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Satellite Nighttime Lights as a Measurement of Economic Growth in Mexico's Municipalities

Luces Satelitales Nocturnas Como Medida del Crecimiento Económico en los Municipios de México

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Abstract

The lack of information regarding economic performance and the temporal limitations of national accounts and economic censuses at a local level in Mexico motivates the exploration of alternative indicators. Based on Henderson (2012), in this document, economic dynamism is analyzed through the use of satellite nighttime lights images. This construction complements the omissions of information and measures economic dynamism at a sub-national level. Results highlight that changes in luminosity observed from outer space are positively related to economic dynamism, therefore the luminosity variable can be used as a proxy to analyze changes in Gross Domestic Product (GDP).

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Resumen

La falta de información sobre el desempeño económico y las limitaciones temporales de las cuentas nacionales y los censos económicos a nivel local en México motiva la exploración de indicadores alternativos. Con base en Henderson (2012), en este documento se analiza el dinamismo económico a través del uso de imágenes satelitales

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de luces nocturnas. Esta construcción complementa las omisiones de información y mide el dinamismo económico a nivel subnacional. Los resultados destacan que los cambios en la luminosidad observados desde el espacio exterior se relacionan positivamente con el dinamismo económico, por lo que la variable luminosidad puede usarse como proxy para analizar los cambios en el Producto Interno Bruto (PIB).

Introduction

It is important to consider that the GDP is a reference gauge, capable of measuring economic growth of countries in general or any region at any level. Its relevance lies in the fact that it is an indicator that is associated with the general well-being and economic development, at the same time, due to its own methodological characteristics in its measurement, it is presented as a macro indicator at a national and state level. However, particularly in Mexico, it has not been possible to obtain such an indicator at any sub national disaggregation, for example, municipalities, cities or micro-regions, including areas where political-administrative delimitations are not present such as lagoon regions or conurbations between two states or municipalities.

Due to the above, the existing empirical literature shows methods for measuring economic growth through remote sensing (satellite images) that manage to capture human activity from outer space. Henderson et al. (2012, pp 1023-1024), for example, used satellite images that capture the light emitted by countries into outer space. In the document, the authors applied a fixed effect panel data model to demonstrate that there is a positive relationship between light levels and economic growth and showed that in areas with limited ability to generate macroeconomic information such as in Sub Saharan Africa, light can be used as a proxy for economic growth.

For countries with well established national accounts systems, luminosity may have a marginal value in analyzing their GDP dynamics, however, for countries with weak national accounts, such an indicator, could potentially add new possibilities to understand economic dynamism at different sub national level, without raising 'reasonable' doubt in terms of statistical reliability.

In this document, as a result, such a novel spatial technique in conjunction with the usual national accounts data, are used to measure and understand the economic dynamism that Mexico's municipalities have as well as any other sub national disaggregation.

Our goal is to understand the spatio-temporal interactions between how the municipalities' economic activities are generated and how the productive clusters are formed.

This research is divided into 5 sections. In the first section, a review framework is explored and, through different empirical works, the use of satellite images to analyze economic dynamism is established. In section two, the characteristics of the data, the sources of information, as well as the development of the luminosity indicator are shown. Section three illustrates methods for instrumenting GDP via the luminosity indicator. The fourth, the applications of the instrument are exposed and the economic integration at a municipality level is shown. Finally, in section five the conclusions of this research are presented.

1. Instrument Applications and use of Satellite Data in Economics.

The existing literature in the field considers many instruments to analyze economic performance. Two examples are Young (2012) and Good (1994). Young (2012) builds proxies to measure consumption growth over 56 developing countries using microeconomic data extracted from demographic and health surveys. Good (1994), similarly, considered the number of letters sent per inhabitant as a proxy for production in 22 sub regions of the Habsburg Empire over the period 1870-1910. In his document, postal activity measured economic growth.

In another example, using remote sensing (satellite images) Burgess et al. (2012), studied deforestation in Indonesia. Forestry is highly regulated in Indonesia, but illegal logging is overlooked given the corruption that is rampant in the country. As a result, administrative statistics are subject to incorrect or modified information. Satellite data, however, allowed the author to measure deforestation. In the results, the author found a significant gap between the data issued by the administrative authorities (manipulated) and the real deforestation captured by satellites, which was considered as a proxy for the degree of corruption in the country.

While the cross-sectional correlation between what is captured with remote sensing and human activity has been observed since shortly after the declassification of the data in 1972 (Croft, 1973; Doll, Muller, and Morley, 2006), currently, the use of luminosity has expanded after the development of new processing methods and a greater distribution of digital files from the National Oceanic and Atmospheric Administration (NOAA) in the 1990s and 2000s.

At the end of the last century, the first luminosity growth mappings were presented by Elvidge et al. (1997) and later Sutton et al. (2007) demonstrated that those changes can be considered as an alternative measurement of GDP.

Elvidge et al. (1997) developed a satellite inventory of human settlements based on night-time light emissions. The work provided insights into the spatial distribution and characteristics of urban development globally. Building upon this foundation, Doll (2008) created a comprehensive thematic guide, which served as a valuable resource for researchers and practitioners interested in night-time light remote sensing applications.

Following that line, Ebener et al. (2005) focused on modeling the distribution of income per capita at the sub-national level using nocturnal luminosity data. The study demonstrated that the use of night-time lights is a good proxy for wealth and highlighted the relationship between socio-economic indicators and health outcomes. Also, the research showcased the potential of night-time light imagery as a means to understand economic disparities and their implications for public health.

Expanding on these findings, Bhandari and Roychowdhury (2011) conducted a similar study in India and utilizing DMSP-OLS night-time images, the authors investigated the link between night lights and economic activity. Their research revealed insights into the spatial patterns of economic development within the country, showcasing the potential of night-time light remote sensing as a cost-effective tool for monitoring economic growth and urbanization. Ghosh et al. (2009), at the same time, showed that the difference between the spatial patterns of nighttime lights (captured via satellite images) and economic activity are a good proxy to estimate the formal and informal economy of Mexico.

Rangel-Gonzalez and Llamosas-Rosas (2019), at the same time, proposed satellite nightlights to measure non-registered economic activity in Mexico. Their research offered a novel approach to capturing economic activity that is not accounted for in official records. By analyzing satellite nightlight data, the authors provided insights into the spatial distribution and magnitude of non-registered economic activity in Mexico. This study shed light on the potential of satellite imagery as a valuable tool for enhancing economic measurement and understanding of the informal sector.

Complementing such document, Petricioli (2015) conducted a study that explored the process of obtaining, processing, and calibrating a time series of satellite nightlight images to estimate the economic growth of different states in the country (Mexico). By leveraging remote sensing data, the author provided valuable insights into the economic dynamics of the Mexican states and the potential of satellite imagery in estimating regional economic growth. The study showcased the importance of utilizing satellite-based approaches to enhance economic analysis at a sub-national level.

Chen and Nordhaus (2011) pointed out the deficiencies of the standard sources of macroeconomic data for some countries and proposed luminosity as the proxy for the standard GDP measurements. Recently, Henderson et al. (2012), using Chen's proposal, estimated economic growth worldwide, showing that capturing nighttime lights from outer space is an efficient proxy for economic growth and works at any subnational or supranational region, the latter is used as a guide for the present work.

The relevance in the use of these measurement alternatives is contrasted by Lee (2016) who used luminosity to measure economic growth in North Korea, emphasizing the advantage of having unmanipulated data over data that may be subject to dictatorial regimes. Thus, the luminosity captured by satellites has transfigured the standard way in which economic activity has been measured. These new measurements or approximation methods can be used as complementary alternatives to strengthen the national account of each country. That is to say, luminosity can be used as an instrument of economic growth; under the assumption that, in any country, lighting increases as income grows (Bils and Klenow 2001, Costa 2001, Young 2012).

2. Data and Methodology

The nighttime satellite images were obtained from the Satellite Global Images of the National Center for Environmental Information[1] (NOAA). In

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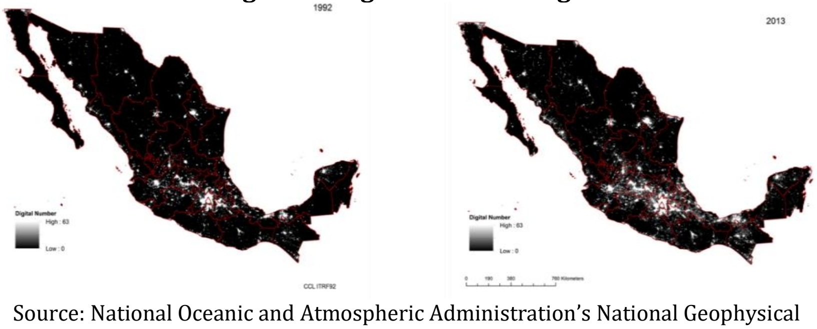
[1] The NOAA manages a fleet of geostationary and polar-orbiting meteorological spacecrafts that provide raw radiance data that are collected by ground stations and archived by National Centers for Environmental Information.

particular, the information was extracted from global images with stable average annual visible light and cloudless coverage, which was available from 1992 to 2013. For each year, there were one or two images available, and they are associated with one or two satellites, respectively. Our satellite selection criteria was based on the most recent images. It is from each satellite that we obtained a global image per year. Each image is free from weather distortions and light is averaged over a period of one year.

In this document, we dedicate our analysis exclusively to Mexico. Each image has approximately 2.5 million pixels of luminosity information. Given the distortion of the geographic coverage of the image by the Lambert conformal conic projection (LCC[2]), the centroid of each pixel was calculated and using the geographic coordinates of the states in Mexico, an overlapping layer was created, so that, at the end, all pixels were matched with the state they belong to.

Some pixels are identified in two or even three states. The luminosity of a pixel is assigned to the state in which its centroid falls. The luminosity of each pixel is taken for each image. The luminosity level is strictly between 0 and 63[3], which causes a limitation problem; if light value in any region at time t is at its maximum, any positive change cannot be captured at time $t+1$, which is the case for Mexico City. From this, a panel-type data matrix is built with all states and a time horizon of 22 years.

Map 1
Nighttime light satellite images



Source: National Oceanic and Atmospheric Administration's National Geophysical Data Center.

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[2] This projection states that all meridians should be lines equally spaced converging to the nearest pole.

[3] To the reader, 63 should be understood as the highest level of luminosity and 0 the lowest level. The NOAA limits the images at 63. The intensity measures the quantity of electromagnetic radiation that is emitted from the Surface of earth and is captured by the satellite sensor.

Maps 1 and 2, depict the luminosity of a pixel mapped to the state it belongs to. Map 1, for example, shows the transition Mexico faced from 1992 to 2013 in terms of luminosity. As can be seen, the growth is noticeable with Mexico City (and all other metropolitan areas) as the predominant. Map 2, relatedly, shows luminosity growth rate, which supports the previous idea.

Map 2
Nighttime light satellite image in differences 1992 – 2013

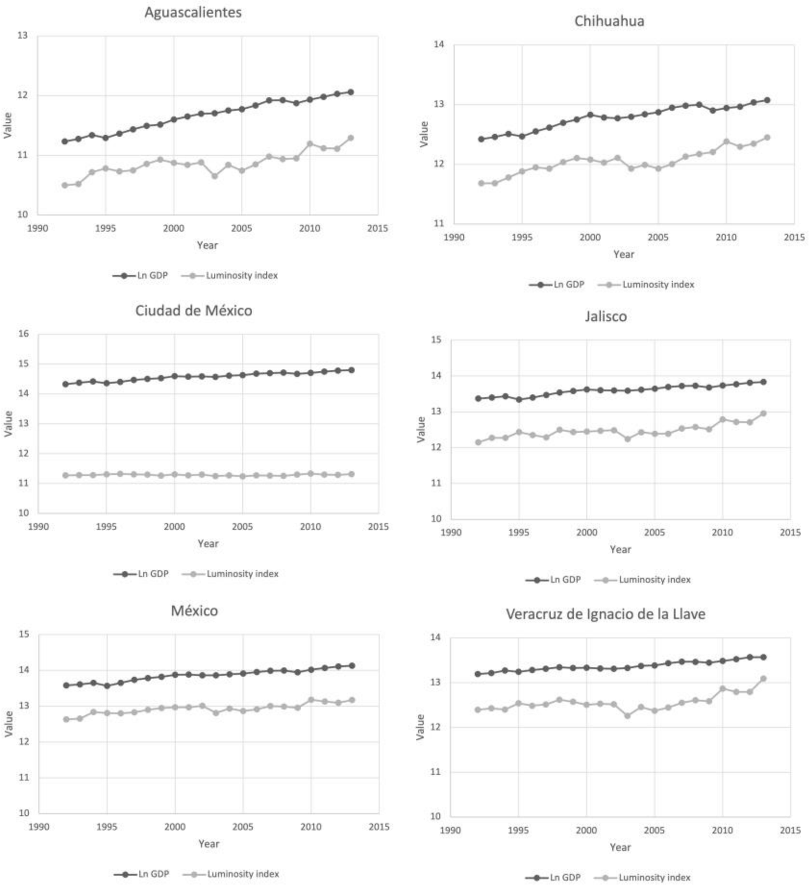
Source: See Map 1.

Graph 1[4], at the same time, using Henderson's methodology, shows yearly growth rates of nighttime light as well as GDP growth for selected states in Mexico thought 1992-2013. As can be seen, the luminosity variable has grown constantly in all states, except for Mexico City, which, due to the limitations of the satellite, remains constant for the period of analysis. For GDP growth, likewise, a similar pattern is depicted; a constant growth in GDP for all states except for Mexico City, where the variable is at its maximum.

Considering all that, it is easy to understand that the behavior of luminosity is quite similar to that of the GDP and although this relationship is just apparent, it opens the analysis for the following section.

[4] See Appendix for full information.

Figure 1
Nighttime light growth and GDP growth by state, Mexico 1992-2013



Source: National Geophysical Data Center, NOAA. INEGI.

3. Nighttime lights as a Measure of Economic Activity

Equation (1) specifies our panel-type data analysis equation. In this application, nighttime light is used to estimate real GDP.

$$Z_{jt} = \theta_0 + \varphi X_{jt} + \beta_1 Dummy_t + \beta_2 Dummy_j + e_{jt} \qquad (1)$$

Where:

Z_{jt} = Log real GDP of the state j at time t
X_{jt} = Log nighttime light per square kilometer $of\ the\ state\ j\ at\ time\ t$
$Dummy_t$ = Control variable for time
$Dummy_j$ = Control variable for state

Table 1 column 1 shows the results of the fixed effect estimation in a log panel regression (equation 1). As can be seen, the estimate of φ is 0.649, is statistically significant at the 5 percent level and the R^2 is 0.793. Column 2 suggests that a quadratic specification does not fit the data given the term ${X_{jt}}^2$ is not significant.

Columns 3 and 4, similarly, incorporated as controls, show variables that refer to the number of pixels with the maximum brightness (${X_{jt}}^{max}$), pixels with zero brightness (${X_{jt}}^{zero}$) and a spatial Gini coefficient (${X_{jt}}^{GINI}$), respectively. ${X_{jt}}^{max}$ is calculated as the count of pixels that show the highest level of luminosity and controls the cities that present high concentration of light and ${X_{jt}}^{zero}$ is the opposite and covers those areas with zero or low light. ${X_{jt}}^{GINI}$, finally, is calculated as the radiance concentration in the state and follows GINI index specification, so that a value close to 0 in that variable means equal distribution of luminosity within the state and a value close to 1 expresses high concentration of luminosity. At the end, from all the above, one can observe that light concentration (${X_{jt}}^{GINI}$) is statistically significant with a p value of 5 percent.

Columns 5, assess the relationship between GDP and light consumption in kilowatt-hours (KWH). The elasticity is 0.747 which is highly significant with a coefficient of determination of 0.81. Finally, column 6 tries to measure the robustness of luminosity (X_{jt}) and we regress GDP (Z_{jt}) against X_{jt} and KWH. As can be seen, even after adding KWH, the luminosity estimator is strongly significant. In here, it is important to note that the fixed effect dummy variables for year and space allow us to compare the light from the satellite with the administrative records of the Federal Electricity Commission.

Table 1
Regression results for Mexico, real GDP

	Z_{jt}					
	1	**2**	**3**	**4**	**5**	**6**
X_{jt}	**0.649****	**0.655****	**0.65****	**0.688****		**0.29***
	0.273	0.292	0.272	0.306		0.172
${X_{jt}}^2$		**-0.009**				
		0.044				
${X_{jt}}^{max}$			**0.003**			
			0.009			
${X_{jt}}^{zero}$			**0.022**			
			0.024			
${X_{jt}}^{GINI}$				**.38****		
				0.306		
KWH					**0.747****	**0.655****
					0.328	0.295
Observations	**704**	**704**	**704**	**704**	**704**	**704**
State	**32**	**32**	**32**	**32**	**32**	**32**
Within Rsq	**0.793**	**0.793**	**0.793**	**0.794**	**0.811**	**0.813**

Note: All panel specifications are for fixed effects.

* Significance level at 1%

** Significance level at 5%

*** Significance level at 10%

From these results, we can extract the instrument. The model suggests that 79 percent of the economic activity in the states is determined by variations in nighttime light, so, statistically speaking, nighttime light can be used as a proxy for economic growth. As mentioned earlier, there are states (for example Campeche or Mexico City) that possess a luminosity value way above that of the rest. Such behavior reveals that there are important economic differences between the states in Mexico and, contrary to what Henderson states, if one tries to use luminosity as a proxy for economic growth, such differences must be considered, otherwise, the instrument may suffer from specification bias.

Table 2 shows equation (1) but now considering data at the state level, so that we end up with 32 regression and 32 sets of results. As can be seen, the coefficients are all significant and more importantly, they are all different from each other, which supports the previous idea. Here, it is important to notice that each regression considers only 22 observations in a time series fashion, therefore, results must be carefully interpreted.

Also, following the above discussion, Campeche and Mexico City are states whose coefficients are nonexistent, however, that comes from the fact that each state presents zero or almost zero variation in the variable given that Mexico City, for example, shows the maximum value of luminosity in each year for the entirety of the period of analysis. In this document, as a result, spatial heterogeneity is controlled by weighting the instrument with the values we present in Table 2.

Table 2
Regression by states, real GDP

State	R-sq	Coef.	Err. Std.
Aguascalientes	0.666	1.093	0.173
Baja California	0.620	0.650	0.114
Baja California Sur	0.838	1.060	0.104
Campeche	0.001	*	*
Coahuila de Zaragoza	0.585	0.941	0.177
Colima	0.682	0.730	0.112
Chiapas	0.718	0.335	0.047
Chihuahua	0.730	0.829	0.113
México city	0.001	*	*
Durango	0.510	0.587	0.129
Guanajuato	0.694	0.736	0.109
Guerrero	0.351	0.282	0.086
Hidalgo	0.712	0.459	0.065
Jalisco	0.639	0.607	0.102
México	0.774	1.020	0.123
Michoacán de Ocampo	0.508	0.498	0.110
Morelos	0.313	0.518	0.172
Nayarit	0.459	0.579	0.141
Nuevo León	0.630	1.123	0.193
Oaxaca	0.347	0.328	0.101
Puebla	0.403	0.754	0.205
Querétaro	0.705	0.963	0.139
Quintana Roo	0.866	1.015	0.089
San Luis Potosí	0.596	0.655	0.121
Sinaloa	0.565	0.419	0.082
Sonora	0.718	0.754	0.106
Tabasco	0.800	0.695	0.078
Tamaulipas	0.598	0.924	0.170
Tlaxcala	0.661	0.580	0.093
Veracruz de Ignacio de la Llave	0.537	0.430	0.089
Yucatán	0.560	0.942	0.187
Zacatecas	0.672	0.683	0.107

Note: All panel specifications are for fixed effects.

It is important to notice that the projection that arises from these tables ($\widehat{Z_{IJ}}$), could be used as a proxy for GDP only in situations in which there is an endogeneity problem, as well as, in situations where a complement for data at a subnational level is required.

4. Empirical applications of the instrument

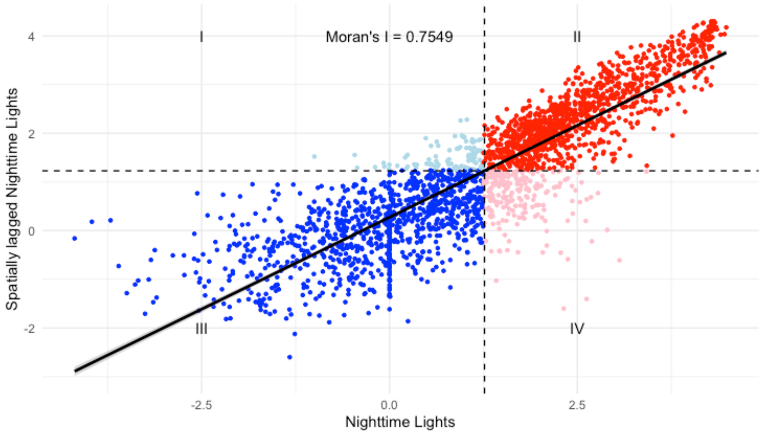
In this section, we present some applications for the luminosity variable. Having obtained our proxy for economic growth, economic performance can be analyzed in regions which wouldn't have otherwise been possible. For example, it is possible to construct a panel data set of production at a municipality level and analyze growth as we as economic integration between nearby neighbors. Also, given the robustness of our instrument, that application can be analyzed in metropolitan areas such as the Metropolitan Area of Mexico City. Here, it is worth mentioning that our instrument works even if cities belong to several municipalities. In these cases, the limits of the areas (metropolitan areas) do not coincide with the administrative political limits, as a result, our instrument is useful at any geographical level.

4.1. Regional economic integration in Mexico

The first approach studies the positives externalities of production on the neighboring economic performance via The Moran's I as show in Graph 2. In this context, in this application, we tried to appreciate the country's economic clustering at different sub national geographical levels. As can be seen, there is a positive spatial correlation of $\rho=0.7549$ which states that, the country, as a whole, presents economic clusters with spatial-temporal dependences.

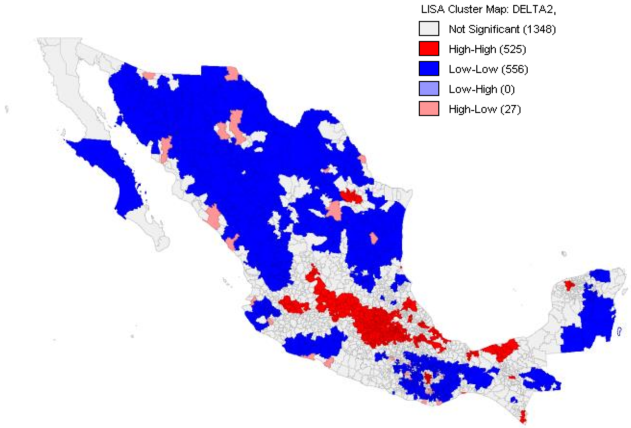
Quadrant II, in the same graph, shows the cluster of municipalities that have high levels of production and show a positive economic integration. Quadrant III, at the same time, displays those whose production is low and shows a positive economic integration. The local Moran's I cluster map (Map 3) shows the geography of micro-regional economic integrations, and as can be seen, it clearly displays the relevance of mainly industrialized areas as well as metropolitan areas.

Figure 2
Moran's index by municipality, Mexico 2013



Source: Own elaboration

Map 3
Local Moran's index (LISA) by municipality, Mexico 2013



Source: Own elaboration

4.2. Autoregressive Spatial Dynamic Model, SAR

With a panel data set of GDP at a municipality level for Mexico (obtained via our instrument) there is room for hypothesis testing. Following

Elhorst (2010), in this section, economic integration between municipalities is analyzed using a fixed effects autoregressive spatial dynamic model. As stated above, our goal is to understand how the spatio-temporal interactions between the municipalities' economic activity are generated and how the productive clusters are formed.

The model presents the production of an i-th municipality (via its GDP proxied by our instrument) as a function of its temporal lag and that of its j-th neighbor. In other words, the economy of each municipality is not only due to how it combines its productive factors, but also, by what happens in neighboring economies in the previous periods, see equation 2.

$$\Delta IVGDP_{it} = \alpha_1 + \alpha_2 \Delta IVGDP_{it-1} + \rho_1 w_{ij} \Delta IVGDP_{jt-1} + \varepsilon_{it} \tag{2}$$

Where:

$\Delta IVGDP_{it}$ = Log nighttime light instrument of municipality *i* in time *t*

$\Delta IVGDP_{it-1}$ = Log nighttime light instrument of municipality *i* in time *t -1*

w_{it} = Spatial matrix of interactions normalized REYNA-type

$\Delta IVGDP_{jt-1}$= Log nighttime light instrument of municipality *j* in time *t -1*

ε_{it} = SAR Spatial dynamic error term of municipality *i* in time *t*

In here, it is important to notice that w_{it} describes spatial interactions between municipalities and their neighbors following a REYNA-type matrix. At the end, in order to analyze spillover effects, this matrix captures better economic integration. A TORRE-type spatial matrix, on the contrary, might exclude some important interactions.

As can be seen, the model captures the externalities generated by the economic performance of the municipality to that of the nearby neighbors in *t-1.* As a result, if one tries to analyze economic regional integration at any sub national level, equation (2) together with our instrument, should be the preferred regression.

Due to the statistical significance of Morans I, table 3 shows that the municipalities grow together when there is a temporal synchronization in their economies (the Morans I coefficient measures the contemporary effect of the economic dynamics). Therefore, if Morans I is statistically significant and positive, the region experiences a positive economic integration at time t. When municipalities grow asynchronously (negative and statistically significant ρ_1), on the contrary, space-time relationships are reflected in the opposite way. This suggests that, if a municipality experienced economic growth, it was at the expense of that of nearby neighbors, which shows that the economies are negatively affected when they present desynchronized dynamics. It is important to notice that the goodness-of-fit between observations (R-sq: between) is better explained for our estimation model than that within observations, that is to say, our model explains the relationship better between the variables crosswise than longitudinally.

In here, there are 3 scenarios. First, when the region is coordinated, there is cooperation, and the economic interdependence of the municipalities generates positive effects emphasizing economic growth and integration. Second, when instead of coordination and cooperation, there is competition, there is a sort of predator, which shows economic growth at the expense of that of nearby neighbors. Third, the economies move independently and are not regionally integrated.

Such scenarios can easily be seen in the following map 3. For example, the south-center region (CDMX, Puebla, Queretaro, Mexico State, Veracruz, Tabasco and Aguascalientes) shows High-High cluster, meaning, they follow the first scenario, i.e, the region is coordinated. The South-East region (Oaxaca, Jalisco not including the capital, Chiapas and Campeche), at the same time, shows the third scenario. The second scenario, finally, is captured by the SAR dynamic Model, therefore, this contemporarily analysis using Map 3 as well as, Morans I, does not display such effect.

Table 3
Spatial Effects of Economic Performance at a Municipality Level, 1992-2013

	Obs	49120	length	20	
	groups	2456	Log-likelihood	-9150.624	
$IVGDP_{it}$		Coef.	Std. Err.	z	P > |z|
Main					
$w_{ij}\Delta IVGDP_{jt-1}$		-0.127	0.0067	-18.79	0.00
$\Delta IVGDP_{it-1}$		0.301	0.0045	65.61	0.00
Morans I		0.718	0.0036	194.38	0.00
σ_e^2		0.079	0.0004	160.05	0.00
			within	0.1637	
R-sq:			between	0.9518	
			overall	0.9061	

Note: Autoregressive spatial panel data model with 20 observation per group.

Conclusions

Based on Henderson et al. (2012), in this document, it is proven that satellite nighttime lights can be used as a proxy for GDP in Mexico. However, contrary to what Henderson stated, rather that utilizing a unique parameter for specification in any regression, in this paper, different recalibrations that controlled for the economic heterogeneity of the country's regions were considered. At the end, economic performance and regional integration at different levels of geographical disaggregation were analyzed and the instrument (GDP instrumented by nighttime lights) showed robustness against any variable INEGI may present for measuring economic performance at regional level. Even that, there are still tacit sources of error when using lights to measure economic growth, however, these do not affect the statistical validity of the estimator.

In the results, it is shown that Mexico’s economic performance can be analyzed through the use nighttime light and more importantly, it also is seen that such performance at any subnational level can be analyzed via our weighted instrument. Therefore, the space-time scale of our instrument makes it possible to analyze the spatial interactions of the areas within the regions and capture positive as well as negative externalities regardless of the political-administrative boundaries into which the country is divided.

There are 3 main scenarios that can be obtained directly from our analysis. First, when the municipalities within the region are coordinated, there is cooperation, and their economic interdependence generates positive effects which emphasizes economic growth and integration. Second, when instead of coordination and cooperation, there is competition. So, in this scenario, there is a sort of predator, which shows economic growth at the expense of nearby neighbors and third, the economies move independently and are not regionally integrated.

From these findings, some main economic policy implications can arise. First, for those micro regions in which there is a contemporary coordination, for example, the central part of the country (the industrial cluster which includes municipalities that belong to states such as Queretaro, Guanajuato and Mexico state), a metropolitan or inter-state development policy can be applied. The goal here, given our methodology and results, would be that such municipalities generate joint strategies so that economic growth is potentialized. The policy should be a unique strategy and should overcome geo-political barriers such as states borders.

When municipalities grow asynchronously, the second policy implication should mitigate predatory behaviors and promote specialization, so that inter-regional competition is minimized.

Finally, the third policy implication refers to those regions that are not integrated (Jalisco's southeast region, for example) and looks to rethink the current development policy so that an economic integration plan based on their own particularly natural characteristics can be exploited.

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