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Physical Sciences

Original article

Illuminating the threat: a decade-long analysis of light pollution in Colombian main urban centers through satellite imagery

Iluminando la amenaza: análisis de una década de contaminación lumínica en los principales centros urbanos de Colombia mediante imágenes satelitales

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Abstract

Light pollution is a form of environmental degradation present throughout the world that affects the natural environment, flora, fauna, and various aspects of human life. Despite the growing concern about this problem, its study in Colombia is still minimal. Here we present a comprehensive analysis of the expansion of artificial nighttime lighting in the main Colombian cities between 2012 and 2022. According to the analysis, light pollution levels in the urban areas of Bogotá, Barranquilla, and Cartagena increased, while in Medellín, Cali, and Bucaramanga, they decreased. However, all the cities evaluated experienced an expansion in the coverage of illuminated areas revealing an evident spatial increase of the problem. In the case of Bogotá, the phenomenon was studied at the locality level. Additionally, we used external data to analyze the relationship between increased light pollution and the installation of new luminaires, the change to LED technologies, and the growing population density and gross domestic product (GDP) in the city. Our results provide valuable information on the threat of light pollution in Colombia and the need to take measures to help control the associated environmental degradation.

Keywords: Light pollution; Sky brightness; Astronomical observation; Environment; Remote sensing.

Resumen

La contaminación lumínica es una forma de degradación ambiental que aumenta cada vez más en todo el mundo y afecta el entorno natural, la flora, la fauna y varios aspectos de la vida humana. A pesar de la creciente preocupación por esta problemática, en Colombia su estudio es aún muy limitado. Aquí analizamos de forma exhaustiva la expansión de la luz nocturna artificial en las principales ciudades de Colombia entre el 2012 y el 2022. Se evidenció así un aumento en los niveles de contaminación lumínica en las áreas urbanas de Bogotá, Barranquilla y Cartagena, en tanto que en las de Medellín, Cali y Bucaramanga disminuyó la radiancia promedio. Sin embargo, en todas las ciudades consideradas en el estudio la cobertura de áreas iluminadas aumentó, con un evidente incremento espacial del fenómeno. En el caso de Bogotá, se analizó detalladamente el fenómeno a nivel de localidades y, a partir de datos externos, se verificaron, además, las relaciones del aumento de la contaminación lumínica con la instalación de nuevas luminarias, el cambio a tecnologías LED, y el crecimiento de la densidad poblacional y el producto interno bruto de la ciudad. Nuestros

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resultados brindan información valiosa sobre la creciente amenaza de la contaminación lumínica en Colombia y respaldan la necesidad de tomar medidas que ayuden a controlar la degradación ambiental asociada.

Palabras clave: Contaminación lumínica; Brillo del cielo; Observación astronómica; Medio ambiente; Teledetección.

Introduction

Light pollution is the excess or misdirection of artificial light in the environment. It is generally caused by building lights, streetlights, and other artificial lighting not properly designed or positioned. Besides disrupting natural darkness and limiting the visibility of the stars (**Falchi *et al.***, 2022), light pollution can have a number of negative effects on the environment and on human health as commented extensively in multiple studies in the last twenty years (**Cinzano *et al.***, 2001; **Falchi *et al.***, 2016; **Góez-Therán & Vargas-Domínguez**, 2021; **Bará *et al.***, 2022). One of the main causes of the increase in light pollution is the rapid growth of urbanization and the accompanying expansion of artificial lighting in urban areas (**Stone**, 2017). As more people move into cities and towns, there is an expected increase in the amount of artificial light in the environment that can lead to a phenomenon known as ”skyglow” by which the night sky appears washed out and is difficult to see due to the excess of light in the atmosphere (**Kyba & Hölker**, 2013). Other factors contributing to the magnification of light pollution include the proliferation of electronic devices and the increasing use of light-emitting diode (LED) lighting with a more intense and longer wavelength than other forms of lighting. Additionally, light-colored surfaces in urban areas reflect and amplify the effect of artificial lighting further contributing to light pollution.

Overall, the increase in light pollution can have several associated direct and indirect adverse effects including plant life damage, interference with animals’ migration patterns, and disruption of the natural sleep cycle, among others currently being studied. It is important for individuals and communities to be aware of the potential impacts of light pollution and to take steps to reduce it where possible. Besides these environmental and health impacts, light pollution wastes energy and resources. Excessive lighting is often used unnecessarily resulting in increased energy consumption and greenhouse gas emissions. Given the interest in light pollution and the dark side of light worldwide in recent years (**Hölker *et al.***, 2010), strategies have been developed to characterize the levels of light pollution and diagnose the situation in various sites of the world relying mainly on satellite imagery (**Sánchez-de Miguel *et al.***, 2021). Photographs of the planet taken by satellites are extensively being used to explore and study various Earth features including land and water bodies, vegetation, and human-made structures such as cities and infrastructure. A very recent study pointed out that the problem of light pollution could be worse than it seemed from the astronomical point of view highlighting the possibility of losing in a few years the visibility of stars (**Kyba *et al***, 2023). The study relied on citizen scientists’ observations of naked-eye stellar visibility and estimated an increase in sky brightness of 7% to 10% per year in the human visible band. The incidence of light pollution in Colombia has been barely studied but it is an increasing topic of interest considering the impact that it may have on astronomy and astrotourism (**Brieva**, 1985; **Pinzón *et al***, 2016), biodiversity and sustainability (**Altamar-Consuegra *et al.***, 2020).

Here we used satellite imagery to measure light pollution emphasizing the need to consider it a new form of pollution that must be considered as newly illuminated areas appear in previously dark places and blue emission peaks from LED lights occur. Furthermore, we include a qualitative analysis of the relationship between the increase in light pollution and other variables such as population and gross domestic product (GDP).

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Methods

Study areas

We focused on the main Colombian cities: Bogotá, Medellín, Cartagena, Cali, Barranquilla, and Bucaramanga, using the irradiance map from 2012 (**Figure 1**) to explore the evolution of artificial light in the last decade in urban centers and surrounding areas. We evaluated the most affected areas and the changes in emitted radiance taking a 0.1-degree window around the rectangle enclosing each area to identify the growth around the cities and the convergence with more rural areas.

Satellite data

Our main source of data was monthly and annual Visible Infrared Imaging Radiometer Suite (VIIRS) images of nighttime light. The VIIRS, VNP46A3, and VNP46A4 data products are global, gridded data products containing the means and standard deviations of radiance values measured at different angles (**Kyba *et al.*,** 2015) and collected by a sensor in the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite used to monitor and

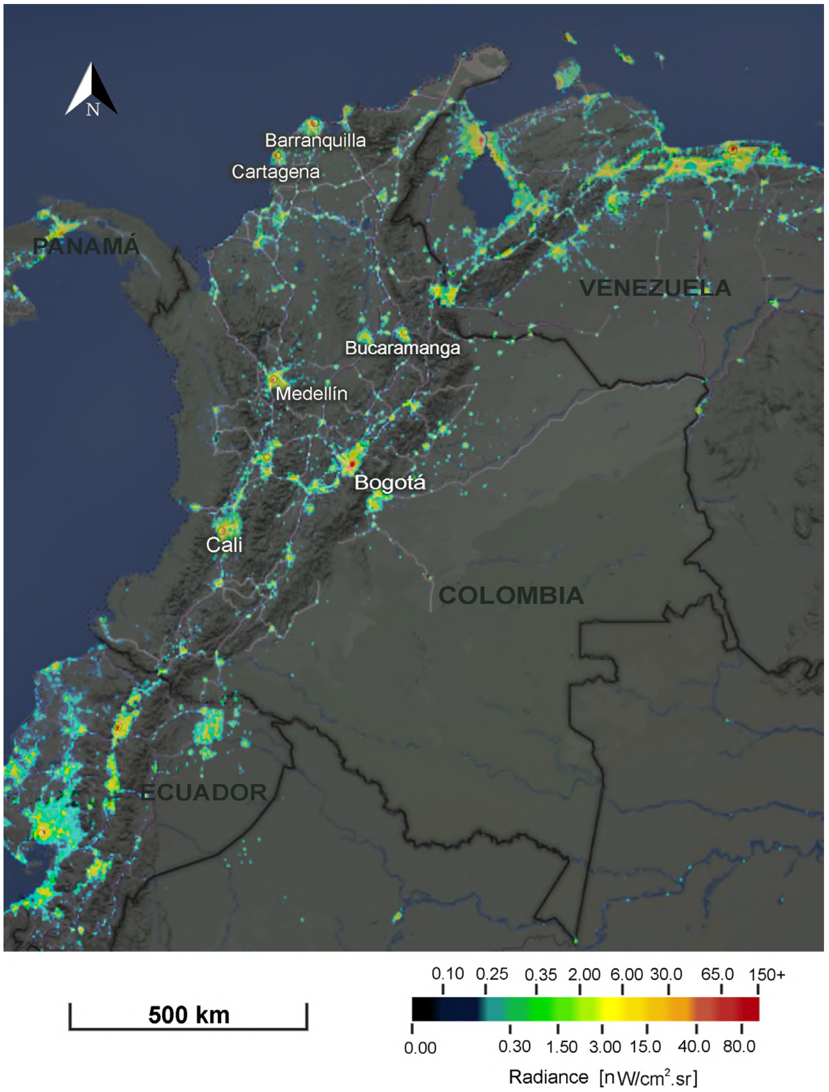

Figure 1. Irradiance image acquired with VIIRS in 2012 overplotted on the map of Colombia. The main urban centers analyzed in this study are labeled in white color.

track various environmental parameters such as land cover, vegetation, snow and ice cover, atmospheric aerosols, among others. The data is subjected to a series of preprocessing steps: radiometric and geometric corrections, atmospheric correction, cloud masking, and data formatting to make it more accurate and valuable. The product shows a group of bands where the Moon illumination has been removed and only retains the measurements produced by artificial lights that are of interest for this work (**Wang *et al.***, 2022). Here we used the all-angle composite snow-free band whose sensor's spatial resolution ranges from 750 to 375 meters. The VNP46A3 data product reports radiance values in nW.cm−2.sr−1. We obtained data from January 2012 to December 2022 framing the latitude (0° to 20°) and longitude (-80° to -70°) region. **Figure 2** shows an example of Bogotá's radiance maps from June 2012 and 2022 using the color convention of the Bortle scale (**Bortle**, 2001) (see also **figure 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366).

Data extraction

As we mentioned, our objective was to investigate the night light emitted by the main Colombian cities. We obtained shapefiles from the *Centros poblados y cabeceras municipales de Colombia* (Populated centers and municipal capitals in Colombia) dataset at the official website of the Colombian National Geographic Institute (*Instituto Geografico Agustin Codazzi*, IGAC). These shapefiles contain geographic information including a set of points that represent population centers and polygons with the boundaries of administrative divisions (cities and municipalities). Using these polygons, population centers within the cities were detected from VIIRS images to analyze the radiance by extracting mean radiance values and creating difference maps in the urban areas. An example of the resulting data and analysis for Bogotá is shown in **figure 3a-c**.

Light pollution trends in urban areas

The study of radiance emitted by a city can be complex, as some areas may have higher emission rates than others due to the type and form of public lighting or the presence of parks, sporadic massive events, and commercial areas, among others. To examine the cities' overall emissions over the past decade, we determined a representative value for each month by computing the average radiance emitted by all the urban centers in the analyzed cities after excluding null data found in the images. Furthermore, we removed any

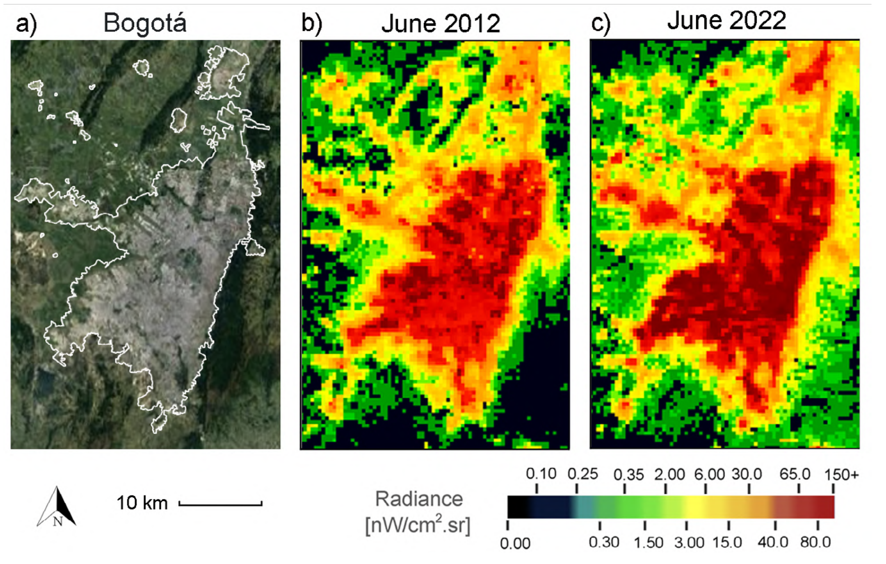

Figure 2. Comparative maps of light measured in Bogotá (a) through satellite sensors, obtained in June 2012 (b) and June 2022 (c), as labeled. The white contours delimit the urban areas in the city. North is up.

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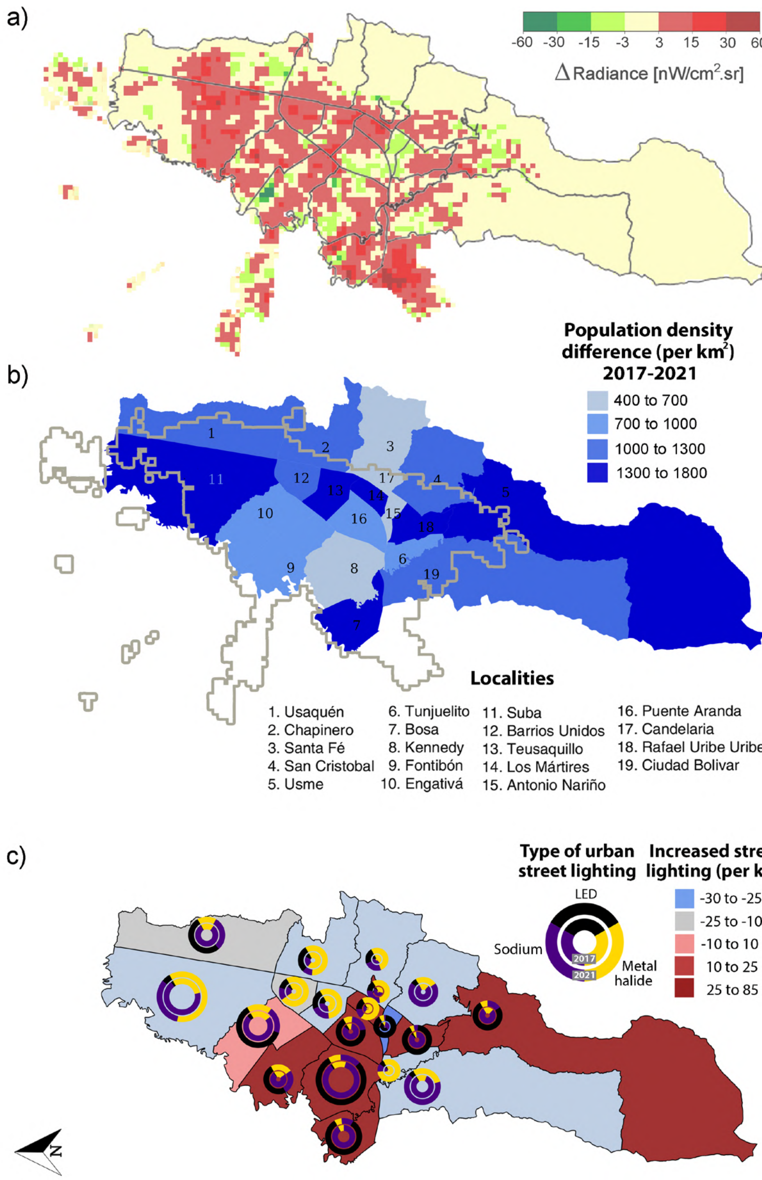

Figure 3. Maps for Bogotá. a. Increments in light emissions from 2017 to 2021 based on satellite imagery overplotted on the map of the city. b. Organization of the 19 urban localities in the city. c. Street lighting growth in localities from 2017 to 2021. The gray contour in the middle panel represents the limits of the urban areas in the city. North is to the left.

outliers through interquartile range analysis to ensure data accuracy. The monthly images enabled us to assess the fluctuations in radiance levels during each month over the years. Therefore, we computed the mean radiance value for every quarter from 2012 to 2022. **Figure 4** shows the plot for Bogotá with color stripes and dots representing the different time periods: January-March, April-June, July-September, and October-December (**Figure 2S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366). The plots of the other cities are shown in the analysis and the supplementary material (**Figures 3S-8S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366).

For the spatial comparative analysis not dependent on the month selected to compare areas of significant increase in cities, we obtained annual images and compared them by taking the difference between the years of interest (**Figure 3a**) for Bogotá between 2017

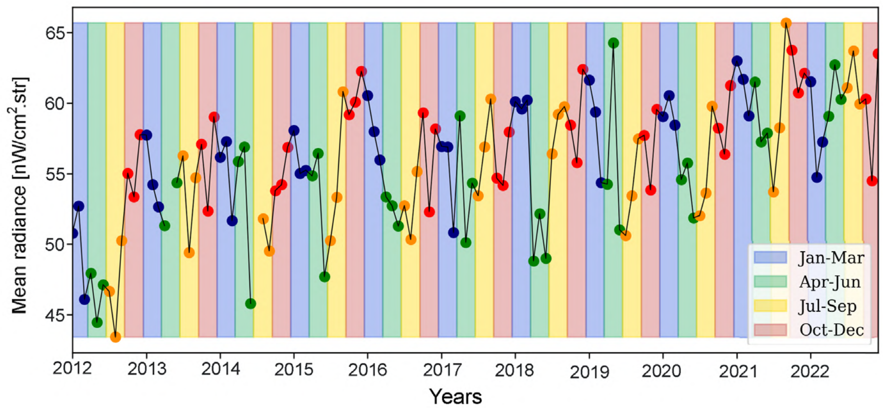

Figure 4. Average monthly light emissions in Bogotá for the decade 2012-2022. Color stripes represent the different quarters for every year, as labeled. The colors of the points correspond to the quarter to which they belong.

and 2021. To visualize and quantify the change in the emitted light, we reported a radiance difference image for each city under study, as will be described in the results. Such maps are particularly useful since they allow the spatial identification of those specific city areas where light emission increases or decreases.

Estimation of transition to LED lighting effects in public luminaries

One of the difficulties we found in the study of light pollution using the VIIRS sensor is that its spectral response is between 480 and 900 nm. Although this range allowed us to study the emission of traditional lights, it left out an emission peak of white LED lights with a wavelength of around 460 nm (**Basu *et al*.**, 2013). Consequently, most of the values are underestimated. A partial solution to this was to study the increase of LED lights in Bogotá using the correction proposed in a previous study (**Sánchez-de Miguel *et al*.**, 2021).

To correct the radiance measured for the increase in LEDs' blue light emission, we analyzed available data about public lighting in Bogotá. **Figure 5a** shows the increase in the number of LED lights from 2017 (when the transition to LED lights began in Bogotá) to 2021 (**Unidad Administrativa Especial de Servicios Públicos-UAESP,** 2022). This allowed us to establish the increase in the number of installed luminaires and the progress of transitioning from traditional technologies, such as high-pressure sodium lamps (HPS) and metal halide lamps, to energy-efficient LED technology. To standardize the comparison of the number of lights across different localities, we calculated the density of lights by dividing the total number of each type of lamp by the area of urban centers in each locality. The unit of measurement was lamps.km^{-2}.

For the correction, we calculated the percentage of LED lights in the total number of public luminaires (p_{LED}). Since it was not possible to distinguish in the radiance measured by the sensor the percentage of light coming from streetlights and other sources such as houses or cars, we assumed the case where all the measured light came from luminaires and used it as an upper bound for LEDs' effect. The correction was then made by multiplying the percentage of emitted radiance corresponding to LED lights by an increase factor (f) between 1.1 and 1.5 depending on the type of LED:

$$R_{corrected} = R(1 + p_{LED}(f - 1)) \quad (1).$$

For blue light low levels, we used a correlated color temperature (CCT) of 2000 K, and for medium levels (the maximum suggested for LED technology lights), we used a CCT value of 3000 K. With these assumptions for CCT values, the corresponding f values were 1.1 in the case of the 2000 K flux and 1.25 for the 3000 K flux (**Sánchez-de Miguel *et al*.,** 2021).

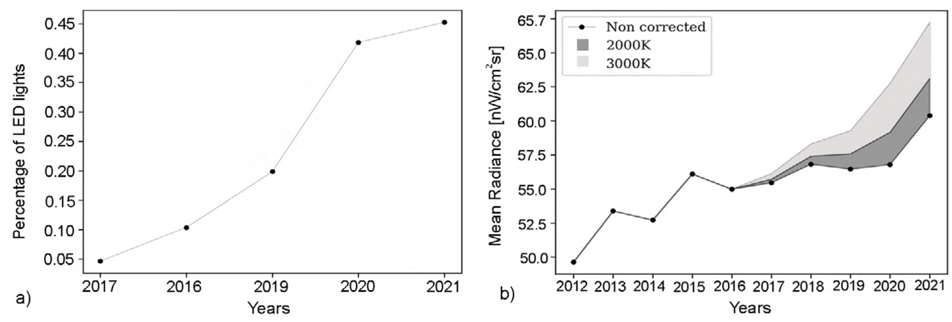

Figure 5. a. Percentage of LED lights replaced in Bogotá's public lighting system. **b.** Average annual light emission from 2012 to 2021. The corrections to be made considering the change to LED light in public luminaries and the type of LED light are shown in gray tones.

Delineating illuminated areas and analyzing urban expansion

The above procedures were designed to extract results for the urban area of each city, i.e., the area delimited by the contours shown in **figure 6**. However, city expansion processes result in newly illuminated areas in the vicinity of the urban centers contributing to the impact of artificial lighting in the context of this study. To study this process, we extracted a fraction of the VIIRS image equal to the smallest square enclosing the urban area of the city and then added 0.1 degrees to each side to obtain a zone that allowed us to study the growth of the cities. Next, we applied thresholding to separate what we considered illuminated zones. The threshold value used was 3.0 nW.cm^{-2}.sr^{-1}, which corresponds to the beginning of the transition from a rural to a suburban sky on the Bortle scale (**Bortle**, 2001), and served to categorize an area as illuminated in our analysis. After separating the zones, we calculate the closed contours of the illuminated areas and the difference between the total illuminated areas in 2022 and 2012. The corresponding contours are plotted in **figure 6** and the difference of areas is listed in **table 1**.

Exploring the relationship between economic growth and light pollution in Bogotá

Recent studies have compared the relationship between the nighttime light index and various social indicators in China and India concluding that the integral indicator GDP has a good linear correlation with radiance when regression is performed in administrative regions (**Han *et al.*,** 2022). However, in previous studies, the data from light pollution remote sensors were combined with economic information from the World Bank to estimate fractional logistic regression models of light pollution. The results indicated that population and GDP per capita were key factors in determining light pollution levels in a country. Besides, it has been established that the relationship between income and light pollution is non-linear and that other economic factors such as foreign investment and land use patterns are also relevant (**Gallaway**, 2010).

Here we aimed to analyze the relationship between Bogotá's GDP and the radiance emitted by the city as a first approach to this type of study in Colombia. To this end, we obtained annual GDP data by departments from the National Statistics Administrative Department (*Departamento Administrativo Nacional de Estadística*, DANE) and the percentage variation by quarters in Bogotá, especially from 2019 to the present to include the COVID-19 pandemic. However, the GDP data for the 2022 fourth quarter was not available at the time of our study, so we assumed that the average growth of the first three quarters of the year would serve for the fourth quarter. We acknowledged that more advanced statistical techniques, such as economic models or time series, could provide more accurate projections. However, our goal was to have a rough estimate of the GDP growth for 2022, and anyway, projections are only approximations that may differ significantly from actual values. After estimating the GDP, values were plotted against the

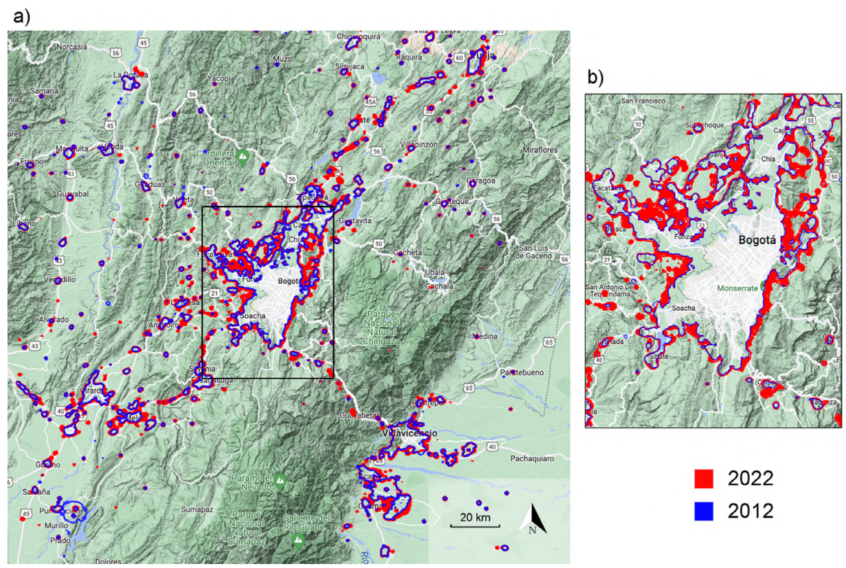

Figure 6. Shaded relief maps of the Savanna of Bogotá (a) and Bogotá city (b). The blue contours delimit the coverage of illuminated areas according to the mean radiance for 2012. The red contours/areas correspond to the extension of the illuminated land over a decade ending in 2022.

Table 1. Data comparison for 2012 - 2022 in all cities under analysis

City	Δ Population density (people/km^2)	Radiance growth rate (%/year)	Δ Illuminated area (km^2)
Bogotá	1677.74	1.73	392
Medellín	1898.59	-1.85	190
Cali	627.54	-1.37	192
Bucaramanga	779.97	-2.26	85
Barranquilla	1008.80	0.56	178
Cartagena	1142.28	1.29	147

emitted radiance in Bogotá for each year as shown in **figure 7a**. We proposed a relationship between the variables based on their apparent behavior that will be commented on in the following section.

Results and discussion

We present first the diagnosis of the city of Bogotá and then that of the rest of the cities under study (**Figure 8a-f**). In the case of Bogotá, we delved into more relevant aspects with readily accessible information, e.g., public lighting and population density variation, as a guide for other large urban centers in Colombia.

The case of Bogotá

In the following subsections, we focused on the description of the case of Bogotá where we used additional information to extract results. **Figure 4** provides an overview of the lighting in Bogotá on a monthly temporal scale visualized by color per quarter. At first glance, it is evident that there has been an increasing trend in light pollution in the city characterized by seasonal oscillations during specific periods of the year. The plot shows, for instance, that in five of the 11 years considered, the maximum yearly radiance value occurred in December from where a relationship with the Christmas season can be inferred.

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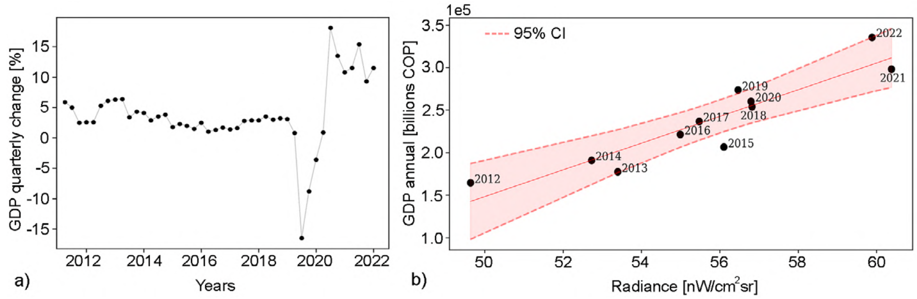

Figure 7. a. Growth rates of Bogotá's GDP compared to the same quarter of the previous year, 2012-1/2022-4. The value of the last quarter of 2022 was assumed, so it may present a significant variation from the value reported by DANE. **b.** Annual Bogotá's GDP as a function of the radiance emitted in the city in the same year. The red line shows the linear fit of the data with the respective confidence intervals.

Two of the other peaks (2014 and 2016) occurred in January following two December peaks, probably as a residual effect of Christmas. Although it would be expected, this behavior was not repeated in all cities. A similar plot for Cali (**Figure 5S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366) showed that the peaks in nine of the 11 years occurred from July to September. In general, the annual cycles in each city were different but consistent on an annual scale. This means that about 15% of the possible light sources were variable, as evidenced by the annual oscillations of ∼10 nW.cm−2.sr−1 in Bogotá. Regarding the growing trend, the annual value was calculated as the average of the year's 12 months (**Figure 9**). After fitting a linear model based on the observations of the figure, the radiance growth rate per year was calculated (**Table 1**). In Bogotá, the night radiance increased by 1.73% each year since 2012. Results for other cities are presented in the same table.

From a spatial point of view, **figure 8a-f** shows difference maps for Bogotá and the other cities quantifying the change in the radiance emitted from 2012 to 2022. For Bogotá, the map evidenced that light emissions have increased to worrying levels (shown in red) in almost all sectors except for tiny areas including city parks such as the Simón Bolívar Park, the area around the international airport, and few others. In the following subsection, we present the results of a more in-depth analysis of Bogotá considering the changes in the last five years (2017-2021).

Lighting installation and population data overview for Bogotá

The 2017 and 2021 radiance maps were used to calculate the difference in the radiance emitted over the years including data from light fixtures in Bogotá (**Figure 3a**) with values ranging from -60 to 60 nW.cm^{-2}.sr^{-1}. Our approach leveraged the power of satellite resolution to conduct studies on smaller scales. By using this methodology, we gain a more comprehensive understanding of how light pollution was influenced by factors such as public lighting and population growth in each locality.

The map of the radiance differences was overlaid on a map with the different localities of Bogotá. **Figure 3b** shows the population density difference between 2017 and 2021. The gray contour represents the urbanized areas of the city, i.e., those with the highest construction density according to the definition by the local government. The zones outside the gray limits include non-urban areas, agricultural areas, or environmentally protected lands. The main population of a locality is concentrated between the limits of the localities and the urbanized area (gray contours).

Between 2017 and 2021, Teusaquillo, Suba, and Bosa localities had the largest increase in population density accompanied by an increase in emitted radiance levels averaging over 4.5 nW.cm^{-2}.sr^{-1} and reaching 8.5 nW.cm^{-2}.sr^{-1}. Los Mártires locality had the highest

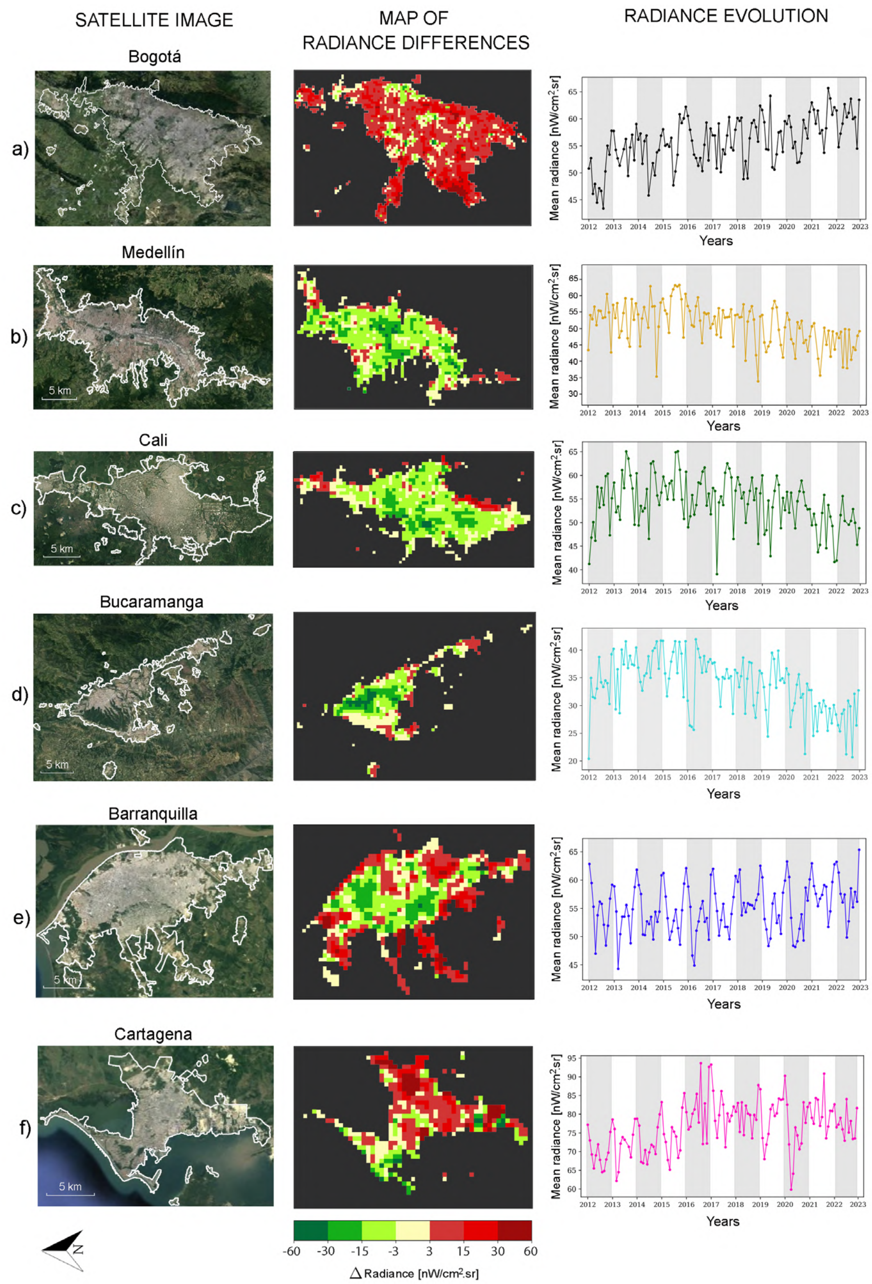

Figure 8. Evolution of the annual mean radiance in main urban Colombian centers for the years 2012 and 2022. Each row shows the results for Bogotá **(a)**, Medellín **(b)**, Cali **(c)**, Bucaramanga **(d),** Barranquilla **(e)**, and Cartagena **(f)**. The left column shows the corresponding satellite image. The middle column shows maps resulting from the radiance difference in the last decade. The plots in the right column correspond to the evolution of the corresponding mean radiance value year after year during the interval analyzed with the corresponding uncertainty bars for each value. The contours superimposed on the satellite images correspond to the delimitation of the urban area in each city as established by the current classification.

population density increase with 1585 people/km^2 and an emitted radiance of 12.46 nW.cm^{-2}.sr^{-1} followed by Soacha, a neighboring municipality almost attached to Bogotá, with 12.72 nW.cm^{-2}.sr^{-1}; Soacha also showed the most significant increase in population density with 5242 people/km^2. On the other hand, the locality of Antonio Nariño showed

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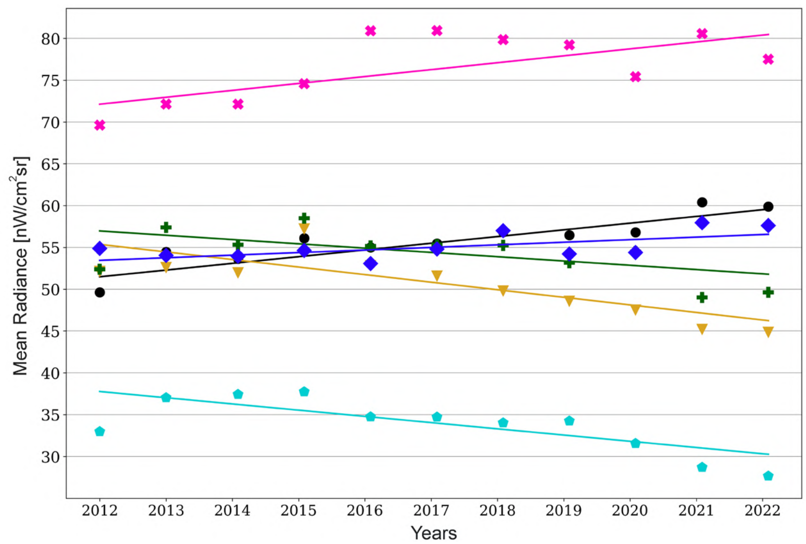

Figure 9. Evolution of the the annual mean radiance over a decade for the five cities analyzed in this work: Bogotá (•), Medellín (▼), Cali (+), Bucaramanga (⬟), Barranquilla (◆), and Cartagena (×). The solid lines are the result of linear fits applied over the data in every case.

the most significant decrease in emitted radiance with a decrease of 4.93 nW.cm^{-2}*sr*$^{-1}$ and the lowest increase in population density with 588 people/km^{2}, only below La Candelaria locality with a decrease in the emitted radiance of 2.95 nW.cm^{-2}.sr^{-1}.

However, it cannot be categorically stated that the increase in population density is the main cause of light pollution increases in Bogotá. There are localities, e.g., Rafael Uribe and Usme, with significant increases in population density (over 1600 people/km^{2}) but reductions in the radiance emitted. Similarly, some localities had low rates of population density increase, e.g., Santa Fé, but high levels of radiance emitted with 5.89 nW.cm−2. sr−1. In future studies, therefore, we propose to consider other factors before determining with certainty the reason behind the increase in light pollution in Bogotá.

Here we analyzed the available data on public lighting in Bogotá focusing on the number of metallic halogen, LED, and sodium lamps.km^{-2} in each locality as shown in **figure 3c.** Bogotá's localities started transitioning from sodium lamps to LED or metallic halogen lamps and six out of eight experiencing decreases in the average radiance as compared to 2017 have completed or nearly completed the transition to LED lamps. La Candelaria started a mixed transition that included replacements with metallic halogen lamps. Ciudad Bolívar changed almost entirely to metallic halogen lamps and experienced a reduction in the total number of lamps.km^{-2}. Suba started its transition to metallic halogen lamps and experienced a positive difference in radiance. Out of the nine localities that changed to LED, replaced more than 200 lamps.km^{-2}, and removed at least 200 sodium lamps.km^{-2}, three registered higher radiance values compared to 2017. Localities with a higher number of LED lamps.km^{-2}, such as La Candelaria and Santa Fé, generally emit higher radiance per unit area. Of the eight localities that as of 2021 had metallic halogens in at least 50% of their public lighting, five emitted radiances above 70 nW.cm^{-2}.sr^{-1}. Of the nine localities where LED lamps were installed in at least 50% of their public lighting, four exceeded the 70 nW.cm^{-2}.sr^{-1} threshold. The two localities where sodium lamps represented more than 50% of their public lighting emitted radiance not exceeding 50 nW.cm^{-2}.sr^{-1}.

Based on these data, it is possible to create a better model of how the type of lighting installed in each locality influences radiance, but this goes beyond the scope of this study. In summary, the data from the public lighting study in Bogotá revealed that the transition from sodium to LED or metallic halogen lamps has impacted the radiance emitted. The number and type of lamps installed also affect light pollution. However other factors such as lamp installation and other sources of lighting, e.g., building lighting and nighttime traffic, should be considered for a more precise assessment of light pollution in the city. It should also be noted that the radiance emitted by public lighting does not represent the total light pollution, which varies depending on the season and human activities.

Pros and cons of LED implementation in Bogotá's public lighting

Despite representing a revolution worldwide and in Bogotá's public lighting since 2017, the low energy consumption resulting from the implementation of white LED light does not imply a reduction in light pollution. Its implementation in shopping malls, warehouses, sports centers, etc., may generate well-being, comfort, and security in some environments of the main cities studied, but its use should be regulated to control the impact of light pollution and its negative implications compared to other types of luminaries like high-pressure sodium and low-pressure or amber LED. It is evident that LED unrestricted use prevails (**Figure 5a**), as evidenced by the increase in light pollution resulting in little benefit to humans and the environment.

In the case of Bogotá, we found that the installation of LED lights added uncertainty to light pollution values. In 2020, for example, apparently, pollution did not increase compared to 2019, but it is plausible that the actual increase was hidden by the installation of new lights. Therefore, the rate of light pollution increases in Bogotá, reported in **table 1** as 1.73%/year, could actually lie between this value and 2.33%/year for 2000 K lights and 3.22%/year for 3000 K lights. These rates would represent more harmful pollution levels for all the processes that are affected by the increase of night lights, as we comment on in our study conclusions. For these reasons, we recommend reassessing the installation sites of these lights and determining their positive and negative effects.

The intersection of light and migration: the changing landscape of Bogotá

In **figure 6**, the area covered by emitted radiance in Bogotá appears highlighted. We set a threshold value of 3 to mark the transition to the suburban sky in the Bortle scale (**Bortle**, 2001), and compared the years 2012 and 2022. In the plot, the contour of the areas is represented in blue for the year 2012 and in red for the year 2022. The areas that did not reach the threshold value in 2012 but exceeded it in 2022 are marked in red. It is evident that there has been a significant increase in the periphery of Bogotá, especially on its eastern border where the area affected by light pollution is expanding towards the hills threatening the environmental protection zone there. New neighborhoods in this area have grown with no regulation. The increase in light pollution there has serious consequences on the environment. Besides, artificial light can interfere with the activity and migration patterns of animals. This increase in radiance is also evident in Bogotá's connections to the surrounding towns of Mosquera and Madrid and the city's exit towards the west, probably due to the increasing presence of industries in a traditionally agricultural area.

On the other hand, Bogotá's growing population rates have led to its inhabitants' displacement to surrounding locations with better accessibility to housing and lower cost of living. Such displacement is triggered by the arrival of people with a higher purchasing power, which forces the original inhabitants to seek cheaper housing and public services. However, Bogotá's neighboring municipalities are not adequately prepared for population increases that exacerbate mobility, housing, and public services problems (**Herrera**, 2015). Naturally, this also extends the area affected by light pollution in the savannah of Bogotá. A study analyzing migration dynamics in Bogotá's surrounding municipalities using birth, death, population, and migration to and from rates (**Secretaría Distrital de Planeación, Subsecretaría de Información y Estudios Estratégicos, Dirección de Estudios Macro**, 2005) concluded that this migration dynamics will continue until 2050 with an increase in their size and, therefore, in the levels of radiance emitted in areas critical for bird migration. In this sense, we think new studies should focus on understanding how species in the savannah of Bogotá are affected now andin the years to come.

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Assessing the correlation between city GDP and radiance emissions in Bogotá

We also analyzed the relationship between light pollution, other relevant variables such as population and economic activity, emitted radiance, and GDP. We found a linear correlation (**Figure 7b**) with a Pearson correlation coefficient of 0.92 and most of the data was within the confidence interval. Notably, in 2019, GDP decreased in some countries and cities, including Bogotá with a 15% reduction. Given the direct correlation with the emitted radiance, this also decreased. **Figure 5b** shows that the radiance emitted in Bogotá remained roughly constant through 2018, 2019 to 2020. However, in 2021, a radical increase in radiance was observed maybe due to the end of the COVID-19 pandemic. To examine the correlation between GDP growth and light pollution, we suggest a comprehensive analysis of economic activity types and land use patterns to determine which sectors and activities contribute the most to the city's light emission increase and be better equipped to make informed decisions and take effective measures to reduce light pollution.

Comparing light pollution across major urban centers in Colombia

The results for all the cities under study (**Figure 8**) include the annual main radiance during 2012 compared to that of 2022. **Figure 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366, shows the annual radiance map for each city; the left column displays the satellite optical image of every city with white contours outlining the urban delimitation; the middle column shows the map of radiance differences in cities' urban areas, which ranged from -60 to 60 $nW.cm^{-2}.sr^{-1}$ (color bar), and the right column shows the plots with the evolution of quarterly radiance values over the years.

The radiance differences graph enabled us to determine spatially where the sources of increased pollution were located in each city. **Figure 9** shows the evolution of the annual mean radiance over the 2012-2022 decade in all the Colombian cities under study. A significant decrease in the radiance emitted was observed in Medellín, Cali, and Bucaramanga but the radiance did increase in some areas. In Medellín, these areas were especially the connections between the urban center and the surrounding municipalities. The plot of radiance evolution (in yellow in the Figure) shows a constant decrease in radiance since 2015. In the supplementary **figure 4S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366, for Medellín, radiance levels did not follow a defined pattern, although, the highest indices were usually registered from July to September and the lowest from October to December.

In Cali, the highest levels of radiance were found in the connection to Yumbo in the southeast. The green plot shows a clear decrease year after year with a negative change rate. In **figure 5S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366, it is evident that the brightest months were from July to September.

As for Bucaramanga, the area connecting to Floridablanca and Piedecuesta showed an increase but, in general, radiance decreased in the main urban area. In the cyan plot, Bucaramanga had the best radiance emission indices and the highest improvement rate (**Figure 6S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366).

In its turn, Barranquilla registered an increase in radiance levels with the highest recorded at the city's exits towards the surrounding municipalities and the area bordering the Magdalena River and its coastal areas. An increase was also observed in the center of the city and in the connection to the municipality of Soledad. The dark blue plot shows an increasing rate of 0.56 units of radiance per year that, although apparently small, is significant if compared to the radiance levels of Bogotá, as the increase in the capital´s population density was considerably higher. The months with the highest brightness values were November and February (**Figure 7S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366).

Cartagena registered the highest emitted radiance levels in this study. This accelerated increase may be mainly due to tourism and the fact that it is one of the main ports in the country. Radiance levels increased at a rate of 1.29 units per year, only behind Bogotá. The radiance peaks occurred from November to February (**Figure 8S,** https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366). Measuring light pollution in Cartagena is important given its coastal location, with negative effects such as the disruption of marine organisms' behavior and feeding patterns and the destabilization of the structure and functions of the ecosystem (**Tamir *et al*.**, 2017). It is important, then, to understand the magnitude of the problem there and take measures to minimize its negative impacts.

Brightest nights: maximum radiance maps for the five cities

To complement the annual averages analyzed so far and illustrate the phenomenon at the monthly level, we computed the worst monthly average of the previous year to identify the highest lighting levels reached, i.e., the worst light pollution scenario to collect inputs to establish the implications of expanded illuminated areas around the main urban cores. **Figures 3S to 8S**, https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366, show these maximum radiance maps for the five cities analyzed here. The maps are superimposed on relief maps with the main names of neighboring towns. In all cases, there is evidence of the extended zones around the demarcation of the urban areas with the maximum radiance (red and yellow areas). Most of the yellow zones correspond to rural lands around the main cities and those close to parks and environmentally protected territories. The maps also reflect the increasing connections between nearby towns and major cities.

Adverse impacts of light pollution and its importance as a measure of sustainability

The protection of the environment from artificial light, or light pollution, is important for various well-documented reasons and its adverse impacts on the following aspects: Biodiversity: Light pollution can disrupt the natural behavior of animals, e.g., birds' migration patterns, and the pollination of plants with negative impacts on biodiversity and ecosystem balance.

Human health: Excessive or inappropriate lighting can disrupt sleep patterns with negative impacts on human health. It can also cause glare, which can be harmful to drivers and pedestrians.

Energy consumption: The use of artificial light consumes energy and resources, which contribute to greenhouse gas emissions and climate change. Reducing light pollution can help conserve energy and reduce the carbon footprint.

Aesthetics: Light pollution can also be negative for the aesthetic and cultural value of the night sky, making it difficult to see the stars and other celestial objects. In indigenous cultures, the stars were used to tell stories and pass down cultural beliefs. The Southern Cross, for example, is an important symbol for many indigenous cultures in the southern hemisphere.

Astronomy: Light pollution can interfere with astronomical observations, making it difficult for astronomers to study the stars and other celestial objects.

Light pollution can be used as a measure of sustainability because it is a proxy for other forms of environmental degradation such as energy consumption, waste, and habitat destruction, and an indicator of the use of energy-efficient and sustainable lighting practices in a community. Reducing light pollution levels can contribute to promoting biodiversity, protecting wildlife, and improving the quality of life in a community. A community with high levels of light pollution is likely to have a high consumption of energy contributing to climate change and low investment in energy-efficient lighting. On the other hand, a community that takes steps to minimize light pollution, such as using shielded lights or turning off lights when they are not needed, is likely to be more energy-efficient and sustainable.

The main Colombian cities have experienced significant growth in the last decade driven by several factors. Colombia has experienced steady economic growth in recent years with a GDP increase of 4% per year on average between 2010 and 2020. This has

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contributed to the development and expansion of large cities with growing business and industry investments. Like many other cities around the world, the largest Colombian cities experienced a trend of urbanization with more people moving from rural areas in search of job opportunities and a better quality of life. This has led to population growth in Bogotá, Medellín, Cali, Bucaramanga, and Cartagena with the corresponding increase in the demand for housing, infrastructure, and other urban services. These cities' local governments have invested in the development of roads, public transportation, and utilities, which, in their turn, has helped to support the growth of the cities. In recent years, these cities have also attracted foreign investment with companies and investors recognizing the potential for growth and development resulting in more international businesses operating in the main cities.

Conclusions

Motivated by the lack of research on light pollution in Colombia, our study made the first diagnosis of the situation. Briefly summarized, our results point to the expansion of illuminated areas in all main urban centers in the country with Cali, Medellín, and Bucaramanga as the three cities that have better controlled the levels of mean radiance over the years for reasons that should be further analyzed in future studies.

It is important to note that satellites can detect the light emitted upwards, however, they cannot accurately measure all wavelengths generated by LED lighting or horizontally radiated light, which means that the actual level of light pollution from the ground can increment significantly.

Here we were able to estimate the uncertainty caused by the presence of LED lights in Bogotá. In the worst case, when the light has a color temperature of 3000 K, and under the assumption that all the light emitted comes from public luminaires, the growth would be 3.22%, nearly doubling the values reported. A less pessimistic picture, assuming color temperatures of 2000 K, gave us a 2.33% per year growth. On the other hand, the recent estimation of the levels of sky brightness from ground observations ranged from 7 to 10% per year in the human visible band (**Kyba *et al.***, 2023). Since it is not possible to estimate the effect of horizontal irradiance from satellite images, the growth in pollution for ground-based observations in cities like Bogotá could still be in this order of magnitude. Nevertheless, proper in-situ measurements should be done to confirm this fact.

As for the other cities, even those showing decreasing levels of mean radiance in the last decade, the actual situation of sky brightness may also be higher measured from the ground which calls for further studies.

Our analysis of Bogotá's localities showed that the increase in population density does not have a direct relationship with the increase in light pollution and there seems to be no relationship either between density (**Table 1**) and pollution values (**Figure 9**). This suggests that the individual activity of people is not the leading cause of increased damage to the night sky. On the other hand, the correlation between nighttime radiance and GDP growth in Bogotá suggests that lighting linked to the production of goods and services, such as in industrial zones, new significant buildings, and road corridors, could be responsible for the problem in this city.

However, the case of Medellín shows that it is possible not only to maintain but even reduce pollution levels with a growing GDP and population density. This is an incentive to conduct studies to outline the practices and behaviors in the installation of lighting there.

Finally, to address the problem of light pollution it is important to raise public awareness on its negative effects and promote more sustainable practices like the use of low-intensity LED lights and the downward orientation of exterior lights. It is also crucial to limit the amount of artificial light in protected natural areas and encourage the adoption of more efficient technologies in terms of energy and light quality. Future studies should quantify more precisely the impact of artificial high-radiance levels on Colombian ecosystems, biodiversity, and human health, among others, and send a message to stop the brightening of the night to our children but especially to national authorities and decision-makers in the country.

Supplementary material

See de supplementary material in https://www.raccefyn.co/index.php/raccefyn/article/view/1867/3366

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Contribution of the authors

KJRE and AFGG: data search and selection, image processing, analysis of the data, and writing of the manuscript. SVD: bibliographic search, image processing, analysis of the data and results, analysis of the results, and writing of the manuscript. MVT, CGT: analysis of the results.

Conflicts of interest

The authors declare no conflicts of interest.

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