RESEARCH PAPER

LAND SUITABILITY OF COFFEE CULTIVATION UNDER CLIMATE CHANGE INFLUENCE IN THE ECUADORIAN AMAZON

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ABSTRACT. In this study, the influence of climate change on land suitability for coffee cultivation in the Ecuadorian Amazon (EA) was investigated using five global circulation models (GCMs) in two different socioeconomic pathways (SSP126 and SSP585). Eleven physioedaphological factors were selected for the analysis and were combined with the most influential bioclimatic variables to model past, present and future suitable areas in five provinces of the EA. In assessing past suitability areas, key determinants varied based on land suitability levels. High suitability areas were primarily influenced by factors such as texture, organic matter content, soil fertility, soil depth, slope, and aspect, while pH, salinity, toxicity, drainage, and stoniness were more associated with moderate suitability areas. The present high suitability areas were influenced by texture, organic matter content, soil fertility, soil depth, and slope, whereas aspect, pH, salinity, toxicity, drainage, and stoniness were more prominent in modeling moderate areas. The ensemble estimation model projected distinct future scenarios for coffee cultivation; under the worst climate scenario (SSP585), Zamora Chinchipe and Morona Santiago, particularly in the east, face considerable unsuitability. Conversely, the more favorable scenario (SSP126) indicates high suitability across Pastaza, Orellana, and Sucumbios, with limited suitability in border areas adjacent to the Highland region. This study highlights the importance of implementing timely adaptation strategies to improve resilience to climate change impacts in the coffee sector.

KEYWORDS: climate-adaptation strategies, coffee, Ecuadorian Amazon, GIS-based modeling, global circulation models

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INTRODUCTION

Within the realms of international trade, coffee holds significant prominence both as a pivotal agricultural commodity and a globally consumed beverage. Ecuador, exhibiting notable prowess as a coffee producer, distinguishes itself by exporting a comprehensive array of coffee types, encompassing washed Arabica, natural Arabica, and Robusta (dos Santos and Boffo 2021). Robusta coffee (*Coffea canephora* Pierre) and Arabica coffee (*Coffea arabica* Linnaeus) stand out as economically consequential coffee varieties in Ecuador. Notably, Arabica coffee enjoys heightened demand owing to its superior quality as a beverage (Zambrano-Flores et al. 2018), however, the heightened sensitivity of Arabica coffee to climatic variables renders it susceptible to the impacts of climate change (Pham et al. 2019). This vulnerability is attributed to Arabica coffee's cultivation within specific temperature and precipitation ranges, delineated as 17-23°C and 800-2000 mm year-1, respectively (Tavares et al. 2018). Existing studies corroborate the deleterious effects of climate change on the suitability of areas for coffee cultivation across diverse regions (Gomes et al. 2020; Chavez et al. 2021; Chemura et al. 2021; Jawo et al. 2022).

Fourteen pivotal agroecological factors exert influence over coffee cultivation and production, encompassing physiographic factors such as slope and aspect, as well as edaphological elements like soil texture, fertility, salinity, and toxicity, among others (Hameed et al. 2020). The combination of these factors results in a unique profile for each soil type, whether local or regional. Consequently, even within identical geographical zones where the same coffee variety is cultivated, discernible variations in soil characteristics persist (Chemura et al. 2021). Despite the dependence of coffee production on specific climatic and physio-edaphological determinants, there is a noticeable dearth of comprehensive studies regarding the impact of climate change on both Robusta and Arabica coffee types in the Ecuadorian Amazon (EA), particularly when examined at the province scale.

The study employs five distinct Global Circulation Models (GCMs) under the best-case (SSP126) and worst-case (SSP585) scenarios, and integrates eleven physio-edaphological factors with the most influential bioclimatic variables to model land suitability maps for coffee cultivation. The resulting models delineate the optimal regions for historical (1970-2000), actual (2023), and future (2040) periods across the five provinces constituting the EA as the study area.

MATERIALS AND METHODS

Study area

The five provinces (Fig. 1), constituting the Amazon region, are situated in the southwestern region of Ecuador. These provinces, namely Sucumbios, Orellana, Napo, Pastaza, Morona Santiago, and Zamora Chinchipe, collectively constitute 43% of the Ecuadorian territory. This region, hereafter referred to as the EA, embodies a critical component of the larger Amazon biome (Cabrera-Barona et al. 2020).

The EA encompasses an expansive area of approximately 120,000 km^2, exhibiting an altitudinal range from 100 to 800 meters above sea level (masl). Recognized for its luxuriant vegetation emblematic of humid-tropical forests, as noted by Espinoza et al. (2018), this region stands as a distinctive ecological entity. Notably, coffee plantations occupy an estimated 60,000 hectares within the EA, with the provinces of Sucumbios, Orellana, and Zamora Chinchipe accounting for approximately 34% of Ecuador's total coffee production.

Bioclimatic data

The WorldClim database version 2.1 was the main source for collecting climate data for the past period (1970-2000) and future period (2021-2040) in the region studied[1]. This database provides comprehensive information on 19 bioclimatic variables (Appendix A), encompassing annual temperature and precipitation trends (Fick and Hijmans 2017).

Four variables (minimum and maximum temperature (°C), average temperature (°C), precipitation (mm)) of past climate data were downloaded at spatial resolution of 30 seconds. By the other hand, future climate data were derived from five distinct Global Circulation Models (GCMs) sourced from the Coupled Model Intercomparison Project Phase 6 (CMIP6)[2]. The selected GCMs included CanESM5, CNRM-CM6-1, HadGEM3-GC31-LL, IPSL-CM6A-LR, and MIROC6. These projections were conducted under the two contrasting climate change scenarios, namely the worst-case scenario (SSP585) and the best-case scenario (SSP126) at 30 seconds of spatial resolution. These models were selected because have demonstrated good performance in simulating historical climate conditions, capturing observed patterns, and showing skill in reproducing key climate features relevant for the study region (Olmo et al. 2022; Reboita et al. 2022). In addition the selected models are known for their ability to simulate the bioclimatic variables relevant to coffee cultivation (Bunn et al. 2015; de Sousa et al. 2019; Gomes et al. 2020).

Studies such as those conducted by Wu et al. (2021) and Monteverde et al. (2022) have substantiated the apt representation of anticipated alterations in global mean temperature and precipitation within tropical and Amazon regions of the chosen GCMs. Employing the

Fig. 1. Geographical location of the study areas

[1]worldclim.org/data/worldclim21.html
[2]https://wcrp-cmip.org/cmip-phase-6-cmip6/

Table 1. Selected GCMs for climate change projections in the Ecuadorian Amazon

Model Name	Institution	Spatial Resolution	Scenario
CanESM5	Canadian Centre for Climate Modelling and Analysis	Global	SSP585 SSP126
CNRM-CM6-1	National Centre for Meteorological Research	Global	SSP585 SSP126
HadGEM3-GC31-LL	Met Office Hadley	Global	SSP585 SSP126
IPSL-CM6A-LR	Institut Pierre-Simon LaPlace	Global	SSP585 SSP126
MIROC6	Research Institute for Global Change	Global	SSP585 SSP126

delta method, the GCM outputs underwent downscaling, enabling the computation of variances between model outputs pertaining to historical conditions (1970-2000), actual (2023), and future projections (2040) concerning changes in land suitability. The outcome comprises a high-resolution surface, duly corrected for bias, characterizing the prevailing climate conditions and the 2060 time-slice across the 19 bioclimatic variables.

Physio-edaphological data

Eleven physio-edaphological factors covered crucial attributes for coffee production such as soil pH, soil texture, salinity, organic matter content, soil fertility, toxicity, drainage, stoniness, soil depth, slope, and soil aspect. This data set was obtained from the agroecological criteria for coffee cultivation established by the Ministry of Agriculture and Livestock (MAGAP) and the National Institute for Agricultural Research (INIAP) within continental Ecuador.

Data collecting

In order to analyze the changes in the spatial distribution of areas suitable for Arabica and Robusta coffee during the past and present periods, only the bioclimatic variables that most contributed to determining the suitability of the land for coffee production were selected. This information was compiled from the available literature for the last 15 years (Appendix B).

The search targeted articles that explicitly provided information on the percentage contribution of bioclimatic variables, as modeled through MaxEnt, concerning both the augmentation and diminution of land suitability for coffee production. The MaxEnt model, widely employed in modeling species distribution, environmental conditions, and the repercussions of climate change on crop suitability, operating at local, regional, and global scales (Akpoti et al. 2019; Khalil et al. 2021; Moya et al. 2017; Sarvina et al. 2022; Zhang et al. 2021).

Starting with an initial search that included 209 global studies, , strict selection criteria were meticulously applied. These criteria comprised the necessity for studies to furnish: (a) percentage contribution values of bioclimatic variables; (b) a focus on neotropical or Amazonian ecosystems; (c) engagement in historical and projected bioclimatic simulation studies; and (d) contextualization within the domain of climate change. Following the application of these criteria, a refined selection yielded a total of 10 studies deemed pertinent for the subsequent analysis and formulation of assessments concerning past, present, and future land suitability within the five provinces of the EA.

Evaluation of the land's suitability for coffee cultivation in the past period

Once the 10 studies were selected, the contribution percentages of each climatic variable reported in the results section or annexes of each article were ranked from highest to lowest based on expert's knowledge. Once ranked, an overall average of the relative contribution of each climate variable was calculated. Finally, only the first five bioclimatic variables that together represented 100% (Table 2) were selected in order to build the maps.
Using the weighted overlay tool in ArcGIS version 10.3 software, each selected bioclimatic variable and eleven physio-edaphological factors were assigned weights based on expert's knowledge. The relative weight of all selected bioclimatic variables was accounted for 50%, and the remaining 50% was accounted for by eleven physioedaphological factors (Table 2).

The weights were normalized in order for all of them to sum up to 1. For the weighted overlay tool, the following formula of normalization was used (Ayehu & Atnafu 2015).

$$Normalized\ weight = \frac{Weight\ of\ \ Factor}{Sum\ of\ all\ weights}$$

For the weighted climate factor the following formula was used (Ferretti & Pomarico 2013).

$$Weighted\ climate\ factor = \frac{Normalized\ weight}{Climate\ variable\ value}$$

Finally, the weighted overlay tool combined these factors to generate a suitability index.

Evaluation of the land suitability for coffee-growing area in the present period

Each physio-edaphological variable underwent classification based on the agro-ecological criteria outlined by MAGAP and INIAP within continental Ecuador and experts' knowledge. These criteria establish land suitability thresholds, ranging from optimal, moderate, marginal, low, and no suitability, in alignment with the agro-ecological requirements stipulated for both Arabica and Robusta coffee varieties.

In the initial phase of the analysis, each layer was procured and imported into ArcGIS in shapefile (shp) format. Following this, all physio-edaphological factors were extracted based on the study area's defined geographical boundaries. Using the reclassification tool, these factors were then classified into four distinct suitability thresholds. The values assigned ranged from 1 to 4, where "1" denoted high land suitability for coffee cultivation, and "4" indicated low owing to inherent soil

Table 2. Selected bioclimatic variables and physioedaphological factors with their weights used to model land suitability maps

	Relative average contribution (%) from the studies	Climatic variable value reported in the specific regions of the studies	Relative weight of factors based on expert consultation
Bioclimatic variable			
Bio 10	32,60	25 °C	12%
Bio 1	17,75	22 °C	10%
Bio 6	17,47	18 °C	8%
Bio 19	17,03	800 -2000 mm	10%
Bio 13	15,81	2500 - 3000 mm	10%
Physioedaphological factors			
Soil texture			10%
Organic matter content	-	-	8%
Soil depth	-	-	8%
Soil fertility	-	-	7%
pH	-	-	6%
Slope	-	-	5%
Drainage	-	-	5%
Aspect	-	-	4%
Stoniness	-	-	3%
Salinity	-	-	2%
Toxicity	-	-	2%

characteristics. Following this reclassification, a homogenization process was undertaken to standardize the geospatial data. The rescaling operation, achieved through the implementation of the resampling tool, resulted in the representation of data in a uniform manner with a 30-meter pixel resolution.

Assessment of the land's suitability for coffee cultivation in the future

Utilizing the five GCMs within specified climate change scenarios (SSP585, SSP126), the climate projections undergo downscaling employing the delta method that corrected the average bias in the monthly GCM projections by first calculating the change (or delta difference between the transient future and historical climate in the GCM simulation), then interpolating this change, and finally adding it to historical observations (e.g., WorldClim). A model ensemble approach by combining the downscaled outputs from the five GCMs was utilized by averaging the results of each model and integrating them with the eleven physio-edaphological variables relevant to coffee cultivation. Finally, the model ensemble estimation by combining the classified outputs of physio-edaphological variables with the ensemble bioclimatic data was executed. Fig. 2 provides a flow chart that summarizes the entire research methodology.

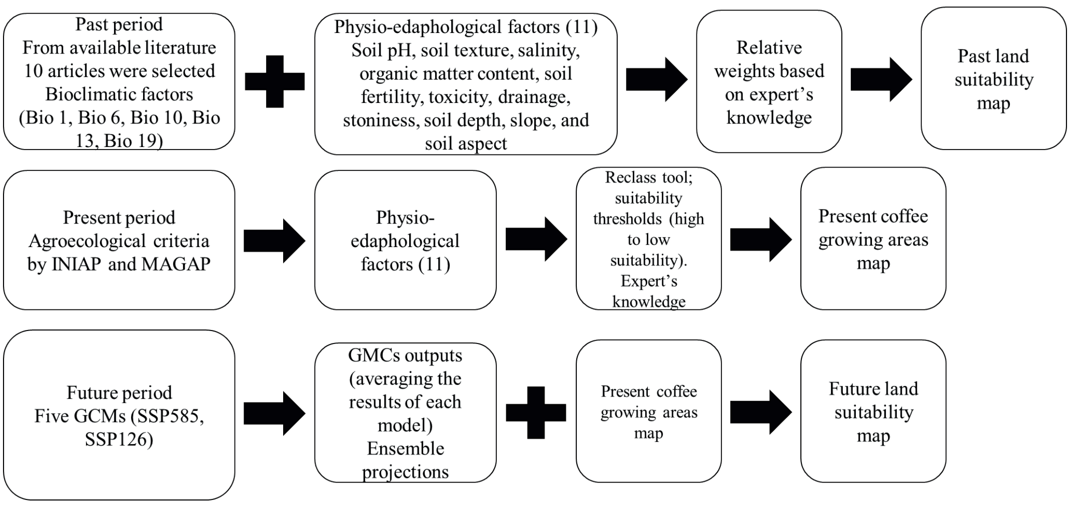


Fig. 2. Methodological framework employed in the research study

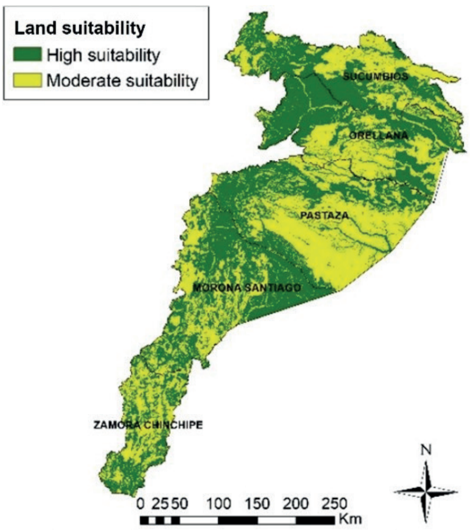
RESULTS

In Fig. 3a, the past reclassified map, which amalgamates ten physio-edaphological factors incorporating climatic parameters, is presented based on the suitability thresholds outlined in the guidelines of MAGAP and INIAP. The outcomes reveal that a total land area of 56,103 km², constituting 54% of the EA territory, exhibits high suitability for coffee production. Conversely, the remaining 47,736 km², representing 46%, is characterized by areas of moderate suitability. Morona Santiago and Orellana provinces emerge as having the largest extents of high suitability, encompassing 27,347 km² (26%) and 26,350 km² (25%), respectively. Additionally, the provinces displaying the most substantial areas of moderate suitability are the southeastern region of Pastaza and the southwestern region of Morona Santiago, spanning 29,231 km² (34%) and 23,930 km² (28%), respectively.

In Fig. 3b, the presentation of the same ten physio-edaphological factors, prescribed by the guidelines of the same institutions (MAGAP and INIAP), provides insights into the alterations within these areas from historical records to the current year. Presently, an aggregate of 86,290 km² encompasses regions of high suitability for coffee cultivation, particularly bordering the highlands region of Ecuador along the EA. Conversely, the residual area of 358,151.65 km² characterizes areas displaying moderate suitability for both coffee varieties. Notably, there are no projections indicating areas that are medium, low, or unsuitability for the current year. The extents of high land suitability range from 5,701 km² to 12,047 km² across all provinces, with the province of Pastaza emerging as the most substantial, encompassing 29,231 km², followed by the province of Morona Santiago with 23,930 km².

The regions characterized by moderate suitability for coffee cultivation, when devoid of the impact of climatic variables, exhibited uniformity across all provinces, encompassing an approximate aggregate of 88,000 km². The sole exception pertains to Zamora Chinchipe, where the extent of such areas measured 5,437 km² (Table 3).

In the ensemble estimation model (Fig. 4), under the worst-case scenario, the findings reveal that the provinces with the most



(a)

(b)

Fig. 3. (a) Delineates a model incorporating climatic parameters and physio-edaphological factors derived from literature. (b) represents a model founded upon physio-edaphological factors prescribed by guidelines of the MAGAP and the INIAP as well as experts' knowledge

Table 3. Temporal dynamics of soil suitability for coffee cultivation across provinces: Comparative analysis of historical and current scenarios. ZC: Zamora Chinchipe; MS: Morona Santiago; PZ: Pastaza; OR: Orellana; SC: Sucumbíos

Provinces	Temporal variations in land suitability areas considering the impact of climate change over time (1970-2000) (km²)		Land suitability areas without considering bioclimatic factors (km²)	
	High	Moderate	High	Moderate
ZC	5.018	7.931	5.701	5.437
MS	11.087	27.347	23.930	88.182
PZ	142.19	21.854	29.231	88.164
OR	111.82	26.350	15.380	88.166
SC	1.843	20.501	12.047	88.201
EA	18.203	103.986	86.290	358.151

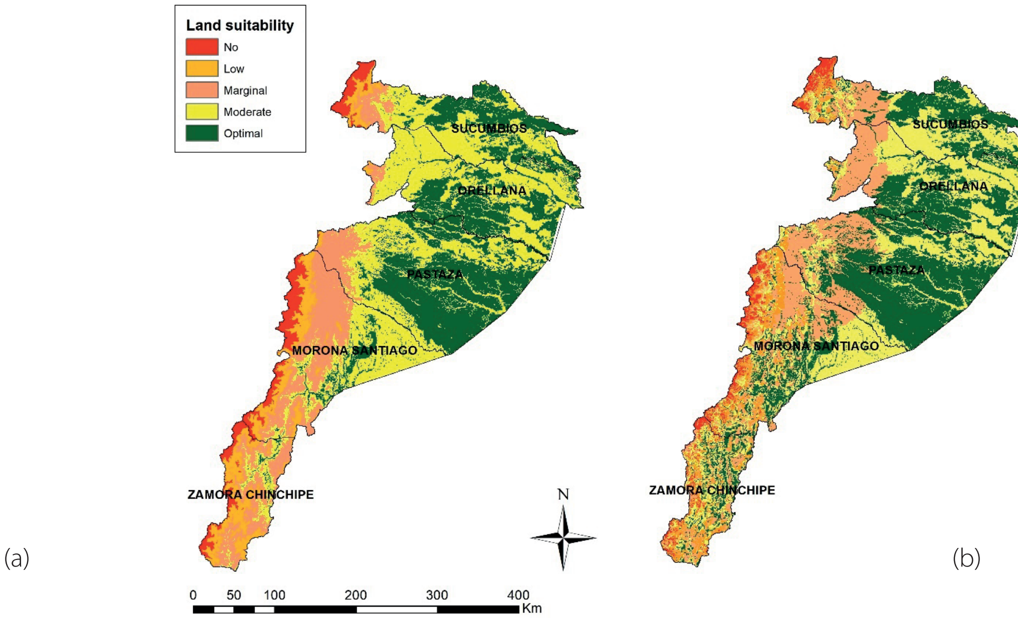


Fig. 4. Ensemble projections for GCMs in its (a) best scenario (SSP126) and worst scenario (SSP585) within the study area

extensive areas unsuitable for coffee cultivation, attributable to the influence of climate change, were Zamora Chinchipe and Morona Santiago, particularly in their eastern sectors. Conversely, in the SSP126 scenario, high land suitability was observed for the provinces of Pastaza, Orellana, and Sucumbios, encompassing their entire territorial expanse. Notably, only the border areas with the Highland region in these provinces were limited to unsuitable areas for coffee cultivation.

Table 4 delineates the percentage variations in high land suitability areas for coffee cultivation across the five GCMs under the best and worst-case scenarios in comparison to existing areas. Broadly, relative to the currently suitable coffee cultivation areas, substantial and predominantly adverse changes in land suitability are evident for both scenarios during the 2021-2040 period. This translates to an approximately 80% reduction in suitable areas, with instances of complete loss noted, particularly pronounced in provinces such as Pastaza and Orellana. In specific instances, the reduction in suitable areas is comparatively modest, as illustrated by the best-case scenario exhibiting an 11% loss for Zamora Chinchipe employing the CNRM-CM6-1 model, and a 30% reduction for Sucumbios with the CanESM5 model.

Table 4. Comparative analysis of changes in land suitability areas for coffee cultivation: Best-case (SSP126) and worst-case (SSP585) scenarios in comparison to current coffee areas. ZC: Zamora Chinchipe; MS: Morona Santiago; PZ: Pastaza; OR: Orellana; SC: Sucumbíos

Provinces	Current coffee growing areas	CanESM5				CNRM-CM6-1				HadGEM3-GC31-LL			
		SSP126		SSP585		SSP126		SSP585		SSP126		SSP585	
	km^2	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
ZC	7.931	455	94	10.047	27	7.029	11	4.990	37	538	93	1.225	85
MS	27.347	8.159	70	6.896	75	7.852	71	6.161	78	6.304	77	2.547	91
PZ	21.854	25.698	18	52	100	421	98	134	99	9.482	57	7	100
OR	26.350	20.632	22	-	100	198	99	99	100	12.664	52	5.7	100
SC	20.501	13.992	32	1.870	91	2.120	90	2.225	89	7.833	62	1.127	95
EA	103.986	68.938	34	18.867	82	17.621	83	13.611	87	36.823	64	4.913	95

Provinces	Current coffee growing areas	IPSL-CM6A-LR				MIROC6			
		SSP126		SSP585		SSP126		SSP585	
	km^2	km^2	%	km^2	%	km^2	%	km^2	%
ZC	7.931	447	94	1.214	85	490	94	656.5	92
MS	27.347	6.352	77	2.549	91	6.317	77	1.019	96
PZ	21.854	9.407	57	7.4	100	9.488	57	-	100
OR	26.350	12.645	52	5.7	100	12.662	52	-	100
SC	20.501	7.770	62	1.134	94	7.837	62	710.2	97
EA	103.986	36.621	65	4.911	95	36.796	65	2.386	98

The provinces with the most pronounced potential reduction in suitable areas for coffee cultivation were identified as Zamora Chinchipe and Morona Santiago, with respective reductions of 77% and 74% in the best-case scenario. Conversely, all provinces, excluding Zamora Chinchipe, displayed substantial reductions of 85%, 99%, and 93%, respectively, in the worst-case climate change scenario. At the broader scale of the EA, these projections signify an anticipated greater reduction in suitable areas for coffee cultivation, particularly evident with the CNRM-CM6-1 model under the best scenario (83%), and the MIROC6 model under the worst scenario (98%).

Moreover, discernible in the provinces of Zamora Chinchipe and Pastaza is a notable expansion in areas deemed suitable for coffee cultivation, exhibiting increases of 27% and 18% in the worst and best scenarios, respectively. It is noteworthy that the magnitude of change in suitable areas for coffee cultivation is more pronounced in the worst scenario, averaging an 87% reduction in surface area across all GCMs, with MIROC6 presenting the highest magnitude. Conversely, in the best scenario, the reduction in suitable areas averages around 64% across all GCMs, with the CNRM-CM6-1 model registering the most substantial reduction.

Fig. 5a, highlights areas sensitive to climate change using the worst-case scenario and zonal changes in specific areas within the EA. It can be noted that compare to current period (Fig. 3b), central areas of all the provinces are sensitive to climate change in the future period, specially Orellana, Morona Santiago, Pastaza and Zamora Chinchipe due to the presence of marginal, moderate and high areas. In the worst case scenario (Fig. 5b) reveal that all provinces show areas with moderate changes in land use. These changes are mainly manifested in the transformation of forests, shrub and herbaceous vegetation, as well as agricultural land to anthropogenic zones, (areas affected by human activity). This could suggest the presence of significant transformations in these areas, either due to the expansion of human activities, changes in forest cover, or evolution in land use for agricultural or livestock purposes. In general, the results indicate that the areas identified in the south and north of Zamora Chinchipe, as well as in the eastern part of the provinces of Morona Santiago, Pastaza, Orellana and Sucumbíos, are experiencing moderate changes in land use, with a tendency towards anthropogenic transformation.

DISCUSSION

This study conducted an assessment of land suitability areas for coffee cultivation, encompassing both Arabica and Robusta varieties, through the integration of climatic and soil physio-edaphological factors. Employing five GCMs, the investigation considered scenarios representing both the best and worst climatic conditions.

The results of our study highlight that the mean temperature of the warmest quarter (Bio10) and annual mean temperature (Bio1) emerge as pivotal climatic factors significantly influencing the modulation of past period land suitability maps. These temperature variables, along with the temperature of the coldest and warmest month, as well as precipitation during the wettest and driest month, have been substantiated as limiting factors in historical projections of bioclimatic variables, as demonstrated by Hijmans et al. (2005).

Vast areas in the EA exhibit significant suitability for coffee production, with approximately 54% of the territory demonstrating high suitability in the recent past. This finding aligns with the growing economic and agricultural importance of coffee cultivation in the region. Morona Santiago and Orellana, in particular, emerge as the most prominent provinces in terms of land area with high suitability, covering an impressive 26% and 25% of the territory respectively. This information supports the potential viability of these provinces as important coffee producers in the future. Comparing these results with previous studies on suitability for coffee cultivation, a coherence in certain patterns can be observed, which highlighted the high suitability of specific regions for coffee production (Chemura et al. 2021; Läderach et al. 2017; Ranjitkar et al. 2016). The coincidence between the present findings and those of previous studies strengthens the validity of the suitability identified in Morona Santiago and Orellana, consolidating the importance of these areas as strategic points for coffee cultivation.

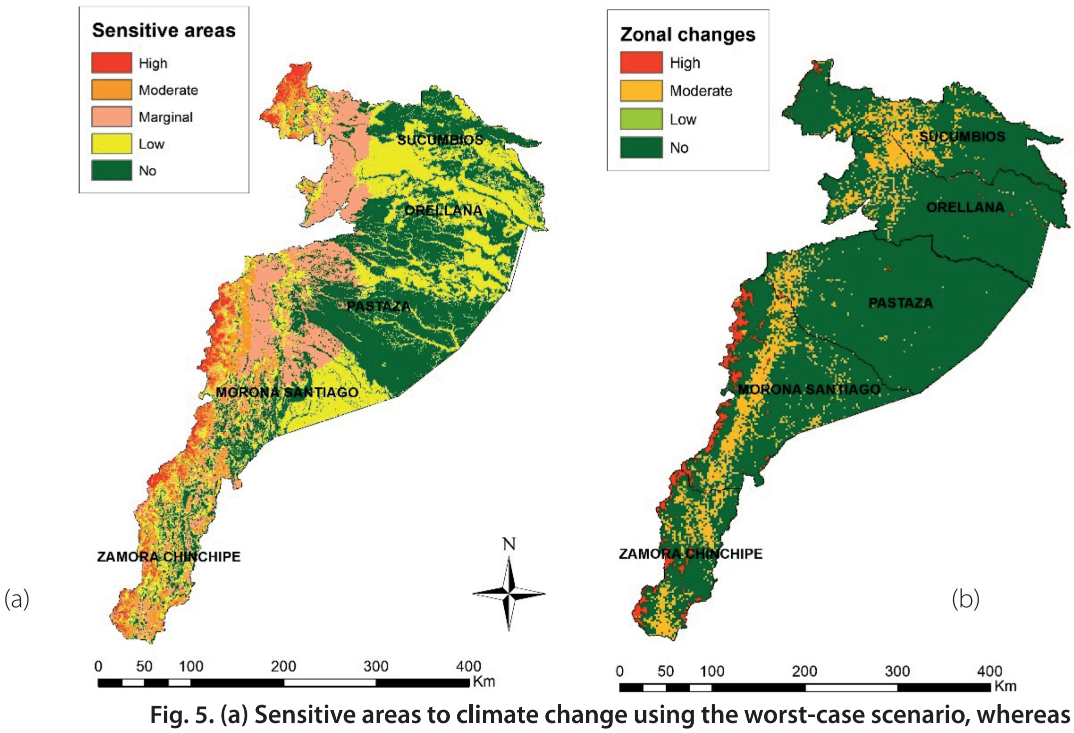


Fig. 5. (a) Sensitive areas to climate change using the worst-case scenario, whereas (b) shows zonal changes in specific areas

Although high suitability for coffee production is an encouraging indicator of agricultural development, it is crucial to consider the sustainability and environmental aspects associated of this activity. Additional studies, have examined the interaction between the expansion of agricultural crops, including coffee, and its impact on biodiversity and ecosystem services (Barrios et al. 2018; De Beenhouwer et al. 2013). In addition, it is essential to address the variability in suitability identified in the present study, especially in the provinces of Pastaza and Morona Santiago, where areas with moderate suitability are observed. Previous studies, have explored agricultural management strategies and sustainable practices to optimize production in areas with moderate suitability (Castro-Tanzi et al. 2012; D'haeze et al. 2005), highlighting the importance of adopting adaptive approaches to ensure the long-term resilience of the coffee sector in these regions.

It is interesting to note that the results do not identify areas of medium, low or unsuitable suitability for coffee cultivation in the present period. This absence of less favorable projections can be interpreted as a positive sign for coffee activity in the study region. Previous studies (Benti et al. 2022; Chemura et al. 2021; Salas et al. 2020), have addressed the influence of climatic and geographic factors on the suitability for coffee cultivation, corroborating the idea that the topography and climatic conditions specific to the highlands of Ecuador contribute significantly to the high suitability that the present study has identified.

In terms of specific extensions of high suitability, variations between 5,701 km^2 and 12,047 km^2 in all provinces were observed, with Pastaza being the province with the largest extension, followed closely by Morona Santiago. This specific distribution highlights intra-provincial variability and underscores the importance of considering local factors in the design of agricultural development strategies.

The results obtained through the ensemble estimation model under different climate change scenarios (SSP585 and SSP126) provide an enlightening view on the susceptibility of Ecuadorian provinces to future conditions. The identification of the provinces of Zamora Chinchipe and Morona Santiago as the most affected in the worst case scenario (SSP585) reflects a worrying trend towards a decrease in areas suitable for coffee cultivation in these regions, especially in their eastern sectors. This finding is consistent with previous research, which also highlighted the vulnerability of other similar regions to the impacts of climate change due to the increase in temperatures and the alteration of climatic conditions traditionally favorable for coffee cultivation (Beltrán-Tolosa et al. 2022; Koh et al. 2020; Rahn et al. 2014).

However, the variability in results between scenarios highlights the need to consider diverse future trajectories in agricultural planning. has explored the utility of ensemble models to address uncertainty associated with climate projections (Parker 2013; Shortridge & Zaitchik 2018; Zumwald et al. 2020). These findings highlight the importance of considering multiple scenarios to inform strategic agricultural decisions and policies, recognizing the complexity of climatic factors and their influence on suitability for coffee cultivation.

On the other hand, the results highlighting the sensitivity to climate change in the central areas of several Ecuadorian provinces, especially Orellana, Morona Santiago, Pastaza and Zamora Chinchipe, shed light on the complex interaction between climate change and land use in the region. This pattern of sensitivity in central areas could have significant implications for agriculture, particularly for coffee cultivation, which is highly dependent on specific climatic conditions. Previous research has also highlighted the vulnerability of these regions to the impacts of climate change, such as changes in precipitation patterns and temperatures, which could potentially impact the suitability of the land for coffee cultivation (Gomes et al. 2020; Jawo et al. 2022; Lemma & Megersa 2021).

The identification of areas with moderate land use changes in all provinces, especially under the worst climate scenario (SSP585), suggests significant landscape transformations. The transition from forests, shrubs, and herbaceous vegetation, as well as agricultural land, to anthropogenic zones, points to changes induced by human activities. This finding is in line with previous studies, which have explored the relationship between the expansion of human activities and changes in land use, highlighting the need for sustainable management strategies to mitigate negative impacts on biodiversity and ecosystem health (Haggar et al. 2013; Navidad et al. 2023; Verbist et al. 2005). The projected changes in temperature associated with the worst-case scenario towards the culmination of the 2040 period appear to contribute to a discernible decrease in high suitability areas. This corroborates findings in the study by Gomes et al. (2020), wherein the anticipated alterations in temperature and precipitation are postulated to result in a substantial reduction in suitability for coffee production. The critical role of these variables (Bio1 and Bio10) lies in the simultaneous increase in temperature and reduction in precipitation, potentially inducing elevated evapotranspiration rates and a subsequent decline in water availability, thereby prolonging dry seasons.

The anticipated change in land suitability by 2040 suggests an average decrease of 63% in the best-case scenario and 87% in the worst-case scenario for coffee cultivation across the EA; this reduction is likely influenced significantly by the extent of each province and the GCMs utilized. Comparable shifts have been documented in global and regional studies, projecting a potential 90% decrease in suitable areas for coffee production by 2050 (Bunn et al. 2015; Läderach et al. 2017).

In the present study, the projected 87% reduction in suitable areas, particularly in the SSP585 scenario, is anticipated to predominantly impact the Amazon forest within the five provinces, potentially impacting the livelihoods of local communities for whom coffee cultivation is a primary activity. Nevertheless, recent research suggests that the expected adverse effects of rising temperatures and altered rainfall patterns on coffee production may be partially offset by a fertilizing effect of CO_2 associated with greenhouse gas emissions, offering a potential offset of 13-21% (Rahn et al. 2018; DaMatta et al. 2019). The analysis by Cassamo et al. (2023) indicates that future scenarios (SSP126, SSP585) could have detrimental effects on the Mozambican Arabica industry, particularly under Agroforestry Systems (AFS) and full sun systems, with the latter experiencing more pronounced adverse effects. By the period 2041-2060, suitable areas are projected to diminish by approximately one-half to two-thirds under AFS, contingent on the specific scenarios considered.

In response to the challenges posed by climate change, particularly the rise in temperatures and precipitation deficits, the adoption of AFS has been proposed as a viable adaptation strategy to preserve the current expanse of high land suitability for coffee production (de Sousa et al. 2019; Sebatta et al. 2019). To mitigate the impact of climate change on coffee production, farmers have the potential to enhance adaptation strategies by increasing the shade cover in AFS beyond the 50% threshold; this necessitates tailored shade management throughout the year, involving reduced shade cover post-harvest when coffee plants require heightened solar energy for node development (Gomes et al. 2020).

The imperative significance of implementing and applying AFS has been underscored in various studies, with notable applications observed, particularly in the Coast region of Ecuador (Jarrett et al. 2017; Vaca et al. 2018). This strategy emerges as a viable option to effectively mitigate the impact of climate change on coffee cultivation. It is crucial that local coffee farmers in the EA region comprehend the nuanced effects of climate change, and this understanding can be fostered through ongoing training sessions facilitated by specialists and scientists within the coffee sector. Furthermore, this study advocates for future research endeavors that integrate climatic, physio-edaphological, and socio-economic factors in modeling predictions, thereby enhancing their informativeness, particularly at the regional or national scale. Such an integrated approach has the potential to generate context-specific recommendations for the successful implementation of coffee agroforestry systems.

CONCLUSIONS

In conclusion, this research highlights the critical importance of climatic variables, specifically the mean temperature of the warmest quarter (Bio10) and the mean annual temperature (Bio1), in the modulation of soil suitability maps in past periods. These climatic variables are revealed as fundamental factors that significantly influence environmental conditions, delineating soil suitability for both varieties of coffee cultivation.

The study also highlighted the high suitability of extensive areas within the study area (EA) for coffee production during the past period, covering approximately 54% of the territory. This finding not only reflects the region's historical relevance in coffee production, but also aligns with the growing economic and agricultural importance of coffee cultivation nationally and internationally.

The provinces of Morona Santiago and Orellana stand out as the most promising in terms of land areas with high aptitude, covering a remarkable 26% and 25% of the territory, respectively. This distribution highlights the significant contribution that these provinces can make to the coffee sector, positioning them as key players in the future coffee production landscape. The identification of these provinces as strategic areas supports effective planning for the region's sustainable coffee growing development .

The detailed analysis of the projections of suitability for coffee cultivation in all the provinces of the study area reveals key aspects that have an impact on the viability and planning of the coffee sector. A particularly significant finding is the absence of areas identified as medium, low or unsuitable for coffee cultivation in the current period in all provinces. This fact, which highlights the homogeneity of favorable conditions in the region, can be interpreted as a positive indicator for coffee activity, suggesting a favorable scenario for the expansion and sustainability of coffee production in the study area.

The ensemble estimation model employed elucidates distinctive scenarios for the future of coffee cultivation in the EA. Under the SSP585 climate change scenario, Zamora Chinchipe and Morona Santiago, particularly their eastern sectors, emerge as provinces facing significant unsuitability for coffee cultivation. Contrastingly, the SSP126 scenario presents a more optimistic outlook, revealing high land suitability across the entire territorial expanse of Pastaza, Orellana, and Sucumbios provinces. It is noteworthy that areas bordering the Highland region within these provinces exhibit only unsuitable conditions for coffee cultivation.

In addition, this study highlights the inescapable interconnection between climate change and land use dynamics in several Ecuadorian provinces, with a special focus on Orellana, Morona Santiago, Pastaza and Zamora Chinchipe. The identification of these core areas as particularly sensitive to climate change sheds light on a complex interaction that could have substantial implications for regional agriculture, especially with regard to coffee cultivation, a sector highly dependent on specific climatic conditions.

This pattern of sensitivity highlights the vulnerability of the core areas of these provinces, pointing to the pressing need for adaptive strategies in agricultural planning and land use management. Coffee cultivation, which is an activity that takes place in a specific climatic environment, is particularly affected by variations in climatic conditions. Understanding this sensitivity provides a solid basis for developing mitigation and adaptation measures to safeguard the resilience of regional agriculture to the challenges of climate change.

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APPENDICES

Appendix A. List of the 19 bioclimatic variables

BIO 1	Annual Mean Temperature
BIO 2	Mean Diurnal Range (Mean of monthly (max temperature - min temperature))
BIO 3	Isothermality (BIO2/BIO7) (* 100)
BIO 4	Temperature Seasonality (standard deviation *100)
BIO 5	Max Temperature of Warmest Month
BIO 6	Min Temperature of Coldest Month
BIO 7	Temperature Annual Range (BIO5-BIO6)
BIO 8	Mean Temperature of Wettest Quarter
BIO 9	Mean Temperature of Driest Quarter
BIO 10	Mean Temperature of Warmest Quarter
BIO 11	Mean Temperature of Coldest Quarter
BIO 12	Annual Precipitation
BIO 13	Precipitation of Wettest Month
BIO 14	Precipitation of Driest Month
BIO 15	Precipitation Seasonality (Coefficient of Variation)
BIO 16	Precipitation of Wettest Quarter
BIO 17	Precipitation of Driest Quarter
BIO 18	Precipitation of Warmest Quarter
BIO 19	Precipitation of Coldest Quarter

Appendix B. Contribution percentajes of bioclimatic variables from avaliableliterature

Reference	Topic	Year	Region	Bioclimatic factors	% Contribution
Purba et al	Modeling the plantation area of geographical indication product under climate change: Gayo Arabica coffee (coffea arabica)	2019	Indonesia	Bio 12 Bio 13 Bio 4 Bio 16 Bio 14 Bio 9 Bio 8 Bio 2 Bio 17 Bio 15 Bio 1	40 26,1 9,6 7 4,6 3 2,9 2,4 2,3 2,1 0,1
Schroth et al	Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico	2009	México	Bio 16 Bio 5 Bio 19 Bio 13 Bio 17 Bio 3 Bio 9 Bio 4 Bio 8	44,7 21 17,8 10,7 10,7 8,5 8,5 6,6 6,5

Fekadu et al	GIS-based assessment of climate change impacts on forest habitable Aframomum corrorima (Braun) in Southwest Ethiopia coffee forest	2020	Ethiopia	Bio 1 Bio 11 Bio 13 Bio 12 Bio 3 Bio 16 Bio 7 Bio 6 Bio 2 Bio 5 Bio 9	49,7 21,4 7,5 5,2 4,3 3,6 2,8 2,3 1,3 1,2 0,4
Gomes et al	Agroforestry systems can mitigate the impacts of climate change on coffee production: A spatially explicit assessment in Brazil	2020	Brazil	Bio 10 Bio 19 Bio 3 Bio 4 Bio 13 Bio 12	63,2 21,4 6,76 5,9 2,59 0,08
Chemura et al	Bioclimatic modelling of current and projected climatic suitability of coffee (Coffea arabica) production in Zimbabwe	2021	Indonesia	Bio 19 Bio 15 Bio 3 Bio 9 Bio 18 Bio 11 Bio 16 Bio 7	43,8 26,3 12,9 5,4 4,7 4,5 2,4 0
Bunn et al	A bitter cup: climate change profile of global production of Arabica and Robusta coffee	2015	Global	Bio 5 Bio 10 Bio 8 Bio 2 Bio 1 Bio 7 Bio 4 Bio 6 Bio 9 Bio 18 Bio 11 Bio 13 Bio 15 Bio 12 Bio 16 Bio 3 Bio 17 Bio 14 Bio 19	11 11 9,5 8 7,5 6,5 5 4,5 4,5 4,5 4 4 4 3,5 3,5 3 2,5 2 2
Zhang et al	AHP-GIS and MaxEnt for delineation of potential distribution of Arabica coffee plantation under future climate in Yunnan, China	2021	China	Bio 6 Bio 5 Bio 12 Bio 7 Bio 4 Bio 15 Bio 14	24,6 20,6 10,7 4 1,3 1,3 0,5
Laderach et al	Predicted impact of climate change on coffee supply chains	2011	Nicaragua	Bio 13 Bio 10 Bio 19 Bio 18 Bio 12 Bio 16 Bio 7 Bio 8 Bio 9 Bio 4 Bio 5 Bio 17	44 23,6 6,5 6,3 6 5,2 3,5 1,2 1,2 0,8 0,6 0,4

Abrha	Climate change impact on coffee and the pollinator bee suitable area interaction in Raya Azebo, Ethiopia	2018	Ethiopia	Bio 15 Bio 18 Bio 19 Bio 7 Bio 14 Bio 3 Bio 16 Bio 17 Bio 8 Bio 5 Bio 4	23,3 21,3 10,7 9,3 7,3 6 5,9 4,3 4,1 3,5 2,8
De Oliveira et al	Influence of temperature and altitude on the expansion of coffee crops in Matas de minas, Brazil	2020	Brazil	Bio 15 Bio 1 Bio 4 Bio 12	17,4 13,7 9,2 5,1

Appendix C. Agroecological requirements for coffee crop in Ecuador proposed by INIAP. (A) Arabica; (R) Robusta

Factor	Variable	Agroecological suitability			
		Optimal	Moderate	Marginal	No suitable
Soil	Slope	0 -25%	25-50%	50-70%	>70%
	Texture	Loam, silt loam, clay loam, sandy clay loam, silty clay loam, clay loam, sandy clay loam, silty clay loam, silty clay loam, sandy clay loam silt loam	Sandy loam, silty loam, sandy loam, sandy loam	Sandy (fine, medium, coarse)	Clay (>60%)
	Depth	Deep	Moderately deep	Shallow	Shallow superficial
	Stoniness	No	Few	Frequent	Abundant
	Drainage	Good	moderate	Poorly drained	Excessive
	pH	Slightly acidic, Neutral	Acidic	Moderately alkaline	Very acidic, Alkaline
	Toxicity	Without	Slight	Half	High
	Organic matter content	Very High, High	Medium	Low	Very low
	Salinity	Without	Medium	High	Very high
	Fertility	Very High, High	Medium	Low	Very low
Climate	Precipitation (mm year^{-1})	800-2000 (A) 2000 – 3000 (R)	500-800; 2000-2500 (A) 3000-3500 (R)		>500; >3000 (A) >4000 (R)
	Temperature (°C)	17-23 (A) 20-26 (R)	16-17; 23-24 (A) 18-20 (R)	17-18 (R)	<16 >24 (A) <17 (R)
	Altitude (asml)	400-1800 (A) 600 (R)	1. 400; 1800-2000 (A)		>2000 (A) >600 (R)