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Risky Business: Modeling the Future of Jamaica's Coffee Production in a Changing Climate

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Abstract: Jamaica produces one of the most expensive coffees on the global market. The local specialty coffee industry plays a significant role in the island's economy and also contributes to the livelihood of smallholders—the majority of whom operate the industry's coffee farms. While climate model projections suggest that Jamaica will continue to experience a warming and drying trend, no study has assessed the future impacts of changing climatic patterns on local coffee-growing areas. This research developed a number of geospatial processing models within the ArcMap software platform to model current coffee suitability and future crop suitability across three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5) and three future time periods (2021–2040, 2041–2060, and 2081–2100). The results validated current locations of coffee production and revealed that there was an observable decrease in coffee suitability across the island, across all SSP scenarios and time periods under study. Most growing regions were projected to experience declines in production suitability of at least 10%, with the most severe changes occurring in non-Blue Mountain regions under the SSP5-8.5 scenario. Implications of this projected suitability change range from decreased production volumes, increased price volatility, and disruption to market operations and livelihood incomes. The paper's findings offer stakeholders within Jamaica's coffee industry the opportunity to develop targeted adaptation planning initiatives, and point to the need for concrete decisions concerning future investment pathways for the industry. It also provides insight into other tropical coffee-growing regions around the world that are facing the challenges associated with climate change.

Keywords: coffee; climate change; Jamaica; Caribbean; suitability modelling; shared socioeconomic pathways

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1. Introduction

Territories within the Caribbean region are particularly vulnerable to climate change due to their small size, dependency on natural resources, and heightened exposure to extreme weather events. These features have been further compounded by deep-seated socioeconomic and political factors that limit their ability to respond to such changes. Regional climate models have acknowledged the increased frequency of storms, extreme temperatures, and drying trends in the Caribbean's climate that will likely continue throughout the century [1–4]. Changes to the region's climate have particularly impacted agriculture, where the sector's sensitivity to varying climatic parameters has led to decreased crop yields, lowered economic revenue, and increased vulnerability of livelihoods [5–9].

Globally, coffee-producing countries have had first-hand experience with these climatic changes, where even coffee-suitable land and average yields are expected to decrease by 2050 [10–12]. According to the ITC [13], "coffee growers are by far the most numerous group that is directly affected and the most vulnerable" to the impact of climate change. Extremes such as increased temperatures and variable rainfall have produced multiplier effects within coffee-producing landscapes, including decreased coffee yields and quality [14–16], a shift and/or decrease in optimal growing areas [17–19], the proliferation of pest and diseases in areas where they were not initially prevalent [20–22], as well as the increased cost of coffee production [23,24]. These changes have severely threatened the coffee industry and intensified the vulnerability of livelihoods [25,26].

The global coffee market has been dominated by the economical production and trade of the Arabica (*Coffea arabica*) and Robusta (*Coffea robusta*) species, where the former accounts for 57.4% of global coffee production in the 2019–2020 coffee year [27]. Arabica characteristically produces higher-quality beans with better taste profiles than Robusta [28,29]. The Arabica varietal has been recognized as more sensitive to changing climatic parameters, particularly during the blossoming and bearing stages of the plant's growth cycle, while Robusta is somewhat heat-tolerant as it can grow at higher temperature ranges without compromising its production capabilities [23,26,29–31]. Hence, *Coffea robusta* has been considered the most 'robust' to withstand the vagaries of climate change and has been suggested as an adaptation strategy to populate coffee-producing landscapes that are projected to become unsuitable for Arabica coffee [32,33]. However, changing climatic conditions feature not only rising temperatures, but also increased variation of other climatic parameters [18]. Hence, though Robusta coffee may generally respond better to increasing temperatures, this does not negate the loss of spatial area and yield of coffee and the migration of its production activities to higher altitudes. Furthermore, Kath et al. [34] noted previous studies may have overestimated Robusta's temperature range and its ability to maintain suitable production levels amidst increased temperatures under climate change. There have been several suitability modeling efforts for coffee worldwide. Locations include Central America, e.g., [35–37], east-central Africa, e.g., [38–40], and Asia [41,42]. Efforts within the Caribbean have been limited.

Since the 1950s, the Caribbean region has observed increased temperatures (along with evidence of more very hot days and very hot nights), increased seasonal and inter-annual variability in rainfall (with small but statistically significant increases in the maximum number of consecutive dry days) and a noticeable increase in the frequency and intensity of extreme weather events such as droughts and hurricanes [4,43,44]. Studies on medium to long-term climate projections for the region indicate these trends continuing toward the end of the century [1,2,4,43–45].

Fain et al. [7] projected a significant loss of coffee suitability in top-producing areas of Puerto Rico. The decline in coffee quality and yield was attributed to temperatures exceeding optimal thresholds, drying conditions due to low levels of precipitation, as well as an increase in insects and diseases. Similarly, Eitzinger et al. [46] acknowledged a projected decline in yield and quality across the Haitian coffee-producing landscape, particularly in lower elevations, while coffee suitability may shift to higher altitudes with cooler conditions. Across the region, the unpredictable seasonal patterns associated with changing climatic conditions have also impacted the ability of farmers to employ traditional agronomic practices. Producers, especially smallholders, have been faced with higher financial costs associated with managing their coffee farms under a new climate regime, ultimately leading to a landscape that is not economically viable for coffee production [7,26,30,35,46,47].

However, despite such changes, a crop suitability model using future climate scenarios has not been used to assess the coffee-growing landscapes across Jamaica. The objective of this paper is to address this knowledge gap by modeling current and future suitability for coffee production on the island under three Shared Socioeconomic Pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) for the near, mid, and far future (2021–2040, 2041–2060, and 2081–2100). These models have the potential to support national-level planning decisions and policy for the island's coffee-producing landscape against progressive climate change as well as add to the current body of literature focused on climate change modeling for the global coffee sector. Like many tropical regions with significant agricultural export commodities, it is critical to have a quantified assessment of the negative impacts of climatic change on the future viability of said commodities. Paired with consideration of other environmental stresses and resource constraints, this paper provides an avenue for creating resilience-oriented pathways to survival.

2. Methodology—The Suitability Modeling Process

Although Jamaica produces less than 0.1% of the global coffee trade, it remains a notable player within the international specialty market as the producer of one of the best-tasting and most expensive coffees in the world—Blue Mountain coffee [48]. Coffee is generally grown in the mountainous central regions of Jamaica, highlighted in Figure 1.

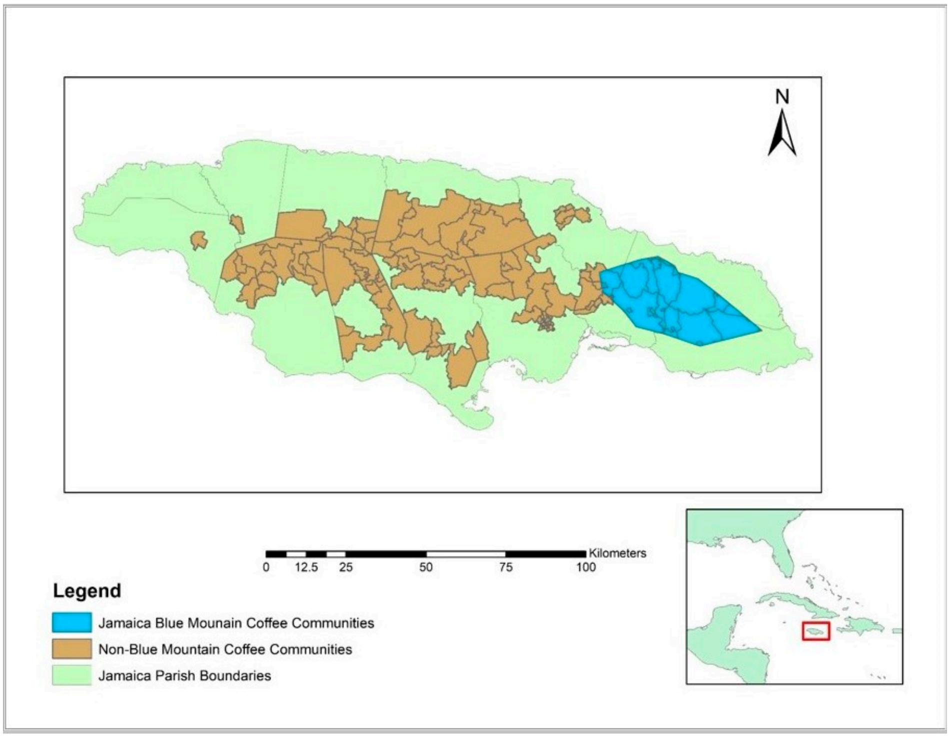

Figure 1. Illustration of coffee growing communities across Jamaica [Reprinted/adapted with permission from [49]. 2015, Mighty].

Jamaica has two distinct coffee-producing zones—the Blue Mountain zone and the non-Blue Mountain zone (High Mountain). Although historically demarcated as such, market demand for the higher elevation Blue Mountain coffee has led to the majority of the island's 6,018 coffee farmers registered (as of 2021) with the Jamaica Agricultural Commodities Regulatory Agency (JACRA) located in this zone. The Arabica varietal grown here can thrive and produces high-quality and flavourful beans. According to the Statistical Institute of Jamaica [50], coffee exports accounted for 83% of traditional agricultural exports in 2016 and earned USD23 million. However, the industry has experienced a 58% decline in export earnings since 2000. Key drivers of this decline include decreased technical support services, higher cost of farm inputs, and increased frequency of hydro-meteorological hazards (see [51–53]). These have contributed to a decline in coffee production, challenges managing pests and diseases, and the abandonment of coffee farms. Taken together, these issues have the potential to be exacerbated by changing climatic conditions.

Crop suitability models have been widely used throughout the literature as a tool for assessing the relationship between crop growth and the surrounding environmental conditions, e.g., [6,8,18,47,54], each operating under different assumptions, parameters, as well as uncertainties surrounding observed and simulated results. Though these prediction models possess some level of uncertainty, their utility provides an opportunity to illustrate the various ways in which changes in climatic variables could influence the suitability of various crops and thus guide policymakers in proactively formulating adaptive strategies for tackling these challenges.

GIS-based suitability models have been widely used in infrastructure planning, sustainable land management, resource allocation, and crop growth and production, e.g., [49,55–58]. Several approaches have been taken to modeling coffee suitability, including MaxEnt [8,42], CaNaSTA [25], CCSM4, and HadGEM2 [17]. Previous work by Mighty [49] utilized the AHP framework to model the ideal coffee-producing landscapes within Jamaica, empirically validating that the areas where coffee is currently growing across the island are indeed the best regions to produce the crop.

The widespread impacts of climate change, specifically the variability in temperature and precipitation, necessitate a reassessment of the nuanced demands of a future that is likely to be reconfigured by these changes. This research first presents the development of a current suitability model for coffee production on the island, then presents models of coffee suitability under future climatic conditions.

2.1. Modeling Current Climatic Suitability for Coffee

Via a combined review of the literature and the use of expert-based knowledge from the Food and Agriculture EcoCrop database, the major parameters which conditioned the suitable growth and production of Arabica coffee were identified as temperature, rainfall, geology, soil type, soil pH, elevation, humidity, wind, slope, and aspect [49,59–61]. However, due to the unavailability or inaccessibility of some datasets, the model focuses on seven agroecological parameters, as shown in Table S1 in the supplementary information. The optimum range represents the ideal conditions in which coffee production is best suited, while the absolute range represents the parameters beyond which growth and production of the crop are constrained.

All data were processed using the ESRI ArcGIS software suite version 10.8.1. The 30 m resolution Digital Elevation Model (DEM) of the island's terrain (obtained from the US Geological Survey's Earth Explorer portal) was used to derive the slope and aspect datasets. The elevation is particularly applicable as an independent suitability indicator/variable considering its relationship with temperature and its influence on the growth of the coffee plant, as well as on the fruit development and flavor profile of beans [25,62]. This dataset was also used to generate the slope and aspect variables used in the model. The soil data from the National Spatial Data Management Division in Jamaica contained information on both soil type and soil pH. Mean monthly temperature and rainfall datasets for weather stations across the island were acquired from the Meteorological Service of Jamaica with a date range of 1970–2020. This range allowed for the calculation of climate means for precipitation and temperatures and provided a homogenized dataset for future scenario modeling.

A five-point suitability scale system was used as it allowed the reader to easily process and differentiate spatial patterns and observations. Each dataset was reclassified as shown in Table 1 below, where 1 = lowest suitability and 5 = highest suitability.

Table 1. Agroecological parameters for ideal growth and production of Arabica coffee.

Agroecological Parameter	Very Unsuitable (1)	Unsuitable (2)	Moderately Suitable (3)	Suitable (4)	Very Suitable (5)
Temperature	<10 °C OR ≥34 °C	10–11.99 and 31.1–33.99 °C	12–13.99 and 28–30.99 °C	14–15.99 and 24–27.99 °C	16–23.99 °C
Precipitation	<62.5 mm OR >350 mm	62.5–80.54 OR 302.78–350 mm	80.55–98.60 OR 255.56–302.77 mm	98.61–116.66 OR 208.34–255.55 mm	116.67–208.33 mm
Soil Type	Clay, sand, peat, gravelly sandy clay, sandy soils, and other soil types	Silty clay, gravelly clay, stony clay, and mixed clay types	Sandy loam, silty clay loam, silt loam, and other loam soils	Fine sandy loam, clay loam, sandy loam, or clay loam (except for stony types)	Channery clay loam, volcanic loam, and loam
Soil pH	Strongly acidic, strongly alkaline, strongly to very strongly alkaline, and very strongly acidic	Acidic, alkaline, medium acidic, medium to strongly acidic, mildly to strongly alkaline, slightly acidic to mildly acidic, and slightly to medium acidic	Mildly alkaline, neutral, slightly alkaline	Slightly acidic	Neutral to slightly acidic, slightly acidic to neutral
Elevation	<0 and >1666.67 m	0–350 m	350–600 m	600–900 m	900–1666.67 m
Slope	>35°	24.8–35°	17.4–24.8°	10.9–17.4°	0–10.9°
Aspect	East	South-east	North-east, South-west	North-west	North, south, west

Mighty [49] provides a detailed rationale for the various parameters utilized in this model. However, a few points bear emphasis here. Arabica coffee thrives best in more temperate climates, where the annual average temperature is between 17 and 25 °C [63,64]. In tropical countries, these temperatures are obtained at higher elevations. With the mean monthly temperature from the dataset ranging from 22 to 28 °C, this means that suitability for this parameter would fall in the three highest categories. JACRA uses three elevation classifications to categorize its coffee region production profiles. Low-elevation coffee (350–600 m), mid-elevation coffee (600–900 m), and high-elevation coffee (900–1500 m). Additionally, the government of Jamaica has designated altitudes over 1666.67 m (5500 ft) as forest reserves, so no coffee cultivation should occur above these elevations. Therefore, the authors utilized these guidelines to guide the reclassification procedure for elevation. With the optimal precipitation range of 1400–2500 mm per year (116.67–208.33 mm/month), this range received a suitability value of 5. Suitability rankings of 2–4 consisted of dividing the remaining absolute ranges of 750–1400 and 2500–4200 mm/year into three equal parts and converting them to their monthly precipitation equivalents in the dataset. This was carried out as the authors found no real guidance from the literature on a gradual suitability change. Values beyond these ranges received a value of 1.

Soil reclassification was guided by the works of Wrigley [64] and Mickle [65], which stated that the best soils for coffee are deep, well-drained loamy soil, slightly acidic, and rich in humus and bases (especially potassium and phosphorous). Volcanic soils, latosols/podsols, and lateritic clays/loams were also good soils. Saline or marshy soil, hardpan (in heavy loam soils), gravel, and those near high water tables were the worst soils to grow coffee. Additionally, soil pH should be between slightly acidic (5.5–6 or 7) and moderately to well drained. Slope and aspect suitability was guided by information from JACRA which indicated that gently sloping landscapes (easier to farm) and non-east-facing slopes (sun exposure later in the day promotes slower maturing and higher-quality coffee berries) were the most ideal for coffee production.

Once the necessary data layers were obtained, they were imported and organized in a file geodatabase using ArcCatalog 10.8.1. In ArcMap 10.8.1, slope and aspect information were extracted from the DEM using the relevant tools in the Spatial Analyst toolset. From there, these three parameters were reclassified according to Table 1. Precipitation and temperature data in the form of a Microsoft Excel (Office 365, version 2304) file were converted into a comma-separated variable file and imported into ArcMap. After being transformed into point-based shapefiles, inverse distance weighting spatial interpolation was used to generate raster datasets for each data layer. A total of 97 stations for precipitation and 14 stations for temperature were used to calculate climatic means. A cell size of 0.00028 decimal degrees was used to approximate the 30 m spatial resolution of the DEM layer used to create the elevation, slope, and aspect layers. The vector-based soil pH and soil type were reclassified and then rasterized.

The reclassified layers were weighted using the Rank Sum (RS) method [66,67]. In the RS procedure, the weights are calculated by ranking each parameter (based on their importance to the growth and production of coffee), then normalized by dividing by the sum of the ranks (see Table 2 below for final weights). Initial rankings were informed by interviews with farmers and industry stakeholders as well as from the literature. The RS formula (Stillwell et al., 1981) is as follows:

$$W_i = \frac{n - r_i + 1}{\sum_{j=1}^{n} (n - r_j + 1)}$$

where W_i = weight of the criteria i; n = total number of criteria to be ranked; and r_i = rank position of the criterion to be weighted.

Table 2. Ranking of the relative importance of agroecological criteria and their assignment of normalized weighted scores.

AgroEcological Criteria	Importance Rank	Weight $n - r_i + 1$	Normalized Weight $\frac{n-r_i+1}{\sum_{j=1}^{n}(n-r_j+1)}$
Temperature	1	7	0.25
Precipitation	2	6	0.21
Soil Type	3	5	0.18
Soil pH	4	4	0.14
Elevation	5	3	0.11
Slope	6	2	0.07
Aspect	7	1	0.04
Total		28	1

Finally, the initial suitability model for the year 2020 was created using the Weighted Sum tool (see Figure S1 in the Supplementary Information).

2.2. Modeling Future Climatic Suitability for Coffee

After the creation of the 2020 suitability model, future coffee suitability models were created to examine the impacts of changes in precipitation and temperature over the next several decades. The projected changes in these variables were taken from Almazroui et al. [1], where the authors had modeled changes in precipitation and temperature for the United States, Central America, and the Caribbean for a near-, mid-, and long-term time span. Table 3 highlights the detailed parameters for modeling changes in temperature and precipitation. The values obtained were based on an analysis of 31 global climate models from Phase 6 of the Coupled Model Intercomparison Project, providing multi-model climate projections based on alternative scenarios of future emissions and land-use changes produced with integrated assessment models [1]. Our paper focused on modeling three of the five Tier 1 Shared Socioeconomic Pathway (SSP) scenarios at various radiative forcing levels by 2100. These included SP1-2.6 (sustainability scenario at 2.6 Wm^2- radiative forcing), SSP2-4.5 (middle of the road scenario at 4.5 Wm^2 radiative forcing), and SSP5-8.5 (fossil-fueled development scenario at 8.5 Wm^2 radiative forcing) (see https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change for a more complete introduction to the SSP scenarios [accessed on 5 April 2023]). These three scenarios correspond to roughly a best-case, middle, and worst-case projection of changes in global temperature and precipitation (see Table 3 below). Almazroui et al. [1] note that the averages calculated did not reflect spatial heterogeneity in the region, especially considering the influence of topography.

ArcGIS ModelBuilder was once again employed to create models that incorporated the changes in precipitation and temperature across the scenarios and time periods (see Figure S2), calculate differences in suitabilities between the suitability model for 2020 and the model for each scenario and time period (see Figure S3), and to calculate the changes in suitability values across the model rasters between the 2020 base model and each of the nine future suitability models (see Table 4 below and Figure S7 in the Supplementary Information). The model to run each future suitability model scenario held all aspects of the coffee suitability model process constant apart from the changes to precipitation and temperature means listed in Table 3 above. The resulting processes would then create a projected suitability model for the respective scenario period. The model to calculate the differences in suitabilities incorporated the use of iterators to optimize the calculation of the needed values.

Table 3. Parameters for modeling changes in temperature and precipitation. [Reprinted/adapted with permission from [1]. 2021, Almazroui et al.”].

Scenario	Temperature Increase (°C)	Precipitation Change	Notes
Base period	Describe average temperature values from 2020 model	Describe average precipitation values from 2020 model	Values here vary across Jamaica, reflecting the spatial heterogeneity of the island
SSP1-2.6	near (2021–2040): 0.69 mid (2041–2060): 0.94 far (2080–2099): 1.04	near (2021–2040): 0.34 mid (2041–2060): −0.64 far (2080–2099): −0.14	SSP1 Scenario: Sustainability
SSP2-4.5	near (2021–2040): 0.71 mid (2041–2060): 1.17 far (2080–2099): 1.94	near (2021–2040): 0.06 mid (2041–2060): −1.50 far (2080–2099):−3.34	SSP2 Scenario: Middle of the road
SSP5-8.5	near (2021–2040): 0.77 mid (2041–2060): 1.62 far (2080–2099): 3.53	near (2021–2040):−1.09 mid (2041–2060):−6.30 far (2080–2099):−19.73	SSP5 Scenario: Fossil-fueled development

3. Results

3.1. Current Coffee Suitability in Jamaica

Figure 2 presents the current (2020) suitability for coffee production on the island of Jamaica based on data collected for the year.

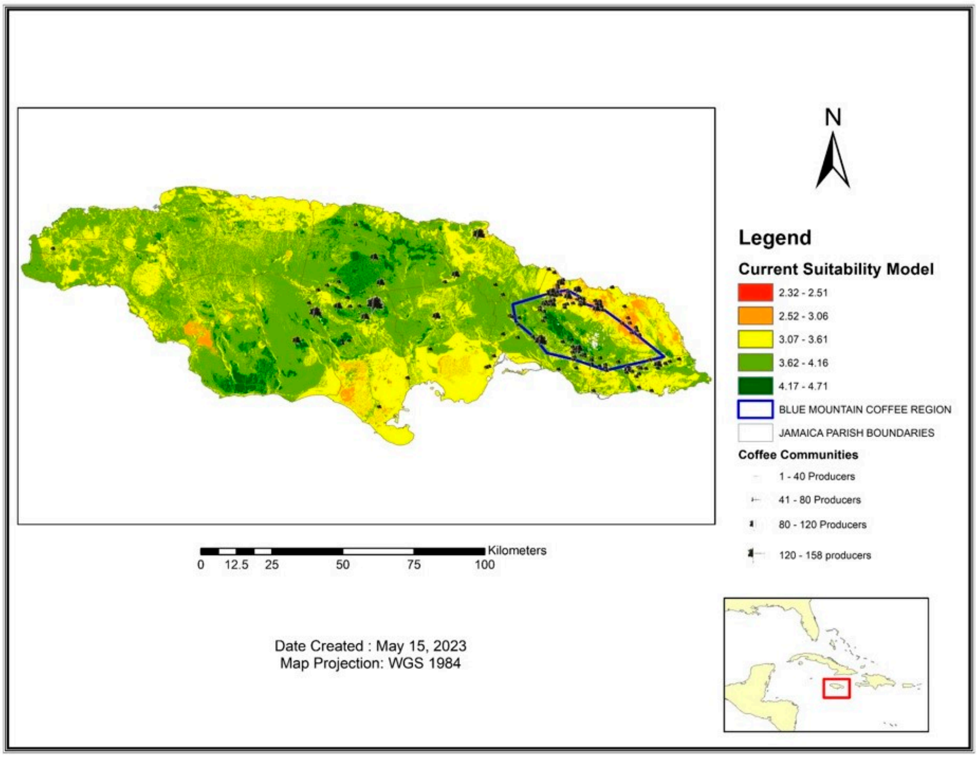

Figure 2. Suitability of coffee production for the year 2020.

For the sake of comparisons with all model results, five classes were used to depict the suitability of coffee across the time periods and scenarios. These classes spanned the absolute range of all the models and divided the suitability into quintiles: 1.96–2.51; 2.51–3.06; 3.06–3.61; 3.61–4.16; and 4.16–4.71. The 2020 suitability model had a minimum value of 2.32 and a maximum value of 4.71 on the 5-point suitability scale. It depicted the most suitable regions for coffee production to be the hilly central and eastern sections of the island as well as portions of the south-western plains. The figure also displays the general location and the number of producers registered with JACRA by community location—larger trees reflect greater numbers. According to a personal communication between the then Coffee Industry Board and one of the authors [49], some farmers provided addresses that were not necessarily in the communities they farmed in; hence the location of some producers in urban or other areas clearly unsuited for agricultural production. The locations of these producers align well with suitability ratings the majority of the time. The results also showed some similarity to the suitability map presented in Mighty [49], where hilly regions of the central and eastern sections of the island were found to favorably accommodate coffee production. Figure 2 also highlights the least suitable areas for coffee production along the coast as well as the north-eastern and south-central sections of the island. Unlike in the work of Mighty [49], this model did not exclude urban regions or protected lands (such as the forest reserves within the Blue Mountains and the Cockpit Country), as this allowed a wider representation of the suitable areas where coffee can be produced.

3.2. Future Coffee Suitability in Jamaica

Our models revealed that coffee suitability in Jamaica decreased under all projected climate change scenarios. This decrease was particularly pronounced in the non-Blue Mountain coffee-producing region. The values presented in Table 4 and the maps shown in Figures 3–5 highlight the results of the differences in suitabilities under each focal period due to the projected changes in precipitation and temperature on coffee suitability. For additional comparisons, Figures S4–S6 in the supplementary information portray a comparison between the suitability models generated for each scenario.

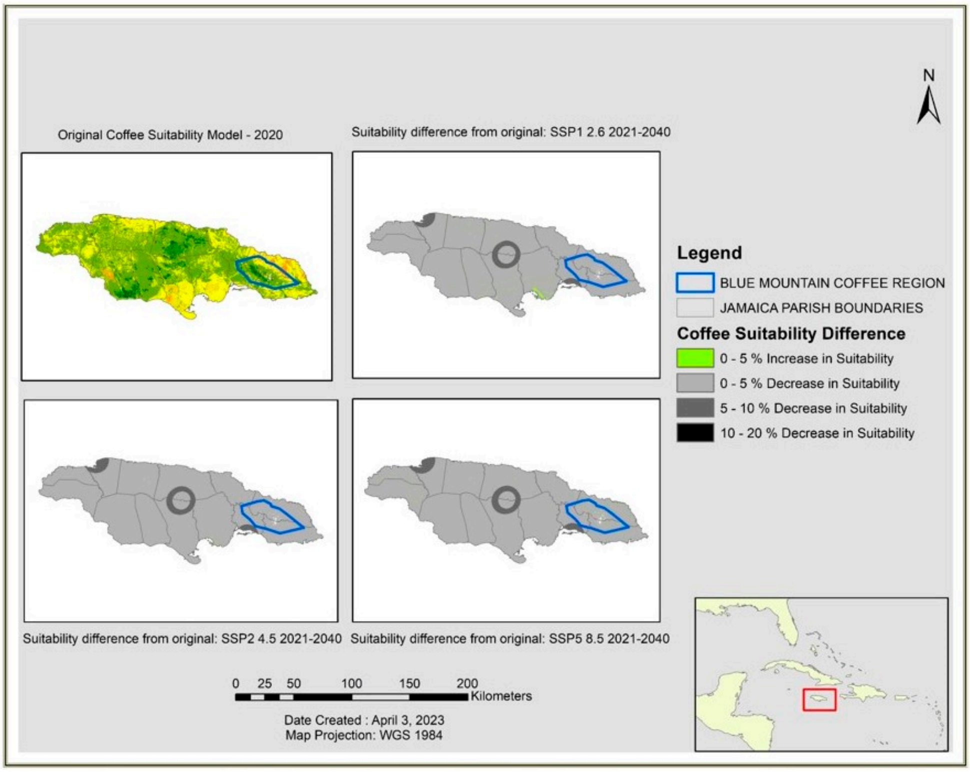

Figure 3. Differences in coffee suitability under each SSP scenario for the near future 2021–2040 period compared to the initial suitability model for 2020.

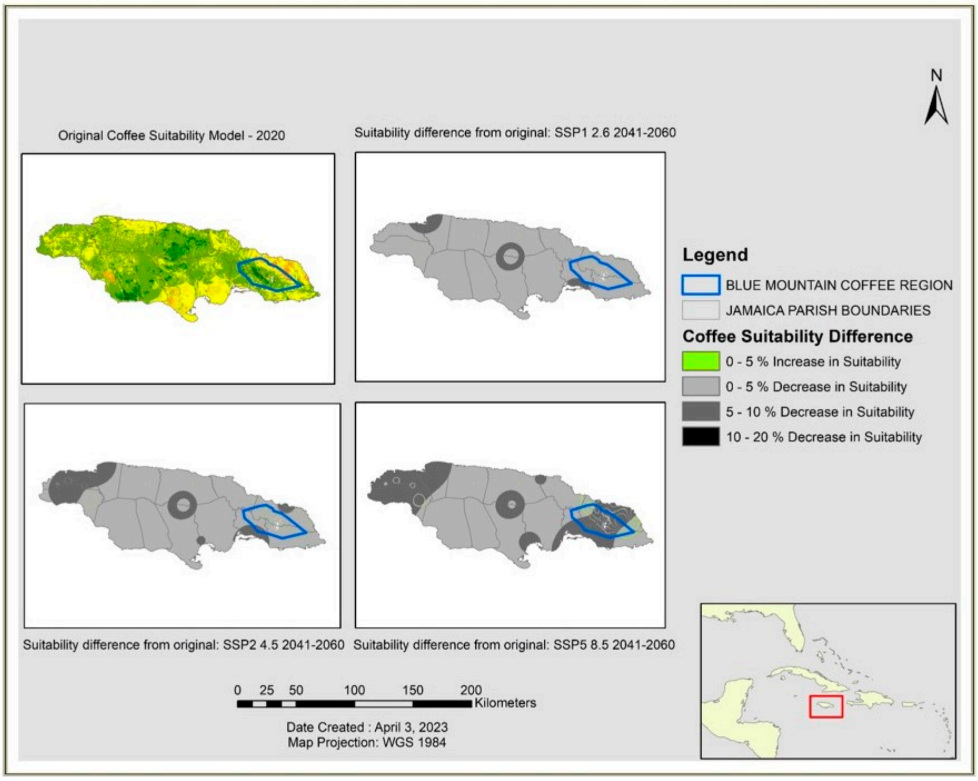

Figure 4. Differences in coffee suitability under each SSP scenario for the near future 2041–2060 period compared to the initial suitability model for 2020.

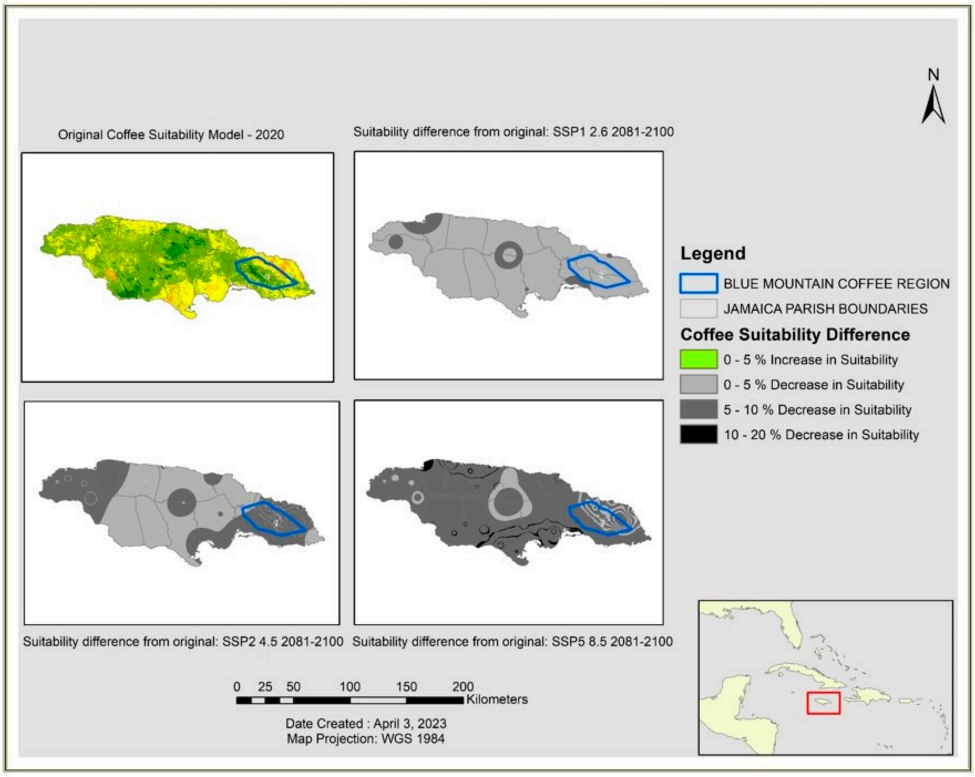

Figure 5. Differences in coffee suitability under each SSP scenario for the near future 2081–2100 period compared to the initial suitability model for 2020.

Table 4. Changes in coffee suitability for each scenario compared to the 2020 base model.

Model Scenario		Change from 2020 Model Base Value				
		No Change from Base Model	0–5% Increase in Suitability	0–5% Decrease in Suitability	5–10% Decrease in Suitability	10–20% Decrease in Suitability
2021–2040	SSP1 2.6	95.13%	0.58%	0.12%	4.16%	0%
	SSP2 4.5	95.5%	0.10%	0.02%	4.33%	0%
	SSP5 8.5	90.74%	0.04%	0.20%	9.02%	0%
2041–2060	SSP1 2.6	92.55%	0.20%	0.86%	6.39%	0%
	SSP2 4.5	81.63%	0.35%	1.99%	16.03%	0%
	SSP5 8.5	58.69%	0.54%	9.09%	31.68%	0%
2081–2100	SSP1 2.6	90.74%	0.04%	0.20%	9.02%	0%
	SSP2 4.5	50.64%	0.06%	4.12%	45.18%	0%
	SSP5 8.5	2.93%	0%	7.23%	86.74%	3.10%

In the 2021–2040 period, the majority of the island experienced no change in suitability for coffee production (see Table 4 above). Under the SSP1-2.6, a slight increase in the suitability of 0–5% above the original suitability values is projected across the central portions of the island, especially in south-central Jamaica. However, this increase is much less apparent in the SSP2-4.5 and SSP5-8.5 scenario models. This increase is likely fuelled by the increased precipitation projected for this time period (see Table 3 above). An even smaller proportion of the island is projected to experience a decrease of 0–5% below original values. A decrease in the suitability of 5–10% of original values is the most notable change across all model scenarios (see Table 4 above). As highlighted in Figure 3 above, this decrease was exhibited in the urban areas of north-western and south-eastern Jamaica (Montego Bay and Kingston metropolitan regions) as well as a notable ring in the Cockpit Country in central Jamaica. The latter region is the only one of concern as the others are not in coffee-producing regions.

In the 2041–2060 period, there is a significant decrease in the area that retains its original coffee suitability rating. SSP1-2.6 projects changes in almost 7.5% of the island, and almost 19% and 42% for the SSP2-4.5 and SSP5 8.5 scenarios, respectively (see Table 4).

The largest changes were calculated to be the 5–10% decrease in the suitability category, followed by the 0–5% decrease category. Spatially, these changes are projected to be across western Jamaica, as well as in the north-eastern and south-central portions of the island for the SSP2-4.5 (see Figure 4 above). The SSP5-8.5 scenario continued the spreading pattern of a 5–10% decrease in suitability in western, south-central, and eastern Jamaica. Sparse patches of increased suitability appeared in the more heavily forested regions of eastern Jamaica, accounting for less than 1% of the island. The expansion of decreasing coffee suitability carries significant implications for coffee-producing communities on the island, as discussed in subsequent sections of the paper.

For the 2081–2100 period, continued decreases in suitability are projected to intensify. Figure 5 displays the emergence of a greater area with a 5–10% decrease in suitability for the SSP1-2.6 scenario, especially in western Jamaica. The SSP2-4.5 scenario showed significant areas with a 5–10% decrease in suitability (from initial values) across the entirety of western Jamaica, a distinct portion of central Jamaica, and most of eastern and south-eastern Jamaica. The SSP5-8.5 scenario exhibited a stark change in suitability. Most of Jamaica is projected to experience a 5–10% decrease in suitability, with only isolated portions of the island escaping with only 0–5% declines. For the first time, areas experiencing 10–20% declines in suitability appeared in south-central Jamaica and the Montego Bay and Kingston metropolitan areas. These spatial patterns are supported by the values in Table 4 above, with SSP1 2.6 showing the most optimistic case of 90% of the island remaining unchanged from the 2020 model. However, the subsequent scenarios leave significantly less area unchanged as most of the island is projected to experience declines of 5–10% in coffee suitability in the most extreme SSP5 8.5 model. These projected changes again carry significant implications for the long-term production of coffee on the island.

4. Discussion: Assessing the Implications for Jamaica's Specialty Coffee Industry

The results presented are consistent with previous studies that showcased the decline in coffee-producing areas due to changes in climatic conditions, particularly temperature and precipitation [7,14,30,35,47]. There was an observable decrease in coffee suitability across Jamaica, across all SSP scenarios and time periods under study. This was particularly notable under the SSP5-8.5 scenario across all time periods. Suitability declines were particularly concentrated within the lower elevation areas of the non-Blue Mountain coffee-producing zone. In comparison to current conditions, this suggested that as climate parameters become untenable, suitable coffee lands will retreat to higher-elevation regions. This is substantial, as the region already operates within a comparatively higher temperature range than the Blue Mountain region. Projected increases in temperatures and/or decreases in rainfall are likely to have disastrous effects on coffee production in non-Blue Mountain areas, as plant health declines as temperatures approach 30 °C, causing yellowing of leaves and physiological abnormalities [29]. This will, in turn, impact the coffee farming livelihoods in these regions and the overall economic viability of the local coffee industry.

According to the CSGM [3], downscaled climate models across all scenarios projected increased temperatures and dry conditions extending from the mid-2030s into the 2050s and throughout the end of the century. Under the worst-case climate scenario, it is suggested that the island will experience temperature increases of up to 3.9 °C by the end of the century. They further acknowledge that the northern and central sections of the island will experience marginally higher levels of warming compared to other areas. In terms of changing precipitation patterns, the southern and eastern sections of the island will experience a greater decrease in precipitation than the northern and western areas from the 2030s. This pattern is likely to continue into the 2050s through to the end of the century, and a general decline in rainfall is expected. The CSGM [3] also acknowledged that although a slight increase in rainfall may occur during the dry season, this would not be enough to offset the general drying pattern. Hence, it is expected that the island will experience "longer and more intense droughts" [8]. These changes would severely affect coffee development (outlined in Table 5 below), especially key moments in the flowering, fruiting, and ripening periods of the plant's life cycle. The island is also projected to experience significant warming during the late wet season as well as during the dry season [68]. These trends potentially have important implications for plant physiology and, by extension, agronomic practices employed by smallholders. Activities such as new planting, fertilizing, and chemical application are dependent on reliable climatic and seasonal patterns for coffee production. Producers have begun to experience the adverse effects of these trends, such as burnt coffee berries, delays in bearing season, and an increase in pests and diseases, among others [69]. Based on the model results, these conditions are expected to worsen, thus further impacting coffee growth and livelihoods.

Considering these challenges, producers must rapidly implement a variety of adaptation strategies to ensure survival [70]. These range from improving shade management practices in the short and medium term to pursuing alternative livelihood activities such as animal husbandry and/or cultivation of other food crops more tolerant of warmer temperatures. Eitzinger et al. [8] modeled the suitability of some of Jamaica's important food crops under future climatic conditions and found that under warmer temperatures, there was minimal loss of suitability for crops such as bananas, yams, oranges, mangoes, and sweet potatoes. Similar results were also found in Rhiney et al. [6], where crops such as pigeon peas and sweet potatoes showed an increase in suitability under scenarios with warmer conditions. Since non-Blue Mountain coffee growing areas receive significantly less socioeconomic investment than those within the Blue Mountain areas [51], the authors anticipate this transition and/or diversification into food crops by local smallholder coffee farmers will occur more quickly than industry regulators anticipate.

Table 5. Crop calendar for Blue Mountain and non-Blue Mountain coffee-growing areas.

Season	Dry Season			Early Wet Season			Mid-Summer Drought		Late Wet Season			Dry Season				Early Wet Season		
Months	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Blue Mt.		**Pre-Flowering**				**Flowering**		**Fruit-Setting**				**Fruiting**				**Full maturity and rapid ripening**		
Season		Late Wet Season			Dry Season				Early Wet Season			Mid-Summer Drought		Late Wet Season			Dry Season	
Months	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J
Non-Blue Mt.		**Pre-Flowering**				**Flowering**		**Fruit-Setting**				**Fruiting**				**Full maturity and rapid ripening**		

Although the model showcased a comparatively higher decline in the non-Blue Mountain coffee-producing zone across timescales and scenarios, coffee suitability within the Blue Mountain region was also impacted. Historically, the eastern section of the island characteristically receives the highest rainfall volumes [68,71], primarily due to its higher elevations and orientation to the trade winds. However, this region is projected to undergo more notable drying trends than the northern and western sections [3]. As the Blue Mountain coffee-producing zone hosts over 90% of the industry's registered coffee farmers, the changes in suitability would dramatically impact the quality and quantity of the coffee produced, and potentially reduce the number of smallholder farmers who can cultivate the crop.

There have already been reports of traditional coffee-growing areas shifting to higher altitudes. According to one advisory officer at a local coffee factory, "farmers have been going higher up into the mountains, what will happen in the future is that they will cut down the trees in the mountains and it will cause disasters such as landslides and floods" (personal communication, Mavis Bank Coffee Factory, Kingston, Jamaica 2015). Ovalle-Rivera et al. [47] and Läderach et al. [72] have also mentioned that higher altitudes are becoming increasingly suitable for coffee production. This shift of coffee-growing areas to higher elevations may mitigate some of the impacts associated with increased temperatures and declining rainfall. However, the steep terrain which characteristically defines the Blue Mountains and the presence of the UNESCO heritage site—the Blue and John Crow Mountains National Park—limit this option. Challenges may also arise among decision makers and stakeholders within the coffee industry and environmental institutions concerning whose framing of adaptation takes precedence under a new climate regime [70]. For example, according to one industry stakeholder, "what one acre of Blue Mountain coffee can do for this [Jamaican] economy, one acre of pine [trees] cannot do it" (personal communication, Wallenford Coffee Company Limited, Kingston, Jamaica 2015). Economically valuable spaces such as the Blue Mountain coffee-producing region may become particularly contested as climate conditions change.

These newer areas of suitability in established conservation sites or national nature reserves are likely to face claims from various stakeholders as they navigate a new climate regime to sustain their livelihoods and economic returns. However, this shift may eventually lead to unintended socio-ecological consequences such as increased pressure on land use and degradation of natural landscapes. Active discussions regarding these conservation sites must incorporate all voices to maintain sustainability for all parties and regions. It is also important to note that even though temperature and rainfall patterns may be suitable at these high altitudes, it is not guaranteed that the other agroecological factors would be as suitable, negatively impacting coffee production. Similar considerations for land-use conflicts in relation to shifts in coffee suitability, as well as the possibility of other agroecological parameters being unsuitable at higher elevations, were also reiterated by Lara-Estrada et al. [35].

Under future climatic conditions, farmers may be increasingly dependent on irrigation systems and greenhouse technology, as the water supply is key to maintaining coffee bean quality [73]. However, the costs associated with such systems are likely to exclude smallholder farmers, who are typically unable to bear the significant financial investments to establish such systems. Thus, the development of a holistic climate change adaptation (CCA) strategy plan (currently absent from the Jamaican coffee industry) is warranted. Such a plan should engage stakeholders at multiple points of the value chain, address underlying institutional barriers, and foster innovative adaptation technologies.

Plans for the coffee industry have focused on increasing production, exports, and expanding marketing reach. An action plan for the coffee industry was developed in 2009, which focused on maintaining coffee quality, increasing environmental practices, enhancing labor productivity, increasing production, as well as improving the wider social and physical coffee infrastructure [74]. Since then, CCA capacity-building initiatives at the local scale have been characteristically ad hoc. Interviews with stakeholders in 2015 suggested that Jamaica's coffee industry is ill prepared for the challenges associated with climate change. According to industry stakeholders:

> "We are in a fragile ecosystem up in the Blue Mountains so [we] see the effects of climate change on diseases, pests, the ease of movement in and out of the community, the fires we've been having; all of these are all climate-related. The roasters do not have a 'Plan B' in case things get worse since we exist to procure Blue Mountain coffee, so anything outside of that will be a different business altogether. So no, we do not have a 'Plan B'." (Manager, Blue Mountain Coffee Ventures, Kingston, Jamaica).

> "We should adapt and we need to advise the farmers. We should go out there to set examples and the government should also take a lead role." (Manager, Jamaica Coffee Corporation Limited, Kingston, Jamaica).

> "Not enough is done in terms of [managing the impacts of] climate change". (Manager, Jamaica Standard Products Company Limited, Kingston, Jamaica).

Moreover, even though climate change was highlighted as a threat in the SWOT Analysis that was documented in the recent Jamaica Agricultural Commodities Regulatory Authority (JACRA) 2022–2026 Corporate Plan, there was a stark absence of strategic objectives for climate change adaptation. This absence of targeted adaptation strategies at the regulatory level may reinforce the ad hoc implementation process of climate change-related projects that have shaped the coffee industry. However, the Corporate Plan does propose activities that may inevitably benefit producers operating under changing climatic conditions. These include conducting research to identify stronger varieties that meet the industry's required taste profile, improving support services such as the provision and delivery of clean planting materials, seedlings, and other inputs, increasing training events for farmers, as well as developing action plans for pest and disease management. Separately, JACRA has also recently collaborated with the Private Investment Enhanced Resilience project to develop a carbon footprint mapping tool and a capacity-building model. The purpose is to conduct a carbon mapping exercise of the Jamaican Blue Mountain coffee value chain, to build the capacity of stakeholders for estimating greenhouse gas emissions, as well as establish related knowledge management solutions. Collectively, this is projected to promote sustainable land-use practices, as well as strengthen the medium and long-term climate resilience (and investment) of coffee value chain operators in Jamaica.

Among the suite of adaptation strategies the literature has suggested for maintaining coffee production under future climatic conditions, several studies have advised expanding Robusta coffee varieties or their hybrids. These are admittedly of a lower value but have a higher tolerance for a broader range of temperatures [29]. However, this may have long-term implications on how Jamaican coffee is branded, particularly impacting its position within the global niche and gourmet specialty coffee market—a market that is defined by a coffee's unique taste and high quality [70]. The signature taste of Jamaica's Blue Mountain Arabica coffee has historically been highly valued across the world. Therefore, incorporating Robusta coffee varieties will impact the marketing capabilities of industry stakeholders, as such products do not occupy strong positions in the specialty market. Additionally, convincing farmers to simply switch to new coffee varieties on a wide scale may prove difficult, faced with lower prices to be paid for the lower quality product.

In essence, assessing future suitability in coffee production goes beyond analyzing the role of changing temperature conditions and rainfall patterns, and involves a holistic analysis of the complex interaction of biotic and abiotic factors [10,11]. Importantly, human and societal factors can strongly affect the suitability of coffee production on the island and for climate-resilient goals. For example, a government-led support program or restricted coffee supply could increase prices to the point where it remains viable to maintain production despite less favorable environmental conditions. However, it is more likely that the number of producers may decline to a level that would severely affect production outputs due to the rising price of inputs, general economic stagnation on the island, and other socioeconomic factors. Therefore, policies and plans which lessen the impact of changing climatic patterns remain vital. The models presented in this paper provide an opportunity for decision-makers to re-evaluate their maintenance of the status quo in tackling the challenges associated with climate change. A sharper focus by industry officials is required toward implementing action-oriented strategies and policy responses. The industry must engage in 'no-regret' measures that are both sustainable and beneficial.

The implications for Jamaica's coffee industry also offer insight into other specialty coffee-producing regions around the world. Though the impact of changing climatic conditions is contextual and site-specific, it is seen that climatic changes can worsen the latent socioeconomic vulnerabilities that often characterize developing nations, particularly small islands. The wide-scale implications may range from decreased production volumes, increased price volatility, and disruption to market operations and livelihood incomes. The models presented offer stakeholders within Jamaica's coffee industry the opportunity to integrate these findings into targeted adaptation planning initiatives based on the spatial and temporal patterns of suitability declines and guide the decision-making process concerning future investment pathways.

Despite the relevance to current climate trajectories, the models presented are not without limitations. The local meteorological datasets that were utilized had occasional missing values for their monthly records, which in turn had a minor influence on the annual mean values for some years. A more notable issue was the spatial distribution of temperature stations across the island. Their locations (see Figure S8 in the supplementary information) did not cover the main Blue Mountain coffee region. While it is understandable that there is no station in the less accessible region, observed data from such a station would improve the model's ability to project changes in this region.

5. Conclusions

This research paper sought to determine the extent to which projected changes in precipitation and temperature would impact the suitability of coffee production across the island of Jamaica over the 21st century. Utilizing three SSP scenarios, and three time periods, it was determined that all areas of the island would experience declines in production suitability, with the most severe changes occurring in non-Blue Mountain regions under the SSP5-8.5 scenario. These areas are highly likely to experience loss, as coffee producers and production operate in both select mountainous regions of central Jamaica, as well as the Blue Mountain zone.

Smallholder coffee farmers have been the first to face the brunt of climate change impacts. As the quality and quantity of coffee produced are affected, there will be negative impacts on exporters and buyers on the international market, ultimately making Jamaican coffee less competitive on the global market. Thus, the local coffee industry needs to shift from fragmented approaches to holistic strategies which foster a cooperative (and likely state-supported) initiative to enable stakeholders to thrive into the 22nd century. These measures should include the incorporation of enhanced agronomic practices, such as soil and water conservation, making greater use of heat-tolerant varieties, improving access to affordable irrigation technology, improving the management of shade cover on farms and agroforestry, expanding industry-wide integrated pest and disease management practices, as well as improving social safety nets such as financing and crop insurance packages. Improving the management of the limited yet vital resources is also particularly important for the sustainability of the island's specialty coffee industry. Unless decisive action is taken, the authors foresee a precarious forecast for Jamaica's coffee industry over the next century.

Supplementary Materials: The following supporting information can be downloaded at https://unaedu-my.sharepoint.com/:b:/g/personal/mmighty_una_edu/EZwsloAcNSFJmURO6lImbpoBzrtyWR_xP4u_F6oMeKs58A?e=7gF4F0 (accessed on 5 April 2023).

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