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Roads illuminate development: Using nightlight luminosity to assess the impact of transport infrastructure

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The research aims to evaluate the impact of paved major roads on economic growth at the municipal level in Bolivia, Paraguay and Ecuador. Due to the absence of municipal information, publicly available satellite data are used to construct a municipal panel dataset on a yearly basis from 2000 to 2013; particularly, nightlight luminosity is adopted as a proxy for economic activity. Methodologically, empirical evidence is obtained regarding the effect of having access to a paved major road on luminosity, as well as the elasticity between GDP and nightlight luminosity; both estimates are then linked to approximate economic growth in benefited municipalities. The findings suggest that, on average, economic activity was 0.5% to 0.6% higher in municipalities that benefited from paved major roads than in municipalities that did not. The effects vary over time and are dependent on whether the benefited areas are located closer to the road or are part of a population center.

KEYWORDS
Luminosity, transport infrastructure, economic growth, satellite data

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Carreteras que iluminan el desarrollo: Uso de la luminosidad nocturna para evaluar el impacto de infraestructura de transporte

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La investigación tiene como objetivo evaluar el impacto de las principales carreteras pavimentadas sobre el crecimiento económico a nivel municipal en Bolivia, Paraguay y Ecuador. Debido a la ausencia de información municipal, se utilizan datos públicos de imágenes satelitales para construir una base de datos de panel a nivel municipal, con frecuencia anual para el periodo 2000-2013. En particular, la luminosidad nocturna es utilizada como proxy para medir la actividad económica. Metodológicamente, se obtiene evidencia empírica con relación al efecto del acceso a las rutas principales pavimentadas sobre la luminosidad nocturna, así como también de la elasticidad entre el PIB y la luminosidad nocturna; se vinculan ambas estimaciones para aproximar el crecimiento económico en las municipalidades beneficiadas. Los resultados sugieren que, en promedio, la actividad económica fue superior entre 0,5 % y 0,6 % en los municipios que se beneficiaron con carreteras pavimentadas, en comparación con los municipios no beneficiados. Los efectos varían en el tiempo, según la cercanía de las áreas beneficiadas a la ruta pavimentada y dada su pertenencia a centros poblados.

KEYWORDS
Luminosidad, infraestructura de transporte, crecimiento económico, datos satelitales

1 | INTRODUCTION

Fay et al. (2017) examine the status of infrastructure in Latin America and the Caribbean (LAC) and assert that the region *"does not have the infrastructure it needs or deserves given its income level. Infrastructure also falls short of what is needed to advance social integration and achieve higher growth and prosperity. Moreover, the region's infrastructure does not correspond to the aspirations of its growing middle class"* (p. 7). Furthermore, they note that *"the transport sector is where Latin America most underperforms its peers. This is partly due to the region's low population density, which makes it extremely hard to affordably develop a dense transport network. Latin America's paved road density is similar to that of Africa ..."* (p. 10).

Indeed, Selod and Soumahoro (2018) state that countries in LAC continue to have low road density and poor road quality, which results in rural regions lacking access to transport infrastructure and cities experiencing severe congestion.[1]

In addition, a variety of internal and external factors influence how governments address shortcomings in transport infrastructure. As a result, some nations outperform others in terms of coverage, quality, safety, and environmental stewardship; others fall behind, and disparities expand not just in comparison to advanced economies, but also to the average Latin American performance (Chauvet and Baptiste, 2019).

With a focus on South America, the examples of Bolivia, Ecuador, and Paraguay are worth examining since they have historically trailed behind in terms of transport infrastructure development; however, they have made significant strides over the past decade. For instance, until 2000, just 13 % of the total road network in Paraguay was paved. Similarly, by 2004, the proportion of paved roads in Bolivia and Ecuador was 7 % and 14 %, respectively; these percentages were among the lowest in South America. Moreover, some estimates indicate that roughly 80 % of these three countries' total road networks remained unpaved by 2011 (Kohon, 2011).[2]

Although road infrastructure in these nations was relatively limited at the onset of the 2000s, significant progress has been made in the last 20 years, particularly in the development of paved main highways. For example, by 2019, almost half of Bolivia's primary road network has been paved, and roughly 77 % of the national roads in Paraguay have been asphalted by 2016.[3]

Furthermore, the previous accomplishments are the result of several financial and management initiatives undertaken by the governments of Bolivia, Ecuador, and Paraguay. Nonetheless, it is worth noting that their endeavors were accompanied by significant foreign finance aiming to augment physical capital on transport infrastructure, primarily from the Development Bank of Latin America (CAF). As a matter of fact, Bolivia, Paraguay, and Ecuador are the top recipients of CAF financing for road projects that connect two or more Integration and Development Hubs, according to the South American Council for Infrastructure and Planning (COSIPLAN).[4]

The literature reveals that road construction stimulates economic growth via a diversity of channels, including reduced transportation costs, increased access to productive inputs

[1] As reported by the 2019 Global Competitiveness Report of the World Economic Forum, Bolivia and Paraguay remain among the countries with the weakest road infrastructure quality in South America.

[2] The total road networks account for primary (national), secondary (departmental or provincial), and tertiary (municipal, community, or neighborhood) roads.

[3] Data are sourced from Bolivia's Instituto Nacional de Estadísticas, and Paraguay's Ministerio de Obras Públicas y Comunicaciones.

[4] As defined by COSIPLAN, an Integration and Development Hub is a transnational geographical region containing specialized natural resources, human settlements, production zones, and logistics services. Transport infrastructure acts as a link, allowing people, goods, and services to flow freely inside this geographical region as well as to and from the rest of the globe.

and technology, expansion of agricultural and non-agricultural output, and an increase in labor demand, among others. For the specific case of LAC, infrastructure would be a synonym of competitiveness, development, economic boost, and integration, while also gradually becoming synonymous with quality of life, democracy, equity, and social inclusion (Serebrisky, 2014).

Yet, there is scant evidence in the literature about the impact of transport infrastructure on the economic activity of Bolivia, Ecuador, and Paraguay; particularly true when analyzing at the subnational level. This is mainly explained by the fact that those nations lack data on economic growth metrics such as Gross Domestic Product (GDP) and others at a highly disaggregated subnational level (e.g., for municipalities or communities).

Therefore, the purpose of the study is to assess the impact of paved major roads on economic growth at the municipal level in Bolivia, Paraguay, and Ecuador. The absence of municipal information is addressed by using publicly available satellite data to characterize municipalities and construct a panel dataset on a yearly basis from 2000 to 2013. In particular, nightlight luminosity measured from space is adopted as a proxy for economic activity.

The content of this study not only fill a void in the literature by evaluating the impact of the paved major roads built in Bolivia, Ecuador, and Paraguay on subnational economic growth, but also serve as a methodological framework for creating panel data with a high degree of geographical and temporal disaggregation exploiting data collected from satellite imagery, which is especially valuable for economies with limited information.

2 | LITERATURE REVIEW

Numerous research on the benefits of transport infrastructure have shown that road upgrades have contributed to economic growth and poverty reduction through a variety of mechanisms (Lokshin and Yemtsov, 2005; Van de Walle, 2002). Additionally, enhanced road connection correlates with increased access to markets and technology, which raise agricultural and non-agricultural productivity by augmenting input availability and decreasing input prices (Binswanger et al., 1993; Khandker et al., 2009), as well as rural enterprise growth (Lokshin and Yemtsov, 2005). Likewise, investment on road improvements leads to gains in productivity and labor demand (Leinbach and Cromley, 1983), while also enhancing education and health (Bryceson and Howe, 1993; Levy, 1996).

On the other hand, when it comes to the literature on the use of satellite nighttime lights as a proxy for economic activity, the study conducted by Henderson et al. (2012) is the one that serves as the primary reference. As part of their research, the authors build a multi-country panel database that incorporates data on GDP and nightlight luminosity captured by satellites. Their findings reveal that fluctuations in luminosity and economic growth are substantially connected, with evidence indicating that luminosity is a suitable proxy for changes in economic activity in the long run.[5]

The adoption of satellite-based luminosity data for applications such as impact evaluations of transport infrastructure is a relatively new field in the literature. Khanna (2016) examines how economic activity in areas linked to India's four main cities is influenced by transport networks and finds that territories located closer to these cities would have enjoyed faster economic growth than those placed farther away; nighttime lights collected in satellite images is used as a proxy variable to assess the increase in economic activity. Alder (2016) evaluates India's most recent road projects, which have enhanced connectivity between the country's four economic hubs, and utilizes luminosity data to determine the

[5]The terms nighttime lights, nightlight luminosity and luminosity are all used interchangeably throughout the document.

effect of those improvements on the revenue at district level; his results imply that the construction of highways boosted aggregate economic activity, yet benefits vary across regions.

Likewise, Storeygard (2016) investigates the repercussion of intercity travel expenses on incomes in Sub-Saharan African cities. In the absence of longitudinal data on economic growth at the local level, the author approximates economic activity fluctuations using satellite luminosity data. The results suggest that cities situated near major ports earn 6 % more than those located farther away.

Employing a sample of 632 of the world's largest cities, Gonzalez-Navarro and Turner (2018) show that cities that have invested in public transportation systems, such as subways, have a more dispersed distribution of luminosity, reflecting a better distribution of economic activity.

Corral and Schling (2017) conducted the first research in Latin America to study the effect of infrastructure investment on economic growth using nighttime lights as a proxy for economic activity. They found evidence that, in the long run, GDP per capita would be greater in coastal regions of Barbados that benefited from stabilizing infrastructure investment, compared to those that did not.

One of the papers with close resemblance to the current study is that of Mitnik et al. (2018) on the case of Haiti. The authors exploit the strong association between luminosity and economic activity to assess the effect of road building on GDP growth at a community basis. Essentially, they correlate changes in GDP growth with fluctuations in luminosity that occur in areas that benefited from road construction. Among their findings is that beneficiaries of road sections have boosted their luminosity by an average of 6 % to 26 %, compared to non-beneficiaries, implying an average GDP rise of between 0.5 % and 2.1 %.

In similar fashion, Bolivar (2020) explores the economic impact of highways on Bolivian communities. The author uses remote sensing data and administrative records to describe communities across time and, for instance, satellite data on nighttime lights is utilized as a proxy for economic activity. According to his findings, paved roads would have fostered not only economic growth (on average, GDP would have increased by 0.5 %), but also agricultural output, urban sprawl, and poverty alleviation.

3 | MAJOR ROADS FOR DEVELOPMENT

3.1 | Major Roads in Bolivia, Ecuador, and Paraguay

As has been well documented in the literature, roads are key infrastructure for socioeconomic development because they lower transport costs and improve access to markets, technologies, and input availability. Besides, they enhance productivity and labor mobility, resulting in higher income and improved population education and health.

Figure 1 depicts the causal chain of road construction based on evidence gleaned from the scientific literature.

In general, the largest benefits of road investments are shown in large-scale projects, namely those that connect cities or towns to a national road network with high mobility for both commodities and people. Table 1 summarizes the major road networks in Bolivia, Ecuador, and Paraguay that match the aforementioned criteria.

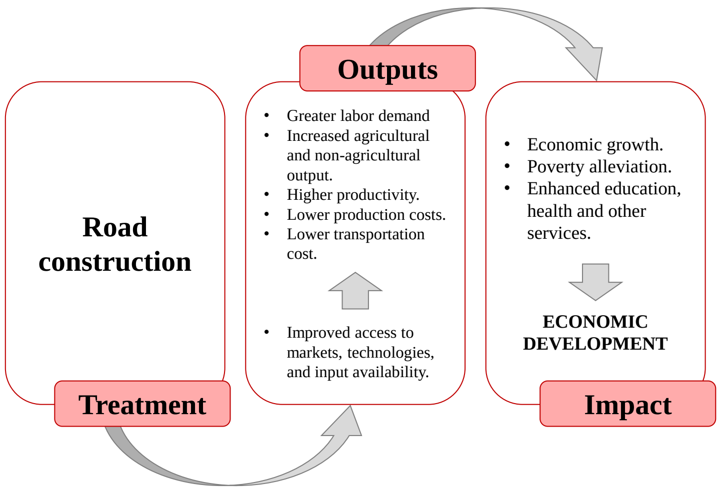

FIGURA 1 Causal chain of road construction. *Source:* Own elaboration.

CUADRO 1 Major roads in Bolivia, Ecuador, and Paraguay

Country	Major Roads	Detail
Bolivia	Red Vial Fundamental	It is composed of roads that connect the departments' political capitals; provide international connectivity by linking to other nations' existing major highways; connect two or more roads of the fundamental network (Red Vial Fundamental) at suitable places; and adhere to environmental protection standards.
Ecuador	Red Vial Estatal	It is the network of highways with the largest volume of vehicle traffic that connects province capitals, canton urban centers, international border ports with or without customs, and large and medium-sized business areas.
Paraguay	Rutas Nacionales	This is a selection of highways that originate in the Republic's capital and enter or cross a large portion of the country's interior; cross two or more departments and/or connect departmental capitals or first category municipalities; are destined to become regional integration road corridors of the Southern Common Market (MERCOSUR for its Spanish initials) due to geopolitical and/or socioeconomic considerations; and link to the State's national ports.

Source: Bolivia's Administradora Boliviana de Carreteras, Ecuador's Ministerio de Transporte y Obras Públicas, and Paraguay's Ministerio de Obras Públicas y Comunicaciones.

The central governments of all three countries are responsible for the management of these networks. For the sake of convenience, they shall be referred to as "major roads"for the remainder of this document. Figure 2 superimposes the major roads on the geographical maps of Bolivia, Ecuador, and Paraguay, showing whether they are paved or not as of 2013.

In this regard, road investments account for a large proportion of any government's

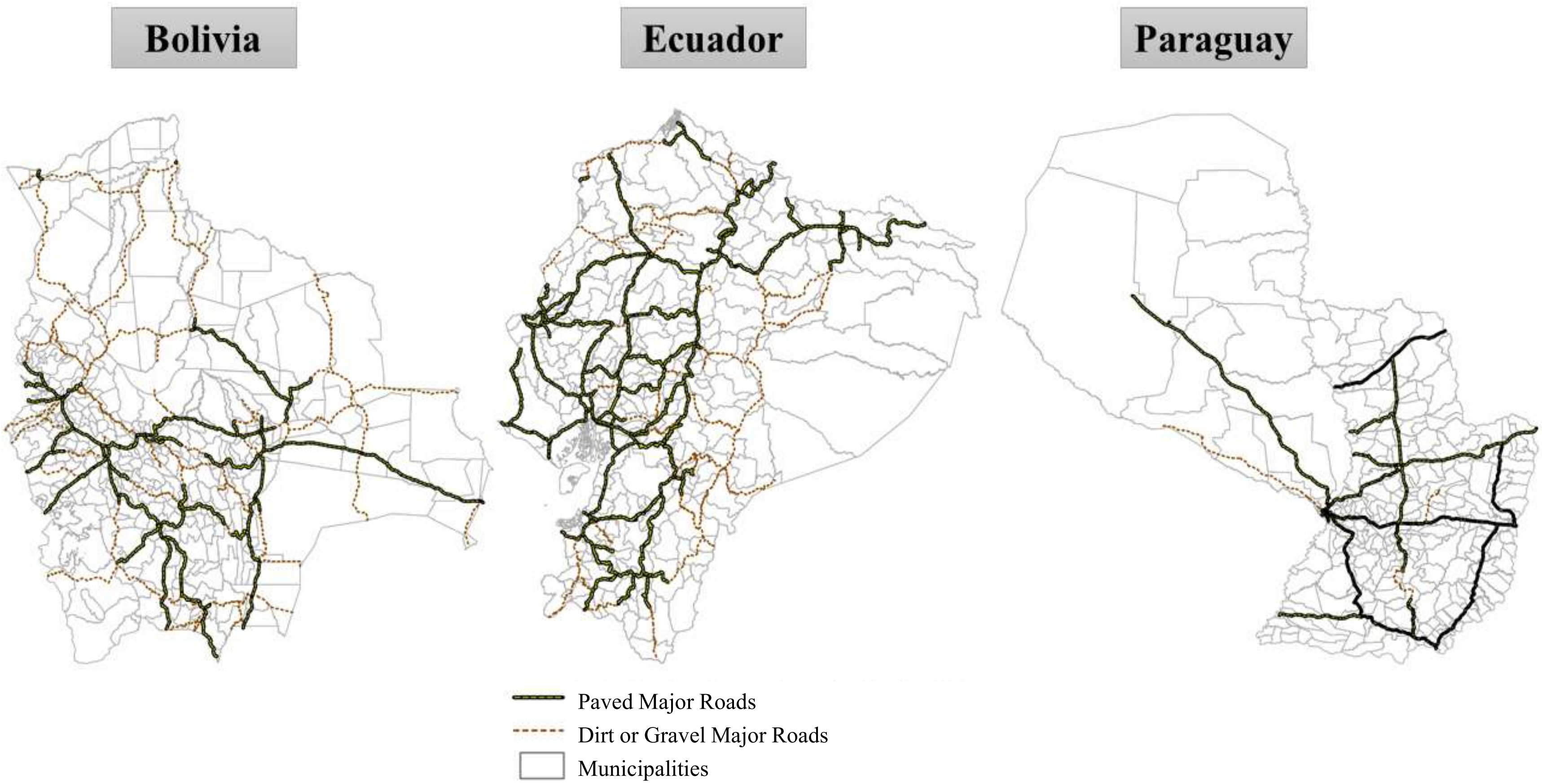

FIGURA 2 Paved Major Roads in Bolivia, Ecuador, and Paraguay, 2013. *Source:* Own elaboration based on Geographic Information Systems from Bolivia's Administradora Boliviana de Carreteras, Ecuador's Ministerio de Transporte y Obras Públicas, and Paraguay's Ministerio de Obras Públicas y Comunicaciones.

budget, since they are a necessary precondition for economic growth, integration, and development. Roads stimulate economic growth in the areas they travel through and are critical to the process of national integration and connection with adjacent nations.

Between 2000 and 2017, noticeable expenditures and upgrades have been observed regarding major roads in these three countries, resulting in the expansion of the the network's overall size and the coverage of pavement surface (See Table 2).

CUADRO 2 Major Roads Investments in Bolivia, Ecuador, and Paraguay

Country	Year	Network size† (Kilometer)	Investment 2000-2017†† (USD millions)
Bolivia	2016	16,343	5,038
Ecuador	2010	9,660	791
Paraguay	2019	8,767	4,008

Source: (†) Bolivia's Administradora Boliviana de Carreteras, Ecuador's Ministerio de Transporte y Obras Públicas, and Paraguay's Ministerio de Obras Públicas y Comunicaciones. (††) South American Council for Infrastructure and Planning (COSIPLAN).

According to the Council of Road Directors of Iberia and Ibero-America (DIRCAIBEA)[6], Bolivia's Red Vial Fundamental had a total length of 15,847 kilometers (km) in 2006, with just 27 % of these paved. Nonetheless, by 2016, the Red Vial Fundamental had grown to 16,343 km in length (i.e., new roads have been added to the network), with 60 % of the network being paved, as per the Administradora Boliviana de Carreteras. Furthermore, congruent with data from COSIPLAN,[7] USD 5,038 million was invested in Bolivia as part of the Initiative for the Integration of Regional Infrastructure in South America (IIRSA) between 2000 and 2017, with 23 road projects completed, which illustrates the magnitude of investments in this sector.

In the instance of Ecuador, the Red Vial Estatal reached a total length of 8,653.5 km in 2001, with 75 % of the routes paved (DIRCAIBEA). By contrast, Ecuador's Ministerio de Transporte y Obras Pblicas reported that the major road network was 9,660 km long in 2010. Additionally, according to COSIPLAN estimates, between 2000 and 2017, a total of USD 791 million was invested in 11 IIRSA road projects in Ecuador.

Finally, DIRCAIBEA reports that paved national roads accounted for 38 % of Paraguay's total road network in 2007. Based on the official statistics from the Ministerio de Obras Públicas y Comunicaciones, the network is now 8,767 km long, with 57 % of it being paved.

3.2 | Sample of Major Roads for Impact Evaluation

The aim of the research is to assess the impact of paved major roads on economic growth at the municipal level in Bolivia, Paraguay, and Ecuador. Accordingly, the first step is to choose a representative sample of major roads for evaluation. The sample of major roads is defined as follows:

[6] DIRCAIBEA is a forum that brings together the administration of the roads of the region to exchange experiences and knowledge on road infrastructure. Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay, and Venezuela are the members of the forum. The data were taken from a variety of this council's reports and publications.

[7] The information is derived directly from the IIRSA COSIPLAN Project Information System. The COSIPLAN Project Portfolio is updated on an annual basis by the twelve South American countries.

- The universe of major roads in the countries of Bolivia, Ecuador, and Paraguay is used as a starting point for this inquiry.
- The year in which pavement of these roads was completed is defined in segments (i.e., pavement is built progressively by specific proportions of large-scale roads). This characterization is based on administrative reports from each country's government agencies and a visual examination of Landsat 7 satellite images, which are combined to identify when the surface of a major road segment switch from dirt to pavement.
- Since impact evaluation methods are applied in the study, the sample of major roads is designed in a manner that allows for the identification of treatment units (i.e., beneficiaries of paved major roads) and control units (i.e., those that have not benefited from the treatment). Further, the sample of major roads could be divided into three groups based on available data, treatment conceptualization, temporal and spatial variability in major road pavement construction, and the requirement that any unit of observation benefited from treatment at the outset of the analysis period (Sections 4 and 5 include further information):
  i. ***Major roads to define treatment units:*** These are major roads that were paved between 2004 and 2013.
  ii. ***Major roads to identify control units:*** These are major roads that remained dirt or gravel until 2013.
  iii. ***Major roads to exclude benefited observation units before the analysis period:*** These are major roads that were paved prior to 2004.

Figure 3 depicts the sample of major roads for Bolivia, Ecuador, and Paraguay. In addition, Appendix A details the dates of pavement completion for the sample of major roads by segments constructed between 2004 and 2013.

4 | DATA, STUDY SAMPLE, AND TREATMENT

Many Latin American countries, as well as other countries in the developing world, have restrictions on data generation and access. At the subnational level, one of the recurrent issues is a shortage of indicators with long time series and high frequency. In the case of economic activity metrics, such as GDP, they are available in historical series and at a relatively high frequency at the national level; in the best-case scenario, statistics are disaggregated at the departmental or provincial level. However, any GDP series or other statistics about economic activity are available when research is done at smaller subnational levels, like municipalities.

Given that the aim of the research is to estimate the effect of paved major roads on economic growth at the subnational level in Bolivia, Paraguay, and Ecuador, it is crucial to obtain statistics on the progress of economic activity that are highly disaggregated in time and space. Additionally, information on the road's pavement completion status and the characteristics of the beneficiaries is requested.

To accomplish these goals, a database is generated using primary data from satellite images and processed with remote sensing techniques. Remote sensing enables the acquisition of information about objects or processes within the Earth's system through the measurement of electromagnetic energy reflected or emitted by them via images from space platforms (e.g., satellites). Thus, satellite images are digital images[8] comprised of a matrix

[8]Digital images are produced by an electronic sensor and, since they are digital, they can be processed by a computer, which opens up a variety of analytical possibilities. On the other hand, a picture taken on photographic film is incompatible with computer processing; the latter instance necessitates a pre-processing

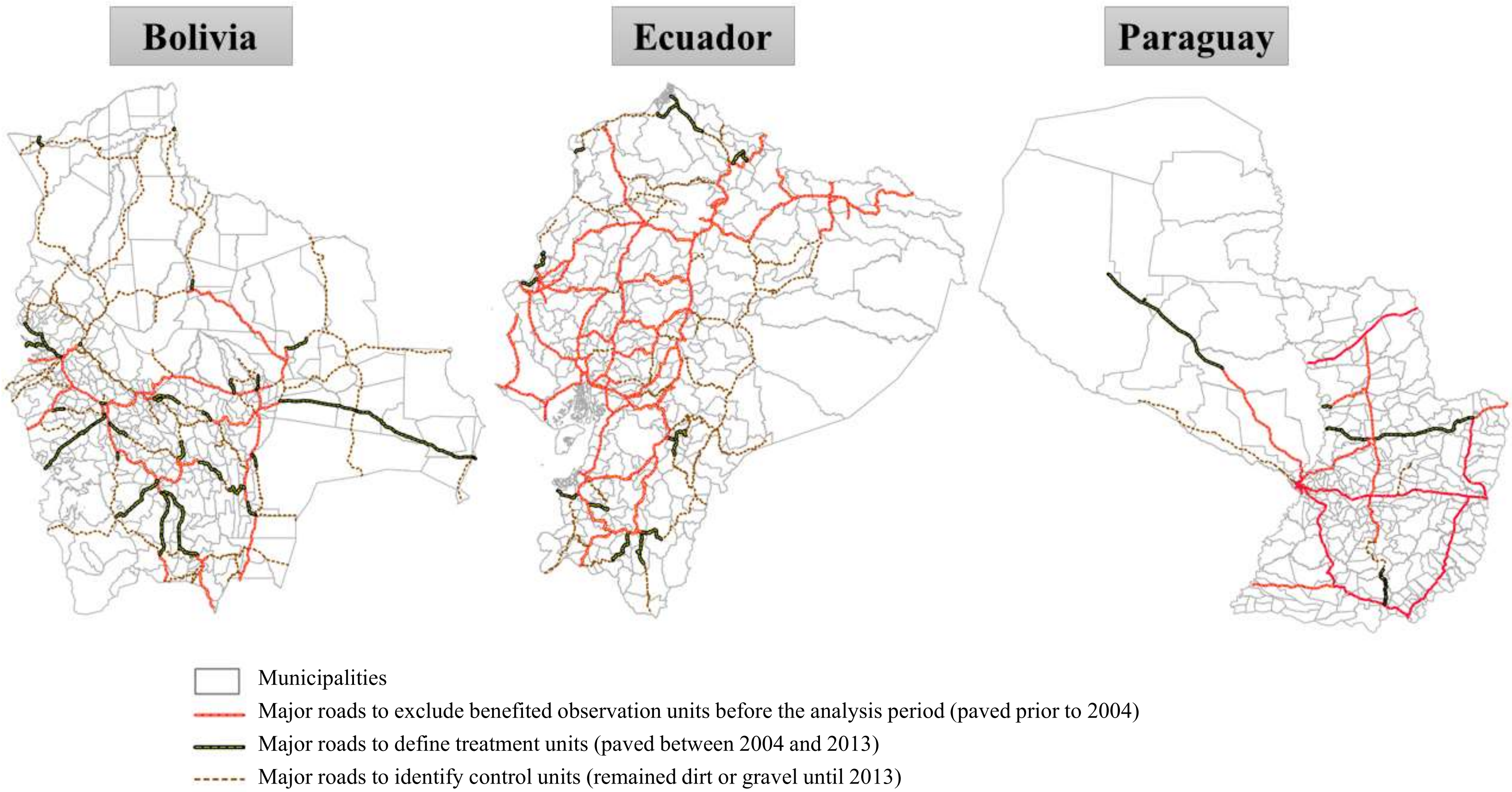

FIGURA 3 Sample of Major Roads for Impact Evaluation. *Source:* Own elaboration based on Geographic Information Systems from Bolivia's Administradora Boliviana de Carreteras, Ecuador's Ministerio de Transporte y Obras Públicas, and Paraguay's Ministerio de Obras Públicas y Comunicaciones.

of elemental points (pixels) collected with remote sensing devices and used to calculate the quantity of electromagnetic energy reflected per unit area at certain wavelengths (bands of the electromagnetic spectrum).

The treatment and, consequently, the sample of study are established using this information together with the dates of pavement completion for segments of major roads. The next subsections cover in further detail how the database was developed, as well as the study sample and treatment definitions.

4.1 | Data

The following process was implemented to create the database:

STEP 1. Satellite images covering the national areas of Bolivia, Ecuador, and Paraguay were downloaded. These images include information on the following:

- ***Nightlight Luminosity.*** Recall the study underlies on the assumption that the variation in nighttime lights is a well suited proxy for economic growth (Henderson et al., 2012).[9] Nightlight luminosity imagery is generated by the NOAA (National Oceanic and Atmospheric Administration) satellite and the US Defense Meteorological Satellite Program's (DMSP) Operational Linescan System (OLS). From 1992 to 2013, annual luminosity data with a spatial (pixel) resolution of 927.67 meters is available. The luminosity of each pixel is represented by an index between 0 and 63, with 0 denoting no luminosity and 63 representing maximum intensity. Each of these annual values is derived by averaging the luminosity levels seen in cloud-free satellite images taken throughout the year.
- ***Land Cover:*** The images were obtained from the MODIS Land Cover Type Yearly Global 500m product (MCD12Q1), which provides global maps of land cover at yearly time steps with a spatial resolution of 500 meters for the period 2001–present (Friedl and Sulla-Menashe, 2015; Sulla-Menashe and Friedl, 2018). The MCD12Q1 International Geosphere-Biosphere Programme (IGBP) legend is adopted to define 17 land cover categories, including forests, scrublands, savanna, grasslands, crops, urban areas, bodies of water, and barren zones. Correspondingly, each pixel has a dominating land cover assigned to it.
- ***Normalized Difference Vegetation Index (NDVI):*** This is a vegetation index that is used to quantify the amount, quality, and growth of vegetation based on the intensity of radiation emitted or reflected by the vegetation in certain bands of the electromagnetic spectrum.[10] For the period 2000–2013, images were collected annually at a spatial resolution of 30 meters from the Landsat 7 Collection 1 Tier 1 Annual NDVI Composite.
- ***Climatic conditions:*** From several sources, raster files providing data on monthly climatic conditions were gathered.[11] These were processed to produce images with a spatial resolution of 927.67 meters and aggregated on the following indicators yearly from 2000 to 2013:
  i. Total annual precipitation (mm/pentad).

step of converting the photograph to a digital image.

[9] Section 6.1 discusses the link between GDP and nighttime lights in further depth for the objectives of this study.

[10] The Normalized Difference Vegetation Index is generated from the Near-IR and Red bands of each scene as $(NIR - Red)/(NIR + Red)$, and ranges in value from −1,0 to 1,0.

[11] Sources of information are: TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces; MODIS/Terra Land Surface Temperature; and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). Abatzoglou et al. (2018) and Funk et al. (2015) for more detail.

ii. Average annual temperature (degrees Celsius).
iii. Average annual wind speed (meters/second).
iv. Palmer Drought Severity Index (negative values are associated with drought and positive values with higher humidity).[12]

- ***Landsat 7 imagery:*** Monthly images with a spatial resolution of 30 meters from the Landsat 7 program were downloaded. Due to the yearly nature of the analysis in this research, annual data for each multispectral band is developed by calculating the median of the monthly results for each pixel. Thus, annual raster files were created from 2000 to 2013.[13]

STEP 2. Given that satellite imagery data are comprised at the pixel level, a grid with 927.67 meters spatial resolution is structured inside the Bolivian, Ecuadorian, and Paraguayan geographic extensions to extract data from the downloaded images. The pixel size of 927.67 meters is defined in accordance with the spatial resolution of the luminosity images.

STEP 3. For each year of the study period, the downloaded satellite images are overlaid on the grid (explained in STEP 2), and the values of the indicators are extracted for each pixel. Thus, a vector file with a spatial resolution of 927.67 meters is constructed that spans the territories of Bolivia, Ecuador, and Paraguay and contains data on luminosity, land cover, NDVI, precipitation, temperature, wind speed, and the Palmer Drought Severity Index for each year from 2000 to 2013. The grid has 1,912,995 pixels in total (1,175,360 in Bolivia, 274,281 in Ecuador and 463,354 in Paraguay).

STEP 4. Given that the unit of observation is the municipality (details in 4.3), it is necessary to construct a database at the municipal level, but with the caveat that is filled with data collected up to STEP 3. To be more precise, the following operations are performed:

- ***Nightlight Luminosity:*** The sum of all individual luminosity levels (l_p) in pixels that overlap or are contained within the municipality's borders ($p = 1, \ldots, P$; where P is the total number of pixels that overlap or are included within the municipality's limits) is calculated to provide a nighttime lights indicator for the municipality (L_i).

$$L_i = \sum_{p=1}^{P} l_p \tag{1}$$

- ***Land Cover:*** The following municipal indicators are generated from the MCD12Q1-IGBP land cover categories:
  i. Forest area (Km^2)
  ii. Shrubland area (Km^2)
  iii. Savanna area (Km^2)
  iv. Barren area (Km^2)
  v. Water bodies area (Km^2)
  vi. Urban area (Km^2)
  vii. Crops area (Km^2)
  The area of each land cover within a municipality ($A_{c,i}$) is estimated by multiplying 0.86 (since each side of the pixel is 0.92767 km, the area is 0.86 km^2) times the total

[12] The Palmer Drought Severity Index quantifies the severity, duration, and geographic extent of drought. This index is calculated employing precipitation, air temperature, and local soil moisture readings, as well as historical values for these measures.

[13] Landsat is a constellation of satellites created and launched into orbit by the United States with the purpose of observing the Earth's surface at high resolution. Landsat 7 has a multispectral resolution of 30 meters and a panchromatic resolution of 15 meters; it includes eight bands: blue-green, blue, red, green, near infrared (NIR), SWIR1, IRT, SWIR2, and PAN.

number of pixels of cover c that fall inside its boundaries (P_c).

$$A_{c,i} = 0{,}86 \times P_c \tag{2}$$

- ***NDVI and climatic conditions:*** Municipal-specific NDVI and climatic conditions were derived by averaging the values of all pixels that overlapped or were included within municipal boundaries.

4.2 | Luminosity data transformations

According to the remote sensing literature, raw luminosity measurements exhibit a blurring or overglow effect. That is, the light released by certain regions, such as cities, often surpasses their respective spatial boundaries, inflating the genuine magnitude of luminosity levels, particularly in pixels near the light production core (Lawrence, 1997; Abrahams et al., 2018).

Another issue that arises when using raw luminosity data is oversaturation, since its values are restricted to a maximum of 63. This limitation restrain the temporal analysis since no fluctuation occurs over time for pixels starting the study period with the maximum luminosity index value.

To address the issues stated above, the literature suggests implementing intercalibration methods on the raw luminosity data. Accordingly, the techniques developed by Wu et al. (2013) are applied to intercalibrate each pixel of raw nighttime lights images covering Bolivia, Ecuador, and Paraguay across the study period.

The intercalibrated luminosity for each municipality ($\tilde{L}_i$) is then calculated as the sum of all intercalibrated pixels ($\tilde{l}_p$) that overlap or fall within its boundaries (p=1,...,P; where P is the total number of pixels that overlap or fall within the municipality's boundaries).

$$\tilde{L}_i = \sum_{p=1}^{P} \tilde{l}_p \tag{3}$$

As an illustration, Figure 4 shows the results of the intercalibration of luminosity levels at various points in time for the Municipality of Quito, Ecuador.

4.3 | Unit of observation and treatment

Given that the sample of major roads is already defined, the next step is to identify the subnational level (i.e., unit of observation) that benefits directly from the treatment. Consequently, the *"Municipality"* is stated as the unit of observation because major roads are primarily used to connect their major cities and towns.[14]

Moreover, in the spirit of all previous definitions, the treatment is described as:

"Having access to a paved major road for the first time between 2004 and 2013."

To put it another way, the treated units are the municipalities in Bolivia, Ecuador, and Paraguay that were the first to gain access to a paved major road between 2004 and 2013. It is worth mentioning again that municipalities that had benefited from a paved major road prior to 2004 were barred from participating in the study. Additionally, municipalities in

[14] Cantons and Districts are the names given to municipal units in Ecuador and Paraguay, respectively. In this document, the designation of Municipality is assumed for the sake of simplicity.

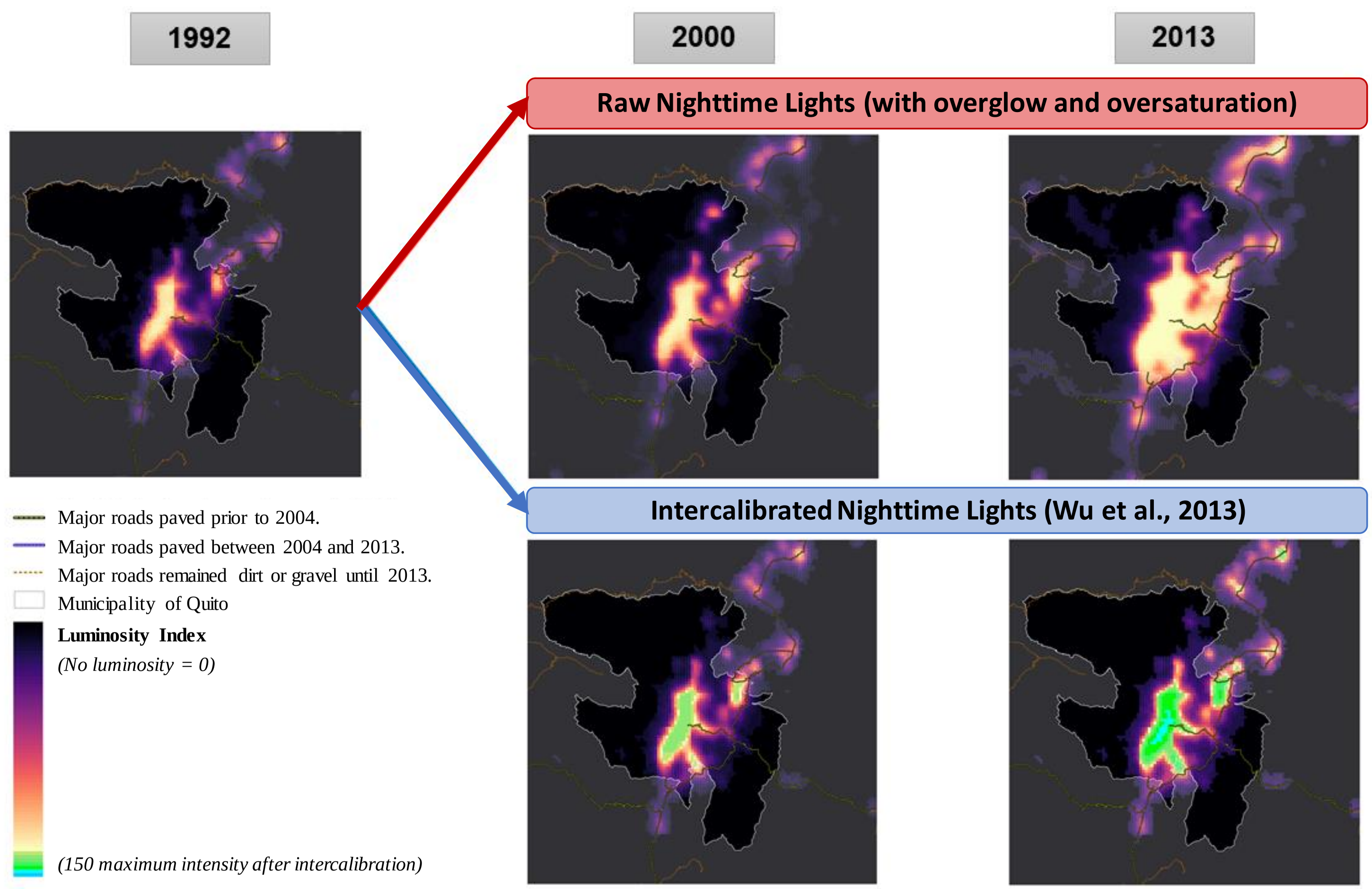

FIGURA 4 Intercalibrated Nighttime Lights: Municipality of Quito, Ecuador. *Source:* Own elaboration based on nightlight imagery from the National Oceanic and Atmospheric Administration.

these countries that did not have access to paved national roads until 2013 are assumed to serve as control units for the objective of conducting a counterfactual scenario.

4.4 | Study Sample

In summary, the study sample includes municipalities in Bolivia, Ecuador, and Paraguay that first benefited from paved major roads between 2004 and 2013, as well as municipalities that did not benefit from paved major roads until after that period. As a result, the sample comprises 479 municipalities. Although the three countries have a total of 815 municipalities, the research omitted 336 municipalities since they benefited from paved major roads prior to 2004.

Additionally, to ensure a somehow homogeneous group, the sample is limited to municipalities of medium and small size. That means, the research involves municipalities with populations of up to 30,000 inhabitants in 2000; about 95 % of the 479 municipalities mentioned above had populations below this level in 2000.[15] The population size constraint is based on data from 2000, since it is the first year of the study period and none of municipalities from the sample benefited with treatment.

Under the constraints outlined above, the final sample of municipalities consists of 446 municipalities spread throughout Bolivia, Ecuador, and Paraguay.[16]

CUADRO 3 Sample size by country and treatment status, 2000-2013

Year	Bolivia		Ecuador		Paraguay		Pool	
	Control	Treated	Control	Treated	Control	Treated	Control	Treated
2000	235	0	79	0	132	0	446	0
2001	235	0	79	0	132	0	446	0
2002	235	0	79	0	132	0	446	0
2003	235	0	79	0	132	0	446	0
2004	235	0	76	3	127	5	438	8
2005	215	20	76	3	122	10	413	33
2006	215	20	76	3	122	10	413	33
2007	209	26	71	8	122	10	402	44
2008	204	31	69	10	122	10	395	51
2009	201	34	66	13	121	11	388	58
2010	201	34	65	14	121	11	387	59
2011	199	36	64	15	114	18	377	69
2012	185	50	62	17	114	18	361	85
2013	179	56	62	17	114	18	355	91

Source: Own elaboration.

On the other hand, the analysis period is set to 2000–2013 in order to verify the reliability of the parallel trends assumption. Since difference-in-differences models are applied, it is guaranteed that, between 2000 and 2003, none of the municipalities in the sample are beneficiaries of paved major roads, thus the parallel trends assumption can be tested properly. Furthermore, the analysis period is bound to 2013 since the data on nighttime

[15] Population data was obtained from the National Statistics Institutes of Bolivia, Ecuador, and Paraguay.
[16] Most of these municipalities are rural, according to data from their National Statistics Institutes.

lights is only available up to that year.

Finally, Table 3 summarizes the sample size by country and their assignment to the treatment or control groups over the study period. Appendix B contains maps of Bolivia, Ecuador, and Paraguay that illustrate the change of treatment allocation in the municipalities included in the study sample across time.

5 | EMPIRICAL STRATEGY

For the study sample, panel data on nightlight luminosity, treatment status, and covariates have been assembled for the years 2000 to 2013. This information is then used to estimate difference-in-differences (DD) models with multiple fixed effects. Accordingly, temporal and spatial variation are exploited to accurately assess the treatment effect by controlling for time-invariant differences between treatment and control groups, as well as time-varying elements that influence both groups in a comparable way.

Consider that, in the absence of municipal data on economic activity indicators (e.g., GDP), variation in nightlight luminosity levels is used as a proxy for economic growth (Henderson et al., 2012). In Section 6.1, the relationship (elasticity) between GDP and luminosity is discussed in greater detail for the cases of Bolivia, Ecuador, and Paraguay.

To approach the causal effect of paved major roads on luminosity, the empirical strategy is based on that of Mitnik et al. (2018) and Bolivar (2020), who evaluate the effects of road infrastructure on nighttime lights for Haiti and Bolivia, respectively. Nevertheless, given the current study examines three countries (Bolivia, Ecuador, and Paraguay), the following econometric specifications are applied:

i. ***Country-specific analysis:*** From the sample described in 4.4, subsamples are taken by country. Thereafter, the following econometric specification is adopted to estimate the causal effect exclusively for the data from Bolivia, then for Ecuador, and finally for Paraguay:

$$Y_{i,t,s} = \beta_0 + \beta_1 T_{i,t} + \beta_2 X_{i,t} + \beta_3 X_{i,t-1} + \lambda_i + \alpha_t + \eta_s + \varepsilon_{i,t,s} \tag{4}$$

ii. ***Pooled analysis:*** The following specification is applied to the complete sample, which includes data from all three countries:

$$Y_{j,i,t,s} = \beta_0 + \beta_1 T_{i,t} + \beta_2 X_{i,t} + \beta_3 X_{i,t-1} + \left(\pi_j \times \text{trend}\right) + \pi_j + \lambda_i + \alpha_t + \eta_s + \varepsilon_{j,i,t,s} \tag{5}$$

The main difference between these specifications is that the pooled analysis includes a country fixed effect (π_j) in addition to a vector encompassing country-specific trends ($\pi_j \times$ trend). They control for unobserved characteristics that may result in time-invariant differences between the countries in the pooled sample, as well as for differentiated evolution of the trend associated with each country j, respectively.

In terms of interpretation, it is sought to estimate the percentage increase in luminosity levels when municipalities benefit for the first time with paved major roads. This could be accomplished by applying logarithms to the luminosity values; however, few small municipalities with dispersed populations in the early years of the study period register zero luminosity, making this transformation impossible. To maintain an equivalent specification, the outcome variable is constructed by means of the Hyperbolic Inverse Sine transformation (HIS), $Y_{i,t,s} = \log\left(y_{i,t,s} + \sqrt{y_{i,t,s}^2 + 1}\right)$. Ergo, $Y_{i,t,s}$ denotes the HIS-transformed luminosity value for the municipality i, the year t, and captured by satellite s.[17]

On the other hand, $T_{i,t}$ it is the treatment variable that takes the value of 1 from the year in which the municipality has access, for the first time, to a paved major road; 0 otherwise.

$X_{i,t}$ is a vector that encompasses two sets of covariates that enable control for time-varying factors that might affect the outcome variable. The first is a set of covariates on the geographical characteristics of the municipalities, which includes the variables of NDVI and the areas of forest, water bodies, scrubland, savanna and arid soil.[18] The first three indicators are related to land and vegetation quality, which influences agricultural productivity and thus stimulates economic growth (i.e., higher levels of luminosity). In comparison, municipalities with extensive scrubland, savanna, or arid soils are expected to have lower agricultural productivity and population density, resulting in lower levels of luminosity. The second set of covariates is based on climatic conditions, which consists of exogenous variables such as precipitation, temperature, wind speed, and severity of drought. Similarly, it is assumed that these factors can alter the environment in which economic activities are developed and the intensity of light captured.

Additionally, $X_{i,t-1}$ aggregates the first lag of the covariates, since the effects of these variables are not necessarily only contemporary. λ_i are fixed effects of municipality, which allow control for possible non-observable characteristics that generate differences between the municipalities of the sample but are constant over time. α_t are fixed effects of time, to control for shocks with common effects in the municipalities. With regards to the satellites that gather nightlight luminosity data, new ones have been added over time with improved technology for data collection; as a result, either two satellites record the luminosity levels for the same year, or there are no reports for the older satellites in some years. To make the best use of all available data and avoid an *ad-hoc* combination of satellite data in this context, a pool of data is used that contains information from all satellites (Gendron-Carrier et al., 2018; Mitnik et al., 2018; Bolivar, 2020); therefore, η_s are satellite fixed effects to control for technological variations that could affect luminosity values. Finally, $\varepsilon_{i,t,s}$ is the error term. Standard errors are clustered at the municipal level to account for potential contemporaneous (within municipality) and serial correlation.

The treatment effect is approximated in this framework by the coefficient β_1. *Ceteris paribus*, a positive estimate for this parameter would imply that municipalities in the sample that gained access to a paved major road for the first time would experience greater increases in luminosity levels over time than non-beneficiary municipalities. Given that the specification follows the rationale of a logarithm-level specification, the result is subject to interpretation in terms of percentage change in luminosity; on average, the percentage increase in luminosity attributable to the treatment would be $(100 \times \beta_1)$.

Methodology and results on GDP-Luminosity elasticities for the pooled sample, as well as for independent subsamples per country, are described in Section 6.1. These calculations are intended to approximate the percentage rise in GDP associated with a 1 % increase in luminosity. This elasticity is crucial because it establishes a relationship between the treatment effect on luminosity and economic growth. The following connection is true in this instance:

$$\Delta \%PIB|_{T=1} = \beta_1 \times \xi_1 \tag{6}$$

Where ξ_1 is the elasticity between GDP and luminosity (see Section 6.1). β_1 is the

[17] Pence (2006) and Mitnik et al. (2018) both use a comparable transformation.

[18] Although the database contains information about the surface area of urban regions and crops, those variables are not included as covariates to prevent endogeneity bias. However, they are utilized as covariates for the pixel-level analysis (see Section 6.4).

percentage increase in nightlight luminosity attributable to the treatment. And $\Delta\,\%\text{PIB}|_{T=1}$ would be the percentage growth in GDP linked to treatment.

Finally, the DD scheme ensures a rigorous estimation of the causal effect even when the treatment and control groups differ in the outcome variable prior to treatment, if they follow a similar pretreatment trend (Angrist and Pischke, 2008). Accordingly, the following approaches are implemented to validate the parallel trend assumption: i) A balanced panel is constructed by excluding all observations after 2003, as no municipality in the sample benefited from paved major roads between 2000 and 2003; the difference in trends is then evaluated to determine whether it is statistically different from zero. ii) An unbalanced panel is developed by removing all observations after the year in which treatment begins for each municipality, and then it is tested whether the trend of the treatment group differs from that of the control group. In both circumstances, the null hypothesis that the difference in treatment and control group trends is equal to zero should not be rejected to support the premise that parallel trends holds.

The results of testing the parallel trend assumption are shown in Appendix C, for both the country-specific and pooled analyses. The findings demonstrate that the DD approach is methodologically adequate for the aims of the current study.

6 | RESULTS

6.1 | GDP-Luminosity elasticity

One of the most essential assumptions of the research is that variations in nightlight luminosity levels are a fair proxy for economic growth. To test the validity of this supposition, the elasticity between GDP and nighttime lights is estimated on data from Bolivia, Ecuador, and Paraguay. As a result, the estimates would indicate the average percentage increase in GDP in response to a 1 % rise in luminosity levels.

GDP data are not readily available in all the countries studied. GDP series are accessible in Bolivia at the national and departmental levels, in real (constant prices) and nominal (current prices) terms. In Ecuador, statistics on GDP at constant and current prices are published; however, only series of Value Added are available at the province (i.e., departmental) level, which are comparable to GDP at basic prices.[19] In Paraguay, only the series on national GDP at constant and current prices were obtained. Furthermore, the temporal horizon covered by these series vary by country and degree of regional disaggregation.

In light of GDP data heterogeneity, the following approaches are assumed to estimate the GDP-Luminosity elasticities:

i. ***Estimates with national GDP series:*** A panel database is constructed with yearly GDP series (at constant and current prices) for Bolivia, Ecuador, and Paraguay from 1992 to 2013; data are sourced from the World Bank's country reports. Similarly, the database collects information on luminosity levels (raw and intercalibrated), which were processed and aggregated at the national level (Analogously to Sections 4.1 and 4.2). Thereafter, the GDP-Luminosity elasticity is estimated by means of a fixed-effect regression:

$$\log(\text{PIB}_{j,t}) = \xi_0 + \xi_1 \log(\text{Lum}_{j,t,s}) + \xi_2 X_{j,t} + \pi_j + (\pi_j \times \tau) + \eta_s + \varepsilon_{j,i,t} \quad (7)$$

Where $\text{PIB}_{j,t}$ and $\text{Lum}_{j,t,s}$ denote the GDP and luminosity levels of the country j in the

[19] According to the Central Bank of Ecuador, the regional accounts are constructed using solely province (i.e., departmental) gross value-added data. This is because GDP must encompass net indirect taxes such as tariff charges, net import taxes, and value added tax (VAT), and none of which may be apportioned across provinces.

year t, respectively, as night lights are measured by satellite s. The vector $X_{j,t}$ contains variables such as population and inflation to account for time-varying effects on the outcome variable. π_j are fixed effects per country that govern any non-observable factors that may cause differences between countries but are constant over time, whereas $(\pi_j \times \tau)$ controls the differentiated evolution of each country's trend. η_s are satellite fixed effects to account for changes in image capturing technology. $\varepsilon_{j,i,t}$ is the error term; standard errors are clustered at the country level.

Additionally, GDP-Luminosity elasticities are estimated for country-specific subsamples. For instance, in the case of Bolivia, a subsample is generated by removing all data belonging to other nations from the pooled panel database; the same approach is adopted in the case of Ecuador and Paraguay. Hence, the econometric specification given below is applied to three independent regressions.

$$\log(PIB_t) = \xi_0 + \xi_1 \log(Lum_{t,s}) + \xi_2 X_{i,t} + \tau + \eta_s + \varepsilon_{i,t} \quad (8)$$

Where PIB_t is the annual series of the national GDP for the country of interest. $Lum_{t,s}$ is a yearly series of luminosity values, with subscript s denoting the satellite that captured it. Also, there are covariates $X_{i,t}$, which include population and inflation variables, as well as trend τ and satellite fixed effects η_s. The error term is $\varepsilon_{i,t}$, and robust standard errors are calculated.

ii. ***Estimates with subnational GDP series:*** Due to a lack of subnational (departmental) GDP statistics in Paraguay, this approach is confined to Bolivia and Ecuador. Furthermore, because real GDP is not reported at the subnational level in Ecuador, estimates based on departmental data are limited to nominal terms. This generates a panel database for the two countries, with the department as the unit of observation. However, the panel is unbalanced since the data from Bolivia spans the period 2000–2013, whereas the data from Ecuador covers just the period 2007–2013. Despite these constraints, GDP-luminosity elasticities are estimated using joint departmental (pooled) data from Bolivia and Ecuador as well as subsamples from each country.

The econometric specification that applies to the pooled sample is as follows:

$$\log(PIB_{j,i,t}) = \xi_0 + \xi_1 \log(Lum_{i,t,s}) + \xi_2 X_{i,t} + \pi_j + (\pi_j \times \tau) + \lambda_i + \alpha_t + \eta_s + \varepsilon_{j,i,t} \quad (9)$$

Equation (9) is a DD model with multiple fixed effects, where $PIB_{j,i,t}$ is the GDP of the department i, in the country j and for the year t. $Lum_{i,t,s}$ is the luminosity level of the department i the year t and captured by the satellite s. The vector $X_{i,t}$ includes covariates as population, and climatic conditions in the department such as precipitation, temperature, wind speed and severity of drought, as well as, the NDVI. Besides, π_j, λ_i, α_t, and η_s are country, department, time, and satellite fixed effects, respectively. Standard errors are clustered at the department level.

In addition, two independent estimates of GDP-Luminosity elasticities are undertaken for Bolivia and Ecuador employing subnational subsamples:

$$\log(PIB_{i,t}) = \xi_0 + \xi_1 \log(Lum_{i,t,s}) + \xi_2 X_{i,t} + \lambda_i + \alpha_t + \eta_s + \varepsilon_{i,t} \quad (10)$$

Whichever specification is chosen, the parameter ξ_1 reflects the elasticity between GDP and nightlight luminosity.

The elasticities between GDP in real terms and nighttime lights are presented in Set A of Table 4. According to the pooled sample, if luminosity levels increase by 1 %, real GDP would expand by an average of 0.08 %. Using country-specific subsamples, the real

GDP-Luminosity elasticity is estimated to be 0.12 %, 0.17 %, and 0.13 % for Bolivia, Ecuador, and Paraguay, respectively.

CUADRO 4 Elasticity between GDP and Nightlight Luminosity

Dependent variable: GDP	Pool (1)	Bolivia (2)	Ecuador (3)	Paraguay (4)
Set A: Real and national GDP				
Luminosity	0.0799**	0.123**	0.168***	0.128***
	(0.0103)	(0.0561)	(0.0386)	(0.0332)
R^2	0.976	0.994	0.984	0.965
Observations	102	34	34	34
Set B: Nominal and national GDP				
Luminosity	0.450**	0.452*	0.356*	0.363**
	(0.0634)	(0.232)	(0.207)	(0.171)
R^2	0.924	0.967	0.930	0.953
Observations	102	34	34	34
Set C: Nominal and subnational GDP				
Luminosity	0.428***	0.692***	0.356*	
	(0.141)	(0.149)	(0.183)	
R^2	0.830	0.860	0.797	
Observations	378	198	180	
Country FE and trend	✓			
Satellite FE	✓	✓	✓	✓
Trend		✓	✓	✓
Covariates	✓	✓	✓	✓
Subnational FE†	✓	✓	✓	
Time FE†	✓	✓	✓	

Notes: ***p<0.01, **p<0.05, *p<0.1. For Sets A and B, standard errors are clustered at the country level in column (1); robust standard errors otherwise. For Set C, standard errors are clustered at the subnational level. The luminosity variable is that of intercalibrated values. (†) Only regressions on Set C use subnational and time fixed effects. Furthermore, the pooled data set comprises samples from Bolivia and Ecuador. *Source:* Own computations.

When dealing with national series of nominal GDP, the findings (Set B of Table 4) show that, on average, nominal GDP would expand by 0.45 % in response to a 1 % increase in luminosity levels. A comparable elasticity is estimated with data from a subsample of Bolivia. The estimates for Ecuador and Paraguay subsamples suggest that the nominal GDP-Luminosity elasticity for both countries would be around 0.36 %.

On the other hand, estimates derived from subnational series of nominal GDP are shown in Set C of Table 4; recall that this approach uses data from Bolivia and Ecuador, exclusively.

Using the pool database, results imply that nominal GDP would increment by 0.42 % on average if luminosity levels changed by 1 %. In the subsample with Bolivian data, the nominal GDP-Luminosity elasticity would be 0.69 %. Finally, the evidence reveals that the elasticity of nominal GDP with respect to luminosity would be near to 0.36 % for Ecuador.

The results discussed in this section were produced using intercalibrated luminosity data. However, in Appendix D, estimates based on raw luminosity series (i.e., without intercalibration) are reported to support the statistical strength of the relationship between GDP and nighttime lights.

6.2 | Treatment Effect on Nightlight Luminosity

This section summarizes the estimated treatment effects on the luminosity of municipalities that gained access to paved major roads for the first time. As described in the empirical strategy, evidence is gathered at the country level and for a pooled dataset comprising municipalities in Bolivia, Ecuador, and Paraguay. Moreover, a set of regressions is examined that gradually incorporates multiple fixed effects and covariates, aiming to analyze the robustness as well as the degree of bias that would result from the absence of these control variables.[20]

For both country-level and pooled analyses, the preferred specification includes all fixed effects (municipality, year, and satellite; in addition, country-specific fixed effect and trend for the pooled sample), as well as contemporary and first lag covariates. In this framework, explanatory variables would be suitable predictors of the outcome variable and would adequately explain the largest amount of variance (e.g., the lowest values of the Akaike Information Criterion are observed).

Panel A of Table 5 provides estimates of the treatment effect in the example of Bolivia. The regression that only includes municipality fixed effects exhibits that the effect on the luminosity attributable to the treatment would be an expansion of 12.1 %. On the other hand, when year and satellite fixed effects are considered, the effect stabilizes at roughly 5.4 %. Controlling for contemporary covariates, the effect steadies at around 5.2 %. If the first lags of the covariates are additionally included (specification of preference), the findings suggest that, on average, the luminosity would have increased by 4.6 % in the municipalities of Bolivia that benefited for the first time from the pavement construction of a major road, compared to those who did not benefit. All of these estimates are statistically significant.

Similarly, it is found in the case of Ecuador (Panel B of Table 5) that the treatment effect is statistically significant across all specifications. The findings of the simplest regression, which accounts for only municipality fixed effects, suggest that treatment would have increased luminosity by 21.5 %. However, the former estimate is upward biased, as the results of the preference specification, which incorporates all control variables, indicates that nightlight luminosity would have increased by 3.5 % in Ecuadorian municipalities that benefited for the first time from a paved major road, compared to municipalities that did not benefit.

In regard to Paraguay (Panel C of Table 5), the majority of the evaluated models demonstrate a positive and statistically significant treatment effect. Considering the preference specification, it is reported that, on average, the luminosity would have increased 4.2 % in the municipalities of Paraguay that benefited for the first time with a major road, relative to the municipalities not benefited.

Additionally, Panel D of Table 5 shows the estimates for pooled data. The findings suggest that, on average, municipalities in the three countries would have benefited from a

[20] In Appendix E, results of regressions similar to those in Table 5 are presented; however, these make use of raw luminosity series.

10 % increase in luminosity after gaining access to a major road for the first time. Also, the estimated treatment effect is positive and statistically significant across all models.

Eventually, these estimates will be exploited to explore the link between the treatment effect on luminosity and economic growth.

CUADRO 5 Treatment Effect on Nightlight Luminosity

Dependent variable: Luminosity	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Bolivia							
Treatment	0.121***	0.0537***	0.0537***	0.0525***	0.0517***	0.0459***	
	(0.0111)	(0.0114)	(0.0114)	(0.0116)	(0.0115)	(0.0115)	
R^2	0.105	0.382	0.418	0.426	0.428	0.430	
Observations	5,170	5,170	5,170	4,700	4,700	3,760	
Panel B: Ecuador							
Treatment	0.215***	0.0539***	0.0539***	0.0375***	0.0377***	0.0348***	
	(0.0134)	(0.0119)	(0.0119)	(0.0124)	(0.0124)	(0.0126)	
R^2	0.138	0.712	0.741	0.756	0.756	0.752	
Observations	1,738	1,738	1,738	1,580	1,580	1,311	
Panel C: Paraguay							
Treatment	0.128***	0.0175	0.0175	0.0276*	0.0337**	0.0422***	
	(0.0275)	(0.0140)	(0.0140)	(0.0150)	(0.0148)	(0.0160)	
R^2	0.0245	0.605	0.683	0.688	0.692	0.685	
Observations	2,904	2,904	2,904	2,640	2,640	2,162	
Panel D: Pool							
Treatment	0.333***	0.262**	0.262**	0.254**	0.161**	0.124**	0.100**
	(0.118)	(0.133)	(0.133)	(0.124)	(0.0629)	(0.0526)	(0.0477)
R^2	0.0139	0.0225	0.0238	0.128	0.665	0.687	0.742
Observations	9,812	9,812	9,812	9,812	8,920	8,920	7,233
Municipality FE	✓	✓	✓	✓	✓	✓	✓
Time FE		✓	✓	✓	✓	✓	✓
Satellite FE			✓	✓	✓	✓	✓
Geographical covariates				✓	✓	✓	✓
Climatic covariates					✓	✓	✓
Covariates $(t-1)$						✓	✓
Country FE and trend							✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the municipal level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

6.3 | Heterogeneous Effects and Robustness

Concerns may arise that certain large-population municipalities are distorting the results. To exemplify that this is not the case, the treatment effect is estimated on subsamples constrained by population size. To ensure pretreatment comparability, population thresholds are based on official population records from the year 2000.[21]

Recall that estimates in Table 5 are based on a sample of the municipalities of Bolivia, Ecuador and Paraguay that had a maximum of 30,000 inhabitants in 2000. In this framework, robustness is tested by producing four subsamples of municipalities with populations of less than or equal to 25,000, 20,000, 15,000 and 10,000 inhabitants, respectively. These cutoff points are chosen to preserve that a suitable number of observations is retained for inference.

According to Panel A of Table 6, the treatment effect for Bolivia is robust regardless the population size limits. In the case of Ecuador (Panel B of Table 6), the results are statistically equivalent for subsamples with municipalities of at least 20,000 inhabitants; however, the effect is positive but not statistically significant for subsamples of up to 15,000 and 10,000 persons. The latter results should be regarded cautiously, as they show a large decrease in the number of observations, reducing statistical power and possibly resulting in a Type II error.

In the case of Paraguay (Panel C of Table 6), the findings indicate that the effect of benefiting for the first time from a paved major road in the country's municipalities would be statistically similar across the various population size subsamples.

With regards to the evidence obtained using the pooled data, the estimated coefficients indicate that the treatment effect will likely decrease when the maximum population size of the municipalities is lowered. However, since these estimates are within the confidence intervals of the estimations from the different population subsamples, the treatment effects would be comparable statistically.

Likewise, sensitivity is tested by the extent to which municipalities extend their territory. Table 7 presents estimates with the sample bounded by area of this geographical unit. Specifically, for both pool and country-specific analysis, two estimates are made: i) with a subsample of municipalities whose area in km^2 is less than or equal to the 50th percentile of the sample; ii) with a subsample of municipalities whose area in km^2 is greater than the 50th percentile of the sample.

Only in the case of Bolivia, the treatment effect would be relatively consistent across all subsamples, regardless of the area. On the other hand, for the analysis of Ecuador, Paraguay, and the pool of the three countries, the results suggest that the rise in luminosity levels associated with receiving a paved major road for the first time would be larger in municipalities with a smaller geographical extent. This tendency is presumably related to the fact that population centers and economic activity are more concentrated in smaller towns, implying that higher levels of luminosity are predicted.

On average, municipalities in the study sample reported being exposed to treatment for 6 years (for the subsamples of Bolivia 5 years, Ecuador 6 years and Paraguay 7 years). As a result, the treatment effect observed in the preference specifications (4.6 % for Bolivia, 3.5 % for Ecuador, 4.2 % for Paraguay, and 10 % for the pool) corresponds to the percentage increase in luminosity observed during the average time municipalities have access to a paved major road. However, the current research digs deeper into the impacts throughout time, providing estimates not just for contemporary effects, but also for effects spread across time following treatment.

[21] Because the methodological scheme is based on DD models, it is desirable to apply the population size restriction to data from the first year of the study period, so that municipalities have a generally homogenous distribution of inhabitants over the pretreatment period. Official population records were obtained from the Bolivian, Ecuadorian, and Paraguayan National Statistics Institutes.

CUADRO 6 Treatment Effect on Nightlight Luminosity by population size

Dependent variable: Luminosity	⩽ 30000 (1)	⩽ 25000 (2)	⩽ 20000 (3)	⩽ 15000 (4)	⩽ 10000 (5)
Panel A: Bolivia					
Treatment	0.0459***	0.0415***	0.0442***	0.0380***	0.0446***
	(0.0115)	(0.0119)	(0.0127)	(0.0137)	(0.0163)
R^2	0.430	0.422	0.415	0.395	0.328
Observations	3,760	3,664	3,520	3,120	2,352
Panel B: Ecuador					
Treatment	0.0348***	0.0331**	0.0280*	0.0217	0.0211
	(0.0126)	(0.0131)	(0.0146)	(0.0166)	(0.0199)
R^2	0.752	0.740	0.737	0.737	0.698
Observations	1,311	1,231	1,065	903	603
Panel C: Paraguay					
Treatment	0.0422***	0.0402**	0.0415**	0.0543***	0.0418*
	(0.0160)	(0.0164)	(0.0180)	(0.0171)	(0.0218)
R^2	0.685	0.682	0.669	0.665	0.682
Observations	2,162	2,081	1,935	1,769	1,444
Panel D: Pool					
Treatment	0.100**	0.0928*	0.0954*	0.0655	0.0683**
	(0.0477)	(0.0507)	(0.0538)	(0.0602)	(0.0268)
R^2	0.742	0.745	0.637	0.667	0.712
Observations	7,233	6,976	6,520	5,792	4,399
Municipality FE	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓	✓
Geographical covariates	✓	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓	✓
Covariates $(t-1)$	✓	✓	✓	✓	✓
Country FE and trend†	✓	✓	✓	✓	✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the municipal level. The luminosity variable is that of intercalibrated values. (†) Only regressions on Panel D use country-specific fixed effects and trend. *Source:* Own computations.

CUADRO 7 Treatment Effect on Nightlight Luminosity by area of municipalities

	Pool		Bolivia		Ecuador		Paraguay	
Dependent variable:	$\geqslant$ p50	$<$ p50	$\geqslant$ p50	$\geqslant$ p50	$\geqslant$ p50	$\geqslant$ p50	$\geqslant$ p50	$\geqslant$ p50
Luminosity	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treatment	0.0859*	0.160***	0.0534***	0.0413***	0.0252*	0.0647**	0.0221	0.0553***
	(0.0470)	(0.0548)	(0.0160)	(0.0156)	(0.0136)	(0.0263)	(0.0181)	(0.0197)
R^2	0.750	0.658	0.388	0.502	0.804	0.688	0.809	0.554
Observations	3,679	3,554	1,920	1,840	681	630	1,074	1,088
Municipality FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓	✓	✓	✓	✓
Geographical covariates	✓	✓	✓	✓	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓	✓	✓	✓	✓
Covariates $(t-1)$	✓	✓	✓	✓	✓	✓	✓	✓
Country FE and trend	✓	✓						

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the municipal level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

For both country and pool analyses, $\beta_1 T_{i,t}$ is replaced by $\sum_{k=0}^{K} \delta_{-k} T_{i,t-k}$ to obtain effects in each year between the completion of the paved major road's construction and the subsequent years, where $T_{i,t-k}$ is a dichotomous variable that takes the value of 1 if the completion of the paved major road occurred k periods ago; 0 otherwise. Consequently, δ_{-k} reflects the treatment effect of a major road that was completed k years ago. Particularly, the specification will include the parameters δ_{-0}, δ_{-1}, δ_{-2}, δ_{-3}, and δ_{-4}, which indicate the contemporary average treatment effect and subsequent post-treatment effects one, two, three, and four years ahead, respectively (Angrist and Pischke, 2008).

The estimates of treatment effects over time are shown in Panel A of Table 8. For Bolivia, Ecuador, and the pool, a common pattern is observed, namely an increasing treatment effect with time. For example, in Bolivia, the contemporary effect (i.e., the year of completion of the major road's pavement) is a 2.4 % rise in luminosity; on the other hand, from the fourth year onwards, the expansion of luminosity levels reaches 10.5 %. Nevertheless, the findings for Paraguay suggest that the biggest benefit occurs two years after the treatment; the effect tends to diminish in subsequent years.

On the other hand, the interest to explore pre-treatment effects arises, as they may be perceived as effects surging in the construction period. To test such possibility, along with the term $\beta_1 T_{i,t}$, the specification includes the $\sum_{k=0}^{Q} \delta_{+k} T_{i,t+k}$, where $T_{i,t+k}$ is a dichotomous variable that takes the value 1 if the treatment occurs k periods in the future and 0 otherwise. Thus, δ_{+1} and δ_{+2} describe the pre-treatment effects of one and two years prior to the completion of the paved major road, respectively.

The estimates of pre-treatment effects for Bolivia, Ecuador, Paraguay, and the pool are reported in Panel B of Table 8. In each of the four models, the estimated coefficients δ_{+1} and δ_{+2} are not statistically different from zero, suggesting the absence of effects during road construction.[22]

[22] If the pre-treatment effects are statistically non-significant, compliance with the assumption of parallel trends is strengthened (Angrist and Pischke, 2008)

CUADRO 8 Treatment Effect on Nightlight Luminosity across time

Dependent variable: Luminosity	Pool (1)	Bolivia (2)	Ecuador (3)	Paraguay (4)
Panel A: Post-treatment effects				
Treatment (t)	0.0837*	0.0243**	0.0118	0.0600***
	(0.0467)	(0.00981)	(0.00951)	(0.0143)
Treatment (t + 1)	0.0898*	0.0145	0.0302**	0.0442***
	(0.0458)	(0.0111)	(0.0132)	(0.0138)
Treatment (t + 2)	0.108**	0.0449***	0.0193	0.0656***
	(0.0545)	(0.0106)	(0.0157)	(0.0162)
Treatment (t + 3)	0.127**	0.0539***	0.0429***	0.0407**
	(0.0554)	(0.0160)	(0.0162)	(0.0163)
Treatment (t + 4)	0.114*	0.105***	0.0659***	-0.00703
	(0.0591)	(0.0203)	(0.0177)	(0.0461)
R^2	0.742	0.448	0.754	0.687
Observations	7,233	3,760	1,311	2,162
Panel B: Pre-treatment effects				
Treatment	0.156*	0.114***	0.0324**	0.0688***
	(0.0849)	(0.0248)	(0.0124)	(0.0187)
Treatment (t − 1)	0.0562	0.00826	-0.00484	0.0432
	(0.0556)	(0.00712)	(0.00347)	(0.0325)
Treatment (t − 2)	0.0877*	-0.00994	-0.00301	0.0235
	(0.0528)	(0.0135)	(0.00563)	(0.0212)
R^2	0.743	0.266	0.752	0.686
Observations	7,233	3,760	1,311	2,162
Municipality FE	✓	✓	✓	✓
Time FE	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓
Geographical covariates	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓
Covariates (t − 1)	✓	✓	✓	✓
Country FE and trend	✓			

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the municipal level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

6.4 | Analysis at the pixel level

Thus far, the empirical strategy has assumed that, within municipalities, cities and/or population centers have direct access to a paved major road. This circumstance is not always true. Additionally, it is anticipated that there will be heterogeneous effects depending on the beneficiaries' proximity to the paved major road. These aspects should be taken into account when estimating the effect of paved major roads on nightlight luminosity levels.

To address these concerns, it is necessary to first establish a pixel-level panel database, as detailed in Section 4.1 (STEPS 1–3). It's worth noting that this database is composed of pixels with a spatial resolution of 927.67 meters that span the countries of Bolivia, Ecuador, and Paraguay and contain data on luminosity, land cover, NDVI, precipitation, temperature, wind speed, and the Palmer Index of Drought Severity for each year of the analysis period. As a result, the grid comprises data for 1,912,995 pixels, with time series encompassing the period 2000–2013; land cover data are available only for 2001.

Second, since treated and control units are defined by their access to a paved major road throughout 2004 and 2013, the strategy for pixel-level analysis entails the delimitation of buffers of influence in the vicinity of these routes. Initially, the buffer of influence is assumed to be a radius of 5 km surrounding major roads of the sample. Although this specification is arbitrary, robustness is then verified by reducing the radius of influence to 3 km, 2 km, and 1 km.[23]

Third, the following panel datasets are produced using the whole gridded data for Bolivia, Ecuador, and Paraguay, where the unit of observation is the pixel:

i. ***Pixel-level panel dataset for 1km-buffer:*** It incorporates data from 2000 to 2013 for each pixel within a buffer of influence of 1 km around major roads of the sample (929,727 observations).

ii. ***Pixel-level panel dataset for 2km-buffer:*** It gathers data from 2000 to 2013 for each pixel within a buffer of influence of 2 km around major roads of the sample (1,464,227 observations).

iii. ***Pixel-level panel dataset for 3km-buffer:*** It includes data from 2000 to 2013 for each pixel within a buffer of influence of 3 km around major roads of the sample (1,982,955 observations).

iv. ***Pixel-level panel dataset for 5km-buffer:*** It comprises data from 2000 to 2013 for each pixel within a buffer of influence of 5 km around major roads of the sample (2,968,218 observations).

Fourth, the pixels that fall inside the buffer of influence of paved (between 2004 and 2013) major roads are defined as treatment units. The remaining pixels are deemed control units; they are located within the buffer of influence of unpaved major roads and do not overlap the buffer of influence of paved major roads. For all the panel datasets described above, pixels inside the buffer of influence of major roads that were paved prior to 2004 are excluded.

Fifth, in order to reduce the computational load associated with processing simultaneo-usly data from the three nations, separate regressions are conducted for each country.

In this context, the empirical approach for estimating the effect of paved major roads on the luminosity of areas (pixels) nearby them entails the estimation of DD models with multiple fixed effects for each country and buffer. In all cases, the following econometric specification applies:

$$Y_{i,t,s} = \beta_0 + \beta_1 T_{i,t} + \beta_2 X_{i,t} + \beta_3 X_{i,t-j} + \lambda_i + \alpha_t + \eta_s + \varepsilon_{i,t,s} \tag{11}$$

$Y_{i,t,s}$ is the luminosity value with the HIS transformation for the pixel i, the year t and captured by the satellite s. On the other hand, $T_{i,t}$ is the treatment variable that takes

[23] For example, Mitnik et al. (2018) performs a pixel-level analysis and use a 2.5 km buffer.

the value of 1 from the year in which the pixel i is within the buffer of influence of a paved major road; 0 otherwise. $X_{i,t}$ is a vector of covariates that controls for factors that are not constant in time and may affect the outcome variable; it consists of the variables on climatic conditions (precipitation, temperature, wind speed and drought severity), the NDVI, and a set of dichotomous variables for land cover (urban areas, crops, forest, water bodies, scrublands, savannah and arid soil). Also, the first lags of continuous covariates are included to account for potential non-contemporary effects. To control for time-invariant characteristics that generate differences between the pixels of the sample, shocks having common effects on the pixels across time and satellite-specific technological aspects, pixel λ_i, time α_t and satellite η_s fixed effects are added. Finally, $\varepsilon_{i,t,s}$ is the error term and standard errors are clustered at the pixel level to deal with contemporary and serial correlation.

CUADRO 9 Treatment Effect on Pixel-level Nightlight Luminosity by buffer of influence

Dependent variable:	1 km	2 km	3 km	5 km
Luminosity	(1)	(2)	(3)	(4)
Panel A: Bolivia				
Treatment	0.180***	0.199***	0.195***	0.170***
	(0.0432)	(0.0456)	(0.0437)	(0.0409)
R^2	0.202	0.178	0.166	0.159
Observations	521,013	824,967	1,121,119	1,688,294
Panel B: Ecuador				
Treatment	0.518***	0.552***	0.551***	0.561***
	(0.111)	(0.108)	(0.104)	(0.108)
R^2	0.202	0.189	0.182	0.179
Observations	299,472	462,366	616,368	897,323
Panel C: Paraguay				
Treatment	0.281**	0.307**	0.296***	0.216***
	(0.120)	(0.126)	(0.108)	(0.0748)
R^2	0.177	0.159	0.147	0.135
Observations	109,242	176,894	245,468	382,601
Pixel FE	✓	✓	✓	✓
Time FE	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓
Land cover dummies	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓
Climatic covariates $(t-1)$	✓	✓	✓	✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the pixel level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

In the example of Bolivia (Panel A of Table 9), the results reveal that when a major road is paved, the luminosity levels in neighboring areas (pixels within a radius of up to 5 km) rise by between 17 % and 20 %, compared to areas alongside unpaved roads.

In respect to Ecuador (Panel B of Table 9), the treatment effect of benefiting for the first time from a paved major road would generate an expansion of luminosity levels of between 51 % and 56 % in places close to this infrastructure, compared to those adjacent to unpaved major roads.

Similarly, findings from Paraguay show that treatment effect is positive and statistically significant regardless the buffer size (Panel C of Table 9). Specifically, the results suggest that the luminosity within a pixel would increase between 21 % and 30 % in areas having close proximity (up to 5 km distant) to a paved major road, compared to areas without such pathways.

Overall, no significant heterogeneity is detected on treatment effect with respect to how far (within a 5 km radius) the benefited area is located from a paved major road; the estimated coefficients are not statistically different among samples restricted by buffer size. The former results provide empirical proof that the building of paved major roads has a beneficial effect on the luminosity, and they complement the evidence reported in Section 6.2.

In addition, since the pixel-level analysis targets beneficiaries more accurately, the results are consistent in the sense that the effects on luminosity are greater in the areas near the paved major roads compared to those obtained at the municipality level.

On the other hand, within the scope of pixel-level analysis, it is envisaged that the largest effects of transport infrastructure would be found in population centers, that is, areas where people and economic activity concentrate. To test this assumption, equation (11) is estimated on a subset of the pixel-level database that only includes data from pixels classified as either urban areas or crops. These land covers would represent the places where the population and economic activities are agglomerated, therefore, they would be useful to identify population centers.

When a major road is paved in Bolivia, it is noticed that the luminosity levels in population centers rise by between 21 % and 34 %, compared to those adjacent to dirt major roads (Panel A of Table 10). The findings confirm that transport infrastructure has greater effects in population centers.

The results in Ecuador (Panel B of Table 10) not only demonstrate that increases in luminosity levels are larger in areas integrating population centers, but also that there are heterogeneous effects depending on the radius of influence of paved major roads. The treatment effect is 43 % when considering pixels within a radius of 1 km; on the other hand, the treatment effect is 78 % when considering pixels within a buffer of 5 km. These findings could be related to the fact that Ecuador has the highest number of pixels classified as either urban areas or crops in the pixel-level analysis, implying that population centers are also of greater geographical extension and, thus, the effects proliferate up to 5 km along paved routes.

In Paraguay, like in the other two countries, the estimated treatment effects for pixels linked with population centers are larger than the estimates for the entire sample. Benefiting for the first time from a paved major road would result in a luminosity growth of between 23 % and 36 % in Paraguayan population centers, in comparison to those with unpaved major roads.

Finally, Appendix F shows that the parallel trend assumption holds for pixel-level estimates, which supports the adequacy of the methodology.

CUADRO 10 Treatment Effect on Population Centers' Pixel-level Nightlight Luminosity by buffer of influence

Dependent variable: Luminosity	1 km (1)	2 km (2)	3 km (3)	5 km (4)
Panel A: Bolivia				
Treatment	0.288***	0.343***	0.315***	0.210***
	(0.0757)	(0.106)	(0.106)	(0.0800)
R^2	0.183	0.176	0.176	0.168
Observations	30,577	42,741	53,938	73,560
Panel B: Ecuador				
Treatment	0.435**	0.541**	0.619**	0.778***
	(0.209)	(0.231)	(0.249)	(0.242)
R^2	0.109	0.106	0.106	0.112
Observations	47,820	69,306	86,433	114,831
Panel C: Paraguay				
Treatment	0.362***	0.317***	0.257***	0.228***
	(0.0972)	(0.0876)	(0.0796)	(0.0721)
R^2	0.225	0.206	0.189	0.180
Observations	21,026	32,280	42,492	61,510
Pixel FE	✓	✓	✓	✓
Time FE	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓
Land cover dummies	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓
Climatic covariates $(t-1)$	✓	✓	✓	✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the pixel level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

6.5 | Effects on economic growth

As discussed in Section 5, estimates of β_1 (i.e., treatment effect on luminosity) and ξ_1 (i.e., elasticity of GDP with respect to luminosity) are necessary to build a link between the treatment effect on luminosity and economic growth. However, estimates for β_1 and ξ_1 vary by country, units of observation, and subsamples. To preserve variability in the results, Equation (6) is computed for the most relevant estimates of these parameters (see Table 11).

i. ***Economic growth at municipalities with access to a paved major road.*** First, at the municipal level, it is observed that the effect of having access to a paved major road would be linked to an economic growth, in real terms (i.e., discounting the price effect), of 0.6 %, 0.6 %, 0.5 % and 0.8 % for Bolivia, Ecuador, Paraguay, and the pooled sample, respectively. It should be recalled that this is the treatment effect that would be generated throughout the average time that municipalities are exposed to the paved road. In addition, when the effect is decomposed over time, the results suggest that the greatest effects occur in the medium-term (4 years ahead and forward), with economic activity expanding by 1.3 %, 1.1 %, 0.5 % and 0.9 % in Bolivia, Ecuador, Paraguay, and the pool of the three countries, respectively.

In nominal values, the municipalities in Bolivia that benefited for the first time with paved major roads would experience economic growth of 2.1 % (3.2 % if the elasticity from subnational GDP series is used) during the average time they have that infrastructure; the contemporary effect would be 1.1 % (1.7 % if the elasticity from subnational GDP series is used) and 4.7 % (7.3 % if the elasticity from subnational GDP series is used) in the medium-term.

In Ecuador, estimates show that the municipalities with paved major roads would achieve a rise of 1.1 % of their economic activity the year of pavement completion and, in the medium-term, this dynamism would reach 2.3 %; these values are equal to both the elasticities estimated with national and departmental series of nominal GDP. With regards to Paraguay, on average, during the years that municipalities have access to a paved major road, a nominal economic growth of 1.5 % would be expected, linked to this benefit.

ii. ***Economic growth in places near to a paved major road.*** On the other hand, as discussed in Section 6.4, the effect of paved major roads would be larger in areas next to this infrastructure, particularly those that comprise population centers, such as urban areas and crops. As a result, Table 11 includes information about the potential economic growth that might occur in places (pixels) adjacent to paved major roads.

In the instance of Bolivia, the findings indicate that when a major road is paved, the economic activity of the surrounding areas (pixels within a radius of up to 5 km) increases by around 2 % in real terms, compared to areas adjacent to unpaved routes. Likewise, real economic growth would be higher (between 2.6 % and 3.5 %) if the areas near the paved major roads belonged to population centers. In nominal terms, the effect of Bolivia's paved major roads on economic activity in neighboring areas would be equivalent to an expansion of 8 % (12 % if accounting for the elasticity estimated on subnational GDP series); the effect is larger in the areas that integrate population centers, where there would be a nominal economic growth of between 9.5 % and 13 % (between 14.5 % and 20 % if accounting for the elasticity estimated on subnational GDP series).

Similarly, in real terms, economic activity in Ecuadorian areas located near to paved major roads would have increased by approximately 9 % relative to zones neighboring unpaved roads; in areas integrating population centers, the increase would be between 7 % and 13 %. In nominal terms, areas in the vicinity of paved major roads would have experienced economic growth of between 18 % and 20 %, compared to areas nearby unpaved routes; with respect to population centers, the expansion would be between 15 % and 28 %.

For Paraguay, the estimates show that areas adjacent to paved major roads would have boosted their economy by between 2.8 % and 3.6 % (between 8 % and 10 % in nominal terms). On the other hand, in areas linked to population centers that gained access to a paved major road for the first time, the effect would be greater, ranging between 3 % and 4.6 % in real terms (between 8 % and 13 % in nominal terms).

Finally, the results presented in this section should be interpreted cautiously as they are approximations that, while based on inferential methods, assume an indirect relationship between the pavement construction of major roads and economic activity predicted on the

CUADRO 11 Economic growth linked to having access to a paved major road

Model	Country	Treatment	GDP-Luminosity elasticity			Economic growth		
		Effect on luminosity	Real and national GDP	Nominal and national GDP	Nominal and subnational GDP	Real and national GDP	Nominal and national GDP	Nominal and subnational GDP
Municipal Panel	Bolivia	4.6	0.123	0.452	0.692	0.6	2.1	3.2
	Ecuador	3.5	0.168	0.356	0.356	0.6	1.2	1.2
	Paraguay	4.2	0.128	0.363	n.a.	0.5	1.5	n.a.
	Pool	10.0	0.080	0.450	n.a.	0.8	4.5	n.a.
Municipal Panel *(Short-term effects)*†	Bolivia	2.4	0.123	0.452	0.692	0.3	1.1	1.7
	Ecuador	3.0	0.168	0.356	0.356	0.5	1.1	1.1
	Paraguay	6.0	0.128	0.363	n.a.	0.8	2.2	n.a.
	Pool	8.4	0.080	0.450	n.a.	0.7	3.8	n.a.
Municipal Panel *(Medium-term effects)*††	Bolivia	10.5	0.123	0.452	0.692	1.3	4.7	7.3
	Ecuador	6.6	0.168	0.356	0.356	1.1	2.3	2.3
	Paraguay	4.1	0.128	0.363	n.a.	0.5	1.5	n.a.
	Pool	11.4	0.080	0.450	n.a.	0.9	5.1	n.a.
Pixel-level Panel *(1 km buffer)*	Bolivia	18.0	0.123	0.452	0.692	2.2	8.1	12.5
	Ecuador	51.8	0.168	0.356	0.356	8.7	18.4	18.4
	Paraguay	28.1	0.128	0.363	n.a.	3.6	10.2	n.a.
Pixel-level Panel *(5 km buffer)*	Bolivia	17.0	0.123	0.452	0.692	2.1	7.7	11.8
	Ecuador	56.1	0.168	0.356	0.356	9.4	20.0	20.0
	Paraguay	21.6	0.128	0.363	n.a.	2.8	7.8	n.a.
Population Centers' Pixel-level Panel *(1 km buffer)*	Bolivia	28.8	0.123	0.452	0.692	3.5	13.0	19.9
	Ecuador	43.5	0.168	0.356	0.356	7.3	15.5	15.5
	Paraguay	36.2	0.128	0.363	n.a.	4.6	13.1	n.a.
Population Centers' Pixel-level Panel *(5 km buffer)*	Bolivia	21.0	0.123	0.452	0.692	2.6	9.5	14.5
	Ecuador	77.8	0.168	0.356	0.356	13.1	27.7	27.7
	Paraguay	22.8	0.128	0.363	n.a.	2.9	8.3	n.a.

(†) The short-term effects correspond to the contemporary treatment effect estimates, that is, the year of pavement completion of the major road. Only in the instance of Ecuador, the one-year-ahead treatment effect is included in the table, as the contemporary effect is not statistically significant. (††) The medium-term effects correspond to the four-year-ahead-and-forward treatment effect estimates. Only in the case of Paraguay, the three-year-ahead treatment effect is reported in the table, as the four-year-ahead-and-forward treatment effect is statistically not significant. (n.a.): Not available. *Source:* Own computations.

estimated elasticities between GDP and luminosity.

7 | CONCLUDING REMARKS

This research is considered to have met its objective of contributing to the literature on impact assessment of transport infrastructure. Furthermore, the contribution gains relevance since there are no precedents for studies, framed in econometric techniques, examining the effects of paved road infrastructure on economic growth at the municipal level in Bolivia, Ecuador, and Paraguay. While Bolivar (2020) evaluates the impact of roads on economic growth in a sample of Bolivian communities, the results presented in this study complement and expand the scope of that country's specific analysis.

Likewise, it is worth noting that data was generated by extracting information from satellite images with remote sensing techniques. Thereby, it was possible to address the issue of unavailable data at the subnational level and, more importantly, it established an innovative framework for data generation using unconventional sources.

Corral and Schling (2017), Mitnik et al. (2018), and Bolivar (2020) have been the only studies in Latin America that combine impact evaluation techniques with information from satellite images to examine the effects of infrastructure. Consequently, the current study is included in this small group and serves as a reference framework for future research involving limited data.

A three-stage strategy is assumed to estimate the effect on economic growth resulting from the benefit of paved major roads: i) the impact of having access to a paved major road on luminosity levels is estimated; ii) the GDP-luminosity elasticity is estimated; and iii) the above two estimates are linked to obtain an approximation of the economic growth in municipalities and nearby areas benefited by a paved major road. This structure is feasible in light of the literature on the use of nighttime lights as a proxy for economic activity.

Regarding the findings, empirical evidence suggests that municipalities in Bolivia, Ecuador, and Paraguay that benefited for the first time from a paved major road would have experienced a greater expansion of their luminosity levels than municipalities that did not benefit. On average, the construction of paved major roads would have increased the luminosity of municipalities in Bolivia, Ecuador, and Paraguay by 4.6 %, 3.5 %, and 4.2 %, respectively.

There was a prior belief that the closer a zone is to a paved major road, the greater the effect on its luminosity. That assumption was confirmed by following a similar empirical strategy to that of municipal analysis but applied to a pixel-level dataset. In fact, several buffers of influence around paved major roads were tested. In addition, it was found that proximity to a paved major road has a greater effect when the beneficiary area is classified as a population center.

One of the research's central assumptions is that variations in luminosity levels serve as an accurate proxy for economic growth. To test this hypothesis, several regressions were conducted to estimate the GDP-Luminosity elasticity for Bolivia, Ecuador, and Paraguay. However, in these countries data on GDP is extremely heterogeneous, with data available at the national level in some cases and at the subnational level in others, in real terms in some cases and only in nominal terms in others. For example, using national GDP series, the estimated elasticity between real GDP and luminosity for Bolivia, Ecuador, and Paraguay is 0.12 %, 0.17 %, and 0.13 %, respectively.

When the treatment effects on luminosity are likened to the GDP-Luminosity elasticities, the results indicate that economic growth (in real terms) was 0.6 % higher in Bolivian and Ecuadorian municipalities that benefited from paved major roads than in municipalities that did not. In the case of Paraguayan municipalities, the expansion of real economic activity would reach 0.5 % during the average time that municipalities benefit from access to paved major roads.

Among other findings, it was observed that having access to a paved major road would reach the highest impact on economic activity in the medium term.

Finally, the effects are greater in municipalities and areas adjacent to paved major roads when economic growth is measured in nominal terms, implying that the increased dynamism of economic activity would be accompanied by a rise in prices.

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A | DATES OF PAVEMENT COMPLETION FOR SEGMENTS OF MAJOR ROADS CONSTRUCTED BETWEEN 2004 AND 2013

CUADRO A.1 Bolivia: Dates of pavement completion

Major Road	Road segment	Pavement completion date
Ruta N° 9	Cuatro Cañadas – Pailón	2005
Ruta N° 2	Huarina - Pucaraní	2005
Ruta N° 2	Boyuibe - Lagunillas	2005
Ruta N° 4	Puerto Qujarro - Puerto Suarez	2005
Ruta N° 12	Oruro - Toledo	2005
Ruta N° 50	Trinidad – San Javier	2005
Ruta N° 16	Huarina - Achacachi	2005
Ruta N° 16	Achacachi - Escoma	2005
Ruta N° 2	Huarina – San Pedro de Tiquina	2005
Ruta N° 2	San Pedro de Tiquina - Copacabana	2005
Ruta N° 13	Cobija - Porvenir	2005
Ruta N° 5	Sucre - Aiquile	2007
Ruta N° 10	San Ramón - Concepción	2007
Ruta N° 35	San Carlos – San Juan	2007
Ruta N° 4	San José de Chiquitos - Robore	2007
Ruta N° 10	Montero – General Saavedra	2007
Ruta N° 10	General Saavedra – Mineros	2007
Ruta N° 6	Lagunillas - Monteagudo	2008
Ruta N° 6	Zudañes - Padilla	2008
Ruta N° 12	Toledo - Corque	2008
Ruta N° 4	Robore – Puerto Suarez	2009
Ruta N° 4	San José de Chiquitos – Pailón	2009
Ruta N° 14	Caiza “D” - Cotagaita	2009
Ruta N° 14	Tupiza – Villazón	2011
Ruta N° 30	Challapata – Santiago de Huari	2011
Ruta N° 6	Machacamarca - Uncia	2011
Ruta N° 14	Cotagaita - Tupiza	2011
Ruta N° 12	Carangas - Sabaya	2012
Ruta N° 7	San Benito - Totora	2012
Ruta N° 10	Mineros – Fernández Alonso	2012
Ruta N° 36	Gutiérrez - Charagua	2012
Ruta N° 5	Potosí - Uyuni	2012
Ruta N° 31	Carahuara de Carangas – San pedro de Totora	2012
Ruta N° 1	Villa San Lorenzo - Tomayapo	2013
Ruta N° 1	Tomayapo – Las Carretas	2013
Ruta N° 1	Las Carretas – Villa Abecia	2013
Ruta N° 1	Caiza “D” – Villa Abecia	2013
Ruta N° 23	San Benito - Arani	2013

Source: Bolivia’s Administradora Boliviana de Carreteras.

CUADRO A.2 Ecuador: Dates of pavement completion

Major Road	Road segment	Pavement completion date
	Piñas - Saracay	2004
	Zaruma – Portovelo - Piñas	2004
	Jivino - Shushufindi	2006
	Redondel entr. Esmeraldas - Atacames	2006
	Lumagpamba - Gualaceo - Sigsig	2007
	Chicty - Sevilla de Oro	2007
	El Descanso – Paute - Chicty	2007
	Catamayo - Gonzanama	2008
	Gonzanamá - Cariamanga	2008
	Bahía - San Clemente - Rocafuerte (incluye puente Los Caras)	2008
	Bolivar - Y del Ángel	2009
	Y del Ángel - Mascarilla	2009
	Huaquillas - Arenillas	2009
	Est. Pinto - S. Martin - S. Agustín - S. Vicente - Arenillas	2009
	San Lorenzo - Y de San Lorenzo	2010
	Y de San Lorenzo - Limite Imbabura	2010
	Y de San Lorenzo - Borbon	2010
	Bahia - San Clemente - Rocafuerte (incluye puente Los Caras)	2011
	Loja - Vilcabamba	2012
	Loja - El Tiro (límite provincial)	2012
	Suma - Pedernales	2012
	Límite prov. Loja (el tiro) - Zamora	2012
	Atacames - Sua	2012
	Sua - Y del Salto	2012
	Y del salto - Muisne.	2012
	Vilcabamba - Yangana	2012

Notes: Major road segments are identified by their official titles as provided by Ecuador's government authorities. Therefore column 1 is empty. *Source:* Ecuador's Ministerio de Transporte y Obras Públicas.

Cuadro A.3 Paraguay: Dates of pavement completion

Major Road	Road segment	Pavement completion date
Ruta Nacional N° 10	San Estanislao – Guajayvi - Yasy Cañi	2004
Ruta Nacional N° 10	Yasy Cañi - Villa Curuguaty	2004
Ruta Nacional N° 10	Villa Curuguaty - Ybyrarobaná	2004
Ruta Nacional N° 10	Ybyrarobaná – Corpus Christi	2005
Ruta Nacional N° 9	Villa Hayes – Benjamín Aceval	2005
Ruta Nacional N° 9	Villa Hayes - Mariscal José Félix Estigarrabia	2005
Ruta Nacional N° 11	Santa Pedro del Ycuamandiyú - Antequera	2009
Ruta Nacional N° 10	San Estanislao – Villa del Rosario	2011
Ruta Nacional N° 8	José Leandro Oviedo – Yuty	2011
Ruta Nacional N° 8	Coronel Bogado – General Artigas	2011
Ruta Nacional N° 8	José Leandro Oviedo – General Artigas	2011

Notes: Due to the lack of official titles for the road segments, the names in the table correspond to the municipalities located at the route's endpoints. *Source:* Paraguay's Ministerio de Obras Públicas y Comunicaciones.

B | MAPS OF TREATMENT ALLOCATION OVER TIME

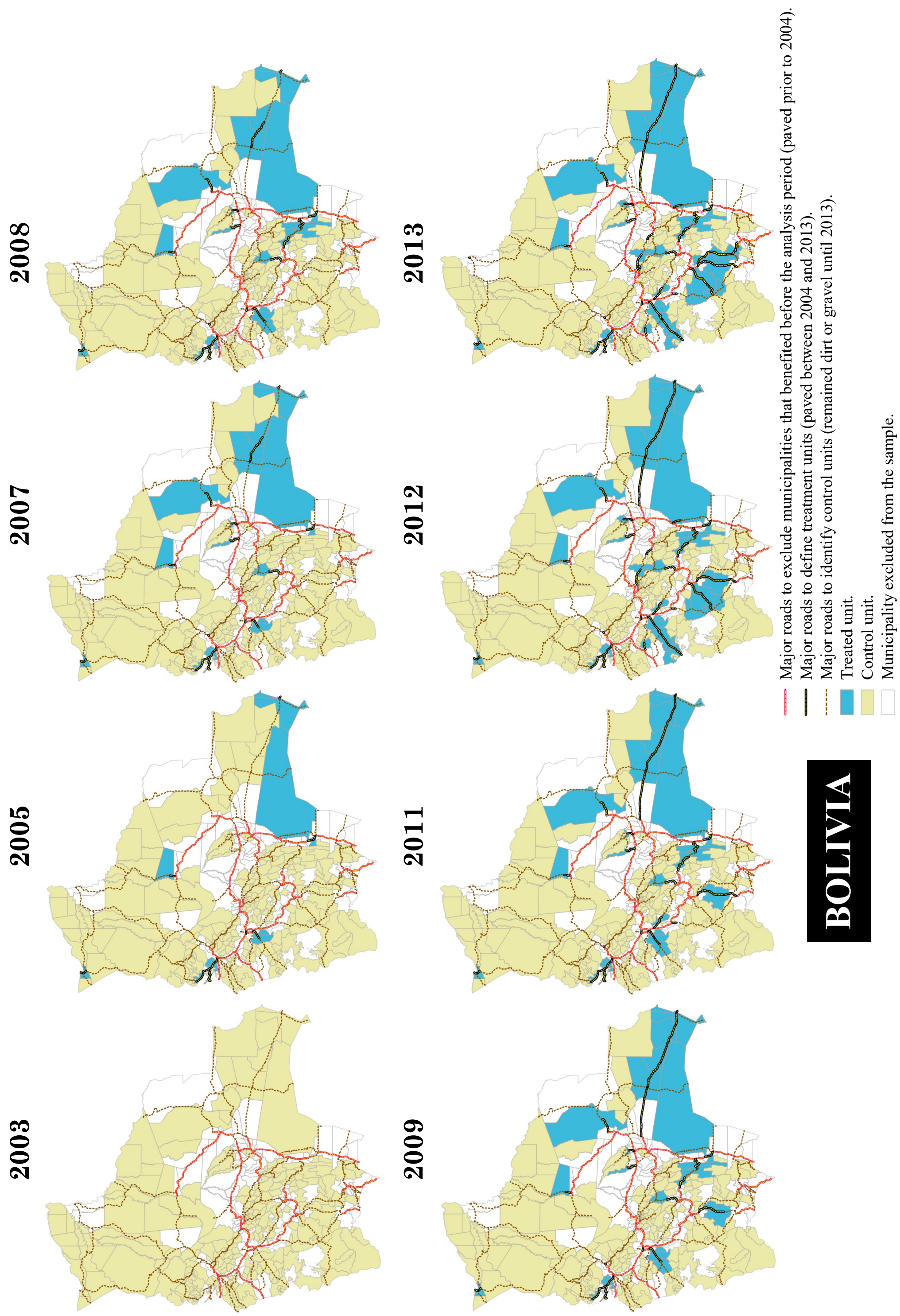

FIGURA B.1 Bolivia: Map of treatment allocation over time. *Source:* Own elaboration.

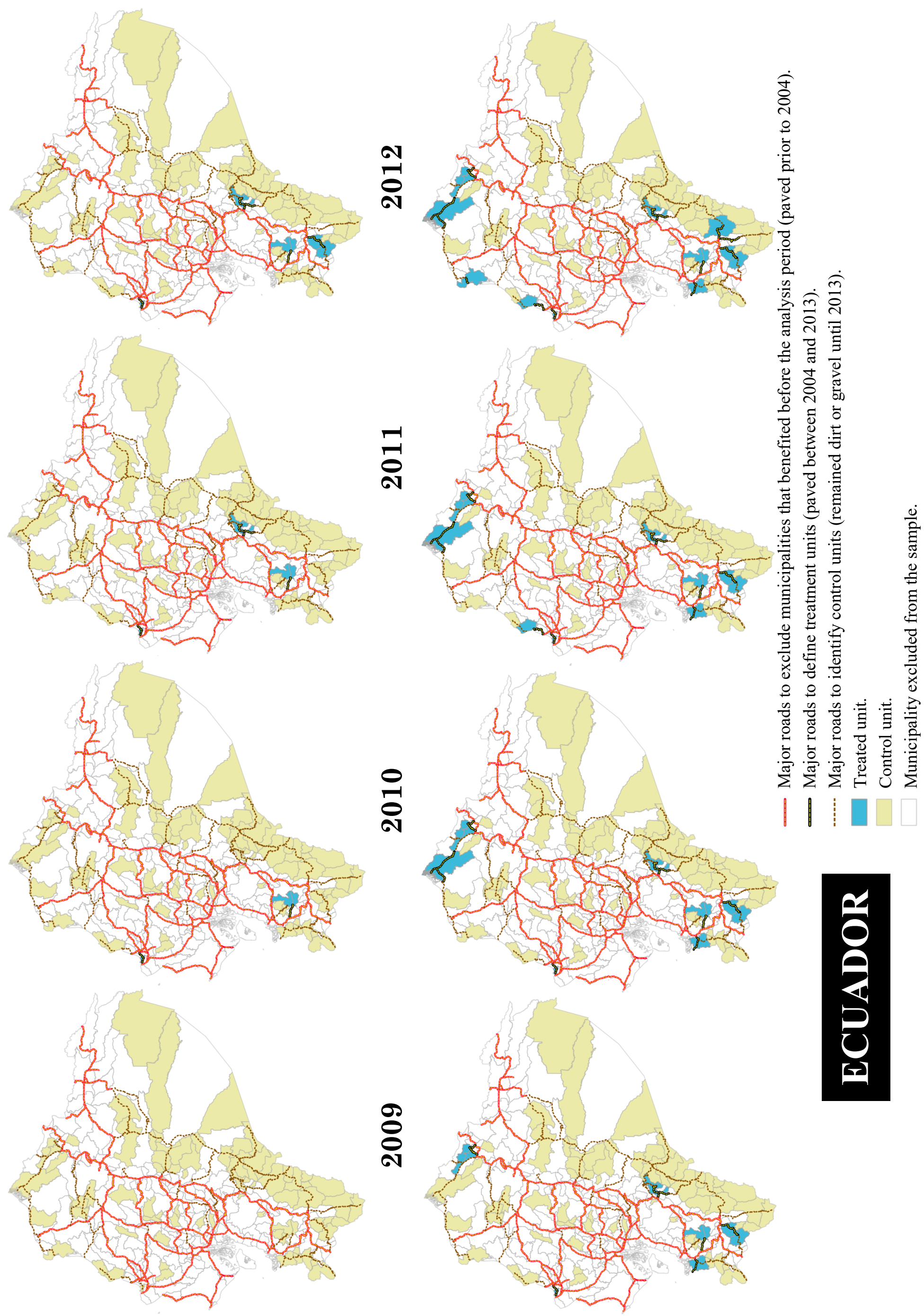

FIGURA B.2 Ecuador: Map of treatment allocation over time. *Source:* Own elaboration.

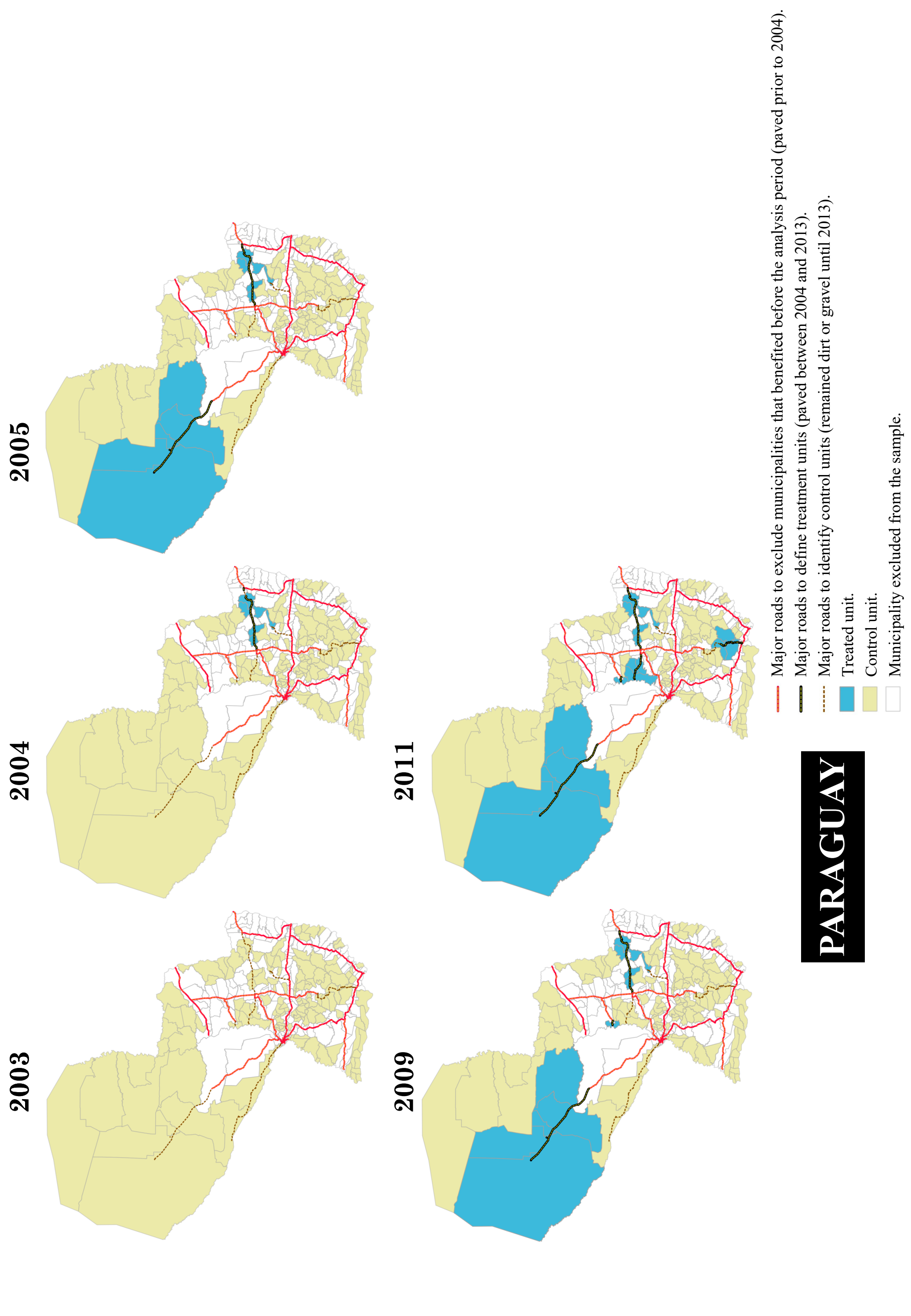

FIGURA B.3 Paraguay: Map of treatment allocation over time. *Source:* Own elaboration.

C | PARALLEL TREND ASSUMPTION

Dependent variable: Luminosity	Bolivia (1)	Ecuador (2)	Paraguay (3)	Pool (4)
Panel A: Balanced panels				
Treated × Trend	-0.165	-0.00538	-0.00166	0.0276
	(0.127)	(0.00571)	(0.0102)	(0.0393)
Trend	-0.0881	-0.0355***	-0.0362**	0.0364
	(0.141)	(0.00511)	(0.0139)	(0.0818)
R^2	0.0626	0.151	0.391	0.797
Observations	940	336	553	1,829
Panel B: Unbalanced panels				
Treated × Trend	0.00217	0.00186	0.00146	-0.0115
	(0.00266)	(0.00476)	(0.00385)	(0.00899)
Trend	0.00733***	0.0193***	0.0138***	-0.0154
	(0.00101)	(0.00182)	(0.00180)	(0.00982)
R^2	0.358	0.696	0.684	0.718
Observations	3,421	1,204	2,020	6,645
Municipality FE	✓	✓	✓	✓
Time FE	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓
Geographical covariates	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓
Covariates $(t-1)$	✓	✓	✓	✓
Country FE and trend				✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the municipal level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

D | ELASTICITY OF GDP AND RAW NIGHTLIGHT LUMINOSITY

Dependent variable: GDP	Pool (1)	Bolivia (2)	Ecuador (3)	Paraguay (4)
Set A: Real and national GDP				
Raw Luminosity	0.0508*	0.104***	0,0282	0.0656*
	(0.0256)	(0.0270)	(0.0387)	(0.0369)
R^2	0.976	0.995	0.991	0.971
Observations	102	34	34	34
Set B: Nominal and national GDP				
Raw Luminosity	0.284***	0.583***	0.0529	0.363**
	(0.106)	(0.124)	(0.190)	(0.171)
R^2	0.976	0.974	0.924	0.953
Observations	102	34	34	34
Set C: Nominal and subnational GDP				
Raw Luminosity	0.478***	0.721***	0.0156	
	(0.123)	(0.158)	(0.0918)	
R^2	0.873	0.904	0.829	
Observations	378	198	180	
Country FE and trend	✓			
Satellite FE	✓	✓	✓	✓
Trend		✓	✓	✓
Covariates	✓	✓	✓	✓
Subnational FE†	✓	✓	✓	
Time FE†	✓	✓	✓	

Notes: ***p<0.01, **p<0.05, *p<0.1. For Sets A and B, standard errors are clustered at the country level in column (1); robust standard errors otherwise. For Set C, standard errors are clustered at the subnational level. (†) Only regressions on Set C use subnational and time fixed effects. Furthermore, the pooled data set comprises samples from Bolivia and Ecuador. *Source:* Own computations.

E | TREATMENT EFFECT ON RAW NIGHTLIGHT LUMINOSITY

Dependent variable: Raw Luminosity	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Bolivia							
Treatment	0.902***	0.223*	0.223*	0.286**	0.288**	0.274**	
	(0.103)	(0.115)	(0.115)	(0.114)	(0.113)	(0.111)	
R^2	0.0274	0.148	0.153	0.170	0.170	0.172	
Observations	5,170	5,170	5,170	4,700	4,700	3,760	
Panel B: Ecuador							
Treatment	0.452***	0.366***	0.366***	0,104	0,0995	0,107	
	(0.0712)	(0.113)	(0.113)	(0.116)	(0.113)	(0.117)	
R^2	0.0134	0.323	0.351	0.452	0.458	0.468	
Observations	1,738	1,738	1,738	1,580	1,580	1,311	
Panel C: Paraguay							
Treatment	0.898***	0.0934	0.0934	0.0389	0.0752	0.181	
	(0.277)	(0.283)	(0.283)	(0.256)	(0.259)	(0.281)	
R^2	0.0147	0.281	0.289	0.317	0.318	0.328	
Observations	2,904	2,904	2,904	2,640	2,640	2,162	
Panel D: Pool							
Treatment	0.940***	0.248*	0.248*	0.249*	0.231**	0.261**	0.222**
	(0.125)	(0.136)	(0.136)	(0.138)	(0.112)	(0.108)	(0.103)
R^2	0.0256	0.166	0.171	0.184	0.267	0.271	0.288
Observations	9,812	9,812	9,812	9,812	8,920	8,920	7,233
Municipality FE	✓	✓	✓	✓	✓	✓	✓
Time FE		✓	✓	✓	✓	✓	✓
Satellite FE			✓	✓	✓	✓	✓
Geographical covariates				✓	✓	✓	✓
Climatic covariates					✓	✓	✓
Covariates $(t-1)$						✓	✓
Country FE and trend							✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the municipal level. *Source:* Own computations.

F | PARALLEL TREND ASSUMPTION FOR PIXEL-LEVEL ANALYSIS

CUADRO F.1 Parallel Trend Assumption on pixel-level data by buffer of influence

Dependent variable:	Balanced panels				Unbalanced panels			
Luminosity	1 km	2 km	3 km	5 km	1 km	2 km	3 km	5 km
Panel A: Bolivia								
Treated × Trend	0.00119	-0.00165	-0.00222	-0.00496	0.000363	0.000302	0.000300	0.000243
	(0.00651)	(0.00610)	(0.00575)	(0.00494)	(0.000339)	(0.000281)	(0.000244)	(0.000198)
Trend	0.00526	0.00542	0.00449	0.00338	0.000928***	0.000776***	0.000664***	0.000520***
	(0.00411)	(0.00395)	(0.00361)	(0.00287)	(0.000269)	(0.000220)	(0.000196)	(0.000155)
R^2	0.00526	0.00437	0.00344	0.00205	0.0228	0.0200	0.0176	0.0133
Observations	212,573	335,554	455,221	683,107	413,149	652,341	883,706	1,323,819
Panel B: Ecuador								
Treated × Trend	0.00214	0.00195*	0.00144	0.00120**	0.00207	0.00326	0.00266	-0.00153
	(0.00131)	(0.00112)	(0.000899)	(0.000577)	(0.00852)	(0.00784)	(0.00734)	(0.00603)
Trend	0.00451**	0.00238***	0.00262***	0.00200***	-0.0420***	-0.0259	-0.0272*	-0.0314**
	(0.00205)	(0.000866)	(0.000697)	(0.000491)	(0.0110)	(0.0184)	(0.0160)	(0.0137)
R^2	0.0728	0.0647	0.0554	0.0373	0.0532	0.0442	0.0357	0.0297
Observations	149,490	227,854	301,413	428,938	166,288	257,042	342,615	498,676
Panel C: Paraguay								
Treated × Trend	0.000370	0.000514	0.000465	0.000176	-0.0108	-0.0105	-0.00953	-0.00738
	(0.000591)	(0.000534)	(0.000440)	(0.000298)	(0.0113)	(0.0102)	(0.00976)	(0.00752)
Trend	-0.000498	-0.000462	-0.000471*	-0.000288*	-0.0151	-0.0128**	-0.00819*	-0.00423
	(0.000338)	(0.000293)	(0.000270)	(0.000171)	(0.00904)	(0.00462)	(0.00358)	(0.00251)
R^2	0.0340	0.0299	0.0249	0.0191	0.0814	0.0778	0.0726	0.0585
Observations	27,850	44,675	61,296	93,949	51,771	84,175	116,927	182,317
Pixel FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓	✓	✓	✓	✓
Land cover dummies	✓	✓	✓	✓	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓	✓	✓	✓	✓
Climatic covariates $(t-1)$	✓	✓	✓	✓	✓	✓	✓	✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the pixel level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.

CUADRO F.2 Parallel Trend Assumption on Population Centers' pixel-level data by buffer of influence

Dependent variable:	Balanced panels				Unbalanced panels			
Luminosity	1 km	2 km	3 km	5 km	1 km	2 km	3 km	5 km
Panel A: Bolivia								
Treated × Trend	0.00639	-0.00355	-0.00206	-0.00280	-0.00387	-0.00430	-0.00555	-0.00960
	(0.0141)	(0.0137)	(0.0116)	(0.0111)	(0.0107)	(0.00956)	(0.00849)	(0.00688)
Trend	-0.0121	-0.00624	-0.00846	-0.00990	0.0403***	0.0362***	0.0340***	0.0278***
	(0.0147)	(0.0143)	(0.0124)	(0.0121)	(0.00645)	(0.00644)	(0.00624)	(0.00609)
R^2	0.0283	0.0218	0.0183	0.0100	0.110	0.0947	0.0842	0.0671
Observations	10,600	14,574	18,223	24,326	14,670	20,284	25,226	33,436
Panel B: Ecuador								
Treated × Trend	-0.000484	-0.000049	-0.000068	0.000445	-0.0122	-0.00128	-0.00119	-0.00574
	(0.00485)	(0.00492)	(0.00439)	(0.00344)	(0.00856)	(0.00733)	(0.00676)	(0.00673)
Trend	0.0134***	0.0111***	0.00931***	0.00603***	-0.0290***	-0.0357***	-0.0343***	-0.0285***
	(0.00304)	(0.00282)	(0.00269)	(0.00166)	(0.00907)	(0.00792)	(0.00744)	(0.00732)
R^2	0.235	0.210	0.186	0.132	0.112	0.0897	0.0752	0.0654
Observations	9,730	13,223	15,607	18,257	27,266	39,670	49,424	65,789
Panel C: Paraguay								
Treated × Trend	0.00137	0.0209	0.0345*	0.0319	-0.0683	-0.0882	-0.0951**	-0.00356
	(0.0228)	(0.0203)	(0.0180)	(0.0218)	(0.0908)	(0.0585)	(0.0415)	(0.00397)
Trend	0.113***	0.0821***	0.0761***	0.0792***	0.0182	0.0334	0.0353	-0.00410
	(0.0173)	(0.0143)	(0.0152)	(0.0106)	(0.0420)	(0.0330)	(0.0291)	(0.00761)
R^2	0.210	0.192	0.156	0.103	0.0734	0.0622	0.0509	0.173
Observations	1,154	1,629	2,086	2,939	11,790	17,712	23,442	34,344
Pixel FE	✓	✓	✓	✓	✓	✓	✓	✓
Time FE	✓	✓	✓	✓	✓	✓	✓	✓
Satellite FE	✓	✓	✓	✓	✓	✓	✓	✓
Land cover dummies	✓	✓	✓	✓	✓	✓	✓	✓
Climatic covariates	✓	✓	✓	✓	✓	✓	✓	✓
Climatic covariates $(t-1)$	✓	✓	✓	✓	✓	✓	✓	✓

Notes: ***p<0.01, **p<0.05, *p<0.1. Standard errors are clustered at the pixel level. The luminosity variable is that of intercalibrated values. *Source:* Own computations.