*sustainability*

MDPI

*Article*

# Panorama of Coffee Cultivation in the Central Zone of Veracruz State, Mexico: Identification of Main Stressors and Challenges to Face

**Loarry Gabriel-Hernández [1] and Victor L. Barradas [2,*]**

[1] Posgrado en Ciencias de la Sostenibilidad e Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico; gabrielhloarry@gmail.com

[2] Laboratorio de Interacción Planta Atmósfera, Instituto de Ecología, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico

* Correspondence: vlbarradas@ecologia.unam.mx

**Abstract:** Coffee is one of the most traded crops worldwide. In the state of Veracruz, Mexico, coffee has been a strategic crop due to its economic, social, environmental, and cultural characteristics that differentiate it from other crops, contributing to the economy of almost 86,000 producers. Several studies have shown that climate is the main cause of the decrease in coffee production and yield. Due to the multi-faceted importance of coffee for the state, the relationship of coffee production and yield with the variables of precipitation (mm) and temperature (°C) from 2003 to 2022 was analyzed through the implementation of a mathematical model that was able to identify that both the total volume of coffee production is decreasing on average at a rate of 7614.9 Mg year$^{-1}$ as well as the yield, with a significant decrease of 0.106 Mg year$^{-1}$. It was also found that the optimum temperature value is 18.7 °C, and the optimal precipitation is 1700 mm for the development of coffee. This model also shows that yield is more sensitive to temperature than to precipitation in the study area. Through the application of surveys to 360 producers in 16 coffee-growing municipalities, seven stressors were identified that together hinder the continuity of the coffee industry in the state. These stressors are (1) economic, (2) climatic, (3) land use, (4) technical, (5) social, (6) political, and (7) other. Finally, some strategies are herein proposed to improve coffee production towards greater sustainability, such as agricultural restructuring at the national, regional, and local levels as well as programs and policies to support producers for the continuity of the crop in the region.

**Keywords:** coffee producers; coffee yield; temperature; precipitation; climate change



**Citation:** Gabriel-Hernández, L.; Barradas, V.L. Panorama of Coffee Cultivation in the Central Zone of Veracruz State, Mexico: Identification of Main Stressors and Challenges to Face. *Sustainability* **2024**, *16*, 802. https://doi.org/10.3390/su16020802

Academic Editors: Baojie He, Siliang Yang, K. Venkatachalam and Amos Darko

Received: 27 September 2023
Revised: 18 December 2023
Accepted: 28 December 2023
Published: 17 January 2024



## 1. Introduction

Coffee is a seed and a fruit [1] as well as a grain produced by a perennial plant [2] and an element that is part of coffee agroecosystems [3], which provide multiple benefits and environmental services [4]. This crop has been highly commercialized worldwide [5] with a high transaction in the main financial markets [6]. It is considered that there are about 125 species of coffee [5], of which the species Arabica (*Coffea arabica* L.) and Robusta (*Coffea canephora* R.) are the most commercialized, the first being the one with the highest demand (60%) due to its high cup quality but lesser resistance to climate changes and the presence of pests and diseases, and the second one with less demand (40%), lower cup quality, and greater resistance to climate changes and pests and diseases [7].

In Mexico, particularly in central Veracruz, 13 varieties are cultivated: Typica, Borbon, Caturra, Mundo Novo, Pluma Hidalgo, Maragogipe, Garnica, Catucaí and Catimor [8], and Catuai Yellow, Caturra Red, Colombia Brote Cafe, and Colombia Brote Verde [9]. Although the varieties of Arabica coffee share similarity, they have genetic and morphological differences that give a different quality to the coffee fruit [10]. Coffee has been a historical reference in the state of Veracruz since its introduction in 1802 [2,11], and its subsequent extension in municipalities such as Córdoba, Coatepec, Huatusco, and Ixhuatlan have been references on a national and international scale in the coffee market due to its high quality [12].

The cultivation of coffee has adapted to the climatic conditions of the ten regions that make up the state of Veracruz, which has enabled its production on a local and national scale [13], thereby achieving for the state the ranking of second place in national coffee production for five years [14].

Although coffee is grown in approximately 80 countries [15], in Latin America, there are 10 countries that grow it, including Mexico, whose economic importance is due to its contribution to the country's primary sector, a sector that corresponds to the productive and marketing chain of the Mexican economy. The coffee industry is considered essential in that it allows the integration of productive chains [16] by exporting 80% of green coffee and dedicating the remaining 20% to national consumption [13].

On an international scale, Mexico occupies twelfth place among coffee-producing countries, with exports mainly to the United States, Germany, Belgium, France, Canada, Italy, the United Kingdom, Cuba, Japan, Australia, and the Netherlands. These exports have allowed an increase in the gross domestic product (GDP) at the state level of 1.34% and 0.66% at the national level [17].

Coffee has adapted to the varied topography of the state and its diversity of climates since it is cultivated from 300 to 3000 m asl [18]. Therefore, today, its production exceeds 140,000 ha [19], whose area occupies almost the entire state with immersion throughout the entire state [11]. Veracruz has 10 regions within in its territory, each with different environmental, economic, social, and cultural characteristics [20]. Given that coffee is grown in each region, it contributes to the economy state, as coffee is an export product that results in economic income such as the generation of foreign currency [21], which is considered key to economic development and the agricultural production chain [22].

Another economic key is the generation of direct and indirect sources of employment for thousands of producers; therefore, its social importance is due to the number of involved actors and the income obtained, which according to [23] originate from coffee-related activities production, commercialization, and export as well as the surface available to produce coffee [24]. In Mexico, coffee is produced mainly by peasant and indigenous families [18] and by a significant part of rural communities [3,25] that belong to ethnic groups such as Totonac, Nahuatl, and Popoluca, with degrees of marginalization, backwardness, and poverty ranging from high to very high. It is considered that, in Veracruz, there are between 67,227 and 67,579 producers [26] and that about 92.7% are concentrated in the center of the region [20].

Environmentally, coffee farming provides multiple benefits, such as the conservation of biodiversity due to the biological richness of traditional shade-grown coffee plantations [18,27] and the diversity of environmental services. Of these services, those such as carbon sequestration [28], soil fertility, water uptake, regulation of the hydrological cycle, climate regulation, and pollination [3,4] and the related socioeconomic benefits stand out [29].

According to [18], the method of producing coffee determines the volume, yield, quality, and aroma. In Mexico, these cultivation systems are classified into sun and shade coffee, with rustic production, traditional polyculture, commercial polyculture, shade monoculture, and sun monoculture [30], of which the shade system is more friendly to the environment due to its contribution to plant conservation [3].

Shade-grown coffee and that produced in agroforests stands out as an integral part of the landscape, whose agroforests function as corridors between forests and forest fragments [31–33] and where the shade and the microclimate it produces favor coffee plants. These microclimates serve as a barrier to regulate the amount of light, temperature, wind speed, soil moisture, and the impact of rain [34].

According to [4], the function of coffee agroecosystems helps reduce the impact of climate variability in the central region of the state. Change has already been detected for 40 years, with important changes reflected in temperature increases and decreases of precipitation [35], which could modify the production, yield, and quality of coffee; in regard to this, coffee plantations are of great help to the ecosystem.

However, regardless of the cultivation system used, weather conditions continue to impact coffee, as it is sensitive to variations in precipitation and temperature that cause direct and indirect effects on the plant [36]. Weather also impacts its stages of development, namely growth, reproduction, and phenology, which is considered of great help in the agricultural sector, especially for agricultural planning [37] and therefore in reducing production costs for producers with scarce economic resources. For an adequate production and yield of coffee, optimal ranges of precipitation and temperature are necessary. Authors such as [38,39] have pointed out that the optimum temperature range for coffee is 17 °C to 23 °C, while some [40] have cited an optimal range from 18 °C to 21 °C. Regarding precipitation, a range from 1200 mm [40] to 2500 mm is required [41]. However, due to the changes in precipitation and temperature attributed to climate change, together with other stressors such as the presence of a crisis in coffee agriculture, the presence of pests and diseases, low coffee prices, and lack of technology, among others, producers maintain an uncertainty in the future of the coffee activity in the state. Nevertheless, despite the economic, social, cultural, and environmental value of coffee, the production area is being reduced, and in many cases, plantations are being replaced by other crops of apparent greater economic value. Some researchers have found that the reduction of coffee-growing areas is due to factors such as the change in land use; among of these are the construction of houses [4] and the low profitability of coffee and high production costs [42]. These changes in land use have been transforming the agroforestry systems of coffee under shade [43], generating another type of agricultural production with a direct displacement of coffee cultivation [44] while creating a complex pressure around coffee growing.

One of the barriers that the coffee industry in Mexico faces is competition both internationally and nationally. On an international level, countries in Latin America such as Brazil, Colombia, and Peru compete with Mexico. According to [45], this competition occurs based on who obtains more foreign exchange income from exports, so the necessary incentives are generated with the intention of attracting investments that help the placement of generated merchandise in the international markets.

At the national or internal level, the establishment of national companies with great financial capacity and transnational companies makes the direct sale of coffee between producers and consumers difficult since, according to [46,47], in recent years, the trade and sale of coffee tends to be concentrated in companies or transnationals. In the state of Veracruz, the presence of the exporter of Café California, S.A. de C.V, Agroindustrias Unidas de México (AMSA) (an intermediary of Nespresso and Nestlé), Cafés Tulipán, Starbucks, and Nestlé monopolize the production and trade of coffee, reducing trade opportunities for the rest of the producers.

Low coffee prices also represent a major obstacle and problem for producers. In the state of Veracruz, the price per kilogram of coffee is MXP 4.00–7.00 (USD 0.23–0.30) depending on the region and the municipality. This amount undoubtedly does not represent the hard work of coffee producers and certainly does not cover their main needs in areas of nutrition, education, health, etc. It has been seen that year after year, since 2020, the price of coffee has been falling, where those who win are the transnational companies and not the producers.

Among the contributions that this paper makes to literature are the following: (1) we were able to detect new precipitation and temperature ranges to obtain higher coffee yields in the central region of Veracruz state, which are very helpful for future studies focused on the phenology of coffee, which are scarce in Mexico; (2) through the identification of stressors, it was observed that the economic and climatic stressors continue to be the most important in the state's coffee industry; and (3) the proposed strategies derived from the current needs of coffee producers must be addressed by the key actors who develop public policies in Mexico.

Therefore, the research question that was posed is the following: Is climate change a direct stressor in the decrease in coffee production in the central region of Veracruz? The objective of this research was to determine the current state of coffee growing in the central region of the Veracruz state and the stressors that undermine this agricultural activity, particularly those attributed to climate change (change in precipitation and temperature variables) and their relationship with coffee production.

To do this, we intended to (1) collect documented information as well as information obtained through the application of surveys to farmers that would allow us to know the stressors that harm the coffee industry in the state; (2) apply a mathematical model including the effect of temperature and precipitation on coffee yield from 2003 to 2022; and (3) propose possible strategies to face climate change as well as recommendations leading to more sustainable production of this crop.

## 2. Materials and Methods

### *2.1. Study Site*

The study area was comprised of the zone that makes up the mountains regions (19°54′08″ N, 96°57′19″ W) [48], with an area of 6053 km$^2$ [49]; the capital region (19°11′25″ N, 96°09′12″ W), with an area of 5327 km$^2$; and the Nautla region (20°12′24″ N, 96°46′23″ W), whose surface is 3119 km$^2$ [50] (Figure 1). This area is in the eastern slope where the neovolcanic axis and Sierra Madre Occidental meet, between 1000 and 1350 m asl. The climate is temperate humid, with an average annual temperature of 18 °C and annual precipitation between 1000 and 1500 mm [51,52]. The dominant soil types are derived from volcanic rock [53], and mountain cloud forest is the dominant vegetation type.

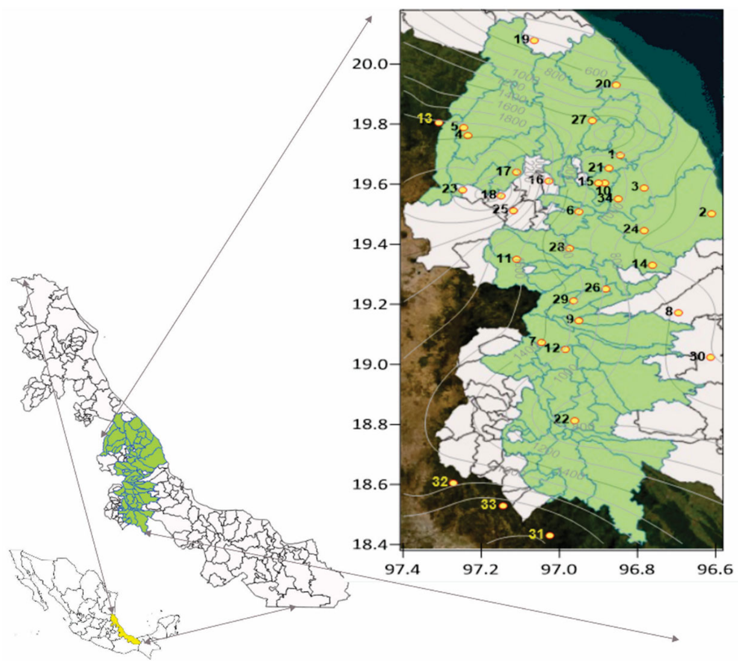


**Figure 1.** Location of coffee-producing municipalities (green zone), the distribution of the 34 weather stations (yellow dots), and rainfall distribution (isolines, mm) in the central region of the state of Veracruz. The yellow area corresponds to the state of Veracruz.

### *2.2. Data and Analysis*

Coffee production and yield data were accessed from the Mexican Consultation Agri-food Information System [54] from 2003 to 2020 (18 years) and the Mexican Food and Fisheries Information Service [55] from 2021 to 2022 (two years). A total of 20 years of coffee production and the yield of the coffee-growing municipalities of the central region of the state were analyzed, considering the mountains region (34 municipalities), the capital region (19 municipalities), and the Nautla region (10 municipalities), making up a total of 63 coffee municipalities. Likewise, the decrease in the areas dedicated to coffee cultivation during 2003–2022 was analyzed.

A database of the production and yield of coffee crop in the agricultural production of Veracruz state was constructed to compile the volume of the production and yield of coffee crop from 2003 to 2020 (18 years) as determined by the Agro-Food Information System of Consultation [54] and from 2021 to 2022 (two years) as determined by the Food and Fisheries Information Service [55]. A total of 20 years of coffee production and yield of the coffee-growing municipalities of the central region of the state were analyzed, making up a total of 63 coffee municipalities. Regarding the climatic variables of temperature and precipitation, 34 active and available weather stations from the National Meteorological Service of Mexico, which is located within the study area (Figure 1; Supplemental Table S1) between 89 and 3102 m asl, were selected.

### 2.2.1. Production and Yield Trend Analyses

Trend analyses on coffee production and yield were performed from 2003 to 2022 (20 years). Increasing or decreasing trends were determined using the Mann–Kendall test [56]. This approach consists of fitting the data series to a distribution function for the derivation of a test parameter ($x$); next, the value of a theoretical parameter ($y$) was determined on the basis of the associated function, after which the test and theoretical parameters were compared to establish the trend ($p < 0.05$), which was calculated with a simple linear regression ($y = ax + b$, where $a$ is the mean trend of the analyzed series). Trend analyses were performed for annual production and yield data.

### 2.2.2. The Envelope Function Analysis

The envelope function analysis weighs the relationship between coffee yield and climatic variables (Pp, T) in this case, although other variables, such as solar radiation and management, and cultural work, such as pruning, fertilization, weed and shade control, or other stressors can be included as soon as they can be accounted for. Through this analysis, graphs representing the optimal yield for the selected variable were constructed [35,57–59].

The effect of each variable on coffee yield was determined with simple models identified as envelope functions. These simple models consist of data selection from a probable upper bound represented by a cloud of points on each graph, constructed by plotting yield as a function of any driving variable (i.e., Pp, T). This analysis has three assumptions: (1) The envelope function denotes the maximum response of coffee yield to the chosen variable (e.g., T); (2) all points under the selected envelope function are due to the change caused by some other variable (e.g., Pp, etc.); and (3) non-synergism is assumed in the envelope limit [35,57–60]. The coffee yield relationship as a function of precipitation (Pp) and temperature (T) was assigned by the values of the envelope-limit function that fit the quadratic equations:

$$\mathrm{Yield}_{\mathrm{Pp}} = \mathrm{A} + \mathrm{BPp} + \mathrm{CPp}^2 \text{ and} \quad (1)$$

$$\mathrm{Yield}_{\mathrm{T}} = \mathrm{a} + \mathrm{bT} + \mathrm{cT}^2\text{, respectively,} \quad (2)$$

where A, B, C, a, b, and c are the envelope-limit function parameters that allow estimating the optimal precipitation ($\mathrm{Pp_O}$) and temperature ($\mathrm{T_O}$) at which the maximum yield ($\mathrm{Yield_{MAX}}$) is obtained and the extreme precipitations and temperatures (minimum and maximum) when yield is null. Additionally, from this equation (Yield vs. Pp, T), a pluvial ($\mathrm{Pp_I}$) and thermal range ($\mathrm{T_I}$) can be obtained (considering this range from the maximum yield to 30%), and the maximum precipitation ($\mathrm{Pp_{MAX}}$) and temperature ($\mathrm{T_{MAX}}$) before yield are diminished by around 50%; this value was used because this reduction is considered to characterize a probable vulnerability and stress that could threaten coffee yields.

Finally, to predict and analyze coffee yield at the present or in the future, a function composition model was used. In this case, a multiplicative model weighted by the effect of each environmental variable [57,61] was used:

$$\text{Yield}_{\text{MOD}} = \text{Yield}_{\text{MAX}}[\bar{Y}(\text{Pp})\bar{Y}(\text{T})], \tag{3}$$

where $\bar{Y}(\text{Pp})$ and $\bar{Y}(\text{T})$ are the envelope functions and are weighted by the effect of each climatic variable, taking a proportionality k from 0 to 1. The maximum value 1 matches with $\text{Yield}_{\text{MAX}}$. Theoretically, $\text{Yield}_{\text{MAX}}$ can be derived from any of the two variables included (Pp, T), and all response variables have the same weight.

### *2.3. Surveys*

The intentional and convenience non-probabilistic sampling method was used according to [62] due to the variety in the number of producers in each municipality surveyed and because it allowed us to select those accessible cases (producers) that agreed to be included.

Three types of questions were addressed: multiple choice, dichotomous, and open. The Likert scale was used for the multiple-choice questions, and they were systematized in a database. The nominal scale was used for the dichotomous questions, and the ratio or proportion scale was used for the open questions. All questions and answers were systematized in a database for analysis.

The surveys were performed according to [63] and were divided into four blocks, namely (1) general information of the producer, (2) production and yield, (3) perception of the presence of climate change, and (4) identifications of problems related to coffee, making up a total of 80 research questions. The first block consisted of determining gender, age, location of the farm, school level, and if they belonged to any social organization. The second block aimed to know what kind of farming system they used: sun or shade coffee, variety, cultural work, how many coffee bean harvests per year, how many kilograms of coffee per hectare, and yield. The third block was dedicated to inquiring the perception of climate change. The fourth block focused on identifying the problems surrounding coffee growing. A total of 360 surveys were completed from February to May 2023. Before the survey's application, the participants were invited and asked for permission to complete the survey. Then, they were informed of the objective and significance of the experiment, and though the survey was completely anonymous, they were assured that the data obtained would be used only for scientific aims. All the persons surveyed contributed voluntarily. The aim for approaching the producers of these municipalities was achieved thanks to the Regional Coffee Council of Coatepec, A.C., who provided the contact information.

### *2.4. Statistical Analysis*

Coffee production and yield data from 2003 to 2022 (20 years) were analyzed with the statistical package XLSTAT to establish whether trends decreased or increased. The Mann–Kendall test [56] was performed to analyze whether production and yield tendencies were significant. The objective of the Mann–Kendall test is to statistically evaluate whether there is a trend that increases or decreases in the variable of interest over time [64,65]. The software package Table Curve 2D 5.0 (SYSTAT, Inpixon, Palo Alto, CA, USA) was used to perform the envelope line analysis. This analysis considers just the upper points of the point-cloud, which are assumed to be the upper-limit function without restriction of any other environmental or cultural variables.

## 3. Results

### *3.1. Coffee Production and Yield*

Figure 2 shows the coffee production of the coffee municipalities that make up the center of the state of Veracruz, with a higher production in fourteen municipalities: Atzalan (6), Tenochtitlan (43), Zongolica (63), Jilotepec (25), Tequila (47), Misantla (32), Vega de Alatorre (57), Juchique de Ferrer (26), Naolinco (39), Mixtla de Altamirano (33), Los Reyes (28), Magdalena (29), Coscomatepec (14), and Colipa (11) ($F_{19,18} = 3.76$; $p < 0.05$).

The lowest production occurred in eight municipalities: Tonayán (55), Rafael Delgado (39), Tlilapan (53), Texhuacan (48), Miahutlan (31), Martinez de la Torre (30), Nautla (36), and Magdalena (29). The municipality with the highest coffee production was Tezonapa, with 35,000 Mg year$^{-1}$, while the municipality with the lowest production was Tonayan (907 Mg year$^{-1}$).

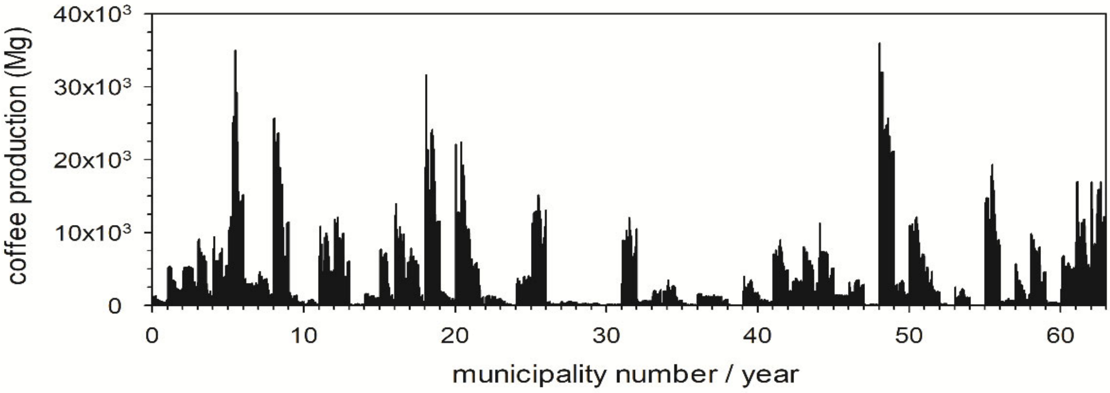


**Figure 2.** Coffee production of the 63 coffee-producing municipalities in alphabetical order. The first 20 years (municipality number 1) are from the municipality of Actopan and so on until the municipality of Zongolica (municipality number 63) (Supplemental Table S2) in the central zone of Veracruz state, from year 2003 to 2022.

Nevertheless, it was found that the volume of coffee production in general is decreasing on average at a rate of 7614.9 Mg year$^{-1}$ ($r^2 = 0.5501$; $p < 0.0004$; n = 20), mainly in the year 2015, and although in 2016 the production had a rebound until 2020, the production was not as high as before 2015 (Figure 3) (production = 7614.9 (year) + 342797; $r^2 = 0.5101$, $p < 0.0004$). As for yield, it has also a significant decline of 0.106 Mg year$^{-1}$ (yield = −0.1061 year + 2.8883; $r^2 = 0.5937$; $p < 0.05$; n = 20); however, this decline in the coffee yield in the region has decreased from year to year starting in 2003 with a high yield (3.00 Mg ha$^{-1}$) and leading to a medium yield (1.75 Mg ha$^{-1}$) towards the year 2022.

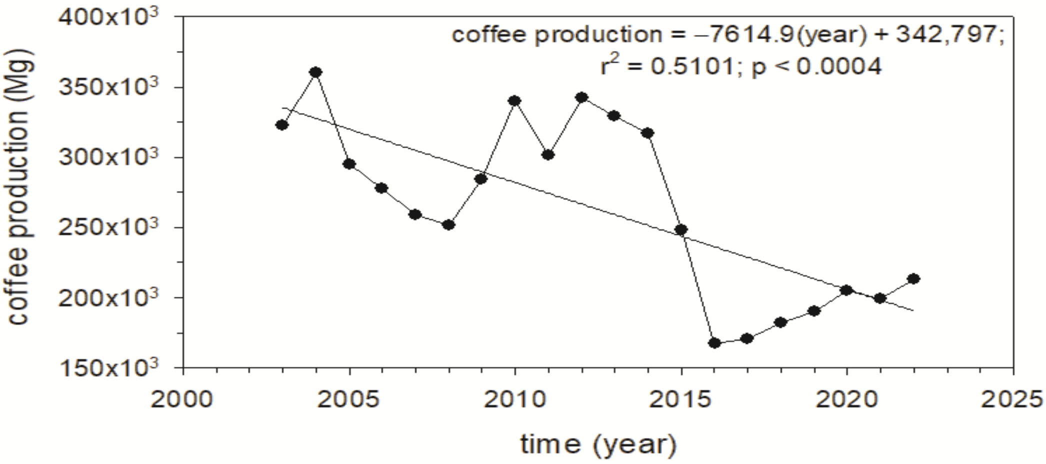


**Figure 3.** Decrease in coffee production in the central zone of the state of Veracruz. The continuous line represents the coffee production decreasing in the average of 20 years.

### 3.2. *Effect of Precipitation and Temperature on Coffee Yield*

The effect of precipitation and temperature on coffee production and yield is evident. This analysis makes it possible to determine with a good degree of precision the optimal values and intervals of greatest performance based on the relationships $Yield_{Pp} = 0.679 + 0.004Pp - 1.08 \times 10^{-6}Pp^2$ ($r^2 = 0.98$; $p < 0.01$) and $Yield_T = -12.803 + 1.821T - 0.049T^2$

($r^2$ = 0.95; $p < 0.01$) and with $Y_{MAX} = 1$: $\bar{Y}_{Pp} = 0.1654 + 0.0009Pp - 0.0000003Pp^2$ and $\bar{Y}_T = -3.0205 + 0.4296T - 0.0115T^2$. The optimum precipitation value is located about 1770 mm in an interval from 570 mm to 3040 mm, with the contingencies that if yield is 2.5 Mg ha$^{-1}$ and if the precipitation decreased towards 1000 mm, the yield would drop significantly and likewise if it increased above 3000 mm (Figure 4A). Yield was higher at temperatures between 17.0 and 21.0 °C, with an ideal or optimum temperature of 18.7 °C, and yield decreased by 50% with a highest temperature of 25.5 °C, and if the temperature dropped below 17.0 °C, the yield also decreased (Figure 4B). In a simple exercise where the temperature was increased by 5 °C from the optimum and the precipitation decreased by 700 mm, it was found using the model given in Equation (3) that the yield was 1.77 Mg ha$^{-1}$, which is equivalent to a loss of 58% of coffee yield. This model also shows that yield is more sensitive to temperature than to precipitation.

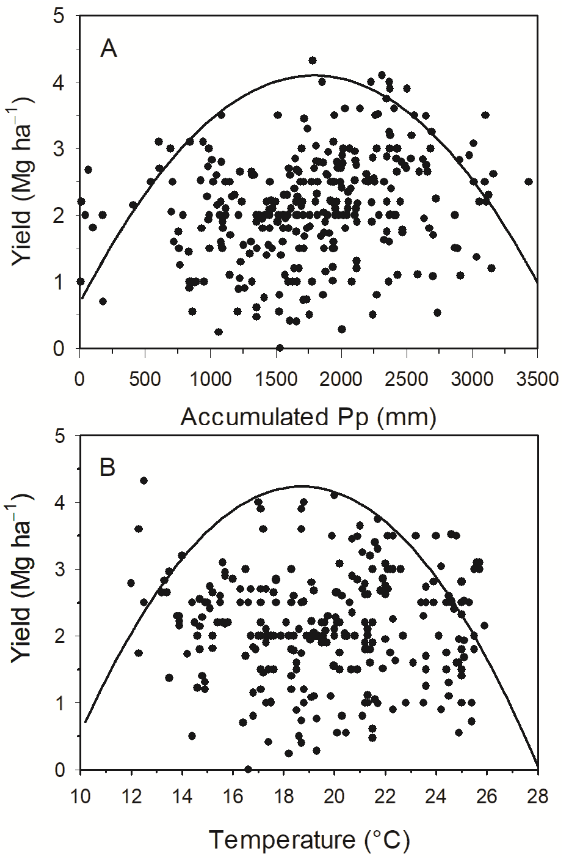


**Figure 4.** Scatter plots and the probable envelope function of coffee yield depending on precipitation (**A**) and temperature (**B**).

This is in agreement with the study by [66], in which temperature is the most important climatic variable in coffee production. However, it differs in the prediction that its model makes by estimating a decrease of 34% by 2020 [66] and 73% and 78% by 2050 [21]. The above may be due to the observed period of analysis of both precipitation and temperature in addition to the method used and the specific study site or region, which can vary in the optimal precipitation and temperature ranges for coffee cultivation.

### *3.3. General Information of the Surveyed Producers*

The age of the producers varied from 25 to 80 years, with a concentration of producers between 56 to 65 years old, as seen in Figure 5. Although age is not the only factor that determines agricultural production in a locality, it can represent a barrier when acquiring access to new agricultural technologies, credits, or loans. According to [67], there has been a notable increase in the number of elderly people in rural areas, so there is a risk that they will be considered invisible by their governments.

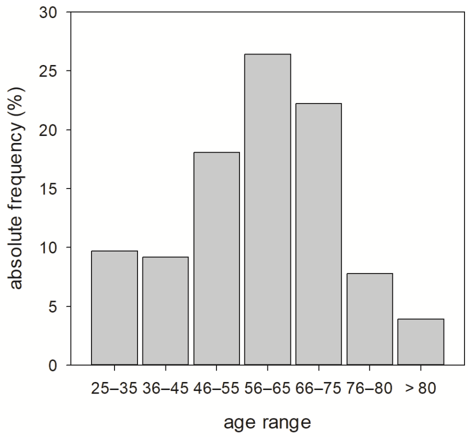


**Figure 5.** Percentage of farmers who responded to the surveys according to age.

Of the total respondents, 80% were men who carry out most of the cultural work or field work, which consists of cleaning the farm, planting, pruning, and fertilization, among others, while the remaining 20% were women who participate in some activities such as cutting coffee, separating beans and weighing coffee, and sometimes coffee sale.

The educational level of the producers also varied: 46.67% have primary school education, 22.22% have secondary school education, 13.06% have high school education, 11.67% have a bachelor's degree, 1.11% have a technical career, 1.67% have a postgraduate degree at the master's and doctorate level, and 3.89% do not have any of the aforementioned.

The surveys were carried out in 68 locations in 16 coffee-growing municipalities. Figure 6 shows a greater participation of producers from the municipalities of Emiliano Zapata (18.06%), followed by Coatepec (11.11%) and Teocelo (11.11%), It can also be seen that 59.72% of the respondents were distributed from the remaining 13 municipalities with percentages less than 10%.

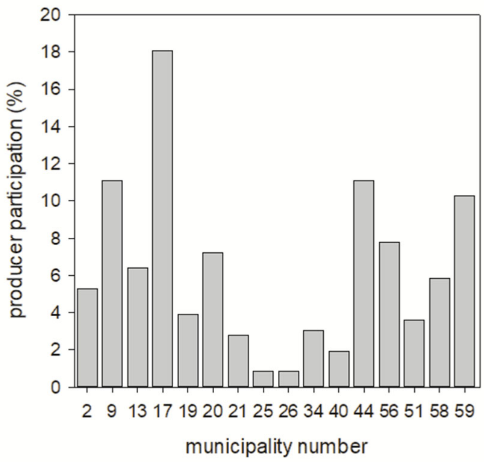


**Figure 6.** Municipalities where the surveys were carried out and percentage of participating respondents.

Of the producers surveyed, 58.89% stated that they belong to organizations or rural schools in their localities, while 41.11% are not associated with any organization. This non-associated group works independently in production and coffee harvest. In the case of producers who do not remain in any organization or rural schools, they have adapted to the existing market conditions in the region, which includes the sale of coffee under the rules stipulated by buyers or intermediaries. Many of them do not have any support, such as the Sembrando Vida Program, which is a program created to support coffee producers in their work.

### 3.4. Farmers Response on Coffee Production, Yield, and Climate Change

The existing coffee production systems in the study area include systems under sun (21.39%), under shade (56.4%), under diversified shade (45.56%), and an agroecological system (1.39%). In the study area, 18 varieties of the Arabica species were planted, with the Costa Rica variety being the one most planted by producers, followed by the Typica variety and the Geisha variety because these give a higher yield, followed by the rest of the varieties, as seen in Figure 7A. In relation to the varieties that show greater resistance to climate changes in the region, e.g., the decrease in precipitation and the increase in temperatures, producers reported that these varieties include the Costa Rica variety and the Geisha variety, as seen in Figure 7B.

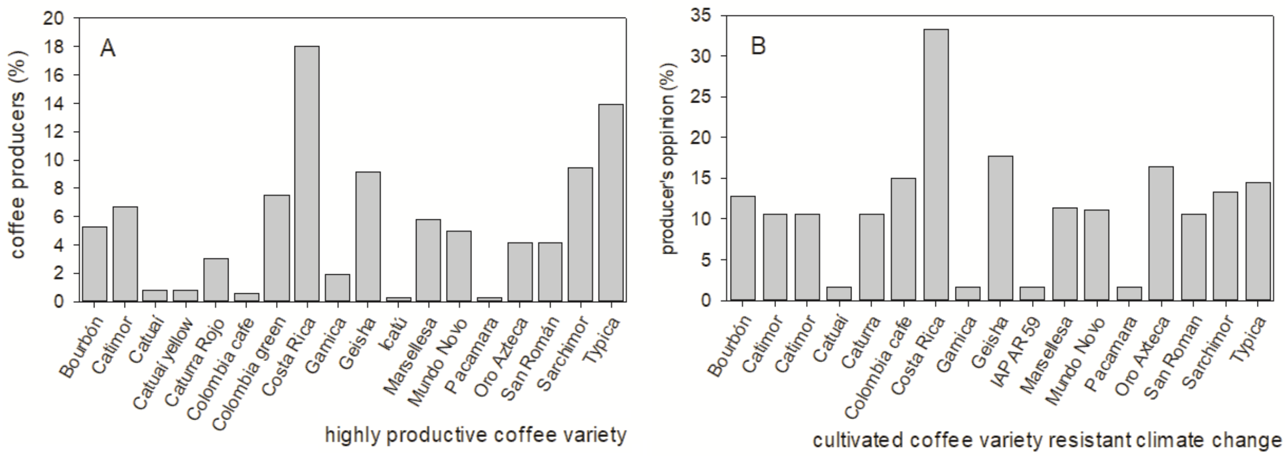


**Figure 7.** Coffee varieties that provide high yields (**A**) and varieties more resistant to climate change, according to farmers' opinions (**B**).

Cultural tasks or practices are essential to obtain greater agricultural production and high crop yields. In the case of coffee, the tasks broadly include the establishment of seedbeds and the management of plantations, which includes the establishment of coffee plantations, pruning and weeding of coffee, the use of shade, soil conservation, management of weeds, pest and disease control, and fertilization, among others. Derived from the interviews, it was found that producers engage in nine different activities, such as those described in Figure 8, according to their economic resources. It should be noted that, in the case of fertilization, it is only carried out once a year due to the high cost of its acquisition, but almost 100% of producers engage in this practice.

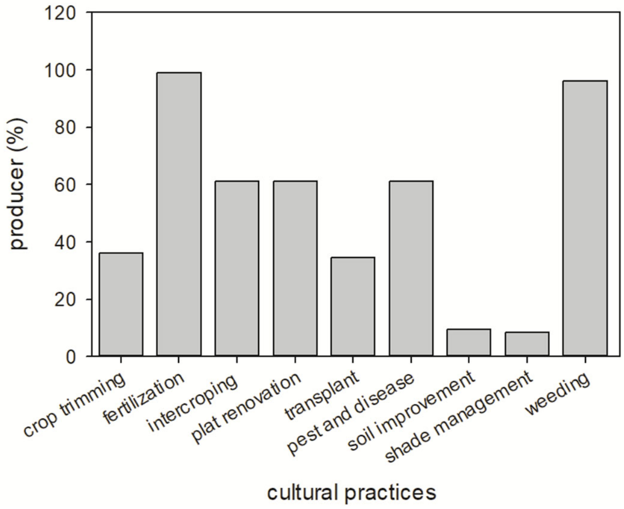


**Figure 8.** Cultural practices carried out by the producers in the different areas of coffee production.

Also, derived from the surveys, it was found regarding the distribution of the property of the coffee plantations that the majority of the respondents are small owners (94.7%); that is, they have a farm of less than 5 ha, and only 5.3% are medium-sized producers with plantations greater than 5 ha. It is worth mentioning that 46.9% of the producers only own 1 ha, which is far too high a percentage (Figure 9).

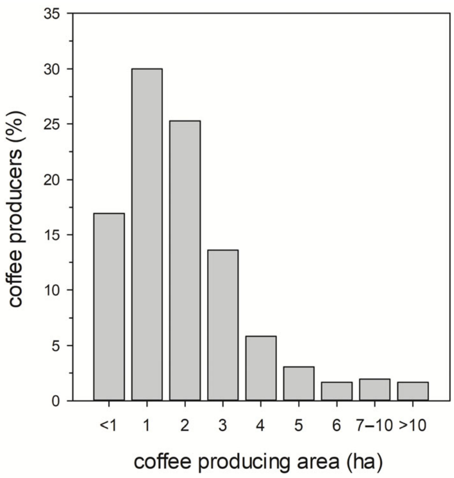


**Figure 9.** Coffee producers classification according to their own producing area.

The coffee yield can vary depending on the variety planted, the climate, the type of soil, the cultivation techniques, the surface available for planting coffee, and the cultural tasks used. It was found that 56.11% of producers obtained more than 1500 kg ha$^{-1}$, as shown in Figure 10. In general, it is known that in 1 ha, it is possible to obtain from 500 to 600 kg of coffee. Therefore, it is considered that coffee production has been maintained in the area. The yield of coffee is very important for producers, according to the interview carried out, due to the change in the rainy and hot season: 4.4% considered that their yield has been very low, 39.44% considered it low, 48.06% had an average performance, while 29% considered that their performance has been high.

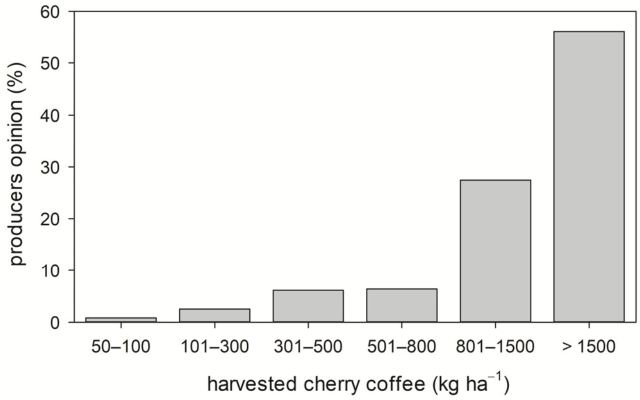


**Figure 10.** Coffee yield (kg ha$^{-1}$) in the surveyed areas according to producers' opinion.

### *3.5. Identification of the Physical-Climatic and Socio-Economic Problems through Surveys or the Identification of Main Stressors*

Derived from the review of the surveys carried out, seven stressors or factors were identified that are directly related to the production and yield of coffee. Figure 11 shows the results of the interviews with the 360 coffee producers, whose responses were divided into seven categories depending on each of the given problems: (1) the crisis of coffee agriculture due to low coffee prices, high input costs, insecurity of the coffee farms, and therefore low profitability; (2) changes in climatic variables; (3) presence of pests and diseases; and (4) the conversion of coffee cultivation in the study region. It should be mentioned that these first four stressors were given by more than 55% of the respondents, while the other three given included the following: (5) the shortage of labor due to migration and the advanced age of the producers in addition to the lack of an intergenerational link to continue growing coffee (lost tradition); (6) the lack of support from government authorities, such as insufficient support programs for producers and the monopolization of transnational companies (cited by about 22% of the producers); and (7) the lack of interest of the same producers and the lack of culture of coffee consumption at the national level (given by about 5% of the producers). However, although these last three stressors comprise less than 30% of the opinions, they are still important in this analysis.

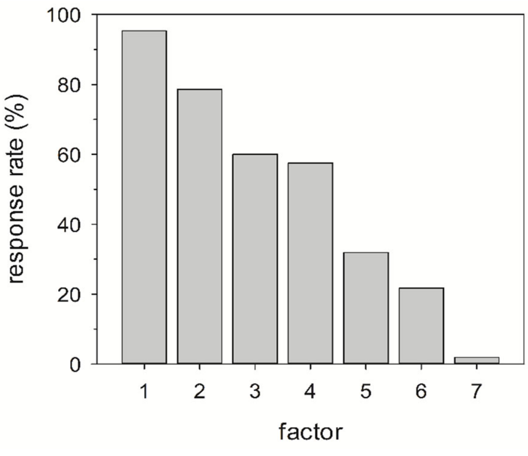


**Figure 11.** Factors/stressors that impact coffee production in the region studied according to the surveys. The factors are ordered from highest to lowest impact and are divided into economic (1), climatic (2), land use (3), technical (4), social (5), political (6), and other (7).

## 4. Discussion

### *4.1. Coffee Production and Yield*

It is clearly evident that both coffee production and yield have been significantly reduced in the central area of the state of Veracruz. Through the envelope function model as well as production and yield trends, it was proven that there has indeed been a decrease in both the production and yield of coffee for the 63 municipalities regardless of the agricultural extension available for coffee cultivation. These declines may be aggravated in subsequent years if factors such as the price of coffee continue to decline, if a coffee policy is not achieved that helps rescue the future of coffee growing in the state and therefore in the country, and depending on changing weather conditions and the presence of pests and diseases.

This is alarming due to the number of producers who depend solely on coffee cultivation to maintain their economy, and it is also a disadvantage for those who use coffee as an alternative crop and, of course, for both international and local consumers. However, the impact of this decrease will also depend on aspects such as the economic capacity of the producers, the level of participation they have in the coffee value chain, and the surface area available to plant coffee, among other things.

Through the analysis, it was possible to identify the municipalities that have a low coffee production, such as Tonayan, Rafael Delgado, Tlilapan, and Texhuacan, where it is recommended to grow medicinal and self-consumption plants alongside coffee as well as the intercropping of crops and plantations of timber trees that can help producers find other economic avenues that serve as income.

Through the surveys, it was possible to determine four main factors or stressors that have affected coffee production and yield, where the main stressor is economic (low price of coffee and high costs of inputs), followed by climate (climate change that has generated changes in precipitation and temperature), land-use change, and technical problems (pests and diseases). In addition, social (labor shortages and migration), political (lack of government support, intermediaries, and hoarding), and other factors comprise a significant proportion. However, some of the stressors are the consequence of another. It is very likely that the change in land use, such as urbanization or conversion to more profitable crops, is a consequence of the low prices that coffee has recently reached.

### *4.2. About Surveyed Producers*

The greater part of producers are men of an average adult age, who carry out most of the coffee-production activities in all the municipalities surveyed. In relation to the education received, it was found that some producers do not have any type of education, while others do. However, although some producers do not have any type of education, this has not limited them from acquiring the minimum knowledge for coffee production. Much of this knowledge about coffee planting, production, and management has been acquired generationally, which has been applied, modified, and adapted to the current conditions of the various regions.

On the other hand, the participation of women is minimal and limited to carrying out activities such as cutting and selecting coffee, weighing, and sometimes selling coffee. These activities are carried out along with household chores, taking care of children, and performing other jobs that serve as an economic complement.

Although education is key to human development, it is also key in rural areas because it contributes to addressing diverse problems in the agricultural sector from different perspectives. As [68] pointed out, education is a tool that helps maximize the potential of producers to face new challenges related to agriculture in addition to improving decision making.

However, belonging to an organization can represent an advantage and/or a disadvantage. If the organization in question has representation, advice, financing, and a well-established union, several advantages can be derived for the producer, from ensuring their participation in government support and programs to improving their production. In this sense, ref. [69] pointed out that belonging to an organization can be a way for the producer to improve his agricultural production and therefore his economic income. However, when the organization does not have strong representation, clear objectives, financial support, and training, it is more difficult to assure the producer a fair price for his product.

Coffee producers also acquire a classification according to the land they have available to plant coffee. This classification considers small producers and medium producers. According to [70], the small producer is also a producer whose coffee-production unit presents low yields, in which case they need to renew or repopulate their plantations to increase their productivity. For [71], the small producer is characterized by belonging to a small holding, with low levels of technology and poverty. These producers have up to 2 ha [72], representing about 25% of those surveyed. Another difference is that small-sized producers carry out practices from cultivation to harvest with family labor, while medium-sized producers combine family work with hired wages, and large-sized producers use a salaried work scheme, which sometimes represents up to 80% [73].

According to [74], the cultivation system used in coffee can determine its growth, development, and yield, combined with the ecological benefits that shade provides in coffee planting; these authors also claimed that a change from cultivation under shade to full sun can affect the environment and the quality of the coffee. Furthermore, it has been proven that growing coffee under shade influences the weight, size, and quality of the coffee bean [75]. It is possible that including agroecological practices will lead to better results in coffee yield. In addition to the fact that agroecology can be a tool to build communities' resilience to the effects of climate change, it also strengthens food systems and health in the face of climate stress factors [76]. Through these practices, it is possible to contribute to sustainability in the coffee agroecosystems themselves, as long as they opt for the use of organic fertilizers [77] or biofertilizers that do not harm the ecosystem but rather help maintain the activity of long-term coffee farming while maintaining environmental benefits.

The variety of coffee planted also influences the volume of production and yield of coffee; in this case, the fact that a large part of the producers plant the Costa Rica variety may be due to the presence of coffee rust (*Hemileia vastatrix*) in the region, the severity of which was recorded with greater intensity in 2012 and since then to date. It represents a threat to producers due to the economic impacts it generates; thus, as a result of this, it is important to improve coffee varieties with genetic improvement, crosses, and new cultivars. Such is the case of Catimor T8667 or Costa Rica variety 95 as a new crop alternative through genetic improvement, with characteristics of productivity and resistance to attack by pests and diseases [78].

It is worth mentioning that 68.61% of the producers said that in the last three years, their coffee production has decreased, while 22.22% stated that their production has remained the same, and 8.61% said that their coffee production has decreased and then increased. The cultural tasks of coffee growing are essential in the production and yield of coffee; each of the tasks carried out during the coffee-production stage can be considered key to improving the coffee value chain. Cultural tasks also provide technical support, knowledge, and a guide for the producer. The continuous establishment of these practices helps the producer to make his resources more efficient, maintain his farm, and strengthen the coffee value chain. These activities are part of the so-called management or integrated management of the crop and give the farmer a tool to improve and maintain the farm [79].

Nine cultural practices or tasks were found (crop trimming, fertilization, intercropping, plant renovation, transplant, pest and disease, soil improvement, shade management, and weeding) that were carried out by producers on their farms, and each of these practices has a specific objective during the stages of coffee growth and production. Some of them are described below.

Fertilization, for example, is essential in the growth of the coffee plant. Through this activity, necessary nutrients are supplied to the plant, such as phosphorus, zinc, magnesium, iron, and calcium, among others, contributing to optimal development; the possibilities are increased to obtain maximum productive potential. It is considered that the quality of the plant depends on fertilization [80]. It is recommended that this activity be carried out at least 2–3 times a year; however, an important factor to consider is the cost of the fertilizer, the amount to be applied, and the application dates. Fertilization can be organic, chemical, or a combination of both, but it is preferable to opt for organic fertilization.

Pest and disease management must be integrated and is based on the orderly use of control strategies, which can be cultural, chemical, ethological, biological, or genetic, all aimed at protecting the crop from the main pests that affect it and cause economic damage [81]. Of course, it is advisable to lean towards cultural and biological control. Cultural control consists of implementing various agronomic practices to protect the crop, such as adequate planting distances, weed control, regulation of shade, pruning, and weeding.

The regulation of shade is important due to its effects on the physiological processes of the plant. The function of shade regulates the microclimate, reduces radiation, improves water balance, and increases relative humidity in coffee plantation, plantations in addition to improving soil fertility [82]. Shade management should be carried out to take advantage of the benefits provided by shaded coffee agroecosystems so that coffee plantations can be maintained in a more sustainable environment. It is advantageous to try to establish a canopy of sparse and uniform shade and avoid areas of excessive shade [81].

Soil improvement and conservation should be implemented with the aim of preventing soil erosion, soil washout, soil drift, or soil loss [82]. Healthy soil is considered to improve coffee production. It is also important to maintain a vegetal cover of weeds that avoid competition from the coffee plant for nutrients. Soil improvement involves balancing the pH of the soil between 4.9 and 5.6 in addition to some conservation practices such as the use of living barriers (intercropping of fruit and forest crops) and application of dead barriers (stone walls and the addition of leaf litter and organic matter to the soil) [83].

Plant renovation is also essential since it is considered that old plants no longer produce the same amount of coffee. It is thus recommended that they be renewed within a period of 20 years. Consequently, the producers mentioned that Costa Rica variety plants, which in theory should have a useful life of 30 years, only last 5 to 7 years.

### *4.3. Identification of Problematic Coffee through Surveys*

#### 4.3.1. The Crisis of Coffee Agriculture Due to Low Coffee Prices

In 1989, extreme competition arose from countries like Vietnam to enter the world coffee market, causing a global oversupply and a 50% collapse in the price of coffee [31] and a profound restructuring and liberalization of the market's international coffee crisis [84] as well as economic destabilization and adverse consequences for various coffee-growing countries. When the agreements of the quota system established by the International Coffee Organization itself were broken, and coffee prices fell in the international market [85], the structure of coffee-growing countries was affected, creating a disarticulation between governments and their institutes, and Mexico was not an exception.

In addition to the above, the abandonment of coffee fields due to the adjustment in the new rules of coffee production and marketing became a problem [86] since the price of coffee was subject to the free market, thereby causing low yields, low- or poor-quality grain production, and a decrease in exports [25] and therefore in the quality of life of producers.

As a result of the disarticulation and the liberalization of agricultural markets, secondary effects were generated, such as low coffee prices, the presence of climate change, phytosanitary problems, low productivity, migration, aging, generational change, and a low level of productivity among producers, which caused a delay and technological regression still affecting coffee production [87].

#### 4.3.2. Changes in the Climatic Variables of Temperature and Precipitation

The climate is also an obvious stressor emanating from the analysis of the coffee yield based on temperature and precipitation. It is possible to elucidate the sites that are most likely not suitable for coffee production since these sites do not meet the hydrothermal characteristics for their optimal development. Although many sites do meet this requirement, yield is low due to the other stressors mentioned. However, there are some studies in which researchers have proposed that coffee is generally produced in the temperature range from 5 °C to 30 °C and from 1200 mm to 2500 mm for precipitation (Table 1).

**Table 1.** Optimal ranges of temperature (T, °C) and precipitation (Pp, mm) for good development of coffee crop, according to some authors.

| Temperature | | | Precipitation | | |
|---|---|---|---|---|---|
| **Range** | **Optimal** | **Author/s** | **Minimum** | **Maximum** | **Author/s** |
| 5–30 | 16–22 | [38] | 1200 | 1600 | [88] |
| −24 | 16 | [89] | 1200 | 1800 | [40] |
| 5–30 | - | [90] | 1200 | 2000 | [38] |
| −25 | 16.0 | [39] | 1600 | 1800 | [91] |
| - | 20.0 | [88] | 1500 | 2000 | [30] |
| 16–25 | - | [92] | 1600 | 1800 | [39] |
| 20 | - | [93] | 2000 | 2500 | [41] |
| | | | 1800 | 2000 | [92] |
| | | | 1900 | 2100 | [93] |
| 17–21 | 18.7 | This paper | 570 | 3040 | This paper |

These precipitation and temperature ranges for the optimal development of coffee contrast among themselves and mainly with those determined in this research. This may be due to several factors, such as the coffee varieties used in each study, the time in which that variety has acclimatized to the sites with different geographical and climatic characteristics, as well as the management to which they have been subjected. In this case, several years of study (20 years, considering that coffee was introduced to this region in 1802) and all the varieties and types of management used in the region were considered in the yield model. However, the threat implied by climate change is clear: If the temperature increases or the precipitation decreases or increases by 4 °C, there will be a decrease in yield of about 50%.

The results of [94] implied that by 2080, the temperature will increase by 4.6 °C, and precipitation will decrease by 5.5%; this involves a loss of about 60%. Ref. [48] analyzed precipitation and average annual temperature data from 1922 to 2008 in the central region of the state and developed a general circulation model to create climate change scenarios with predictions to 2025, 2050, 2075, and 2100, finding that local climate will change with decreases in precipitation of 700 mm and increases in temperature of ~9 °C towards the year 2100. This shows that climate change will truly be one of the strongest stressors on coffee yields in the region.

Furthermore, climate change will not just affect coffee production and yield but will also have implications, as noted by [29] when they analyzed the consequence of local and regional climate on the cultivation of shade coffee in the center of Veracruz as well as the factors that intervene in the change in land use. They found a decrease in socioeconomic indicators due to the high rate of deforestation, which in turn causes changes in precipitation and the frequency of fog.

#### 4.3.3. Crop Reconversions

Given the uncertainty of coffee prices and their international variations, the presence of pests and diseases, climate change, as well as the lack of economic support to improve coffee production, a significant number of producers have chosen to expand their diversification with crops such sugar cane, Persian lemon, Hass avocado, and passion fruit with the aim to obtain economic resources and as a strategy derived from government programs [31] alongside a reconversion of coffee cultivation to something more profitable.

In Veracruz, many coffee plantations were converted to other more economically profitable crops such as sugar cane, a crop that has been expanding since 1970 and has become the main perennial crop in the state, with a presence in 173 municipalities [95], or the Hass avocado, with important plantings in the municipalities of Alpatlahua, Calcahualco, Coscomatepec, and Ixhuatlan del Café in the central area of the state [96]. Furthermore, these crops do not have the environmental advantages of coffee, such as the conservation of biodiversity [18,27] and microclimate regulation.

However, despite the economic profitability represented by some crops such as sugar cane, basic grains, or grasses, among others, it is very likely that soil fertility problems will arise due to the continuous extraction of nutrients with minimal or no incorporations of organic matter into the soil [97]. This situation must be considered in the future in the state's agricultural planning. Furthermore, all these new crops do not have the cultural and environmental value of coffee and therefore can exacerbate climate change and cause the loss of the agroecological tradition of shade-grown coffee cultivation.

Combined with the above, the existing deforestation in the state has also led to the reconversion of coffee [24], especially in areas with lower altitudes whose climatic conditions are not optimal to produce this crop; if the coffee is produced, it does not have the desired quality [31], thereby representing a disadvantage for the producer.

#### 4.3.4. Pests and Diseases

Another important stressor are pests and diseases that can put the production, yield, and economy of producers at risk depending on their pathogenicity, distribution, and quantity. According to [98], the presence of coffee root corchosis related to the joint infestation of root-knot nematodes (*Meloidogyne* spp.) and soil fungi, in addition to rust, has been reported in coffee trees (*Hemileia vastatrix*) as well as leaf-cutter ants and coffee fruit borer (*Hypothenemus hampei*). The latter is considered the most destructive pest in coffee farming, with losses of between 30 and 80% in coffee production [99], mainly in high areas, due to increased temperatures [100].

During 2012 and 2013, the presence of coffee rust was recorded, unleashing a health epidemic and bringing with it socioeconomic problems for coffee growers due to the difficulty of controlling it. Later, in 2014, rust spread throughout the region of Coatepec, Huatusco, and the Veracruz coffee corridor, with a wide dispersion due to the increase in temperature and the effects of climate change [101]. This caused the introduction of new coffee cultivars with resistance to rust, such as Colombia, Oro Azteca, Costa Rica 95, and the Sarchimores [102].

Many factors could be involved in this decrease, the most important of which could be the reduction in the coffee-harvesting area because of urbanization expansion or due to the presence of coffee rust, which caused a drop in yields at an average annual rate of 3.7%, with reductions of 1.8%, according to the Mexican Trusts Established in Relation to Agriculture [103].

A total of 84.72% of the producers stated that they had suffered economic losses due to the presence of a pest or disease in their coffee plantations. The pests that have most affected the coffee plantations of the producers are the borer (*Hypothenemus hampei*) (53.62%), followed by the stem borer (*Plagiohammus colombiensis*) (16.64%), the mealybug (*Planococcus lilacinus*), and blind hen (*Phylophaga* spp.) (7.22%). Regarding diseases, producers stated that rust (*Hemileia vastatrix*) has been the most devastating disease, generating the greatest losses. In that sense, 85.56% mentioned that they have had this disease in their coffee plantations, followed by rooster's eye (*Mycena citricolor*) (10.38%).

#### 4.3.5. Prices of Coffee

A total of 48.05% of producers stated that their coffee sales have decreased in the last two years, while 50.6% stated that sales have remained the same or increased. Of this, 1.94% stated that sales have decreased a lot, and 46.11% said that sales have decreased. While 40% stated that sales have remained the same, 9.72% said that sales have increased, and 0.83% said that sales have increased a lot. On the other hand, 97.72% of the producers stated that the current price at which coffee is sold is not adequate since they barely received USD

0.26 per kilogram during 2023 [104]. Regarding prices, many producers stated that a fair price per kilogram of cherry coffee ranges between MXP 20 and 25 (USD 1.05–1.46). These prices would be more profitable for them since the maintenance of coffee farms necessitates having sufficient economic resources to achieve the desired profitability.

The issue of coffee prices has become a delicate issue in the state of Veracruz due to the presence and actions of transnational companies in the region against coffee producers in the fight for fair prices for the crop.

### 4.4. Coffee Growing Challenges and Strategies to Implement

Due to the socioeconomic, environmental, and cultural importance of coffee, we consider it necessary and urgent to implement the following strategies and recommendations. A restructuring is necessary in agricultural planning at the national and local level for the coming years. Such planning must consider attention to the state of coffee growing in the country and consequently the state of Veracruz, including the extension of support and benefit programs and policies for small coffee producers for the purchase of seeds, acquisition of inputs for planting and growing coffee, access to technology, improvement of loans, construction of new market niches, agricultural risk insurance, as well as the eradication of intermediaries, among others.

It is important that agricultural planning and programs focused on coffee cultivation have short- and medium-term objectives and that they are measurable and monitored in a way such that the government and decision makers can see the degree of progress in coffee growing. According to [105], much of the success of agricultural programs depends on creative, performative (dynamic) reorganizations of production, labor, and the value of agricultural spaces. In this sense, it is worth mentioning that 93% of coffee producers mentioned the importance of having a coffee farm since, in addition to being a source of self-consumption of coffee and other crops, it represents symbolic and generational value.

In this sense, it is necessary to create a public organization whose function is to safeguard this activity in the long term. In addition, the issue should be a transversal and disciplinary manner between key government institutions such as the Ministry of Agriculture and Rural Development (SADER), the Secretariat of the Environment and Natural Resources (SEMARNAT), and the Secretariat of Welfare to increase competitiveness and quality as well as the local, national and international coffee trade.

The lack of inter- and multidisciplinary work between institutions can result in barriers to the coffee trade on a national and international scale. At the national level, coffee farming may simply cease to be an economic alternative, as it would no longer increase the gross domestic product. On an international scale, it could represent opportunities for countries like Vietnam, which has been positioning itself little by little in the international coffee market, becoming one of the countries with the largest coffee exports [106].

Likewise, a new coffee policy is required that includes the fair and equitable participation of the rural producers who represent the majority of labor in the coffee industry for the production, marketing, and sale of coffee while reducing high rates of marginalization, poverty, and social backwardness that exist in several municipalities of the state of Veracruz. Moreover, in addition to the above, it is necessary to improve coffee agriculture in addition to providing the producer with the economic, technological, and training support that is essential for the renewal of coffee plantations, purchase of inputs, and support in coffee certifications as well as social benefit programs that provide for small producers and their families medical care and free literacy assistance. Access to credit is also urgent and necessary to reactivate coffee growing in the state. Therefore, it is urgent to update the list of coffee growers by 2023. According to [107], farmers who do not invest in innovation (and technology) can suffer from obsolescence in equipment and machinery and generate a low market share.

It is required that, through public policy, financing be allocated for soil improvement techniques and for the purchase of inputs with the intention of protecting the soil and obtaining good returns for the producer. As determined by [107] in their research, the improvement of agricultural practices, which includes soil improvement, can have a positive impact on the environment. For example, the work of [108] showed that agricultural practices such as manure application, conservation tillage, integrated soil fertility management, sustainable soil management, composting, as well as land management of crop residues improve land productivity and increase crop yields.

Farmers must be acquainted with new technological arenas through the provision of awareness campaigns for utilizing the most profitable cultivars/varieties of coffee for cultivation. Moreover, equal opportunities must be provided to lower-sector farmers/rural communities for the promotion of coffee cultivation as well assisting them in meeting their daily domestic needs.

Another important aspect is to opt for the extension of the public policy of payment for environmental services to coffee producers. This incentive can be offered in exchange for producers planting their coffee in the shade and with agroecological techniques.

In the technological field, it is important to highlight that, in the state, infrastructure is needed for the coffee industry. To increase the competitiveness of Mexican coffee, it is required that there be decaffeination centers, solubilizers, and freeze-dried coffee factories as well as roasters where small producers can have access to continue improving their product and have the possibility of improving their economic income. It is important for this infrastructure to strictly adhere to current environmental regulations.

It is necessary to reconsider the role of coffee organizations and cooperatives themselves, which must be accompanied by a multidisciplinary group to better address the complexity of problems related to coffee growing, such as the case of coffee prices. A success story of the work carried out by described in [109], where some of their benefits were illustrated, such as better organization of producers, including better communication and access to information, as well as an increase in crop production. On the other hand, the role of coffee cooperatives has been key in maintaining coffee agriculture, as they are considered as an entity of help, guidance, and orientation for coffee producers, which has been evidenced in maintaining the viability of this agricultural practice over time. In that sense, ref. [110] demonstrated that cooperatives themselves are the result of a democratic process with free election of leaders or representatives and with clear association strategies to increase member participation in Huatusco and Veracruz, Mexico. Likewise, it is important to give special recognition to older farmers since they represent a source of traditional knowledge in coffee production that can be useful to young farmers.

It is evident that climate change plays an important role in coffee production and yield, both directly and indirectly, as an increase in temperature can, on the one hand, affect yield and, on the other hand, exacerbate pests and diseases, also reducing coffee production/yield. From this point of view, it is recommended that coffee be grown in the optimal temperature and precipitation ranges enclosed in the model presented herein.

Despite the continuous changes in coffee prices, the change in rain and temperature patterns, adverse conditions such as the high cost of inputs, as well as the change from coffee cultivation to other crops that are apparently more profitable, 83.33% of producers stated that their available area for planting coffee has not decreased. This may mean an opportunity for the continuity of coffee planting, considering that 83.61% stated that they would not change, or they would not replace coffee with some other crop.

Although the producers stated that they would not change the coffee crop for any other, there is no doubt that it is necessary to analyze the process by which the producers have adapted to climate change and evaluate the strategies implemented, such as the change of coffee seeds that are more tolerable to the climate change. Also, change to organic or natural fertilizers that are more economical and less harmful to the ecosystem or the intercropping of crops with coffee to migrate from monoculture to polyculture as well as the establishment of agroecological practices and the exchange of knowledge between producers as route for coffee growing in the state should be analyzed.

Regarding stressors, there are other aspects that must be analyzed, such as the effectiveness of support programs for coffee producers, the migration of producers, the growth of urbanism in the main coffee-growing regions of the state, illegal logging, participation and forms of production, and trade of large companies established in the region. It would also be valuable to study the production and yield of each variety cultivated in the state of Veracruz and the sale prices of cherry coffee.

## 5. Conclusions

Coffee cultivation does not only represent not an agricultural activity but also has economic, environmental, cultural, and identity value for thousands of producers. Although it is true that, in Mexico, coffee growing began to have substantial problems after the disappearance of the Mexican Coffee Institute (INMECAFÉ), it is still possible to give it the necessary attention that this activity deserves and preserve its status as a heritage and a topic of national interest.

In accordance with the analysis performed in this paper, we identified seven major stressors (economic, climatic, land-use change, technical, social, political, and other) that impact coffee production and yield in the central region of the state of Veracruz, which represents a multi-faceted impact for the thousands of coffee producers. These stressors have been generated from the so-called coffee crisis created in 1989 and, over time, have been accentuated in a different way in each of the coffee municipalities according to the economic capacity of the producers, the area they have available to plant coffee, the cultural work they put into practice, and their level of participation throughout the coffee value chain.

Although there are 63 coffee municipalities in the central region of Veracruz, the largest coffee production is concentrated in 14 municipalities that continue to maintain the coffee production in the region. However, pressures on the producers' economy are likely to continue due to low coffee prices and the lack of government support programs that include all producers in all municipalities and coffee-growing towns. Furthermore, producers have to plant coffee, and they need agricultural insurance to cover crop losses in the presence of any stressor identified in this work, such as climate change and the presence of pests or diseases.

The present analysis was able to determine that both the production and the yield have been decreasing based on the analyzed period from 2003 to 2022. Through the implemented model, it was possible to detect that coffee is more sensitive to temperature and changes in it, and we were also able to obtain the optimal precipitation and temperature ranges for coffee growth, which can be helpful for the agricultural planning of the producers. It is necessary for the coffee producer to know these new precipitation and temperature ranges in which coffee can be produced and decide whether to continue planting the crop.

It is necessary to open new niches of opportunity for the great majority of producers that continue planting coffee in the central region, as this also represents a window of opportunity for public policies related to coffee growing, considering the analysis of the adaptation strategies in the presence of climate change that producers have used and whether they have helped to face the current coffee crisis and the constant variation in coffee prices. On the other hand, through the stressors, the process of transformation of land use was evident during the period analyzed; this can cause the loss of soil cover, the loss of forest area, and therefore the area available for planting of coffee. Consequently, determining the rate of deforestation in the region as well as urban growth is an issue pending of analysis since the information derived from this knowledge can improve the monitoring of natural resources in the region. It is important that government decision makers promptly address the issue of coffee growing. The problems detected in this work not only affect current generations of producers but also represent a serious threat to future generations of producers and compromise the agricultural activity itself in the future.

One of the limitations of the present research lies in the fact that the 63 coffee-growing municipalities were not surveyed, and this is because there is no exact number of producers per municipality or per locality. This is because there is no updated registry of producers by municipality, much less by locality. That is why it is necessary to urge the authorities to prepare said registry to obtain the necessary, timely, and real information on the number of existing producers for the following year. The application of a survey that covers all municipalities would involve considerable time and personnel. It is necessary to have sufficient personnel for its application where, among other things, the distance between communities, access roads, and the time required of the producers would have to be taken into account.

Also, there is no updated registry of producers in the state, and this has been a continuing, pending issue for several years. The state must expedite this update to better address the coffee agricultural situation in the area. As mentioned previously, one of the objectives of this research was to directly establish the support that should be given to producers without intermediaries. This support could be in kind or economic in order to carry out coffee-growing tasks, which, as analyzed in this work, influence the production and yield of coffee, and should consider the possible integration of producers to social security as a right to health.

Many producers could not be surveyed because they have almost no time since the farm represents a full-time job that includes weekends. Several respondents were also reluctant to share information about how much coffee they produce and how they sell their coffee due to the presence of intermediaries. In addition, several of the producers have other commercial activities or trade that serve as an economic complement to meet their food, clothing, and education needs, among others.

Finally, it is important to mention that in Veracruz, coffee farming must continue to be promoted from an agroecological approach, with incentives for all producers in order to prolong its existence and benefit thousands of producers in the long term. In this sense, the task that the various rural schools have been carrying out as well as the agroecological activities that derive from it are fundamental for (1) continuing the production coffee in an agroecological way and in balance with the environment, (2) reducing the costs of inputs for producers, and (3) establishing a new form of agriculture that will be the basis for new generations of producers.

It is very important that the activities carried out by rural schools and that are focused on promoting and implementing agroecological practices are monitored and evaluated so that the transition from agriculture without agroecological practices to purely agroecological agriculture is subsequently analyzed in each of the coffee-growing municipalities.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16020802/s1, Table S1: Location of the weather stations used in this study and the period covered by the observation years (Figure 1); Table S2: Decrease/growth of coffee productivity (Mg $yr^{-1}$, CP) in each of the 63 municipalities in the central zone of the state of Veracruz, Mexico. In general, almost all municipalities present a decline in productivity except for fourteen municipalities (numbers in bold) ($p < 0.05$ and n = 20).

**Author Contributions:** Conceptualization, L.G.-H. and V.L.B.; Methodology, L.G.-H. and V.L.B.; Formal analysis, L.G.-H. and V.L.B.; Investigation, L.G.-H. and V.L.B.; Resources, V.L.B.; Writing—original draft, V.L.B.; Writing—review & editing, L.G.-H.; Project administration, V.L.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Instituto de Ecología of the Universidad Nacional Autónoma de México (UNAM) with no external funding. The first author (L.G.-H.) thanks to the National Council of Science and Technology, "CONACYT", for the Ph.D. scholarship (750110).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Written informed consent has been obtained from the respondents to publish this paper.

**Data Availability Statement:** Data are contained within the article and Supplementary Materials.

**Acknowledgments:** We appreciate the support provided by the Regional Council of Coffee Coatepec, A.C., from the state of Veracruz and the Territorial Coordination Region 17 Production Program for Well-being of SADER-INIFAP Technical Support Strategy. The first author extends acknowledgment to the Ph.D. Program in Sustainability Sciences, UNAM "Doctorado en Ciencias de la Sostenibilidad, Universidad Nacional Autónoma de México".

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Roth, I.; Lindorf, H. Anatomía y desarrollo del fruto y de la semilla del Café. *Acta Bot. Venez.* **1971**, *66*, 197–238.
2. Gómez, G. Cultivo y beneficio del café. *Rev. Geogr. Agric.* **2010**, *45*, 103–193. Available online: https://www.redalyc.org/articulo.oa?id=75726134008 (accessed on 28 September 2023).
3. Manson, H.R.; Contreras, H.A.; López, B.F. Estudios de la biodiversidad en cafetales. In *Agroecosistemas Cafetaleros de Veracruz*; Biodiversidad, Manejo y Conservación; Manson, H.R., Hernández-Ortiz, V., Gallina, S., Mehltreter, K., Eds.; INECOL-INE-SEMARNAT: Mexico City, Mexico, 2008; pp. 1–348. ISBN 970-709-112-6.
4. Ruelas-Monjardín, L.C.; Nava-Tablada, M.E.; Cervantes, J.; Barradas, V.L. Importancia ambiental de los agroecosistemas cafetaleros bajo sombra en la zona central montañosa del estado de Veracruz, México. *Madera Bosques* **2014**, *20*, 27–40. [CrossRef]
5. Krishnan, S. *Sustainable Coffee Production*; Oxford University Press: Oxford, UK, 2017.
6. Figueroa-Hernández, E.; Pérez-Soto, F.; Godínez Montoya, L. Importancia de la comercialización del café en México. In *Ciencias Sociales: Economía y Humanidades*; Pérez-Soto, F., Figueroa-Hernández, E., Godínez-Montoya, L., Eds.; México, S.C. Universidad Autónoma del Estado de Chapingo; ECOFARN: Mexico City, Mexico, 2015; pp. 64–84. Available online: https://dialnet.unirioja.es/servlet/articulo?codigo=5365588 (accessed on 30 September 2023).
7. Velásquez, O.R. *Guía de Variedades de Café*; Asociación Nacional del Café (ANACAFE): Guatemala City, Guatemala, 2019; pp. 1–48. Available online: https://www.anacafe.org/uploads/file/9a4f9434577a433aad6c123d321e25f9/Gu%C3%ADa-de-variedades-Anacaf%C3%A9.pdf (accessed on 9 September 2023).
8. Escamilla, P.E.; Centro de Investigaciones Económicas, Sociales y Tecnológicas de la Agroindustria y de la Agricultura Mundial (CIESTAAM). *El Café Cereza en México, Tecnología de la Producción*; Universidad Autónoma Chapingo, Dirección de Centros Regionales: Ciudad Victoria, Mexico, 1993; pp. 1–116.
9. López-García, F.J.; Escamilla-Prado, E.; Zamarripa-Colmenero, A.; Cruz-Castillo, J.G. Producción y calidad en variedades de café (*Coffea arabica* L.) en Veracruz, México. *Rev. Fitotec. Mex.* **2016**, *39*, 297–304. [CrossRef]
10. Steiger, D.L.; Nagai, C.; Moore, P.H.; Morden, C.W.; Osgood, R.V.; Ming, R. AFLP analysis of genetic diversity within and among *Coffea arabica* cultivars. *Theor. Appl. Genet.* **2002**, *105*, 209–215. [CrossRef] [PubMed]
11. Hernández-Martínez, G.; Espíndola, V.R.; De la Rosa, P.A. *El Café de México. La Riqueza de sus Regiones*; Cafecol A.C. México: Mexico City, Mexico, 2018; pp. 1–84. Available online: http://www.cafedemexico.mx/assets/elcafedemexico-2019.pdf (accessed on 12 September 2023).
12. Mestries, F. Entre la migración internacional y la diversificación de cultivos. Los pequeños productores de café en dos localidades de Veracruz. *Sociológica* **2006**, *21*, 75–108. Available online: https://www.scielo.org.mx/scielo.php?pid=S0187-01732006000100075&script=sci_abstract&tlng=en (accessed on 12 September 2023).
13. SAGARPA. Café Mexicano. In *Planeación Agrícola 2017–2030*; SAGARPA: Mexico City, Mexico, 2017; pp. 1–20. Available online: https://www.gob.mx/cms/uploads/attachment/file/256426/B_sico-Caf_.pdf (accessed on 12 September 2023).
14. SADER—SIAP. *Panorama Agroalimentario. Conectando Conocimiento Ancestral y Moderno para Lograr la Autosuficiencia Alimentaria*; SIAP: Mexico City, Mexico, 2021; pp. 1–213. Available online: https://nube.siap.gob.mx/gobmx_publicaciones_siap/pag/2021/Panorama-Agroalimentario-2021 (accessed on 15 September 2023).
15. Chinchilla-Soto, C.; Duran-Quesada, A.M.; Monge-Muñoz, M.; Gutiérrez-Soto, M.V. Quantifying the Annual Cycle of water use efficiency, energy and $CO_2$ Fluxes using micrometeorological and physiological techniques for a coffee field in Costa Rica. *Forests* **2021**, *12*, 889. [CrossRef]
16. Marín Garza, T.; Aguilar Rivera, N.; Castañeda Castro, O. Mexican Coffee Agribusiness, trends, challenges and goals towards sustainability. *Curr. Politics Econ. U.S. Can. Méx.* **2019**, *21*, 52–71.
17. SIAP. *Escenario Mensual de Productos Agroalimentarios. Café, Mexico*; SIAP: Mexico City, Mexico, 2021; pp. 1–2. Available online: https://www.gob.mx/cms/uploads/attachment/file/667940/Escenario_cafe_ago21.pdf (accessed on 15 September 2023).
18. Moguel, P.; Toledo, V.M. El café en México, ecología, cultura indígena y sustentabilidad. *Ciencias* **1996**, *43*, 40–51.
19. Hernández, M.D.L.S.; Sánchez, C.E.; Alarcón Pulido, S.A.; Cabrera Núñez, A. Economía agroalimentaria: Análisis de la producción, comercialización y problemática del cultivo de café. *Rev. Biol. Agropecu. Tuxpan* **2019**, *7*, 79–85. [CrossRef]
20. Escamilla, P.E.; Licona, V.A.L.; Díaz, C.S.; Santoyo, C.H.V.; Sosa, R.; Rodríguez, R.L. Los Sistemas de producción de café en el centro de Veracruz, México. Un análisis tecnológico. *Rev. Hist.* **1994**, *30*, 41–67.
21. Gay, C.; Estrada, F.; Conde, C.; Eakin, H. Impactos Potenciales del Cambio Climático en la Agricultura: Escenarios de Producción de Café para el 2050 en Veracruz (Mexico). In *El Clima Entre el Mar y la Montaña*; García Codrón, J.C., Liaño, D.C., de Arróyabe Hernández, F.P., Pedraja, G.C., Álvarez, R.D., Eds.; Asociación Española de Climatología y Universidad de Cantabria: Santander, Spain, 2004; pp. 651–660.
22. Arana-Coronado, J.; Trejo-Pech, C.; Velandia, M.; Peralta-Jimenez, J. Factors influencing organic and fair trade coffee growers level of engagement with Cooperatives: The case of coffee farmers in Mexico. *J. Int. Food Agribus. Mark.* **2018**, *31*, 22–51. [CrossRef]

23. Robles Berlanga, H.M. *Los Productores de Café en México: Problemática y Ejercicio del Presupuesto*; Mexican Rural Development Research Reports; Woodrow Wilson International Center for Scholars: Washington, DC, USA, 2011; Volume 14, pp. 1–62.
24. SADER. *Programa para Desarrollar un Sistema Local de Innovación de Café en el Estado de Veracruz*; Secretaría de Agricultura y Desarrollo Rural: Mexico City, Mexico, 2020; pp. 1–70. Available online: https://www.gob.mx/cms/uploads/attachment/file/683364/Innovaci_n_Caf__2020.pdf (accessed on 15 September 2023).
25. García, S.B.; Gallardo, L.F.; Nava, T.M.E.; Ruíz, R.O.; Escamilla, P.E. Factores que limitan la certificación del café orgánico en el esquema de comercio justo en cinco organizaciones en México. *Rev. Mex. Caribe* **2006**, *10*, 205–226.
26. Perea Quezada, J.; Rivas Tovar, L.A. Estrategias competitivas para los productores cafetaleros de la región de Córdoba, Veracruz, frente al mercado mundial. *Contad. Adm.* **2008**, *224*, 9–33. [CrossRef]
27. González-Zamora, A.; Esperón-Rodríguez, M.; Barradas, V.L. Mountain cloud forest and grown-shade coffee plantations: A comparison of tree biodiversity in central Veracruz, México. *For. Syst.* **2016**, *25*, e055. [CrossRef]
28. Pineda López, M.R.; Ortiz Ceballos, G.; Sánchez Velásquez, L.R. Los cafetales y su papel en la captura de carbono: Un servicio ambiental aún no valorado en Veracruz. *Madera Bosques* **2005**, *11*, 3–14. [CrossRef]
29. Loreto, D.; Esperón-Rodríguez, M.; Barradas, V.L. The climatic-environmental significance, status and socioeconomic perspective of the grown-shade coffee agroecosystems in the central mountain region of Veracruz, Mexico. *Investig. Geogr. Bol. Inst. Geogr. Mex.* **2017**, *92*, 87–100.
30. Moguel, P.; Toledo, V.M. Conservar produciendo: Biodiversidad, café orgánico y jardines productivos. *Biodiversitas* **2004**, *55*, 2–16.
31. Ellis, E.A.; Baerenklau, K.A.; Marcos, M.R.; Chávez, E. Land use/land cover change dynamics and drivers in a low-grade marginal coffee growing region of Veracruz, Mexico. *Agrofor. Syst.* **2010**, *80*, 61–84. [CrossRef]
32. Blackman, A.; Albers, H.J.; Ávalos, S.B.; Murphy, L.C. Land cover in a managed forest ecosystem: Mexican shade coffee. *Am. J. Agric. Econ.* **2008**, *90*, 216–231. [CrossRef]
33. Schroth, G.; da Fonseca, G.A.B.; Harvey, C.A.; Vasconcelos, H.L.; Gascon, C.; Izac, A.N. Introduction: The role of agroforestry in biodiversity conservation in tropical landscapes. In *Agroforestry and Biodiversity Conservation in Tropical Landscapes*; Schroth, G., da Fonseca, G.A.B., Harvey, C.A., Gascon, C., Vasconcelos, H.L., Izac, A.N., Eds.; Island Press: Washington, DC, USA, 2004; pp. 227–260.
34. Villarreyna, A.R.; Avelino, J. *Efecto de la Sombra Sobre las Plagas y Enfermedades, a Través del Microclima, Fenología y Estado Fisiológico del Cafeto*; CATIE: Turrialba, Costa Rica, 2016; pp. 1–22. Available online: https://agritrop.cirad.fr/581152/1/Reporte%201_Sombra%20y%20Plagas%20y%20E_RV_%20JA_BV_RV.pdf (accessed on 15 September 2023).
35. Barradas, V.L.; Cervantes, P.J.; Ramos, P.R.; Puchet, A.C.; Vázquez, R.P.; Granados, R.R. Meso-scale climate change in the central mountain region of Veracruz State, Mexico. In *Tropical Montane Cloud Forests*; Bruijnzeel, L.A., Scatena, F.N., Hamilton, L.S., Eds.; Cambridge University Press: Cambridge, UK, 2010; pp. 549–556.
36. Schroth, G.; Läderach, P.; Dempewolf, J.; Philpott, S.; Haggar, J.; Eakin, H.; Castillejos, T.; García, M.J.; Soto, P.L.; Hernández, R.; et al. Towards a climate change adaptation Strategy for coffee communities and Ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitig. Adapt. Strateg. Glob. Change* **2009**, *14*, 605–625. [CrossRef]
37. Menzel, A. Trends in phenological phases in Europe between 1951 y 1996. *Int. J. Biometeorol.* **2000**, *44*, 76–81. [CrossRef] [PubMed]
38. Benacchio, S.S. *Algunas Exigencias Agroecológicas en 58 Especies de Cultivo con Potencial de Producción en el Trópico Americano*; FONAIAP—Centro Nacional de Investigación Agropecuaria, Ministerio de Agricultura y Cría: Maracay, Venezuela, 1982; pp. 35–39.
39. Carvajal, F.J. *Cafeto: Cultivo y Fertilización*; Instituto Internacional de la Potasa: Bern, Switzerland, 1984; pp. 1–254. Available online: https://www.ipipotash.org/uploads/udocs/65-carvajal-cafeto-cultivo-y-fertilizacion.pdf (accessed on 16 September 2023).
40. DaMatta, F.M.; Ronchi, C.P.; Maestri, M.; Barros, R.S. Ecophysiology of coffee growth and production. *Braz. J. Plant Physiol.* **2007**, *19*, 485–510. [CrossRef]
41. Arcila, P.J.; Farfán, V.F.; Moreno, B.A.; Salazar, G.L.F.; Hincapié, G.E. *Sistemas de Producción de Café en Colombia*; Cenicafé: Chinchiná, Colombia, 2007; pp. 1–309. Available online: https://www.cenicafe.org/es/publications/sistemas_de_produccion.pdf (accessed on 15 September 2023).
42. Thiébaut, V.; Velázquez-Hernández, E. Entre la Agricultura y el trabajo urbano: Dos estudios de caso en la periferia de Xalapa, una ciudad media del estado de Veracruz (México). *LiminaR* **2017**, *15*, 142–162. [CrossRef]
43. Espinosa-Guzmán, M.A.; Sánchez Velásquez, L.R.; Pineda López, M.R.; Sahagún Sánchez, F.J.; Aragones Borrego, D.; Reyes García, Z.F. Dinámica de cambios en el agroecosistema de cafetal de sombra en la cuenca alta de la Antigua, Veracruz. *Madera Bosques* **2020**, *26*, e2621974. [CrossRef]
44. Ruiz-López, K.I.; Garrido Calleja, A. Transiciones productivas en el municipio de Coatepec, Veracruz (2003–2018). *Quivera. Rev. Estud. Territ.* **2021**, *23*, 27–47. Available online: https://www.redalyc.org/journal/401/40168622002/40168622002.pdf (accessed on 15 September 2023). [CrossRef]
45. Rivera Rojo, C.R. Competitividad del café mexicano en el comercio internacional: Un análisis comparativo con Brasil, Colombia y Perú (2000–2019). *Anál. Econ.* **2022**, *37*, 181–199. Available online: https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2448-66552022000100181 (accessed on 22 October 2023). [CrossRef]
46. Bianco, G.B. Climate Change adaptation, coffe, and corporate social responsibility: Challenges and opportunities. *Int. J. Corp. Soc. Responsib.* **2020**, *5*, 1–13.

47. Panhuysen, S.; Pierrot, J. *Coffee Barometer 2018*; Hivos: Hague, The Netherlands, 2018; pp. 1–36. Available online: https://federaciondecafeteros.org/static/files/5Barometro_de_cafe2014.pdf (accessed on 22 October 2023).
48. Esperón-Rodríguez, M.; Bonifacio-Bautista, M.; Barradas, V.L. Socio-economic vulnerability to climate change in the central mountainous region of eastern Mexico. *AMBIO* **2016**, *45*, 146–160. [CrossRef]
49. SEFIPLAN. *Programas Regionales Veracruzanos. Programa Región las Montañas 2013–2016*; Gobierno del Estado de Veracruz, Secretaría de Finanzas y Planeación del Estado de Veracruz: Veracruz, Mexico, 2013; pp. 1–111. Available online: http://www.veracruz.gob.mx/wp-content/uploads/sites/2/2014/04/tf07-pr-montana.pdf (accessed on 7 July 2023).
50. SEFIPLAN. *Estudios Regionales para la Planeación*; Región Capital, Gobierno del Estado de Veracruz, Secretaría de Finanzas y Planeación del Estado de Veracruz: Veracruz, Mexico, 2011; pp. 1–50. Available online: http://www.veracruz.gob.mx/wp-content/uploads/sites/2/2012/01/tf07-er-07-capital-reg.pdf (accessed on 7 July 2023).
51. CONABIO. *El Bosque Mesófilo de Montaña en México: Amenazas y Oportunidades para su Conservación y Manejo Sostenible*, 1st ed.; Toledo, A.T., Ed.; Comisión para el Conocimiento y Uso de la Biodiversidad, Distrito Federal: Tlalpan, Mexico, 2010; pp. 1–177. ISBN 978-607-7607-35-9.
52. González-Espinosa, M.; Meave, J.A.; Ramírez-Marcial, N.; Toledo-Aceves, T.; Lorea-Hernández, F.G.; Ibarra-Manríquez, G. Los bosques de niebla de México: Conservación y restauración de su componente arbóreo. *Ecosistemas* **2012**, *21*, 36–52. Available online: https://revistaecosistemas.net/index.php/ecosistemas/article/view/26 (accessed on 7 July 2023).
53. Gómez-Pompa, A. Ecology of the vegetation of Veracruz. In *Vegetation and Vegetational History of Northern Latin America*; Graham, A., Ed.; Elsevier: Amsterdam, The Netherlands, 1978; pp. 73–148.
54. SIACON (Sistema de Información Agroalimentaria de Consulta). *Servicio de Información Agroalimentaria y Pesquera de la Secretaría de Desarrollo Rural*; SADER: Mexico City, Mexico, 2021. Available online: https://www.gob.mx/siap/documentos/siacon-ng-161430 (accessed on 20 July 2023).
55. SIAP. Avance de Siembras y Cosechas, Mexico. 2022. Available online: https://nube.siap.gob.mx/avance_agricola/ (accessed on 15 July 2023).
56. Nasrallah, H.A.; Brazel, A.J.; Balling, R.C. Analysis of the Kuwait City urban heat island. *Int. J. Climatol.* **1990**, *10*, 401–405. [CrossRef]
57. Jarvis, P. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **1976**, *273*, 593–610.
58. Fanjul, L.; Barradas, V.L. La importancia de la cobertura arbórea en la temperatura del agroecosistema cafetalero. *Biótica* **1985**, *9*, 415–421.
59. Jones, H.G.; Corlett, J.H. Current topics in drought physiology. *J. Agric. Sci.* **1992**, *119*, 291–296. [CrossRef]
60. Ramos-Vázquez, A.; Barradas, V.L. El efecto del microambiente en la conductividad estomática de Buddleia cordata HBK, en la Reserva del Pedregal de San Ángel. *Bot. Sci.* **1998**, *62*, 63–71. [CrossRef]
61. Ballinas, M.; Barradas, V.L. The urban tree as a tool to mitigate the urban heat island in Mexico City: A simple phenomenological model. *J. Environ. Qual.* **2016**, *45*, 157–166. [CrossRef]
62. Rozalia, M. Non-Probabilistic Sampling Use in Qualitative Marketing Research. Haphazard Sampling, Volunteer Sampling. *Manag. Mark.* **2007**, *3*, 955–959. Available online: https://www.researchgate.net/profile/Manuela-RozaliaGabor/publication/260284359_Non_-_probabilistic_sampling_use_in_qualitative_marketing_research_Haphazard_sampling_Volunteer_sampling/links/565725a608ae4988a7b52a81/Non-probabilistic-sampling-use-in-qualitative-marketing-research-Haphazard-sampling-Volunteer-sampling.pdf (accessed on 22 October 2023).
63. Casas Anguita, J.; Repullo Labrador, J.; Donato Campos, J. La encuesta como técnica de investigación. Elaboración de cuestionarios y tratamiento estadístico de los datos. *Aten. Primaria* **2003**, *31*, 527–538. [CrossRef]
64. Mann, H.B. Non-parametric tests against trend. *Econometrica* **1954**, *13*, 163–171.
65. Kendall, M.G.; Gibbons, J.D. *Rank Correlation Methods*, 5th ed.; Arnold, E., Ed.; Oxford University Press: Oxford, UK, 1990; pp. 1–260.
66. Gay, C.; Estrada, F.; Conde, C.; Eakin, H.; Villers, L. Potential Impacts of climate change on Agriculture: A case of study of coffee production in Veracruz, Mexico. *Clim. Change* **2006**, *79*, 259–288. [CrossRef]
67. Woodsong, C. Old farmers, invisible farmers: Age and agriculture in Jamaica. *J. Cross-Cult. Gerontol.* **1994**, *9*, 277–299. [CrossRef] [PubMed]
68. Fielke, S.J.; Bardsley, D.K. The importance of farmer education in South Australia. *Land Use Policy* **2014**, *39*, 301–312. [CrossRef]
69. Tolno, E.; Kobayashi, H.; Ichizen, M.; Esham, M.; Balde, B.S. Economic analysis of the role of farmer organizations in enhancing smallholder potato farmers' income in middle Guinea. *J. Agric. Sci.* **2015**, *7*, 123–137. [CrossRef]
70. SADER. Programa de Apoyos a Pequeños Productores, Componente PROCAFE e Impulso Productivo al Café, Mexico. 2017. Available online: https://www.gob.mx/agricultura/acciones-y-programas/programa-de-fomento-a-la-agricultura-procafe-e-impulso-productivo-al-cafe (accessed on 12 September 2023).
71. Ramírez, V.B.; González, R.A. La Migración como respuesta de los campesinos ante la crisis del café: Estudio entres municipios del estado de Puebla. *Ra Ximhai* **2006**, *2*, 319–341. Available online: http://uaim.edu.mx/webraximhai/Ej-05articulosPDF/02%20cafe.pdf (accessed on 20 September 2023). [CrossRef]
72. Nájera, O. El café orgánico en México. *Cuad. Desarro. Rural* **2002**, *48*, 1–48. Available online: https://www.redalyc.org/pdf/117/11704804.pdf (accessed on 20 September 2023).

73. Díaz-Cárdenas, S.; Robledo, D. *Plan Rector del Sistema Producto de Café en México*; SAGARPA/CMC/INCA Rural: Mexico City, Mexico, 2005; pp. 1–92. Available online: https://sursureste.org.mx/wp-content/uploads/2022/08/Plan-Rector-Nacional-del-Sistema-Producto-Cafe-2005.pdf (accessed on 18 May 2023).
74. Alemu, M.M. Effect of three shade on coffee crop production. *J. Sustain. Dev.* **2015**, *8*, 66–70. [CrossRef]
75. Muschler, R.G. Shade improves coffee quality in a sub-optimal coffee zone of Costa Rica. *Agrofor. Syst.* **2001**, *85*, 131–139. [CrossRef]
76. Amoak, D.; Luginaah, I.; McBean, G. Climate Change, Food Security and Health: Harnessing Agroecology to build climate-resilient Communities. *Sustainability* **2022**, *14*, 13954. [CrossRef]
77. Castro-Tanzi, S.; Dietsch, T.; Urena, N.; Vindas, L.; Chandler, M. Analysis of management and site factors to improve the sustainability of smallholder coffee production in Tarrazú, Costa Rica. *Agric. Ecosyst. Environ.* **2012**, *155*, 172–181. [CrossRef]
78. Aguilar, G. *Variedad Costa Rica 95*; Instituto del Café de Costa Rica (ICAFE): San José, Costa Rica, 1995; pp. 1–33. Available online: https://www.mag.go.cr/bibliotecavirtual/F30-6749.pdf (accessed on 22 October 2023).
79. Durán, E.D.G.; Carmona, A.G. *Labores Culturales y Recolección de Los Cultivos Ecológicos*, 1st ed.; AGAU0108; IC Editorial: Antequera, Spain, 2018; pp. 1–308.
80. Instituto Interamericano de Cooperación para la Agricultura (IICA). *Guía Práctica de Caficultura*; IICA: San José, Costa Rica, 2020; pp. 1–78. Available online: https://iica.int/sites/default/files/2020-11/impresion%20GPCAFI%2010.2020.pdf (accessed on 10 November 2023).
81. Ministerio de Medio Ambiente y Recursos Naturales de la República Dominicana. *Manejo Integrado del Cultivo de Café con Énfasis en Prácticas MIP. Proyecto Biodiversidad en Paisajes Productivos*; Ministerio de Medio Ambiente y Recursos Naturales de la República Dominicana: Santo Domingo, Dominican Republic, 2021; pp. 1–16. Available online: https://bvearmb.do/handle/123456789/3335 (accessed on 10 November 2023).
82. Instituto del Café de Costa Rica (ICAFE). *Guía Técnica para el Cultivo del Café*, 1st ed.; ICAFE-CICAFE: Heredia, Costa Rica, 2011; pp. 1–72. Available online: https://www.icafe.cr/wp-content/uploads/cicafe/documentos/GUIA-TECNICA-V10.pdf (accessed on 10 November 2023).
83. Moreno-Seceña, J.C.; Nava-Tablada, M.E.; Hernández-Sánchez, M.I. Actitud de cafeticultores sobre el manejo de conservación de suelos del Sitio Ramsar, Cascadas de Texolo. *Agric. Soc. Desarro.* **2015**, *12*, 1–14. Available online: https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1870-54722015000400553 (accessed on 15 November 2023). [CrossRef]
84. Hausermann, H.; Eakin, H. Producing "viable" landscapes and livelihoods in Central Veracruz, Mexico: Institutional and Producer responses to the coffee Commodity crisis. *J. Lat. Am. Geogr.* **2008**, *7*, 109–131. [CrossRef]
85. Paré, L.P. ¿Adelgazamiento del INMECAFE o de los pequeños productores? *Soc. Méx.* **1990**, *5*, 1–9. Available online: http://www.sociologicamexico.azc.uam.mx/index.php/Sociologica/article/view/927 (accessed on 20 May 2023).
86. Vásquez, P.J. Crisis del café y cultura del trabajo en el contexto de la acumulación flexible en el centro de Veracruz, México. *Rev. Entorno Geogr.* **2014**, *10*, 136–151. Available online: https://entornogeografico.univalle.edu.co/index.php/entornogeografico/article/view/3653/5579 (accessed on 18 May 2023). [CrossRef]
87. Escamilla Prado, E.; Díaz Cárdenas, S.; Nava Tablada, M.E.; Cantú Peña, F. El Relevo generacional en el sector cafetalero: La experiencia de los cursos de café para niños en Chocomán, Veracruz, México. *Agroproductividad* **2018**, *11*, 48–54. Available online: https://www.researchgate.net/publication/339080333_El_relevo_generacional_en_el_sector_cafetalero_la_experiencia_de_los_cursos_de_cafe_para_ninos_en_Chocaman_Veracruz_Mexico (accessed on 18 May 2023).
88. Alegre, C. Climates et cafeiers d' Arabie. *Agron. Trop.* **1959**, *14*, 23–58.
89. Soto, F.; Vantour, A.; Hernández, A.; Planas, A.; Figueroa, A.; Fuentes, P.; Tejeda, T.; Morales, M.; Vázquez, R.; Zamora, E.; et al. La Zonificación Agroecológica del *Coffea arabica* L. en Cuba. Macizo Montañoso Sagua-Nipe-Baracoa. *Cultiv. Trop.* **2001**, *22*, 27–51.
90. Fournier, L.A. *Fundamentos Ecológicos del Cultivo de Café*; Miscellany, Instituto Interamericano de Cooperación para la Agricultura (IICA): San José, Costa Rica, 1980; Volume 230, pp. 1–29. Available online: https://repositorio.iica.int/handle/11324/8801 (accessed on 11 May 2023).
91. Enríquez, G. *Ecofisiología del Cultivo. Manual del Cultivo de Café*; INIAP; GTZ Quevedo; FUNDAGRO: Quevedo, Ecuador, 1993; pp. 1–40. Available online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjnzqepsba-DAxUfJEQIHfVMAjcQFnoECAsQAQ&url=https://repositorio.iniap.gob.ec/bitstream/41000/1619/1/Manual%2520del%2520cultivo%2520de%2520cafe.pdf&usg=AOvVaw1w9XQT5Zj_ (accessed on 11 September 2023).
92. González, J. *Datos Climáticos de Zonas Cafetaleras de la República Mexicana*; Campo Gárnica, Departamento de Climatología: Mexico City, Mexico, 1978.
93. Villers, L.; Arizpe, N.; Orellana, R.; Conde, C.; Hernández, J. Impactos del cambio climático en la floración y desarrollo del fruto del café en Veracruz, México. *Interciencia* **2009**, *34*, 322–329. Available online: http://ve.scielo.org/scielo.php?script=sci_arttext&pid=S0378-18442009000500006 (accessed on 11 May 2023).
94. Granados, R.R.; Medina, B.M.d.l.P.; Peña, M.V. Variación y cambio climático en la vertiente del Golfo de México. Impactos en la Cafeticultura. *Rev. Mex. Cienc. Agríc.* **2014**, *5*, 473–485. Available online: https://www.scielo.org.mx/scielo.php?pid=S2007-09342014000300011&script=sci_abstract&tlng=pt (accessed on 11 September 2023). [CrossRef]
95. Aguilar Rivera, N. Reconversión de la cadena agroindustrial de la caña de azúcar en Veracruz México. *Nova Sci.* **2014**, *6*, 125–161. Available online: https://www.scielo.org.mx/scielo.php?pid=S2007-07052014000200007&script=sci_abstract&tlng=pt (accessed on 4 September 2023).

96. Nataren-Velazquez, J.; Angel Pérez, A.; Megchún-García, J.V.; Ramírez-Herrera, E.; Meneses Márquez, I. Caracterización productiva del aguacate (*Persea americana* Mill) en la zona de alta montaña Veracruz, México. *Rev. Iberoam. Bioecon. Cambio Clim.* **2020**, *6*, 1406–1419. [CrossRef]
97. Landeros-Sánchez, C.; Moreno-Seceña, J.C.; Escamilla-Prado, E.; Ruiz-Bello, R. Diversificación de cultivos. In *La Biodiversidad en Veracruz: Estudio de Estado Volumen I*; CONABIO: Tlalpan, Mexico, 2011; pp. 1–14. Available online: https://www.researchgate.net/profile/Cesareo-LanderosSanchez/publication/280319363_Diversificacion_de_los_cultivos/links/55b2873208aec0e5f431cf2b/Diversificacion-de-los-cultivos.pdf (accessed on 4 September 2023).
98. Carrión Villarnovo, G.L.; Williams, T.; Mercado Vidal, G.; Valenzuela González, J.E.; Villain, L. Implemento de un manejo integrado de plagas y enfermedades en cafetales de la zona Centro del Estado de Veracruz. In *Diagnóstico, Productividad y Ambiente en Cafetales. Estudios Regionales y de Caso*, 1st ed.; López Morgado, R., Díaz Padilla, G., Eds.; Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP): Mexico City, Mexico, 2020; pp. 1–46.
99. Government of Veracruz. *Programa de Trabajo de la Campaña contra la Broca del Café, del Incentivo de Prevención de Plagas Fitosanitarias Reglamentadas del Programa de Sanidad e Inocuidad Agroalimentaria 2017, del Estado de Veracruz*; Government of Veracruz: Veracruz, Mexico, 2017; pp. 1–10. Available online: https://www.gob.mx/cms/uploads/attachment/file/276138/Broca_del_caf_.pdf (accessed on 4 September 2023).
100. Jaramillo, J.; Chabi-Olaye, A.; Kamonjo, C.; Jaramillo, A.; Vega, F.E.; Poehling, H.M.; Borgemeister, C. Thermal tolerance of the coffee berry borer *Hypothenemus hampei*: Predictions of climate change impact on a tropical insect pest. *PLoS ONE* **2009**, *4*, e6487. [CrossRef]
101. Castillo, A. El café en los tiempos de la Roya. *J. Veracruz* **2015**, *53*, 1–8. Available online: http://fgm.org.mx/wp-content/uploads/2018/07/Jarocho-cuantico-53.pdf. (accessed on 3 December 2022).
102. Sánchez Hernández, S.; Escamilla Prado, E.; Mendoza Briseño, M.A.; Nazario Lezama, N. Calidad del café (*Coffea arabica* L.) en dos sistemas agroforestales en el centro de Veracruz, México. *Agroproductividad* **2018**, *11*, 80–86.
103. FIRA. *Panorama Agroalimentario*; FIRA: Mexico City, Mexico, 2017; pp. 1–25. Available online: https://www.fira.gob.mx/InfEspDtoXML/abrirArchivo.jsp?abreArc=68637 (accessed on 13 September 2022).
104. Luna, A. Precios del Café Cereza Están por los Suelos: Movimiento Cafetalero A.C. El Sol de Córdoba. 2023. Available online: https://www.elsoldecordoba.com.mx/local/cuanto-cuesta-el-kilogramo-de-cafe-cereza-10849562.html (accessed on 23 October 2023).
105. Diro, S.; Tesfaye, A.; Erko, B. Determinants of adoption of climate-smart agricultural technologies and practices in the coffee-based farming system of Ethiopia. *Agric. Food Secur.* **2022**, *11*, 2–14. [CrossRef]
106. Wardhiani, W.F.; Karyani, T.; Setiawan, I.; Rustidja, E.S. The Effect of Performance on the Sustainability of Coffee Farmers' Cooperatives in the Industrial Revolution 4.0 in West Java Indonesia. *Sustainability* **2023**, *15*, 4901. [CrossRef]
107. Velandia, M.; Trejo-Pech, C.; Rodríguez-Padrón, B.; Servín-Juárez, R.; Stripling, C. Challenges and managerial strategies of coffee cooperatives from the Huatusco region in Mexico: The perspective of leaders. *Agrociencia* **2022**, *56*, 1–16. Available online: https://agrociencia-colpos.org/index.php/agrociencia/article/view/2741/2182 (accessed on 13 December 2023). [CrossRef]
108. Flachs, A. Degrowing alternative agriculture: Institutions and aspirations as sustainability metrics for small farmers in Bosnia and India. *Sustain. Sci.* **2022**, *17*, 2301–2314. [CrossRef]
109. Utrilla-Catalan, R.; Rodriguez-Rivero, R.; Narvaez, N.; Díaz-Barcos, V.; Blanco, M.; Galeano, J. Growing Inequality in the Coffee Global Value Chain: A complex network assessment. *Sustainability* **2022**, *14*, 672. [CrossRef]
110. Piedade Santos, V.; Cabral Ribeiro, P.C.; Brito Rodrigues, L. Sustainability assessment of coffee production in Brazil. *Environ. Sci. Pollut. Res.* **2023**, *30*, 11099–11118. [CrossRef]