**RESILIENCIA DEL AGROECOSISTEMA CAFÉ ANTE EL CAMBIO CLIMÁTICO †**

**[RESILIENCE OF COFFEE AGROECOSYSTEMS IN LIGHT OF CLIMATE CHANGE]**

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**SUMMARY**

**Background.** Climate change puts pressure on the agroecosystems, and the cultivation of *Coffea arabica* may not be resilient under these conditions. **Objective.** The objective of this study was to determine the impact of climate change on coffee agroecosystem resilience. **Methodology.** *Maxent* software was applied to model current and future scenarios. The current scenario was developed using 19 bioclimatic variables obtained from the *Worldclim* database with climate records for the period 1960-1990. As for the future scenario, the impact of climate change was modeled based on climate projections for the year 2050 using 3 different global climate models: CCCMA, HADCM3, and CSIRO. The variables in this study were analyzed using *Statistica* and *Gephi* software. **Results**. The results showed under the climate change scenario that 15% of the plots were distributed in unsuitable / non-resilient areas and 85% in moderately suitable and suitable/resilient areas for the establishment of *C. arabica*. Also, the adaptation indicators showed a higher frequency (30) of negative values in coffee agroecosystem (C-AES) plots in areas of both high impact and low impact. **Implications**. The data could allow the redesign of the coffee agroecosystems to improve the weak elements of its structure. Even the structure reinforcement could be direct with farmers or by public politics, government institutions, organizations, and coffee businessmen. **Conclusion.** It was concluded that after 2050, the conditions for coffee cultivation will be reduced and as a consequence, the proportion of plots at lower altitudes will remain outside the optimal environmental conditions. On the other hand, there will be plots within the area with suitable conditions for cultivating *C. arabica*, therefore these will be resilient to climate change, but these will need to establish precise adaptation strategies for the disturbances that will take place in the immediate future.
**Key words:** adaptation; regime; socioecological; sustainability; impact.

**RESUMEN**

**Antecedentes.** El cambio climático ejerce presión sobre los agroecosistemas, y el cultivo de *Coffea arabica* podría no ser resiliente bajo dichas condiciones. **Objetivo.** Por lo anterior, el presente trabajo tuvo como objetivo determinar el impacto del cambio climático sobre la resiliencia del agroecosistema café. Metodología. Se utilizó el programa *Maxent* para modelar el escenario actual y el escenario futuro, utilizando 19 variables bioclimáticas del sitio W*orldclim*. También, se analizaron datos de distribución obtenidos en 34 bases pertenecientes a herbarios, colecciones botánicas y estudios florísticos realizados en México. As for the future scenario, the impact of climate change was modeled based on climate projections for the year 2050 using models of global circulation A2 (CCCMA, HADCM3, and CSIRO). Las variables de este estudio fueron analizadas mediante el programa *Statistica y Gephi*. **Resultados.** Los resultados mostraron bajo el escenario de cambio climático que el 15 % de las parcelas se distribuyeron en áreas no aptas/no resilientes, y el 85 % en áreas medianamente aptas y aptas/resilientes para el establecimiento de *C. arabica*. También,

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los indicadores de adaptación mostraron mayor frecuencia (30) de valores negativos en parcelas del agroecosistema café (C-AES) en áreas tanto de impacto alto e impacto bajo. **Implicaciones.** Los datos podrían permitir el rediseño del agroecosistema café para mejorar los elementos débiles de su estructura. Incluso, el refuerzo de la estructura podría ser directamente con el productor o mediante políticas públicas, instituciones de gobierno, organizaciones y empresarios cafetaleros. **Conclusiones.** Se concluyó que después de 2050, las condiciones para el cultivo de café se reducirán y como consecuencia la proporción de parcelas a menor altitud quedarán fuera de las condiciones ambientales óptimas. Así mismo, existirán parcelas dentro del área con condiciones para el cultivo de *C. arabica* por lo que serán resilientes al cambio climático, pero se deberán establecer estrategias precisas de adaptación ante las perturbaciones que se presenten en el futuro inmediato.
**Palabras clave:** adaptación; régimen; socioecológico; sustentabilidad; impacto.

## INTRODUCTION

Global climate change have been present throughout the geological history of the planet. However, since 1800 (considered as the beginning of Anthropocene) up to the current year, the concentration of greenhouse gases in the atmosphere has increased mainly due to carbon emission from the combustion of fossil fuels products and the steady decline in global forest cover (Quante, 2010; Hallegatte, 2014). Therefore, it can be considered that current climate change has been caused by human beings, contributing to what some define as Anthropocene. According to IPCC (2015) climate change is defined as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.

Climate change leads to an increase in temperature, precipitation variability and an increase in droughts frequency. Climate change is expected to impact the distribution of wild plant communities and agroecosystems, with consequences such as loss of agrodiversity, decrease in agricultural production, decrease in food security, and increase in food prices (Moukrim *et al*., 2017) and, eventually, in loss of human lives. Regarding crops, the impact can be negative for some species and positive for others, depending on their geographic location. Concerning *Coffea arabica*, there are areas that are not suitable for growing it at this moment, mainly due to altitude and weather conditions. However, in the future to cope climate change and genetic improvement, conditions suitable for coffee growing could be developed (Schroth *et al*., 2015). However, current cultivation area of *C. arabica* (the highest quality coffee species) will be severely affected due to the reduction of environmental conditions favorable to its development. Around the world, countries such as Indonesia could increase coffee production due to the appearance of new favorable areas, and in Latin American countries, production could decline due to the reduction of land suitable for coffee growing (Schroth *et al*., 2015). In Mesoamerica, the reduction in the cultivable area of *C. arabica* would be between 55 and 62%, mainly at altitudes between 400 and 700 meters above sea level, and this loss could be partially compensated by an increase of between 9 and 13% of the area in lands with an altitude above 1800 m (Sousa, 2019).

In light of climate change scenarios, new genetic materials and environmental conditions will be sought to enable the various crops to adapt. Resilience, as an emergent property, occurs after the adaptation stage and is defined as the tendency of a social-ecological system subject towards change to remain within a stability domain, continuously changing and adapting, but remaining within critical thresholds (Folke, 2010). The resilience of the coffee agroecosystem could become operational using the conceptual model proposed by Walker *et al.* (2004):

- Latitude: the maximum amount a system can be changed before losing its ability to recover. Basically, the width of basin of attraction. Wide basins mean a greater number of states can be experienced without reaching transformation.
- Resistance: the ease or the difficulty of changing the system. It is related to the topology of the basin. Deep basins of attraction indicate that greater forces or perturbations are required to change current state of the system to another one.
- Precariousness: how close the current trajectory of the system, with respect to a limit or "threshold" that, if breached, makes recovery difficult or impossible.
- Panarchy: an influence on the system from the states and dynamics of (sub) systems at scales above and below (Walker *et al*. 2004).

However, if there is an external disturbance that disrupts feedback processes of systems, this triggers a change that modifies the structure and performance of agroecosystems (AESs). As the timescale progresses, perturbations put pressure that makes AESs lose stability, decrease their ability to express resilience, and eventually breach the threshold, then a regime shift occurs (Sheffer and Carpenter, 2003; Folke, 2006; Shackleton *et al*., 2018). The C-AES of the study area could be impacted by climate change, through the increase in temperature and decrease in precipitation, which act as an external disturbance that leads the coffee agroecosystem to a regimen shift represented by environmental conditions that are not suitable for coffee growing and prevent the expression of resilience of the agroecosystem. Therefore, the aim of this study was to determine the effect of climate change on the resilience of coffee agroecosystem in the region of Tezonapa.

## MATERIALS AND METHODS

### Impact of climate change

The climate data imported for modeling the current and future distribution of *C. arabica* were extracted free of charge from Worldclim global database (Hijmans *et al*., 2005; Schroth *et al.*, 2009; Schroth *et al*., 2015). The database consists of 19 bioclimatic variables and monthly climatic data related directly to the physiological aspects of plants (Table 1). In order to model the current distribution of *C. arabica* and achieve a better understanding of the study area, we first delimited the climatic conditions in a quadrant between X coordinates -96.9504 to -96.58424 and Y coordinates -18.83333 to 18.33494.

### Modeling of the current distribution of *Coffea arabica*

The 19 climatic variables were filed in format **.grd* to be subsequently exported as an ASCII file (**.asc*). Each variable analyzed contains records made at meteorological stations for 30 years in the period from 1960 to 1990 (Hijmans *et al*., 2005). To determine both current and potential distribution of *Coffea arabica*, meteorological data were modeled using *Maxent* software and its maximum entropy algorithm (Schroth *et al.*, 2009; Scheldeman and Van Zonne, 2011). This modeling was based on the identification of environments similar to those where *C. arabica* is grown as areas of possible impact. Occurrence data of *C. arabica* were obtained from 34 databases of herbaria, botanical collections, and floristic research and 52 records made in the study area. With occurrence data of *C. arabica*, a potential presence-absence analysis was performed based on the interaction with the 19 environmental variables. In the study area, similarities were calculated among the environmental values in each specific cell and the values of the niche of *C. arabica* (Scheldeman and Van Zonne, 2011*)*.

### Modeling the impact of climate change and its impact on resilience

In order to perform a quick assessment of the potential impact of climate change on the distribution of coffee agroecological conditions, we proceeded to detect changes in distribution based both on current climatic conditions, including potential distribution areas and on the current climatic preferences of the species under future climatic conditions. As for the future scenario, the impact of climate change was modeled based on climate projections for the year 2050 using models of global circulation A2: CCCMA, HADCM3, and CSIRO (Hijmans *et al*., 2005). It was verified that current and future condition data have the same raster properties, resolution, and vertex parameters. Climate data were extracted from the World Climate Database (www.worldclim.org/CMIP5v1) and include 19 daily, monthly, and annual bioclimatic variables, as well as combined data between variables and seasonality. Each *raster* under assessment shows a resolution of 2.5 min equal to 5 $km^2$ (Scheldeman and Van Zonne, *2011*).

**Table 1. Bioclimatic variables used as a reference for modeling both current and future distribution of *C. arabica.***

| Bioclimatic variables are coded as follows: | |
|---|---|
| BIOC1 = Annual mean temperature | BIOC10 = Mean temperature in warmest quarter |
| BIOC 2 = Mean diurnal *range* (mean of monthly (max temp – min temp)) | BIOC11 = Mean temperature of coldest quarter |
| BIOC3 = Isothermality (BIO1/BIO7) * 100 | BIOC12 = Annual precipitation |
| BIOC4 = Temperature Seasonality (standard deviation) | BIOC13 = Precipitation of Wettest Month |
| BIOC5 = Max Temperature of Warmest Month | BIOC14 = Precipitation of Driest Month |
| BIOC6 = Min Temperature of Coldest Month | BIOC15 = Precipitation Seasonality (Coefficient of variation) |
| BIOC7 = Temperature Annual Range (BIO5-BIO6) | BIOC 16 = Precipitation in the Wettest Quarter |
| BIOC8 = Mean Temperature of Wettest Quarter | BIOC 17 = Precipitation of Driest Quarter |
| BIOC9 = Mean Temperature of Driest Quarter | BIOC 18 = Precipitation of Warmest Quarter |
| | BIOC 19 = Precipitation of Coldest Quarter |

Binary *rasters* of presence and absence were created in the modeled distribution areas with current conditions and future projections, which were compared to identify the distribution areas that will be severely affected by climate change, as well as areas where the impact will be less severe and new areas of occurrence (Scheldeman and Van Zonne, *2011*). The binary data generated were exported to Q-Gis 2.6 software where these were reclassified into four potential situations that may arise (Table 2).

**Table 2. Classification of the future distribution of *C. arabica* under the impact of climate change.**

| Situation | Index Values | Impact on the resilience of coffee-AES |
|---|---|---|
| (i) High impact areas | -1 | Non resilient |
| (ii) Outside the fulfilled niche | 0 | |
| (iii) Low impact areas | 1 | Resilient |
| (iv) New suitable areas | 2 | |

The number of plots inside and outside low impact areas, the areas outside the niche and high impact areas was quantified. Due to climate change acts as a driver of change (Walker *et al*., 2004; Gunderson, 2008; Rocha *et al*., 2018) AESs within low impact areas were considered as resilient within low impact areas, and those located in areas outside the niche and in high impact areas as non-resilient (Table 2). Six variables were measured with a structured questionnaire (Table 3) related to adaptation and resilience development (Altieri and Nicholls, 2014).

The values obtained in the variables of table 3 were standardized to do use of the equation [1] proposed by Hahn *et al.* (2009).

$$I_v = \frac{I_a - I_{min}}{I_{max} - I_{min}} \quad 1)$$

Where $I_v$ is a standardized value of the indicator, $I_a$ is the value for a particular agroecosystem, $I_{min}$ for total lower value from total agroecosystem, $I_{max}$ for the higher value of agroecosystem total (Hahn *et al*., 2009).

**Statistical Analysis**

The data were analyzed using descriptive statistics (central trend), and frequency analysis for dichotomous and nominal variables. Further a Spearman correlation analysis was performed to identify trends and analysis of variance to determine if there are significant differences between current and simulated conditions in the climate change scenarios. For this purpose, we used *Statistica® 7.0* software.

## RESULTS

**Changes in the Environmental Conditions for *C. arabica* Growing**

According to modeling, currently, the sample plots are distributed in an area where environmental conditions are favorable (index values 0.6 and 0.9) to *C. arabica* (Figure 1). Taking as a reference World Coffee Research's altitude classification (2018), a frequency of the following plots was identified (n = 52) low altitude (14), medium altitude (23) and high altitude (15) plots in a range between 142 – 1367 m above sea level.

**Table 3. Practices related to the promotion of resilience in AESs.**

| Resilience-building practices | Definition | Unit of measure |
|---|---|---|
| Land Slope | Level of land slope. Plots with a steeper slope are more susceptible to erosion and plot management is hindered. | % slope |
| Producer's number of cultivars of *C. arabica* | Diversity of cultivars with their own performance capabilities in different scenarios. | % |
| Use of the media to gain access to information | Media available and in use that allow access to information | % |
| Agroecological techniques used in the coffee plantation | Techniques that allow sustainable production in the agroecosystem | Number of techniques |
| Association of usable plants with the coffee plantation | Diversity of cultivable plants and plants for human consumption associated with coffee plantations | Number of plants |
| Technical Assistance and Producers' Organization | Private or public technical support, as well as organization that ease agroecosystem management | % |

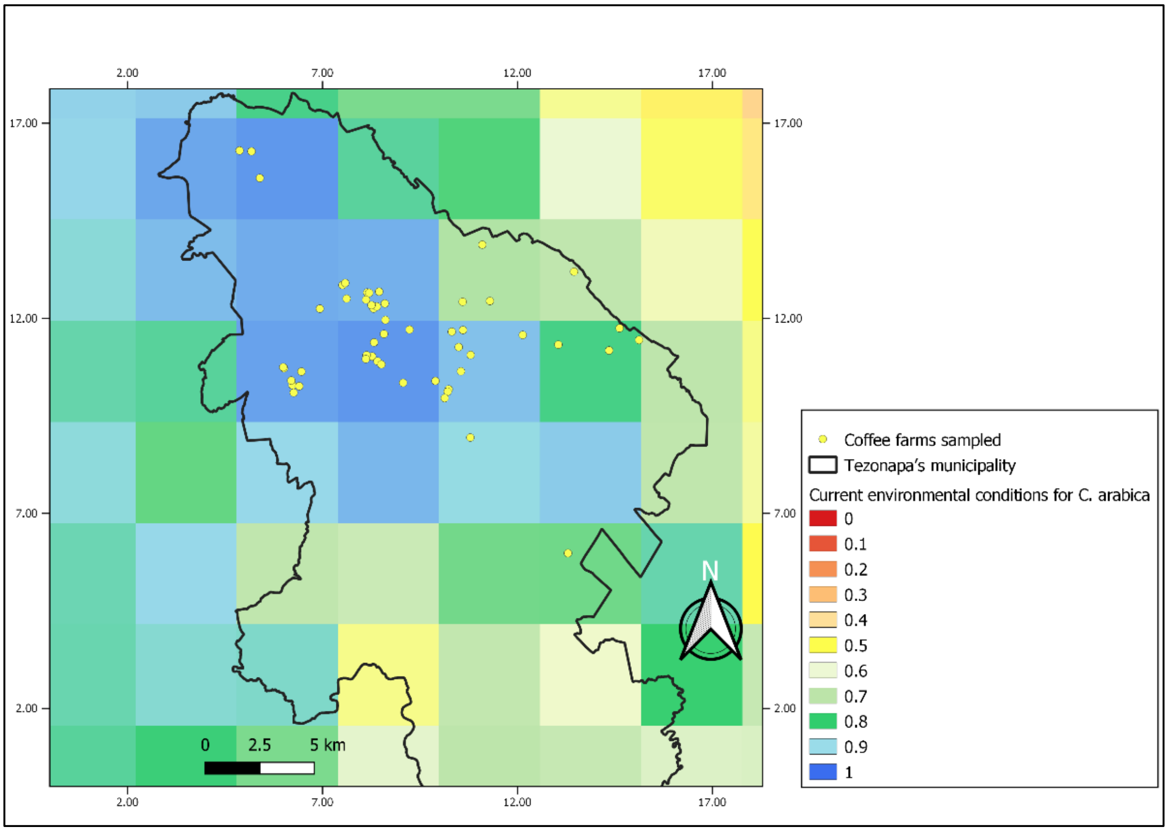

**Figure 1.** Distribution of sampled plots and both favorable and unfavorable environmental conditions for *C. arabica*.

Environmental conditions allow coffee growing to be associated with native shade tree species such as *Trema micrantha*, *Virola guatemalensis*, *Inga vera* and *Alchornea latifolia* (Sánchez *et al*., 2017) which in turn are associated with vegetation types with environmental parameters similar to those found in the plots. Shade tree species are associated with high evergreen forest and annual mean precipitation above 2000 mm and annual mean temperature between 22 and 26 °C. The medium evergreen forest with annual mean precipitation above 1500 mm and annual mean temperature below 18°C, and the sub-evergreen forest with annual precipitation between 1100 and 1300 mm (Pennington and Sarukhán, 2005). Temperature and precipitation can be considered to be influenced by elevation and orography because the higher the elevation, the lower the temperature and the higher the precipitation.

By 2050, as a result of climate change, 18% of plots would be located in areas with unfavorable growing conditions (0-0.5), 42% would be located in an area with threshold of change (0.5-0.6) and 40% under conditions that are still favorable for *C. arabica* growing *(0.6-1)*. Due to the above, plots with conditions that are still favorable for *C. arabica* growing must apply adaptation strategies to maintain a condition far from the agroecosystem's tipping point (Figure 2).

The elevation of the landscape where plots are located within the area under study may act as "buffer" for climate change due to both a trend that the higher the altitude, the better the environmental conditions, as well as a significant correlation of 0.838 between both variables was found.

Climate change promotes environmental conditions that exceed the limit of resistance of *C. arabica*. However, there are also plots with tipping point conditions and others in areas suitable for *C. arabica* growing. This may benefit other species and allow them to occupy an ecological niche under the new conditions (Figure 3).

The reduction of the area suitable for *C. arabica* growing agrees with the findings of a research performed in other coffee-producing regions such as Indonesia (Schroth *et al.*, 2014), Latin America (Schroth *et al*., 2009; Laderach *et al.*, 2016; De Sousa *et al.*, 2019) and Africa (Capitani *et al*., 2018) in which it was determined that the current coffee-growing area will be reduced, due to environmental changes caused by climate change.

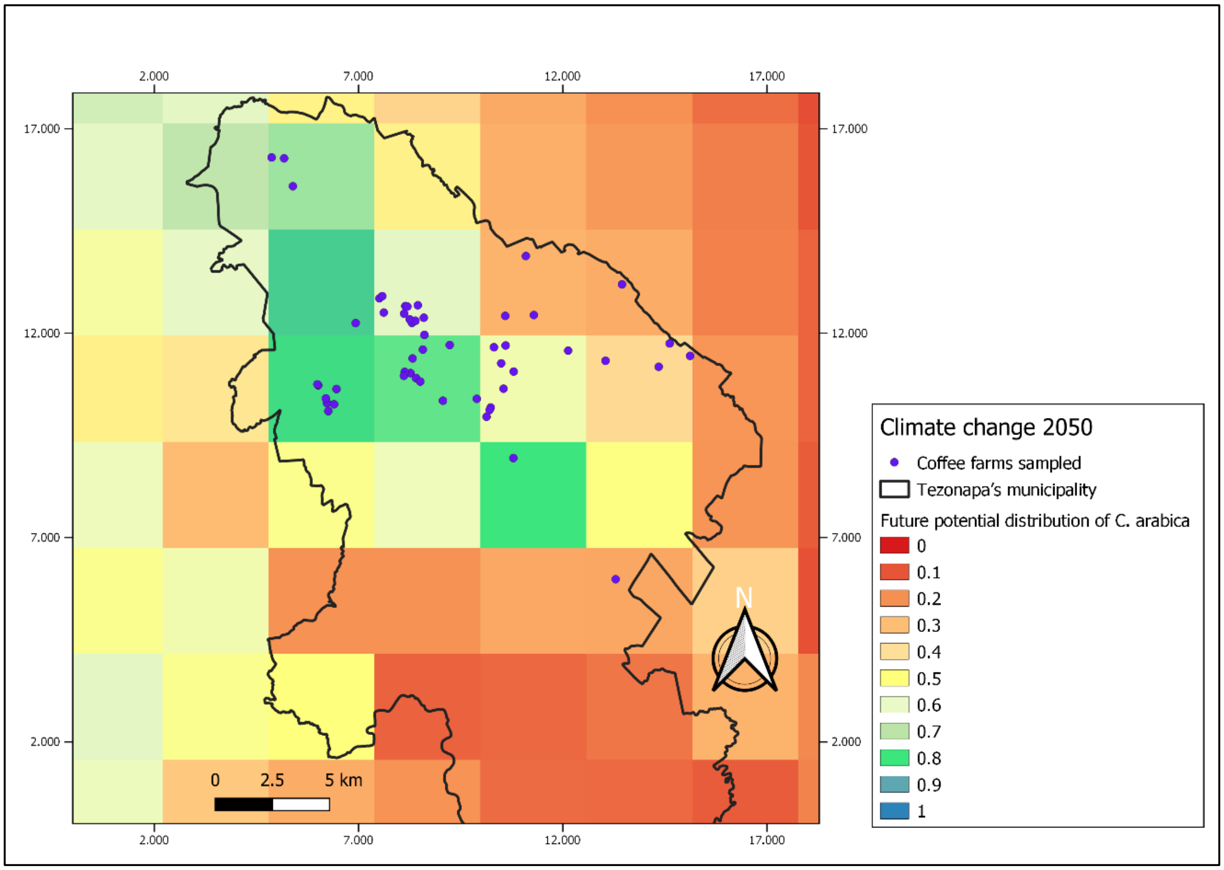


**Figure 2.** Geospatial modeling of future environmental conditions under the influence of climate change and the current distribution of coffee cultivated plots.

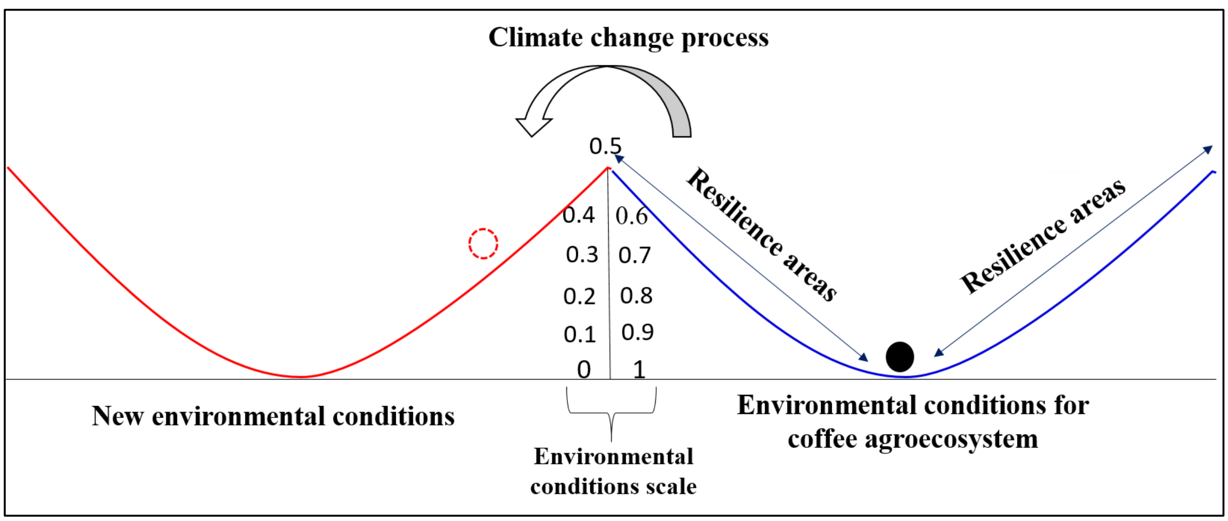


**Figure 3.** Transformation of the coffee agroecosystem due to the impact of climate change. As amended from Walker *et al*., 2004.

**Impact of climate change on the resilience of coffee agroecosystem**

By 2050, 15% of the sampled plots would be in high impact areas where conditions will no longer be suitable for *C. arabica*, while 85% were in low impact areas where the species is likely to occur now and, in the future, and no new ideal areas were found in the study area (Figure 4).

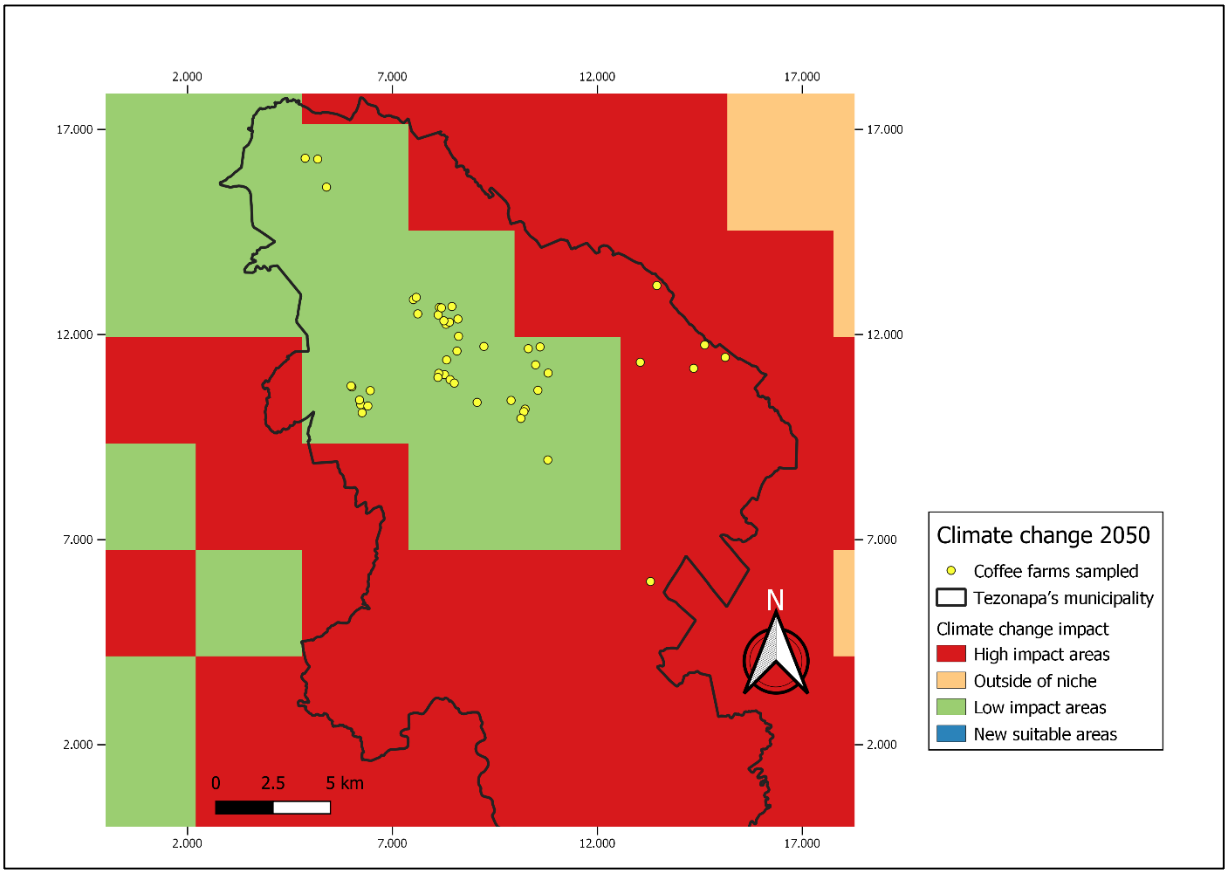


**Figure 4.** Impact of climate change on the distribution of agroecosystems after 2050.

The emergence of new areas that are climatically favorable or suitable for coffee growing could have the limitation of being considered as environmental protection areas or show non-optimal agronomic conditions such as the presence of shallow soils with low fertility and significant slope, or because they are remote areas that would hinder the transportation of inputs for the establishment of plantations or harvesting (Schroth *et al*., 2009, Schroth *et al*., 2015; Laderach *et al*., 2016; Capitani *et al*., 2018 and De Sousa *et al*., 2019).

In areas with high climate change impact, the temperature increase could have direct impact on *C. arabica* especially if leaf surface area is exposed for a long period of time to temperatures higher than 30 °C (Da Matta and Cochicho, 2006). In addition, longer exposure to solar radiation implies the development of chlorosis and burns on leaf surface (Da Matta and Cochicho, 2006). The optimum temperature for coffee growing is considered between 18 - 21 °C, so temperatures above this range could cause problems during the fruition process (Montoya and Jaramillo, 2016). The increase in temperature could influence an accelerated loss of leaves with its respective negative effect on the conditions of coffee trees. In addition, long-term exposure of coffee plant to high temperatures of 28°C decreases the development of flower buds, which is totally inhibited at 33°C. High temperatures also promote floral malformation. (Drinnan and Menzel, 1994).

It has been documented that precipitation is one of the main factors affecting coffee productivity, and that under climate change scenarios a decrease in precipitation could adversely affect the production of cherry coffee (Rivera *et al*., 2013). Another effect that climate change could cause is water shortfall that could be reflected in the loss of turgor, and combined with the dynamics of the weather, the effects could be severe on plants, even causing total desiccation (Da Matta and Cochicho, 2006). However, there is the likelihood that in a scenario that experiences lower precipitations, irrigation systems could be implemented, if the landscape allows it, but there is the drawback that the volume of water available for irrigation is being reduced, which could impact coffee and other crops generating water stress as it has been documented in the northern region of China where, according to Sun *et al.*, (2018), it was reported that under RCP 4.5 and RCP 8.5 scenarios, a reduction between 34 and 37% of irrigation water is expected, with a direct impact on extensive crops.

**Current Use of Adaptation Strategies in Areas with High and Low Climate Change Impact**

Plots within the area with high climate change impact (n = 8) showed negative values in variables *"land slope"* "*cultivar diversity*" and "*plant association*" regarding resource use by humans. The *"use of agroecological techniques*" shows a medium value, with a positive trend, and the variables "*access to information through the media*" and "*Technical Assistance and Organization*". In connection with the plots in the low-impact area (n=44), these showed three negative variables: "*land slope*", "*number of cultivars*", "*plant association*" and "*technical assistance and organization*". The variable "*use of the media*" showed a medium and "*use of agroecological techniques*" a positive value for the development of *C. arabica* (Table 4).

The plots located inside and outside the high and low impact zones show negative values with eventual risk to water and wind erosion, due to the fact that they are located in marginal areas with slopes between 26-56.6 %. The use of sustainable practices allows for the development of resilient AESs as indicated by Hekelman *et al.*, (2018) who evaluated organic and conventional rice agroecosystem management and determined that organic systems are more climate resilient compared to conventional AESs. Also, diversification of AESs allows for increased resistance to external disturbances. For example, Li *et al*., (2019) found out that diversified AESs showed a 14% advantage to disturbances, such as pests and diseases, compared to non-diversified AESs. However, environmental conditions are not favorable in high impact areas for the development of *C. arabica*. Therefore, the strategies pointed out by Li *et al*., (2019) and Hekelman *et al*., (2018) would not be enough to maintain *C-AES*. Accordingly, new conditions could lead farmers to switch to another crop that is more adaptable to the new conditions, or to migrate in search of better economic, social, and environmental conditions, as documented in the Philippines (Bohra-Mishra *et al*., 2017), Bangladesh (Bell *et al*., 2021) and countries mainly dependent on agriculture (Ruohong *et al*., 2016) where climate has significantly influenced people's relocation.

**Table 4. Conditions and current usage strategies that promote adaptation to climate change in high and low impact areas.**

| Impact of climate change | Land Slope | Number of cultivars | Use of the media | Use of agroecological techniques | Asso-ciation of plants | Technical assistance and organization |
|---|---|---|---|---|---|---|
| High | 0.292 | 0.088 | 0.666 | 0.592 | 0.371 | 0.888 |
| Low | 0.361 | 0.334 | 0.539 | 0.658 | 0.418 | 0.302 |

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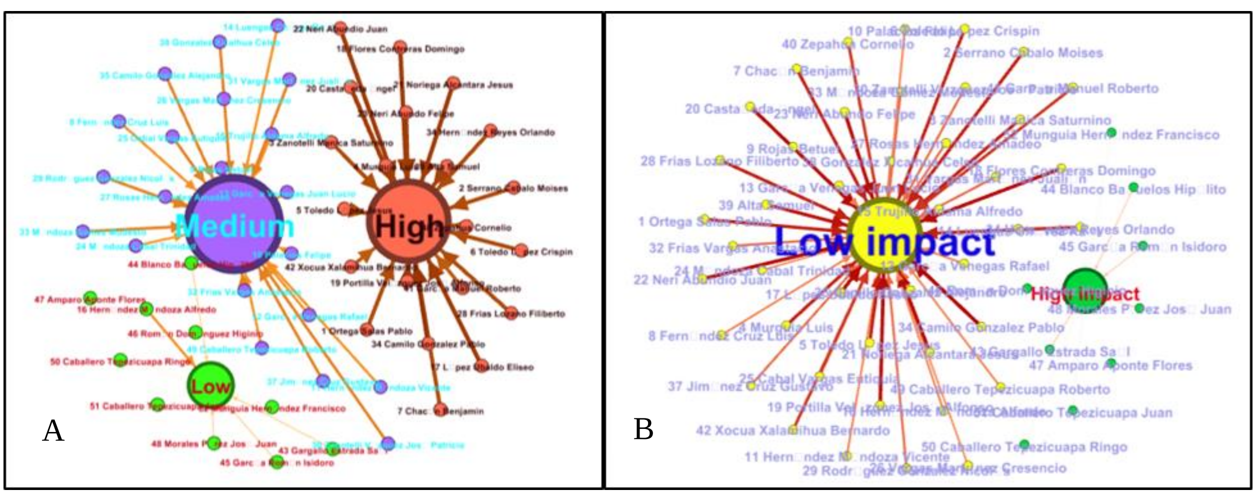


**Figure 5.** The coffee agroecosystem plots and their relation to altitude, and areas of high and low climate change impact: A) plot association with the altitude coffee research classification: high (Weighted In-degree 15.003), medium (Weighted In-degree 11.262), and low (Weighted In-degree 3.139); the thickness connections represent positives values to the average of six adaptation indexes. B) Association of plots with high impact areas (Weighted In-degree 2.621), or not resilient, and low impact areas (Weighted In-degree 26.783) or resilient, where the slight connections represent negatives values to an average of six adaptation indexes.

About the index adaptation average, the plots localized at low altitude, the "high" frequency value was 3, "medium" was 3, and low was 8. In the plots localized at medium altitude, the frequency of value "high" was 4, "medium" was 6, and low was 13. The plots localized at low altitude was 3, "medium" was 4 and low was "9". Concerning the areas of climate change low impact, the frequency of the adaptation index with "high" value was 7, "medium" was 10, and "low" was 26. In the area of high impact, the adaptation index with "high" value was 2, "medium" 3, and "low" was 4 inside of the area with positive conditions or the low impact areas to *C. arabica* development (Figure 5).

In the adaptation index assessed, negative values were frequent, due to it, is necessary to enhance the practices already implemented by coffee growers to maintain a condition far from the threshold of change and avoid its transformation. Due to the above, one option would be to implement strategies based on the Climate-Smart Agriculture (CSA) approach, which would allow guiding the necessary actions to foster the resilience of coffee AESs and effectively support development in the light of a changing climate environment. Therefore, CSA may lead coffee AESs to achieve goals such as: 1) sustainable increase in agricultural productivity and income; 2) adaptation and building resilience to climate change; and 3) reduction and/or absorption of greenhouse gases (FAO, 2013; McCarthy and Brubaker, 2014; Makate *et al.* 2019).

## CONCLUSIONS

After 2050, environmental conditions suitable to the current distribution and *C. arabica* growing at areas located at lower elevation will be reduced. This will have an impact on the resilience of the farms because climate change will act as a driver of change that will lead to the transformation of some coffee farms and, consequently, resilience will no longer be present as an emerging attribute because coffee agroecosystem would be unable to adapt to new climatic conditions, which could benefit the establishment of another crop, livestock activity or economic activity. However, regarding the farms within the area with conditions for coffee growing, it is necessary to enhance components of the structure through the use of agroecological practices or strategies based on CSA, which will allow maintaining a state of precariousness away from the resistance threshold of AESs and thus ensure that C-AES is maintained as a livelihood for farmers.

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**Compliance with ethical standards.** This research was carried out based on the code of ethics for research and research action. In addition, the project was approved by the municipality of the study area.

**Data availability.** Descriptive statistics and maext results are available at https://doi.org/10.5281/zenodo.6616963. Additional data is available with the main author (iquiroz@uv.mx)

**Author contribution statement (CRediT). I. Quiroz-Guerrero** - Conceptualization, data curation, funding acquisition, formal analysis and writing original draft., **A. Pérez-Vázquez** – Conceptualization, supervision, formal analysis, writing- review & editing., **C. Landeros-Sánchez** – Formal analysis, writing- review & editing., **F. Gallardo-López** – Writing- review & editing., **J. Velasco-Velasco -** Writing- review & editing., **G. Benitez-Badillo**- Writing- review & editing.

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