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Effects of change in land use and climate change on the potential distribution of sugarcane at Valle del Chota, Ecuador

Efectos del cambio de uso de suelo y cambio climático en la distribución potencial de la caña de azúcar en el Valle del Chota, Ecuador

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Abstract

Sugarcane is a socio-economically important crop, which is not exempt from internal and external disturbances. This research was carried out at the Chota Valley, one of the sectors where sugarcane is traditionally grown in Ecuador. The aim is to determine the effects of future land cover change on its development until 2031 and the effects of climate change on its distribution for the period 2025-2035 in the scenarios RCP 4.5 and RCP 8.5. For this purpose, land use was projected for 2022 and 2031, using land use coverages for 1999-2011 as the base information. Future projections under climate change scenarios were carried out using the agro ecological zoning of crops and changes in temperature and precipitation climate scenarios. The results forecast that due to land use change, sugarcane cultivation will decrease its area by about 14.65% from 2022 to 2031. However, the research findings under the RCP 4.5 and RCP 8.5 climate scenarios for the 2025-2035 period indicate a significant increase in the optimal areas for sugarcane production in equal proportion, mirroring the rise in water availability.

Keywords: Sugarcane, Land use change, climate change, RCP, Chota.

Resumen

La caña de azúcar es un cultivo de importancia socioeconómica, el cual no está exento de perturbaciones internas y externas. La presente investigación se desarrolló en el Valle del Chota, que es uno de los sectores donde tradicionalmente se cultiva la caña de azúcar en Ecuador. El objetivo es determinar los efectos del cambio futuro de cobertura de suelo en su desarrollo hasta el año 2031 y los efectos del cambio climático en su distribución para el periodo 2025-2035 en los escenarios RCP 4,5 y RCP 8.5. Para ello, se proyectó el uso de suelo a los años 2022 y 2031 utilizando como información base las coberturas de uso de suelo de los años 1999 y 2011. Para la proyección futura bajo escenarios de cambio climático se utilizó la zonificación agroecológica del cultivo y los cambios que ocurrirán en la temperatura y precipitación en los escenarios climáticos. Los resultados pronostican que, por efecto del cambio de uso de suelo, el cultivo de caña de azúcar disminuirá su superficie en alrededor del 14,65% desde el año 2022 hasta el 2031. En contraste, bajo los escenarios climáticos RCP 4,5 y RCP 8,5, para el periodo 2025-2035 las superficies óptimas para la producción de caña de azúcar aumentarán en igual proporción, reflejando un aumento de la disponibilidad hídrica.

Palabras clave: Caña de azúcar, Cambio de uso de suelo, Cambio climático, RCP, Chota.

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1 Introduction

Sugarcane (*Sacharum officinarum*) is a perennial plant of the Poaceae family belonging to the *Saccharum*, genus, used primarily for sugar production. Sugarcane transformed the industrial business activity, shifting from being a food-providing crop to one that supplies inputs for the chemical and energy industries (Gómez-Merino et al., 2015). The economic importance of this crop lies in three main characteristics: (a) it has a high production capacity; (b) it efficiently utilizes productive resources and inputs; and (c) it can be locally processed into higher-value products such as sucrose, molasses, ethanol, and energy (Gómez-Merino et al., 2015). Currently, it is one of the most important crops worldwide, as its production contributes to the nourishment of over half of the global population (Moraes et al., 2015; Som-ard et al., 2018). Global production has increased from 448 million tons cultivated over 8.9 million hectares in 1961 to 2 billion tons over 27 million hectares in 2020 (El Chami et al., 2020).

Sugarcane originates from the tropical, warm-temperate regions of Southeast Asia and New Guinea and is primarily cultivated in tropical and subtropical regions worldwide (Som-ard et al., 2021). In Ecuador, sugarcane was introduced to tropical and subtropical zones during the Spanish conquest and currently it covers more than 82,000 hectares (Mendoza et al., 2005). The Chota Valley, located between the provinces of Carchi and Imbabura in Ecuador, is one of the subtropical areas with suitable edaphic conditions for cultivating this crop (Echeverría and Uribe, 1981). Sugarcane arrived in the Chota Valley with the first Spanish landowners around 1550; however, it was not until 1570 that sugarcane began to replace the primary crops of the time-coca and cotton (Coronel Feijoo, 1991). Sugarcane production has become one of the main sources of income for the population in this area, which is the second-largest Afro-descendant settlement in Ecuador. Nevertheless, this agricultural activity has not been immune to internal and external disturbances, such as crop replacement (Espín Díaz, 1999) or the potential effects of climate change.

Globally, agriculture is the economic sector most affected by climate fluctuations, making it essential to implement effective strategies for adaptation and mitigation (Zhao and Li, 2015). Climate change results from disruptions in the Earth's energy balance, caused by both natural factors and human interventions (Intergovernmental Panel On Climate Change (IPCC), 2023). This phenomenon presents new challenges for agricultural productivity, as it will eventually alter climatic and agroecological zones, particularly in regions such as Latin America (López Feldman and Hernández Cortés, 2016). According to Organización Internacional del Azúcar (2013), climate change by 2050 could increase the area suitable for sugarcane cultivation by 160 %. Changes in climatic and atmospheric conditions-such as temperature rise, solar radiation, and CO_2 concentration-are expected to increase sugarcane yields (Guerra and Hernández, 2012).

However, there is no global consensus on the potential local effects of climate change on sugarcane production. While Marin et al. (2013) and Todd et al. (2015) suggest that climate change could improve sugarcane yields in Brazil and Louisiana (USA), respectively-due to improved water use efficiency in Brazil and reduced frost incidence in Louisiana-Singh and El Maayar (1998) found that in the Southern Caribbean, sugarcane yields could decrease by 20–40 % under a scenario of doubled CO_2 concentration. Similarly, Knox et al. (2010) used climate models to predict a future decline in sugarcane yields in Swaziland, Africa.

These findings confirm that farmers must adapt to new conditions for sugarcane cultivation under the possible effects of climate change, whether positive or negative. In Ecuador, according to Representative Concentration Pathway (RCP) projections, national temperatures could rise by up to 2 °C, except in the Amazon and Insular regions (Ministerio de Ambiente de Ecuador, 2019). This temperature change would reduce the adaptive capacity of Ecuadorian cities to climate change (Arias-Muñoz et al., 2022), and inevitably affect the yields of crops such as sugarcane. Moreover, future sugarcane yields may not only be impacted by climate change but also by dynamics related to land-use change. Therefore, the aim of this study is to determine the current extent of sugarcane cultivation (in 2022) and project its area to the year 2031 under a baseline scenario with land-use change trends, and under two climate change scenarios (RCP 4.5 and RCP 8.5). Land-use changes were assessed using a transition matrix, and land-use projections, including sugarcane coverage, were developed using Markov chains.

Future projections under climate change scenarios were based on the crop's agroecological zoning and the anticipated impacts of temperature and precipitation on agroecological requirements. Thus, the challenge was to identify optimal agroecological zones, assess possible future changes and emerging needs, and propose adaptation strategies aimed at minimizing the impact of climate change to foster sustainable development (Oviedo and León, 2010).

2 Materials and Methods

2.1 Study area

The study area of this research corresponds to the dry valley of the Chota River, located in northern Ecuador between the provinces of Imbabura and Carchi, within the meridians 78° 15′ and 77° 55′ West longitude, and parallels 0° 30′ and 0° 7′ North latitude (Espín Díaz, 1999). It covers an area of 9,247 hectares and is characterized as an enclosed valley within the Chota basin, situated between two branches of the Andes mountain range (Winckell et al., 1997) The valley is also characterized by plains and peneplain relief, with the Chota River being the main watercourse traversing it (Figure 1).

The Chota Valley features a lower montane dry shrubland vegetation formation (Sierra, 1999) and is located at elevations ranging from 1,500 to 1,800 meters above sea level (Espín Díaz, 1999). According to Pourrut's climatic classification Pourrut (1983), the valley's climate is considered megathermal arid to semi-arid, with an average annual temperature ranging from 17.2 to 19.5 °C and an average annual precipitation between 559 and 945 mm. The characteristic vegetation of the area includes species such as *Acacia macracantha* and *Mimosa pudica* (algarrobo), *Mimosa quitensis* (huarango), *Spondias mombin* (ovo), *Phaseolus vulgaris* (common bean), *Cajanus cajan* (pigeon pea), and *Saccharum officinarum* (sugarcane) (Mena, 2001).

The population of the Chota Valley is predominantly Afro descendant. The Afro-Ecuadorian community that settled in the valley traces its origins to the importation of enslaved labor by the Jesuits for sugarcane plantations (Carrascal Jijón, 2016). This historical process gave rise to a culturally and historically distinct Afro-descendant community in the Chota Valley. In fact, it is considered the second-largest Afro-descendant settlement in Ecuador, surpassed only by the province of Esmeraldas (Ortiz Villalva, 2011). The valley comprises the following population centers: Piquiucho, Chalguayaco, Juncal, Pusir Grande, Pusir Chiquito, Carpuela, Tumbatú, Ambuquí, San Vicente de Pusir, Chota, and Mascarilla. Within these communities, it is estimated that approximately 64.4% of the population lives in poverty, and as of 2001, around 15% of the population was considered illiterate (Ortiz Villalva, 2011; Peralta et al., 2001).

The primary economic activities include agriculture (86%), manufacturing (10%), and commerce (4%) (Peralta et al., 2001). However, agriculture in the region has faced significant challenges due to excessive land fragmentation, insufficient irrigation water, limited agricultural technology, and the introduction of new market demands (Ortiz Villalva, 2011). These conditions have led to population migration toward urban areas, continuous crop rotation, and even the pursuit of alternative economic activities (Espín Díaz, 1999).

On the other hand, in 1964, the Ingenio Azucarero del Norte (IANCEM) sugar mill was established to take advantage of the region's favorable conditions for sugarcane cultivation and to improve the economic conditions of local farmers (Espín Díaz, 1999). Nevertheless, the valley only briefly served as a sugarcane supplier for the mill, as local farmers found other crops-such as common beans (*Phaseolus vulgaris*), chili peppers (*Capsicum annuum*), and tomatoes (*Lycopersicon esculentum*)-to be more profitable in nearby local markets such as Pimampiro, Ibarra, and Tulcán (Espín Díaz, 1999).

2.2 Determination of the current (2022) and future expansion (2031) of sugarcane (*Saccharum officinarum*) cultivation

The current (2022) and projected (2031) distribution of sugarcane was determined based on land use projections for the Chota Valley, using data from the reference years 1999 and 2011, through the application of ArcGIS 10.8.2 and TerrSET 1.0 software. The projection of land cover and land use change (LULC) considered the following predictive variables: land slope, digital elevation model (DEM), Euclidean distance from urban areas, roads, and Euclidean distance from roads (Figure 2a–e).

The variables were classified as either static or dynamic, according to their characteristics. The following were defined as static variables: (a) the digital elevation model (DEM), and (b) slope, as these are elements that do not change over time. In contrast, the dynamic variables included: (c) Euclidean distance from populated areas, (d) Euclidean distance from roads, and (e) road networks.

Furthermore, for the land cover and land use (LULC) projection, as recommended by Ortega Chuquín and Arias Muñoz (2022), the spatial characteristics of the predictive variables-slope, altitude, distance to roads, and distance to urban areas-were standardized, along with the spatial data files corresponding to the reference years for land cover and land use (1999 and 2011). This process involved the harmonization of both the spatial and radiometric resolution of the geospatial datasets (Table 1).

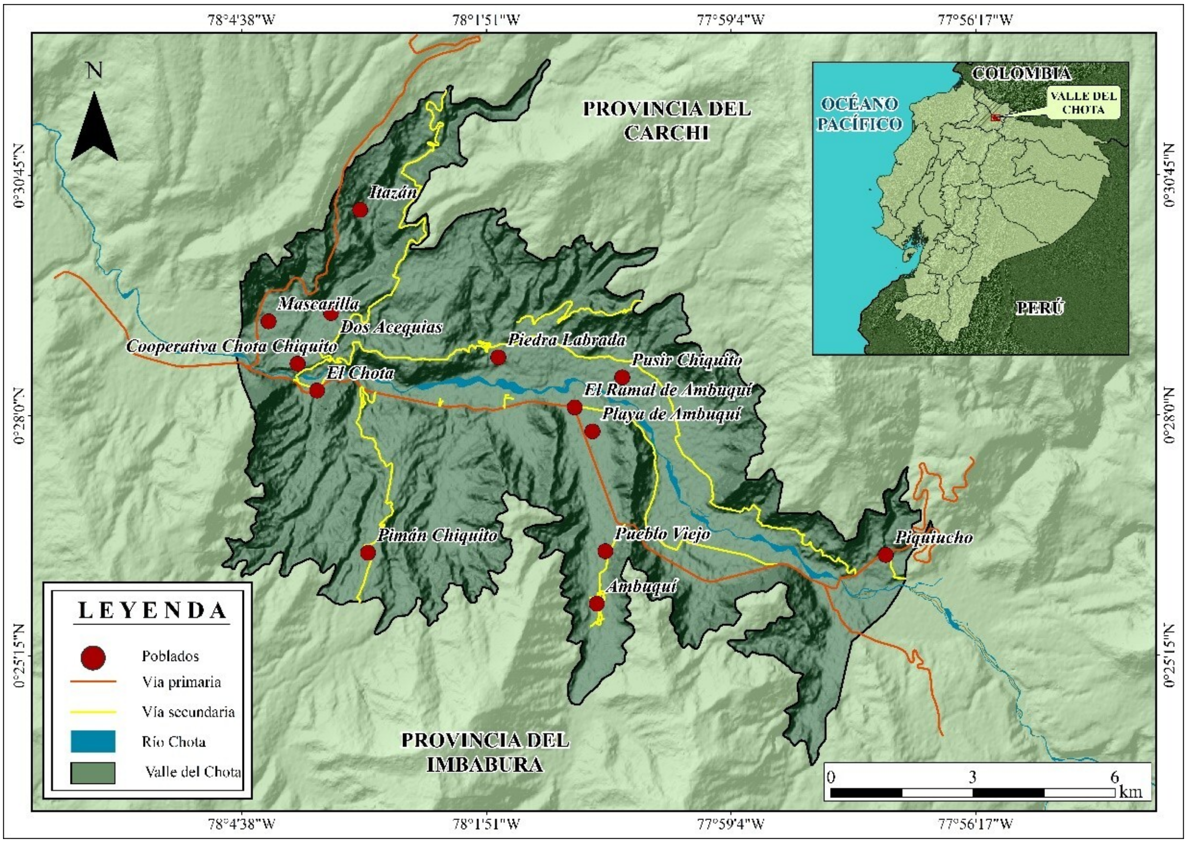

Figure 1. Location of the Chota Valley.

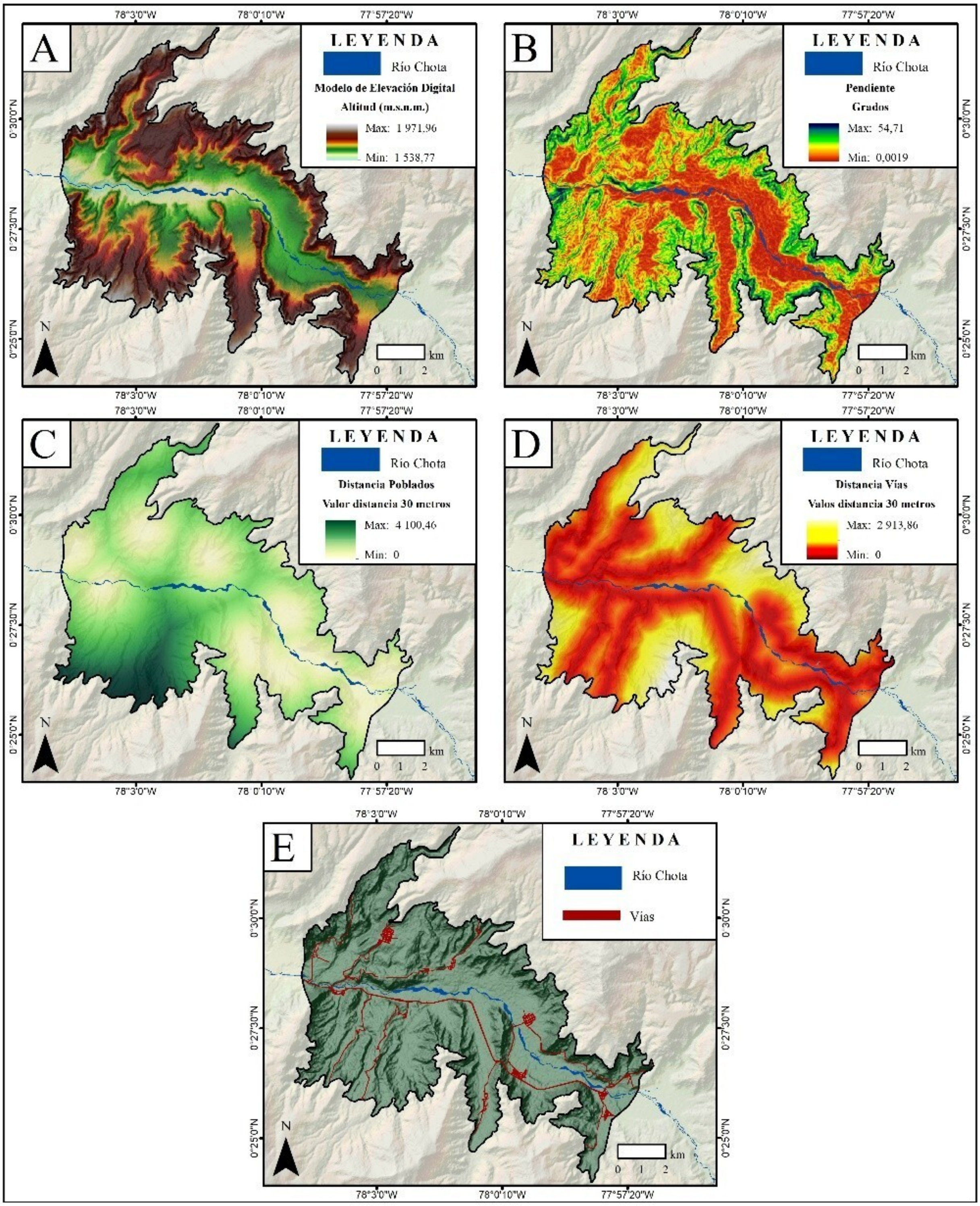

Figure 2. Static and dynamic variables: a) DEM and elevation model, b) slopes, c) Euclidean distance of settlements, d) Euclidean distance of roads and e) roads.

Table 1. Characteristics of geospatial files

Raster information	Features
Columns and rows	502-497
Number of bands	1
Pixel size	30 m × 30 m
Formato	TIFF
Pixel type	Unsigned integer
Radiometric resolution of the pixel	4 bits

To establish the land cover and land use (LULC) for the years 2022 and 2031, the Land Change Modeler (LCM) tool from the TerrSET 1.0 software was used. This enabled the development of potential transition models, prediction models, and land use change scenarios. In this study, a submodel titled "Disturbances"was developed, based on identifying the most predominant trends in land cover and land use change among the different categories (Table 2).

Table 2. Disturbance submodel

Transition		Sub - Model
From:	Change to:	
Sugarcane cultivation	Other crops	Disturbances
Xerophytic vegetation	Sugarcane	
Sugarcane cultivation	Non-vegetated area	
Other crops	Sugarcane	

Once the submodel was established, Cramér's V test was applied to the previously generated static and dynamic variables. This test is used to measure the association between two categorical variables and it enables the calculation of the relationship between variables based on their effect (Table 3).

Table 3. Interpretation of Cramer's V test results

Effect Size	Interpretation
$\leqslant$0.2	The result is weak. Although the result is statistically significant, the fields are only weakly associated.
$0.2 < ES \leqslant 0.6$	The result is moderate. The fields are moderately associated.
$>$0.6	The result is strong. The fields are strongly associated.

Based on this interpretation of Cramér's V test, variables with moderate and strong levels of association were identified, as shown in Table 4, allowing for the development of the transition model for the years 2022 and 2031. Finally, to assess land cover and land use change for 2022 and 2031, the CA-Markov analysis was performed using TerrSet 1.0 software. This model is based on Markov chains, originally proposed by Russian mathematician Andrei Markov in 1907 (López Granados et al., 2001).

Table 4. Cramer's V test analysis

Variables	Cramer's V Test
Slope	0.546
Elevation model	0.573
Euclidean distance from settlements	0.457
Roads	0.321
Euclidean distance from roads	0.441
Sugarcane cultivation to non-vegetated area	0.393
Sugarcane cultivation to other crops	0.645
Xerophytic vegetation to sugarcane cultivation	0.498

2.3 Future sugarcane crop zoning under climate change scenarios to 2031

First, the agroecological requirements of the crop were identified and used to zone the optimal areas for the development of sugarcane (Table 5). Agroecological requirements help define suitable zones for crops based on combinations of soil, physiography, and climate (FAO, 1978).

Additionally, they contribute to the spatial zoning of crop distribution and the identification of potential impacts of climate change on the future viability of agriculture. Crops require optimal conditions for their development, which may include physical, chemical, topographic, and climatic factors-such as temperature and precipitation-that can limit the growth and development of the crop (Ruiz Corral et al., 2013).

Table 5. Agroecological conditions of sugarcane cultivation

Average annual temperature	15 to 33 °C
Average annual precipitation	1200 a 1500 mm/year
pH	5.5 to 8
Type of soil recommended	Loam, clay loam or sandy-clay loam

Source: Duarte Álvarez and González Villalba (2019)

Subsequently, the agroecological requirements for temperature and precipitation were replaced with the estimated values under the RCP 4.5 and RCP 8.5 scenarios. The climate projection data were obtained from the Climate Projections Report of Ecuador developed by the Ministry of the Environment, Water and Ecological Transition (Ministerio de Ambiente, Agua y Transición Ecológica (MAATE), 2020).

This report provides a future simulation based on dynamic downscaling for the period 1985–2070. It models the likely temperature and precipitation conditions under two climate scenarios known as Representative Concentration Pathways (RCP 4.5 and RCP 8.5). The RCP 4.5 scenario suggests a probable temperature increase of at least 2 °C, while RCP 8.5 projects an increase greater than 3 °C (Armenta et al., 2016).

MAATE provided daily temperature and precipitation data in cells or pixels with defined central points. The pixels used were: F17C50, F17C51, F17C52, F17C53, F18C50, F18C51, F18C52, F18C53, F19C50, F19C51, F19C52, F19C53, each covering an area of 10,000 hectares. Additionally, discrepancies between *in situ* data and comparative data were assessed using percentage bias (BIAS) and root mean square error (RMSE) between the available historical data and the simulated data for each climate scenario over the 2011–2015 period (Equation 1 and Equation 2).

$$BIAS = \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (2)$$

Where P represents the predicted data, O the observed data, and N the total number of data points.

BIAS indicates the average tendency of the simulated data to be higher or lower than the observed data (Gupta et al., 1999). This statistic reaches its optimal value when it equals zero, which would indicate that the simulation is accurate (Moriasi et al., 2007). RMSE provides a measure of the average magnitude of forecast errors, which is equivalent to representing the standard deviation of the model errors (Righetti et al., 2019). The model's predictive capability improves as the RMSE value decreases, as this would indicate that the predictions are closer to the actual values (Arias-Muñoz et al., 2023).

The results obtained from the BIAS and RMSE analyses were used to determine whether correction of the climate data simulated by Ministerio de Ambiente, Agua y Transición Ecológica (MAATE) (2020) was necessary. Subsequently, using the validated climate data for the period 2025–2035, suitable areas for sugarcane cultivation were identified under the two climate scenarios: RCP 4.5 and RCP 8.5. This process included interpolation of annual temperature and annual precipitation for the 2025–2035 period using the Spline method in ArcGIS 10.8.2 (Figure 3). Finally, the simulated optimal zones were compared with the current optimal zones.

3 Results and Discussion

3.1 Current situation (Year 2022) and future projection of sugarcane (*Saccharum officinarum*) cultivation for the year 2031

Although sugarcane cultivation in the Chota Valley is not agroclimatically viable due to its failure to meet the minimum required precipitation of 1,200 mm, supervised classification of land cover and land use indicates that sugarcane is nonetheless cultivated in the area. In fact, between 1999 and 2011, a decrease of 1.4% in the cultivated area was observed.

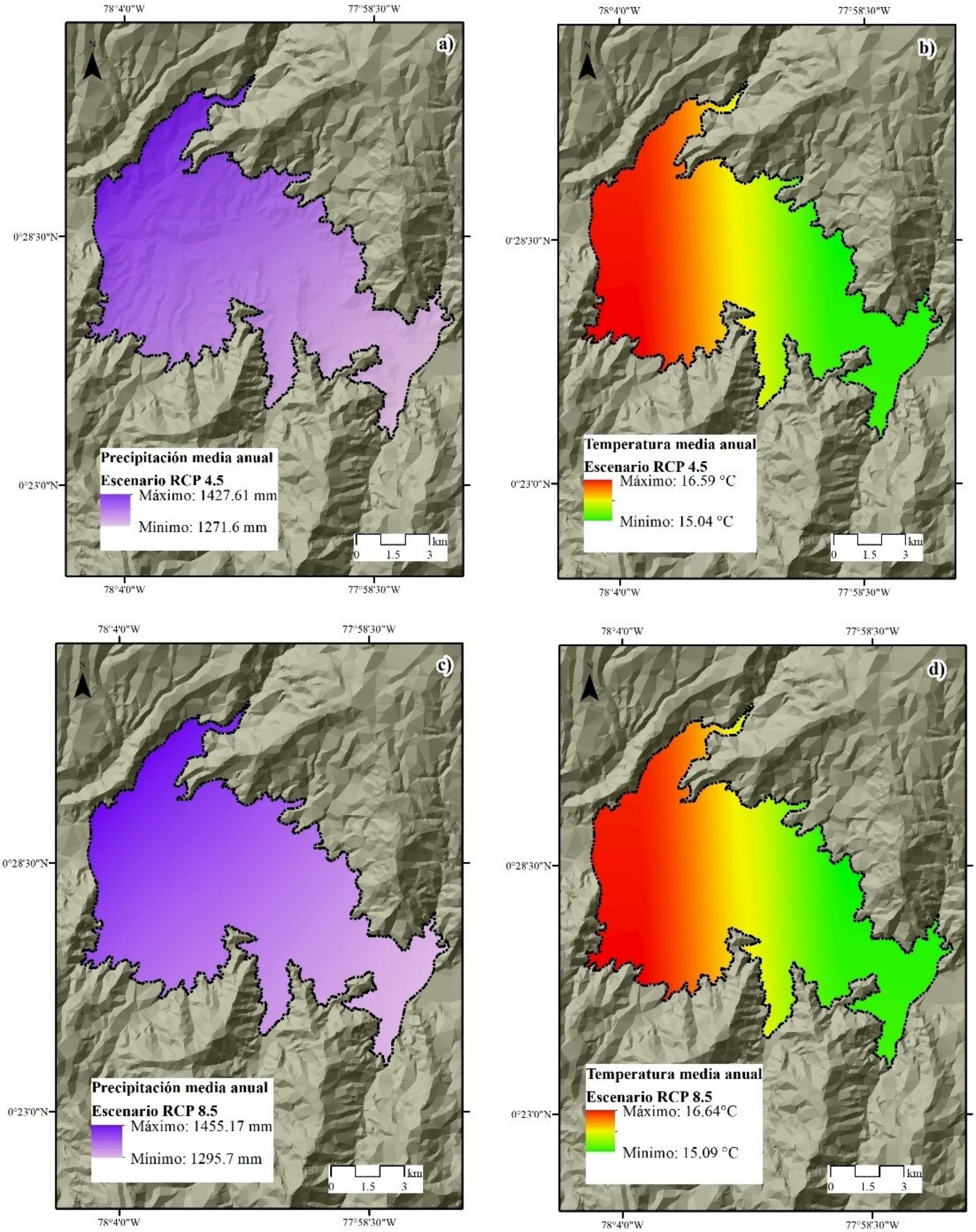

Figure 3. Interpolation of future precipitation and temperature for the period 2025-2035. a) Precipitation under RCP 4.5 scenario, b) Temperature under RCP 4.5 scenario, c) Precipitation under RCP 4.5 scenario, e) Temperature under RCP 8.5 scenario.

By 2011, sugarcane covered 530.52 hectares, representing 5.7 % of the total area. Thus, despite the absence of favorable climatic conditions, the crop is consistently cultivated in this territory. This persistence may be attributed to the use of two irrigation methods-drip and gravity irrigation-as well as the inherent adaptability of the species. By 2022, sugarcane cultivation occupied 481.52 hectares, equivalent to 5.21 % of total land cover, representing a 0.49 % decrease compared to 2011. Currently, sugarcane in the Chota Valley is cultivated by local farmers, and the harvest is generally sold to the Ingenio Azucarero del Norte (IANCEM). In contrast to sugarcane, other crops and urban settlements have shown greater expansion, increasing by 6.91 % and 2.66 %, respectively.

Based on simulated data for the near future, further changes are anticipated. By the year 2031, the sugarcane cultivation area is projected to decline from 481.52 hectares in 2022 to 410.99 hectares, representing a reduction of 14.65 %. This suggests that sugarcane will continue to be replaced by other crops such as mango, common beans, and chili peppers. As a result, these and other crops are expected to expand from 639.38 hectares to 681.36 hectares (an increase of 6.57 %), occupying approximately 7.37 % of the total area of the valley. Additionally, urban settlement areas are projected to grow by approximately 10.46 %, from 245.80 hectares to 271.52 hectares, primarily replacing semi-arid zones in the territory (Figure 4).

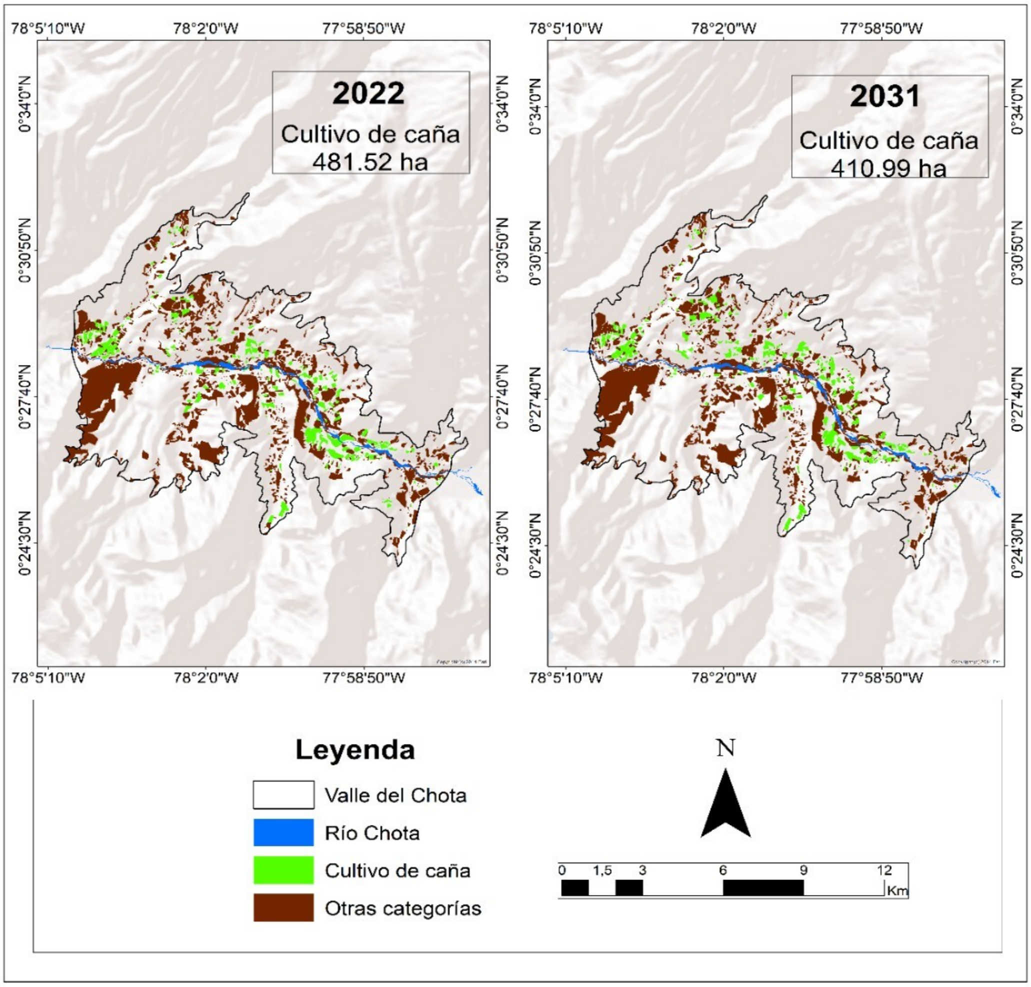

Figure 4. Land cover and land use change model for the period 2022–2031

3.2 Zoning of Sugarcane Cultivation under Climate Change Scenarios for the Period 2025–2035

First, it was determined that there is no need to correct the climate data simulated by Ministerio de Ambiente, Agua y Transición Ecológica (MAATE) (2020), as in both climate scenarios (RCP 4.5 and RCP 8.5), the values obtained for percentage bias (BIAS) are close to zero, and the RMSE values for precipitation fluctuate at most up to 2 mm, while those for temperature are close to zero (Table 6). These relatively low RMSE values suggest that the predictions are close to the actual values.

Consequently, for the 2025–2035 period, changes in precipitation and temperature are projected to affect sugarcane production in the Chota Valley as a result of climate change. Under both the RCP 8.5 and RCP 4.5 scenarios, the areas suitable for sugarcane cultivation are expected to increase proportionally, with optimal zones rising from currently nonexistent to covering 70.83 % of the area in both climate scenarios (Table 7 and Figure 5). This is because the average annual precipitation under these scenarios is projected to range between 1,261 mm and 1,455 mm, and the average annual temperature is expected to vary between 15 °C and 16.65 °C (Figure 3), thereby meeting the climatic requirements for the optimal development of the crop (Table 5). In this regard, according to the scenarios analyzed climate change will result in the emergence of optimal zones for sugarcane cultivation, in contrast to the current situation. As a result, it would be possible to cultivate sugarcane without relying on irrigation water supply.

Like other crops, sugarcane is not only influenced by climatic conditions during the agricultural year but also by the level of interest that farmers have in cultivating it (Silva et al., 2014). The reduction in sugarcane cultivation area from 1999 to 2022 demonstrates a gradual decline in the interest of local farmers in this crop. This trend persists despite the presence of the Ingenio Azucarero del Norte (IANCEM), a sugar mill located in the area that sustains product demand-a condition that, according to Moreno Izquierdo et al. (2018), supports optimal yields in regions with suitable natural conditions for sugarcane production. However, due to fluctuating prices and the crop's 18-month vegetative and production cycle, farmers reported in interviews that they prefer crops with shorter production cycles and greater market demand in nearby cities.

Espín Díaz (1999) noted that farmers in the valley have historically favored other crops over sugarcane due to easier market access. As a result, sugarcane is being replaced by crops such as mango (*Mangifera indica*), cucumber (*Cucumis sativus*), chili pepper (*Capsicum annuum*), and common bean (*Phaseolus vulgaris*). These crops not only have shorter growing cycles but also respond positively to the climatic and edaphic conditions of the region. Consequently, the area dedicated to sugarcane cultivation is not expected to increase by 2031, and the trend toward substitution with other crops will likely continue. The primary reasons are the declining interest and the need for faster-return crops. In general, studies conducted in Ecuador have shown that cultivated areas are projected to increase in various regions, such as the Amazonian forests (Heredia-R et al., 2021), the Chambo River basin in south-central Ecuador (Ross et al., 2017), and the Guayllabamba River basin (Abad-Auquilla, 2020). However, these studies do not specify which crops will replace others.

Table 6. BIAS and RMSE values between historical and simulated data for the climate variables precipitation and temperature

Variable	Climate scenario	BIAS	RMSE
Precipitation	RCP 4.5	-0.10	2.67
	RCP 8.5	-0.25	2.75
Average temperature	RCP 4.5	-0.41	0.64
	RCP 8.5	-0.45	0.66

On the other hand, the climatic influence on crop production highlights that climate variability in the region will increase the optimal zones for sugarcane cultivation in the Chota Valley. Under both RCP 4.5 and RCP 8.5 scenarios, precipitation is expected to increase between 1,271.6 mm and 1,427.61 mm in the former, and between 1,295.7 mm and 1,455.17 mm in the latter. According to Aguilar-Rivera et al. (2015), sugarcane requires at least 1,364.23 mm of water annually. Thus, climate change over the 2025–2035 period would meet the crop's water requirements. In some regions of Brazil, climate change has also been shown to enhance sugarcane production due to increased water availability (Marin et al., 2013). Similarly, Pereira De Souza et al. (2008) demonstrated that in controlled environments, higher CO_2 concentrations reduce stomatal conductance in sugarcane, thereby increasing photosynthesis. However, such physiological mechanisms could not be demonstrated in this study, nor were interactions between CO_2 and other climatic factors in natural conditions explored.

Table 7. Optimal areas for sugarcane cultivation in the Chota Valley under climate change scenarios for the period 2025-2035

Period	Scenario	Optimum zone		Suboptimal area	
		Ha	%	Ha	%
2025-2035	RCP 4.5	6526.27	70.83	2687.91	29.18
2025-2035	RCP 8.5	6526.27	70.83	2687.91	29.18

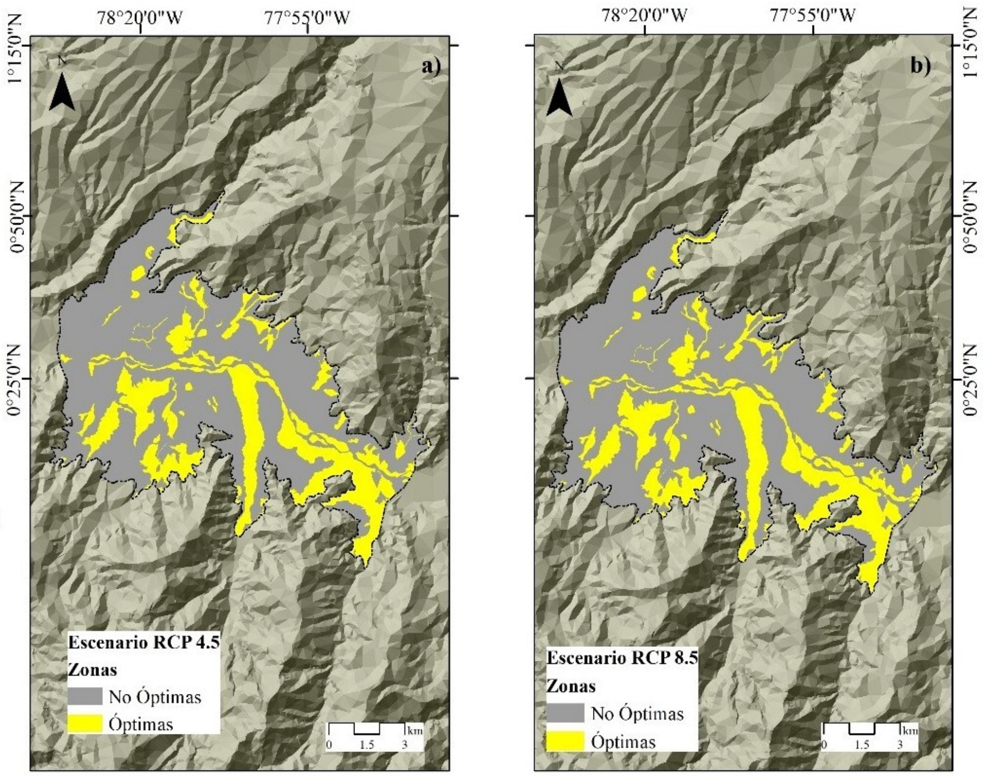

Figure 5. Zoning of sugarcane cultivation under climate change scenarios: a) Period 2025–2035, RCP 4.5 scenario; b) Period 2025–2035, RCP 8.5 scenario.

The negative impact on sugarcane yields is mainly associated with rising temperatures. Nevertheless, the projected temperature increase in the Chota Valley due to climate change is expected to remain between 15.04 °C and 16.64 °C, not exceeding the local minimum and maximum ranges of 13.2 °C and 26.7 °C. Therefore, no increase in water deficit is anticipated. This contrasts with the Southern Caribbean, where climate change is expected to cause a water deficit and result in yield reductions of 20% to 40% (Singh and El Maayar, 1998). Likewise, in Swaziland, sugarcane yields are expected to decline unless future models incorporate irrigation optimization (Knox et al., 2010). However, extreme weather events such as frosts may have less impact on crops like sugarcane, potentially allowing for increased yields (Todd et al., 2015).

Additionally, due to the inter-Andean location of the Chota Valley, other impacts of climate change may not significantly affect sugarcane production-unlike in Australia, for instance, where cultivated sugarcane areas are expected to expand further south of the tropics (Linnenluecke et al., 2020). Nonetheless, sugarcane production remains vulnerable to climate change, which increases the frequency and intensity of extreme weather events such as droughts, heatwaves, floods, and frosts (Jaiphong et al., 2016; Todd et al., 2015).

Therefore, the potential rise in such events in the Chota Valley could also negatively impact sugarcane yields. This is particularly true for drought, considering the region's warm climate, as climate change exacerbates water stress, affecting the plant's growth and development (Zhao and Li, 2015). Additionally, other constraints could influence the impact of climate change in the Chota Valley, such as the depletion of soil organic matter due to continuous cultivation, which, according to Aguilar-Rivera et al. (2015), increases soil vulnerability to climatic and environmental influences.

4 Conclusions

Despite the lack of optimal agroclimatic conditions, sugarcane cultivation has persisted for years in the Chota Valley. However, from 1999 to 2022, the cultivated area has steadily declined. This reduction, though not exceeding 2%, has led to sugarcane occupying 5.21% of the valley's total area as of 2022. Projected land use change is expected to cause a further reduction in sugarcane area by 2031, amounting to a 14.65% decrease compared to 2022. The primary reason for this decline is the replacement of sugarcane with other short-cycle crops. Most of the sugarcane is produced by local farmers, and although the Ingenio Azucarero del Norte purchases their product, growers perceive the crop's long growth cycle as economically unsustainable. Therefore, they opt for crops with shorter harvest times, such as beans and chili peppers.

The effects of climate change under both RCP 4.5 and RCP 8.5 scenarios are projected to be beneficial for sugarcane cultivation, as the future period (2025–2035) will see an increase in optimal growing areas by approximately 70.83% compared to the current situation. This is due to increased precipitation in both scenarios, surpassing the crop's minimum water requirement of 1,364.23 mm. Moreover, the negative impact of temperature is expected to be minimal, as temperatures will remain within the historical range, not exceeding 16 °C to 19 °C.

Ultimately, the findings of this study demonstrate that maintaining optimal growing zones alone is insufficient to sustain interest in sugarcane production. The potential positive effects of climate change in the Chota Valley, such as improved water availability, may not be enough to prevent the replacement of sugarcane with other crops that generate greater interest among farmers, whether due to shorter production cycles or higher profitability.

Authors' contribution

P.A.M: Conceptualization, data curation, formal analysis, methodology, project administration, resources, supervision, validation, visualization, original draft structure, writing-review and editing. E.L.Ch.B.: Data curation, research, methodology, original draft writing. S.A.P.Y.: Data curation, research, methodology, original draft writing. G.J.A.: Validation, visualization, supervision, writing-review and editing. O.R.: Validation, visualization, supervision, writing-review and editing.

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