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POTENTIAL IMPACT OF CLIMATE CHANGE ON COFFEE PRODUCTION UNDER A RICARDIAN APPROACH

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ABSTRACT

Climate change (CC) has adversely affected coffee production and producer in-come. The Mazateca and Cuetzalan regions in Mexico are highly economically de-pendent on coffee-growing and vulnerable to CC. This study assesses the potential impact of CC on coffee production in these regions. In 2019, data from a sample of 180 farms were collected and analyzed using the Ricardian approach, based on the analysis of land value (LV), to estimate the impact on the profitability of coffee farming under different CC scenarios. The results showed that CC will have a considerable impact on the LV in coffee-growing areas, especially for smallholder coffee farmers and in the Cuetzalan region. Based on projections, CC could have a positive impact on the LV in the Mazateca region in most scenarios, but in all sce-narios, the impact in the Cuetzalan region will be highly detrimental, with over 40% LV loss. Moreover, the negative impact of CC will be exacerbated for smallholder farmers, given their preexisting socioeconomic vulnerability and limited adaptive capacity. In conclusion, CC will have a marked impact on LV, varying from region to region, which could be irreversible for coffee production. Based on these find-ings, agricultural and non-agricultural production diversification strategies should be developed to replace the high farmers' dependence on coffee-growing, thereby improving their income and reducing their vulnerability.

Keywords: coffee farmers, income, land value, regions.

INTRODUCTION

Agriculture is an economic activity highly susceptible to climate variability and climate change (CC) (Jawid, 2020). Changes in temperature, rainfall patterns and extreme weather events, such as floods and droughts, are having negative effects on food production and food security, with small producers being the most affected (Jawid, 2020; Malhi *et al*., 2021). Any impact on the livelihoods of these farmers to produce food would significantly affect the rural economy and the food security of the population (Estrada *et al*., 2022).

Small producers fundamentally depend on agriculture as their main source of income and subsistence (Toledo and Barrera-Bassols, 2017). They often do not have access to resources and technologies needed to adapt to changing climatic conditions, making them particularly vulnerable to the effects of CC (Nor Diana *et al*., 2022).

In Mexico, this type of agriculture is prevalent and constitutes 81.3% of the rural economic units in the country (Ramirez-Juárez, 2022). This sector plays an essential role in the welfare of the rural population, where the majority of small farmers depend on this activity (Estrada *et al*., 2022).

So, it is necessary to address the potential impact of CC in small producers' activity to dimension the environmental and economic risks that CC represents in those vulnerable agroecosystems in order to generate strategies and public policies for sustainable development focused on adaptation and mitigation (Guerrero-Carrera *et al.,* 2020; Raihan and Tuspekova 2022).

Coffee farming is a good case study because it represents an example that encompasses the aforementioned problems (Guerrero-Carrera *et al*., 2020). Coffee production is one of the agricultural activities most threatened by CC (Campbell, 2021). Mexico is one of the ten main coffee-growing countries worldwide, and over half a million coffee growers depend on this activity in the country (Gumencindo-Alejo *et al.,* 2021). However, in recent decades, coffee growers have faced various problems in Mexico, such as low income due to the low profitability of coffee caused by international price fluctuations, which often result in a decline in prices (Avalos *et al.,* 2023). Moreover, in 2012, coffee rust damaged vast swaths of Mexican plantations, forcing replanting (Henderson, 2020).

Globally, studies suggest a progressive CC impact on coffee production, which will affect from 30 to 90% of all coffee-growing areas (Läderach *et al*., 2017; Imbach *et al*., 2017). Furthermore, CC facilitates the spread of coffee pests and diseases (Avalos *et al.,* 2023).

Then, it is necessary to understand how climate variations are affect production, profitability and land value (LV) in coffee farming, as well as to identify the adaptation measures that are implemented to reduce the negative impacts of CC (Mora *et al*., 2010; Guerrero-Carrera *et al*., 2020). Because of the vulnerability of coffee growers, such research is needed to provide them with information to anticipate CC effects and to design local strategies, programs, and policies for CC adaptation and mitigation accordingly (IPCC 2007; Craparo *et al*., 2015). Similarly, studies with an economic approach (such as the Ricardian model) are particularly relevant to assessing the potential impact of CC on agriculture (Mora *et al*., 2010; Jawid, 2020)

THEORETICAL FRAMEWORK

For last two decades, great interest has been expressed in analyzing and measuring the effects of CC in agriculture. In these efforts, several models are reported in the literature, ranging from agronomic, agro-climatic, and economic approaches (López and Hernández, 2016). Within the latter are those that use a general equilibrium model, the production function model, and the Ricardian approach (Mora *et al.,* 2010).

The agronomic approach simulates crop growth during the plant life cycle and measures the effect of changed climatic conditions on crop yield and input requirements (Schlenker *et al*., 2006). Agronomic models provide evidence that technological solutions would increase yields but they fall short of justifying whether farmers will actually choose these techniques or even whether these strategies would be economically beneficial responses (Reilly, 1999). An important disadvantage is that economic aspects of the problem are not considered (Schlenker *et al*., 2006).

Agroclimatic models use base scenarios and climate projections to estimate the effects of CC on crop production. According to Candelaria *et al*. (2011), these models are used to simulate sustainability, under a holistic and systemic vision. Another important evolution has been to consider the producer as a subject who participates in modeling. Adams *et al*. (1990) carried out the first study to analyze the effects of CC on agriculture in the United States from an economic point of view. The results showed that CC leads to a slight reduction in the total cultivated area in the United States. The Computable General Equilibrium (CGE) approach models agriculture in relation to the other major sectors of the economy and allows resources to move between sectors in response to economic incentives.

In summary, agronomic models do not fully capture farmers' adaptation and mitigation strategies to face CC and, on the other hand, CGE models are only appropriate for highly aggregated sectors of the economy (Schlenker *et al*., 2006).

The production function approach estimates the impacts of CC on agriculture by varying one or a few input variables, such as temperature, precipitation, and carbon dioxide levels (Gay *et al.,* 2006). Numerous studies employing this methodology have predicted severe yield reductions for various crops across different regions as a consequence of global warming (Lobell *et al*., 2011). However, these studies fail to consider the adaptive measures that farmers can implement in response to changing environmental conditions. By not accounting for these potential adaptations, previous studies may have overestimated the extent of damage caused by environmental changes (Mendelsohn and Dinar, 2009).

Mendelsohn *et al.* (1994) developed the innovative Ricardian approach, which corrects the bias in the production function technique by using cross-sectional economic data on LV. This approach examines how climate affects net income, allowing for a more comprehensive analysis of the effect of climatic and non-climatic variables on LV and farm income. Despite the emergence of new models and techniques in the years following its introduction, the Ricardian approach remains a valuable and widely used tool in research on CC and agriculture due to its ability to capture farmers' adaptation and provide more realistic estimates of long-term economic impacts.

The Ricardian approach allowed for substitution in land uses. Therefore, when the CC, a piece of land becomes unsuitable for typical agricultural uses, but is still suitable for other valuable, non-agricultural uses, this will be reflected in the price of the land and should be picked up in the regression hedonic, which can be estimated using ordinary least squares (OLS) (Schlenker and Roberts, 2009). In this case, an agronomically focused analysis that looked closely at agricultural uses would exaggerate the value loss induced by CC, while the Ricardian approach would correctly identify that substitution of appropriate non-agricultural uses reduced the value loss. Thus, the model reduces estimation biases; however, it does not take into account the social, economic, and environmental implications of such a change in land use (Schlenker *et al*., 2006).

One aspect that makes the Ricardian model very attractive is that it takes adaptation into account, while the others do not. We know theoretically that adaptation reduces harm. The Ricardian approach finds less harm to American agriculture than the other approaches. This is empirical evidence of the power of adaptation (Schlenker *et al*., 2006).

The Ricardian approach has been widely applied in various regions of the world to assess the impact of climate change on agriculture. For example, Kurukulasuriya and Mendelsohn (2007) applied this method in several African countries, finding that lowland farms are more sensitive to climate change than highland farms. In Asia, Jawid (2020) used the approach in Afghanistan, revealing significant impacts on rainfed agriculture. These studies demonstrate the versatility of the Ricardian method in different geographical and agricultural contexts.

Although the Ricardian approach has disadvantages and weaknesses like other approaches that evaluate the impact of CC on agricultural production, this model has characteristics of ease of estimation and greater possibilities of obtaining the required data, considering that this model can capture the potential adaptation measures that producers could incorporate in their production units due to the climatic conditions that could be in place.

Among the methodological improvements in the present study, the following aspects were included: a) a technological level index of the production units was constructed and incorporated as control variables in the specifications, b) this model jointly integrated the agricultural and non-agricultural incomes of the production units and their influence on LV. Additionally, c) georeferencing techniques of the production units were used in this study to obtain more precise locations and achieve more accurate climatic values in the developed geospatial interpolations. These contributions enhance the understanding of the potential impact of CC on coffee production.

This study tests two hypothesis:

Hypothesis (H1): CC has a negative economic impact on coffee production in Cuetzalan and Mazateca region in México.
Hypothesis (H2): Small coffee farmers are more vulnerable to CC than large coffee commercial farms by comparing the climate sensitivity of small and large farms in Mexico.

METHODS

This section addresses the specifications of the Ricardian model, the study area, sociodemographic data, climate and soil variables, as well as the climate scenarios and statistical analysis.

Model specifications

The Ricardian method is named after David Ricardo, who first noted that the LV or Farmland Net Revenues (π) reflects the farmland net productivity (Mendelsohn *et al*., 1994). In this study, the units of analysis are the production units (PUs), according to Malagón and Prager (2001) and Stamberg (2015), the PUs can be defined as a family entity engaged in productive activities where interactions and feedback occur among various internal components. These components encompass natural resources, inputs, technological equipment, production processes, and the generated outcomes or products. Additionally, the influence of external factors such as climate, soil conditions, and markets must be taken into account as they exert a significant impact on agricultural production and profitability. Clear examples of production units are farms and estates.

The Ricardian approach assumes that farmers maximize their net income (π) given by the following equation:

$$\pi = \sum P_i Q_i \left(X, F, Z, G \right) - \sum W_x X \quad (1)$$

where P_i: market price of crop *i*; Q_i: output of crop *i*; *X*: vector of purchased inputs; *F*: vector of climate variables; *Z*: vector of other control variables, such as soil, market access, and altitude; *G*: vector of sociodemographic variables; *Wx*: vector of input prices.

By assumption, the farmer selects Q and X to maximize the LV by hectare given the characteristics of the (temperature, precipitation, and soils) and market prices (Ajetomobi *et al*., 2011; Mendelsohn and Dinar, 2009).
The optimal function is expressed as in equation (2):

$$\pi = f\left(P_i, F, Z, W_x\right) \tag{2}$$

Equation (2) was used to determine how changes in exogenous variables contained in F and Z affected the farmland's net productivity. Thus, the LV represented the present value of the net revenue flow, whose notation is:

$$LV = \int_n^\infty \pi_t^* \cdot e^{-rt} dt \tag{3}$$

In equation (3), r is the market interest rate. The standard Ricardian model is a quadratic formulation of climate and a linear function of all other variables and can be econometrically expressed as in Equation (4):

$$LV = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 P + \beta_4 P^2 + \beta_5 TP + \sum \delta_j z_j + e \tag{4}$$

where *LV* is the farmland value by hectare; *T* and *P* are the temperature and precipitation, respectively. Temperature and precipitation are commonly differentiated by season of the year. Similarly, *Z* represents the set of socioeconomic variables of *PU* indexed from *i*=1 to *n*, and soil, β_k and δ_j are estimated parameters, and *e* is an error term (Mora *et al*., 2010). Explicitly, the estimated equation is in equation (5).

$$\begin{aligned} LV = {} & \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 P + \beta_4 P^2 + \beta_5 TP + \beta_6 TS + \beta_7 TI + \\ & \beta_8 DM + \beta_9 EX + \beta_{10} ES + \beta_{11} INC + \beta_{12} GE + \beta_{13} HC + e_i \end{aligned} \tag{5}$$

where *T* is temperature (°C); *P* is precipitation (mm); *EX*: farmer experience (in years); *ES*: education of household head in years; *INC*: *per cápita* income (in thousand MXN); *HC*: home computer (dummy variable); *GE*: age of household head and gender of household head; *LA*: land area; *TS*: type of soil; *TI*: technology index; *DM*: market access (in minutes).

Linear and quadratic terms of temperature and precipitation are incorporated into Equation (4) to capture non-linear crop responses to climate. Laboratory experiments suggest that crops tend to show an inverted U-shaped response as a function of temperature (Mendelsohn and Dinar, 2009). Additionally, at low (temperate) temperatures, the farmer's optimal decision may be to grow Arabica coffee (*Coffea arabica*). However, as the temperature increases, the marginal profit of this product decreases until it becomes negative. Then, the farmer should make the decision to optimize profits by selecting a crop adaptable to higher temperatures (warm temperatures). In this context, this crop could be Robusta coffee (*Coffea canephora*). Similar reasoning can be applied to crops sensitive to rainfall. In some range, interaction of temperature and rainfall could reinforce their effects on crop yield (Mendelsohn and Dinar, 2009). By following this logic, the Ricardian model assumes that farmers adapt their behavior throughout the intertemporal production cycle (Mendelsohn *et al*., 1994; Ordaz *et al*., 2010). The explanatory consistent variables of each of the regressions were as proposed in literature (Kurukulasuriya and Mendelsohn, 2007; Mora *et al*., 2010; Mendelsohn and Dinar, 2009) and then, we test a couple of additional variables based on its statistical significance.

The Ricardian model estimates the potential future effects of CC on LV. Through the set of coefficients of the climatic variables of the specifications, the marginal impacts on temperatures and precipitations are estimated, the results may reflect positive effects or negative effects on LV (Mendelsohn and Dinar, 2009). Subsequently, the model incorporates scenarios with different levels of greenhouse gas emissions and the estimated changes in temperatures and precipitation. The model then uses these projections to estimate how CC might affect future LV and income (Mendelsohn *et al*., 2010).

The marginal impact of climatic variables on LV was evaluated using equation (6).

$$\frac{\partial LV_i}{\partial T} = \beta_{ti} + 2\beta_{2i}T + \beta_{5i}P \quad (6)$$

Thus, different levels of the sensitivity to CC of each i PU was determined by the characterisation of its specific profile. The annual effect of a marginal change in the climate variable in question was calculated by adding the marginal effects of this variable (Mora *et al*., 2010).

Theoretically, the quadratic formulation can change not only the magnitude but also the sign of the marginal effect (Mendelsohn *et al*., 2010). When the quadratic term is positive, the function has a U shape, and when the quadratic term is negative, the function has an inverted U shape (Mendelsohn *et al*., 2010). For each crop, growth is optimal at a known temperature across seasons. Many crops have a broader, flatter inverted U-shaped curve. However, seasonal climate variables display a more complex relationship, which may include

a mixture of positive and negative squared coefficients between seasons (Mendelsohn *et al*., 2010).
The change in annual welfare (ΔW), resulting from a CC from C0 to C1 (measured as the difference in LV in two periods) is given by:

$$\Delta W = W\left(C_1\right) - W\left(C_0\right) \tag{7}$$

Changes that increase LV are beneficial, and changes that decrease LV are detrimental. Therefore, this approach is a comparative static analysis, not a dynamic model. The Ricardian model does not measure the effects of annual CC but rather those of long-term CC (Mendelsohn *et al*., 2010).
The optimal values of the significant climate variables (temperature and precipitation) were calculated using equation 8 (Mendelsohn and Dinar, 2009).

$$\textit{Inflection}\ \text{point} = \frac{\beta\ \textit{Temperature}}{2x\beta\ \textit{Temperature}^2} \tag{8}$$

Study area

This study was conducted in the Mazateca region of Oaxaca and in the Cuetzalan Puebla region (Figure 1). These regions strongly depend on coffee-growing because they are two of the main Mexican coffee-producing regions (Moguel and Toledo, 1999), and they are highly vulnerable to CC (Monterroso *et al*., 2014).

Data

LV, income, and sociodemographic data were gathered from Production Units (PU) which are the unit of analysis, defined as a decision-making unit of production and sales of coffee. The sample of PU were retrieved from a survey of coffee growers and verified by key informants from the Mazateca region of Oaxaca and from the Cuetzalan Puebla region in 2019, totalling 180 landowners of coffee PUs from 16 coffee-growing municipalities. The main variables of the study were based on Waha *et al*. (2016). Therefore, the questionnaire was divided into 8 sections: 1) Home, 2) Employment, 3) Production unit, 4) Agricultural activities, 5) Livestock activities, 7) Access to information, 8) Income (Table 1).

Climate variables

Climate data were collected from the National Water Commission (Comisión Nacional del Agua – CONAGUA) webpage and the National Meteorological

Figure 1. Location of Mazateca region of Oaxaca and Cuetzalan Puebla.

Service (Servicio Meteorológico Nacional – SMN) (CONAGUA, 2019). These data were extracted from 25 meteorological stations located in the two regions of the study area. The climatological normals used for this purpose spanned from 1951 to 2010. The climate conditions of each location and PU were assigned using the kriging interpolation method for precipitation and the Inverse Distance Weighting (IDW) interpolation method for temperature (Oliver and Webster, 1990). The interpolations were processed in ArcGIS software (Mendelsohn *et al*., 2010; Fries *et al*., 2012). To this end, communities and PUs were georeferenced using latitude, longitude, and altitude data.

The analysis was conducted by year. Since coffee is a perennial crop, it is necessary to include the variation of temperature and precipitation. The climatic variables were incorporated into the econometric model as variables, each one representing a season of the year, namely spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February). These seasons

Table 1. Variables used in the questionnaire.

Sections	Variables
I. Household	1. Household members (sex, age, and education)
II. Employment	1. Employment of the household head (agricultural and non-agricultural activities)
III. Production Unit	1. Agricultural activities 2. PU size (ha), broken down by activity 3. Land tenure 4. PU value
IV. Agricultural Activities	1. Crop, planting date, harvest date, proportion of farmed land area, amount harvested and yield 2. Amount of consumed, sold, and lost crops and value of sold crops 3. Seeds, fertilisers and pesticides, and costs 4. Agricultural machinery, equipment, and buildings 5. Market access to supply sales and purchases, and mode of transportation to the market 6. Total costs of transportation, marketing, storage, and post-harvest losses
V. Access to Information	1. Farmers' access to information, advice on farming activities and on the sources and cost of this information
VI. Income	1. Estimation of the total income of the agricultural household (for both agricultural and non-agricultural activities)

Note: the mean and standard deviation of the variables used in the analysis were calculated for the entire sample and by region.

were chosen because they represent climatic contrasts during an annual cycle and play a key role in the phenological development periods of coffee plants (Villers *et al*., 2009). For example, weather conditions such as rain, humidity, solar radiation, and temperature are essential in regulating flowering and fruit development (Craparo *et al*., 2015; Descroix and Snoeck, 2009). Similarly, agricultural management practices and coffee harvesting are closely related to climate and weather (Villers *et al*., 2009).

The farmers agree that spring, summer, and winter are the most important seasons for coffee production. Spring coincides with the flowering period, which is the most important for coffee production (Villers *et al*., 2009; Arcila, 2007). During the flowering period, the maximum temperature is related to the harvest volume; very high temperatures negatively affect yields, whereas moderate maximum temperatures lead to satisfactory harvests (Fournier and Di Stefano, 2004). Similarly, extreme rainfall during this period markedly affects flowering (Villers *et al*., 2009, Arcila, 2007). Summer coincides with the leaf growth and fruit development periods (Villers *et al*., 2009). In turn, in winter, the climatic conditions directly affect the fruit ripening process and the harvest (Villers *et al*., 2009).

Gay *et al*. (2006) used the same equations in an economic study on the CC impact on coffee production. The number of seasons used in these studies varies with the research objective. In other studies, involving the Ricardian method, two and three seasons have been used (Gbetibouo and Hassan, 2005; Kabubo-Mariara and Karanja, 2007).

Control variables

Soils: Just as climate is crucial for agricultural crop yield, soils are also essential for determining output and LV (Kabubo-Mariara and Karanja, 2007). Information on soil types was obtained from the map of dominant soils of the Mexican Republic, whose metadata is available on the official website of the National Commission for the Knowledge and Use of Biodiversity (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad – CONABIO). Interpolation was used to estimate soil types at a local scale for each production unit (PU) within the study regions, using ArcGIS software. This process allowed for capturing soil variations within the Mazateca and Cuetzalan regions, considering spatial heterogeneity. The Mazateca region contains alisol and leptosol, while eutric vertisol and eutric cambisol are found in the Cuetzalan region.

PU characteristics: Distance from the City (minutes); Coffee Land Area (ha); Coffee Land Area (Squared); Non-agricultural Activities (Yes, No); Land Area of Other Crops (ha); Altitude (metres above sea level [masl]); Altitude2 (Squared); Terrain Slope (3=steep, 2=moderate, 1=flat) (Ajetomobi *et al*., 2011; Mendelsohn *et al*., 2010; Kurukulasuriya and Mendelsohn, 2007). Data for these variables were obtained through the survey of producers and field visits.

Socioeconomic variables: Sex of the Household Head (Male, Female); Age of the Household Head (Years); Experience in Coffee-growing (Years); Education of the Household Head (Years); Average Education of the Household (Years); Home Computer (Yes, No); Household members (Number); Head of Household (Yes, No); Household size (3, 2, 1) (Ordaz *et al*., 2010; Mora *et al*., 2010; Mendelsohn, 2009; Mendelsohn *et al*., 2010). The index of technology was formed by the average of the components of the recommended technological package in the study regions; planting density, fertilization doses, pest control, disease control, pruning and varieties used in the plantation (Jaramillo-Villanueva *et al*., 2022).

Climate scenarios

The CC scenarios were taken from the National Centre for Meteorological Research (Centre National de Recherches Météorologiques – CNRMCM5), climate models of the institutional repository of geospatial scientific data, Center for Atmospheric Sciences (Centro de Ciencias de la Atmósfera – CCA), National Autonomous University of Mexico (Universidad Nacional Autónoma de México – UNAM) (Fernández *et al*., 2015). The following CC horizons were used: Representative Concentration Pathway (RCP) 4.5 (low emissions) and RCP 8.5 (high emissions). The horizons are: Near future (2015-2039) and Medium future (2045-2069).

To perform the simulations of the climate scenarios, the corresponding layers were obtained from the CCA repository. Subsequently, interpolations were carried out using ArcGIS software to obtain more precise values for the specific locations of the PUs within the study regions. This process ensured that the climate projections were adjusted to the relevant local scale for the analysis, which allowed for a more accurate assessment of the impact of CC on coffee production. In this way, it was possible to determine the increase or decrease in temperatures and precipitation for each PU in the study regions.

To obtain the results of the potential impact of CC on LV under climate scenarios, the results of the marginal effects are utilized, which are estimated using equation 6, as previously explained. These marginal effects, which capture the sensitivity of LV to changes in climatic variables, are employed to project changes in LV under different CC scenarios.

The results of these climate scenarios indicate the magnitude and direction of the potential impacts of CC on coffee production, reflected through changes in LV. Given the sensitivity of the coffee crop to climatic conditions, even small changes in temperature or precipitation can have significant effects on its production and, consequently, on LV.

Econometric analysis

The models were estimated using ordinary least squares (linear regression) estimation procedures in the software STATA 15.1. Diagnostic tests were applied to assess OLS assumptions, including tests for omitted variables to assess whether they were relevant in a specific model. To overcome heteroscedasticity and multicollinearity problems, the standard errors were estimated.

The assumptions of the OLS tests were performed; the Shapiro-Wilk W test for normality, the Cook and Weisberg test for heteroscedasticity, the variance inflation factor (VIF) test for Multicollinearity, and the regression specification error test (RESET) for omitted variables.

RESULTS

The average LV per hectare of coffee-growing area was $42,557 for the Mazateca region and $83,874 for the Cuetzalan region. The mean annual temperature was 19.1 °C for all PUs, 17.5 °C for the Mazateca region and 20.81 °C for the Cuetzalan region. The mean annual precipitation was 2,9930 mm for the entire sample, 3,301 mm for the Mazateca region, and 2,633 mm for the Cuetzalan region. The plot size also differed between regions, averaging 1.07 ha in the Mazateca region, and 1.46 ha in the Cuetzalan region.

Regarding soil types, differences were observed between the study regions. In the Mazateca region, Alisol (18%) and Leptosol (82%) soils predominate, while in the Cuetzalan region, eutric vertisol is the dominant soil type (88%). In the overall sample, which includes both regions, the means for Alisol, Leptosol, and Vertisol_e are 0.09, 0.44, and 0.41, respectively, reflecting the contribution of each region to the total distribution of soil types.

The overall mean altitude of the plots was 1,066 masl, with 1,324 masl for the Mazateca region and 764 masl for the Cuetzalan region. The farmers' mean age was 57 years for all PUs, 54 years for the Mazateca region and 60 years for the Cuetzalan region. The mean education of the household head was 5 years for the whole sample, 4.8 years for the Mazateca region and 5.3 years for the Cuetzalan region. The farmers' coffee-growing experience was 25.9 years overall, 23.9 years for the Mazateca region and 28.2 years for the Cuetzalan region.

The specification results for the Mazateca region showed that the temperature variables in spring and autumn, as well as the precipitation variables in spring and winter, have a significant impact on the coffee LV (Table 2). Furthermore, it was found that other variables, such as soil type, age and experience of the head of household, their educational level, the presence of a computer in the home, and the technological index, also significantly influence the land value in this region.

On the other hand, in the Cuetzalan region, the specification results indicated that the precipitation variables in summer and autumn do not have a significantly different effect on the coffee LV. However, it was found that other variables do have a significant influence on the land value, such as altitude (masl), land area, age and gender of the head of household, and household income.

The absence of values for certain variables in the specifications is due to the use of model selection techniques, such as stepwise regression and best subset selection. These techniques identify the most relevant and significant variables that explain the variation in the coffee LV while minimizing multicollinearity and improving model parsimony. Variables that do not meet the predetermined statistical criteria are omitted in the final specification, ensuring that only essential and significant variables are included. The evaluation of the model shows normality of the error term, no heteroscedasticity, no collinearity, and no omitted variables.

Table 2. General statistics of variables included in the economic model.

Variable	Overall		Mazateca		Cuetzalan	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Value of coffee per Ha ($)	61,609	27,808	42,557	12,036	83,874	24,236
Mean spring temperature (°C)	20.39	3.20	19.18	3.82	21.81	1.25
Mean summer temperature (°C)	20.77	4.60	18.18	4.67	23.79	1.86
Mean autumn temperature (°C)	18.70	3.74	16.88	4.19	20.81	1.25
Mean winter temperature (°C)	16.23	2.16	15.71	2.64	16.85	1.14
Spring precipitation (mm)	309.6	80.5	287.2	79.2	335.9	74.3
Summer precipitation (mm)	1,399.0	391.0	1,695.0	275	1,054.0	152.0
Autumn precipitation (mm)	1,006.0	162.0	1,041.0	172	966.0	140.0
Winter precipitation (mm)	276.0	67.0	277.0	72	276.0	61.0
Alisol	0.09	0.29	0.18	0.38	-	-
Leptosol	0.44	0.50	0.82	0.38	-	-
Vertisol_e	0.41	0.49	-	-	0.88	0.33
Altitude (masl)	1,066.0	514.0	1,324.0	556.0	764.0	210.0
Plot area (ha)	1.25	1.00	1.07	0.82	1.46	1.16
Age of the household head (years)	57.08	13.71	54.39	14.76	60.22	11.69
Experience in coffee-growing (years)	25.88	14.81	23.88	13.10	28.23	16.36
Education (years)	5.04	3.87	4.81	3.94	5.31	3.80
Technological index	4.09	1.71	3.58	1.69	4.69	1.53
Per cápita income	1.82	0.64	1.59	0.61	2.10	0.55
Home computer	0.05	0.22	0.02	0.14	0.08	0.28
Observations	180		97		83	

Source: own elaboration with survey data.

By employing equation 8, the optimal values for the significant climatic variables (temperature and precipitation) were determined. It was found that an average spring temperature below 19.9°C is detrimental to LV in the Mazatec region, indicating that temperatures above this range are beneficial for profitability (Table 3).

In the Cuetzalan region, a different pattern was observed. An average spring temperature below 22.2°C was beneficial for LV. Similarly, for summer, an average temperature above 25.4°C negatively impacted LV, indicating that high temperatures in spring and summer could have unfavorable consequences for the coffee crop.

Regarding precipitation, in the Mazatec region, it was found that in spring, precipitation above 297 mm benefited LV. This indicates that an optimal water level during this season is favorable for coffee cultivation. On the other hand, precipitation above 266 mm in winter had a negative impact on LV.

In the Cuetzalan region, it was found that precipitation above 404 mm in spring negatively affected LV. As for winter, precipitation above 262 mm was

Table 3. Influence of climatic variables on LV. Specifications by región.

Value per ha of café	Mazateca Oaxaca		Cuetzalan Puebla	
	Coefficient	t-value	Coefficient	t-value
Mean spring temperature (°C)	-173,615	-1.98*	3,246,814	2.10*
Spring temperature (Squared)	4,352	1.97*	-73,243	-2.08*
Mean summer temperature (°C)	75,206	1.14	841,656	1.63
Summer temperature (Squared)	-1,916	-1.11	-16,574	-1.7**
Mean autumn temperature (°C)	67,691	1.80	-2,756,455	-2.27*
Autumn temperature (Squared)	-2,062	-1.75	65,100	2.22*
Mean winter temperature (°C)	-28,443	-0.98	-1,012,346	-2.02*
Winter temperature (Squared)	1,042	1.35	26,982	1.91**
Cumulative spring precipitation (mm)	-7,111	-2.67*	2,004	2.03*
Spring precipitation (squared)	11.9	2.60*	-2.48	-1.9**
Cumulative summer precipitation (mm)	1,596	1.14	3,559	1.21
Summer precipitation (squared)	-0.5	-1.26	-2.6	-1.46
Cumulative autumn precipitation (mm)	-173	-0.13	-52.4	-0.02
Autumn precipitation (squared)	0.2	0.35	0.91	0.52
Cumulative winter precipitation (mm)	2,597	2.09*	-12,075	-1.80**
Winter precipitation (squared)	-4.8	-2.19*	23.0	1.80**
Alisol	-49,897	-2.48*		
Masl			-449.8	-1.63
Masl_2			0.2	1.43
Land area (ha)			-3,862	-1.90**
Age of the household head	-221	-2.04*	617	3.37*
Farmers' exper. coffee-growing	252	2.31*		
Education of the household head	-3,322	-1.70**	-1,391	-0.62
Sex of the household head			10,748	1.62
Home computer	13,361	1.71**	10,525	1.36
Technological Index	3,984	3.00*		
Per capita income	78.9	0.04	22,056	5.33*
Market access			582.1	1.47
Constant	83,137	0.15	-83,431	-3.08*
R-Squared	0.59		0.67	
Shapiro-Wilk (Prob > z)	0.088		0.128	
Breusch-Pagan (Prob > chi^2)	0.721		0.608	
Variance inflation factor (VIF)	2.55		1.98	
Ramsey test (Prob > F)	1.29		2.12	

*Significant at 95% (p≤0.05); **Significant at 90% (p≤0.1).
Source: Own elaboration with survey data.

beneficial for LV in this region, as water deficit during this period could affect coffee vegetative growth and timely flower development.

These results demonstrate that climatic requirements in coffee production can significantly impact land profitability according to each region. This is related to the crop type and specific local climatic characteristics of each production region.

In the Cuetzalan region, it was observed that production units (PUs) located at an altitude higher than 937 meters above sea level experienced an increase in LV.

Access to technology had a positive effect on coffee LV in the Mazateca region. Producer age showed a differentiated effect between regions: while in the Cuetzalan region older producers were associated with a higher LV, suggesting better adaptation to local conditions, in the Mazateca region greater producer age had a negative impact on LV. Finally, higher *per cápita* income evidenced a positive effect on coffee LV in both regions, although it was only statistically significant in the Cuetzalan region.

The marginal impacts of CC were striking in the Cuetzalan region but low in the Mazateca region. The temperature margins were -45,000 pesos (-54%) per degree centigrade for PUs in the Cuetzalan region. In the Mazateca region, by contrast, the temperature effects increase the LV by 1,203 pesos (2.83%) per degree centigrade. The losses of LV in the Cuetzalan region are associated with the autumn and winter temperatures. Given the decreased precipitation, the LV will decrease 0.91% per mm precipitation in the Cuetzalan region and increase 0.52% per mm precipitation in the Mazatec region (Table 4).

Scenario projections

According to CNRMCM5 climate scenarios (low and high emissions) (Table 5), the results suggest that the increase in temperature and the decrease in precipitation will affect the LV of coffee-growing areas.

For the Mazatec region, the scenarios indicate temperature increases ranging from 0.78 to 2.31 °C under low emissions and from 0.84 to 3.31°C under high emissions. In terms of precipitation, in the low emissions scenario, the greatest decrease is expected mainly in the near horizon, with -44.5 mm; similarly, in the high emissions scenario, precipitation is expected to decrease mainly in the near horizon. For the Cuetzalan region, the scenarios indicate temperature increases ranging from 0.77 to 1.78 °C under low emissions and from 0.82 to 3.26 °C under high emissions. In terms of precipitation, the greatest decrease should occur mainly in the medium horizon, in the low emissions scenario, with -34.7 mm. For the Mazateca region, projections under low emissions show 25 and 9.8% gains of LV for the near and medium horizons, respectively. Projections under high emissions show an 11.9% gain of LV in the near horizon and, in turn, 12.9 % loss of LV. For the Cuetzalan region, projections under low emissions show drastic losses of LV ranging from 67.5 to over 100%. For projections under high emissions, the losses of LV range from 40.4 to over 100%.

Similarly, the effect of CC on LV was estimated according to the size of the PUs, distinguishing between small (0.8 ha on average), large (2.6 ha on average), and

Table 4. Marginal impact of climatic variables on LV by región.

Variable	Mazateca Oaxaca			Cuetzalan Puebla		
	Coefficient	Impact (m)	Percentage	Coefficient	Impact (m)	Percentage
Temperature						
T Spring	-173,615.70	-$ 6,654.83	-15.64 %	3,246,814	$ 51,442.92	61.3%
T Summer	75,206.30	$ 5,511.54	12.95 %	841,656.6	$ 53,125.07	63.3%
T Autumn	67,691.34	-$ 1,942.19	-4.56 %	-2,756,455.0	-$ 46,685.71	-55.7%
T Winter	-28,443.79	$ 4,288.63	10.08 %	-1,012,346.0	-$ 103,194.48	-123.0%
Annual		$ 1,203.16	2.83 %		-$ 45,312.20	-54.0%
Precipitation						
P Spring	-7,111.25	-$ 244.61	-0.57 %	2,004.85	$ 341.44	0.41%
P Summer	1,596.85	-$ 119.03	-0.28 %	3,559.06	-$ 1,926.96	-2.30%
P Autumn	-173.12	$ 260.64	0.61 %	-52.49	$ 1,704.17	2.03%
P Winter	2,597.49	-$ 118.43	-0.28 %	-12,075.35	$ 647.31	0.77%
Annual		-221.43	-0.52 %		$ 765.96	0.91%

Source: own elaboration with survey data.

the general sample that includes both strata. The marginal impacts indicate that the effects of temperature are stronger for small PUs than for the general sample. For the general sample, when the temperature increases by 1°C, the LV decreases by 3,900 pesos, while for small farms, it decreases by 6,500 pesos. In contrast, for large farms, a 1°C increase in temperature raises the LV by 5,700 pesos.

Table 5. Projections of the CC impact on LV by región.

	Mazateca model			Cuetzalan model		
Low emissions						
CNRMCM5 4.5	Δ (C) and (mm)	Δ($)	Δ(%)	Δ (C) and (mm)	Δ($)	Δ(%)
	0.78	$938.46	2.21%	0.77	-$34,890.39	-41.60%
Near Horizon (2015-2039)	-44.55	$9,864.71	23.18%	-28.34	-$21,707.31	-25.88%
		$10,803.17	25.38%		-$56,597.70	-67.48%
	2.31	$2,781.97	6.54%	1.44	-$65,249.57	-77.79%
Medium Horizon (2045-2069)	-6.19	$1,370.65	3.22%	-34.68	-$26,563.49	-31.67%
		$4,152.62	9.76%		-$91,813.06	-109.47%
High emissions						
CNRMCM5 8.5	Δ (C) and (mm)	Δ($)	Δ(%)	Δ (C) and (mm)	Δ($)	Δ(%)
	0.84	$1,014.66	2.38%	0.82	-$37,055.31	-44.18%
Near Horizon (2015-2039)	27.50	-$6,089.33	-14.31%	4.18	$3,201.71	3.82%
		-$5,074.66	-11.92%		-$33,853.60	-40.36%
	3.20	$3,851.45	9.05%	1.92	-$86,848.38	-103.55%
Medium Horizon (2045-2069)	-7.37	$1,631.94	3.83%	-30.86	-$23,637.53	-28.18%
		$5,483.39	12.88%		-$110,485.91	-131.73%

Source: own elaboration with survey data.

Regarding the expected impacts under the climate scenarios, the impact on the LV of large farms will initially be negative (-7.37% in the near horizon with low emissions) but will become positive in the medium and long-term horizons (9% to 18.6%). This change is explained by the influence of precipitation on LV; in the short term, precipitation will decrease, negatively affecting LV; however, an increase in precipitation is expected in the medium and long-term horizons, which will contribute to an increase in LV for large farms. As for small PUs, the impact of CC will generate losses in LV ranging from 8.84% to 20.5% in the low emissions scenario and between 8.7% and 35.8% with high emissions.

DISCUSSION

Regional contrasts reflected in socioeconomic indicators are a result of environmental conditions, historical trajectories, communication dynamics, and social contexts specific to each region (Rahn *et al.*, 2018; Donatti *et al.*, 2019). These differences largely determine the differentiated impact of CC on LV in the Cuetzalan and Mazateca regions. These findings are consistent with previous studies that have analyzed the impacts of CC on Mexican agriculture using the Ricardian approach. Similar to Galindo *et al.* (2015) and Mendelsohn *et al*. (2010), differentiated impacts are found across regions and types of production units (PUs), with southern regions and small-scale producers being the most affected. The magnitudes of the projected impacts are comparable to those reported by Mendelsohn *et al.* (2010), who estimate losses between 42 and 54% of LV by 2100. However, as Arellano (2018) points out, the use of market values for land in the context of incomplete markets may underestimate the relationship between climate and agricultural productivity, suggesting that the impacts could be even greater.

Temperature affects LV more than precipitation due to the narrow optimal ranges for key physiological processes such as flowering, fruit development, and the impact of pests and diseases (Camargo, 2010; Guerrero-Carrera *et al.*, 2020). Cuetzalan is likely to face temperatures above these maximum thresholds more frequently, exacerbated by the associated water deficit, negatively impacting coffee plantation LV even in the short term (Thioune *et al*., 2020).

The severe and even total reduction of LV in Cuetzalan towards the medium and long term is consistent with previous projections of extreme damage in areas unsuitable for coffee under warming scenarios in Latin America (Läderach *et al.*, 2017; Imbach *et al.*, 2017). Considering the narrow ecophysiological thresholds documented for the optimal development of *arabica coffee*, it is highly likely that irreversible limits will be exceeded, beyond which incremental adaptation will not be sufficient, compromising the sustainability of coffee-based livelihoods in this region (Villers *et al.*, 2009; Harvey *et al.*, 2018).

Our results on the impact of climate change on coffee production in Mexico are consistent with studies conducted in other producing regions. For example, Ovalle-Rivera *et al.,* (2015) projected a significant decrease in suitable areas for coffee cultivation in Tanzania and Vietnam by 2050. Similarly, Bunn *et al,*. (2015) found that climate change could reduce the suitable area for coffee cultivation in Ethiopia by half. These studies, like ours, underscore the vulnerability of small producers and the need for region-specific adaptation strategies.

Additionally, López-Feldman and Mora-Rivera, (2019) highlight the distributive implications of CC, finding significant increases in poverty and inequality, particularly in the southeast. This is relevant given the context of marginalization of many coffee producers and suggests that the estimated impacts could exacerbate pre-existing socioeconomic vulnerabilities, as is the case in the Mazateca region. Moreover, impacts are expected to be more acute in small PUs, with the potential to worsen due to inequalities, prices, market conditions, high productive dependence, and lack of specific policies (Rahn *et al.,* 2018; Campbell, 2021). Thus, the adaptive capacity of small-scale producers could be seriously compromised due to the potential deterioration of LV, difficulties in accessing financing, lack of adequate technologies, scarcity of technical education, resource limitations, and weak institutional support in climate risk management by public policies (Donatti *et al.,* 2019; Avelino *et al.,* 2015).

When designing adaptation strategies, it is crucial to consider the relationship between adaptation and resilience. Although transitioning to other productive activities could be an option in extreme cases where coffee cultivation becomes unviable, this change can have profound implications for the resilience of households and communities that depend on coffee, eroding the social capital, traditional knowledge, and cultural identity associated with this activity (Bacon *et al.,* 2014; Campbell, 2021). Therefore, adaptation policies should seek to strengthen the resilience of coffee systems, promoting strategies that allow coffee-based livelihoods to be maintained as much as possible, including climate-resilient agricultural practices, productive diversification, and reduction of structural vulnerabilities that limit the adaptive capacity of households (Campbell, 2021). A holistic approach that integrates adaptation and resilience will be key to facing the challenges of CC in the coffee sector, particularly for small-scale producers in highly vulnerable regions such as the Mazateca region and the Cuetzalan region.

CONCLUSIONS

This study provides a rigorous assessment of the potential impacts of climate change on coffee production in the Mazateca and Cuetzalan regions of Mexico using the Ricardian approach. The study integrates climatic, geographic, and socioeconomic variables in a robust statistical analysis to evaluate their interaction with land value. The research contributes to the existing literature by demonstrating the differential effects of climate change on land value according to region and farm size, highlighting the vulnerability of small-scale coffee producers, especially in the Cuetzalan region. The results warn that changes in temperature and precipitation can have significant and potentially irreversible impacts on coffee production, with damages reaching 100% of land value in some scenarios.

A crucial aspect to consider is the adaptive measures that coffee producers could adopt in the face of climate change impacts. Some producers may choose to completely abandon coffee cultivation and switch to other productive activities, while others may decide to switch to more resistant coffee varieties or diversify their crops. The choice of adaptive measures will depend on the economic, social, and ecological resilience of coffee-growing households, as well as the implementation of effective and timely public policies that support this activity.

This study opens avenues for future research, such as the exploration of databases that integrate additional climatic variables relevant to coffee production and the expansion of the geographic scope of the study. The results have significant implications for public policy, suggesting a systemic approach that reduces the vulnerability of producers and promotes sustainable management practices.

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