Artículo Original / Article

The Oil Resplendence: Evolution of the Oil Extraction Areas in Ecuador through the Night Luminosity

El resplandor petrolero: evolución de las zonas de extracción petrolera en el Ecuador a través de la luminosidad nocturna

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Abstract: This article assesses a frequently overlooked impact, namely, the artificial illumination emanating from infrastructures associated with oil extraction installations from 2012 to 2019 located in the Amazon region, one of the places with the greatest biodiversity in the world. The primary dataset utilized in this study is derived from VIIRS nighttime satellite imagery. The significance of this research lies not only in examining light pollution but also in presenting a method for utilizing these images. The analysis focuses on Ecuador, one of the principal oil-producing nations in Latin America. The findings suggest a discernible correlation between the evolution of luminosity and the volume of crude oil production, although the luminosity shows a much higher growth rate than crude oil production. Additionally, it is observed that the elevated radiance levels in oil-rich areas yield luminous impacts comparable to those generated by major Ecuadorian cities. Consequently, this study's approach contributes to elucidating the territorial repercussions of the evolving patterns in oil consumption in a non-artificialized territory with high biodiversity. The results obtained herein aspire to instigate discourse on the environmental conditions engendered by extractive activities in their respective habitats. Furthermore, this study seeks to underscore the potential inherent in the selected data source and methodology.

Keywords: Ecuador, extractive activities, light pollution, night satellite images, oil areas

Resumen: Este artículo tiene como objetivo evaluar el impacto —al que a menudo se le presta una atención limitada— de la luz artificial emitida por las infraestructuras asociadas a las plantas de extracción de petróleo desde el año 2012 al 2019, y que están localizadas en la región amazónica, uno de los lugares con mayor biodiversidad en el mundo. La principal fuente de información utilizada es la serie de imágenes satelitales nocturnas VIIRS. La contribución de esta investigación consiste no solo en el análisis de la contaminación lumínica, sino que también presenta un método para el uso de estas imágenes. El análisis se ha centrado en uno de los principales países productores de petróleo de América Latina: Ecuador. De acuerdo con los resultados, existe una cierta relación entre la evolución de la luz y el volumen de producción de crudo, aunque la luz crece a un ritmo mucho mayor que el volumen de producción. Asimismo, se observa que los altos niveles de resplandor de las áreas petroleras provocan impactos de luminosidad comparables a los generados por algunas de las principales ciudades ecuatorianas. Por tanto, el planteamiento de este estudio contribuye a mostrar cómo la evolución del consumo de petróleo impacta en territorios no artificializados y con ecosistemas naturales de gran importancia biológica. Los resultados obtenidos buscan generar un debate sobre las condiciones que generan las actividades extractivistas en el hábitat donde se ubican, y también expresar el potencial que ofrece la fuente y la metodología utilizada.

Palabras clave: Ecuador, actividades extractivistas, contaminación lumínica, imágenes satelitales nocturnas, áreas petroleras

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Introduction

The evolution of human societies has significantly hinged upon the energy sources to which they have had access, ranging from primitive sunlight utilization to the current widespread dependence on fossil fuels. Notably, the Industrial Revolution marks a pivotal juncture, as fossil fuels, particularly oil and its derivatives, have played a central role in shaping energy consumption patterns (Díaz, 2016; Fernández y González, 2013).

Since then, oil has emerged as the predominant global energy source, fueled by the escalating consumption of fossil fuels, leading to the intensive and extensive utilization of hydrocarbons. This heightened energy availability has resulted in increased societal complexity, prompting modifications in societal structures (Smil, 1994; Tainter, 1988). Consequently, this surge has spurred the development of capitalism while concurrently inducing profound alterations in the biosphere, manifesting significant environmental impacts (Fernández y González, 2013). The direct linkage of oil usage to the emission of greenhouse gases, global warming, air pollution, and climate change further underscores the environmental ramifications (Smith, 2012). Carbon emissions, originating from oil extraction to the utilization and disposal of derivatives, have notably escalated since the pre-industrial era, with fossil fuel combustion contributing approximately 78 % to the greenhouse gas increase from 1970 to 2010 (Intergovernmental Panel on Climate Change [IPCC], 2014).

Moreover, it is imperative to acknowledge that oil consumption entails a finite and non-renewable product formed over millions of years. Despite its finite nature, a significant portion of these reserves has been depleted in just over a century (Riba, 2011).

Within this context, using such energy sources is precipitating a collapse in the natural environment, wherein the exploitation limits of non-renewable resources are inadequately considered in current energy demands. The depletion of non-renewable energy resources appears imminent, exacerbated by population growth, heightened resource consumption, and energy wastage, rendering the prevailing development model unsustainable (Smith, 2012).

To avert a societal collapse, a paradigm shift in the current development model is imperative, necessitating a consideration of the planet's resource limitations (Riba, 2011; Sans y Pulla, 2013). Consequently, the imperative for cleaner technologies and the exploration of new energy sources becomes evident. Nevertheless, as these alternatives are developed, the predominant share of current energy demand is met by fossil fuel derivatives extracted globally. Substituting oil with an alternative source that matches its quantity and quality of energy provision remains a formidable challenge for now (Riba, 2011).

The study of hydrocarbon extraction effects has been ongoing for several years, encompassing diverse environmental, territorial, economic, cultural, and social perspectives. Contemporary studies incorporating innovative tools and methods further shed light on these effects. Notably, the use of nighttime brightness satellite images from NASA (Elvidge et al., 2016) for 2012-2018 unveils burning sites on Earth. This approach facilitates the estimation of gas volume based on nocturnal luminosity, offering insights into the radiance emitted by these areas. VIIRS images emerge as an effective tool for monitoring and assessing efforts to curtail environmental and light pollution from burning sites, thus contributing to a more comprehensive understanding of the environmental impacts of oil activities.

In this context, various techniques have been developed to measure light pollution. Studies by Falchi et al. (2011) have evaluated the spectral response of the human eye to artificial light using nighttime satellite images. This type of analysis is crucial, as research has shown that light pollution is increasing globally in intensity and extension (Kyba et al., 2017). This growing phenomenon generates significant environmental and ecological problems (Navara & Nelson, 2007). For instance, the disruption of natural light cycles negatively impacts ecosystems, exerting increased pressure on the environment (Gaston et al., 2014). Additionally, light pollution affects the quality of life and health of populations living in or near these artificially lit environments (Boslett et al., 2021). Consequently, this study delves into the evolution of nighttime luminosity resulting from hydrocarbon extraction activities in Ecuador from 2012 to 2019. It endeavors to quantify light pollution and scrutinize its progression in 65 areas designated by the Ministry of Hydrocarbons in 2017. The article seeks to substantiate the hypothesis by positing a correlation between crude oil production and nocturnal luminosity.

Following this introduction, the article comprises three sections. The first delineates the methodological process, providing a general overview of the fundamental information sources. The second section unveils the principal analysis results, encompassing the calculation of radiant intensity and average radiance per oil area, alongside the correlation between luminosity and crude oil production volume. This section also includes a comparative analysis of light pollution in settlement and oil areas, elucidating urban light intensity disparities. Lastly, the third section presents conclusions drawn from the results obtained.

Oil Extractivism in response to energy demand. The case of Ecuador

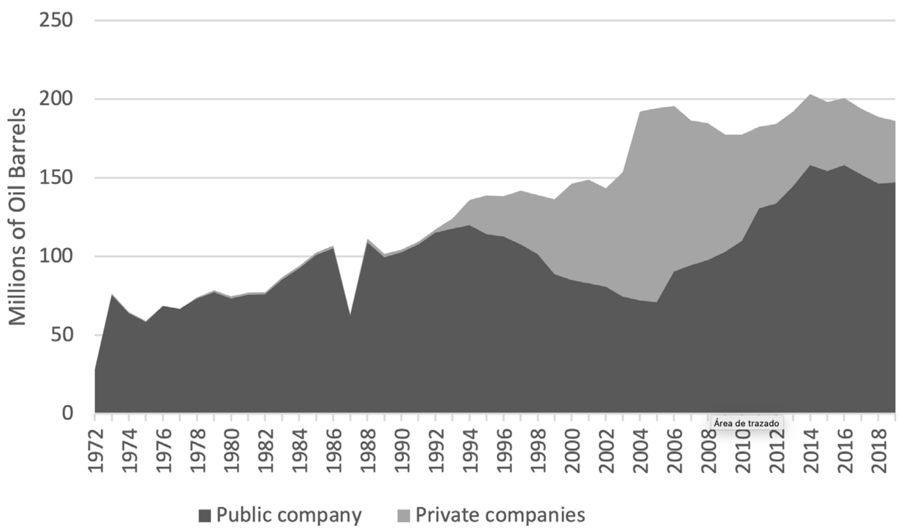
The oil demand, spurred by the Industrial Revolution, has resulted in exploiting resources in regions often distant from primary consumption centers. In Ecuador's case, most of these exploitation sites are situated north of the Amazon region.

Oil extraction in Ecuador commenced in the 1920s but gained prominence in 1972 during the Oil Boom. Since then, oil has become a pivotal component of the Ecuadorian economy (Larrea, 2006). Despite being one of the world's most biodiverse nations, Ecuador has ascended to become the fifth-largest oil producer in Latin America (British Petroleum [BP], 2018) and holds the 29th position among oil-producing countries globally (The World Factbook, 2016).

Over the past century, oil extraction has experienced a gradual increase. This expansion has translated into a significant surge in production, escalating from approximately 40 million barrels in the early 1970s to 200 million in the second decade of this century (Figure 1). Consequently, within less than half a century, oil production has quintupled. According to the Central Bank of Ecuador, mineral products, predominantly oil, constitute the most substantial export income for the country. In 2012, it constituted 58 % of the total exports, reducing to 39 % in 2019 due to oil price fluctuations.

Figure 1

The volume of oil production in thousands of barrels. Ecuador, 1972-2019



Note. Central Bank of Ecuador, Macroeconomic Statistics, 2020.

The continuous growth in oil extraction has raised concerns about the depletion of proven reserves, yet the extraction rate has essentially remained constant. In 2017, the Reserve-to-Production (R/P) ratio was calculated at 42.7, representing the number of years the reserves would last if the current production volume is sustained (BP, 2018).

Early exploration efforts focused on the northern and central zones of the Ecuadorian Amazon, a region of immense biological diversity and ecological significance. While northern deposits, located in territories inhabited by non-warrior communities, contained light oil of high quality, central deposits were found in regions inhabited by more territorial communities, limiting access for prospecting and exploitation. Despite local opposition, expeditions in the central region determined heavy crude deposits, leading to more intensive exploitation in the northern region, corresponding to the provinces of Sucumbíos and Orellana (Vogliano, 2009).

Despite the imperative to preserve the environment and embrace sustainable technologies, the oil industry remains a cornerstone supporting the country's economic development. Oil-derived economic benefits underpin significant state development plans (Burchardt et al., 2016), making it challenging to alter the structural foundation of the national economy.

The initiation of oil activities in the Amazon region triggered various social, cultural, economic, and ecological impacts (Burchardt et al., 2016). These include environmental deterioration, violation of indigenous rights, dispossession of ancestral lands, and disruption of social structures (Becerra et al., 2013). Native communities' resistance against oil activities has yielded varied outcomes (Fontaine, 2009). Overall, a national government policy has emerged, aiming to compensate local communities through diverse projects focused on generating sustainable development and fostering regional progress. However, the outcomes have not always met expectations despite implementing various plans and projects. Some initiatives have incurred significant social costs, fostering greater economic dependence on oil and an expansion of the oil frontier (Wilson y Bayón, 2017).

Impacts in traditionally non-urban areas

The need to analyze anthropogenic activities that, although not traditionally associated with urban uses, generate similar effects on the natural environment has been identified. These territories, which are not primarily designated for human settlements, host activities that exert pressures comparable to those in urban residential areas. Recently, significant advances have been made in evaluating these types of impacts in both urbanized areas (Henderson et al., 2003) and natural ecosystems (Rodrigo-Comino et al., 2023). The research encompasses various approaches, methods, and scales to address this issue.

Effects on human health have been documented (Afroz-Hossain et al., 2019; Benedetto & Contin, 2019), as well as impacts on natural ecosystems (Adams et al., 2019; Firebaugh & Haynes, 2019) and behavioral dynamics of species (Ciach & Fröhlich, 2019). For example, studies have employed various methodologies, such as analyzing retinal degeneration caused by light emitted by LED diodes (Benedetto & Contin, 2019) and using artificial LED light to study animal behavior (Firebaugh & Haynes, 2019). Additionally, satellite imagery has been used to measure light intensity in various contexts, including military conflicts (Li et al., 2021), economic development (Li et al., 2013), maritime activities (Elvidge et al., 2015), and regional disparities (Coscieme et al., 2017; Elvidge et al., 2011).

Among these studies, VIIRS images have proven particularly useful for measuring the volume of natural gas flaring (Elvidge et al., 2016). Moreover, by measuring radiant emissions in terms of both intensity and spatial dispersion, comparisons have been made with radiance levels in urban areas (Nel·lo et al., 2017). It is particularly interesting to compare the impacts of expanding urbanization with those of oil extraction. Both activities produce significant environmental effects that alter surrounding ecosystems. However, in urban areas, light pollution is more visible due to the artificial modification of the land, whereas in oil extraction sites, although there may not be a physical transformation of the land, the natural environmental balance of surrounding ecosystems is still disrupted.

Methodology: The estimation of the night luminosity in the oil areas

The methodology comprises two discernible stages: one dedicated to the pre-treatment of images and another focused on the processing necessary for calculating the indicators essential to fulfill the objectives of the current investigation.

Pretreatment of images

The research considers a series of night satellite images called Version 1 VIIRS Day/Night Band Nighttime Lights to analyze light pollution. These images have great potential for the analysis of territorial processes. The images are sourced from the new SNPP satellite, which includes a calibration system. They consist of the average data radiance of the Day/Night Band (DBN) of the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument. These images are available from the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) of the United States government. Monthly compositions from April 2012 to the present are accessible through the Earth Observation Group (EOG) database. Additionally, daily and yearly products are available. These images exhibit superior quality and resolution compared to previous night satellite images such as DSMP OLS (Elvidge et al., 2013).

The images utilized in this study are accessible on the NGDC website:

https://ngdc.noaa.gov/eog/viirs/download_dnb_composites.html

The VIIRS series of images provides information about the Earth's surface radiance, presenting radiance values in nanoWatts/cm2/sr. The radiometric detection range is extensive, allowing the distinction between very bright and barely illuminated areas. Analysis of the intensity and magnitude of radiance values enables the identification of different types of land use. Some authors have examined the intensity of urban areas and human activities (Checa y Nel·lo, 2018; Li et al., 2015). Others have correlated luminosity with population density, GDP fluctuation, and other socioeconomic variables (Elvidge, et al., 2012; Levin & Duke, 2012; Liang et al., 2014; Zhao et al., 2011).

The nighttime images are georeferenced and available in a raster format with 14-bit radiometric quantification. Compared to previous images, VIIRS images avoid supersaturation in the most illuminated areas, allowing the study of extreme values. The Day/Night Band (DNB) sensor has 11 spectral bands at night and 21 during the day. The pixel resolution is 15 arc seconds, and the spatial resolution is 742 x 742 m (Elvidge et al., 2013), making it suitable for territorial analysis. In summary, the images generated by this satellite exhibit good characteristics in terms of resolution, calibration, and quality.

It is important to note that data from tropical areas are affected by cloud presence, hindering the registration of valid Earth surface radiance values. Additionally, at the poles, luminosity is affected by solar lighting in the summer months. However, products provide information about the number of valid observations obtained during the month. As will be seen, the processing of the images considers this information about cloud presence and valid observations.

The process begins with the download of monthly satellite images from April 2012 to December 2019. It is necessary to consider that the images are available for the entire planet from latitude 75N to 65S, in a set of 6 images divided by the equator and for every 120 degrees of longitude. To analyze Ecuador, it is necessary to download two areas of images corresponding to the northern and southern hemispheres and longitude from 60W to 180W. Once the files of the two hemispheres are downloaded, two products are available: one corresponds to the average brightness of the Day/Night Band (DNB) with an extension of avg_rade9h.tif, and the other includes the number of observations without clouds with an extension of cf_cbg.tif. Products of the same temporality but different hemispheres were joined, and an image containing information between 75N and 65S of latitude and 60W and 180W of longitude was generated. In order to obtain information only about our study territory, it was necessary to extract an area of 720 x 780 km, which encompasses continental Ecuador. Thus, two products were obtained for each month of the years studied: one corresponding to the average brightness and the other to the number of observations.

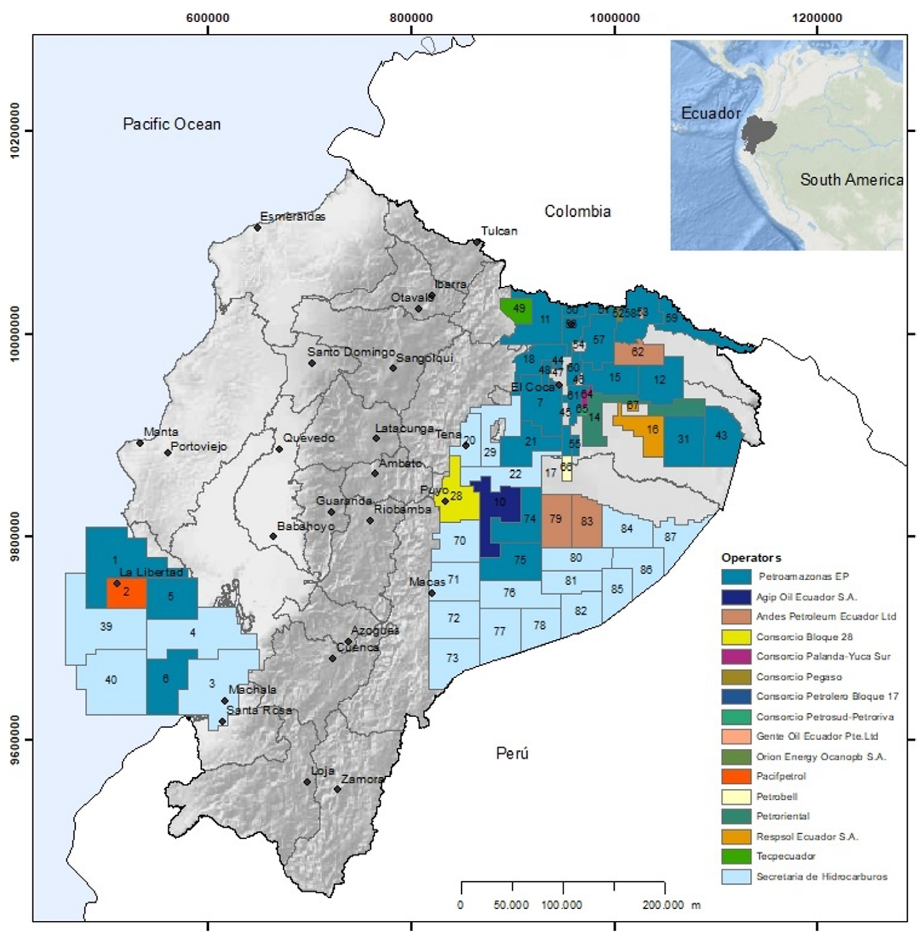
Next, to have a common language with other sources of information, all data sources were assigned a projected coordinate system, WGS-1984_UTM_ZONE_17S. After that, all the images were converted to a vector format, allowing for more efficient quantitative anal. For this process, it was necessary to convert the radiance values to an integer number.

Considering cloud presence to prevent incorrect average data was essential. Therefore, areas with no measures of radiance due to clouds were delineated in the images containing valid observations of radiance. Then, the same areas were identified in the file corresponding to radiance values. In these cases, the value 0 was replaced by a Null value. Finally, operations were performed using the monthly images to obtain the annual average value. With this process, areas without valid observations were excluded from the operations.

Regarding the study area of this research, the areas identified on the Map of Petroleum Areas of Ecuador from the Ministry of Hydrocarbons (Figure 2) for the year 2017 were used. The map delineates 65 oil areas in the country, with 8 located in the coastal area and 57 in the Amazon region. The same source of information indicates the operators assigned to each area: 24 areas are operated by Petroamazonas, an Ecuadorian state company, and private companies operate 20. The other 21 areas are under the management of the Secretary of Hydrocarbons, implying that they are not assigned to any operator and do not generate crude oil production.

Figure 2

Petroleum Areas of Continental Ecuador



Note. Ministry of Hydrocarbons and Secretary of Hydrocarbons of Ecuador, own elaboration.

Additionally, the annual crude oil production of public and private companies was identified. This information is published in the statistical bulletins of the Hydrocarbons Regulation and Control Agency (ARCH) and by the Central Bank of Ecuador.

Measuring brightness: Radiant intensity and average radiance

Before delving into the results, defining the units used to measure the magnitude and intensity of luminosity is essential. On the one hand, magnitude is a value reflecting the total radiance emitted in a delimited space, known as radiant intensity. The measuring unit corresponds to W/sr. To calculate this value, it was necessary to intersect the nighttime images with the oil areas and then calculate the sum of the radiance values for each oil area. On the other hand, the average radiance value indicates the mean radiance of each area, resulting from dividing the total emitted radiance by the surface of the considered area. It is expressed in $nW/cm^2/sr$.

Additionally, to conduct a spatial comparative analysis, a methodology was applied to compare the oil areas' light impact with the country's main populated centers in square kilometers. The procedure applied considers a threshold value of radiance that delimits urban areas in terms of intensity of use through the radiance emitted by the territory. The use of a threshold has been considered in various studies employing these satellite images. However, for this specific study, the methodology used is based on the research called 'The City Light' (Nel·lo et al., 2017). It allows us to measure the effect of light scattering in oil areas with intensities similar to those of urban areas.

The method establishes a threshold of urban light, enabling an analysis of the evolution of the surfaces that reach the defined threshold. This urban luminosity threshold is obtained through an intersection between night satellite images, and polygons of urban uses delimited in land use maps. In the Ecuadorian case, we utilized the database of the National Information System of Rural Lands and Technological Infrastructure - SIGTIERRAS (2016) of the Ministry of Agriculture and Livestock for the delimitation of these polygons. Once the layer of polygons of urban uses intersects with the pixel with radiance information, we proceed to compare the surfaces with different levels of brightness. Through this procedure, a radiance value that corresponds to the maximum coincidence between urban areas and illuminated pixels was determined.

This threshold allows us to analyze the evolution of the surfaces affected by the natural gas flaring site located in the oil areas. These sites emit considerable levels of radiance that illuminate the surrounding territory. Therefore, the luminosity recorded in satellite images enables us to observe the impact of light scattering, where the degree of light scattering, among other factors, depends on the level of radiance registered in a certain territory. In principle, greater light intensity generates greater light dispersion. Thus, light scattering can explain that the surface of the oil areas, mostly characterized by agricultural and forestry features, located close to oil extraction centers reach luminosity levels similar to those of consolidated urban areas.

Hence, the threshold of the radiance of typically urban areas applied in the oil areas shows us the magnitude of the surface that is polluted by similar levels of urban light outside the strict limit.

Results: The evolution of night brightness

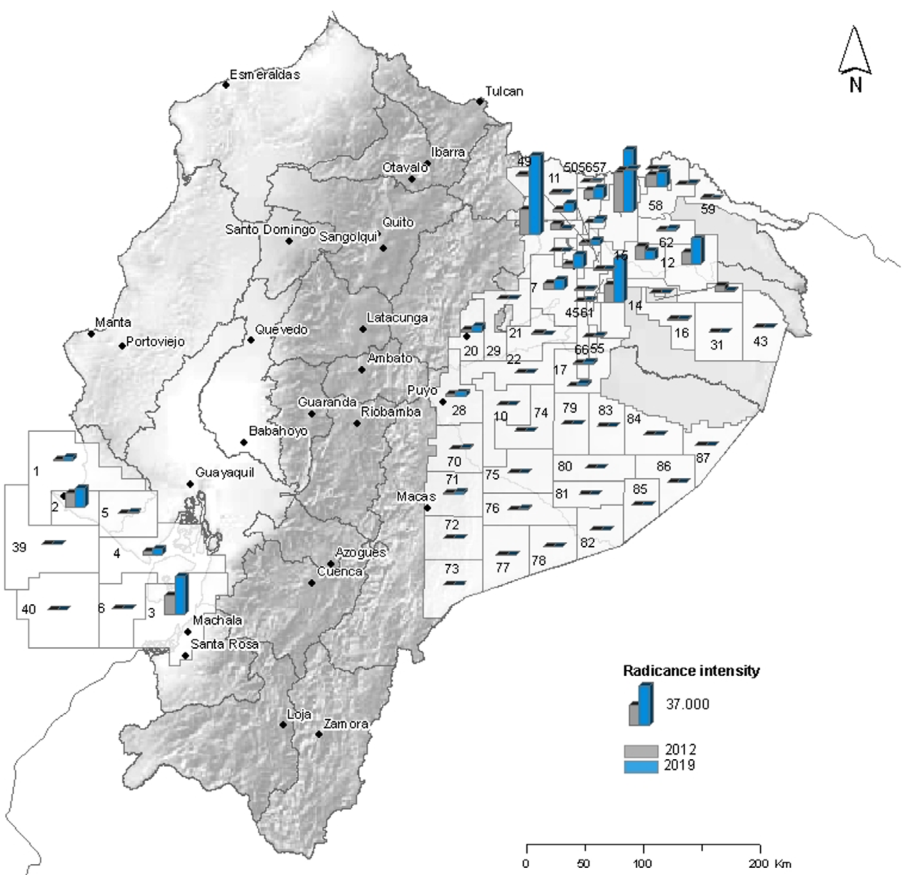
Having outlined the general framework and methodology of the study, let us now present the main results. Firstly, we determined each oil area's evolution of radiant intensity and mean radiance. Subsequently, we explored the relationship between radiance evolution and the volume of crude oil production by companies. Finally, a comparative analysis was conducted using the threshold of urban light to measure the light impact in oil areas and main Ecuadorian urban areas.

Luminosity evolution in oil areas: Radiance intensity

The evolution of radiance emitted in the oil areas, encompassing 65 oil areas, reveals a considerable increase during the analyzed period. Radiance has surged from 165 778 W/sr in 2012 to 307 150 W/sr in 2019, implying an 85 % increase. This trend is noteworthy, particularly given that most of these territories are situated in areas with abundant biodiversity, such as the Amazonas region.

Figure 3

Radiant intensity by oil area. Ecuador 2012-2019



Note. VIIRS, own elaboration.

It is crucial to acknowledge that the oil areas are operated by different companies, each with distinct characteristics in terms of technology, infrastructure status, and site management. These differences influence the radiance intensity of each area (Figure 3). By calculating the radiance of the 65 areas over the last 7 years, it is evident that radiant intensity has multiplied by factors within a wide range, ranging from 0.2 to 253. In most cases, radiance intensity has increased by percentages around 70 %.

In terms of absolute values, three areas —60-Sacha, 57-Shushufindi Libertador, and 61-Auca— emit the highest levels of radiance intensity. Notably, these three areas are operated by Petroamazonas-EP, a public company. For instance, 60-Sacha reached 73,480 W/sr in 2019, tripling its indicator in the last 7 years. According to the Petroamazonas 2017 Management Report, this area is the most profitable in terms of barrels of production and income in dollars, ranking third in barrels of oil per day, after Shushufindi and Auca. In three areas, the recorded percentage increases in radiance exceed the percentages of increases in crude oil production.

Three areas also stand out for remarkable increases: Area 43-ITT, 53-Singue, and 54-Eno Ron. Area 43-ITT has multiplied its radiance emission by 253 times between 2012 and 2019, from 3 to 701 W/sr. This area, located partly in Yasuní National Park, attracted international attention through the Yasuní ITT Initiative. Despite various policies over the years, the radiance emission in this area reflects a sharp increase since 2013.

Regarding Area 53-Singue, although its radiance intensity does not reach the highest values, the evolution process has been extreme. It is the second smallest area, but its radiance increased by 166 times from 8 to 1303 W/sr between 2012 and 2019. A considerable correlation coefficient (R^2 = 0.73) between oil production and recorded radiance highlights the parallel increase between the two.

Finally, the 54-Eno Ron multiplied its initial value by 25, increasing from 165 to 4203 W/sr in the analyzed period. The first record of crude oil production in this area was in 2014, coinciding with a substantial increase in radiance levels. A correlation coefficient of 0.84 between radiance and oil barrel production suggests a parallel increase.

In these three areas, the impact of oil extractive activities on light is significant, capturing changes in the natural environment from near-zero radiance values to illuminated territories, coinciding with the commencement of extractive activities. This radiance increase implies extreme transformations in the habitat of flora, fauna, and human settlements within these mega-diverse areas. Additionally, extractive activities not only influence the light factor but often alter other aspects of the natural environment, impacting air and water quality, noise levels, and more.

It is important to note that the increase in radiance in oil areas is also linked to the urbanization processes within these areas. Urbanization is often part of negotiation policies with local communities for compensation, such as Millennium Cities projects. New infrastructures are implemented to serve local communities, directly linking urbanization processes and light emission to oil extraction. However, these urban areas have much lower radiance levels than burning sites.

Evolution of light intensity in oil areas: Average radiance

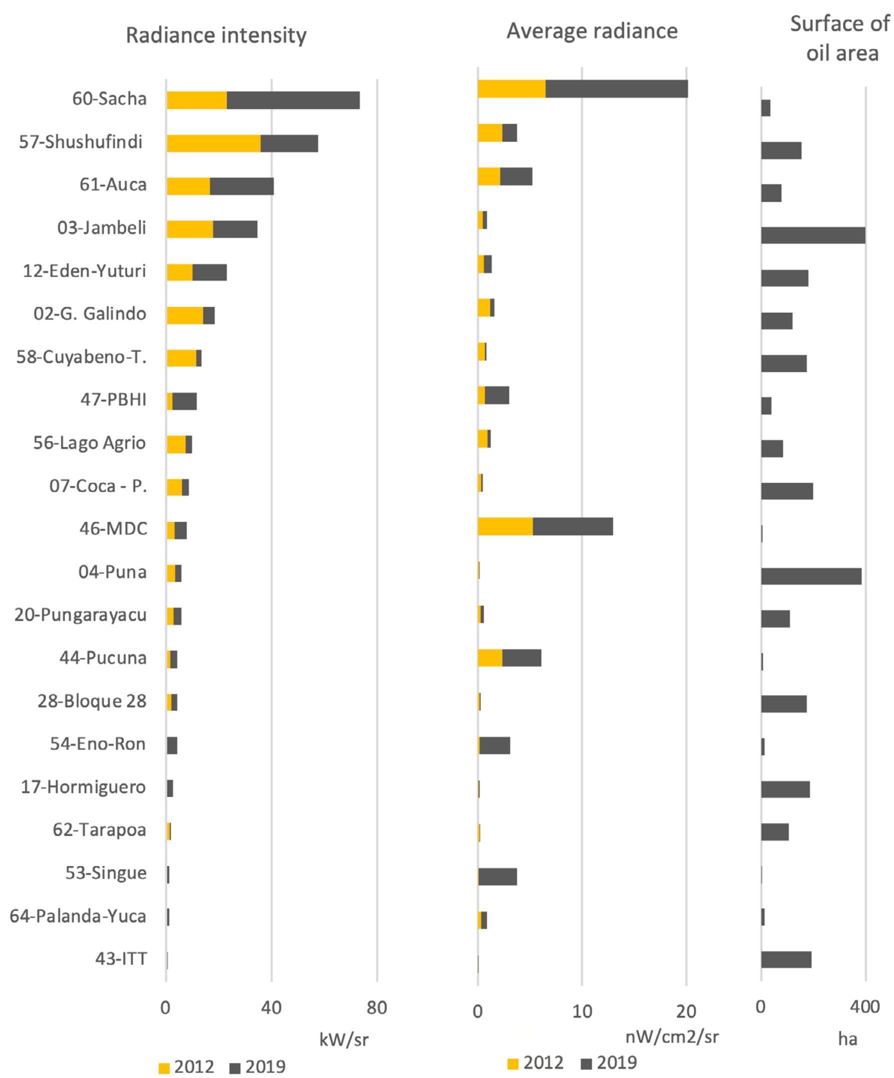
To better visualize differences between oil areas, the average radiance of each one has been calculated. Considering that total emitted radiance is linked to the area's extension, the average radiance allows for a comparison between areas of varying sizes. It is obtained by dividing the total emitted radiance by the total area, providing a value reflecting the average radiance recorded across the analyzed area.

The increase in mean radiance is directly tied to the rise in total emitted luminosity discussed in the previous section. However, average radiance values express the intensity of territory each company uses. Therefore, areas emitting lower total radiance levels might still have high mean radiance if concentrated in a small territory. The highest average radiance values correspond to areas with greater intensity of use, indicating a significant light impact on the considered area.

Both radiant intensity and average radiance are crucial indicators of the impact on the natural environment. Figure 4 illustrates both indicators for the main Ecuadorian oil areas.

Figure 4

Evolution of radiance intensity and average radiance by oil areas 2012-2019



Note. VIIRS, Agency for Regulation and Control of Hydrocarbons and own elaboration.

In the set of 65 areas, mean radiance has increased by 86%, from 205 to 382 pW/cm^2/sr between 2012 and 2019. The areas 60-Sacha and 46-Mauro Dávalos Cordero record the highest average radiance, significantly increasing their levels by 3 and 2.5 times, respectively, in the last 7 years.

Certain areas emit high radiance intensity but have low average radiance due to concentrated light sources and a large extension, maintaining dark areas within their limits. Both radiance intensity and average radiance reflect values characterizing each oil area, serving as crucial indicators of the impact on the natural environment.

Night luminosity and oil production

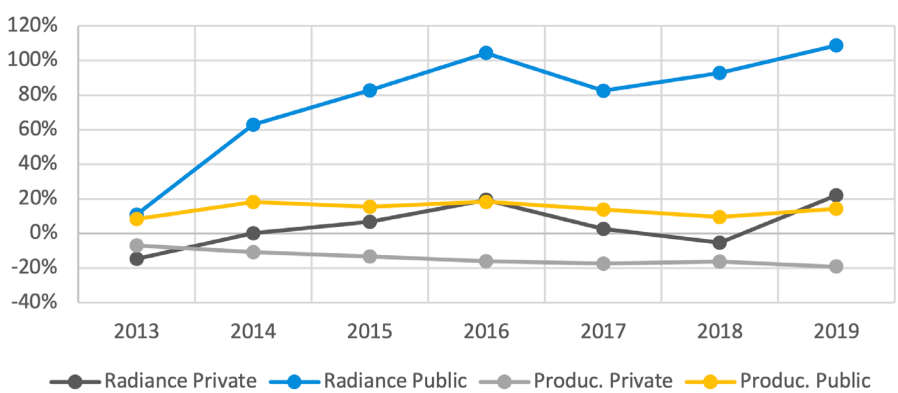
As explained, the relationship between oil activities and night luminosity has been explored through the brightness indexes of each oil area, indicating a correlation between registered radiance level and oil production. The main oil production areas generally correspond to those emitting the greatest radiance, while areas under the Ministry of Hydrocarbons not currently exploited register mostly low or zero radiance values.

Examining the evolution of radiance intensity between 2012 and 2019 for areas assigned to operating companies, a distinction is observed between public and private companies. Radiance intensity within areas assigned to Petroamazonas, a public company, increased by 109%, whereas private companies only saw a 22% increase (Table 1).

To establish the relationship between radiance evolution and the volume of oil production, determination (r^2) and Spearman coefficients between radiant intensity and the volume of barrel production were calculated (Table 1).

Figure 5

Variation of the radiance intensity and the volume of production in millions of barrels per year by operating companies concerning the year 2012. Ecuador 2013-2018



Note. Own elaboration based on VIIRS images and data from the Central Bank of Ecuador (2020).

Table 1

The relationship between the evolution of oil production and radiance intensity. Ecuador 2012-2019

	Radiance Intensity (W/sr)		Evolution absolutes (W/sr)	Evolution %	Oil production (Millions of barrels)		Evolution absolutes (MoB)	Evolution %	R2 (radiance)	Spearman coeff.
Companies	**2012**	**2019**			**2012**	**2019**				
Public	120.876	252.343	131.467	109%	134	153	19	14%	0,57	0,77
Private	44.901	54.807	9.906	22%	51	41	-10	-19%	0,29	-0,40
Total	165.778	307.150	141.372	85%	184	194	9	5%	0,32	0,57

Note. OLS. Standard error 95 %.
Source. Own elaboration based on VIIRS images and data from the Central Bank of Ecuador (2020).

Excluding areas under the Ministry of Hydrocarbons, there was an 85 % increase in radiance intensity between 2012 and 2019, while crude oil production increased by only 5 % during the same period. This significant difference suggests that luminosity evolution is more independent and grows much faster than crude oil production.

Analyzing data by companies, areas operated by Petroamazonas, a public company, showed a correlation coefficient (R^2) of 0.8 between production volume and radiance intensity from 2012 to 2017, decreasing to 0.6 when considering data until 2019. Despite an increase of 109 % in radiance between 2012 and 2019, oil production only increased by 14%. This implies that even a slight increase in production can generate a substantial radiance impact (Figure 3).

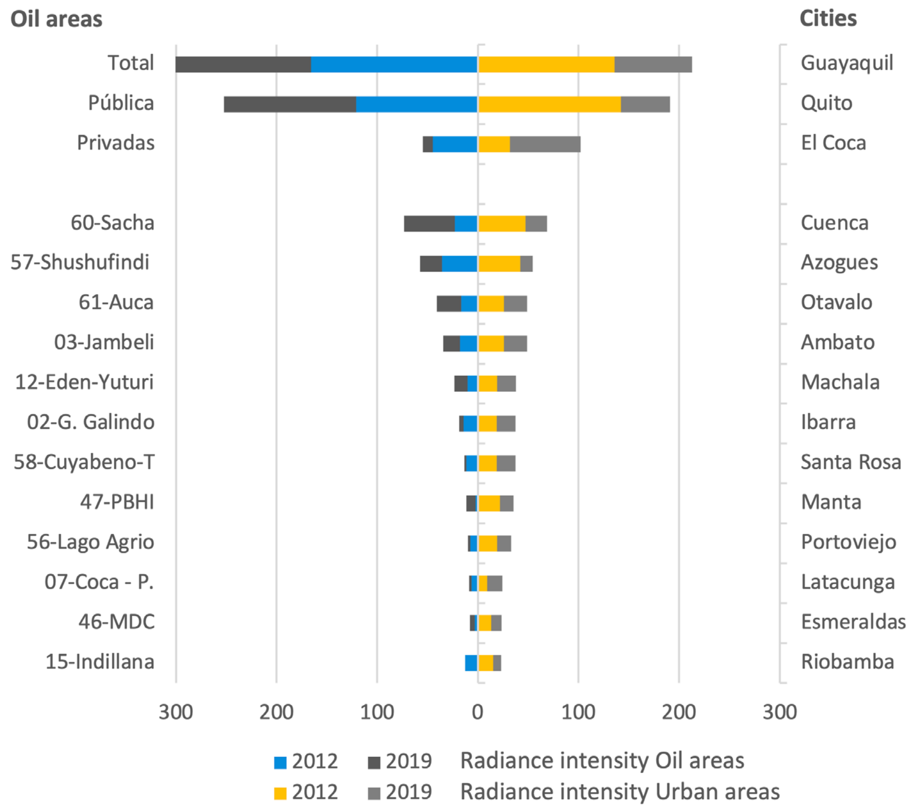
Areas managed by private companies exhibited different behavior, with a low r^2 coefficient. The production of these areas decreased by 19%, while radiance intensity increased by 22%, indicating that radiance evolution remained relatively stable with a slight increase compared to a slight decrease in crude oil production (Figure 4).

It is essential to consider that differences observed between areas managed by different companies are not solely related to total production but also to other factors, such as well conditions, drilling frequency, technology use, and more. In this regard, private companies have generated less light pollution than public entities. This could be attributed to stricter oversight or adherence to specific standards required for obtaining operational permits.

Additionally, the evolution of radiance is related to crude oil prices. Over the period 2012 to 2019, the r^2 coefficient between price per oil barrel and radiance intensity is 0.78, with a correlation coefficient of -0.88, indicating an inverse relationship. When oil prices decrease, radiance intensity tends to increase, and in turn, as mentioned in the previous paragraph, production increases. The observed trend aligns with the country's clear dependence on income generated by this extractive activity, especially during periods of lower oil prices, emphasizing the impact on luminosity evolution in oil areas. In this sense, it can be intuited that when oil prices drop, companies and governments in oil-producing countries often ramp up production to maintain revenue levels despite lower prices per barrel. This increased activity in oil extraction and related industries requires more energy, leading to a rise in radiance intensity. Consequently, this heightened production has a noticeable impact on the evolution of light pollution (or radiance) in regions where oil extraction is a major activity.

Figure 6

Evolution of the radiance intensity by oil areas and cities. Ecuador 2012-2019



Note. Own elaboration based on VIIRS images.

Luminosities with urban intensities

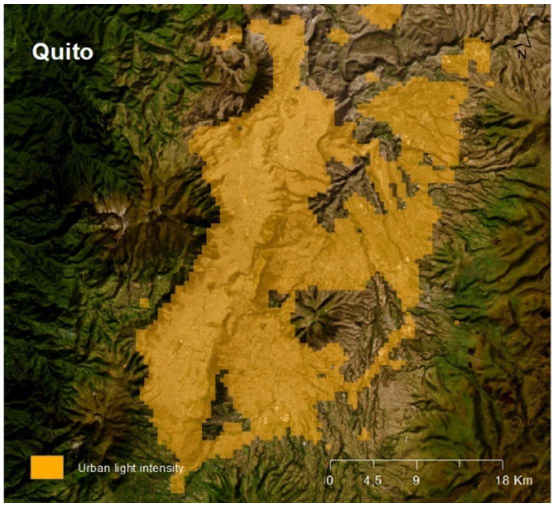
To provide an overview of light pollution in Ecuador, a comparative analysis was conducted between oil areas and the country's main cities. The radiance intensity of cities was calculated by considering the centroids of the main settlements identified in the National Plan of Development (PNBV, 2012). Circular areas with a radius of 25 km were generated from these centroids, and radiance intensity values were extracted from nighttime images.

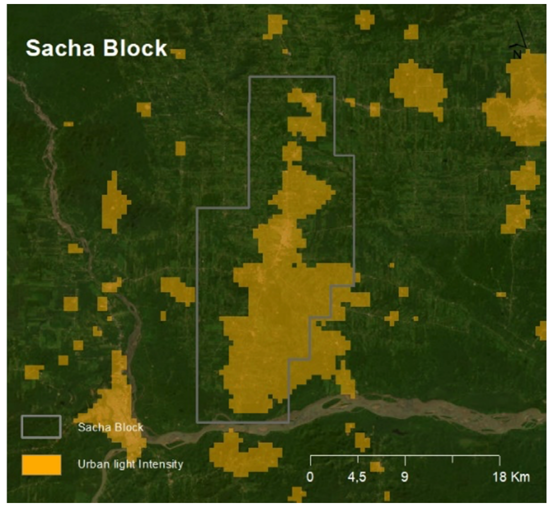
The analysis revealed that the radiance intensity in main cities increased by 56 %, compared to an 85 % increase in oil production areas. This indicates that the radiance in oil areas has increased at a higher rate than in the main Ecuadorian urban centers. In a more detailed analysis, territories linked to extractive uses showed radiance values comparable to those generated by the main populated centers in the country.

Results highlighted that metropolitan areas like Quito and Guayaquil emit less radiance than oil areas assigned to the Ecuadorian Public Company. However, the latter's impact on the natural environment is considerably more significant due to the distribution of light emission over habitats of abundant biodiversity, such as the Amazon (Figure 5, Figure 6, Figure 7).

Figure 7

Surfaces with urban radiance intensity, Quito and Area 60





Source. VIIRS and ARCH, own elaboration.

Compared with urban areas without oil inclusions, it was found that some local and small cities related to oil extraction zones emit higher radiance values than the country's most important cities. Territorializing luminosity values, areas reaching an 'urban' luminosity threshold of 6 nW/cm^2/sr were visualized. This threshold encompasses surfaces with native forests, small cultivation plots, and grasslands. The analysis revealed that due to the high radiance levels recorded in these soils, there is excessive light scattering, indicating an impact of oil areas beyond their strict surface limits.

The luminosity impact on oil areas was like that of urban areas, as evidenced by comparing surface evolution with urban light intensities. The surface with urban radiance in oil areas increased by 192 % between 2012 and 2019, while in the main settlements of the country, the increase was 38 % (Table 2). This indicates that the consumption of land through light in areas related to crude oil extraction is much higher than the urbanization process in major Ecuadorian cities.

Table 2

Evolution of surfaces with urban intensities

	2012 (km^2)	2019 (km^2)	2018 (increase in km^2)	% Increase
Urban settlements				
Urban Areas	2113,5	2924,8	811,3	38 %
Oil Areas				
Public	263,1	835,7	572,6	218 %
Private	63,4	118,6	55,2	87 %
Total	326,6	954,3	627,8	192 %

Note. VIIRS and own, own elaboration.

In summary, the results emphasize that urban brightness in oil areas serves as an indicator of light scattering, significantly increasing and establishing that the surface with urban luminosity in oil areas more than doubles that of urban areas located in the rest of the country.

Conclusions and Policy Implications

This research highlights the significant environmental impact of oil extraction activities in Ecuador, particularly light pollution. Despite the relatively small surface area occupied by oil infrastructures, the study reveals that the effects on the natural environment extend far beyond their physical limits. The key conclusions and policy implications are summarized as follows:

1. **Exponential increase in light pollution:** The study demonstrates an exponential increase in light pollution in oil areas over the past seven years. Radiant intensity has increased by 85%, significantly outpacing the 5 % increase in crude oil production. This indicates that the patterns of brightness escalation exceed those of oil volume production. Even though the increase in oil production has been slight, and even in the case of private companies, it has been reduced, the operational activities that have generated the amount of light emitted have increased. This phenomenon may result from factors related to the energy demand required to extract oil from a source that is becoming increasingly depleted, the reduction in the efficiency of the equipment, changes in the procedures applied, etc. In any case, the activities generally increase pollution in a territory with a high environmental value. Following this line of research, It has been proved that light is a stress factor (Aubrecht et al., 2010) that alters the natural cycle of the ecosystem (Gaston et al., 2014)

2. **Light impact beyond infrastructure:** The study quantifies the areas affected by light intensities comparable to major urban centers. Oil areas such as Sacha, Shushufindi-Libertador, and Auca generate significant light pollution, illuminating large swaths of non-artificialized soil. The impact of extractive activities spreads beyond the immediate areas occupied by oil infrastructure. This underscores the need to analyze oil extraction's comprehensive costs and impacts, considering environmental, ecological, and social impacts.

3. **The magnitude of light impact:** Areas with urban luminosity within oil zones have nearly tripled (192 % increase) in the analyzed period, while urban areas experienced a much lower increase (38 %). This suggests that the dispersion of light in oil areas is growing at a much higher rate than in major urban centers. This means that the increase rates in areas with typically urban light intensity far exceed those recorded in urban areas. Furthermore, it has been shown that despite the relatively small surface area occupied by extraction infrastructures, the effects that they cause on the natural environment far exceed their limits. This reflects the impacts of global trends, such as the continued demand for oil. In this sense, the study allows us to appreciate how political and economic decisions change the landscape and alter the natural ecosystem.

4. **Methodological potentials:** The research demonstrates the potential of using nighttime satellite images and tested procedures to analyze the light impact of oil extraction activities. This methodology, relying on globally available data, can be applied to other areas to assess extractive activities' environmental consequences. More recent studies explore the ability of images to locate anthropogenic activities and their impacts (Zhao et al., 2020). Thus, this study aligns with research

that has related luminescence to the artificialization of soil (Checa Rius y Nel·lo, 2018; Henderson et al., 2003; Liu & Leung, 2015)

5. **Promoting sustainable policies:** The study advocates reconsidering territorial policies and anthropic uses governing oil extraction areas. It calls for a balance between environmental conservation and the exploitation of non-renewable resources to achieve sustainable social, economic, environmental, and territorial development. The research questions the sustainability and equity of the current extractive model, emphasizing the need for new models that prioritize protecting natural resources and encourage less environmentally aggressive activities.

The scientific contribution of this study lies in the fact that it analyses the impacts to which only limited attention is paid, although their effects have become increasingly intense and extensive on the territory. It addresses the impacts of non-urban astronomical uses corresponding to operational spaces linked to urban uses. Therefore, the results allow us to re-evaluate the impact of extractive activities and urge policymakers to go beyond purely economic considerations, prioritizing the responsible use of natural resources for the benefit of present and future generations. In addition to the results, the methodological aspect has great scientific relevance since it shows the potential for analyzing night-time satellite images, which offer us spatial and temporal indicators of light pollution.

Conflict of interest

The author has no conflicts of interest to declare.

Authorship Statement

Verónica Mejía: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing-original draft, Writing-review & editing.

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