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ORIGINAL ARTICLE

# Assessment of crop risk due to climate change in Sao Tome and Principe

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## Abstract

Sao Tome and Principe is a small insular country in the west coast of Central Africa. The small dimensions of the islands and the limited natural resources put these islands under highly vulnerable to climate change. To assess the possible future impacts and risks on their agricultural activities, the high-resolution 4-km downscaled climate change projections using Eta regional climate model are used. A crop risk index (CRI) is proposed to assess the risk of climate change on cocoa (*Theobroma cacao* L.), pepper (*Piper nigrum* L. and *Piper guinesse* L.), taro (*Colocasia esculenta* (L.) Schott), and maize (*Zea mays* L.). The index takes into account the vulnerability to climate conditions and the crop yield in the future, and it is classified into *very-high*, *high*, *moderate*, *low*, and *very-low*. The climate change projections indicate increase in the risk of taro crop, partly due to thermal stress and partly due to the susceptibility to the leaf blight crop disease in taro. The risk of production of the pepper crop is very-high, mainly due to water stress. In mountain regions, the greater risk is due to the thermal stress caused by low temperatures. The cocoa crop is at risk due to water stress, mainly in the northwestern part of the Sao Tome Island, where major local production occurs. The projection indicates increase of the area with very-high risk to maize crops due to the increase of thermal stress and susceptibility to rust. In addition, in parts of the coastal regions, the risk changed from very-low to high risk, due to the low productivity potential. In general, the risks of the four major crops of Sao Tome and Principe increase in the future climate conditions.

**Keywords** Crop risk index · Climate change · Small Islands Developing States · Eta model · Agriculture risk assessment

## Introduction

In Sao Tome and Principe (STP), agriculture is crucial in the production for staple food and for exportation. According to the data from the African Economic Outlook (2014), agriculture in the region represents 22.5% of the composition of the gross domestic product (GDP). Among agriculture products, cocoa is the crop that contributes the most to the GDP in STP, by accounting for about 17% of the GDP (INE-STP 2016). Despite the reduction of productivity in the last decades, the islands produce an average cocoa yield of around

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120 kg ha$^{-1}$, considering the period 2005–2014 (FAOSTAT 2016). The cultivation of pepper, which is also destined for exportation in STP, has proven to be an alternative for agricultural diversity in the region. Above all, this is an alternative to the low yield obtained by cocoa in recent years (Almeida 2012).

In addition, other crops are important for staple food, such as taro and maize. Taro, locally known as *matabala*, is important for STP feeding and for the family income. The average crop yield between 2005 and 2014 was approximately 6000 kg ha$^{-1}$ (FAOSTAT 2016). The crop has good adaptability to different soil and climatic conditions, which allows the cultivation from marshy areas to the high slope (Nolasco 1994). Maize has strategic importance in human and animal feeding in STP (DRSTP 2012). Although maize is one of the most versatile cereal crops, previous studies in tropical areas showed that its growth and productivity are likely to be affected by climate changes (Martins et al. 2019).

The First National Communication of Sao Tome and Principe (DRSTP 2005) resulted in the National Action Plan for Adaptation to Climate Change (DRSTP 2006). The Second Communication used the low and high emission scenarios of the IPCC (DRSTP 2012). Those reports provided a subjective assessment of the impacts of climate change on the agriculture sector, and valuable information was provided to help STP reach responsiveness and planning adaptation measures to face climate change impacts.

Given the small dimensions of the islands, the study of impact, vulnerability, and adaptation require high spatial detail of climate change in the region. Therefore, it is necessary to use very-high-resolution models to generate detailed climate change projections and assess the impacts. In this context, the downscaled climate scenarios for STP using regional climate model Eta (Chou et al., 2020) were used for developing the crop risk index (CRI). This research aimed to assess the impacts of climate change on cocoa (*Theobroma cacao* L.), pepper (*Piper nigrum* L. and *Piper Guinesse*), taro (*Colocasia esculenta* (L.) Schott), and maize (*Zea mays* L.) in terms of crop yield, disease susceptibility, and vulnerability. The relevance of this study is the limited agriculture resources of the small islands and their vulnerability due to the climate change. As one of the Small Islands Developing States (SIDS), Sao Tome and Principe shares similar climate-related risks as other islands (Murray et al. 2012), being highly vulnerable to climate change and having low adaptive capacity. The study is unique in studying the impacts on agriculture using high-resolution climate change projections in one SIDS. It is also important to note that the methodology can be adapted and applied to different regions and different crops to assess the risk of production and to assist in the creation of mitigation measures.

## Material and methods

### Description of the study area

Sao Tome and Principe (STP) are the two major islands that name the country, and they are located in Guinea Gulf, Africa. The islands are organized in seven districts, as shown in Fig. 1. The small size of STP islands renders STP as highly vulnerable to climate change.

The total population in STP is about 198,000 inhabitants (World Bank 2018), and the Human Development Index is considered as medium but below the global average (UNDP 2018). One-third of the population lives below the poverty line, and more than two-thirds are considered poor. The districts of *Caué* and *Lembá* are the poorest of the islands (Word Bank 2018). The STP economy is based on fishing and agriculture. The latter is responsible for more than 20% of the gross domestic product—GDP (African Economic Outlook 2014). Pepper and cocoa are the two major crops for exportation, while taro and maize are staple food crops. As the climate is one of the major factors that affect agriculture, climate change impacts can put at risk the major sector of the economy in STP.

These small islands have a monsoon climate according to Köppen climate classification, with two well-defined rainy seasons. The first rainy season occurs between February and May and the second one occurs between October and December. The climate in Sao Tome is complex. The small island has a unique topography with elevations that exceed 2000 m in an area of only 1000 km$^2$ (Fig. 1). For that reason, different climatic regimes occur around the island, with annual rainfall less than 1000 mm year$^{-1}$ in the northeastern part of the Sao Tome island and almost 7000 mm year$^{-1}$ in the southern part. The annual precipitation in Principe Island follows the same rainfall regime as in Sao Tome, but with less rain.

Water scarcity is particularly common in the north of Sao Tome Island. All areas where rainfall is less than 50 mm per month during the dry season have difficulties in maintaining horticultural crops without irrigation. Nevertheless, these regions have the highest population densities (DRSTP 2012). Not only water scarcity can contribute to crop yield losses but also an increase in temperature and humidity may favor crop disease spread. Due to the exposure and vulnerability of STP to climate change, it is urgent the assessment of climate change impacts in all sectors, especially in agriculture, which is key to food security and their economy.

### Eta regional climate projections

The high-resolution climate change projections are provided by the Eta regional model (Mesinger et al. 2012; Chou et al. 2012; Lyra et al., 2017; Chou et al. 2020). The Eta model uses the vertical eta coordinate, which is more appropriate for

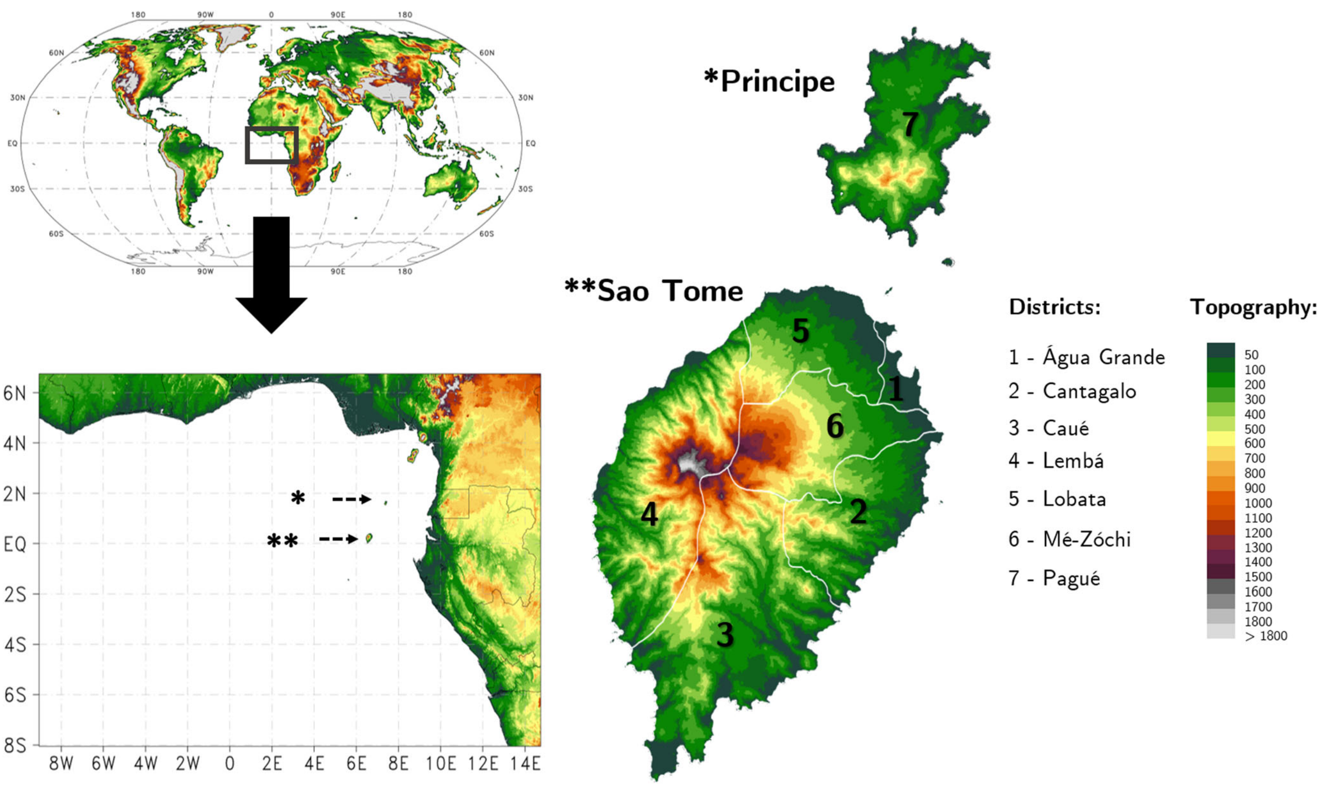

**Fig. 1** Sao Tome and Principe topography (meters) and the districts

simulations in high resolution in regions of complex topography (Mesinger, 1984), such as STP.

The climate simulation dataset is a 4-km resolution downscaling (Chou et al., 2020) of the global climate model CanESM2 (Arora et al. 2011) for the periods between 1971 and 2000, and between 2041 and 2070, under the RCP8.5 and the RCP4.5 greenhouse gas concentration scenarios. The downscaled scenario has shown the skill to reproduce reasonably the climate of STP. This research has been a pioneer in using high-resolution simulations to assess changes in STP climate. The spatial resolution is essential given the small extension of both islands and that the current global climate models cannot represent such small areas.

The main findings regarding climate projection in STP (Chou et al., 2020) concluded that, although the projections for temperature in both islands showed a warming tendency, varying from 1.5 to 2.0 °C in RCP4.5 and reaching 3.5 °C in RCP8.5, the projected precipitation points out large uncertainties between RCP4.5 and RCP8.5 scenarios. Under the RCP4.5 scenario, precipitation increases in the wet season and slightly decreases in the dry season. On the other hand, under the RCP8.5 scenario, almost all the months of the year suggest reduction in precipitation. Those projections indicate warmer nights, which may enhance the plant metabolic processes, in particular the respiration rate. This is a serious concern, as plant respiratory processes can consume large portions of total photosynthates (Paembonan et al. 1992), thereby reducing crop yield (Zheng et al. 2002). The annual accumulated precipitation in STP indicates increase in the RCP4.5 scenario, but decrease in RCP8.5, and the maximum consecutive dry period shows an increase in both scenarios. Even though, in the RCP4.5, the total annual precipitation amount increases, the increase in the consecutive dry period lengths leads to fewer precipitation events, which can seriously damage agriculture production, especially the most drought-sensitive crops.

## Future crop risk assessment

The assessment was based on daily values of air temperature, precipitation, and reference evapotranspiration. Reference evapotranspiration was estimated based on the daily maximum and minimum temperatures, dew point temperature, atmospheric pressure, wind speed at 10-m height, and solar radiation of the downscaled scenarios using the Penman-Monteith method according to Allen et al. (1998).

The crop risk index (CRI) was developed in this study to assess the impacts of climate change on crops in STP. This index was constructed from a combination of four partial indicators to estimate crop stress due to high air temperature ($I_{\mathrm{TMP}}$), water stress ($I_{\mathrm{WAT}}$), disease susceptibility ($I_{\mathrm{DIS}}$), and crop yield ($I_{\mathrm{YIE\%}}$). Each crop requires optimal edaphoclimatic conditions for its development and growth; therefore, the partial indicators were evaluated individually for each crop.

Thresholds of plant parameters were based on the literature and were defined for each crop. Then, these threshold values were used to calculate the partial indicators of thermal stress, water stress, and disease susceptibility. These thresholds are values above which climate conditions impair the crop. Based on the critical meteorological conditions for crop development, as well as the meteorological conditions for the occurrence of diseases, we considered risk factors (or indicators) for each one of the crops assessed: cocoa, pepper, taro, and maize (Table 1).

The partial indicator of crop yield ($I_{\mathrm{YIE}}$) is obtained by the linear crop-water production function proposed by Doorenbos and Kassam (1979). It relates to the reduction in crop yield to a shortage of soil water (Eq. 1). The ratio between actual ($\mathrm{ET_r}$) and potential evapotranspiration (ETP) is used to account for the impact of a shortage of soil water on crop yield by defining a crop yield index given by Eq. 1.

$$I_{\mathrm{YIE}} = \left[1-K_{\mathrm{Y}}\left(1-\frac{\mathrm{ET_r}}{\mathrm{ET_P}}\right)\right] \tag{1}$$

Since $I_{\mathrm{YIE}}$ is a partial indicator of the crop yield, $K_{\mathrm{y}}$ is a coefficient that describes the reduction in relative yield according to the reduction in $\mathrm{ET_P}$ caused by a shortage of soil water. This relationship considers that potential evapotranspiration is a function of the reference evapotranspiration ($\mathrm{ET_o}$) and uses a correction made by the crop coefficient ($K_{\mathrm{c}}$), as expressed in Eq. 2. The actual evapotranspiration ($\mathrm{ET_r}$) is calculated according to the water balance proposed by Souza et al. (2001) and Rossato et al. (2005). The root depth adopted for calculating the water balance was 0.40 m for maize (Albuquerque and Resende 2002), 0.20 m for taro (Vieira et al. 2015), 0.40 m for cocoa (Carr and Lockwood 2011), and 0.40 m for pepper (Ramos et al. 1984).

$$\mathrm{ET_P} = \mathrm{ET_o}.K_{\mathrm{c}} \tag{2}$$

For each crop, we used its specific coefficients according to literature (Table 2).

The partial indicator of crop yield aims to evaluate the crop yield concerning soil water restriction. Thus, an $I_{\mathrm{YIE}}$ close to 1 means that the water supply conditions in the soil are favorable to the crop and that the crop can reach its maximum production (potential yield). Similarly, an $I_{\mathrm{YIE}}$ close to zero indicates a high deficiency of water in the soil, which renders the region unsuitable for cultivating this crop.

Those partial indicators assumed equal weights. It was sought to gather the largest number of climate-related variables affecting the production of the crop in order to assess the risk of producing in a given location.

Once the partial indicators were determined, the calculation of the CRI has been adapted from Nardo et al. (2005), following two steps. In the first step, we normalized the partial indicators $I_{\mathrm{WAT}}$, $I_{\mathrm{TMP}}$, and $I_{\mathrm{DIS}}$, to make possible comparisons among them. For this purpose, we adopted Eq. 3:

$$\mathrm{IP_{ji}} = \frac{I_{\mathrm{ji}}-I_{\mathrm{jw}}}{I_{\mathrm{jb}}-I_{\mathrm{jw}}} \tag{3}$$

in which $\mathrm{IP_{ji}}$ = the normalized value of the indicator *j* in the *i*-th grid or the partial indicator of the category *j* in the *i*-th grid, where $I_{\mathrm{ji}}$ = value of partial indicator *j* in the *i*-th grid, and $I_{\mathrm{jp}}$ = partial indicator value *j* in the worst situation, and $I_{\mathrm{jm}}$ = indicator *j* value in the best situation. We define the worst situation as the situation with highest risk, and the best situation as the one with lowest risk.

This normalization was necessary so the $I_{\mathrm{WAT}}$, $I_{\mathrm{TMP}}$, and $I_{\mathrm{DIS}}$ indices vary from 0 to 1, where 0 is the highest risk and 1

**Table 1** Crop-specific thresholds used in the partial indicator calculations due to stress by water ($I_{\mathrm{WAT}}$), temperature ($I_{\mathrm{TMP}}$), and susceptibility to the disease ($I_{\mathrm{DIS}}$). The abbreviations $P_{\mathrm{annual}}$, $T_{\mathrm{ave}}$, $T_{\mathrm{min}}$, and $R_{\mathrm{H}}$ mean, respectively: annual precipitation, average temperature, minimum temperature, and relative air humidity

| Index | Cocoa[1] | Pepper[2] | Taro[3] | Maize[4] |
|---|---|---|---|---|
| $I_{\mathrm{WAT}}$ | Number of years with:<br>$P_{\mathrm{annual}}<1200$ mm or $P_{\mathrm{annual}}>2800$ mm | Number of years with:<br>$P_{\mathrm{annual}}<600$ mm or $P_{\mathrm{annual}}>1250$ mm | Number of years with:<br>$P_{\mathrm{annual}}<810$ mm | Number of years with:<br>$P_{\mathrm{annual}}<550$ mm or $P_{\mathrm{annual}}>5000$ mm |
| $I_{\mathrm{TMP}}$ | Numbers of days with:<br>$T_{\mathrm{min}}<15$ °C and $T_{\mathrm{ave}}>36$ °C | Numbers of days with:<br>$T_{\mathrm{ave}}<23$ °C or $T_{\mathrm{ave}}>32$ °C | Numbers of days with:<br>$T_{\mathrm{ave}}<21$ °C or $T_{\mathrm{ave}}>27$ °C | Numbers of days with:<br>$T_{\mathrm{ave}}<24$ °C or $T_{\mathrm{ave}}>30$ °C |
| $I_{\mathrm{DIS}}$ | Risk of disease:<br>Brown rot<br>Numbers of days with: 30 °C$<T_{\mathrm{ave}}<$34 °C and 95%$<R_{\mathrm{H}}<$97% | Risk of disease:<br>Spot of Cercospora<br>Numbers of days with:<br>$T_{\mathrm{ave}}>25$ °C and $R_{\mathrm{H}}>90\%$ | Risk of disease:<br>Leaf burning<br>Numbers of days with:<br>25 °C$<T_{\mathrm{ave}}<$28 °C and $R_{\mathrm{H}}>95\%$ | Risk of disease:<br>Rust<br>Numbers of days with:<br>23 °C$<T_{\mathrm{ave}}<$28 °C and $R_{\mathrm{H}}>95\%$ |

References used: [1] Leitão (1983), Carr and Lockwood (2011), Schroth et al. (2016), Duniway, (1983), and Clerk, (1972); [2] Doorenbos et al. (1979), Jones et al. (2000), and Lopes et al. (2007); [3] Filgueira (2000) and Plucknett and De La Peña (1971); [4] Melching (1975), Shurtleff, (1992), Balmer and Pereira (1987), Juliatti (2005), Rhind et al. (1952), Melching et al. (1975), and Dudienas et al. (2013)

**Table 2** Description of the coefficients of sensitivity to water stress ($K_y$) and the crop coefficients ($K_c$) for each crop and phenological phase, used in Eq. 1 and Eq. 2

| Crop | Coefficient | Phenologic phases | | | | |
|---|---|---|---|---|---|---|
| | | Vegetative development | Flowering | Grain filling | Maturity | Source |
| Maize | $K_c$ | 0.40 | 0.80 | 1.15 | 0.70 | Doorenbos et al. (1979) |
| | $K_y$ | 0.40 | 1.50 | 0.50 | 0.20 | |
| Taro[1] | $K_c$ | | 1.10 | | | Fares (2013) |
| | $k_y$ | | 1.00* | | | Allen et al. (1998) |
| Cocoa[1] | $K_c$ | | 1.10 | | | Allen et al. (1998) |
| | $k_y$ | | 1.00* | | | |
| Pepper[1] | $K_c$ | | 1.05 | | | Doorenbos et al. (1979) |
| | $k_y$ | | 1.00* | | | |

[1] The crop coefficients ($K_c$) and water sensibility coefficients ($K_y$) were considered as an average over the phenologic phases

*Due to the absence of water stress coefficient values for some crops, Allen et al. (1998) suggested using $k_y = 1$, which indicates that the yield drop is directly proportional to the water deficit

the lowest risk. Equation 3 was not applied to $I_{YIE}$ index as it already considered this 0 to 1 variation.

The second step addressed the calculation of the CRI index and assigned the index into a category. The CRI consists in determining the partial indicator, which imposed more risk (lower IP) in each grid: $IP_{YIEi}$ = partial indicator of crop yield in the *i*-th grid, $IP_{TMPi}$ = partial thermal stress indicator in the *i*-th grid, $IP_{WATi}$ = partial water stress indicator in the *i*-th grid, and $IP_{DISi}$ = partial indicator of disease susceptibility in the *i*-th grid.

Thus, the crop risk index (CRIi) is defined as the partial indicator of the greatest impact on crops, that is, CRIi expresses the minimum value among the partial indicators, according to Eq. 4.

$$\mathrm{CRIi} = \min\left(\mathrm{IP}_{\mathrm{ji}}\right) \tag{4}$$

where CRIi is the crop risk index of the crop in the *i*-th grid and *j* is the analyzed indicator.

We assumed values between zero and one, representing, respectively, the worst and the best situation of each grid, according to the aspects related to the risk of producing. The CRI was classified according to the intervals for its possible gradations (between the extreme values), as shown in Table 3.

**Table 3** Risk classification for agricultural crops

| Classification | Description |
|---|---|
| Very high | Less than or equal to 0.2 |
| High | Higher than 0.2 and less than or equal to 0.4 |
| Moderate | Higher than 0.4 and less than or equal to 0.6 |
| Low | Higher than 0.6 and less than or equal to 0.8 |
| Very low | Higher than 0.8 |

The crop risk index (CRI) was calculated considering a unique season per year for cocoa, pepper, and taro. Since maize is cultivated in two distinct seasons, CRI was calculated separately for the 1st growing season, which occurs from October to January, and for the 2nd growing season, from February to May.

## Results and discussion

The CRI was developed for each crop, considering the baseline period 1971–2000 and the period in the future 2041–2070, under the greenhouse gas concentration scenarios RCP4.5 and RCP8.5. The following assessment shows the categories of risk for each crop and the most restrictive factor. The risks are classified into 5 categories, *very-high*, *high*, *moderate*, *low*, and *very-low*. The causes are divided into *water stress* (slanted lines), *thermal stress* (vertical lines), disease occurrence (dots), and low potential yield (horizontal lines).

### Cocoa (*Theobroma cacao*) crop risk index

Simulations of the baseline period show moderate risk in Sao Tome and low risk in Principe (Fig. 2). Although the risk is moderate, some areas, such as the southern Sao Tome, are already facing the risk of low crop yields. In the central and northwestern areas, the risk due to water stress is the most expressive. The projections under the RCP4.5 scenario maintain the risk category in the areas, mostly due to low crop yield. However, under the RCP8.5 scenario, the risk may increase to very-high in the areas to the north of *Lembá*, west of *Lobata*, and *Mé-Zóchi*, due to water stress (see Fig. 1 for the location of these districts). Projections for the Principe Island show no changes to the baseline moderate risk category.

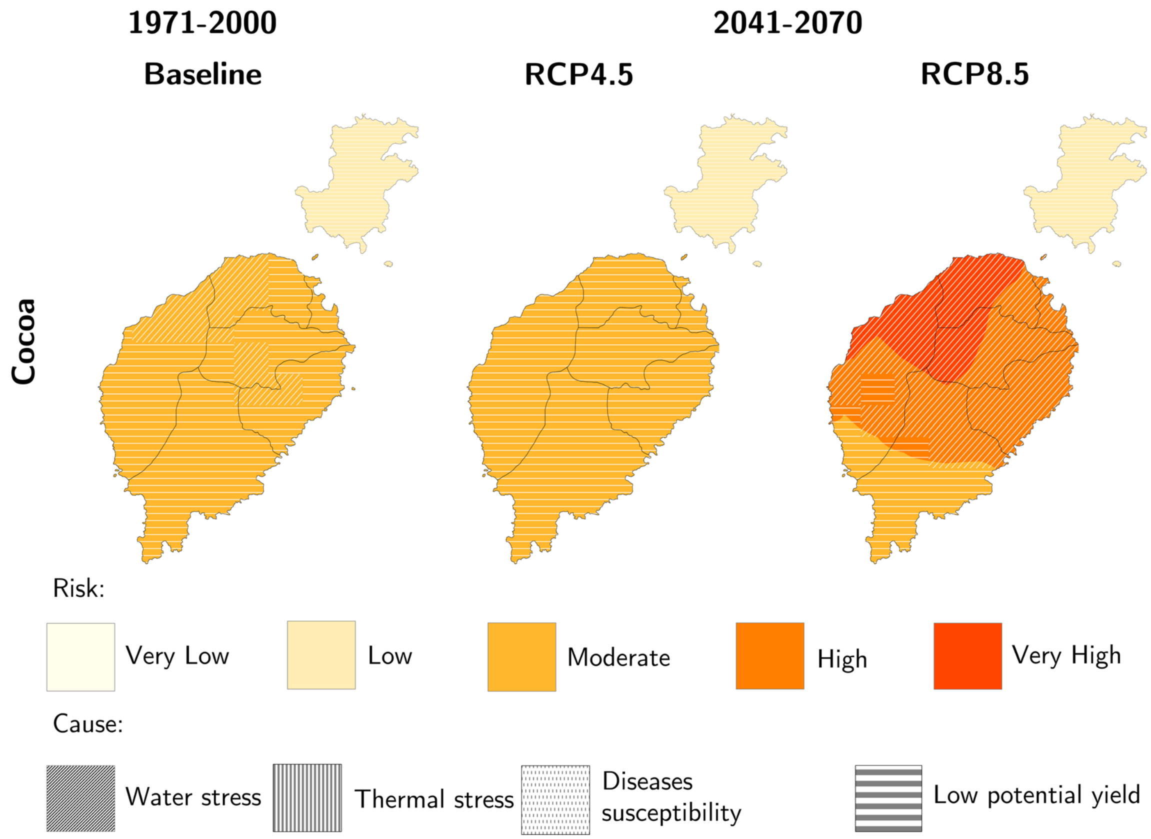

**Fig. 2** Cocoa crop risk index (CRI) and the main causes of crop production risks according to historical simulation (1971–2000, first column) and projections for the period 2041–2070, under RCP4.5 and RCP8.5 greenhouse gas scenarios

Water stress is a more significant threat than thermal stress due to high temperatures for cocoa (Carr and Lockwood 2011). On the other hand, high temperatures increase evapotranspiration, which leads to an increased shortage of soil water (Schroth et al. 2016) and therefore increased water demand. Consequently, low cocoa crop yield is expected. In order to attain good cocoa production, it is necessary a well-distributed rainfall during the year and a dry period of at least 3 months (FAO 2007).

High-resolution climate change projections for the future period 2041–2070 under the RCP8.5 scenario (Chou et al., 2020) indicate precipitation reduction varying from −25 to −100 mm/month. Precipitation reduction is projected in almost all the months of the year, except in January and December, when projections show increased precipitation of up to 100 mm/month in some areas of *Caué*, *Lembá*, and *Cantagalo*, and in August, when projections show no changes. That reduction in precipitation in consecutive months in STP could slash potential cocoa production caused by the exceedance of the cocoa crop tolerance to droughts. The number of consecutive dry days is projected to increase in the future. Although a dry season induces uniform cocoa flowering, in general, yields are greater when no dry periods occur (Zuidema et al. 2005).

According to Läderach et al. (2013), there is a concern that the projected global temperature increase, with the concomitant increase in potential evapotranspiration (ETP) and an increase in plant water demand, may result in increased drought stress for cocoa during the dry season.

However, under the RCP4.5 scenario, projections show an increase of precipitation in STP. Therefore, even though temperature increases, the increase in precipitation could compensate for the expected increase in ETP, as shown by Schroth et al. (2016). Keeping unaltered the CRI in the future for both islands.

Therefore, these future agricultural projections for cocoa in STP, the cocoa crop risk will remain unchanged under the RCP4.5 scenario, but it will increase to high and very-high under the RCP8.5 scenario in most of Sao Tome, excluding the Southern part of Sao Tome and Principe Islands. The leading causes of the increased risk are attributed to the reduced monthly precipitation and the increasing air temperature, which leads to increased ETP and a shortage of soil water.

## Pepper crop risk index

The simulation of the baseline period shows areas of high and very-high risk in the districts of *Caué*, *Lembá*, in the western part of the district of *Mé-Zóchi*, and southwestern part of the district of *Lobata* (Fig. 3).

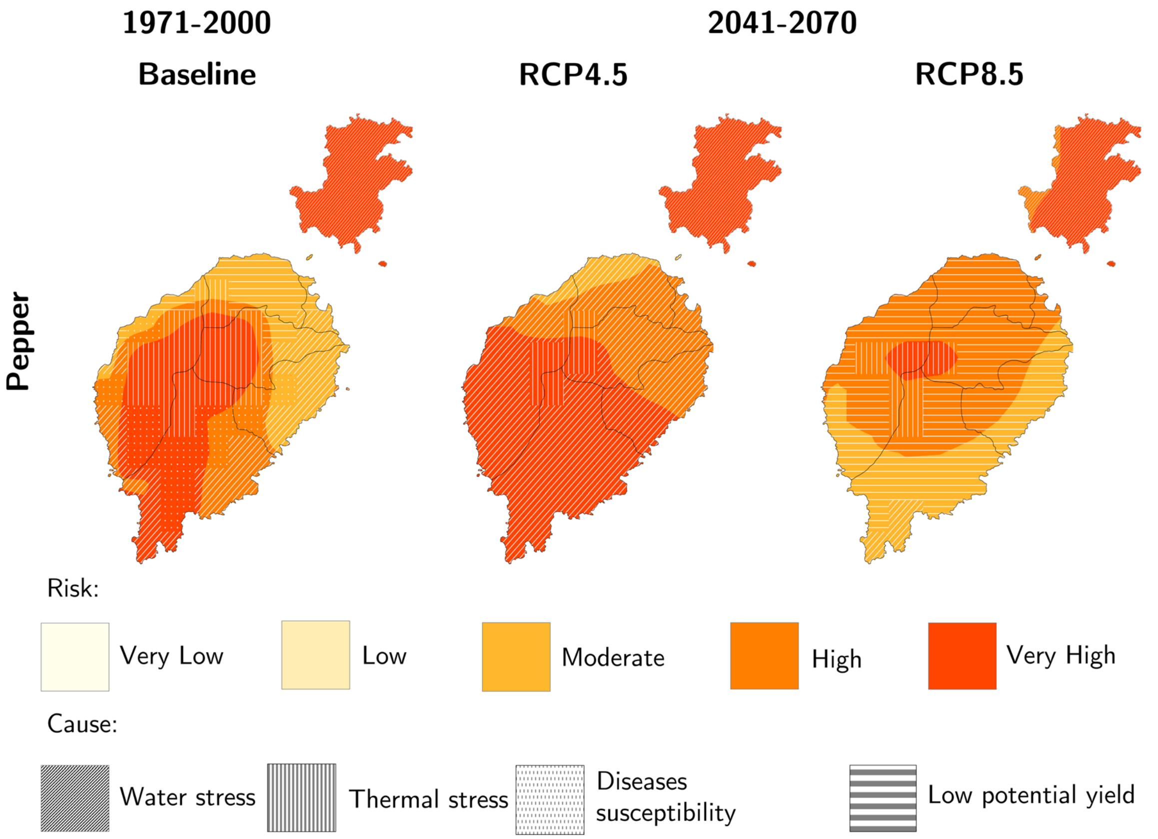

**Fig. 3** Pepper crop risk index (CRI) and the main causes of crop production risks in the baseline period (1971–2000) and future projections (RCP4.5 and RCP8.5, 2041–2070)

In the baseline period, in the border of the districts of *Lembá*, *Caué*, *Mé-Zóchi*, and *Lobata*, the high risk occurs due to thermal stress, where the temperatures are usually lower than 23 °C. Pepper seed germination is strongly affected by temperature. The optimum germination temperature is between 30 and 35 °C. Seeds do not germinate when the temperature is above 40 °C or below 20 °C. In addition, the temperature may also affect the initial water intake by seeds (Li et al. 2010). There are areas of very-high risk due to the occurrence of the Cercospora spot disease in the districts of *Lembá* and *Caué*. In the coastal regions, and the southern part of the Sao Tome island, there are areas of high and very-high risks for pepper production due to water stress. In the northern part of the Sao Tome Island, mainly in the district of *Lobata*, there are areas of moderate to low risk for pepper crop yield due to a shortage of soil water.

The future projections under RCP4.5 scenario indicate areas of high and very-high risks in the entire Sao Tome island; the very-high risk areas are found in the central-south part of the Sao Tome. The risks of producing pepper are mainly due to water stress. Nevertheless, in the mountainous region of the island (the border of the districts of *Lembá*, *Caué*, and *Mé-Zóchi*), the strongest stress occurs due to thermal stress caused by low temperatures. The pepper crop risk is higher in the RCP4.5 scenario than in the RCP8.5. However, the risk in the RCP8.5 scenario will be very-high in the mountainous region of Sao Tome due to thermal stress. There is also high-risk indication in the north-central part of the island due to the low crop yield. Moderate risk occurs in the southern region of the island. In the southern part of the *Caué* district, there is moderate risk due to water stress.

In Principe Island, in the baseline period, the risk of pepper production is very-high due to the water stress caused by the excess of precipitation on the island. Under the RCP4.5 and RCP8.5 scenarios, the risk remains mostly unchanged, although under the RCP8.5 scenario, a small part of the western coast region, risk reduces from very-high to high risk.

The total annual precipitation and its distribution along the year play essential roles in the pepper production, as heavy rains during the pepper flowering stage may reduce the rate of pollination and limits flowering (Kandiannan et al. 2014). Pepper crop growth is affected by excessive heat and dryness. The projections indicate an increase in the number of consecutive dry days under the RCP4.5 scenario and even more substantial increase under the RCP8.5 scenario (Chou et al. 2020). The rainfall is heavier in the RCP4.5 than in the RCP8.5 scenario in the central and southern parts of Sao Tome and in the entire island of Principe what makes these areas the most vulnerable in the future.

## Taro crop risk index

In the baseline period, the taro CRI indicates that the crop production is at very-high risk in the mountainous and most of the coastal zone areas of Sao Tome Island (Fig. 4). In the mountainous areas, the very-high risk is due to temperature occurrence below 21 °C, and in the coastal areas, the very-high risk is due to the susceptibility to the leaf blight of taro disease. On the other hand, in most parts of the Sao Tome island, the risk is classified as low or very-low. In the Principe island, the risk for taro production ranges from very-low to moderate risk in the entire island. The risk is due to the susceptibility to leaf blight of taro disease. At some locations along the coast, the risk may be classified as high risk for taro production.

The risks related to taro production are mainly due to leaf blight disease of taro and thermal stress. Epidemics of leaf blight may occur throughout the year during rainy, overcast weather when nighttime temperatures range between 20 and 22 °C and daytime temperatures range between 25 and 28 °C (Trujillo 1965; Trujillo and Aragaki 1964; Ooka 1990).

The projections under RCP4.5 and RCP8.5 scenarios indicate an increase in the risk of the taro crop in Sao Tome and Principe. The risk increases more strongly in Sao Tome Island under the RCP8.5 scenario. In the extreme south of the island and in some locations along the coast, the risk is projected to be a high or very-high risk due to the occurrence of temperatures above 27 °C. The risk due to the susceptibility to the leaf blight disease in taro crop will vary from moderate to very-high in most parts of the Sao Tome island, especially on the eastern coast. In the Principe island and in both RCP scenarios, projections indicate high risk due to susceptibility to the leaf blight disease in the southern parts of the island.

Studies on taro production indicate the vulnerability of taro crop to drought by showing a substantial reduction on the yield, on the number of leaves and leaf area, and on the height of the crop, which result in decreasing response to water stress (Sivan 1995; Sahoo et al. 2006; Mabhaudhi et al. 2013). Although the major risk in STP is not related to water stress, attention should be taken as the high-resolution projections in the RCP8.5 scenario indicate a sharp decrease of monthly and annual precipitation in future climate (Chou et al. 2020). According to Ganança et al. (2015), under the ongoing climatic changes, it is estimated that the taro production will decrease in the next 30 years because of drought constraints.

## Maize crop risk index

In the baseline period and considering the first growing season of maize in Sao Tome and Principe, the simulated maize CRI

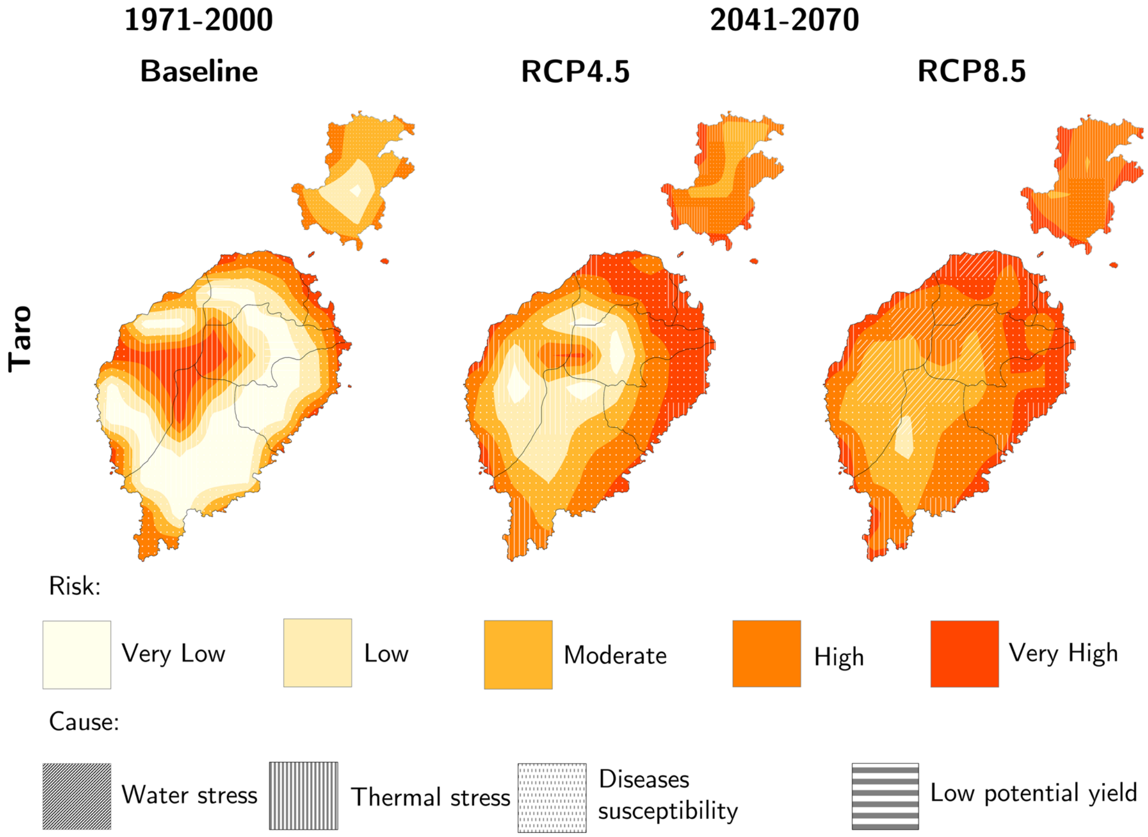

**Fig. 4** Taro crop risk index (CRI) and the main causes of crop production risks in the baseline period (1971–2000) and future projections (RCP4.5 and RCP8.5, 2041–2070)

for the preference period varies from moderate to very-high risk (Fig. 5). The high risk occurs mostly in the central and elevated areas due to the low temperatures. Considering the second growing season, the risk ranges from high to very-high. In the Principe island, in the first growing season, the risk varies from moderate to high, and in the second season, the risk varies from high to very-high, mainly due to susceptibility to rust disease.

The projections for the period between 2041 and 2070, under the RCP4.5 scenario, show a reduction of areas classified as high risk this is due to the temperature increase in central areas of Sao Tome in both growing seasons. In the boundaries between the districts of *Caué* and *Lembá*, the susceptibility to rust leaf becomes the major cause of the high risk. In the coastal areas of Sao Tome, the risk ranges from moderate to high risk due to low crop yield caused by a

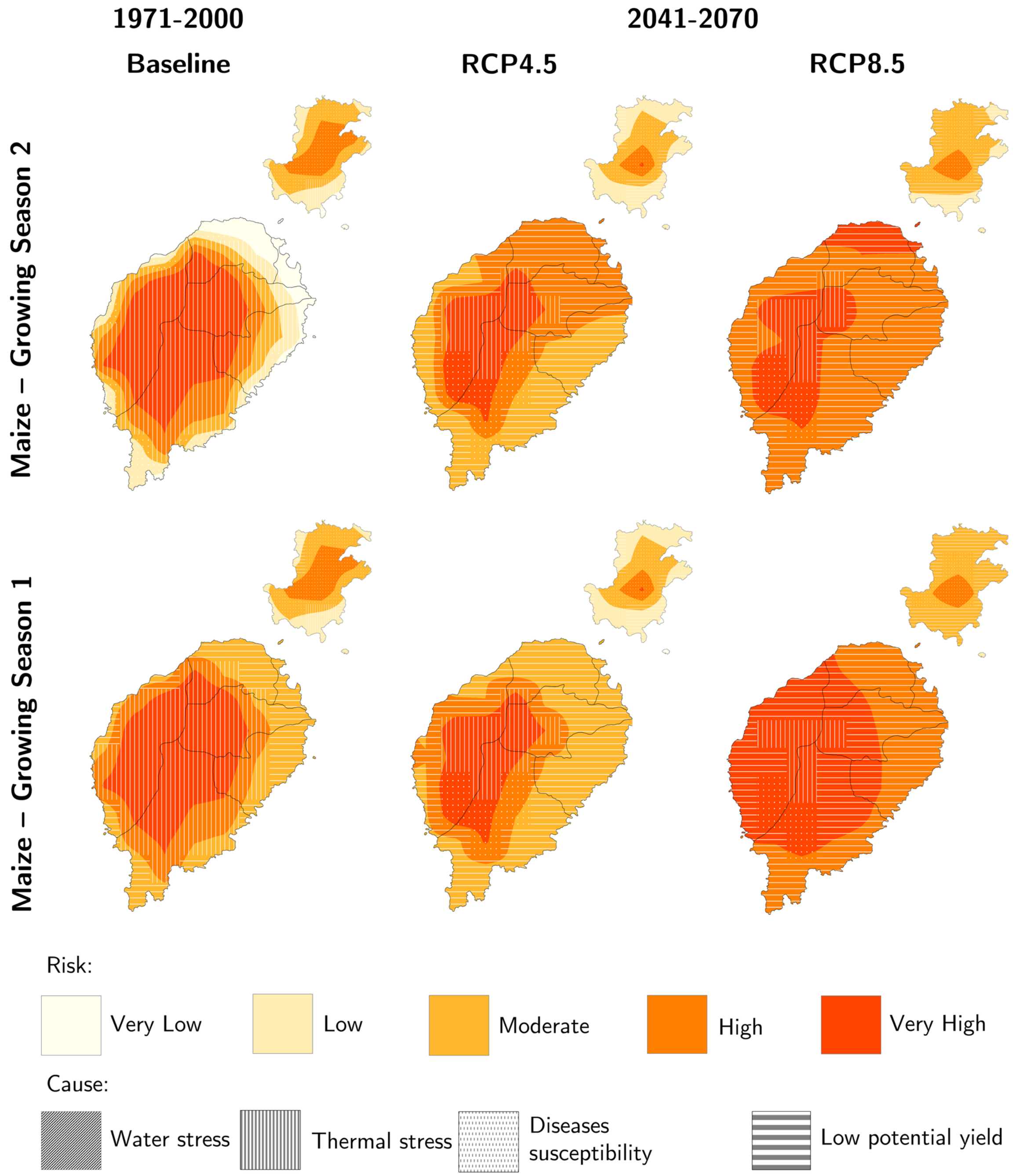

**Fig. 5** Maize crop risk index (CRI) and the main causes of crop production risks according to historical simulation (1971–2000, first column) and future projections (RCP4.5 and RCP8.5, 2041–2070). The analysis was divided into growing season 1 (first line) and growing season 2 (second line)

shortage of soil water. In Principe Island, projections show a reduction of areas of high and moderate risks, which resulted from the reduction of areas susceptible to rust disease.

In the future, under the RCP8.5 scenario, projections indicate the reduction of the areas classified as high and very-high risk due to low crop yield, including the coastal areas that in the baseline were already considered as low risk (in the 2nd season) and moderate risk (in the 1st season). In the Principe island, under the RCP8.5 scenario, projections show an increase in the areas of moderate risk in the entire island. The central area maintains the high risk mainly due to the susceptibility to rust leaf disease and low potential yield.

The rust leaf in maize occurs when the temperature varies between 23 and 28 °C, and the relative humidity is above 95%. While in the baseline, in Principe, the average temperature varies from 22 to 26 °C, in the future, temperatures are expected to increase up to 3.5 °C (Chou et al. 2020).

Although the risk due to the low temperatures in the central and elevated parts of Sao Tome tends to decrease in the future, the areas with risk due to low crop yield should significantly increase. While under the RCP4.5 scenario, precipitation is expected to increase in March and April, which favors the first growing season. In the 2nd season, projections of no changes or a small increase in precipitation are expected. The increase in temperature contributes to increase the evapotranspiration and to increase the shortage of soil water. Under the RCP8.5 scenario, the risk becomes worse due to a strong reduction in precipitation during both seasons and an increase of up to 4 °C in air temperature.

Studies have shown that besides the impact of precipitation limiting the shortage of soil water, the impact of increased temperature can lead to the reduction of crop cycle length, and consequently lead to the reduction of final yield (Ojeda-Bustamante et al. 2011; Prasad et al. 2018; Martins et al. 2019).

The projections shown in the previous section raise the issue of how to improve crop production in a changing climate. In this context, further researches need to be developed to suggest better management and adaptation measures in STP, such as control soil erosion, natural pest and disease spread (Rainforest Alliance, 2019), avoid deforestation and forest degradation (Ameyaw et al. 2018), and prioritize a conservative agriculture system, which can be more resilient to seasonal rainfall variability than conventional agriculture (Thierfelder et al. 2015). Vasconcelos (2017) listed water management practices that can be applied in São Tomé and Principe, to increase water retention and minimize the risk of flooding during torrential rainfall.

## Conclusions and final considerations

This study assessed areas in STP vulnerable to future climate change, with different levels of risk due to the main abiotic variables that cause damage to their agriculture production. The risk maps provided information to support decision-makers to design locally adequate adaptation measures and to bring simple actions that can be applied directly by farmers. Along with a simple but robust methodology, it was possible to map hotspot areas, which need urgent attention to create resilience and adaptation measures.

For each crop and each climate projection scenario, there are areas at greater risk. Regarding cocoa, the RCP8.5 scenario highlights the regions to the north of *Lembá*, west of *Lobata*, and *Mé-Zóchi*, of great importance for local production, which showed very-high risk mainly due to the water stress. Other regions of the island, where risk classification increased, also had water stress as the major cause.

In the future scenario RCP4.5, the risk of production of the pepper crop is very-high, mainly due to water stress. However, in the border of the districts *Lembá*, *Caué*, and *Mé-Zóchi*, the greater risk occurs due to the thermal stress caused by low temperatures. In the RCP8.5 scenario, the southernmost region of the *Caué* district indicates moderate risk due to water stress.

The projections indicate an increase in the risk of taro due to thermal stress (south of *Caué* district). The risk due to the susceptibility to the leaf blight disease of taro varies from moderate to very-high in most of the island of Sao Tome, especially on the eastern coast, where this risk is very high.

The border regions between the districts of *Caué* and *Lembá* are at high risk of production in the first maize growing season due to susceptibility to rust (scenario RCP4.5). For the RCP8.5 scenario, there is an increase of the areas with very-high risk due to the increase of thermal stress and susceptibility to rust. In the second growing season, it is highlighted that some coastal regions that had changed in the classification of the risk from very-low to high associated with the low productivity potential.

One of the major difficulties of this assessment was the lack of information on the historical productivity of each crop in each district for a robust validation and on the physical and hydraulic properties of soils, which is essential to estimate the availability of water in the soil.

According to Chou et al. (2020), the unique spatially detailed climate change projections in STP could only be provided due to the high-resolution runs employed, and additional runs would be recommended to account for model uncertainty. However, the authors added that this would be extremely computationally demanding. For this reason, a limitation of the present research is that a single global climate model was used to address climate risk.

Despite the limitations in the development of the work, the results shown here can be useful to support public policies of adaptation and sustainable development under the climate change, to reduce the impacts, and to increase the resilience in STP. Furthermore, the methodology developed in this research can be applied, with appropriate adjustments, to different regions and crops. The proposed methodology of construction crop risk index can be used to support the risk assessment in other regions, to increase the resilience to global climate change, and support planning of food security.

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