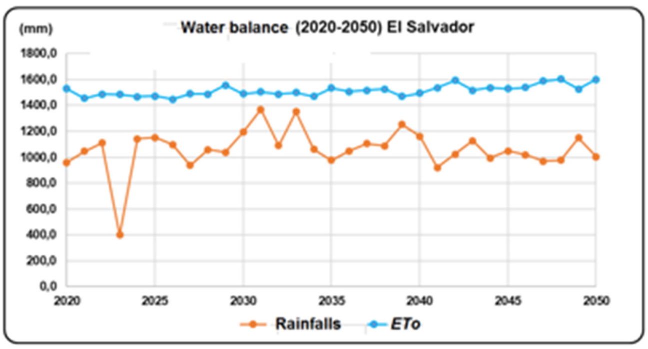


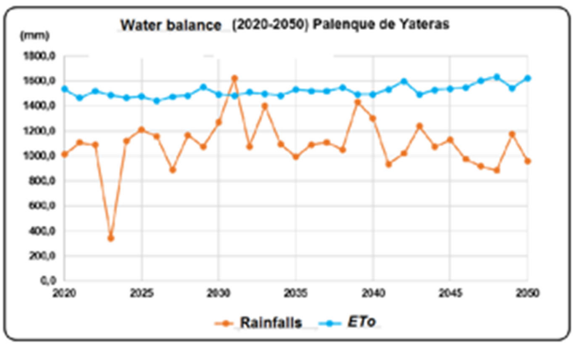
a) La Palma **b) Jibacoa**





c) Guisa **d) Cruce de los Baños.**





e) El Salvador **f) Palenque de Yateras**

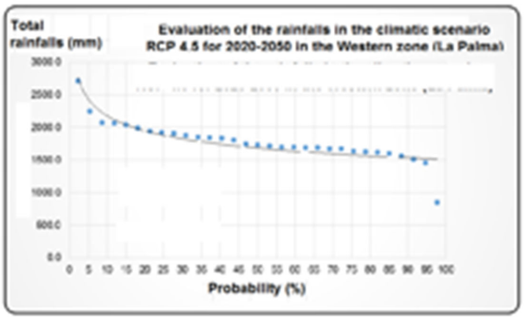
Figure 3. Behavior of the variables of the rainfalls and reference evapotranspiration (ET_0) for the study sites.

All the sites of the RCP 4.5 scenario (Figure 4) show a similar behavior with what was proposed by authors such as Planos (2014) and Centella (2017).

Irrigation demand of coffee plants for each site studied, as a function of rainfall probabilities for the RCP 4.5 climatic scenario

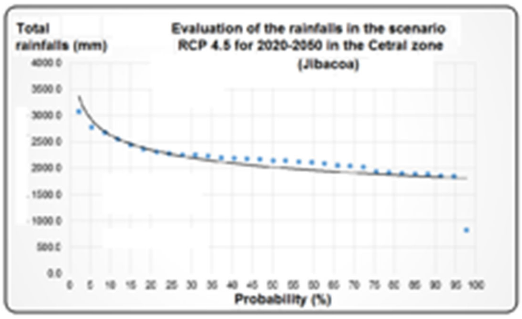
Table 6 shows how crop evapotranspiration (*ETc*) performed according to the hydrological year, with the highest values at the Guisa site for the three years (wet, medium and dry) and the lowest at the Jibacoa site. The irrigation strategy obtained through programming guarantees that the reduction in yielding does not exceed 3 %.

The same table shows that the total net water requirements varied according to the year, with values ranging from 753.1 mm per year to 920.5 mm per year depending on the site and altitude. The total reduced net water requirements in correspondence with the years, was in the range of 190.5 mm and 746.1 mm per year.



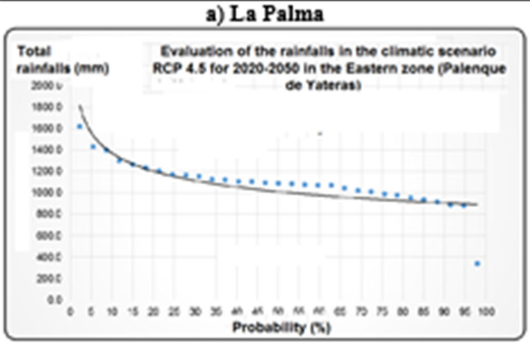
Hydrological year	Year	Rainfall (mm)
Wet	2029	1 923.73
Medium	2048	1 729.90
Dry	2020	1 633.25

a) La Palma



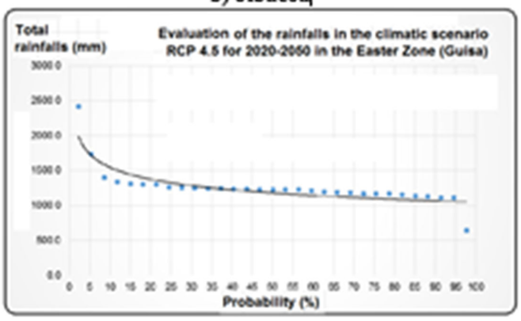
Hydrological year	Year	Rainfall (mm)
Wet	2026	2 286,87
Medium	2039	2 148.27
Dry	2048	1 938.91

b) Jibacoa



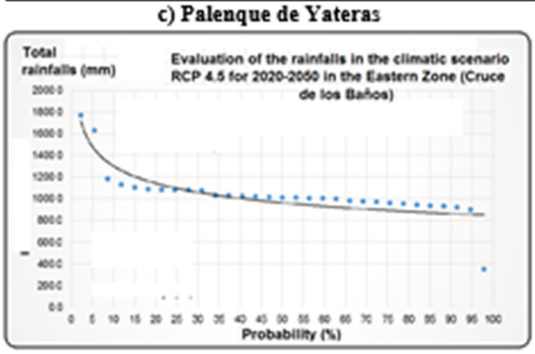
Hydrological year	Year	Rainfall (mm)
Wet	2049	1 173.01
Medium	2036	1 090.10
Dry	2035	992.96

c) Palenque de Yateras



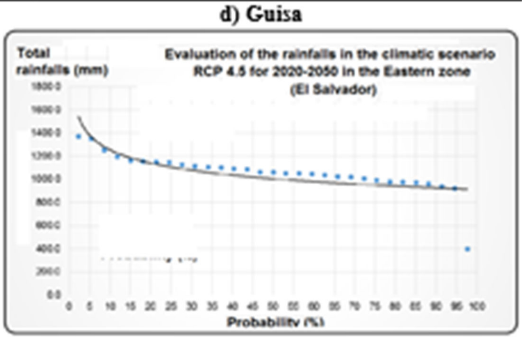
Hydrological year	Year	Rainfall (mm)
Wet	2020	1 261.55
Medium	2028	1 228.30
Dry	2035	1 163.55

d) Guisa



Hydrological year	Year	Rainfall (mm)
Wet	2049	1 083.18
Medium	2022	1 014.05
Dry	2047	964.35

e) Cruce de los Baños



Hydrological year	Year	Rainfall (mm)
Wet	2024	1 142.58
Medium	2028	1 058.01
Dry	2044	993.49

f) El Salvador

Figure 4. Evaluation of the rainfalls in the climatic scenarios RCP 4.5 for the study sites.

Table 6. Distribution of the total net, partial net and reduced net water requirements for each site according to the hydrological year

Place	Rainfalls probability (%)	ETc (mm)	Total net requirements (mm)		Partial net requirements (mm)		Irrigation number		Yield reduction (%)
			SR	**CR**	**SR**	**CR**	**SR**	**CR**	
La Palma Pinar del Río	25	1 290,0	862.3	190.5	17.25	27.21	50	7	2.5
	50	1 378.8	876.1	404.6	18.25	26.97	48	15	2.3
	75	1 320.0	844.7	264.6	17.60	26.46	48	10	2.2
Jibacoa Villa Clara	25	1 026.6	603.4	214.2	15.47	19,47	39	11	2,2
	50	1 078.6	681,4	325.6	14,20	20.35	48	16	2,5
	75	1 193.4	863,5	451.8	14,16	21.51	61	21	3.2
P. de Yateras Guantánamo	25	1 482.3	826.8	522.2	25.84	37.30	32	14	2.7
	50	1 441.6	815.8	569.7	26.32	37.98	31	15	2.8
	75	1 481.4	879.3	576.9	26.65	38.46	33	15	2.7
Guisa Granma	25	1 544.5	857.3	422.5	25.98	38.41	33	11	3.0
	50	1 557.6	858.3	575.1	26.01	38.34	33	15	2.6
	75	1 563.9	893.3	546.1	26.27	39.01	34	14	2.8
C. de Baños Stgo. de Cuba	25	1 412.9	775.3	615.7	23.49	32.41	33	19	3.0
	50	1 377.2	753.1	504.9	22.82	33.66	33	15	3.1
	75	1 435.6	863.7	600.8	22.73	33.38	38	18	3.0
El Salvador Guantánamo	25	1 415.6	886.6	702.0	26.08	36.95	34	19	3.2
	50	1 426.5	920.5	740.3	26.30	37.02	35	20	3.1
	75	1 489.0	895.0	746.1	26.32	37.31	34	20	3.3

Legend: *SR: no reduction; CR: with reduction*

The partial net water requirements reached values ranging from 14,2 mm (142 $m^3 \cdot ha^{-1}$) to 26,6 mm (266,0 $m^3 \cdot ha^{-1}$) values very similar to those obtained by Cisneros *et al.* (2006) irrigating coffee plants in the area of San Andrés Pinar del Rio with a localized irrigation system with micro-sprinklers under the principle of total coverage.

When analyzing the behavior of the total net water requirements by zones it is appreciated that these vary according to the water balance of the region, since according to the climate scenario RCP 4.5 for the western and central regions in most years the precipitation exceeds the reference evapotranspiration and therefore the difference between the total and reduced norms differs between 48 and 78 % (Figure 5). While for the eastern region, where the balance of the reference evapotranspiration exceeds the rainfalls, the difference between the norms oscillates from 17 % to 51 %. This behavior is normal considering that in the western region a large part of the water demand of the coffee plants is covered by the rainfalls, but this is not the case in the eastern region.

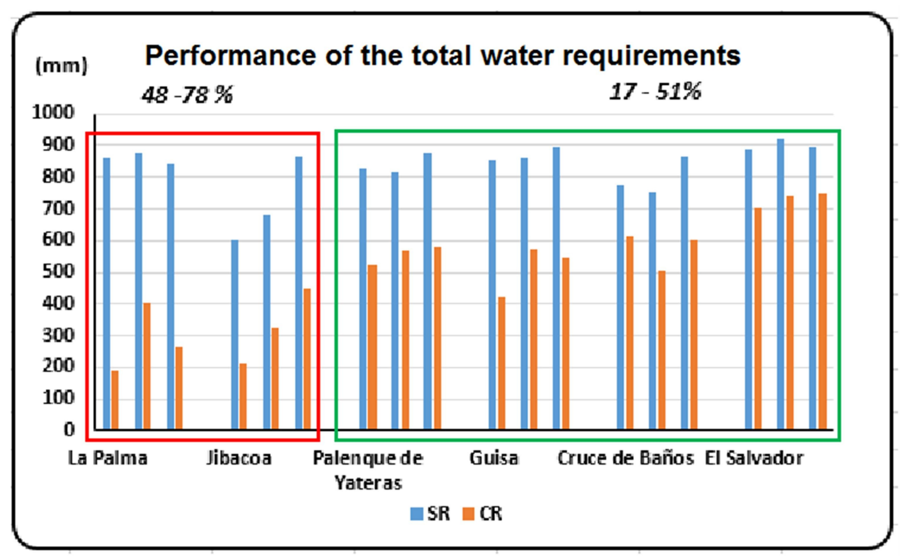


Figure 5. Distribution of water demand by study sites.

Regarding the number of irrigations (Figure 6), there is a similar behavior. In the western and central regions, the differences between the variant of full and reduced water requirements vary between 39 and 61, with reduced requirements ranging between 7 and 21 irrigations. A similar analysis for the eastern region shows that this range is reduced, with values of 31 and 38 full irrigations. For the reduced water applications these range vary from 11 to 20 irrigations, which means 56 % less than those of the western and central regions on average.

Study of the total and reduced net requirements obtained by CropWat program and approved in INRH Resolution 17/2020

Table 7 shows the total irrigations approved by INRH in Resolution 17/2020 GOC-Cuba (2020) and those estimated through the CropWat program. For La Palma site, in the three hydrological years, the estimates are higher than the current one in percentages that vary between 8.8 and 12, so that in the future for the RCP 4.5 scenario, the coffee trees will need higher number of irrigation than the current one to meet water needs.

In the central region, represented by the Jibacoa site, in the wet and medium years, the net water requirements obtained through the CropWat runs are lower than the current ones, overestimating those approved in the Resolution 17/2020 by 25 and 15.3 respectively. The same is not true for the dry year, where it exceeds the current one by 7.3 %.

Palenque de Yateras is where the largest increases in total net water demands are predicted, varying between 32.1 % for the wet year and 40.5 % for the dry year. In this site it is necessary to pay special attention to the management of water resources in the future if it is desired to guarantee a good quality coffee production, taking into consideration the weight of the yields of this site in the Cuban coffee economy.

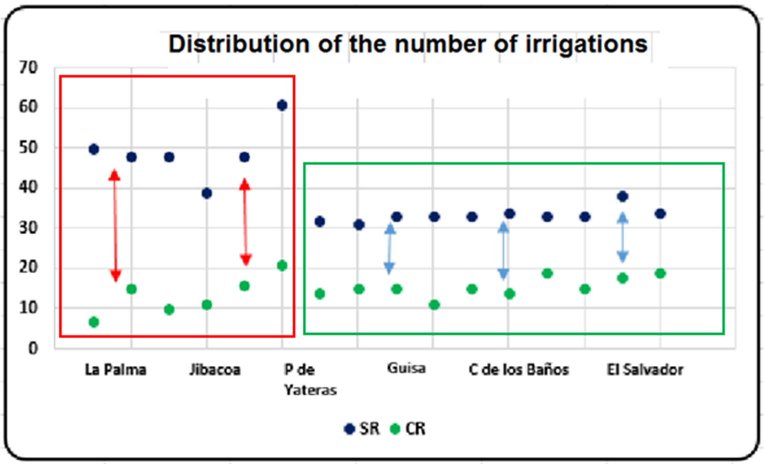


Figure 6. Differences in the number of irrigations by study sites.

Table 7. Comparison between the total net requirements estimated and that approved in the Resolution 17/2020 (GOC-Cuba, 2020)

Place	Probability of rainfalls (%)	Total net requirements estimated by CROPWAT (mm)		Total net Requirements by INRH (mm)	Difference	% Increment
		SR	CR		SR	
La Palma Pinar del Rio	25	862.3	190.5	770.6	91.7	10.6
	50	876.1	404.6		105.5	12.0
	75	844.7	264.6		74.1	8.8
Jibacoa Villa Clara	25	603.4	214.2	804.9	-201.5	0
	50	681.4	325.6		-123.5	0
	75	863.5	451.8		58.6	7.3
Guisa Granma	25	857.3	422.5	823.8	33.5	4.0
	50	858.3	575.1		34.5	4.2
	75	893.3	546.1		69.5	8.4
Cruce de Baños Stgo. de Cuba	25	775.3	615.7	786.0	-10.7	0
	50	753.1	504.9		-32.9	0
	75	863.7	600.8		77.7	9.9
P. de Yateras Guantánamo	25	826.8	522.2	626.0	200.8	32.1
	50	815.8	569.7		189.8	30.3
	75	879.3	576.9		253.3	40.5
El Salvador Guantánamo	25	886.6	702.0	789.5	97.1	12.3
	50	920.5	740.3		131.0	16.6
	75	895.0	746.1		105.5	13.4

Legend: *SR: no reduction; CR: with reduction*

The Guisa and Cruce de los Baños sites have the lowest increases in future net water requirements, which only exceed the current ones by between 4.0 % and 8.4 % in Guisa. At Cruce de los Baños, the present one is overestimated with respect to the future by 1.4 % for the wet year and 4.2 % for the dry year.

Finally, at the El Salvador site, the increases in net water requirements estimated by the CropWat program compared to the current ones vary between 12.3 % and 16.6 %.

In general, for none of the sites studied, the total estimated future net water requirements exceed the current ones by more than 50 %, so they can be considered as normal if it is taken into account that most of the scenarios according to Planos (2014) and Cortés *et al.* (2013) tend to a significant reduction in the rainfalls and a significant increase in the average air temperature, climatic variables that directly influence water consumption by crops and therefore the increase in irrigation needs.

CONCLUSIONS

- The estimation of the total net irrigation requirements for coffee trees according to climatic variability in the coming years for the study sites indicates that there will be an increase ranging from 8 447.0 $m^3 \cdot ha^{-1}$ in La Palma (Pinar del Rio) to 8 793.0 $m^3 \cdot ha^{-1}$ in Palenque de Yateras (Holguin).
- The greatest differences between the total and the reduced net water requirements for the RCP 4.5 scenario are in the western and central regions, which vary between 48 % and 78 %, being smaller for the eastern region where they are in the range of 17 % to 51 %.
- When comparing the estimated total net water requirements with those approved in *Resolution 17/2020*, these are higher by between 8.8 % and 40.5 %, which indicates that there will be strong pressure on water resources in the coffee-growing areas studied.
- The criterion of reducing the net water requirements for coffee plants in the initial phases of flowering-fruiting and the ripening-harvest phase allows significant water savings with yield effects that do not exceed 3 %.

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