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Articles

Drought: the silent evil of Central American migration in the period 1990 to 2019

La sequía: el mal silencioso de la migración centroamericana en el periodo 1990 a 2019

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Abstract

The objective is to analyze in the period 1990 to 2019 the effects of climate and the tendency of individuals to leave a territory, measuring the weight of precipitation or lack thereof in the Central American Dry Corridor. A stochastic frontier model was developed to study this process. As a primary result, it was found that there is a greater tendency to migrate when a drought occurs, understanding it as an extreme event for the environment and society. This tendency is evaluated with a system that includes series of controls such as other extreme weather events such as El Niño (ENSO) and hurricanes, violence levels, economy and exchange rate, which leads to the conclusion that drought above any other climatic event motivates the population to migrate. These findings contribute to the formulation of prevention, mitigation and resilience policies.

Keywords: migration, drought, Central American Dry Corridor, frontier model, climate change, extreme climate events.

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Resumen

El objetivo es analizar en el periodo 1990 a 2019 los efectos del clima y la tendencia de los individuos a dejar un territorio al medir el peso que tiene la precipitación o la falta de esta en el Corredor Seco de Centroamérica. Para estudiar este proceso se desarrolló un modelo estocástico de frontera. Se encontró como resultado principal que se tiene una mayor tendencia a migrar cuando se presenta una sequía, entendida como un evento extremo para el ambiente y la sociedad. Esta propensión se evalúa con un sistema que incluye una serie de controles como eventos climáticos extremos como El Niño (ENOS) y huracanes, niveles de violencia, economía y tipo de cambio,

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que lleva a concluir que la sequía por encima de otro evento climático motiva a la población a migrar. Estos hallazgos permiten contribuir en el planteamiento de políticas de prevención, mitigación y resiliencia para cada evento climático.

Palabras clave: migración, sequía, corredor seco de Centroamérica, modelo de frontera, cambio climático, eventos climáticos extremos.

Introduction

Since the second half of the twentieth century, there has been concern about studying climatic factors as determinants of migratory phenomena in different parts of the world (Canales Cerón & Rojas Wiesner, 2018; Carrasco & Suárez, 2018). By 2020, it was estimated that between two hundred thousand and one million people worldwide left their residences due to climatic events, such as droughts, floods and hurricanes (Maretti et al., 2019; Martínez Sanesteban, 2020). These figures multiplied throughout the 21st century to reach tens or hundreds of millions of climate-displaced persons (Rigaud et al., 2018). Therefore, Central America is among the regions that have been and will continue to be affected by climate change: hot spells and decreased seasonal rains. Among the most affected regions is the Northern Triangle of Central America, comprising El Salvador, Guatemala and Honduras, particularly in the Central American Dry Corridor on the Pacific coast of these countries (Figure 1).

Figure 1. Dry Corridor, Northern Triangle of Central America

Source: own elaboration, modified from https://www.sica.int, 2023

The Corridor exceeds the three countries mentioned above, extending from Chiapas, Mexico, the west of Costa Rica, Nicaragua and the western provinces of Panama.

The Corridor includes different dry tropical forests and is among the most variable regions worldwide from a climatic standpoint because in El Niño years, rainfall usually decreases by 30% to 40% (Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO], 2012), while hurricanes and tropical cyclones occur every other year (Calvo-Solano et al., 2018; Rejas Ayuga et al., 2019).

However, the Northern Triangle of Central America will be studied from a macro-regional perspective since this geographical intersection represents a point of great interest in the study of migration induced by climate change. From 2014 to 2019, in this region, peasant families contemplated how drought affected their corn and bean crops with feelings of helplessness (Gustin & Henninger, 2019). This effect of the climate left them without crops, commercial opportunities or the resources to face the next agricultural season. From this perspective, a high flow of immigrants occurred from the Dry Corridor to neighboring countries and the Mexican border, intending to reach the United States to escape hunger and to search for better life opportunities (Gandini, 2020).

Although it is known that climate change has increased migration flows, relatively little is known about how extreme variations in rainfall, ranging from excessive rains to droughts, influence the behavior of individuals who leave their homes in search of better life prospects. This insufficient knowledge highlights the need for more in-depth research to address the complexity of migration decisions in the context of changing climatic conditions (Organización de las Naciones Unidas para la Alimentación y la Agricultura, 2015).

In this paper, our main objective is to analyze the effects of drought on human migration. Thus, we attempt to estimate the effect that an extreme weather event has on an individual's decision to leave their home. A stochastic frontier analysis model has been developed, allowing us to envision migratory flows as a dynamic process subject to multiple factors that cannot always be controlled and generate random trends in migratory behavior. Therefore, we estimate that poverty, job shortages, insecurity and environmental devastation are additional elements that contribute to the relocation of a population.

The study findings reveal that droughts drive individuals to decide to change residences more than other climatic events (Olivera Villarroel et al., 2023). This observation can guide the development of programs to anticipate this migratory phenomenon, preventing loss of life and the dissolution of families. In addition, it suggests migration policies that encourage cyclical or circular migration rather than trying to suppress it, thus avoiding the creation of permanent and undocumented migrations.

This study is organized into four sections. The first section provides a description of the Dry Corridor that passes through parts of the countries of Honduras, Guatemala and El Salvador. The second section presents a discussion on the theories of migration and climate change and how this has been approached in the literature, to understand the factors that can explain migratory behavior. Finally, the third section addresses the methodology and data used in developing the proposed model to understand the phenomenon of drought and population migration. Finally, the conclusions and discussion of the findings are used to evaluate to what extent drought, understood as the absence of precipitation, motivates the population to migrate more than other climatic events. The increase in food prices drives these migrations, the

shortage of seeds and the loss of crops for self-consumption, resulting in the search for nonagricultural jobs, which leads families to depend on remittances to access consumer goods to support their well-being.

Context: climate change in the Dry Corridor of Central America

Climate change threatens agriculture worldwide, mainly the production of coffee, beans and corn, which is the basis and livelihood of many farmers in Central America. The Dry Corridor of Central America is considered to be a "hot spot" with periodic reductions in rainfall according to the sixth version of the Intergovernmental Panel on Climate Change (IPCC), where it is predicted that "Under all future scenarios and levels of global warming, average and extreme temperatures are expected to continue to increase with greater warming in the northern subregions of Central America" (Lynn & Peeva, 2021; Olivera et al., 2020). These changes endanger the agricultural industry, which employs nearly one-third of the population (Gustin & Henninger, 2019; Hotez et al., 2020) and production for self-consumption in the region.

Coupled with the plethora of climate catastrophes, the Dry Corridor experiences complexity due to other social problems, such as violence and poverty. These issues have led millions of people to leave their countries searching for areas that provide job stability and sustenance for their families. The areas most affected and those most vulnerable to climate change will be the most neglected. Considering this dark horizon, Central America will suffer a significant increase in emigration by 2050, according to the report by Martin et al. (2018). The number of internal climate migrants could reach approximately 143 million worldwide. There are 40 million people in the sub-Saharan region of Africa, 17 million in South Asia and 17 million in Central America.

The context of social diversity, natural resources and its geostrategic position has made this one of the historically most exciting regions of the American continent, although paradoxically, it is one of the most complicated, primarily due to social aspects. The population of Central America is approximately 50 million. Despite complexity due to social factors, the location also makes it vulnerable. Central America is exposed to geological hazards, including earthquakes and volcanic eruptions. In 1972, the Managua earthquake devastated the capital of Nicaragua. A volcanic arc crosses this region from southern Mexico to Panama. It has hundreds of volcanoes, some of which are highly active, such as Pacaya and Santa María, which are in Guatemala.

In addition to the geomorphological and water stress aspects, the socioeconomic and institutional conditions that involve an increasing number of factors, which could influence the choice to move by the population of the Dry Corridor, are observed, particularly in the effects that left the El Niño phenomenon in its wake between 2015 and 2016. These effects differed for each nation; some detected it quickly and were prepared for its arrival. However, each country has different capacities to predict these phenomena, which depend on resources, economic investment, activating protocols and allocating funds for preventive measures.

For example, the governments of Guatemala, Honduras and El Salvador prepared food security and humanitarian aid. In contrast, countries such as Costa Rica and Belize took advantage of the few rain events that occurred to encourage and attract tourism. However, paradoxically, water is essential in this sector, which has caused problems related to the supply of basic services for hotel areas or areas with a large influx of tourists (Hartley-Ballestero & Suárez-Espinoza, 2020; Schatan et al., 2010).

The El Niño phenomenon that occurred at the beginning of 2015 was one of the worst rain cycles on record, and its effects continue to be felt in Central America, exacerbating the damage caused by two consecutive years of drought. As a result, some 3.5 million people need humanitarian assistance, and 1.6 million people suffer from moderate or severe food insecurity in the most affected countries, namely, El Salvador, Guatemala and Honduras (Caldes, 2019).

To conclude, it is important to note that the consequences of this El Niño phenomenon are also strongly associated with the economic dimension, which requires the development of economic and social policies aimed at curbing the effects, which range from food shortages to the decisions of hundreds of thousands of people to migrate from these territories, both inside and outside the country. They aim to improve their living situations, which are affected by prolonged droughts, the rise in the Earth's surface temperature and the social crises that these phenomena have caused for the population.

The next section will investigate the contributions of migration theories and hydrometeorological events to deepen the understanding of the relationship between climate and population migration.

Theory: migration and climatic phenomena

Analyzing migrations is difficult due to the variety of research approaches that exist. This difficulty is due to the vast diversity in forms, types, processes, actors, motivations and socioeconomic and cultural contexts in which migrations usually occur (Arango, 2003). No theory alone can explain such a very specific phenomenon in its dynamics and the context in which it develops. There is a theory of rational choice to explain migration as a macrosocial phenomenon (Gómez Walteros, 2010), as well as the concept of families as agents with migration strategies that are supported by local contact networks and in place of destiny (Durand & Massey, 2003, p. 15). Alternatively, from a macrostructural perspective, the countries with migrants are asymmetrically integrated into the world or hemispheric market, where the high cost of labor in industrialized countries and regions attracts peasants from rural areas (García-Zamora et al., 2007, p. 981).

In this sense, an analysis framework that can measure the relationship between climate and population movements begins with a review of the first theoretical proposals, which were intended to find an explanation for the impact of climate change on migration. These theories consider the existence of a series of unidirectional factors that motivate people to migrate (Koubi, 2019). In other words, the mere appearance of

unpleasant weather events was enough for people to migrate. However, recent studies have adopted a new model called the "increased gravity model", in which it is possible to observe that climatic events exacerbate different socioeconomic problems related to migration, such as poverty, lack of job opportunities, lack of food and depletion of natural resources (Koubi, 2019).

As a result, migration must generate endless strategies and heterogeneous responses to climate change that are only sometimes easy to track. Occasionally, even climatic events do not result in people moving; instead, they are limited to areas where living conditions are complicated (Cattaneo et al., 2019). This phenomenon, combined with the methodological challenges that the study of migration and climate change represents, enables us to address a complicated situation that requires more effort from researchers, just as it motivates a necessary dialog among different disciplines.

However, despite all the difficulties encountered in studying these phenomena, it is possible to obtain solid conclusions based on the existing evidence. The first noteworthy fact is offered through an analysis carried out in 90 countries of the world by Bekaert et al. (2021), who reported that exposure to different adverse climatic events causes environmental stress in people, which can directly influence their intentions to move to other places as a strategy to address these situations. Additionally, people who live in cities seem more inclined toward domestic migration than those who live in rural areas, as the latter report a greater willingness toward intraregional migration (that is, within the same subcontinent).

On the other hand, rainfall and extreme temperatures are positively associated with migration, whereas phenomena such as floods and sea level rise are not significantly associated. Likewise, on average, hurricanes do not seem to increase migration; thus, it is unlikely that they will have a significant effect (Beine & Jeusette, 2021). There are two possible explanations for these differences. The first explanation suggests that climatic events that occur over long periods allow people to prepare for and obtain sufficient resources to migrate. However, with phenomena that occur suddenly, people obtain fewer resources and, therefore, do not migrate. Another possible explanation is that suddenly occurring phenomena are more difficult to track because they generate irregular migrations over short distances (Šedová et al., 2021).

In the meta-analysis above by Šedová et al. (2021), it was established that in studies where the origin of migrants was an urban area, a nonsignificant effect of climatic events was more likely to occur than in those whose origin was a rural area. The most plausible explanation is that in rural areas, the activities performed are more dependent on the climate, and thus, migrating can be considered an adaptive strategy. However, few studies are available, so more research is needed. Women are less likely to adapt their migration strategies, probably because the men of the household typically migrate to seek alternative means of living. Finally, as part of the conclusions of this meta-analysis, depending on the intensity of a phenomenon, the effect on migration is more significant; for example, intense droughts can result in migratory movements.

However, although phenomena, such as droughts or rainfall, have a more significant effect on migration in rural areas, the impacts in urbanized areas continue to be economically and socially significant. First, because of accelerated urbanization,

people from the countryside travel to cities for better living opportunities (Beine & Jeusette, 2021; Šedová et al., 2021). Some estimates mention that by 2050, more than 60% of the world's population will live in urban areas. This estimate will be different worldwide because in Europe and America, for example, it is estimated that more than 80% of the population will live in urban areas, while in Africa, approximately 60% will remain in rural areas (Arslan et al., 2019).

On the other hand, there is evidence, especially in Latin America, that droughts decrease the probability of inhabitants being employed and that workers' labor income decreases due to the reduction in the number of hours worked. The impact of droughts on the labor market can be greater than that of extreme rainfall, even when droughts cause flooding (Desbureaux & Rodella, 2019). Droughts also significantly impact youth migrations, even exceeding the effects that other phenomena, such as hurricanes, can have on migratory flows (Baez et al., 2017).

Some studies have shown that certain climatic phenomena are more or less strongly associated with temporary migrations. For example, storms and floods displace many people from their homes; however, most of them return approximately one year later (Koubi et al., 2016). These results allow us to observe a significant difference in the impact of sudden climatic events and those that occur over a long-term period, as with the former, it is possible to see that migration will only be temporary.

The immediate effects of climatic phenomena that have repercussions on migration and those that they cause in the economic and social activities conducted by those affected have been identified. A case that can help to better illustrate this situation and that serves the interests of this research is provided due to the situation in the countries that comprise the Central American Northern Triangle (El Salvador, Guatemala and Honduras). In this region, coffee production is of the utmost importance for various communities; however, due to climate change, droughts and diseases have affected this activity and forced thousands of people to migrate under difficult conditions without any assistance from their states (Lynch, 2019).

Unfortunately, the study of these climatic factors has been overshadowed by other factors, such as violence, whose relationship with migration seems more direct at first. However, climate change has had diverse effects on the conditions in this region, among which the intensification of storms and droughts are notable. These problems are especially damaging for activities like agriculture, as they depend largely on rainfall patterns, a lack of rain and high temperatures. If it is considered that the agricultural sector employs approximately 30% to 40% of the economically active population in the region, then the migratory patterns are not surprising (Lynch, 2019).

Climate events produce different migratory responses that, in turn, are determined by economic or social factors. Thus, it is possible to observe some gender differences in the reaction to climate change, as well as some generational differences. Weinreb et al. (2020) analyzed the changes in climate patterns in 41 countries in sub-Saharan Africa from 1980 to 2015. They determined that the type of migration most sensitive to climate change was rural migration by young adults, especially with the occurrence of low rainfall, low variability in rainfall and high temperatures. Additionally, increased

temperature variability is associated with greater rural migration by children and older adults. These data are revealing, as they again demonstrate the complexity of the link between migration and climate change.

Another important factor that must be considered in the study of migration due to climatic events is the scope. That is, at the international or local level, migration can occur in different ways. Through an analysis conducted in the municipalities of Guatemala, Cavazos Hernández (2021) found that frequent exposure to droughts and heat waves discouraged population migration at the inter-municipal level. Similarly, if people's activities were related to agriculture and if they had children, migration was reduced.

Leyk et al. (2017) analyzed the relationships between climatic events, such as rain, and internal and international migration in Mexico and considered different factors, such as economic activity and other political and social factors. Researchers have found that a decrease in rainfall affects migration patterns, especially in communities highly dependent on agriculture. In addition, they determined that lower amounts of rain than expected are associated with migration in municipalities where agriculture is rainfed and in those that are irrigated. However, the former is mostly associated with international mobility, while the latter is secondarily associated with internal mobility. In a study also conducted in Mexico, Nawrotzki and DeWaard (2016) found that a warming trend was associated with higher levels of international migration, while high precipitation levels reduced the probability of internal mobility.

One of the most recurrent themes in the literature is climatic events' impact on economic activities, such as agriculture. This occurs because people migrate as a strategy to address the problems that the effects of climatic phenomena present, as well as because of the possible effects that this may have on other sectors.

An example of this could be the probability of an impact on agricultural productivity, which would cause the displacement of labor to local nonagricultural sectors and urban areas, which would reduce marginal productivity and wages in agriculture. This example would cause a reduction in the demand for goods and services in the nonagricultural sector, which would decrease wages and limit the flow of labor in local urban areas. Thus, negative climatic anomalies also encourage migration due to reduced profits in nonagricultural sectors (Neog, 2022), allowing us to observe the diversity of effects that climate change causes.

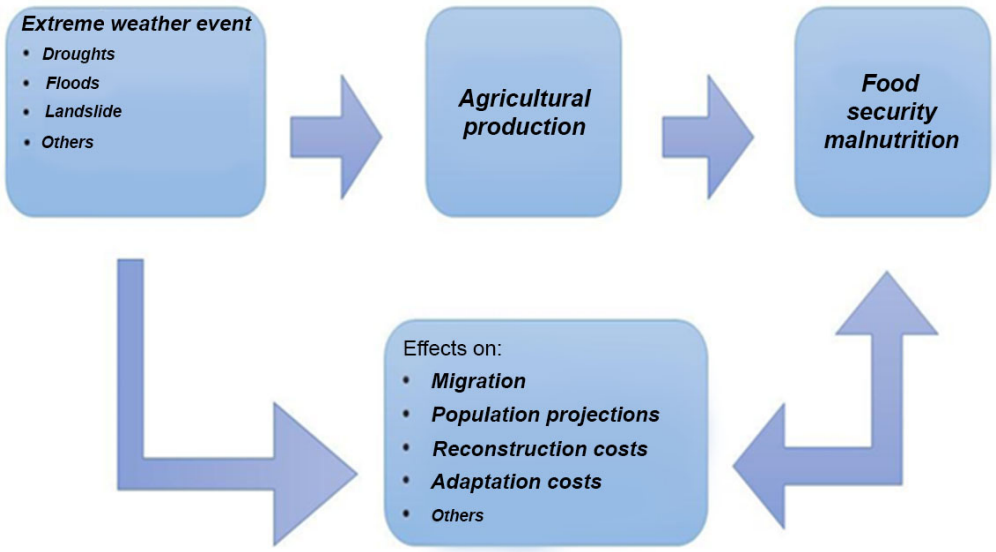
Of course, another important consideration that must be considered is that in each region, there are different events and climatic anomalies; thus, the repercussions will vary significantly. For example, it is estimated that in Latin America and the Caribbean, three different types of events will greatly impact the displacement of the population in the future: disasters, such as cyclones, heavy rains and floods, in addition to droughts, and an increase in the level from the sea (Kaenzig & Piguet, 2014).

There has been a broad, methodological and conceptual discussion on understanding climate migration. However, this study seeks to contribute to the discussion by analyzing drought. In this study, we propose that the extreme effects of drought have a relevant role in understanding this behavior, and its impact is estimated. The hypothesis is that the extreme climatic event of drought prompts people to migrate. Likewise, drought events affect the region's agricultural production by exposing the population

to food insecurities given the loss of crops and increases in the costs of seeds and production for self-consumption. These factors result in individuals considering leaving the area in search of new work sources to cover their living expenses (Figure 2).

Based on previous research and possible drivers of migration, such as drought, a statistical regression model of the "frontier" type was developed to estimate the impact of a set of analytical variables on migration. These variables include temperature, rainfall and various control variables that explain the social contexts of the countries analyzed. The model's objective is to determine these variables' effect on migration. Both rain and a lack of rain can lead the population to decide to emigrate; thus, we can observe the profound changes that the Dry Corridor of Central America has witnessed. This area is among the most important food corridors worldwide, located in the northern region of the Neotropics (see Table 1).

Figure 2. Effects of extreme weather events



Source: Olivera Villarroel, 2022

Central America faced its worst drought in recent decades in 2009, and the fields and the peasant population were largely affected by the drought and the loss of crop plots. Approximately 40% of the agricultural lands inspected by governments were affected, which specifically caused deficits in corn, beans, wheat and sorghum crops (Rojas Wiesner & Ángeles Cruz, 2019).

In the main cities of the Dry Corridor, the population suffered from water shortages; from this, the residents of poor neighborhoods captured water trucks, and different social tensions began. Among the region's countries that have been dealing with this problem is Guatemala, which was declared a "state of calamity", where drought resulted in a shortage of primary food crops, such as corn and beans (Klein, 2015). As an example of this critical situation, Honduras is one of the countries most affected by both the lack of water and extreme intensity hurricanes, which has led the Honduran population to migrate due to the loss of crops and deaths of animals, reaffirming that climate change is among the most important reasons for

leaving the country and attempting to find a better life elsewhere, mainly in the United States. Likewise, an increase in internal migration is anticipated in Central America (Barthel-Bouchier, 2013).

Table 1. Determinants of migration flows

Pull factors	Thrust factors	Other factors
Wages	Movement costs and uncertainty	Regional dummy variables: regional peculiarities
Jobs	Unemployment	Individual characteristics of migrants
Production structure: industry and services	Productive structure: agriculture	Characteristics of the regional population
Public expenditures	Taxes	
Weather	Weather	
	House prices	

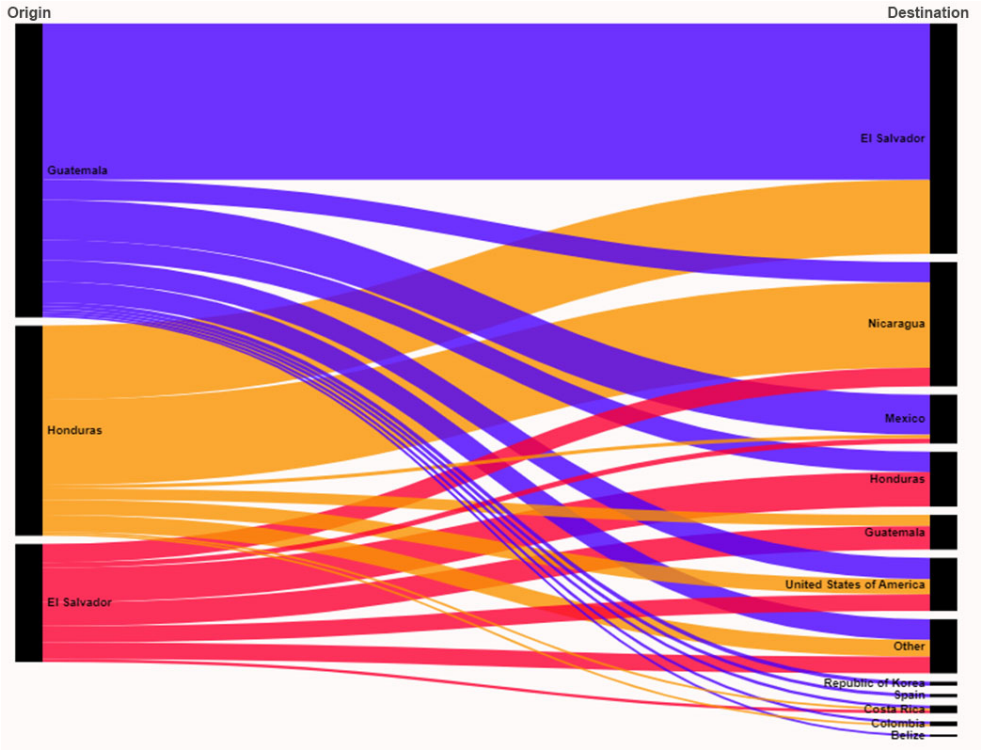
Source: modified from Aguayo Lorenzo, 2011

Methodology and results of the study

The information used in the study was derived from two large databases. For the migration indicators, the Data Hub of the Migration Policy Institute (MPI, https://www.migrationpolicy.org/programs/migration-data-hub and https://www.migrationpolicy.org/programs/data-hub/international-migration-statistics) shows the most recent demographic, social and economic data on the existence of population flows, citizenship and the net and historical migrations of countries in Europe, America, Africa, among others. In the case of Central America, information has been generated every five years since 1990. In the last decade, three additional studies have been conducted to understand the migratory dynamics of the region (MPI, n. d.). For the climatic and socioeconomic data, the World Bank database was used for compilation at the country level (https://datos.bancomundial.org/pais), as was the Climate Change Knowledge Portal (n. d.).

As shown in Table 2, the variables generated for the study include migratory information from the countries of the Northern Triangle of Central America between 1990, 1995, 2000, 2005, 2010, 2013, 2015, 2017 and 2019. As shown in Figure 3, the main destinations of the migratory flows of the three analyzed countries are their bordering countries, with more than 50% of the migration displaced to the region. However, between the years of study, migration to the United States of America represented 7.25% of the migratory flow from Guatemala and Honduras, and from El Salvador, migration to the United States represented 13.93% of the migratory flow.

Figure 3. Origin-destination of migration in the Northern Triangle of Central America (1990-2019)



Source: own elaboration, using data from MPI

By focusing on the relationships between climatic factors and migration in the studied countries, this study uses the levels of precipitation and temperature as the main variables for analysis and the anomalies of these variables for the three countries in the years analyzed. The socioeconomic characteristics of the three economies were analyzed as control variables. After reviewing the academic literature, we use the exchange rate, the consumer price index, the levels of violence in different countries and the levels of economic inequality as analytical variables to account for any other factors that could influence individuals to decide to migrate. Notably, migration was used as a dependent variable, measured annually and with a spatial resolution at the country level, where precipitation and the other covariates converge at this temporal and spatial resolution.

Table 2. Historical information on migratory flows and climatic and socioenvironmental variables for Guatemala, Honduras and El Salvador between 1990, 1995, 2000, 2005, 2010, 2013, 2015, 2017 and 2019

Variables	Description
Migration from the countries of the Northern Triangle Central America	Migratory flow from Guatemala, Honduras and El Salvador, which are the countries of origin
Precipitation and annual temperature in millimeters	Accumulated precipitation and average annual temperature at the country level
Anomalies in precipitation and temperature	Precipitation greater and less than the average and standard deviation at the country level, accumulated annually (abundant rains and droughts)
El Niño-Southern Oscillation (ENSO)	Oscillatory changes in sea surface temperature in the equatorial Pacific that affect climatic conditions throughout the American continent
Social and economic variables for the Northern Triangle countries	Levels of violence, economic inequality, exchange rate, inflation level, among others

Source: own elaboration

Implemented method

Stochastic frontier models were originally proposed by Aigner et al. (1977) and by Meeusen and Van den Broeck (1977). The original specification was implemented for the production function for the cross-section, where the error term has two components: a random component plus another nonnegative random component. Reviews of the literature can be found in Førsund et al. (1980), Schmidt (1986), Bauer (1990) and Greene (1993). In the case of migratory models, the application of stochastic frontier models is based on the fact that human migration should be conditioned to factors that would lead to human movement from one region to another in an optimal way; however, this dynamic of optimal movement is distorted when there are other types of factors that limit the ability to reach this migratory optimum. Therefore, using a stochastic frontier model enables the random components of the process to be captured and more consistent estimates of migratory flow to be generated (Gray & Wise, 2016; Yang et al., 2016).

The stochastic frontier model separates the observed output into two components: the efficiency component and the inefficiency component. In this case, the efficient component represents the migration that can be efficiently achieved. In contrast, the inefficiency component captures the deviation from the border due to factors, such as measurement errors or obstacles, imposed on migration. Since migration largely depends on the intentional action of the people who move, it can be analyzed in terms of its efficiency, understood in the sense that the migrant carries out its purposes. Unlike linear regression GLM, which focuses on estimating the relationships between

variables, the stochastic frontier model focuses mainly on estimating the efficiency frontier and the final level of inefficiency observed. Stochastic frontier models are valuable for analyzing efficiency and performance issues in various domains, such as economics, agriculture, health care, environmental studies and migration.

In this sense, a stochastic frontier model can be defined as follows:

$$yit = f(xit; \beta) \exp(vit - uit); i = 1..., N, \quad (1)$$

where *yit* is the migration from country *i* in year *t*, and it is assumed that *vit* is independently and identically distributed, with a distribution with a zero mean and a standard deviation $\sigma U2$-*(iid*$|N(0,\sigma U2)|$)-;[1] *xit* is a vector of factors, attractors and push that condition migration in country *i* in year *t*; *xi* is a vector $k \times 1$ of independent variables; and β is a vector of unknown parameters. *vit* is a random variable *iid.* $N(0,\sigma V2)$ and independent of *uit* are nonnegative random variables that measure the technical inefficiency of migration in country *i* in year *t* and are *iid* $|N(0,\sigma U2)|$ (Huang et al., 2014; Tsionas, 2002). In the case of migration models, a stochastic frontier model was applied for panel data (unbalanced), according to the Center for Macroeconomic Studies of Argentina (Notas sobre modelos de fronteras estocásticas, 2023).

$$yit = xit\beta + (vit - uit); i = 1..., N, t = 1..., T, (2)$$

The *vit* values are random migratory trajectories *iid* $N(0,\sigma V2)$, independent of the $uit = (ui^{exp}(-\eta(t-T)))$; the *ui* values are nonnegative and reflect the technical inefficiency in the migratory processes; and the *iid* values are assumed to be zero-truncated realizations of a distribution $N(\mu,\sigma U2)$, where η is a parameter to be estimated. The panel needs to be completed. According to Battese and Corra (1977), it is possible to replace $\sigma V2$ and $\sigma U2$ with $\sigma 2 = \sigma V2 + \sigma U2$ and $\gamma = \sigma U2/(\sigma V2 + \sigma U2)$.

The parameter γ must be between 0 and 1, and this is used as an initial value in the iterative process of maximizing the maximum likelihood function. Battese and Coelli (1992) present this model. This model specification assesses the significance of the parameter γ. If the null hypothesis that γ is zero is accepted, then $\sigma U2$ is zero, and therefore. Therefore, the *uits* can be eliminated from the model, leaving a specification that can be consistently estimated by ordinary least squares (OLS).

The model assumes that the migratory processes of population displacement outside their place of origin have various error components, one of which is transnational migration from the countries of origin as a measure of these displacements, as they do not consider population movements within the country (Ryan, 2015). In this sense, the model is used to control the different types of errors generated by measurement or legal and formal limitations intrinsic to human mobility between countries and largely covers the error components of a process as complex as the one analyzed.

[1] *iid*$|N(0,\sigma U2)|$ is the variable distributed independently and identically distributed, with a distribution with a zero mean and a standard deviation $\sigma U2$.

Results

The statistical results are based on the development of a stochastic frontier model that uses a dataset covering the years 1990, 1995, 2000, 2005, 2010, 2013, 2015, 2017 and 2019 for Guatemala, Honduras and El Salvador. The parameter estimation is compared with a generalized linear model (GLM) under the same specifications (see Table 3). The first version of the model addresses the relationships between migratory flows by a country and their elevation and climatic variables, such as precipitation and temperature, as well as their relationships with oscillatory changes in sea surface temperature in the equatorial Pacific (ENSO). In addition, socioeconomic variables, such as the exchange rate, economic inflation, the levels of violence in each country and specific measures of economic inequality in each nation are considered in the study.

As detailed in Table 3, the variable that exhibits a statistically significant relationship with migratory flows is the annual accumulated level of precipitation. In this context, the parameters associated with precipitation (127.8 for precipitation and -0.0195 for precipitation squared, negative parabolic function) indicate the existence of a migratory impulse due to the scarcity or excess of rainfall.

Regarding excess precipitation, the parameter value is 31 365, which represents the number of people prone to migrate in the event of a hurricane or extreme rains in the region. In this scenario, excess or shortage anomalies are measured about their deviation from the average rainfall compared to the historical standard deviation. This finding shows that, generally, rains act as incentives for migratory movements, either as attractors to the region or as impulses to initiate migratory processes. Although heavy rains can result in local displacements, a pull effect prevails in regions with abundant rainfall.

On the other hand, lower than average rainfall, that is, drought, triggers considerable migratory movements, which is the predominant effect in the region. For every 100 millimeters less rainfall than the average, a more than 12 000 people migration is anticipated (precipitation parameter value of 127.8). This phenomenon significantly impacts regions with annual average rainfall of 1 500 millimeters and droughts totaling less than 500 millimeters per year.

Another group of variables used in the model estimation was the socioeconomic variables for the countries analyzed. Most of these variables were not statistically significant for explaining migration processes at the country level, which does not imply that their importance should be discarded to clarify migration at the local level. These variables include levels of economic inequality, the rate of inflation, and economic development between countries. In addition, a change in the dollar parity exchange rate generates the process of attracting migrants to the analyzed economy, with an attraction parameter value (-1 083.00) that indicates the arrival of nearly one thousand people considering an appreciation of the local currency for a period of time, and the unit is the US dollar.

Likewise, control variables, such as extreme violent events, including civil wars that destroyed the region until the end of the 1990s, are incorporated with a parameter value of 127 601, which indicates the migration of more than one hundred thousand people per year during the event. The number of homicides per hundred thousand inhabitants has a parameter value of 280 people who migrated in the face of increased homicides and a categorical variable that is activated when the homicide rate exceeds

90 deaths per hundred thousand inhabitants per year, which generates a migration of 5 053 people. These variables were expressed annually based on the independent variable in the model, that is, the migration measured between 1990 and 2019, in five-year and three-year intervals, according to the efforts of the MPI (institution that collects migration information).

The occurrence of the El Niño phenomenon measured by ENSO was not significant in the development of the statistical model. Notably, the El Niño phenomenon is expressed as a change in the distribution of rainfall and temperature, so there is a level of collinearity that affects the significance level of the variable.

Table 3. Estimates using a stochastic border model and a GLM model to calculate the migration flow of the countries of the Northern Triangle of Central America

Variables	Border models *Migration*
Annual precipitation in millimeters	127.8***
	(-0.0232)
Annual precipitation in millimeters squared	-0.0195***
	(-4.62E-06)
Precipitation anomalies, rains greater than the mean and the standard deviation (abundant rains)	31 365*** (-4.059)
Temperature °C	-7 068***
	(-6.321)
Temperature anomalies, temperatures higher than the average and one standard deviation, at the country level. High temperature (heat stroke)	25 257*** (-4.998)
Exchange rate to U.S. dollars	-1 083***
	(-0.421)
Years of civil war (dummy variables)	127 601***
	(-9.37)
Local violence and homicides (homicide rate per 100 000)	280.4*** (-0.293)
Homicide rate with more than 90 deaths per 100 000 year	5 053*** (-6.051)
Constant	36 060***
	(-163.9)
lnsig2v	-9.517
	(-230.6)
lnsig2u	21.39***
	(-0.272)
Remarks	27
Consumer price index	Not significant
ENSO (sea surface temperature fluctuations in the equatorial Pacific) El Niño	Not significant
Social inequality and economic level (Gini index)	Not significant
Annual data based on migration surveys	*** p < 0.01, ** p < 0.05, * p < 0.1 Standard errors in parentheses

Source: own elaboration

Discussion

The results of this model reveal a significant probability of induced climatic migration under various circumstances. In a year with little rainfall, more than 12 000 people could migrate because of a 100-millimeter reduction in average rainfall. Similarly, temperatures above 40 °C could induce the migration of more than 25 000 people, and extreme rainfall events, such as hurricanes, could trigger the migration of more than 31 000 people. In summary, in a difficult year, more than 68 000 people could have incentives to migrate from the Central American Dry Corridor region without considering the social conditions and the violence factors in each country in the area studied.

Given the climatic trends, according to the IPCC scenarios (Lynn & Peeva, 2021), a negative impact is anticipated for multiple climatic factors that would affect the region's agricultural sector. Water stress, the disappearance of surface water resources, saline intrusion on coasts, floods and desertification of agricultural lands are all phenomena that could be aggravated. Although there are specific variations in each country, the high water stress in the region as a whole coincides with the specific literature (Cavazos Hernández, 2021).

In particular, drought, especially long-term drought, is the most influential factor stimulating migration by the regional populations (Olivera Villarroel et al., 2023). Although the potential impacts of extreme rains are not underestimated, it is emphasized that extreme drought events have a more pronounced impact on the migration of large human groups.

It is essential to recognize that drought affects crops by exposing them to solar radiation, a lack of moisture and a loss of soil nutrients, which are factors exacerbated by increased temperatures and a prolonged lack of rainfall. The effects on the planting of maize, one of the most affected crops, have been devastating for the rural populations, who depend heavily on this crop for their livelihoods.

Drought poses a critical problem for farmers, who must decide how long to wait for rains to arrive. Waiting too long could result in a loss of crop investment, while not waiting long enough could affect plant development. In the worst case, the rains could be insufficient to grow essential crops, such as corn or beans, which would seriously affect food security in the Central American Dry Corridor region (Olivera Villarroel et al., 2023).

Considering a lack of agricultural income, remittances from migrated family members are vital. Although a short-term solution, migration can become permanent and generate significant economic impacts on affected economies. The observed resilience, characterized by cycles of migration followed by years dedicated to local agriculture, is hampered by restrictive migration policies, leading to the need for drastic decisions by migrants.

A prominent aspect of the descriptive model is the periodic migration between neighboring countries, influenced by climatic and political conditions. This back-and-forth cyclical function reflects the resilience of agricultural economies, enabling farmers to temporarily work elsewhere in difficult years and engage in local agriculture in prosperous years. The decision to migrate, return or relocate becomes a dilemma for Central American farmers.

This research raises new questions and potential lines of research to address public policies on climate change mitigation and adaptation. This paper highlights

the importance of considering violence as an intrinsic factor in Central American societies, which can overlap and contribute to the displacement of people within and outside the region.

It is important to mention this study's limitations, especially the lack of disaggregation of data at the municipal level. This prevents gaining a more detailed understanding of migration between rural and urban areas and local differences in precipitation. These limitations, especially in measuring migration, highlight the need for more detailed future investigations to generate more accurate scenarios.

Conclusions

The model results suggest that droughts could trigger migration by affecting subsistence food production. Reducing precipitation by just 100 millimeters, which results in low rainfall, could drive the migration of more than 12 000 people throughout the region. Although this number may seem modest, it constitutes the first action that can be amplified by environmental conditions, such as extreme rains or hurricanes, or economic and social nature, such as exchange rate management, violence and political stability in the Central American region.

In this context, migration can be a response to local food production and searching for alternatives to guarantee income and food. Many of those who migrated permanently at the beginning contemplated the possibility of returning at some point; the sending of remittances and the support of families, despite the distance, generated the expectation of an eventual return.

The findings of this study raise new questions and outline new areas of future research to evaluate public policies aimed at mitigating and adapting to climate change. One of these questions focuses on the contradictions between migration security policies and the authorization of cyclical migration. For example, closed-wall policies affect circular migration both within Central America and to the United States and Mexico, which leaves Latino immigrants trapped in the United States without the possibility of returning home. This situation could increase the proportion of undocumented immigrants. The opportunity to migrate for short periods could result in order in the current migratory waves and represent a measure of adaptation to climate change over the region's medium- and long-term periods.

It is crucial to recognize that migration should be understood as a circular movement and that hindering it could generate a counterproductive phenomenon, as has been observed in the United States from the 1970s to the present. A similar scenario in Central America could particularly affect Mexico, as it is a new country of reception and permanent migration in the region.

Another significant aspect of this study is gaining an understanding of the violence factors in the region and their links with both migration and the occurrence of climatic phenomena. This association opens a new avenue for analysis, which is expected to expand with the growing amount of migration information generated for the region.

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