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# Estimating the Incidence of Venezuelan Migration and Other Socioeconomic Factors on Urban Growth in Colombia

**Pablo Blas Tupac Silva Barbosa [1,¶], Andrés Peña-Galindo [2,*,µ], Andrés Miguel Sampayo [3,µ], Sebastian Londoño-Méndez [3,≠], Ivan Enrique Contreras Cala [4,∞], David Granada Donato [4,∞], Jenny Rocío Beltrán Pérez [4,∞] and Alejandro Feged-Rivadeneira [3,£]**

[1] Department of Mathematics, Faculty of Sciences, Universidad Nacional, Bogotá, Colombia.
[2] Faculty of Political Sciences, Group of Political and Legal Studies, Universidad El Bosque, Bogotá, Colombia.
[3] Faculty of International, Political, and Urban Studies, Universidad del Rosario, Bogotá, Colombia.
[4] IMMAP, Bogotá, Colombia.
[*] Correspondence: aapenag@unbosque.edu.co
[¶] Data curation, Investigation, Methodology, Software, Visualization.
[µ] Conceptualization, Formal analysis, Investigation, Supervision, Project administration, Validation, Writing – original draft, Writing – review & editing.
[≠] Data curation, Visualization.
[∞] Data curation, Methodology.
[£] Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing.

**Abstract:** This study investigates the intricate relationship between Venezuelan migration and urban growth in Colombia from 2018 to 2021. The study employs remote sensing data and social network metrics to uncover migration patterns and their impact on urban expansion. The methodology consists of three stages. Firstly, nighttime satellite imagery is used to analyze year-over-year urban growth in Colombia. Secondly, social network data estimates Venezuelan migration, overcoming challenges of underreporting and informal border crossings. Lastly, an econometric analysis explores the quantitative link between Venezuelan migration and urban growth, integrating socioeconomic variables to address endogeneity. The findings reveal the complex interplay of Venezuelan migration, socioeconomic factors, and urban growth. The study outlines remote sensing analysis, introducing the Anthropogenic Footprint Expansion Index (AFEI) to quantify urban growth. Facebook API data estimates migration trends and explores socioeconomic impacts on urban expansion. The analysis uncovers migration, poverty, aging, and urban population proportion as key factors affecting Colombia's urban landscape. Furthermore, the research underscores how Venezuelan migration affected short-term urban expansion pre- and post-COVID-19. Migration had a notable effect before the pandemic, but this influence waned afterward. The study highlights migration's short-term nature and emphasizes age demographics' role in medium-term dynamics.

**Keywords:** venezuelan migration; urban growth; colombia; remote sensing analysis; social network data

## Introduction

Venezuelan migration has become a recurrent issue for various areas of regional policy in Latin America and the Caribbean. The phenomenon has prompted the production of research covering a wide range of issues ranging from health [1] and mental health [2] to the effects on education in the countries receiving these migrants [3]. In addition, warnings have been issued on the capacity of the Western Hemisphere to respond to the Venezuelan migration crisis [4], on perceptions of criminality [5], the effect on the labor market [6], among others. The figures highlighted by the International Organization for Migration (IOM) [7], of the United Nations (UN), explain why the phenomenon in question is so prevalent. According to said organization [7], by June 2021, around 5.6 million Venezuelans had left their country, of which 4.6 million - 85% - had gone to another country in the

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region, mainly to Colombia, Peru, Chile, Ecuador, and Brazil. In short, according to the same report: "The current situation in Venezuela has had a significant impact on migration flows in the region and continues to constitute one of the largest displacement and migration crises in the world".

Given that Colombia, due to its large common border area, has been the main recipient of Venezuelan migrants, there has been an increase in studies on the policy responses adopted by Bogota with respect to the phenomenon. In this context, both militaristic [8] and more critical responses focused on poststructural approaches have been proposed [9]. The International Labor Organization (ILO) together with the United Nations Development Program (UNDP) have even proposed strategies to guarantee the labor rights of Venezuelan migrants arriving in Colombia [10], as well as in other countries of the region. However, and beyond the denoted urgency of obtaining data for the formulation of efficient public policies to address the Venezuelan migration phenomenon to Colombia, there is no research aimed at exploring the effect of such migration on Colombian urban growth. However, it is worth mentioning that some studies have been published that have referenced the relationship between urban growth and Venezuelan migration, more from a socioeconomic perspective. For example, the 'Analysis of Venezuelan migration in the city of Pasto: Characteristics and perceptions of migrants, 2021,' [11] which argues the perceptions of the migrant population regarding the reasons that motivated them to leave their country. The significant finding is that the migrant population emigrates primarily due to economic aspects such as inflation and food scarcity. They later decide to settle in commercial areas of the city and in housing that allows monthly or daily rent. Another study called 'Urban Mixed Migration: A Case Study of Bogotá, 2020' [12] yields interesting results, where the migrant population allows itself to settle in the city for reasons such as finding low-cost accommodations, economic opportunities, and the presence of a family support network. However, a significant number of migrants are located in marginal neighborhoods.

Publications such as 'How Venezuelan Migration is Changing Urban Expansion in Cucuta, Colombia, 2019' [13] offer a more geospatial approach, suggesting the use of satellite images and georeferencing tools to build localized data and quality information about the urban integration of migrants and their needs. However, few publications have been released addressing the issue of urban growth in Colombia due to Venezuelan migration. Beyond the aforementioned ones - and considering that one of them does not correspond to a scientific investigation -, the majority of explorations have been focused on issues related to the rights of migrants [1,14–17]. Furthermore, studies related to urban growth resulting from international migrations, encompassing regions beyond Colombia and Venezuela, are also limited. For example, Mathias Lerch [18] investigates the disparity in the impact on urban growth between internal and international migration in cities within the Global South, aiming to ascertain that international migration has proven more significant across most of these urban centers. Jonas Gamso and Farhod Yuldashev [19] inquire whether external aid for rural development diminishes international migration, and find that this hypothesis indeed holds true. Ronald Skeldon [20] shifts his focus to Asia, investigating the interplay between internal and international migration, concluding that it constitutes a cyclical relationship where internal migration triggers international migration and vice versa. Subsequently, Skeldon, along with Russell King [21], revisits the aforementioned cycle to reaffirm its relevance and delineate the characteristics of urban regions within this process.

On the other hand, studies on internal migration in Colombia have been carried out [22–25], even with a particular focus on the urban transformation that migratory processes imply [26,27], but there is a striking lack of studies that account for urban transformations in Colombia as a consequence of a phenomenon as impacting and current as Venezuelan migration. In this sense, this research examines the effect of Venezuelan migration on Colombian urban growth, with the aim of providing accurate data for making appropriate policy decisions in favor of people who already suffer the process of becoming migrants.

Research on urban growth due to migration has been carried out in different countries. Since the 1960s Peter Schöller [28] already questioned the growth in Japanese cities and found that interurban migration generated growth in several cities, while the growth of Tokyo was due to a factor of attraction typical of capital cities. Similarly, Orjan Sjoberg and Tiit Tammaru [29] studied urban

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growth in Estonia, as a nation of the former Soviet Union, due to migration and found, among other conclusions, that internal migration patterns differ from the migration patterns of foreigners arriving in the country. On the other hand, R. B. Bhagat and Soumya Mohanty [30], observe in India an urban decline during the 1990s, beyond the increase in migration to the cities.

In more recent work, Nick Dines [31] evaluates the differential impact of migration on urbanism in a city in the global South and one in the global North, to draw attention to the importance of studying urban phenomena due to migration in less developed cities. Qirui Li and Cyrus Samimi [32] examine the impact of international migration from Sub-Saharan Africa on the Sustainable Development Goals, to show that migration occurred mainly in the same region - Sub-Saharan Africa - to low-resource but densely populated countries. Following the questions about the relationship between migration and urban growth, carried out worldwide, it is important, given the relevance and magnitude of Venezuelan migration, to carry out a study of this nature, but having urban growth in Colombia as the dependent variable.

Given the pronounced significance of both issues – urban growth as a consequence of migration and the current context of Venezuelan migration to Colombia – this article seeks to contribute to the paradoxically underexplored question: What is the impact of Venezuelan migration on Colombian urban growth? The findings reveal that the effect of migration on urban growth was predominantly evident prior to the pandemic, with the most notable impact occurring during the period of 2018-2019. Although the subsequent periods still exhibited a statistically significant effect of Venezuelan migrants on urban expansion, the magnitude of this effect was comparatively smaller.

Furthermore, the influence of Venezuelan migration on urban growth is predominantly a short-term phenomenon that was observed in the years leading up to the pandemic. As for the medium term and post-pandemic years, this effect diminished. In contrast, the demographic composition of the population and multidimensional poverty emerged as the primary factors influencing medium-term urban expansion. A comparison between the years 2018 and 2020 revealed that a higher proportion of young individuals and a lower incidence of multidimensional poverty significantly impacted urban growth in Colombian municipalities. Spatial autocorrelation within the examined phenomenon is evident, implying that geographically proximate municipalities exhibit similar dynamics. This validates the application of spatial econometrics models as presented in this study.

To test the hypothesis that the effect of Venezuelan migration on urban expansion is more pronounced, econometric analyses were conducted to evaluate the significance and magnitude of the impact of urban migration on Colombian urban growth. This involved segmenting the national territory based on the distance to border crossings between Colombia and Venezuela. However, the findings did not yield significant results. Consequently, it is concluded that transportation costs do not decisively influence the location decisions of Venezuelan migrants. Conversely, the effect of Venezuelan migration is more pronounced in more developed municipalities – those that significantly contribute to the national value added. This underscores that the workforce of Venezuelan migrants is more inclined to settle in population centers with a higher degree of economic development.

Subsequent studies should delve into determining the indirect and long-term effects of Venezuelan migration on Colombian urban growth. This could involve exploring the influence of Venezuelan migration on the labor market and economic structure of cities. Additionally, these studies should validate the outcomes of the present research using diverse datasets and account for additional factors such as internal migration between municipalities and the dynamics of rural-urban migration. By doing so, a more comprehensive understanding of the relationship between migration and urban growth in the Colombian context can be achieved.

**Remote sensing and social network connections data**

This paper analyzes the short-term relationship between the migration dynamics of Venezuelans and the growth of urban areas in Colombia during the period 2018-2021. This period is of particular interest for two reasons: the first is that it coincides with a massive increase in the number of Venezuelan migrants in the country: according to National Administrative Department of Statistics

[33] and the data obtained from GEIH, there has been a sustained growth in the total number of Venezuelan migrants between 2014 and 2020. The average annual variation of this population has been 80.6%, with the highest growth recorded between 2017 and 2018 at 167.5%. This period marked a significant intensification of the migratory phenomenon. As a result, by 2020, the total number of Venezuelan migrants reached 2.26 million people [33]; the second reason for the selection of the period of analysis is that it allows for an examination of migration dynamics on municipalities in the country before and after the COVID-19 pandemic.

The wide availability and quality of geospatial data facilitates the study of the relationship between socio-economic phenomena, such as migration, and anthropogenic expansion, especially in relation to their impact on the physical environment and for diagnosing urban growth dynamics. This approach has been used in previous related research to study the effect of socio-economic phenomena on urban growth both in Colombia [27] and in several other countries [34,35].

The analysis of migratory dynamics presents many complexities, including those derived from the lack of robust statistics on the geographical location of migrants and their evolution over time. Although migration authorities in Colombia have formal records on the total number of Venezuelan migrants at the national and departmental level [36], there is no official information on the distribution of these migrants at the municipal level, nor a periodic uniform collection of this data. This situation is exacerbated by underreporting due to migratory flows through over 200 informal crossings along the 2,219-kilometer land border between Colombia and Venezuela [37].

Given this information gap, this study proposes the use of data on the scope of social networks as a proxy to approximate Venezuelan migration dynamics at the municipal level. This approach is an added value of the present research, as to our knowledge, there are no precedents in the literature regarding the study of the relationship between municipal-level migratory flow, approximated using data from social media reach, and its relation with urban growth in Colombia. Although this strategy may have limitations and endogeneity concerns (see [38]), it is seen as a suitable and statistically rigorous approach, in the absence of official records, to monitor migratory flows. Precedents for this approach can be found globally [39], in the United States [40], and in Europe [38]. In the section **Materials and Methods**, we discuss the nature and scope of the data used in this study.

## Study aims and objectives

In this academic article, we present a comprehensive methodology that leverages existing data and geospatial platforms to enhance our understanding of the complexities of the articulation of Venezuelan migration towards Colombia, which affect economic, demographic, social dynamics, among others, with the displacement of individuals towards urban areas. Our focus is on the unique context of Colombia, characterized by ongoing armed conflict and dynamic urbanization processes. Our primary goal is to examine the intricate relationship and dynamics between migration from Venezuela and land use and cover change, as well as other anthropogenic and socioeconomic transformations. With Colombia as our case study, our specific objectives revolve around employing remote sensing techniques to quantify nationwide anthropogenic changes spanning the period from 2018 to 2021, which coincides with a socio-politically significant phase of Venezuelan migration to Colombia. Subsequently, we delve into the discussion of how migration and socioeconomic factors, such as multidimensional poverty or the demographic structure of the population, can influence various aspects such as land use planning, public health systems, and ecological transformations. By adopting such an approach, we aim to enhance our comprehension of the political, demographic, and economic factors that drive anthropogenic alterations in land cover, as well as their influence on migration patterns and demographic shifts in developing nations.

## Materials and Methods

The proposed methodology for this study encompasses three key stages. In the first stage, we measure year-over-year urban growth of the populated centers in Colombia for the period 2018-2021. In order to achieve this objective, we employed data from nighttime satellite imagery as a primary source, in consistency with previous research studies that have addressed similar objectives and have

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demonstrated the effectiveness of nighttime data in assessing urban expansion dynamics [27], which were cited in previous sections of this paper. In the second key stage, based on data on the reach of social networks, we estimate the number of Venezuelan migrants and their annual evolution in each municipality of Colombia. Finally, through different econometric specifications, we analyze the quantitative relationship between the two exposed phenomena, considering not only venezuelan migration, but a complete set of economic and social variables that can explain the urban expansion and avoid problems of endogeneity in the econometric proposed model. The conceptual approach and the statistical treatment in each of the three stages of the proposed methodology are described below.

**Remote sensing analysis of nighttime lights data**

In order to approximate the dynamics of urban expansion at the municipal level in the country, we identify those regions where the luminosity intensity (and consequently, the urban footprint) has significantly increased during the analyzed period. To achieve this objective, a significant data source was utilized: nighttime satellite images captured by the Earth Observation Group (EOG), which is part of the National Geophysical Data Center (NGDC) of the United States National Oceanic and Atmospheric Administration (NOAA). These images, openly accessible on the cloud-based geomatics Google Earth Engine platform, are sourced from Suomi National Polar Partnership satellite (NPP), provide crucial information on Average Day/Night Band (DNB) radiance values measured in nanoWatts/cm2/sr (band "avg_rad") from the visible Infrared Imaging Radiometer Suite (VIIRS) sensor, which has a spatial resolution of 750 meters and 22 bands with a total spectral range of $4-12.5\mu m$ . The DNB band has a wavelength range of $0.5-0.9\mu m$ and 14 bits spectral resolution.

For each municipality $i$, the Anthropogenic Footprint Expansion Index from the year $t$ to the year $t+k$, namely, $AFEI^i{}_{[t,t+k]}$ (equation 1) was calculated as the ratio between variables $INRA^i{}_{[t,t+k]}$ and $TMA^i$. On the one hand, $INRA^i{}_{[t,t+k]}$ corresponds the area of the municipality $i$ that showed a significant increase in nighttime radiation in year $t+k$ with compared to year $t$. On the other hand, $TMA^i$ represents the total area of the municipality $i$.

$$AFEI^i{}_{[t,t+k]} = \frac{INR\ ^i{}_{[t,t+k]}}{TM\ ^i} \qquad (1)$$

This research proposes the study of the dynamics of urban expansion in the short term. Consequently, four periods of analysis are considered: $T_1=[2018,2019]$, $T_2=[2019,2020]$, $T_3=[2020,2021]$ and, finally, the entire period $T_4=[2018,2021]$. A detailed description of the methodology used for construct the Anthropogenic Footprint Expansion Index ($AFEI$), including the characteristics of the nighttime light data used, as well as the preprocessing of this data, can be found in *Appendix 1-Remote sensing analysis for the identification of anthropogenic footprint expansion*.

The objective of constructing the index $AFEI$ is to identify those municipalities that have experienced a significant increase in their urban area, approximating this variable by the nighttime light footprint. This, in turn, aims to establish the relationship between this phenomenon and the presence of Venezuelan migrants in the municipalities of the country. In the next section, we deepen in the statistical methodology used to approximate the Venezuelan migration dynamics in Colombia.

**An approach to the migratory dynamics of Venezuelans at the municipal level in Colombia**

Data on connections among Venezuelan refugees and migrants in Latin America are obtained using Facebook's "Application Programming Interface (API)" for advertising data. The method referred to is the 'Ad Account Delivery Estimate,' which is understood as a tool that allows advertisers to manage functionalities related to advertising and ad management published through Facebook. This method enables obtaining various information, including an estimate of 'Monthly Active Users' (MAU) on Facebook that usually match specified criteria such as age, gender, and geographic

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attributes. The data obtained from the API is publicly accessible and can be used by anyone or users with a Facebook advertising account [41].

For this study, the API shows connections of Facebook user accounts that were originally created in Venezuela and are now connecting abroad, in this case Colombia. Facebook API data is collected every 15 days for better tracking of resulting connections. The estimates presented in this document are obtained using specific filters and based on the behavior of Facebook users over the last 30 days.

The data is based on self-reported information provided by each Facebook user, such as their current city, city of origin, and characteristics of their friend network (e.g., having at least two Facebook friends in the home country and two Facebook friends in the destination country) in order to validate the existence of an active account. It is then possible to estimate the number of "migrants" in Colombia by residence and in two time periods, which are compared to validate the percentage variation of some record changes. As mentioned in Spyratos et al. [42], the documentation of Facebook's advertising platform defines users who have "lived in country X" as "people who used to live in country X and now live abroad." Due to the lack of detailed information in this regard, it is unclear what specific criteria Facebook's advertising platform uses to establish the previous country of residence for each user or the times they lived there. Despite this lack of documentation, it is possible to understand that two factors play a key role in identifying expatriates on Facebook. The first factor is the "current city" and "hometown" self-reported in the "places you've lived" list that users or accounts complete for their Facebook profile. The second factor is the friendship structure in the network (for example, having at least two Facebook friends in the home country and two Facebook friends in the destination country [42]).

As for limitations, it is important to note that the estimates presented are not designed to match censuses or other official sources. Facebook does not provide online censuses or statistics on refugees and migrants. Consequently, these estimates should be considered as a source of data that can be used for triangulation and identification of trends, variations in the behavior of accounts originating from Venezuela. Facebook only provides information on certain population groups (in this case, Venezuelan expatriates). Moreover, it does not provide statistical or historical data, so there will be gaps in information in some months or years when no queries were made. These limitations are commonly referenced in studies of this kind, where Facebook API data is used for analysis and estimations of certain populations, as mentioned in Grow et al. [43].

However, when carefully evaluating the validity of Facebook's estimates and comparing them with data from reliable sources, it is concluded that the estimates can be used for trend analysis and early warning purposes. Additionally, it is a suitable source of data for the study of short-term migration dynamics between Venezuela and Colombia.

For the purposes of this study, the independent variable of interest is the *estimated number of Venezuelan migrant connections* in each municipality $i$ of Colombia in year $t$: $EnVMC^{i}{}_{t}$. This variable is a proxy for the number of Venezuelan migrants in the absence of official data at the municipal level. The evolution of $EnVMC$ in Colombia during the period of analysis of this research is presented in Figure 1.

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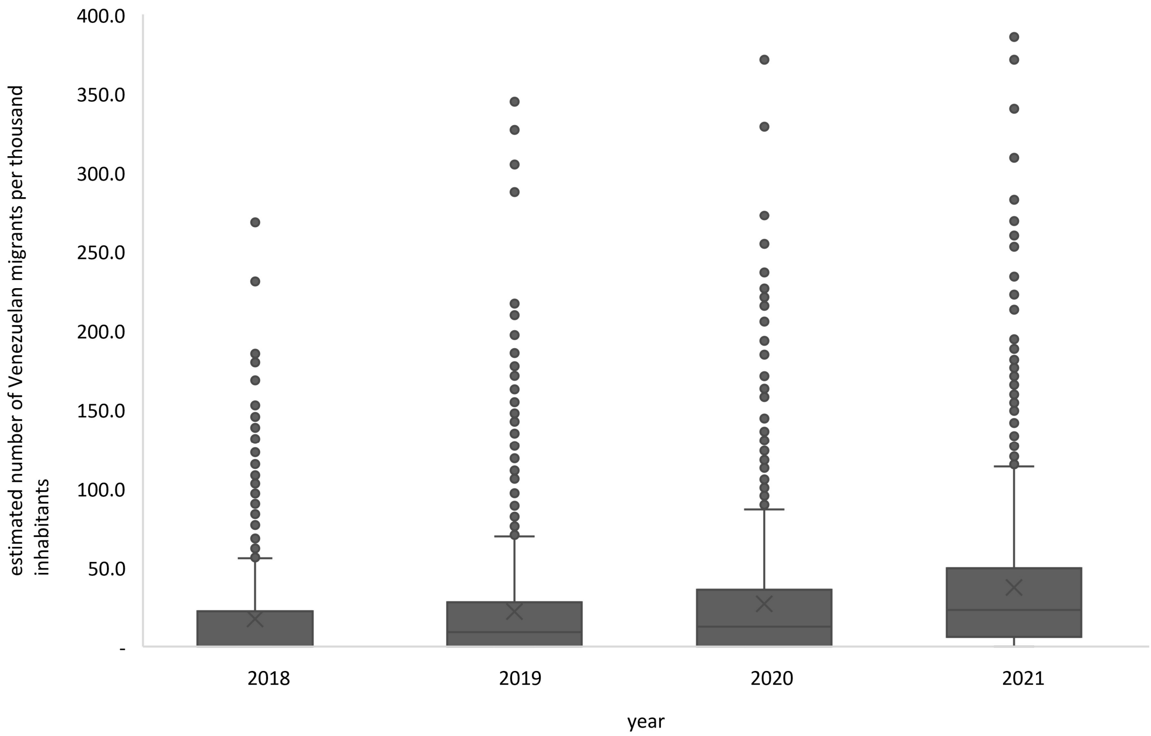


*Source: Own elaboration based on data from Facebook's API.*

**Figure 1.** $\boldsymbol{EnVMC}$ per thousand inhabitants during the period 2018-2021.

Although the data source provides biweekly measurements of this data, the annual average value of EnVMC in each municipality will be considered as the principal variable. The purpose of this is to prevent economic seasonality and labor commutation rates between municipalities from affecting the estimation of the magnitude of the number of migrants in each municipality.

To provide a comprehensive analysis of the quantitative relationship between the migration of Venezuelan citizens and urban expansion in Colombia, we consider not only the estimated number of migrants, captured by the variable ${EnVMC^i}_t$ , but also a variable representing the flow of Venezuelan migrants: *Venezuelan Migrant Flow Index* (${VMF^i}_{[t,t+k]}$). This variable measures the proportion of population growth between years $t$ and $t+k$ in each municipality that can be explained by the presence of Venezuelan migrants (Equation 2).

As in equation 1, $i$ represents each municipality in the country and $t$ corresponds to each year between 2018 and 2020. With the inclusion of the variable $VMF^i$, our research approach focuses not only on how marginal changes in the number of Venezuelans affect the growth of the urban footprint, but also on how the increase in migratory flow, weighted by the total population, influences the phenomenon of urban footprint expansion in the municipalities of Colombia.

$${VMF^i}_{[t,t+k]} = \frac{{EnVM^i}_{t+k} - {EnVM^i}_t}{Total\ population^i_t} * 100 \qquad (2)$$

It is worth noting that Figure 1 displays a significant shift in Venezuelan migration dynamics during 2020, a year of particular interest due to mobility restrictions implemented in the country as a strategy to mitigate the impact of COVID-19. The above justifies the choice of the four analysis periods specified in the previous section.

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It is important to note that the estimated number of connections of Venezuelan migrants may be influenced by the internet coverage and connectivity rates in different municipalities of the country. In order to correct for this potential bias, an additional variable was included in the model: municipal internet penetration index ($MIPI^i$), which represents the internet coverage at each municipality in Colombia. This allows isolating the effect of interest in this study, as the estimated coefficients for the variables of interest, $EnVMC^i$ and $VMF^i$, will specifically reflect the effect of the estimated number of Venezuelan migrants and not the internet coverage rate.

In order to account for socio-economic factors (in addition to Venezuelan migration) that could influence urban growth, we consider the following variables: the incidence of multidimensional poverty ($imp^i$), the municipal aging index ($mai^i$) -which represents the ratio of people over 60 years old to those under 15 years old-, and the proportion of urban population. Additionally, to analyze the heterogeneous footprint expansion according to the degree of urbanization of municipalities, a dummy variable $city^i$ was included, indicating whether the municipality is a city-urban agglomeration, or a rural municipality. Table 1 presents the descriptive statistics of all variables considered in this study. The source of the control variables used in this research is the National Administrative Department of Statistics (DANE).

**Table 1.** Summary statistics of the variables used in this research.

| **Variable** | **Obs** | **Mean** | **Std.Dev.** | **Min** | **Max** | **Description** |
|---|---|---|---|---|---|---|
| $AFEI_{[2018,2019]}$ | 1121 | 0.009 | .039 | 0 | .586 | |
| $AFEI_{[2019,2020]}$ | 1121 | 0.002 | 0.012 | 0 | 0.241 | Anthropogenic Footprint |
| $AFEI_{[2020,2021]}$ | 1121 | 0.005 | 0.028 | 0 | 0.478 | Expansion Index |
| $AFEI_{[2018,2021]}$ | 1121 | 0.008 | 0.041 | 0 | 0.620 | |
| $EnVMC_{2018}$ | 960 | 1470.929 | 15255.05 | 0 | 427143 | |
| $EnVMC_{2019}$ | 960 | 1492.907 | 13151.09 | 0 | 324286 | Estimated number of |
| $EnVMC_{2020}$ | 960 | 1857.253 | 15184.16 | 0 | 342083 | Venezuelan migrants |
| $EnVMC_{2021}$ | 960 | 1688.958 | 12023.46 | 0 | 317897 | |
| $VMF_{[2018,2019]}$ | 960 | 0.579 | 3.542 | -41.844 | 33.006 | Venezuelan Migrant |
| $VMF_{[2019,2020]}$ | 960 | 0.615 | 3.504 | - | 36.862 | Flow Index |

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| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | 33.111 | | |
| $VMF_{[2020,2021]}$ | 960 | 1.251 | 4.158 | -38.169 | 35.873 | |
| $VMF_{[2018,2021]}$ | 960 | 2.422 | 4.953 | -26.069 | 44.375 | |
| $mipi$ | 1117 | 0.056 | 0.067 | 0 | 0.457 | Proportion of the population with internet access in the municipality |
| $imp$ | 1121 | 0.418 | 0.173 | 0.045 | 0.985 | Proportion of the population in multidimensional poverty condition at year 2018 |
| $mai$ | 1121 | 0.599 | 0.315 | 0.048 | 2.121 | Ratio of population over 60 years old to population under 15 years old at year 2018 |
| % Urban population in 2018 | 1121 | 0.437 | 0.239 | 0 | 0.999 | |
| % Urban population in 2019 | 1121 | 0.440 | 0.239 | 0 | 0.999 | Proportion of the population living in urban areas |
| % Urban population in 2020 | 1121 | 0.443 | 0.240 | 0 | 0.999 | |
| $city$ | 1121 | 0.428 | 0.495 | 0 | 1 | Dummy variable: 1= the municipality is a city or |

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| | |
|---|---|
| | urban agglomeration; 0=the municipality is rural |

Source: Own elaboration.

The specification of the econometric model and the statistical approach of the work are discussed in detail in the next section.

**Statistical model specification**

The main objective of the proposed econometric models is to rigorously analyze the quantitative relationship between the independent variables $EnVMC^i{}_t$ and $VMF^i{}_{[t,t+k]}$ with the dependent variable $AFEI^i{}_{[t,t+k]}$ during the analysis periods mentioned in the previous section. This approach aims to achieve two objectives. Firstly, it seeks to examine the impact of a marginal increase in the number of Venezuelan migrants during the initial year of the analysis period on urban growth throughout the specified period. Secondly, it aims to investigate the relationship between variations in migrant influx and urban growth. The basic structure of the proposed model is presented in equation 3.

$$AFEI^i{}_{T_k} = \alpha^i + \beta \cdot ln(EnMV^i{}_{T_{k0}}) + \gamma \cdot VMF_{T_k}{}^i + \theta \cdot SD'^i{}_{T_0} + \varepsilon^i{}_{T_k} \qquad (3)$$

where $T_k$ is each of the period analysis from $T_1$ to $T_4$. $AFEI^i{}_{T_k}$ represents the Anthropogenic Footprint Expansion Index in municipality $i$ during period $T_k$ , $\alpha^i$ represents the fixed effects of the department to which each municipality belongs, allowing to control the heterogeneities that characterize each department of the country, $ln(EnMV^i{}_{T_{k0}})$ represents the natural logarithm of the number of venezuelan migrants in municipality $i$ during the initial year of period $T_k$ and $VMF_{T_k}{}^i$ is the Venezuelan Migrant Flow Index during the period $T_k$.

Complementary, $SD'^i{}_{T_0}$ is a vector of sociodemographic variables, namely: the Incidence of multidimensional poverty ($imp^i$), Municipal aging index ($mai^i$), the percentage of urban proportion in $T_{k0}$ ($UrbanPop$), $city$, a dummy variable indicating whether the municipality in question is a city-urban agglomeration or a rural municipality, and $mipi^i$ is the municipal internet penetration index.

The statistical analysis was conducted in three stages using cross-sectional data for each of the analysis periods $T_1$ to $T_4$. At the first stage of the analysis, we ran ordinary least squares regression (OLS) to study the quantitative relationship between Venezuelan migration and urban expansion in Colombia. At the second and third stage of the quantitative research we ran, respectively, a Durbin spatial error model and a Durbin model for spatial lags, in order to investigate whether there is a spatial relationship between the variables of interest. All econometric analysis was conducted using STATA 16 software. In the following section we present the results of the estimated models.

**Results and Discussion**

In this section we present the results obtained through the econometric models proposed above. Firstly, we expose and analyze the national-level results of the OLS robust model. Then, we show the results of the spatial error and spatial lag models. Lastly, we comment on the results of additional tests carried out with the aim of deepening the statistical relationship between the variables of interest. The objective of these tests was to examine whether there is a differential impact of Venezuelan migration on the urbanization of Colombian municipalities based on this variable.

Variable $EnVMC$ exhibits a positive and statistically significant effect on urban expansion during the periods $T_1$ and $T_2$. Results from Table 2 indicate that a 1% increase in the number of Venezuelan migrants in 2018 leads to a 0.0008-point increase in the urban expansion index for the period $T_1$, which is statistically significant at the 5% level. A similar interpretation applies to period $T_2$, although the magnitude of the independent variable's marginal effect is four times smaller. Results for $T_3$ and $T_4$ are not statistically significant. These findings suggest that, after the COVID-19 pandemic, the effect of Venezuelan migration on the urban expansion in Colombia diminished significantly. The explanation for this finding lies in mobility restrictions, economic disruptions caused by the pandemic, and political changes in the Colombia-Venezuela relationship between 2018 and 2021.

**Table 2.** OLS robust regression analysis on the Anthropogenic Footprint Expansion index.

| | **OLS Robust regression model** | | | |
|---|---|---|---|---|
| **Independent variables** | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
| ln_EnVMC | 0.008** | 0.002** | 0.003 | 0.005 |
| | (0.003) | (0.001) | (0.002) | (0.004) |
| VMF | 0.001* | -0.000 | 0.000 | -0.000 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| % urban population | -0.036*** | -0.006* | -0.017** | -0.037*** |
| | (0.012) | (0.003) | (0.008) | (0.014) |
| imp | -0.051*** | -0.002 | -0.036*** | -0.061*** |
| | (0.015) | (0.006) | (0.011) | (0.018) |
| mai | -0.009 | -0.005* | -0.013** | -0.045*** |
| | (0.014) | (0.003) | (0.005) | (0.011) |
| city | 0.022*** | 0.004** | 0.014*** | 0.018*** |

| | | | | |
|---|---|---|---|---|
| | (0.007) | (0.002) | (0.004) | (0.007) |
| mipi | 0.239*** | 0.055*** | 0.106*** | 0.227*** |
| | (0.067) | (0.014) | (0.032) | (0.066) |
| Constant | -0.014 | -0.013* | 0.001 | 0.006 |
| | (0.024) | (0.008) | (0.015) | (0.026) |
| Observations | 522 | 714 | 783 | 522 |
| R-squared | 0.411 | 0.234 | 0.310 | 0.406 |
| AIC | -1755.162 | -4050.119 | -3326.604 | -1704.602 |
| BIC | -1606.144 | -3880.996 | -3154.068 | -1555.584 |
| Log-likelihood | 912.5812 | 2062.06 | 1700.302 | 887.301 |

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. AIC: Akaike Information Criterion. BIC: Bayesian information criterion. *Source: Own elaboration.*

With respect to the flow of migrants, a marginal increase in this indicator, represented in the variable $VMF$ implies an increase of 0.001-units in the urban expansion index $AFEI$ during period $T_1$, and this effect is statistically significant. However, this effect vanishes in subsequent periods. This finding, combined with the previous paragraph's insights, indicate that migration had a significant impact on short-term urban expansion previous to year 2020, but that gradually faded in subsequent years.

A notable result is that the multidimensional poverty index (*imp*) has a negative and statistically significant effect on urban expansion in Colombia. In other words, poverty is inversely related with urban growth in Colombia. For the $T_1$ period, a marginal increase in $imp$ leads to a 0.051-point decrease in the urban expansion index. Similar to the aforementioned variables, this effect diminishes over time. Nevertheless, the relationship of variables $imp$ and urban expansion is of greater magnitude and statistical significance in period $T_4$: an increase in $imp$ leads to a 0.061-point decrease in variable $AFEI$. This means that, in the medium term, poverty is a crucial variable that negatively affects urban growth.

An analogous pattern emerges concerning variable $mai$, exhibiting a negative and statistically significant effect in periods $T_2$ to $T_4$, with the most pronounced effect observed in the last period: a one-unit increase in the $mai$ index results in a 0.045-point decrease in $AFEI$ variable. This finding highlights that the effect of a higher presence of young people on urban growth is predominantly a medium-term phenomenon rather than a short-term one.

The variable representing the proportion of urban population exhibit a consistent and statistically significant negative effect on the $AFEI$ index in the presented model. This finding indicates that in Colombia, cities with a smaller urban population are witnessing more significant growth in the short run. This observation may be attributed to the economic dynamics of intermediate cities. It is important to highlight that in [16], the authors identify a positive and statistically significant impact of the same variable on urban expansion. This disparity can be attributed to the variances in the time frames examined in the respective studies, with the previous research considering a medium-term perspective while the current study focuses on the short term.

Lastly, $city$ variable shows a positive and significant effect on the $AFEI$ index, indicating that cities, as opposed to rural areas, are the municipalities experiencing expansion. The internet penetration rate ($mipi$ variable) exhibits a similar behavior. This finding should be further explored in future research, which could incorporate internal migration and study rural-urban migration patterns as explanatory factors for city growth in Colombia.

It is worth noting that the econometric models presented in this study employed the variance inflation factor as a tool to assess potential multicollinearity among the variables. This test confirmed the absence of multicollinearity among the variables used.

The preceding analysis is further enhanced by a comprehensive econometric examination. For all the analysis periods considered, the p-value of Moran's I-index is found to be less than 0.001, indicating spatial autocorrelation in the studied phenomenon. This implies a significant geographical effect, that is, nearby locations exhibit similar dynamics, and therefore justifies the utilization of a spatial error model. The Lagrange multiplier also exhibits a p-value less than 0.001, providing evidence of a spatial lag and further validating the adoption of a spatial lag model. The outcomes of both the spatial error model and the spatial lag model are presented in Tables 3 and 4, respectively.

**Table 3.** Spatial error regression on the Anthropogenic Footprint Expansion index.

| | **Spatial error regression** | | | |
|---|---|---|---|---|
| **Independent variables** | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
| ln_EnVMC | 0.008*** | 0.002*** | 0.003*** | 0.005** |
| | (0.002) | (0.001) | (0.001) | (0.002) |
| VMF | 0.001 | -0.000 | 0.000 | -0.000 |
| | (0.001) | (0.000) | (0.000) | (0.000) |

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| | | | | |
|---|---|---|---|---|
| % urban population | -0.029** | -0.006* | -0.016** | -0.033*** |
| | (0.012) | (0.003) | (0.007) | (0.013) |
| imp | -0.042* | -0.002 | -0.034*** | -0.052** |
| | (0.022) | (0.006) | (0.012) | (0.023) |
| mai | -0.014 | -0.005* | -0.011** | -0.040*** |
| | (0.011) | (0.003) | (0.005) | (0.012) |
| city | 0.019*** | 0.003 | 0.012*** | 0.015** |
| | (0.006) | (0.002) | (0.004) | (0.007) |
| mipi | 0.211*** | 0.054*** | 0.104*** | 0.216*** |
| | (0.042) | (0.012) | (0.023) | (0.044) |
| lambda | 0.938*** | 0.659*** | 0.898*** | 0.950*** |
| | (0.061) | (0.295) | (0.100) | (0.050) |
| Constant | 0.039 | -0.010 | 0.071** | 0.066 |
| | (0.056) | (0.015) | (0.032) | (0.060) |
| Observations | 522 | 714 | 783 | 522 |
| AIC | -1770.131 | -4045.005 | -3334.24 | -1726.255 |

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| | | | | |
|---|---|---|---|---|
| BIC | -1599.824 | -3857.599 | -3143.051 | -1555.948 |
| Log-likelihood | 925.0656 | 2063.502 | 1708.12 | 903.1273 |

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. AIC: Akaike Information Criterion. BIC: Bayesian information criterion. *Source: Own elaboration.*

The results presented indicate that the Log-likelihood statistic consistently yields higher values in the spatial lag model compared to the OLS and spatial error models. Consequently, this approach is considered to have the highest statistical explanatory power. In general terms the results presented in Tables 3 and 4 are consistent with those of the OLS model (Table 2). However, it is worth noting some differences in the statistical significance of the independent variables. The main difference corresponds to the statistical significance of the the variable $EnVMC$. Both in the spatial error regression model and in the spatial lag regression model, this variable is statistically significant for all analysis periods. However, there is evidence of a decrease in the magnitude of the effect, which is more marked for period $T_1$ than for the other periods (Tables 3 and 4).

**Table 4.** Spatial lag regression on the Anthropogenic Footprint Expansion index.

| | **Spatial lag regression** | | | |
|---|---|---|---|---|
| **Independent variables** | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
| ln_EnVM | 0.008*** | 0.002*** | 0.003*** | 0.005** |
| | (0.002) | (0.001) | (0.001) | (0.002) |
| VMF | 0.001 | -0.000 | 0.000 | -0.000 |
| | (0.001) | (0.000) | (0.000) | (0.000) |
| % urban population | -0.028** | -0.006* | -0.015** | -0.033*** |
| | (0.012) | (0.003) | (0.006) | (0.012) |
| imp | -0.037* | -0.000 | -0.031*** | -0.048** |

| | | | | |
|---|---|---|---|---|
| | (0.021) | (0.006) | (0.011) | (0.022) |
| mai | -0.013 | -0.005* | -0.011** | -0.040*** |
| | (0.010) | (0.003) | (0.005) | (0.011) |
| city | 0.019*** | 0.003 | 0.011*** | 0.014** |
| | (0.006) | (0.002) | (0.004) | (0.007) |
| mipi | 0.216*** | 0.054*** | 0.105*** | 0.219*** |
| | (0.041) | (0.012) | (0.023) | (0.043) |
| rho | 0.960*** | 0.800*** | 0.929*** | 0.965*** |
| | (0.039) | (0.178) | (0.070) | (0.035) |
| Constant | 0.034 | -0.014 | 0.059** | 0.059 |
| | (0.043) | (0.015) | (0.030) | (0.045) |
| Observations | 522 | 714 | 783 | 522 |
| AIC | -1796.357 | -4050.636 | -3345.59 | -1751.678 |
| BIC | -1626.051 | -3863.23 | -3154.401 | -1581.371 |
| Log-likelihood | 938.1787 | 2066.318 | 1713.795 | 915.839 |

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. AIC: Akaike Information Criterion. BIC: Bayesian information criterion. *Source: Own elaboration.*

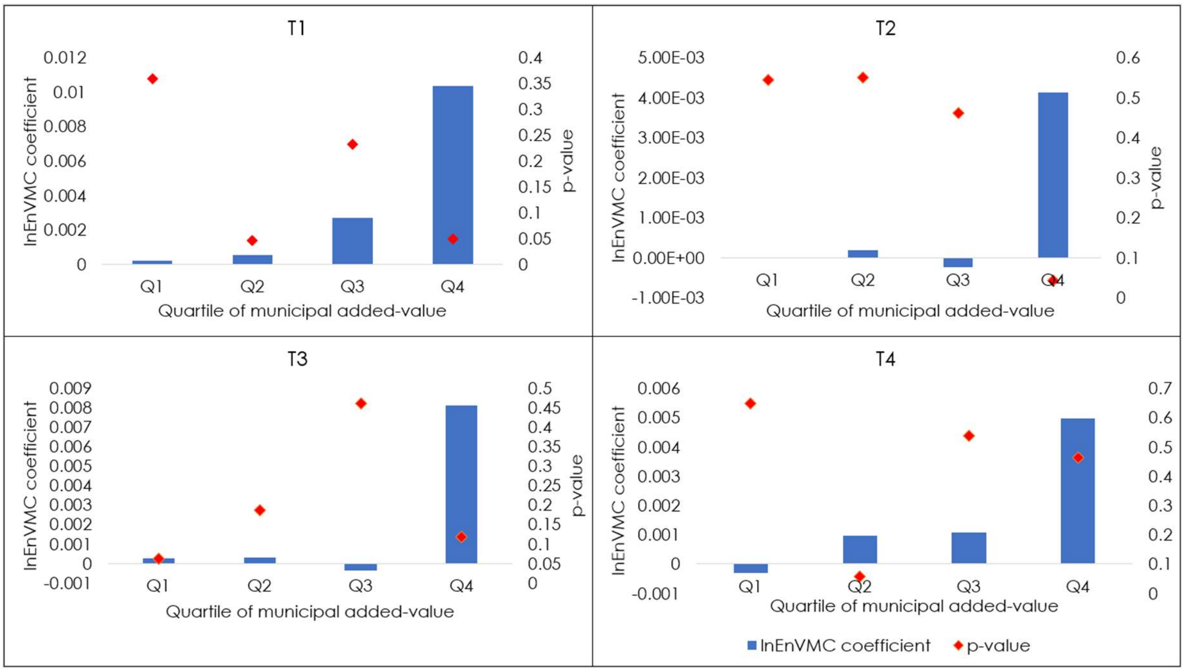
**Additional Statistical Tests**

With the aim of further exploring the statistical relationship between Venezuelan migration and urban growth, various complementary statistical tests were conducted. Initially, the hypothesis was proposed that Venezuelan migration would have a greater impact on Colombian municipalities close to the border crossings between Colombia and Venezuela. It was assumed that transportation costs could act as a barrier to Venezuelan mobility within Colombia. To address this issue, a variable was created to identify the distance of each municipality in the country to the nearest migratory border crossing point. Subsequently, all municipalities were classified into four groups based on quartiles of the mentioned variable. Regression models, as presented in Table 2, were then run for each quartile.

However, the results of this analysis are inconclusive, as no significant relationship was found between the impact of the number of Venezuelan migrants (variable $EnVMC$) on the urban expansion of Colombian municipalities and the distance to migratory crossing points. From this exercise, it can be concluded that transportation costs do not play a decisive role in the decision-making process of Venezuelan migrants when choosing which municipalities to settle in Colombia.

Our hypothesis is that Venezuelans would be attracted to settle in municipalities with a more dynamic economy, and consequently, the effects of migration on urban expansion would be felt more strongly in those municipalities whose production of goods and services contributes more significantly to the national value added, because these municipalities can offer greater employment opportunities and more development prospects. To assess this idea, all municipalities were divided into four groups based on their value added. Subsequently, the corresponding regression model was performed within each group.

The results of this second analysis were significant. During the study periods, it was observed that Venezuelan migration (measured by the coefficient of the variable $EnVMC$) had a more prominent effect in municipalities that contributed more to the country's value added. Additionally, these municipalities presented the lowest p-value (see Figure 2). The results of these statistical tests suggest that Venezuelan migration in Colombia is more influenced by the level of economic development of municipalities than by the distance to border crossings.




*Source: Own elaboration*

**Figure 2.** Magnitude of the coefficient of variable $EnVMC$ and its p-value in the regression within each quartile of municipalities according to added value.

One of the study's main limitations is precisely the source of the Facebook connections data. Since these data come from Venezuelan accounts connecting in Colombia, there may be a bias regarding the official data reported by the national government. For example, not all Venezuelan refugees and migrants likely have Facebook accounts, which would underestimate the reporting of migrants in the country. On the other hand, those with an active account may have a different socioeconomic profile than most of the Venezuelan population. Thus, Facebook connections may differ in age groups from the total universe of Venezuelan migrants in the country.

Additionally, because Facebook connections at the municipal level depend on the level of connectivity that each place has to an internet network, those municipalities with a low infrastructure level and sizeable Venezuelan population maybe show a lower level of Venezuelan migrants than they have. Thus, it is essential to use controls of measures of internet connectivity in the model. However, these data are absent at the municipal level for the period analyzed.

Overall, this research emphasizes the effect of Venezuelan migration on short-term urban expansion in Colombia, both before and after the COVID-19 pandemic, showing that before the pandemic Venezuelan migration had a significant effect on urban sprawl, but that this faded after the pandemic.

The effect of migration on urban growth is predominantly a short-term phenomenon rather than a medium-term one. In the latter, factors such as the age composition of the population become relevant. This is evident in the negative and statistically significant impact of the aging index on urban growth: the higher the ratio between the number of older adults and the number of young individuals, the lower the rate of city expansion. This result suggests that future research should investigate the indirect impact of Venezuelan migration on urban growth, specifically how the age composition of the migrant population affects the aging index of municipalities and, in turn, urban expansion. The currently available data does not allow for this type of analysis to be conducted. Subsequent studies should also explore how patterns of rural-urban internal migration affect city growth in the medium and long term.

Finally, urban growth depends not only on international migration phenomena but also on endogenous population growth and internal migration flows. In fact, because of the armed conflict and the economic disparity between urban and rural areas in Colombia, there has been a pronounced population movement from the national peripheries to large cities (citation). While this study captures endogenous population growth through the controls, again, due to the precariousness of the data, it is difficult to capture the effect of internal migration on urban growth. By not controlling for this phenomenon, we may be generating a bias in the results of the effect of the arrival of Venezuelan migrants on urban growth.

## Supporting information

### Appendix 1-Remote sensing analysis for the identification of anthropogenic footprint expansion.

The aim of this supplement is to provide a detailed exposition of the technical aspects involved in the construction of the dependent variable of the model: Anthropogenic Footprint Expansion Index. This index provides information about those regions whose nighttime light radiation experienced a significant increase compared to the previous year of comparison, and was constructed according to the following methodology:

**Phase 1-Estimation of the annual median level of radiation** In this stage, the annual median level of radiation in the national territory was estimated for each year between 2018 and 2020, this information is crucial for establishing a reference point and analyzing changes in nighttime radiation in each region.

**Phase 2-Calculation of radiation difference between years.** The difference between the radiation value in the last year of the analysis period (t + k) and the reference year (t) was calculated. This difference allows us to identify regions where nighttime radiation has significantly increased compared to the previous year.

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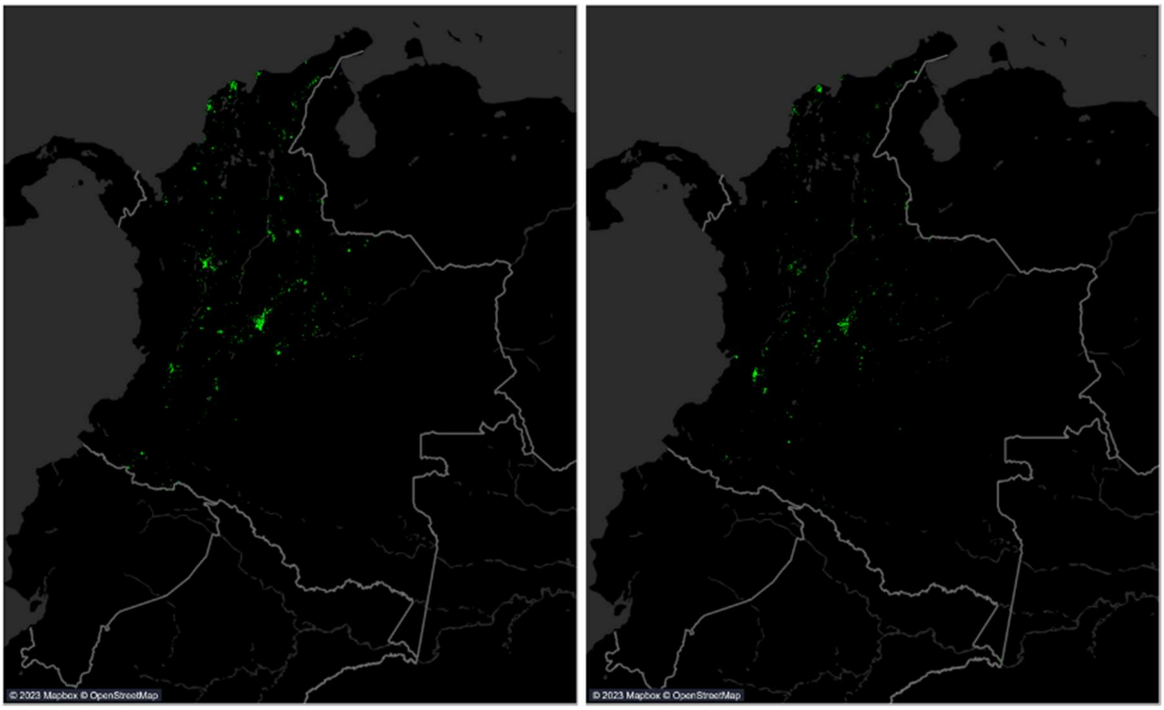
**Phase 3-identification of areas of interest.** Regions where the estimated difference exceeded the median of the difference across the entire national territory where identified as areas of interest. These areas represent locations where nighttime radiation intensity has undergone a relevant change, and are illustrated, for each period $T_1$ to $T_4$, in figures S1 and S2.

**Period** $T_1$ **Period** $T_2$




*Source: Own elaboration*

**Figure S1.** Areas of the national territory that experienced a significant increase in the radiation of nocturnal lights for periods $T_1$ and $T_2$

**Period** $T_3$ **Period** $T_4$

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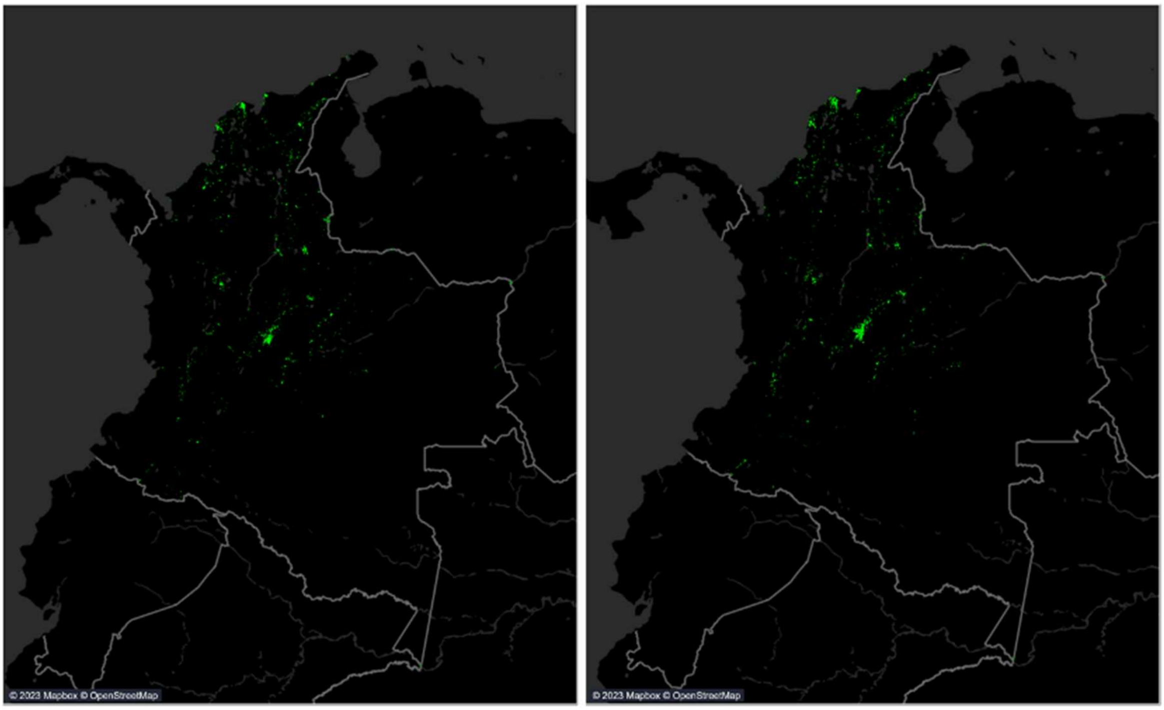


*Source: Own elaboration*

**Figure S2.** Areas of the national territory that experienced a significant increase in the radiation of nocturnal lights for periods $T_3$ and $T_4$

**Phase 4-Calculation of the Anthropogenic Footprint Expansion Index (AFEI).** Using ArcGIS 10.6 software, the area of each municipality that experienced a significant increase in nighttime radiation was calculated. The map of the national territory and its municipalities that was used for the mentioned calculation corresponds to the shapefile provided by the National Administrative Department of Statistics (DANE) [44]. Based on this data, the proportion of this area to the total municipal areas was estimated, resulting in the AFEI (Equation S1). AFEI provides a quantitative measure of anthropogenic footprint expansion in each municipality.

$$AFEI^{i}_{[t,t+k]} = \frac{INRA^{i}_{[t,t+k]}}{TM^{\ i}} \qquad (S1)$$

the annual median level of radiation in the national territory was estimated. Subsequently, the same indicator was estimated for the final year of the analysis period (t+k). Then, the difference between the two aforementioned values was calculated. Regions where the estimated difference is significantly high were identified, considering this to be those regions where this difference is higher than the median of the estimated difference throughout the national territory. Thirdly, using ArcGIS Desktop 10.6 software, we calculated the area that presented a significant increase in nighttime radiation in year t+k with respect to year t for each municipality in the country (INRA). Finally, the proportion of this area with respect to the total municipal area (TMA) was estimated. The result is the index AFEI (equation S1), where i corresponds to each municipality of Colombia and t to each year between 2018 and 2020.

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