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The effects of projected climate change on crop water availability in the U.S. Caribbean

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ABSTRACT

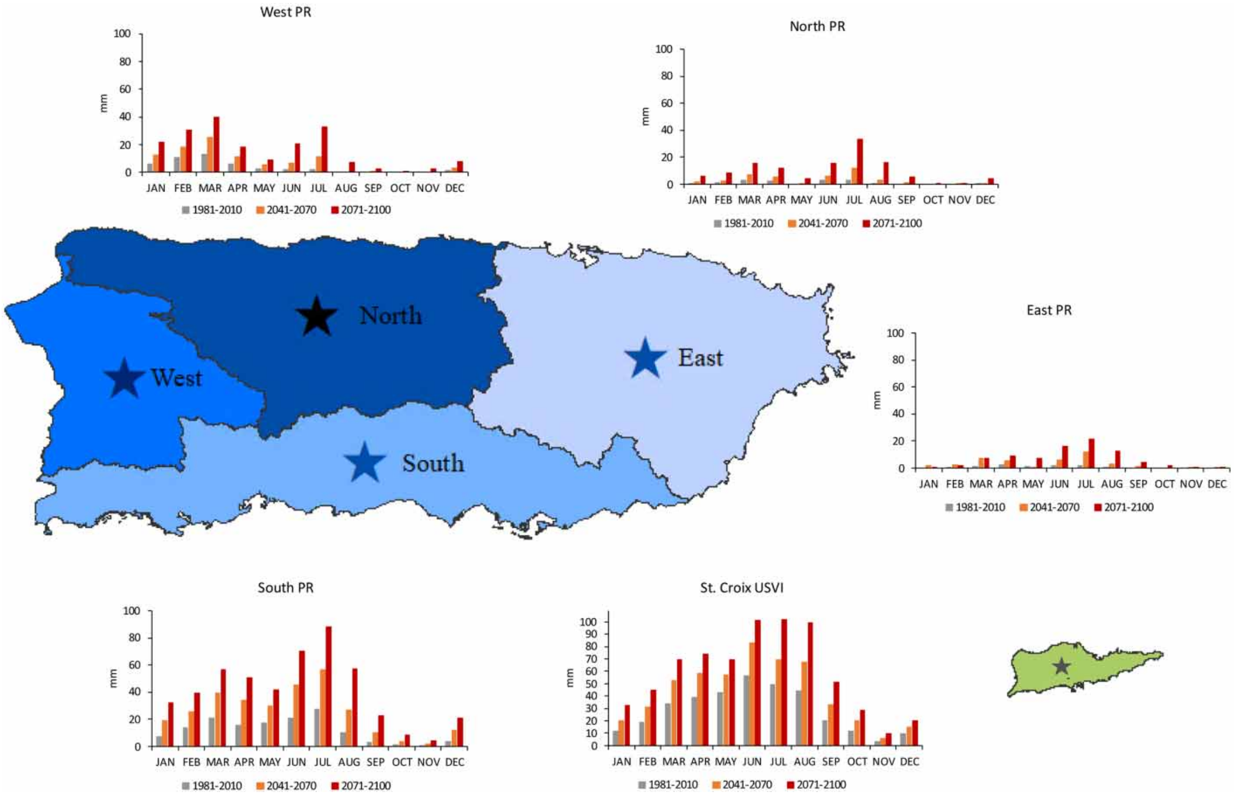
Anthropogenic climate change affects small islands, and farming systems in the Caribbean are vulnerable to climate change due to their high dependence on rainfall. Therefore, this work evaluated how temperature and precipitation projections affect water crop needs in Puerto Rico and St. Croix. We used Daymet data to create a baseline climatology (1981–2010) and the Coupled Model Intercomparison Project Phase 6 (CMIP6) to create future climatologies (2041–2070 and 2071–2100). A water budget model estimated the water deficit, and the crop risk (CROPRISK) model determined crop suitability for sweet pepper, banana, and plantain. Results indicated an increase in water stress after 2041 for most of the region from June to August, except for western Puerto Rico, where it will occur from January to March. For sweet pepper, banana, and plantain, the most water-stressed season is projected to be January–July. November will be the only month during which all crops are projected to be highly suitable through the end of the 21st century. These findings suggested that Puerto Rico and St. Croix crop water stress may be more sensitive to changes in temperature than precipitation.

Key words: agriculture, climate change, climate models, crop water, small islands, US Caribbean

HIGHLIGHTS

- Water stress will increase in Puerto Rico and St. Croix from June to August after 2041.
- Crops such as sweet pepper, banana, and plantain will only be highly suitable in the U.S. Caribbean in November through the end of the 21st century.
- Changes in temperature have a greater influence on future water stress in Puerto Rico and St. Croix than changes in precipitation.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Anthropogenic climate change particularly affects the small island developing states (SIDS) (Karnauskas *et al.* 2018). The rainfall variability, and the effects of low-frequency atmospheric circulation patterns on rainfall and drought events, as well as the lack of freshwater resources in the insular Caribbean, point to its vulnerability to climate change (Giannini *et al.* 2001; Karnauskas *et al.* 2018; Ault 2020; Robinson & Wren 2020). Accordingly, a predicted increase in temperature, decreased length of the rainy season, increased length of the dry season, more intense rainstorms, and increase in sea level for the Caribbean could result in the reduction of the already scarce water availability due to the increase of evapotranspiration rates, more flooding and aquifer depletion (reduced recharge), and salinity intrusion into groundwater and coastal aquifers (Cashman *et al.* 2010; Farrell *et al.* 2010; Pulwarty *et al.* 2010; Ault 2016; Karnauskas *et al.* 2016).

Because agricultural activities depend on water, this sector will be directly impacted by future drying trends, with smallholder farmers, in particular, being the most dependent upon the amount and timing of annual rainfall (Bates *et al.* 2008; Curtis *et al.* 2014). The Caribbean is already facing poverty and food insecurity together with limited land availability, which means that global climate change will further exacerbate the challenges in the agricultural sector (Trotman *et al.* 2009; Connell *et al.* 2020). Studies have found farming systems in the Caribbean to be vulnerable to projected climate change, especially changes in temperature and precipitation, due to their relatively high dependence on rainfall (Bates *et al.* 2008; Cashman *et al.* 2010; Curtis *et al.* 2014). Impacts of a drier and warmer Caribbean climate can include but are not limited to reduction in plant-available moisture due to increased rates of evapotranspiration, increased spread of some pests and diseases, a decrease in crop suitability, and increased stress on food productivity and sustainability (McGregor *et al.* 2009; Cashman *et al.* 2010; Curtis *et al.* 2014).

However, much of the research on climate change and agriculture has been more general and of regional scope (Farrell *et al.* 2007; Trotman *et al.* 2009; Pulwarty *et al.* 2010; Barker 2012; Karnauskas *et al.* 2018; Ault 2020), so there is a clear need for more studies focusing on specific islands within the Caribbean. Additionally, to our knowledge, there is no research comparing the impacts of long-term climate change on agriculture on an island in the Greater and Lesser Antilles.

Therefore, this work used a crop risk model (CROPRISK) (Batjes 1987) to analyze how water deficit and crop water stress in Puerto Rico (Greater Antilles) and the U.S. Virgin Island of St. Croix (Lesser Antilles) can be affected by future temperature and precipitation changes by the mid-century (2041–2070) and late-century (2071–2100). For this analysis, we choose to focus on the crops sweet pepper, banana, and plantain due to their agricultural importance to Puerto Rico and St. Croix, as well as their sensitivity to water deficits.

2. DATA AND METHODS

In order to evaluate how temperature and precipitation projections for mid-century (2041–2070) and late-century (2071–2100) can affect water stress and crop suitability in Puerto Rico and St. Croix, a multi-step methodology was developed, which included creating a baseline climatology and two future climatologies, using the Thornthwaite water budget model to estimate potential and actual evapotranspiration (AET) used to calculate water deficits, as well as using the CROPRISK model to assess crop suitability in current and future climates. These steps are explained below.

2.1. Study area and climate data

The first steps in our analysis were to define the study area and to create the baseline climatology and the two future climatologies. To account for the different climatic regions in Puerto Rico associated with the topography of the island, we divided the island into four basins (North, South, East, and West) according to the eight-digit hydrologic units from the U.S. Geological Survey (USGS) (Figure 1). These four basins were then used to clip the climatological data for Puerto Rico and to perform the water stress and crop suitability analyses. Because St. Croix is a smaller island (with an area of approximately 220 km^2), and its agriculture is mostly located in the center, we did not divide the island to perform the analysis (Figure 1).

For baseline climatology, we used daily gridded weather data from Daymet (Version 3) at 1 km resolution (precipitation, maximum temperature, and minimum temperature) from 1981 to 2010. Daymet data offer gridded estimates of daily weather variables for North America and the U.S. Caribbean distributed from 1 January 1980 to 31 December 2019 (Thornton *et al.* 2016). The methodology used in the current data set is intended to create spatially continuous gridded products over large regions of complex terrain and to accomplish the heterogeneous distribution of stations by using an iterative station density algorithm (Thornton *et al.* 1997). Daymet was previously used in studies analyzing rainfall patterns in the complex terrain of Puerto Rico (Mote *et al.* 2017; Miller *et al.* 2019). Daymet Version 3 was used instead of Version 4 because preliminary analysis indicated that Version 3 performed better in Puerto Rico when compared to observed runoff (Jazlynn Hall, Columbia University, personal communication). By using Puerto Rico four basins' shapefiles and St. Croix's shapefiles, we clipped the Daymet data from each location, averaged precipitation and temperature over the area and created a 30-year monthly

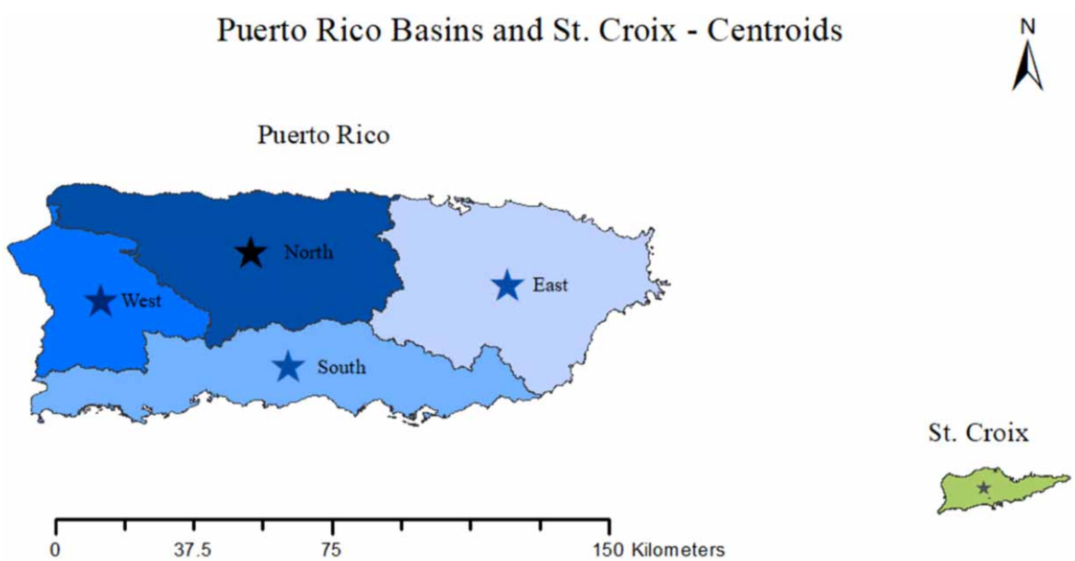


Figure 1 | Puerto Rico 8-digit hydrologic units used to divide the island in north, south, east, west (*source*: US Geological Survey), and St. Croix Island. The stars indicated the centroids of each basin/island used to remap the CMIP6 models data.

mean baseline climatology for Puerto Rico and St. Croix (Figures 2 and 3). Maximum and minimum temperature data from Daymet were averaged to create the 30-year monthly mean temperature for the baseline climatology.

For future climates, we used the Coupled Model Intercomparison Project Phase 6 (CMIP6) and selected the five models based on their common and smaller grid cell size (100 km), since Puerto Rico's and St. Croix's areas are small to work with the coarser spatial resolution of the other models. Models included in this analysis were downloaded from https://esgf-node.llnl.gov/search/cmip6/ and are found in Table 1. The goal of this work was to compare the baseline climate (1981–2010) to mid-century (2041–2070) and late-century (2071–2100) climatologies, to analyze long-term future changes in climate, and not near-future changes. Therefore, we downloaded and selected both historical (1981–2010) and future (2041–2100) monthly precipitation and surface temperature data from each model. For future data, we downloaded the shared socioeconomic pathway-representative concentration pathway (SSP-RCP) scenario SSP5-8.5, which is an updated version of RCP8.5 in CMIP5 used in Curtis *et al.* (2014) in a similar study, and refers to the scenario with higher CO_2 emissions by the end of the century (O'Neill *et al.* 2016). Using the same SSP-RCP scenario from Curtis *et al.* (2014) allows us to compare the results of this work with another work also applied to a Caribbean island country.

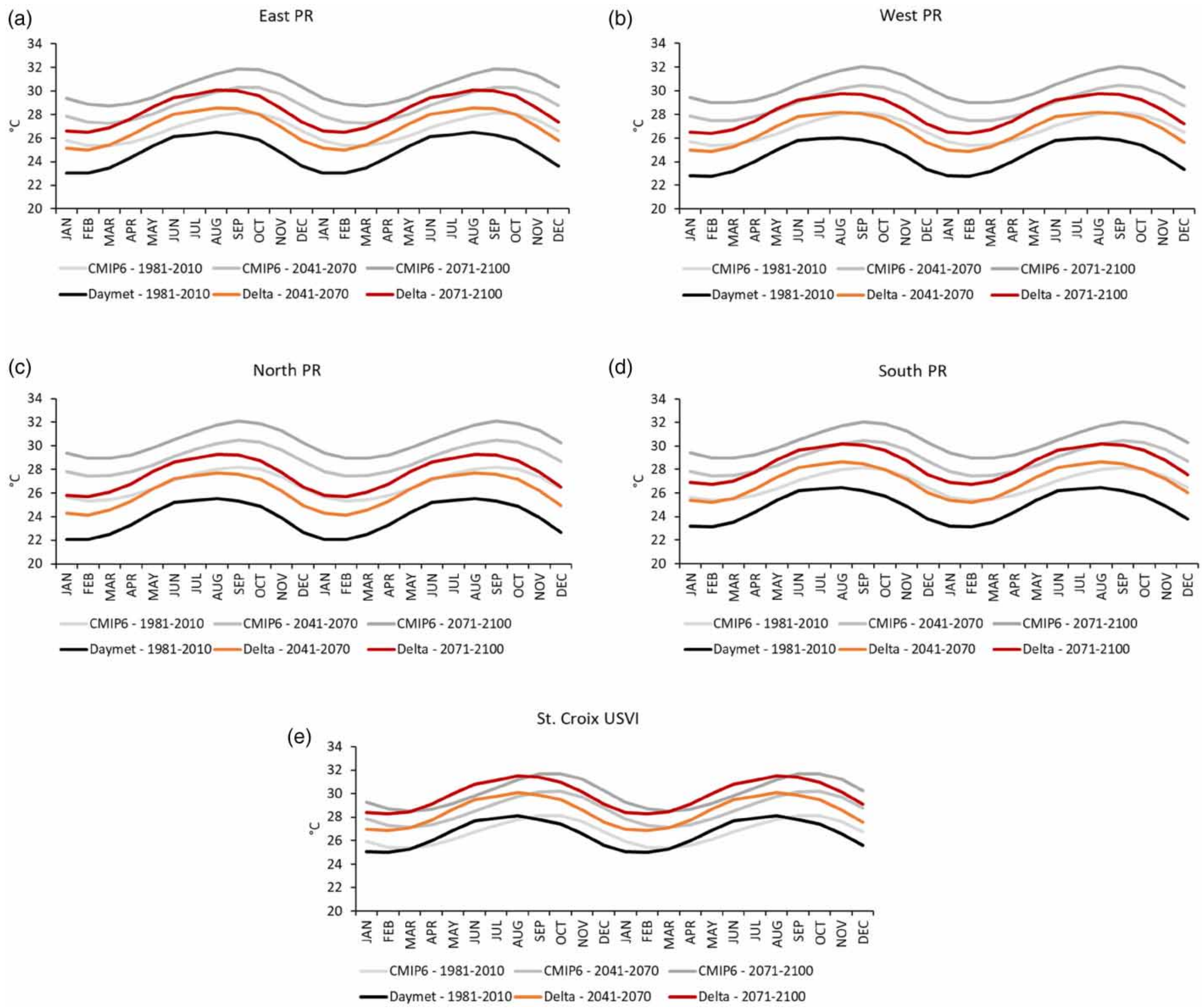


Figure 2 | The 24-month annual cycle of temperature (°C) for Puerto Rico Basins (a) East; (b) West; (c) North; (d) South; and for (e) the US Virgin Island of St. Croix. Daymet baseline climatology (1981–2010) is in black, bias-corrected Delta – 2041–2070 is in orange, and bias-corrected Delta – 2071–2100 is in red. The CMIP6 outputs are in shades of gray. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2023.398.

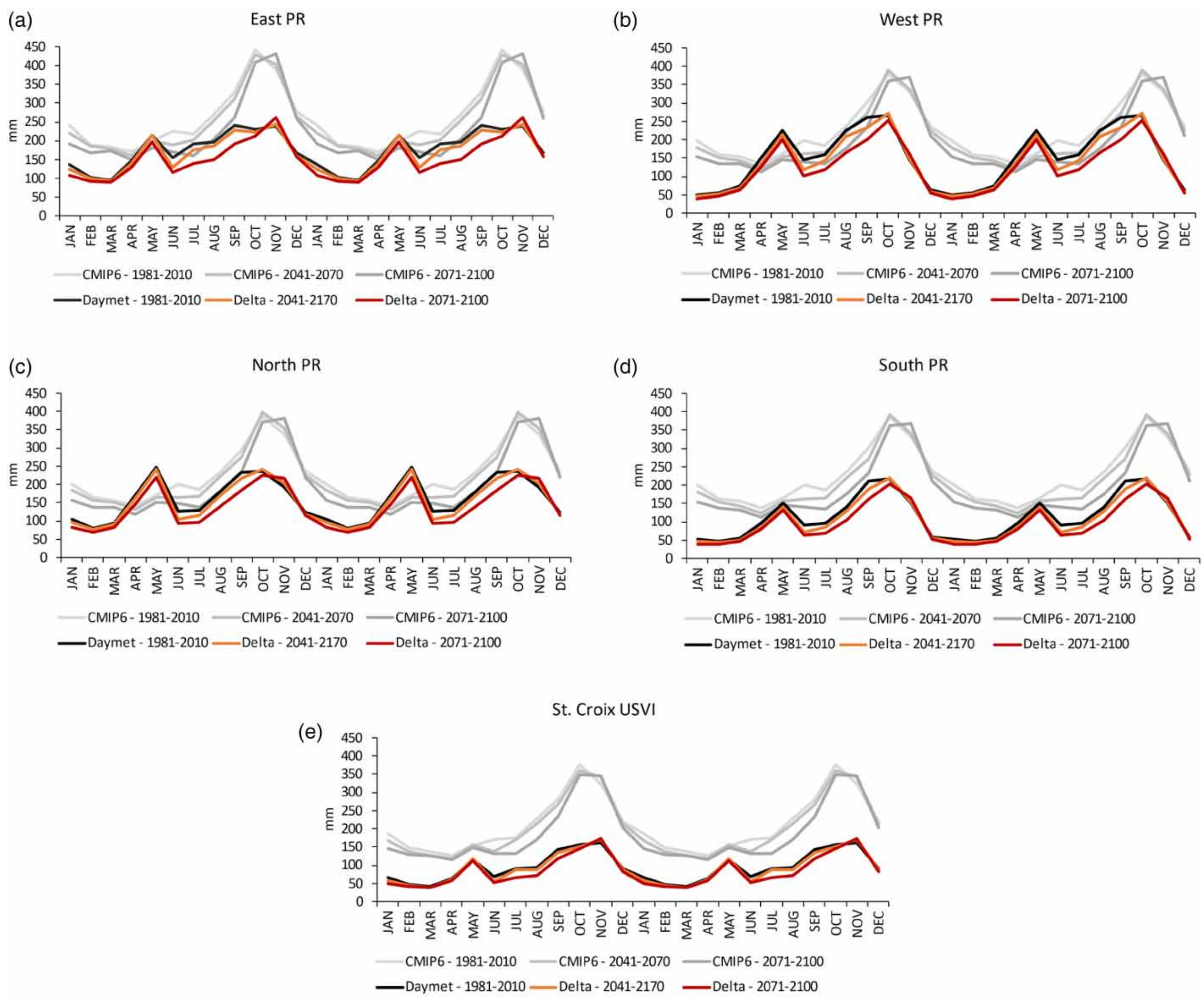


Figure 3 | The 24-month annual cycle of precipitation (mm) for Puerto Rico Basins (a) East, (b) West, (c) North, and (d) South, and for (e) the US Virgin Island of St. Croix. Daymet baseline climatology (1981–2010) is in black, bias-corrected Delta – 2041–2070 is in orange, and bias-corrected Delta – 2071–2100 is in red. The CMIP6 outputs are in shades of gray. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2023.398.

Table 1 | Detailed information about the general circulation models (GCMs) from CMIP6 used in this study with their acronyms, expanded names, the emission scenario, and their origins

Acronyms	Expanded names	Emission scenario	Origins
CIESM	Community Integrated Earth System Model	SSP5-8.5	Department of Earth System Science, Tsinghua University, Beijing 100084, China
E3SM 1.1	Energy Exascale Earth System Model	SSP5-8.5	LLNL Climate Program, L-103, 7000 East Avenue, Livermore, CA 94550, USA
EC-Earth3	EC-Earth3	SSP5-8.5	EC-earth consortium, Rossby Center, Swedish Meteorological and Hydrological Institute/SMHI, SE-601 76 Norrkoping, Sweden
EC-Earth3-Veg	EC-Earth3-Veg	SSP5-8.5	
FGOALS-f3-L	FGOALS-f3-L	SSP5-8.5	Chinese Academy of Sciences, Beijing 100029, China

Source: https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_source_id.html.

Then, the data were remapped to account for the different grid systems used by the models, even though they have the same resolution. The remapping used the nearest-neighbor remapping function (*remapnn*) from the climate data operators (CDO) to select the grid cell corresponding to the centroid of each basin in Puerto Rico and of the island of St. Croix (Figure 1). We used the nearest-neighbor approach since other studies have indicated that this approach does not smooth the extremes of the models (Wang *et al.* 2019). Then, we created the 30-year monthly mean surface temperature and precipitation for historical and future climates.

We applied the delta method for climate model bias correction. This method has proven to reduce climate model bias by at least 50–70% and to be effective in preparing the data for assessing the impacts of climate change on agriculture (Navarro-Racines *et al.* 2020), so we used it to correct our future climate conditions (2041–2070 and 2071–2100) for Puerto Rico and St. Croix. In this bias correction method, a change factor or delta is derived from the CMIP6 models and then applied to the observations (Daymet). The delta is defined as the difference between the 30-year mean of precipitation and temperature in the future and the historical period simulations. Following the approach applied by Navarro-Racines *et al.* (2020), we calculated the absolute difference in temperature (Equation (1)), and the proportional differences for precipitation (Equation (2)), because the relative changes for precipitation avoid negative values when applying the CMIP6 delta values into observed Daymet.

$$\Delta X_i = X_{Fi} - X_{Ci} \quad (1)$$

$$\Delta X_i = \frac{X_{Fi} - X_{Ci}}{X_{Ci}} \quad (2)$$

where ΔX_i is the delta change, X_{Fi} is the 30-year mean of the climate variable in the future climate, and X_{Ci} is the 30-year mean of the climate variable in the historical climate of the CMIP6 models in the month i.

We then applied the delta (also called anomalies) to the baseline climate from Daymet to get the bias-corrected future climatologies. For temperature, we simply added the delta values in degrees Celsius to the value from Daymet (Equation (3)), while for precipitation, we used the absolute value of the change relative to the baseline climatology (Equation (4)) to avoid negative monthly precipitation values (Navarro-Racines *et al.* 2020).

$$X_{DCi} = X_{OBSi} + \Delta X_i \quad (3)$$

$$X_{DCi} = X_{OBSi} \times (1 + \Delta X_i) \quad (4)$$

where X_{OBSi} is the baseline climatology from observations (i.e., Daymet), ΔX_i is the delta change calculated in Equations (1) and (2), and X_{DCi} is the calculated future climatology of the CMIP6 models in the month i. The observed, simulated, and bias-corrected future climatologies can be seen in Figures 2–4.

2.2. Crop water stress and agroclimatic suitability

After processing the climate data, we performed the sensitivity analysis of water availability in Puerto Rico and St. Croix, followed by the analysis of agroclimatic suitability for specific crops in the islands. For water availability analysis, we used the Thornthwaite Monthly Water Balance Model as developed by the USGS (McCabe & Markstrom 2007), available at https://www.usgs.gov/software/thornthwaite-monthly-water-balance-model. This model was the same used by Curtis *et al.* (2014) in their study focusing on crop water stress in Jamaica and is designed to work with the tabular monthly climate data used in this study. The input parameters for the model were the same as those used by Curtis *et al.* (2014) in their analysis of Jamaica. This model is driven by a graphical user interface in which some parameters can be specified, and the input data are monthly temperature and precipitation from a specific location. The model analyzes the components of the hydrologic cycle according to Thornthwaite (Thornthwaite 1948; McCabe & Markstrom 2007). We ran the model for each one of the four basins of Puerto Rico and the island of St. Croix using the following parameters for the five locations: 18° N as the latitude parameter; 5% as the fraction of precipitation that becomes direct runoff from infiltration-excess overflow; 150 mm as the soil-moisture storage capacity, and the runoff generation as 50% of the surplus water produced after the soil-moisture storage surpasses its capacity (Wolock & McCabe 1999; McCabe & Markstrom 2007; Curtis *et al.* 2014).

Among the outputs of the water budget model, only the AET and potential evapotranspiration (PET) were retained; the difference between those values is the water deficit, also referred to here as crop water stress. Past studies suggested that PET–AET is directly related to drought stress in agricultural fields (Stephenson 1998; Curtis *et al.* 2014). In addition, the water deficit was used to estimate the deficit from the maximum crop yield (Equation (5)) following the CROPRISK developed by Batjes (1987) for Jamaica:

$$DY = ky(ETC - AET)/ETC \quad (5)$$

where DY is the deficit from maximum crop yield, ky is the yield response factor that indicates the effect of water stress on a crop, and ETC is equal to $kc \times PET$, where kc is the crop coefficient for the specific growing stage and type of crop, which typically ranges from 0.35 to 1.15 (Curtis *et al.* 2014). The values of ky and kc are presented in the next Section (2.3), together with the crops we chose to analyze in this study.

Finally, we used the deficit from maximum crop yield to establish the agroclimatic suitability classes defined by Batjes (1987). These classes depend on the number of years in which at least 80 and 60% of the crop's maximum yield can be obtained, as follows:

- Highly suitable (HiS): when the 80% condition of a crop's maximum yield is met at least 60% of the years and the 60% condition is met at least 80% of the years.
- Moderately suitable (MoS): when the 80% condition of the crop's maximum yield is met for at least 40% of the years and the 60% condition is met for at least 60% of the years.
- Marginally suitable (MaS): when the 80% condition of the crop's maximum yield is met for at least 20% of the years and the 60% condition is met for at least 40% of the years.
- Not suitable (NS): when the 80% condition of a crop's maximum yield is met in less than 20% of the years and the 60% condition is met in less than 40% of the years.

Both crop water stress (PET – AET) and agroclimatic suitability classes were determined on the annual cycle for the baseline climatology (1981–2010), the future climatology representing the mid-century (2041–2070), and the one representing the late-century (2071–2100) for each one of the four basins in Puerto Rico and the island of St. Croix. Through the analysis of these future climatologies, we expect to evaluate the role of temperature and precipitation changes in future agricultural suitability and water stress in both the Greater and Lesser Antilles.

2.3. Agricultural data

In Puerto Rico, the most recent census of agriculture from the U.S. Department of Agriculture (USDA 2020a) indicated that the number of farms has decreased from 2012 to 2018, and the number of cropland harvested farms decreased from 10,008 to 4,888, representing a reduction of more than 17,806 ha. The irrigated land has also decreased its area since 2012 by at least 10,360 ha, which leaves more than 20,000 ha of harvested cropland mostly dependent on rainfall.

Puerto Rico's major crops include plantains and bananas, which were cultivated in 2,035 and 1,157 farms, respectively, in 2018 (USDA 2020a). Although the number of farms cultivating plantains and bananas has decreased since 2012, their economic value is still among the highest, with an average of the market value of products sold in 2018 equal to $31,243 per farm for plantain, and $13,521 per farm for bananas (USDA 2020a). More farms grow peppers than any other vegetable in Puerto Rico, with sweet peppers cultivated at 290 farms in 2018, and other types of peppers cultivated in 62 farms. These numbers also decreased when compared to the 2012 agricultural census, when peppers were cultivated in 603 farms (USDA 2020a). Sweet peppers also lead the vegetables with the majority number of farms (>100 farms) with a market value of agricultural products sold of >$60,000.

On the contrary, St. Croix has quintupled its area of cropland in 10 years, from 106 farms (161 ha) in 2007 to 336 farms (851 ha) in 2018. Vegetables represented the largest category of production with sales of $1.1 million (USDA 2020b). Notably, an increase in land irrigated also occurred, from 81 ha in 2007 to 223 ha in 2018 (USDA 2020b). Despite this increase, there are still at least 600 ha of cropland dependent on rainfall.

Among the vegetables produced in St. Croix, peppers also lead the number of farms as the primary crop with a total of 121 farms in 2018, within which more than 20 farms have a market value of agricultural products sold of >$10,000. Plantains and bananas are also some of the main fruits cultivated in St. Croix, based on the number of farms. In 2018, 119 farms cultivated plantains and 220 farms cultivated bananas, compared to only 33 farms cultivating plantain and 57 farms cultivating bananas in 2007. The market value of the agricultural products sold was >$10,000 for at least 9 plantain and 24 banana farms in St. Croix (USDA 2020b).

On top of the economic value, these crops also have an important cultural value for the islands. For the Puerto Rican community that lives either in Puerto Rico or in St. Croix, a particular sweet pepper, locally known as *Ají dulce* (*Capsicum chinense*), is popular and used in culinary seasoning, giving characteristic flavor to most Puerto Rican recipes (Palada *et al.* 2003). The historical significance of banana and plantain for the small islands in the Caribbean also make those crops relevant for our analysis. It is estimated that the production of bananas is one of the largest employers of labor and sustains thousands of small farmers in the Caribbean, providing a foundation for the economic viability and social and political stability in the region (Bernal 2020).

Besides the economic and cultural importance of banana, plantain, and sweet pepper, these crops were widely cultivated across Puerto Rico in 2016, according to the agricultural statistics interactive platform created by the USDA Caribbean Climate Hub (https://caribbeanclimatehub.org/tools-apps/agricultural statistics/). In 2016, sweet pepper, banana, and plantain were cultivated in at least 148, 156, and 430 neighborhoods, respectively, in Puerto Rico. Although we understand the importance of coffee plantations for Puerto Rico, we decided to not include coffee in this analysis because it is not cultivated in St. Croix and a recent study has examined the impact of climate change on coffee in Puerto Rico (Fain *et al.* 2018). Therefore, we chose to use sweet pepper, banana, and plantain as the crops to analyze the future agroclimatic suitability in Puerto Rico and St. Croix.

2.3.1. Crop coefficient (*kc*) and yield response factor (*ky*)

The values of *kc* and *ky* used for the CROPRISK model were related to each crop. Sweet pepper *kc* during its mid-growth stage is 1.05 and during its late-growth stage is 0.90 (Allen *et al.* 1998; Harmsen *et al.* 2003; Kisekka *et al.* 2010). Here we followed the approach of Curtis *et al.* (2014) and chose a value of 1.0 to represent the harvest time of sweet pepper and avoid negative *DY*s, which are possible with smaller *kc* values. For sweet pepper *ky,* we used a value of 1.10 (Batjes 1987). Because bananas and plantains are a member of the same crop group, we used the same values of *kc* and *ky* (Allen *et al.* 1998): $kc = 1.10$, based on the average *kc* for mid-and late-growth stages for the first and second years of cultivation, and $ky = 1.27$. Water stress increases on a crop with *ky* values greater than one (Curtis *et al.* 2014), which suggests that sweet pepper, banana, and plantain are all crops with increased sensitivity to water availability.

3. RESULTS AND DISCUSSION

3.1. Temperature and precipitation change

After downloading and processing the climate observations (Daymet) and CMIP6, this study analyzed how temperature and precipitation of mid-century (2041–2070) and late-century (2071–2100) climatologies will change when compared to the baseline climatology (1981–2010). Figure 2 presents the 24-month annual cycle of temperature (°C) for all the observed and projected climatologies for the four basins in Puerto Rico and St. Croix. For observed data (Daymet), the higher monthly average temperature occurred in July–August, while for simulated data (CMIP6), the higher temperatures occurred in September–October for both the historical and future climatologies. However, the future climatologies, here called 'Delta' to indicate they were bias-corrected projections, also peaked in July–August, but with temperatures ranging from 1.8 to 2.2 °C warmer in 2041–2070 than the baseline climatology in Puerto Rico and St. Croix. For 2071–2100, differences in temperatures ranged from 3.2 to 3.7 °C warmer in Puerto Rico and St. Croix when compared to the baseline climatology.

Among the basins in Puerto Rico, the East basin registered a slightly smaller difference between the observed temperature and the two future climatologies in July–August than the rest of the island. This smaller increase in future temperature in eastern Puerto Rico could be related to the presence of the El Yunque National Forest, a tropical rainforest located in the Luquillo Mountains with an area of around 100 km^2. The effect of tropical rainforests in controlling temperature is mainly related to their high evapotranspiration demands, which use the available latent heat, and consequent cloud formation, which decreases incoming solar radiation at the surface (Fetcher *et al.* 1985; Brovkin 2002; Lawrence & Vandecar 2015). On the other hand, the fact that St. Croix registered the smallest change in temperature between observed and future climatologies, when compared to Puerto Rico Basins, could be related to the maritime effect being more efficient in the smaller island climate, resulting in smaller temperature ranges (Granger 1985).

The observed (Daymet) 24-month annual cycle of precipitation (Figure 3) confirmed the bimodal cycle of rainfall in the eastern Caribbean, with two rainy seasons occurring in April–July (early rainfall season) and August–November (late rainfall season), separated by a drier period in June–July (mid-summer dry spell), and a dry season occurring in December–March (Taylor *et al.* 2002; Curtis & Gamble 2008; Angeles *et al.* 2010). The mid-summer dry spell is less apparent in the East Puerto Rico Basin (Figure 3(a)), probably because this region has local mechanisms of rainfall along the year, such as the orographic effect and the presence of the tropical rainforest (Sobel *et al.* 2011; Ramseyer & Mote 2016; Jury 2020), that make it wetter than the rest of the island.

Before bias correction was applied, the CMIP6 models did not represent the bimodal cycle in precipitation. They could not simulate the December–March dry season and the April–July rainy season, while they overestimated the August–November rainy season in Puerto Rico and in St. Croix. However, after bias correction was applied, the future climatologies are projected to have the same pattern as the observed precipitation. The 2041–2070 precipitation was predicted to have from 54 to 74 mm less than the baseline climatology, mainly from June to October, in the four basins of Puerto Rico, and 36 mm less in St. Croix over the same period. The greater difference in precipitation is expected to occur between the baseline period and 2071–2100, when the West Puerto Rico Basin is projected to have 215 mm less precipitation from June to October, and St. Croix 96 mm less precipitation. The only month when projected precipitation was expected to be greater than the observed precipitation was November, which can indicate a future shift in the peak of the hurricane season that currently occurs in September (Kossin 2008; Martinez *et al.* 2019).

The overall increase in temperature and decrease in precipitation by mid-to-late-century found here was also observed in past studies that used earlier versions of CMIP6 (CMIP5 and CMIP3) to assess crop suitability in Jamaica and Puerto Rico (Curtis *et al.* 2014; Fain *et al.* 2018). Although uncertainties still exist, mainly regarding the precipitation projections, those findings using different models and different bias correction methods all pointed to a likely warmer and drier insular Caribbean starting in 2041 if the worst-case CO_2 emission scenario in CMIP6 is not avoided.

3.2. Water deficit

The Thornthwaite water budget model was applied to each one of the four basins of Puerto Rico and St. Croix during the baseline climatology (1981–2010) and the two future climatologies representing the mid-century (2041–2070) and late-century (2071–2100). Using PET and AET outputs from the model, we computed water deficits and crop suitability for each basin and St. Croix under those three climatologies.

Figure 4 shows the annual cycle of crop water stress for the baseline and the two future climatologies. In the baseline climatology, there was almost no crop water stress occurring in the East and North Puerto Rico Basins during the annual cycle. This is probably related to their greater annual precipitation compared to other basins, due to tropical forest and orographic rainfall discussed earlier. However, some crop water stress was exhibited during the dry season (January–March) in the West Basin, while the most severe crop water stress during the baseline climatology occurred in the South Puerto Rico Basin and St. Croix, with the highest values in June–July. These months coincided with the mid-summer dry spell, when the region experiences its highest temperature and a reduction in precipitation (Figures 2–4). South Puerto Rico and St. Croix were the driest regions in the study, but monthly temperatures were as high as the wetter regions, indicating a potential increase in evapotranspiration demand and greater vulnerability to water stress. In fact, the South Puerto Rico Basin is known as a drier region and was classified as a 'dry forest' based on its humidity, annual precipitation, and PET (Holdridge 1967). The region is geographically located to the south of the Central Mountain Range, which creates a shield blocking the Atlantic moisture and making the south drier than other regions of Puerto Rico (Torres-Valcárcel *et al.* 2014).

For the future climates, the overall crop water stress was also highest from June to August, except for the West Puerto Rico Basin where the higher values occurred in January–March. This means that even wet regions such as the East and North Puerto Rico basins, which are not currently facing water stress during the mid-summer dry spell, will start to have problems with water available for crops during these drier months after 2041. In the South Puerto Rico Basin and St. Croix, where crop water stress is already occurring in the first half of the year, the late-century climatology suggested as much as a double the current water stress during the mid-summer dry spell in St. Croix and almost three times the water stress in southern Puerto Rico. These climate projections indicate that crop risk in those areas will be high after 2041. A similar result was found by Curtis *et al.* (2014) when analyzing the crop water stress for Jamaica by the end of the 21st century, indicating the mid-summer dry spell as a key component for future regional water stress. They suggest that one of the causes for the mid-summer water stress increase could be associated with the Caribbean low-level jet (CLLJ), which has its relative

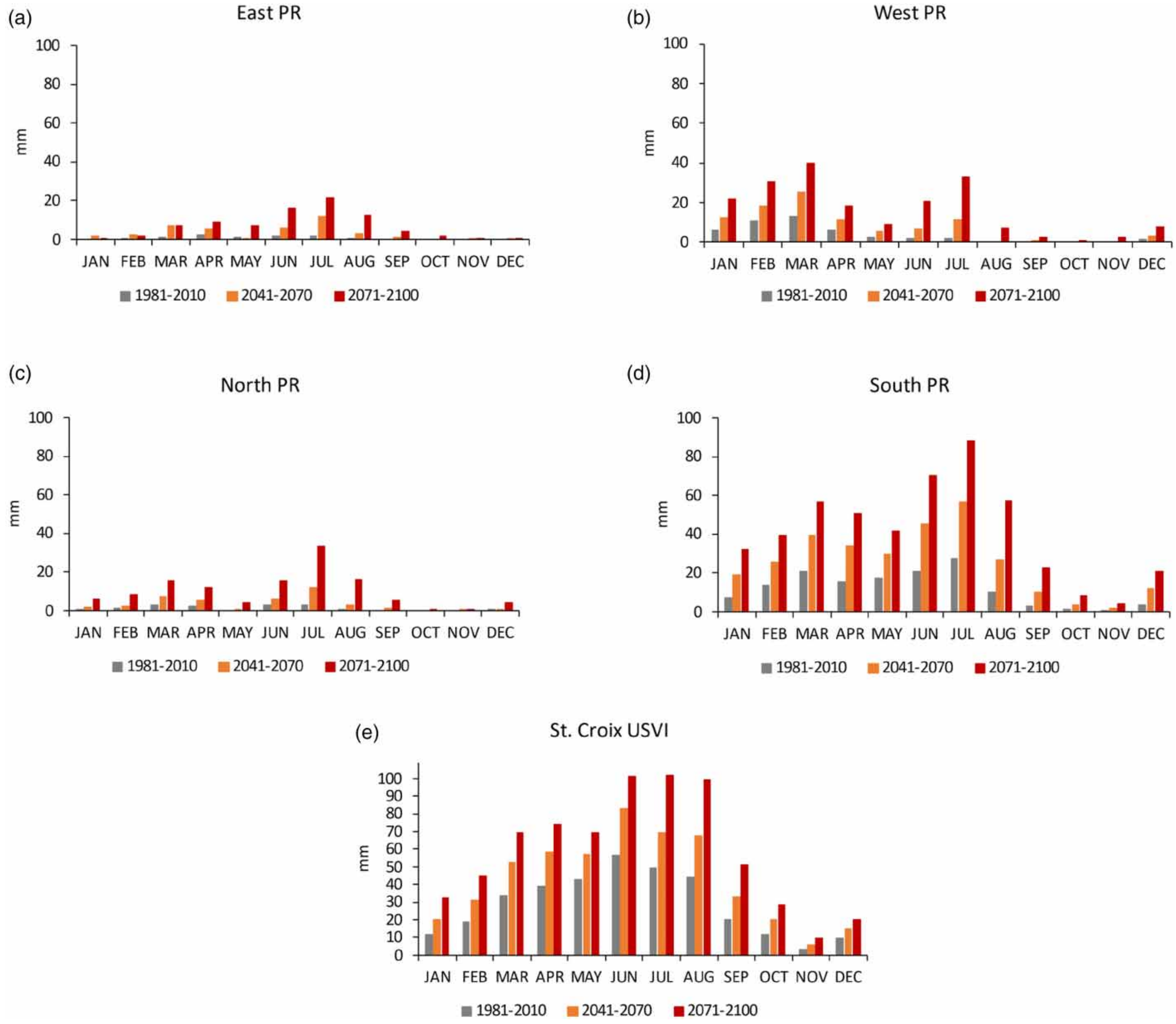


Figure 4 | Annual water stress (PET–AET) for Puerto Rico Basins (a) East, (b) West, (c) North, (d) South, and (e) St. Croix. The gray bars represent the water stress for baseline climatology (1981–2010), the orange bars are for mid-century (2041–2070), and the red bars are for late-century (2071–2100) climatologies. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2023.398.

maximum in July (Gamble & Curtis 2008; Curtis *et al.* 2014). The Providing REgional Climates for Impacts Studies regional model simulated the patterns of the CLLJ by the end of the 21st century and suggested that an intensification of the CLLJ will occur from May to November and reach Jamaica, Hispaniola, Puerto Rico, and the north coast of South America resulting in a drier climate for the Caribbean (Taylor *et al.* 2013). The CLLJ together with the North Atlantic subtropical high (NAHP) is an important atmospheric pattern responsible for the current lower values of precipitation during the boreal summer in the Caribbean, transporting moisture from the Caribbean to Central America (Gamble & Curtis 2008; Gamble *et al.* 2008; Cook & Vizy 2010). The period when CLLJ is projected to be more intense (Taylor *et al.* 2013) aligned with the months for which the future climatologies here projected less precipitation and a higher average temperature (more evapotranspiration) for all the four basins of Puerto Rico and St. Croix (Figure 3). Thus, the changes of these atmospheric variables with climate change can justify the drier mid-summer dry spell and the increase in water stress across those islands in the future.

3.3. Crop suitability

After analyzing crop water stress, we ran the CROPRISK model to assess agroclimatic suitability for sweet pepper, banana, and plantain in the four basins of Puerto Rico and St. Croix. We ran the model for each crop and each region over the three periods of analysis. Tables 2 and 3 show the suitability classes for each month. The overall results indicate that conditions for banana and plantain cultivation will be less suitable than those for sweet pepper in the South and West Puerto Rico Basins and in St. Croix by the end of the 21st century.

When focusing on sweet pepper (Table 2) during the baseline climatology, the results indicated that this crop was highly suitable over the entire year for the East, West, and North Puerto Rico Basins, while in the South Puerto Rico Basin and St. Croix, the highly suitable class is limited to August–January and October–January, respectively. During the early rainfall season (April–July), sweet pepper was already moderately suitable for the South Puerto Rico Basin and marginally suitable for

Table 2 | Annual cycle of agroclimatic suitability for sweet pepper in the four basins of Puerto Rico and in St. Croix during the baseline climatology (1981–2010), and the two future climatologies: mid-century (2041–2070) and late-century (2071–2100)

Sweet Pepper	East PR			North PR			West PR			South PR			St. Croix USVI		
Month	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100
JAN	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	HiS	MoS	MaS	HiS	MoS	MaS
FEB	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MaS	MoS	MaS	NS	MoS	MaS	NS
MAR	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MaS	NS	MaS	NS	NS	MaS	NS	NS
APR	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MaS	NS	MaS	NS	NS
MAY	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MaS	MaS	NS	NS
JUN	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MaS	NS	MaS	NS	NS
JUL	HiS	HiS	HiS	HiS	HiS	MoS	HiS	HiS	MoS	MoS	NS	NS	MaS	NS	NS
AUG	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	NS	MaS	NS	NS
SEP	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MoS	MaS
OCT	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MoS
NOV	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS
DEC	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	HiS	MoS	MoS

Highly suitable class is in green, moderately suitable in yellow, marginally suitable in orange, and NS in red.

*HiS: when 80% condition of crop's maximum yield is met at least 60% of the years and the 60% condition is met at least 80% of the years; MoS: when 80% condition of crop's maximum yield is met at least 40% of the years and the 60% condition is met at least 60% of the years; MaS: when 80% condition of crop's maximum yield is met at least 20% of the years and the 60% condition is met at least 40% of the years; NS: when 80% condition of crop's maximum yield is met in less than 20% of the years and the 60% condition is met in less than 40% of the years.

Table 3 | Annual cycle of agroclimatic suitability for banana and plantain in the four basins of Puerto Rico and in St. Croix during the baseline climatology (1981–2010), and the two future climatologies: mid-century (2041–2070) and late-century (2071–2100)

Banana / Plantain	East PR			North PR			West PR			South PR			St. Croix USVI		
Month	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100	1981-2010	2041-2070	2071-2100
JAN	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MaS	MaS	MoS	MaS	NS	MoS	MoS	NS
FEB	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MaS	NS	MaS	NS	NS	MaS	NS	NS
MAR	HiS	HiS	HiS	HiS	HiS	MoS	MaS	MaS	NS	NS	NS	NS	NS	NS	NS
APR	HiS	HiS	HiS	HiS	HiS	MoS	HiS	MoS	MoS	MoS	NS	NS	NS	NS	NS
MAY	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MaS	MaS	NS	NS	NS
JUN	HiS	HiS	MoS	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MaS	NS	NS	NS	NS
JUL	HiS	HiS	MoS	HiS	MoS	NS	HiS	HiS	MaS	MaS	NS	NS	NS	NS	NS
AUG	HiS	HiS	HiS	HiS	HiS	MoS	HiS	HiS	HiS	HiS	MaS	NS	NS	NS	NS
SEP	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MaS	NS
OCT	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MoS	MaS
NOV	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS
DEC	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	HiS	MoS	MaS	MoS	MoS	MoS

Highly suitable class is in green, moderately suitable in yellow, marginally suitable in orange, and NS in red.

*HiS: when 80% condition of crop's maximum yield is met at least 60% of the years and the 60% condition is met at least 80% of the years; MoS: when 80% condition of crop's maximum yield is met at least 40% of the years and the 60% condition is met at least 60% of the years; MaS: when 80% condition of crop's maximum yield is met at least 20% of the years and the 60% condition is met at least 40% of the years; NS: when 80% condition of crop's maximum yield is met in less than 20% of the years and the 60% condition is met in less than 40% of the years.

St. Croix from 1981 to 2010. Future climatologies, starting in 2041, did not change the high suitability of sweet pepper in the East and North Puerto Rico Basins, except for July in the northern basin, in which the crop became moderately suitable after 2071. However, a gradual decrease in sweet pepper suitability was evident in the West Puerto Rico Basin in January–April, when this region is under water stress, and each month reduced at least one suitability class. On the other hand, the South Puerto Rico Basin presented a drastic change in sweet pepper suitability, mainly from February to August when the crop that used to be moderately suitable during the baseline climatology will become unsuitable after 2071. In St. Croix, the decrease of crop suitability occurred first because sweet pepper will be unsuitable from March to August starting in 2041.

For bananas and plantains (Table 3), the agroclimatic suitability assessment was even less optimistic. During the baseline climatology, the East and North Puerto Rico Basins were still highly suitable, but some moderately suitable categories will start to occur during the mid-summer dry spell in the East basin after 2071. For the North basin, only July is moderately suitable after 2041, while after 2071, this region has a drastic change to NS for banana and plantain. In the West Puerto Rico Basin, suitability also decreased from highly to moderately suitable in the baseline climatology to marginally-NS in January–March after 2041. However, a drastic decrease in banana and plantain suitability occurs in the South Puerto Rico Basin, from January to August, where most of the months that used to be moderately to marginally suitable became NS. The exception for this region is the hurricane season, from September to November, when crop suitability is high throughout the end of this century. In St. Croix, where bananas and plantains are already NS to be rainfed from March to August in the baseline climatology, the decrease in suitability expanded to 9 months of the year (January–September) after 2071. The greater decrease in banana and plantain suitability is probably related to the fact that they are more prone to water stress than sweet pepper. As mentioned previously, the *ky* value greater than one indicates crops are more sensitive to water availability, and the *ky* for banana and plantain is greater than the one for sweet pepper.

Therefore, the overall crop suitability in the region is predicted to decay during the first half of the year (January–July), affecting the early rainfall season and the two drier seasons' agroclimatic suitability. The effects of the crop suitability reduction will be mostly felt in St. Croix and southern Puerto Rico. On the other hand, November is the only month when all crops, independent of the period and the region, will remain highly suitable. This is most likely due to the increase in precipitation projected by the future climatologies that were previously discussed (Figure 3).

These results suggested that temperature increases have a slightly larger impact than precipitation on crop suitability and water stress. While the temperature increase is predicted to occur yearlong, the greater reduction in precipitation is projected to occur only from June to October, which is not the months with the greatest water stress and poorest crop suitability. Similarly to what Curtis *et al.* (2014) found in Jamaica, the effect of temperature on agriculture suitability was probably related to the projected warming in the boreal winter, which increases the evapotranspiration demand during the Caribbean dry season.

3.4. Crop suitability, food security, and climate change

The results discussed here indicated that southern Puerto Rico and St. Croix, which are already sensitive to water deficits, will face difficulty in keeping crop suitability for sweet pepper, banana, and plantain during most of the annual cycle after 2041 (Tables 2 and 3). For short rotation crops studied in Jamaica, drought and water deficits are major problems already affecting growth rate, fertilization, and yield (Rhiney *et al.* 2018), which will also be the case of sweet pepper analyzed here, whose life cycle ranges from 60 to 90 days. Other studies suggested that important crops such as coffee production would have an estimated reduction in up to 84% of highly suitable growing conditions in top-producing municipalities in Puerto Rico by 2070 (Fain *et al.* 2018).

Therefore, one of the strategies that may be considered to adapt to climate change is finding alternatives to sweet pepper, banana, and plantain, including more drought-tolerant crops, such as sweet potato and cassava (Campbell *et al.* 2011; Curtis *et al.* 2014). Furthermore, irrigation may also be an option, as parts of the South Puerto Rico Basin were already classified as conditional farmland soils, meaning the soils there typically need irrigation (Gould *et al.* 2017). Another alternative could be to invest in farmer field schools with farmer-centered approaches for collaboration and participation to solve the problems and plan for the future, which may increase the chances for knowledge diffusion and collective action (Tomlinson & Rhiney 2018).

Additionally, it is important to emphasize that agriculture was highlighted as one of the human systems most impacted by climate change at the community level (Robinson & Wren 2020), while results from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) indicated that climate change will impact agriculture in the Caribbean mainly due to changes in temperature and water availability (Lincoln Lenderking *et al.* 2021). Therefore, the reduction in agroclimatic suitability assessed here (Tables 2 and 3) and in past studies reinforced the likelihood of climate change being a threat to food security in Puerto Rico and St. Croix, because food security depends not only on food availability but also on food access, utilization, and stability that are all significantly affected by climate change (Rhiney *et al.* 2018; Lincoln Lenderking *et al.* 2021).

Finally, when comparing the results of Puerto Rico and St. Croix, we can see the different impacts of climate change on the Greater and Lesser Antilles. While Puerto Rico will still have some areas remaining suitable for crops most of the year until the end of this century, St. Croix will suffer more and sooner with water stress and crop suitability, with a chance to have most of the year without the ability to rely on rainfed crops. The differences in island areas (St. Croix is at least 50 times smaller than Puerto Rico) and water resource availability can play an important role in defining the islands that are going to feel the consequences of climate change first.

4. CONCLUSIONS

This work investigated how future climate can impact water stress and crop suitability for four basins in Puerto Rico (South, North, East, and West) and the island of St. Croix using the CROPRISK model. When comparing the baseline climatology (1981–2010) and two future climatologies (2041–2070 and 2071–2100), the results indicated that the projected increase in temperature and decrease in precipitation will continually decrease crop suitability and increase water stress over most of Puerto Rico and St. Croix after 2041. Among the regions, we highlighted the South Puerto Rico Basin and St. Croix as the most sensitive to future changes due to their greater water stress and lower crop suitability when compared to the other regions. By 2041, St. Croix will not be suitable for sweet pepper, banana, and plantain for at least half of the year, while southern Puerto Rico will follow the same path after 2071. Other regions of Puerto Rico will keep crop their suitability and lower water stress for almost the entire year, with the exception of the mid-summer dry spell months (June–July), when all regions exhibit the effects of climate change in their water deficits and banana/plantain crop suitability.

Overall, results indicated that bananas and plantains were more sensitive to water deficits than sweet pepper and that the effects of future climate change on water stress and crop suitability will be worse from January to July. This indicates that the projected temperature increase will have a slightly larger impact than precipitation on crop suitability and water stress in Puerto Rico and St. Croix. While the temperature increase is predicted to occur yearlong, the greater reduction in precipitation was projected to occur only from June to October, which are not the months with the greatest water stress and poorest crop suitability in the islands.

The reduction in crop suitability and greater water stress from January to July also indicated that the two dry seasons and the early rainfall season will be the periods when planning for agriculture will be critical in order to keep crops suitable in the future. Among the options for planning and adaptation, focusing on more drought-resistant crops and/or having an irrigation plan at the government level could be alternatives. Preserving forested and highly vegetated areas would also be important, as we saw their roles in controlling temperature range and precipitation in eastern Puerto Rico. Moreover, we believe that any effort that helps to reduce CO_2 emissions should be taken into consideration to prevent a drastic increase in temperature and its consequent impact on SIDS and smallholder farmers.

For future work, we recommend the replication of the methods applied here using other crops of interest in Puerto Rico and St. Croix. We believe that further investigation is needed to assess the possible impacts of climate change on Puerto Rico and St. Croix's agriculture, as well as to better understand the spatial distribution of those impacts. It would also be important to apply a similar approach to other nations in the insular Caribbean to understand the regional impacts of future climate on crop water stress, and, hopefully, to encourage a regional action/plan to better prepare and adapt to mitigate food insecurity. Finally, we understand that the outputs from the climate models used here should be interpreted as projected climate trends for an extreme climate change scenario, rather than predictions of future weather.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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