Carrying the Weight of Autonomy? Growth and Spatial Inequality Among Municipalities in Colombia

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Abstract

This paper examines the impact of fiscal decentralization on income convergence across Colombian municipalities. To overcome the lack of consistent economic data, we estimate municipal value added per capita from 1993 to 2018 using an Artificial Neural Network trained on Night-Time Lights. We then embed decentralization measures in an augmented Solow model and estimate their effects using two-stage least squares with novel instruments. Results show that revenue-based decentralization significantly accelerates convergence, with annual rates of 2.7–4.2%—above Barro's "iron law"—implying that the poorest municipalities would close half their income gap with richer ones in roughly 30 years. These effects are strongest among poorer municipalities, where public capital is more productive, while expenditure-based measures prove less robust. Overall, the findings highlight that effective local revenue autonomy—rather than greater discretion over spending—is central to fostering spatial equity and long-run convergence in unequal, decentralized contexts.

JEL Classification: H71, H72, O47, R11
Keywords: Fiscal decentralization, income convergence, spatial inequality, Night-Time Lights, Colombia, local governments

1. Introduction

Despite decades of decentralization reforms across the developing world, territorial inequality remains one of the most persistent barriers to inclusive growth. In Colombia— where local governments are tasked with the delivery of core public service—the question of whether fiscal decentralization has contributed to the convergence of population adjusted income levels across municipalities remains unresolved. Understanding whether poorer municipalities are catching up with richer ones is fundamental to evaluating the long-run equity and efficiency effects of fiscal decentralization. This paper investigates whether fiscal decentralization has enhanced income convergence across Colombian municipalities, drawing on a new panel dataset that spans nearly three decades.

The question lies at the intersection of two major strands of economic research. On one side is the theory of fiscal federalism, which argues that decentralization improves allocative efficiency by aligning public service provision with local preferences and conditions (Oates, 1999; Prest & Musgrave, 1959; Tiebout, 1956). In this view, subnational governments are better equipped to identify and address local needs, especially in diverse countries with marked regional heterogeneity. On the other side is the literature on economic growth and convergence, which explores whether poorer regions grow faster than richer ones over time, thereby reducing spatial income disparities. According to standard neoclassical growth models, convergence occurs as capital flows to places where it is scarcer and more productive, and as workers migrate toward areas with higher wages (Barro & Sala-i-Martin, 1992; Gennaioli et al., 2014; Islam, 2003; Lessmann & Seidel, 2017). However, empirical findings on regional convergence are mixed, especially in developing countries, where mobility is limited, and institutions are unequal.

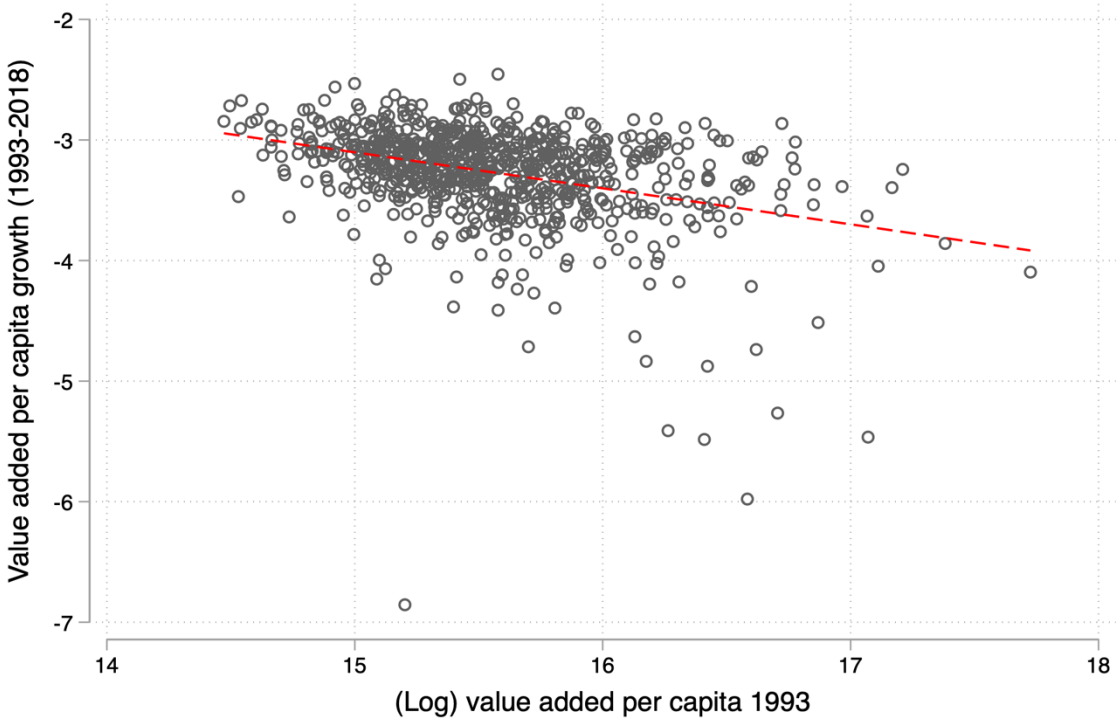
This paper seeks to reconcile these two frameworks by developing a simple theoretical model of municipal growth under fiscal decentralization. Following the spirit of the theoretical framework presented by Gennaioli *et al.* (2014), we extend the neoclassical Solow model to include both public and private capital, as well as imperfect factor mobility across municipalities. In this setting, municipalities with lower initial income levels can catch up with richer ones, but the speed of convergence depends not only on standard fundamentals—such as human capital, savings, and productivity—but also on fiscal policy choices. Government spending on productive public goods has a dual effect: on the one hand, it contributes directly to capital accumulation; on the other hand, it may crowd out private investment. The net effect depends on the relative productivity of public versus private capital. If fiscal decentralization enhances the efficiency and productivity of public spending, then we should expect a positive effect on the rate of convergence. Otherwise, decentralization may have no effect—or even negative effects—if it leads to inefficient allocation of resources.

To test these theoretical predictions, we compile a novel dataset of Colombian municipalities covering the period 1993–2018. A central challenge in subnational growth analysis is the lack of reliable, long-term income data at the municipal level. To address this, we estimate municipal value added (VA) per capita using an artificial neural network (ANN) based on Night-Time Lights (NTLs) imagery. This approach, now common in development economics (Lessmann & Seidel, 2017), allows us to construct consistent, comparable estimates of economic activity at the municipal scale. These estimates are then merged with detailed fiscal data, along with demographic, geographic, and institutional covariates.

To illustrate the empirical relevance of our analysis, Figure 1 shows the cross-sectional relationship between municipal income levels in 1993 and their annual growth rate through 2018. The negative slope suggests the presence of β-convergence, whereby poorer municipalities tend to grow faster than richer ones.

However, the dispersion around the trend line reveals substantial heterogeneity in local growth trajectories. Complementing this, Figure 2 tracks the evolution of the standard deviation of (log) municipal value added per capita over time. The series shows alternating phases of convergence and divergence, with marked increases in dispersion during the early 1990s—following the decentralization reforms—and again during the commodity boom of the mid-to-late 2000s. These dynamics underscore the importance of examining not just whether convergence is occurring, but under what institutional and fiscal conditions it takes place.

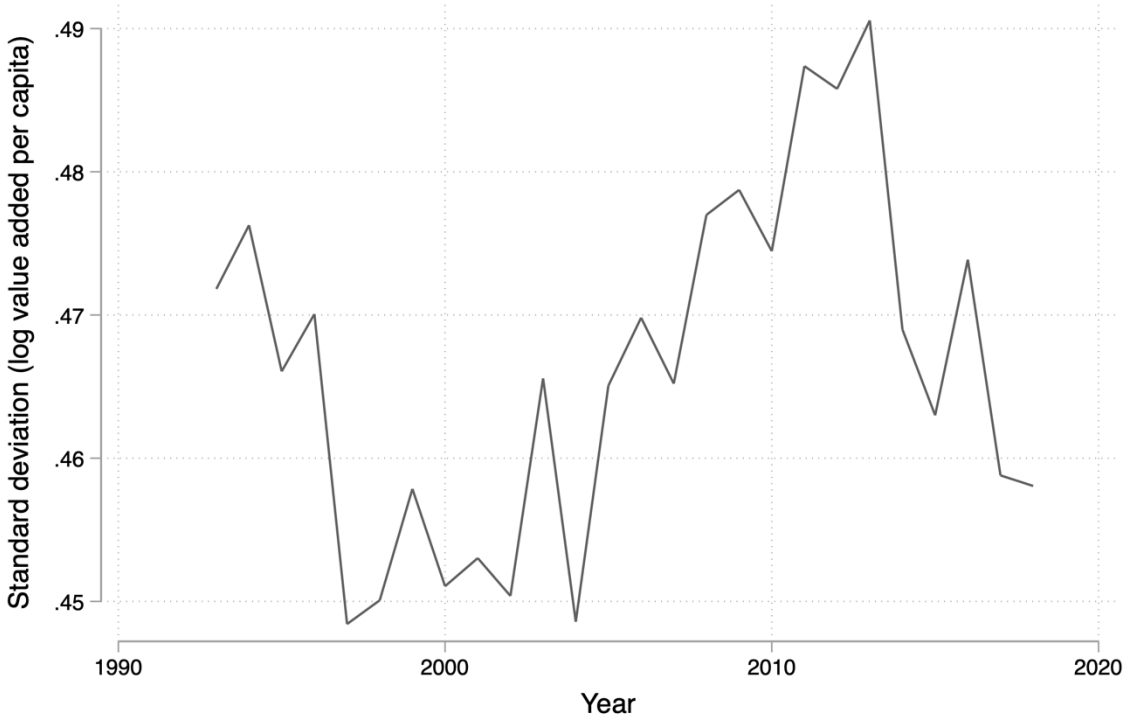
Figure 1. Beta Convergence



Source: Authors' calculations using predictions from a machine learning model trained on data from Li and Zhou (2017), DANE, Mapbiomas, and DNP.

Note: Beta convergence is estimated using the annual growth rate of value added per capita between 1993 and 2018 (y-axis) and the logarithm of value added per capita in 1993 (x-axis). The negative relationship indicates beta convergence: municipalities with higher initial income levels in 1993 experienced lower growth rates.

Figure 2. Sigma Convergence



Source: Authors' calculations using predictions from a machine learning model trained on data from Li and Zhou (2017), DANE, Mapbiomas, and DNP.

Note: Sigma convergence is estimated using the standard deviation of value added per capita across all municipalities included in the sample (y-axis) for each year between 1993 and 2018 (x-axis).

We assess income convergence using conditional β-convergence regressions, controlling for initial income and other covariates. A key challenge in growth regressions is the potential endogeneity of the explanatory variables. This has extensively been explored when assessing the effect of fiscal decentralization on economic growth (Martinez-Vazquez et al., 2017). A bias in our estimates can arise if improvements in fiscal efficiency attributed to decentralization are, in fact, a consequence of economic growth, or if rising per capita income creates increased demand for more fiscal autonomy. In addition, bias is also present if we are unable to account for unobserved persistent municipal characteristics that influence long-run income. To isolate the causal effect of decentralization, we implement a two-stage least squares (2SLS) strategy, using lagged variables and institutional instruments for fiscal decentralization to address endogeneity

concerns. We construct several measures of decentralization—based on revenue, expenditure, and fiscal autonomy—to test whether different dimensions of decentralization matter.

Our empirical findings provide robust evidence that fiscal decentralization—particularly on the revenue side—accelerates income convergence across municipalities. In our baseline results, we find convergence rates in the range of 2%, consistent with (Barro, 2015) "iron law" of convergence. When decentralization is included, convergence rates increase somewhere in the range between 2.7% and 4.2% annually, depending on the specification. Our analysis also finds a positive and statistically significant relationship between fiscal decentralization and income growth, with a 1% increase in the unit used to measure decentralization triggering a 0.16% to 0.28% rise in the value-added growth rate on average. Moreover, we find that the marginal effect of decentralization is greater in poorer municipalities, where the productivity of public capital is presumably higher. This supports the idea that decentralization can have progressive effects on growth, provided that local governments have real fiscal authority.

However, our results also suggest that not all dimensions of decentralization matter equally. Expenditure-based decentralization shows no significant effect on growth or convergence. This finding lends empirical support to Bird's (2012) argument that Colombia may be experiencing a system of delegation rather than true decentralization. Under delegation, subnational governments are responsible for delivering public services but have little discretion over spending decisions or resource allocation. In such a system, the formal appearance of decentralization may mask a deeper centralization of fiscal control. Our results suggest that broadening the real authority of municipalities—particularly over revenue generation and spending decisions—could reduce local inequality.

We also document an important contrast between municipal and departmental dynamics. While municipal-level data show clear evidence of convergence,

departmental-level trends suggest divergence. A simple correlation between initial gross domestic product (GDP) per capita since 2000 and subsequent growth shows that wealthier departments have grown faster, widening the gap with poorer ones. Moreover, the dispersion of departmental per capita income has remained virtually unchanged since 2006, despite some improvement in the early 2000s. This divergence highlights a key paradox in spatial analysis, known as Simpson's Paradox, that occurs when the relationship between variables appears to be different or even reversed when analyzed at different geographic scales. This means that what is true for a larger area might not be true for a smaller, more localized area. Not only are municipalities the main units of public service provision and the focus of most spending allocations, particularly through transfers from the national government, but using municipalities as the appropriate scale for evaluating the growth effects of decentralization allows us to capture convergence within departments.

This paper contributes to three strands of literature. First, it builds on the growing body of work that uses remote sensing data—particularly satellite-recorded Night-Time Lights—to measure economic activity in the absence of reliable subnational income data. The pioneering work of (Henderson et al., 2012) demonstrated that luminosity can serve as a proxy for economic growth, especially in developing countries where national statistics are infrequent or inaccurate. By applying machine learning techniques to NTLs data, this paper constructs consistent estimates of municipal income over time in Colombia, enabling the analysis of convergence dynamics at a granular level. In doing so, it contributes to the growing literature on using alternative data sources for development economics and opens new avenues for subnational policy evaluation in data-scarce environments or to look at long-term trends.

Second, the paper contributes to the literature on fiscal decentralization and its effects on economic growth and spatial inequality. Theoretical arguments grounded in fiscal federalism (Oates, 1999; Tiebout, 1956) posit that

decentralization enhances efficiency through better allocation of public resources, yet empirical findings remain mixed. Thornton (2007) highlights the ambiguous growth effects of fiscal decentralization across countries, while Filippetti and Sacchi (2016) show that the benefits of tax decentralization depend on the degree of accompanying administrative and political autonomy. In terms of inequality, (Rodriguez-Pose & Ezcurra, 2010) find that decentralization can reduce regional disparities in high-income countries but may exacerbate them in low- and middle-income ones. This paper adds to this debate by examining the effects of decentralization within a single developing country, using variation across municipalities to isolate the role of local fiscal autonomy in driving income convergence. By doing so, it tests whether decentralization's benefits are conditional on local context—particularly the productivity of public capital in poorer areas.

Finally, this study contributes to the literature on regional convergence in Colombia and the role of subnational spending in closing the gap on the provision of public goods and services, a topic that has received renewed attention in recent years. Previous work on convergence (Bonet & Meisel, 1999; Cárdenas & Pontón, 1995; Galvis-Aponte et al., 2017) and poverty persistence (Galvis-Aponte & Meisel-Roca, 2010) has largely focused on the departmental level, due to the absence of consistent municipal income data. (Lozano-Espitia & Julio-Román, 2015) find that increased fiscal autonomy had a positive effect on departments' economic growth. At the local level, (Ramírez et al., 2016) document the impact of local fiscal effort on poverty reduction, but do not explore broader income dynamics across municipalities. Faguet and Sánchez (2014) find a clear link between decentralization (mainly fiscal) and higher enrollment rates in public schools and access to public health services by poorest households. By constructing a long-run panel of municipal-level income and combining it with detailed fiscal data, our paper fills a key gap in the literature. It is, to our knowledge, one of the first studies to analyze income convergence and the role of

fiscal decentralization at the municipal level in Colombia, offering new insights into the subnational dimensions of economic development.

The remainder of the paper proceeds as follows. Section 2 reviews the institutional evolution of fiscal decentralization in Colombia and its conceptual foundations. Section 3 introduces the theoretical model of income convergence under fiscal decentralization. Section 4 presents the empirical and identification strategy. Section 5 describes the data sources and methodology used to estimate municipal income. Section 6 presents the main empirical findings, while Section 7 discusses their implications. Section 8 concludes.

2. History and Conceptual Framework

Since the 1980s, many countries have pursued fiscal decentralization—among administrative and political decentralization—to push for a more efficient public sector. For instance, from a sample of 75 developing economies, (Garman *et al.*, 2001) found that 80% were undergoing some process of political or fiscal decentralization; the case is quite similar for developed economies (Hooghe *et al.,* 2010). However, the effects of fiscal decentralization on economic growth and regional inequality remain inconclusive. The mobility of citizens and firms across jurisdictions raises important questions about the role of subnational governments in the provision of public goods and the spatial distribution of economic activity. Addressing these questions requires an analytical framework capable of identifying the channels through which decentralization influences local economic outcomes.

A. Historical Background

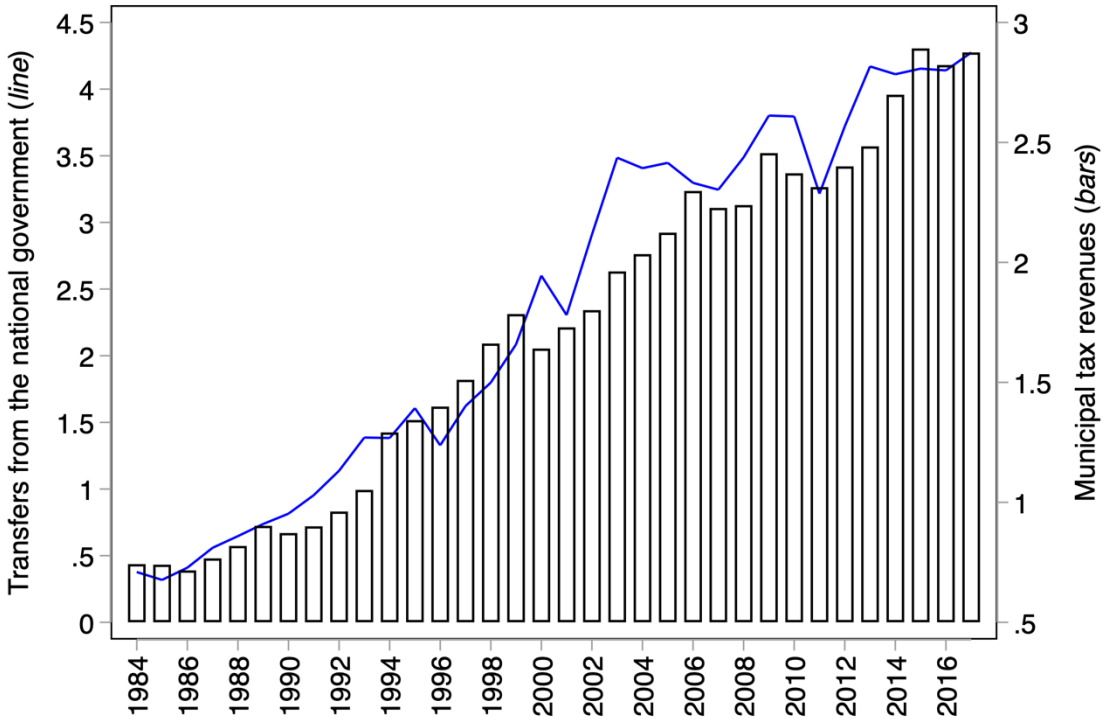
Until the early 1990s, subnational governments in Colombia had limited fiscal autonomy. The national government collected most taxes, carried out public spending, and set the rules for allocating municipal revenues, with only modest enhancements to local tax powers in the 1980s for property, excise, and sales taxes.

The 1991 Constitution redefined intergovernmental responsibilities and deepened political and administrative decentralization. Law 60 of 1993 operationalized this mandate by assigning departments and municipalities clear responsibilities for service delivery and establishing formulas for national transfers—mainly through the *situado fiscal* and the *participaciones municipales*[1]. The new fiscal measures delegated most of the provision of public services and social investment to subnational governments, particularly in education, health, sanitation, and transportation infrastructure, while increasing transfers from the central government to regional and local governments.[2] Transfers from the central government rose from 0.4% of GDP in 1984 to over 4.2% in 2017 (Figure 3), leading to a marked rise in local public spending since the mid-1990s.

Figure 3. Transfers from the National Government and Municipal Tax Revenue (% of GDP)

[1] While the *situado fiscal* regulated departments' participation on the national current income, the *participaciones municipales* regulated national transfers to municipalities. Law 715 of 2001 subsequently merged both the *situado fiscal* and the *participaciones municipales* into the General System of Participations (SGP for its acronym in Spanish).

[2] Colombian decentralization process departs from the standard model of fiscal federalism. According to Bird (1981), fiscal federalism was not a real option as most municipalities were (and still are) characterized by a small tax base that wouldn't allow them to generate the required income to meet new responsibilities.



Source: Authors' calculations based on data from DNP.

Note: Transfers from the national government and municipal tax revenues both measured as percentage of national GDP.

Transfers became the main fiscal instrument of decentralization (Maldonado, 2011), representing more than half of total local revenues on average. All but the largest municipalities remain heavily dependent on them via the General Revenue-Sharing System (Sistema General de Participaciones, SGP). Nevertheless, local revenues also improved, with municipal own-source revenue growing from 0.7% of GDP in 1984 to over 2.9% in 2017 (Figure 3). This was not due to economic growth but to improved property and industry tax collection and the introduction of new revenue streams like the gasoline surtax (Faguet & Sánchez, 2014; Ramírez et al., 2016).

Despite the growth in subnational revenues, Colombia's model is best understood as one of delegation rather than devolution (Bird, 2012). Transfers

are tightly earmarked—especially for education and health[3]—limiting local discretion (Ramírez *et al.*, 2016). Some differences exist, however, between departments and municipalities in the level of autonomy with respect to own-tax sources. While municipalities have fewer tax sources than departments, they enjoy greater flexibility in determining how much revenue they can raise and how to allocate it.

B. Fiscal Decentralization: What it is and How to Measure it.

Fiscal decentralization entails transferring decision-making powers to subnational governments over the collection and allocation of resources. It is a key instrument of decentralization, allowing lower levels of government to implement local public policies.

The foundational arguments for fiscal decentralization stem from the work of (Prest & Musgrave, 1959) and (Oates, 1974), which built upon (Tiebout, 1956) "pure theory of local expenditures". Tiebouts' model, which inspired the traditional approach to fiscal federalism,[4] posits that competition among subnational governments leads to efficient public service provision, as citizens can move ("vote with their feet") to jurisdictions with a more optimal provision of public services. Oates (1974) formalized this into the decentralization theorem, arguing that decentralized provision is welfare-enhancing when preferences vary and externalities are limited.

[3] Since 2007 the allocation of national government transfers (SGP) is as follows: 4% for special allocations (pension debt, school meals, indigenous reserves and municipalities bordering the Magdalena River), 56.2% to be spent in education, 23.5% to be spent in health, 5.2% to be spent in water and sanitation, and 11.1% for general purposes (of which 60% is earmarked to be spent in water and sanitation, sports, and other activities).

[4] For a discussion of how the Tiebout model has influenced the fiscal federalism literature see (Boadway & Tremblay, 2012).

Following this logic, there are efficiency gains when subnational governments are allowed to raise their own taxes and provide local public goods, while assigning the task of redistribution and stabilization to the national government (Boadway & Tremblay, 2012). To support this, central governments use transfers to internalize spillovers, close vertical and horizontal fiscal gaps, and equalize differences in fiscal capacity. However, such disparities in local capacity may undermine the benefits of decentralization (Prud'homme, 1995; Rodriguez-Pose & Ezcurra, 2010), potentially widening regional inequalities.

Competing theories have produced mixed empirical findings about decentralization's impact on growth and socioeconomic outcomes. Measurement challenges and endogeneity are partly responsible for this ambiguity. Despite progress in developing better indicators of fiscal decentralization—partly the result of improvements in the quality and granularity of available data—, properly addressing endogeneity remains challenging.

Measuring the degree of fiscal decentralization across subnational units is not as straightforward as one might predict. First, fiscal decentralization is usually a two-sided reform affecting both revenues and expenditures. Second, the devolution of decision-making powers from central to subnational governments is a multi-dimensional process (Martinez-Vazquez & McNab, 2003), as subnational governments face different degrees of effective autonomy over the collection and allocation of expenditures. Third, fiscal decentralization involves a complex network of flows between central, regional, and local governments, making the measurement of real fiscal resources available at each government level challenging. Therefore, no single measure can adequately capture all components to quantify the degree of fiscal decentralization. (Martinez-Vazquez *et al., 2017)* suggests including all distinct components relating to the measurement of fiscal decentralization separately in regression models in the most flexible

functional form, reducing the loss of information resulting from measures that aggregate into a single indicator all dimensions of fiscal decentralization.

Studying decentralization within a single country like Colombia, which has a comprehensive dataset of municipal fiscal executions compiled since the 1980s, allows us to effectively measure the degree of revenue and expenditure autonomy of subnational governments. In other words, those funds over which subnational governments have greater discretion. We use two different measures of fiscal decentralization, reflecting both sides of the budget:

(i) ***Locally raised own revenues.*** Measures the fiscal capacity of each municipality. It is estimated as follows: revenue raised from local taxes as a share of total revenue excluding capital income (royalties, grants, local or foreign loans, gross operating surplus, interest).

(ii) ***Autonomy on expenditure decisions.*** Measures the degree of discretion by local governments to allocate expenditures. It is estimated as the ratio of Freely Disposable Current Income (FDCI) to total expenditures. The FDCI has been measured annually by the Comptroller General of the Republic (CGR) since 2002.

Higher values for both measures indicate a higher degree of effective decentralization. As a robustness check, three additional measures are used to capture different degrees of local government autonomy:

(iii) ***Non-earmarked tax revenues.*** It is a narrower measure of each municipality's fiscal capacity as it considers only the taxes over which local governments have the most autonomy (excludes earmarked taxes, shared taxes, and those decided by higher levels

of government). It is estimated as follows: revenue raised from property and business tax as a share of total current revenue.

(iv) ***Transfer independence.*** Measures the importance of transfers from the national government and royalties (SGR) in revenues. It is estimated as follows:

$$1 - [(SGP + SGR + other\ transfers) / total\ revenues]$$

(v) ***Municipal independence.*** Captures the extent to which transfers from the national government to local governments are subject to the intervention of departmental governments (Faguet & Sánchez, 2014). It is measured as a dummy variable that registers which municipalities are classified as "certified" to manage transfers for education and health expenditure.[5]

Now, as discussed in the literature, these measures of fiscal decentralization are likely to create problems of endogeneity in growth equations or those estimating regional inequality. While governments could have implemented decentralization reforms in an effort to increase subnational economic growth or reduce spatial disparities, higher growth rates most certainly increase tax collection, which will be reflected in higher values of the different decentralization measures. Therefore, endogeneity issues could arise not only through omitted variables but also from possible reverse causality (Kyriacou *et al.*, 2015; Martinez-Vazquez *et al.*, 2017). Section 4 includes a detailed explanation of the instruments that deal with this possible endogeneity. On the other hand, decentralization and the provision of public goods at that local level are likely to produce mobile capital. If local investments are directed toward public goods that enhance human capital, such as education and health, this can have the counteractive effect of incentivizing migration of skilled workers to more affluent

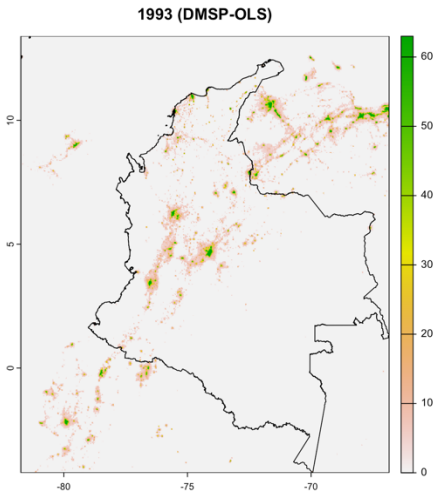
[5] While certified municipalities receive transfers directly from the national government, non-certified municipalities receive these resources via departmental governments, which have a say over the conditions to distribute these funds to local governments, particularly in the provision of education and health.

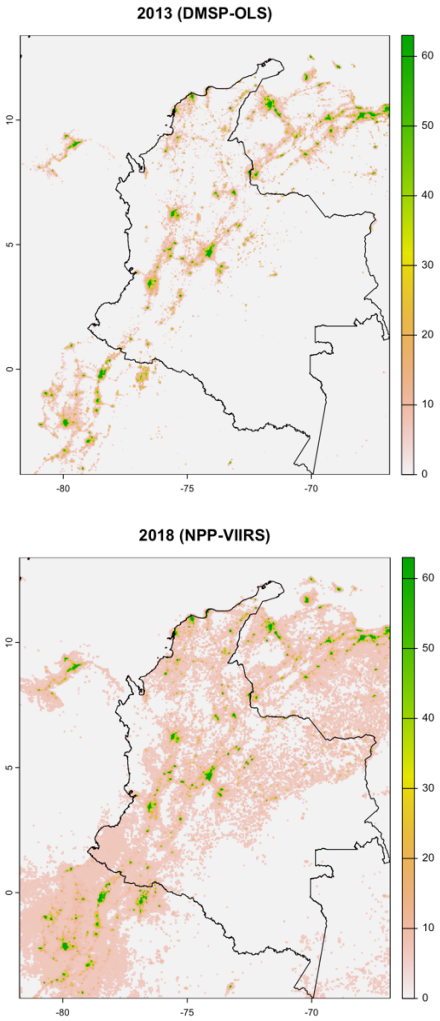
areas, which will underestimate the true effect of fiscal decentralization on growth regressions over time.

C. Measuring Municipal Economic Activity Using Night-Time Lights

Although the statistical capacity of institutions like the Department of National Statistics (DANE, for its acronym in Spanish) has improved, Colombia still lacks regular, municipality-level income and welfare surveys. In this context, Night-Time Lights (NTLs) offer a practical alternative for estimating economic activity and income distribution at the micro-spatial scale (Beyer *et al.*, 2022; Henderson *et al.*, 2012; Pérez-Sindín *et al.*, 2021; Pinkovskiy & Sala-i-Martin, 2016). NTLs capture both outdoor and indoor night-time consumption, as well as certain productive activities like night mining and construction, making them useful proxies for economic activity. Figure 4 shows NTLs changes in Colombia between 1993 and 2018, based on data from the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) and the Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS), both described in Section 5.

Figure 4. DMSP-OLS & NPP-VIIRS Night-Time Lights (1993, 2013, 2018)





Source: Li and Zhou (2017)

Note: The three panels show luminosity as measured by the Digital Number (DN) captured by the DMSP-OLS (1993 and 2013) and NPP-VIIRS (2018) satellites within Colombia. DN values range from 0 to 63, where 0 indicates no detectable light and 63 represents the maximum light intensity detectable by the satellite.

Like other proxies of economic activity, NTLs have strengths and limitations. A major issue is sensor saturation—both at the upper and lower bounds. In dense urban areas, light emissions often exceed the maximum recordable value, underestimating activity. Conversely, in sparsely populated rural areas, the absence of detectable light results in a Digital Number (DN) of zero, which may misrepresent actual economic activity.

Despite these issues, NTLs are highly correlated with economic indicators. They explain long-term national income trends (Beyer et al., 2022; Chen & Nordhaus, 2011; Henderson et al., 2012; Pinkovskiy & Sala-i-Martin, 2016) and capture short-term subnational variation (Hodler & Raschky, 2014; Michalopoulos & Papaioannou, 2013, 2014). A key advantage is that their measurement errors—often due to weather or calibration—are independent of errors in national accounts. Table 1 presents the correlation between NTLs and per capita value-added using Colombian data. Per capita value-added explains more than 75% of the variation in NTLs across municipalities. Prediction errors by quartile are minimal, further supporting their reliability.

Table 1. Correlation Between Local Per Capita Value Added and Night-Time Lights (2011 – 2018)

Dependent Variable	Slope	S.E.	R2-Within	R2-Between
Panel A: Univariate Regression				
Night-Time Lights	89.5974	(0.000)	10.8%	75.6%
	Quartile 1 (%)	Quartile 2 (%)	Quartile 3 (%)	Quartile 4 (%)
Panel B: Prediction errors per quartile				
Night-Time Lights	-0.0056	-0.0323	-0.0091	1.9550

Source: Authors' calculations based on data from DANE and Li and Zhou (2017)

Note: All regressions include year fixed effects plus a constant. Value added per capita is rescaled to millions ($COP). Prediction errors are measured in percentage points.

Recent literature has raised concerns about the declining sensitivity of NTLs due to widespread use of LEDs, which emit wavelengths harder for satellites to detect. Still, as shown in Table 1, NTLs remain effective predictors of local economic activity. Moreover, this study uses data calibrated with NPP-VIIRS sensors, which offer better radiometric detection for short wavelengths (discussed in Section 5.B). Finally, while the effectiveness of NTLs in rural and low-income contexts is debated, evidence remains mixed. Chen and Nordhaus

(2011) found NTLs unreliable in low-GDP areas. In contrast, (Pérez-Sindín et al., 2021) found that even in rural Colombian municipalities—particularly those not covered by forests—NTLs serve as useful proxies for economic activity.

3. Conditional Convergence and Fiscal Policy

This section presents an augmented neoclassical growth model to test empirically for convergence across Colombian municipalities. As in the spirit of (Gennaioli et al., 2014), the model allows for limited factor mobility. Within a single country, factors can flow more easily across municipal borders. In this sense, labor and capital (and thus human capital) can move to municipalities where they are better remunerated. The effect of fiscal policy—and, by extension, fiscal decentralization—on income convergence is modeled by explicitly incorporating the public sector into the production technology. The underlying assumption is that government spending on public goods does not substitute for private capital accumulation.

Each municipality, indexed by $i \in [0,1]$, uses a Cobb-Douglas technology to combine private-sector capital K_{P_i}, public-sector capital K_{G_i}, human capital or quality-adjusted labor H_i, and raw labor L_i. Each municipality is also characterized by a parameter that indexes its relative position to an exogenous technology frontier $\bar{A}$, $\hat{A}_i \in [0,1]$, so that total factor productivity (TFP) in the municipality i is given by $A_i = \hat{A}_i \bar{A}$.[6] No technological growth over time is assumed, given the inability to directly assess the role of TFP growth with the available data. Therefore, the production function featured by a municipality at time t is given by:

[6] For a municipality close to the frontier, continued growth is only possible if the frontier moves, but for municipalities far from the frontier, $\hat{A}_i$ can change rapidly due to the implementation of new policies or better institutions at the municipal level. Endogenous growth theory is particularly concerned at the forces that determine the evolution of the technology frontier, $\bar{A}$. But in the case of developing countries this is considered exogenous.

$$y_{i,t} = A_i {k_{P}}_i^{a} {k_{G}}_i^{b} h_i^{c} \ , \tag{1}$$

where output per worker, $y \equiv Y/L$, depends on capital-labor ratios, $k \equiv K/L$, and human capital per worker, $h \equiv H/L$. Consistent with the existing literature, the analysis assumes that local governments operate under a balanced budget, thereby excluding the possibility of debt-financed government spending. In addition, public spending (G) is financed through a flat-rate income tax τ_i. In this setting, local governments influence private capital accumulation through the tax rate and public capital accumulation through public spending. All government spending is assumed to create productive public capital (Gennaioli *et al.*, 2014). In this case, the composition of government expenditures does not affect the economic growth rate. Municipalities differ in terms of the share of income that households invest as physical and human capital, s_{k_i} and s_{h_i}, which are assumed to be a constant factor of output, in the tax rate set by local governments to finance spending, τ_i, and in terms of population growth rates, n_i.

The capital endowments —both physical and human— of municipality i at time $t+1$ can be approximated by the following *laws of motion*, assuming equal depreciation rates δ for different kinds of capital:

$$\hat{k}_{P_{i,t+1}} \cong s_{k_i}(1-\tau_i) y_{i,t} + (1-\delta-n)\hat{k}_{P_{i,t}} \ , \tag{2}$$

$$k_{G_{i,t+1}} \cong \tau_i y_{i,t} + (1-\delta-n) k_{G_{i,t}} \ , \tag{3}$$

$$\hat{h}_{i,t+1} \cong s_{h_i} y_{i,t} + (1-\delta-n)\hat{h}_{i,t} \ . \tag{4}$$

Following (Gennaioli *et al.*, 2014), the relationship between the initial private capital endowments, $\widehat{K}_{P_{i,t+1}}$and $\widehat{H}_{i,t+1}$, and the capital employed in production,

$K_{P_{i,t+1}}$ and $H_{i,t+1}$, depends on capital mobility. If mobility costs are infinite, each municipality employs its capital endowment, such that $K_{P_{i,t+1}} = \widehat{K}_{P_{i,t+1}}$ and $H_{i,t+1} = \widehat{H}_{i,t+1}$. But if mobility costs are zero, the returns on capital are equalized across municipalities. Note that in our setting public capital is created at the local level and, therefore, is fully employed within its borders, so that $K_{G_{i,t+1}} = \widehat{K}_{G_{i,t+1}}$. In addition, capital migrates after new capital is created but before production happens.

The specification for private physical and human capital employed by municipality i at time $t+1$ is adopted from (Gennaioli et al., 2014) and is expressed as follows:

$$k_{P_{i,t+1}} = \phi_{k_{t+1}} \cdot \left(\hat{k}_{P_{i,t+1}}\right)^{\sigma} \cdot \left(\hat{A}_i \cdot k_{P_{t+1}}\right)^{1-\sigma} , \tag{5}$$

$$h_{i,t+1} = \phi_{h_{t+1}} \cdot \left(\hat{h}_{i,t+1}\right)^{\sigma} \cdot \left(\hat{A}_i \cdot h_{t+1}\right)^{1-\sigma} , \tag{6}$$

where $\sigma \in [0,1]$ proxies for mobility costs, which are assumed equal for physical and human capital for simplicity, $\phi_{k_{t+1}}$ and $\phi_{h_{t+1}}$ are normalization factors common to all municipalities, and $k_{P_{t+1}}$ and h_{t+1} are the aggregate private physical and human capital in the country.[7]

Now, to obtain closed form solutions, assume no population growth (n =0) and full depreciation ($\delta = 1$). From Eqs. (2)-(6) we can derive expressions for per capita growth for all factors employed by municipality i. Exploiting the fact that Eq. (1) implies that the growth rate in municipality i between times t and $t+1$ is given by $ln\left(y_{i,t+1}/y_{i,t}\right)$, the following result can be derived:

[7] Normalization factors are defined as follow by Gennaioli *et al.* (2014):

$$\phi_{k_{t+1}} \equiv \frac{k_{P_{t+1}}^{\sigma}}{\int (\hat{k}_{P_{i,t+1}})^{\sigma} (\hat{A}_i)^{1-\sigma} d_i}; \quad \phi_{h_{t+1}} \equiv \frac{h_{t+1}^{\sigma}}{\int (\hat{h}_{i,t+1})^{\sigma} (\hat{A}_i)^{1-\sigma} d_i} .$$

Proposition 1 (Gennaioli et al., 2014) *In steady state there exists a unique equilibrium that is characterized by non-zero municipal per capita incomes* y_i^* *and aggregate per capita income* $y^* = \int y_i^* di$. *Starting from non-zero income, each municipality converges to this steady state according to the equation:*

$$\frac{y_{i,t+1}}{y_{i,t}} = \Pi \cdot \left(s_{k_i}(1-\tau_i)\right)^{a\sigma} \cdot (\tau_i)^b \cdot \left(s_{h_i}\right)^{c\sigma} \cdot \left(y_{i,t}\right)^{\sigma(a+c)+(b-1)} \cdot \left(y_t\right)^{(1-\sigma)(a+c)}, \tag{7}$$

where,

$$\Pi = \left(\phi_{k_{t+1}}\right)^a \cdot \left(\phi_{h_{t+1}}\right)^c \cdot (s_k)^{a(1-\sigma)} \cdot (s_h)^{c(1-\sigma)} \cdot A_i \cdot \left(\hat{A}_i\right)^{(1-\sigma)(a+c)}.$$

Proposition 1 suggests that because of diminishing returns, municipal per capita incomes eventually converge to their steady state.

If we had complete information at the municipal level on private and public capital accumulation and human capital, then one could simply take logs and estimate Eq. (7). However, due to the absence of data on municipal private physical capital, it is assumed that private capital accumulation is a function of both public and human capital, such that $K_P = \Gamma K_G^{\theta} H^{1-\theta}$, where Γ maps how productive public capital and human capital are used to accumulate private capital, and $0 < \theta < 1$. So, by using the above definition for private capital and relabeling terms, after taking logs Eq. (7) can be written as:

$$ln\left(\frac{y_{i,t+1}}{y_{i,t}}\right) = \begin{bmatrix} \upsilon_{t+1} + \eta_i + \gamma \cdot ln\, \tau_i + \alpha\sigma \cdot ln\, s_{h_i} \\ -(1-\alpha\sigma-\gamma) \cdot ln\, y_{i,t} + \alpha(1-\sigma) \cdot ln\, y_t + \varepsilon_{i,t+1} \end{bmatrix}, \tag{8}$$

where $\alpha = a(1-\theta) + c$ and $\gamma = a\theta + b$. The influence of characteristics that are common to all units but vary across time is captured by υ_{t+1}, municipal specific

relative productivity is captured by η_i, and $\varepsilon_{i,t+1}$ captures idiosyncratic shocks experienced by municipality i at time $t+1$. Note that v_{t+1} is comprise of the normalization parameter ϕ_h and the aggregate human capital share, s_h. In the empirical estimation, time fixed effects are frequently included to capture the influence of time-varying factors, including national per capita income, y_t.

4. Empirical Approach

Eq. (8) analyzes the determinants of municipal per capita income growth. The coefficient on initial income per capita $y_{i,t}$ captures conditional convergence: a negative sign implies that poorer municipalities grow faster. The speed of convergence is also influenced by relative productivity, the human capital saving rate, and national per capita income. The latter implies that holding local income constant, higher national income boosts local growth by increasing capital availability.

According to Eq. (7), government consumption has two opposing effects on growth: it directly contributes to productive public capital accumulation but may crowd out private investment $\left[s_{k_i}(1-\tau_i)\right]$. The overall effect will be driven by capital productivity. As long as capital productivity is the same in both public and private sectors, changes in fiscal policy will have neutral effects on growth. However, Eq. (8) assumes no crowding out, based on how the relationship between public and private capital is modeled.

Furthermore, Eq. (8) also predicts that growth increases with human capital accumulation. Increasing human capital is harder to achieve than physical capital growth. Human capital accumulation can be proxied using average years of schooling following the Mincerian equation $h_i = e^{\lambda S}$, where returns to education are captured by parameter λ.

There are two well-known issues when estimating cross-country (or in this case cross-municipal) growth regressions. First, omitted variables bias. Since TFP is unobservable, OLS may create downward bias on the convergence rate. Including municipal fixed effects, as often done, addresses this but introduces a Hurwicz-type bias that overstates convergence.[8] This is especially true in datasets with short sample lengths—*i.e.*, the number of years covered and not the frequency of the observation (Barro, 2015). Given that single-country analyses likely suffer less from omitted variable bias than cross-country ones, this study excludes municipal fixed effects in the main specification.

Now, the second issue in growth regressions is the potential for reverse causality. Fiscal decentralization may be endogenous if economic growth affects decentralization or vice versa (Gemmell et al., 2013). The paper addresses this by testing three instruments. First, we consider four-year lags of the fiscal decentralization measures. This common approach in the literature (Akai & Sakata, 2002; Del Granado et al., 2018; Filippetti & Sacchi, 2016; Gemmell et al., 2013; Ligthart & Van Oudheusden, 2015; Sacchi & Salotti, 2014) helps mitigate contemporaneous endogeneity problems, as current economic performance is less likely to influence fiscal policy decisions taken in the past.

Second, in line with (Faguet & Sánchez, 2014) we use the share of exogenous transfers (i.e., not associated with conditions at the local level such as relative poverty, government efficiency, or access to public services) in total expenditure following predetermined formulas set by the central government in articles 356 and 357 in the Political Constitution, Laws 60 of 1993, Legislative Act 1 of 1995, 715 of 2001, and 1176 of 2007, to account for the possible endogeneity in the expenditure composition. The logic behind this instrument is twofold. First, it is unlikely to be associated with local conditions affecting income growth, except

[8] See Arellano and Bond (1991) and Nerlove (2000) for further reference.

through its influence on the degree of expenditure autonomy, as higher transfers reduce the pressure on local administrations to finance public investments. Second, since these transfers are determined by formulas set by the central government—often based on historical values of municipal shares in national revenue— they can be considered exogenous to contemporary factors influencing each municipality.

Third, as property tax accounts for most municipal tax revenues, this study exploits the idiosyncratic timing of cadastral updates (Martínez, 2025). Because cadastral information sets out the tax base used by municipalities for the property tax, cadastral updates will likely increase municipal revenues. In addition, by law, municipalities should update cadasters every five years. Although this rarely happens, the instrument is a policy decision of the national government carried out by the *Geographic Institute Agustín Codazzi*—except for Bogotá, Cali, Medellín, and the rest of municipalities in the purview of the Department of Antioquia, which have their own cadastral agencies—which, in principle, should not affect growth rates through other means than by increasing local tax revenues. Since municipal cadastral updates in a year can cover either urban or rural areas or both, the instrument is defined as the number of years since the last update.

Finally, we include demographic, geographic, institutional, and economic covariates commonly used in growth regressions (Barro, 2015; Cárdenas & Pontón, 1995; Gennaioli et al., 2014). Since municipal value added per capita is estimated using remotely sensed NTLs (See Section 5.B), current value added is instrumented with its four-year lag to mitigate measurement error.

5. Data

Our findings are based on an initial sample of 833 municipalities in Colombia,[9] where different fiscal and socio-demographic indicators are available. See the Online Appendix for additional details on variables and sources of information.

A. Fiscal and Socio-Demographic Data

As detailed in Section 2.B, fiscal and budgetary executions were used to estimate different measures of fiscal decentralization. A broad array of municipal fiscal indicators has been published by the National Planning Department (DNP for its acronym in Spanish) since 1984, while a more detailed dataset of municipal budgetary executions is available from 2002 onwards. Colombia's Statistical Department has estimated municipal value-added since 2011 and is available uninterruptedly for all municipalities. Data on the production of oil, gas, coal and precious metals was obtained from the administrative registries of the Ministry of Mines and DNP. At the same time, all geographic controls were calculated using DANE's geographical information system.

Population estimates are annually projected by DANE from census data; these datasets are publicly available for the complete timeframe of the study. Average years of schooling, which account for human capital in the general model specification in Eq. (8), are interpolated between the national censuses (1993, 2005, and 2018). Additional demographic and institutional controls are collected from the Center for Development Studies at Universidad de los Andes (CEDE, for its acronym in Spanish) municipal dataset, which offers a wide array of indicators encompassing five categories: state capacity, conflict and violence, education, government, health and services, and agriculture.

[9] As of 2018, Colombia had 1,106 official municipalities and 11 districts, which include the capital district of Bogotá.

Following (Perry et al., 2014), the number of education facilities per student and the number of teachers per student are used as proxies for the number of public officials in each municipality, these variables are available for most municipalities from 1996 onwards. Furthermore, the ongoing armed conflict has played an important role in the development of municipal capacities, with direct implications for long-term growth dynamics. The analysis includes variables that capture incidences of conflict directed at specific individuals (e.g., number of homicides) as well as those affecting the broader population (e.g., terrorist attacks and anti-personnel mines). All conflict-related variables are recorded by CEDE, based on the number of events reported in the Unique Registry of Victims (URV). To proxy internal migration—which, as discussed in Section 2.B, may influence the effect of fiscal policy on municipal growth—the total number of individuals entering and leaving each municipality due to forced displacement, as reported by the URV, is used.

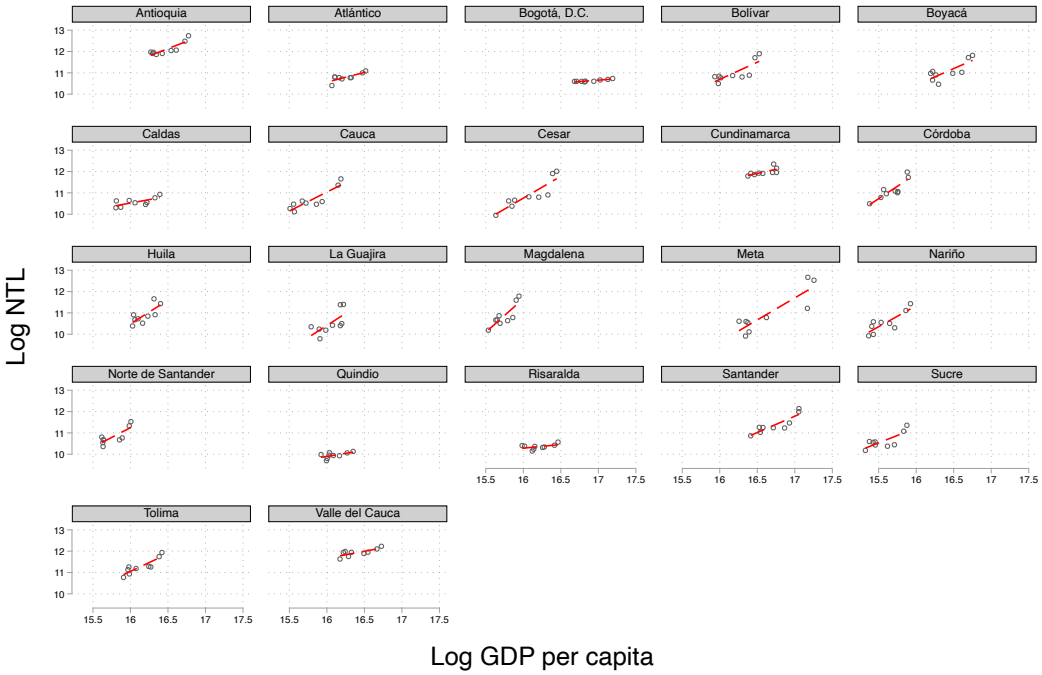
B. A Simple Artificial Neural Network to Predict Value Added at the Municipal Scale

A growing number of studies have applied machine learning—particularly artificial neural networks (ANNs)—to estimate economic activity using Night-Time Lights data (Jean et al., 2016; Keola et al., 2015; Khachiyan et al., 2022). One key advantage of neural networks is their ability to capture non-linear relationships between variables, often outperforming traditional regression methods when non-linearity is present.

While cross-country analyses show that the relationship between income and NTLs varies substantially (Hu & Yao, 2022; Phan, 2023), estimating income within a single country avoids cross-institutional variability. However, regional disparities within Colombia still influence the income-NTLs relationship, suggesting that linear models may be insufficient. Figure 5 illustrates how this relationship differs across departments, likely reflecting differences in

institutional quality, productive structure, and light-intensity of economic activities.

Figure 5. Log GDP Per Capita and Log Night-Time Lights by Department



Source: Authors' calculations based on GDP data from DANE and NTLs data from (Li & Zhou, 2017).

Note: All regressions include year fixed effects plus a constant. Value added per capita is rescaled to millions ($COP). Prediction errors are measured in percentage points.

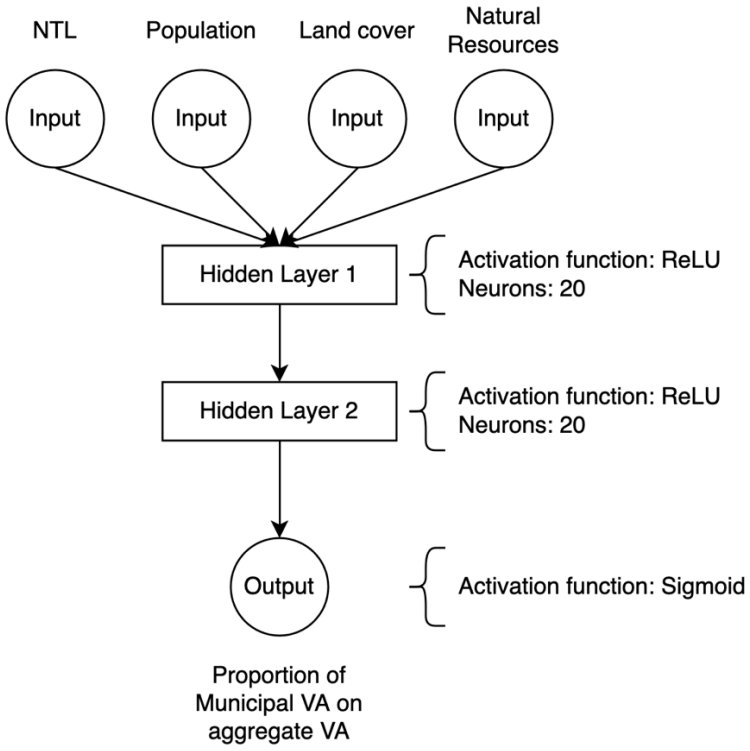
To estimate municipal per capita value added (VA), NTLs data was used as input in an ANN model. The NTLs series was derived from DMSP-OLS (1992–2013) and NPP-VIIRS (2013–present). A calibrated series produced by (Li & Zhou, 2017), which integrates both the DMSP-OLS and NPP-VIIRS, was used to obtain a continuous and harmonized series across the two satelites. To account for economic activity not captured by light emissions—especially in rural or agricultural regions—the model also incorporated land cover yearly estimates from the MapBiomas 1.0 collection, including urban sprawl, agricultural expansion, silvopastoral areas, oil palm plantations, and mining.

To avoid populating the sample with bottom-coded pixels—an issue particularly prevalent in larger but poorer regions—the approach proposed by (Michalopoulos & Papaioannou, 2013, 2014) was followed, whereby 0.01 was added to bottom-coded pixels to account for unobserved economic activity. This procedure is justified since unlit pixels do not necessarily mean the absence of light or economic activity; instead, they are most likely the result of satellite saturation. Furthermore, departments with systematic issues of bottom-coding were also dropped from the sample, which includes all departments that were considered national territories before the 1991 constitution,[10] Chocó, and Caquetá. The Online Appendix summarizes the average number of municipalities within each department with a DN sum equal to 0 in a given year.

Given Colombia's heterogeneous geography and uneven development, a simple ANN architecture was designed to capture non-linearities in the income–NTLs relationship while incorporating other key inputs such as agriculture, oil production, and population. The model consists of an input layer, two hidden layers, and a sigmoid-activated output layer, trained to estimate the share of municipal value-added in national value-added per year (see Figure 6). Input and output variables were normalized to enhance optimization. Hyperparameters for the hidden layers were optimized via cross-validation, while training was conducted over 500 epochs using the Adam optimizer, known for its adaptive learning rate and memory efficiency. The Online Appendix contains a detailed workflow.

Figure 6. Neural Network Pipeline

[10] These departments are: Amazonas, Arauca, Casanare, Guainía, Guaviare, Putumayo, San Andrés, Providencia y Santa Catalina, Vaupés and Vichada.

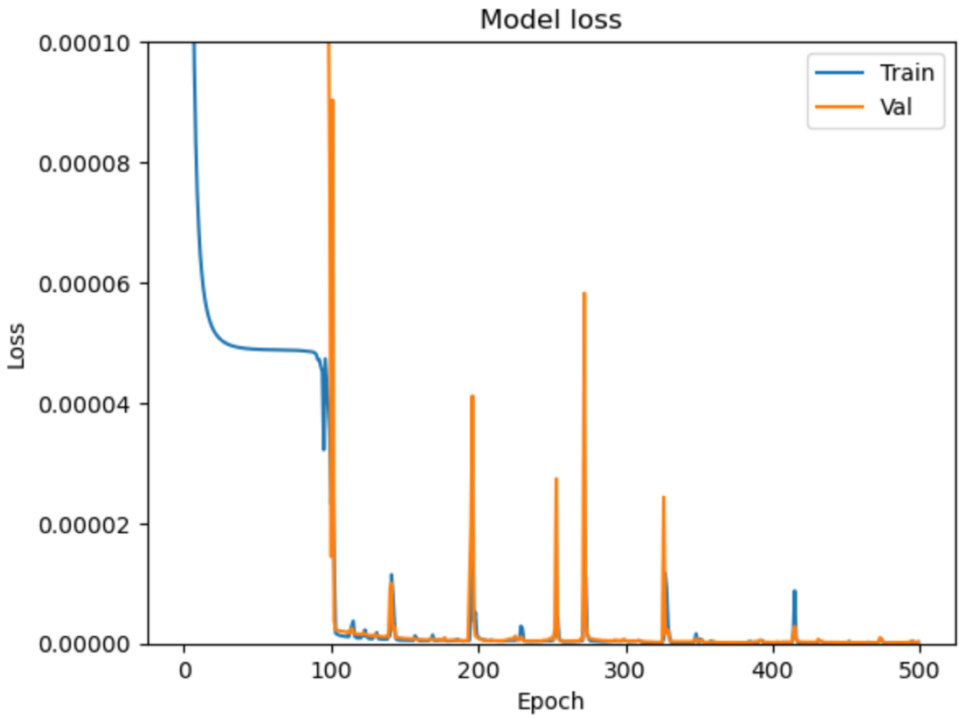


Source: Authors' elaboration.

The model used ten inputs across four categories: (1) nightlights (municipal and urban DN sums), (2) population (interpolated from the 2018 census), (3) land cover (urban, agriculture, forestry, mining), and (4) oil production (annual). A time variable was also included.

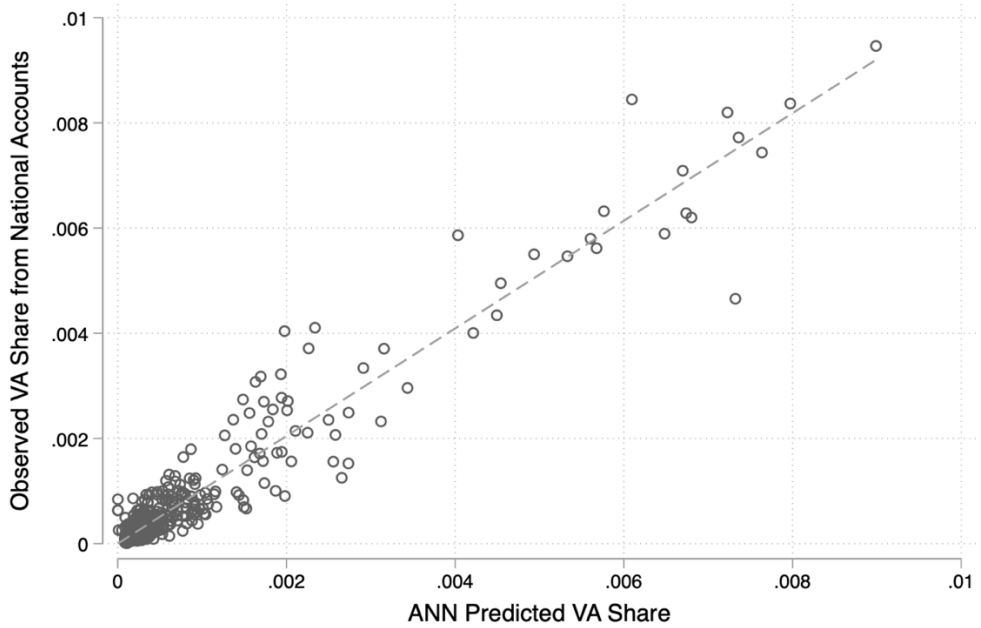
Model performance was evaluated using mean squared error between predicted and actual value-added shares. The ANN converged within the first 100 epochs, and validation loss remained stable (Figure 7). A univariate regression of predicted vs. observed value-added shares yielded a slope near 1 and R^2 of 0.99 (Figure 8), indicating high predictive accuracy.

Figure 7. Train and Validation Loss During Model Training



Source: Authors' elaboration based on model training results.

Figure 8. Correlation Between Value Added Prediction and Observed Share (Test Set)



Source: Authors' elaboration based on model testing results. Observed municipal value-added data from DANE.
Note: All regressions include year fixed effects plus a constant. Value added per capita is rescaled to millions ($COP). Prediction errors are measured in percentage points.

Despite strong performance, the model presents limitations. Predictions are based on observed relationships from 2011–2018—the only years with available municipal value-added labels—and may not capture structural dynamics before 2011. Additionally, the ANN is trained on value-added shares rather than absolute or per capita values. While this choice improves training stability, it requires an extra step to convert predicted shares into per capita VA. This is done by distributing national value added from DANE using predicted shares and dividing it by municipal population estimates. The transformation may introduce discrepancies from observed value-added values. To mitigate this, an outlier analysis excluded municipalities with extreme growth rates, as detailed in the Online Appendix.

6. Results

Table 2 compares growth regressions across different model specifications, each one including a different fiscal decentralization measure described in Section 2.B. Although it would be desirable to control for all observed and unobserved determinants of growth through municipal fixed effects, doing so renders unlikely high convergence rates, which are consistent with the Hurwicz-type bias described in Section 4. Therefore, all models include only year fixed effects.

The main results use yearly intervals for per capita value-added growth. Nevertheless, regressions using three-year growth averages are also reported in the Online Appendix, proving that convergence results are also consistent even when using a more flexible growth timeframe. The first column gives us the baseline OLS results for conditional convergence, excluding variables accounting for fiscal decentralization. Columns (2) and (3) test the main decentralization

measures, with column (2) evaluating locally raised own revenue and column (3) using an expenditure-based decentralization measure based on autonomy of expenditure decisions. Columns (4)-(6) include the three complementary measures discussed in Section 2.B: non-earmarked tax revenues, national government revenue-sharing independence, and municipal expenditure autonomy.

Columns (2)-(6) report the 2SLS approach using four-year lags of the decentralization measures, the number of years since the last cadastral update, the weight of exogenous transfers in public expenditure, and the interaction between the lags of current per capita value added and the lags of the decentralization measure as instruments. First-stage results, presented in the Online Appendix, indicate a strong relationship between the instruments and the endogenous regressors, as evidenced by high Sanderson-Windmeijer F-statistics and relatively elevated Shea partial R-squared values across all first-stage regressions. Furthermore, Table 2 reports the Anderson-Rubin F-statistics for the joint relevance of all instruments, accounting for weak instrument problems, confirming that the instruments are relevant. On the other hand, the small Hansen J-statistic in Columns (2), (3), (4), and (6) suggests that the overidentifying restrictions hold for most model specifications, providing partial support for the validity of the included instruments. Notably, after using the Generalized Method of Moments (GMM) as an alternative estimation method, the Hansen J-statistic remained unchanged, reinforcing this conclusion. It's worth mentioning that observations are reduced in Columns (2), (4), and (5) due to the selection of instruments in the IV approach. Furthermore, observations drastically fall for Columns (3) and (6) since information on freely disposable current revenue and municipality certification (see Section 2.B) is only available for the year 2002 onward.

Table 2. Determinants of Growth (1-year intervals)

Dependent variable: Yearly per capita VA growth rate						
	(1)	(2)	(3)	(4)	(5)	(6)
Ln (VA pc municipality)	-0.022***	-0.041***	-0.031	-0.042***	-0.036***	-0.027***
	(0.002)	(0.004)	(0.025)	(0.005)	(0.006)	(0.003)
Ln (Locally raised own revenues)		0.277***				
		(0.038)				
Ln (Va pc municipality) x Ln (Locally raised own revenues)		-0.018***				
		(0.002)				
Ln (Autonomy on expenditure)			0.057			
			(0.267)			
Ln (VA pc municipality) x Ln (Autonomy on expenditure)			-0.004			
			(0.016)			
Ln (non-earmarked tax revenues)				0.176***		
				(0.030)		
Ln (VA pc municipality) x Ln (non-earmarked tax revenues)				-0.011***		
				(0.002)		
Ln (Transfer independence)					0.160***	
					(0.057)	
Ln (VA pc municipality) x Ln (Transfer independence)					-0.011***	
					(0.003)	
Municipal independence						-0.079
						(0.245)
Ln (VA pc municipality) x Municipal independence						0.006
						(0.015)
Obs	18,144	13,725	7,105	13,710	13,728	8,703
Estimation	OLS	IV	IV	IV	IV	IV
R-squared	0.27	0.28	0.27	0.28	0.28	0.25
AR F-statistic	NA	25.44	18.30	23.86	23.66	20.94
Hansen J-statistic [p-value]	NA	6.198 [0.045]	3.959 [0.138]	2.581 [0.275]	11.927 [0.003]	5.551 [0.062]

Standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.0$

Note: All regressions control for population density, the Euclidian distance to the departmental capital measured in Kilometers, latitude, oil production measured as number of barrels produced in a given year, the number of educational facilities per 100,000 students, the number of teachers per 10,000 students, the number of homicides per 100,000 people,

the number of terrorist occurrences per 100,000 people, the number of antipersonnel mine occurrences per 100,000 people, the departmental inflation rate, the number of displaced individuals received by the municipality in a given year, and the number of displaced individuals expulsed by the municipality in a given year. All variables included were transformed into a logarithmic scale.

The initial results indicate that the estimated convergence rate is slightly higher than Barro's "iron law" of 2%, which is commonly observed in cross-country convergence studies. The OLS specification estimates a cross-municipal convergence rate of 2.2% annually. When the main measures of fiscal decentralization are included in columns (1) and (2), the convergence rate rises to a level between 3.1% and 4.1% per year, although only the coefficient in column (1) is statistically significant. Regarding the effect of fiscal decentralization, locally raised own revenue is positively and significantly associated with income growth, with a 1% increase in municipal tax revenue ratio resulting in a 0.28% increase in the per capita value-added growth rate. Additionally, locally raised own revenue appears to enhance the convergence rate, as indicated by the negative and significant coefficient on the interaction term. Column (3), which captures the effect of autonomy in expenditure decisions, shows the coefficient following the same direction as column (2), but the results are not statistically significant.

Columns (3) and (4) further support the positive relationship between fiscal decentralization and convergence, with non-earmarked tax revenues and transfer independence contributing to a similar rate of convergence, as seen in column (1). This adds robustness to the main results, particularly because these measures are more closely related to revenue-based decentralization. However, while the convergence rate in column (6)—which accounts for municipal autonomy—exceeds the OLS result and is statistically significant, the coefficients for the effect of municipal autonomy on growth and its interaction follow different directions than those observed in other specifications, although they are not statistically significant. This suggests an interesting trend, where

measures associated with expenditure-based decentralization show no clear relationship with income growth or cross-municipal convergence.

6.1 Regional Level Results

Table 3 compares three of the five Colombian regions—Caribbean, Pacific and Andean—across three model specifications. Row (1) evaluates locally raised own revenues; Row (2) uses autonomy of expenditure decisions; and Row (3) evaluates the more restrictive measure of expenditure-based decentralization—municipal expenditure autonomy or "independence." In general, results are consistent with the ones observed in the national sample, with locally raised own revenues having a positive and statistically significant effect over both the VA growth rate and the convergence rate. Nevertheless, small differences emerge across regional samples. The Pacific region converges at a faster 5.4% annually, whereas the Andean region exhibits a stronger effect of locally raised own revenues on growth and on the overall impact of decentralization on convergence. Conversely, the Caribbean sample exhibits a smaller effect of locally raised own revenues on both growth and convergence when compared with other regions and the national sample.

As observed in the national sample, expenditure-based decentralization (Row 2) has no statistically significant effect on convergence, with individual regions exhibiting a negative coefficient of the expenditure-based decentralization measure on growth. When using a more restrictive measure of expenditure autonomy (Row 3), only the Pacific region exhibits a positive effect of expenditure-based decentralization on growth and convergence.

Table 3. Determinants of Growth (1-year intervals) in Three Colombian Regions

Dependent variable: Yearly per capita VA growth rate							
		Caribbean Region		**Pacific Region**		**Andean Region**	
		Coefficient	Obs.	Coefficient	Obs.	Coefficient	Obs.
(1)	Ln (VA pc municipality)	-0.044*** (0.011)	2548	-0.054*** (0.013)	2168	0.042*** (0.004)	8825
Revenue based decentralization (Locally raised own revenues)	Ln (Decentralization)	0.165* (0.096)	2548	0.233* (0.131)	2168	0.313* (0.047)	8825
	Ln (Va pc municipality) x Ln (Decentralization)	-0.011* (0.006)	2548	-0.016* (0.008)	2168	0.020* (0.003)	8825
(2)	Ln (VA pc municipality)	-0.015 (0.087)	1312	-0.036 (0.062)	1098	0.024 (0.055)	4606
Expenditure based decentralization (Autonomy of expenditure decisions)	Ln (Decentralization)	-0.187 (0.686)	1312	-0.061 (0.530)	1098	-0.545 (0.644)	4606
	Ln (Va pc municipality) x Ln (Decentralization)	-0.013 (0.042)	1312	0.001 (0.033)	1098	0.032 (0.039)	4606
(3)	Ln (VA pc municipality)	-0.035*** (0.009)	1860	-0.043*** (0.012)	1374	0.025*** (0.003)	5350
Expenditure based decentralization (Municipal independence)	Ln (Decentralization)	0.576 (0.386)	1860	2.073*** (0.709)	1374	0.175 (0.414)	5350
	Ln (Va pc municipality) x Ln (Decentralization)	0.036 (0.024)	1860	-0.126*** (0.043)	1374	-0.009 (0.025)	5350

Standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.0$

Note: All regressions control for population density, the Euclidian distance to the departmental capital measured in Kilometers, latitude, oil production measured as number of barrels produced in a given year, the number of educational facilities per 100,000 students, the number of teachers per 10,000 students, the number of homicides per 100,000 people, the number of terrorist occurrences per 100,000 people, the number of antipersonnel mine occurrences per 100,000 people, the departmental inflation rate, the number of displaced individuals received by the municipality in a given year, and the number of displaced individuals expulsed by the municipality in a given year. All variables included were transformed into a logarithmic scale. Region were selected using administrative boundaries of departments.

7. Discussion

The results for revenue-based decentralization align with what would be expected from cross-municipal convergence rates. As suggested by Gennaioli *et al.* (2014), lower barriers to capital mobility between regions (in this case, municipalities) within the same country allow for income to equalize across

regions at a faster rate than observed in cross-country regressions. As explained in Section 3 and formally established in Eq. (8), the public sector can play a significant role in the production function of municipalities and, consequently, in their growth rate, which in turn enhances convergence. However, the approach used in this paper still falls short of addressing why—despite high convergence rates—substantial income disparities persist between municipalities in Colombia. It is important to emphasize that although the model controls for internal migration to account for capital movement across regions, it does not capture other key determinants of growth, such as technological diffusion across municipalities and the quality of human capital.

Nevertheless, as it has been extensively stated in this paper and in the literature (Bird, 2012; Filippetti & Sacchi, 2016; Gemmell et al., 2013; Kyriacou, Muinelo-Gallo, et al., 2015; Thornton, 2007), fiscal decentralization is a two-sided issue. Lower growth rates in the context of fiscal decentralization can be influenced by deficient political and administrative decentralization (Filippetti & Sacchi, 2016), meaning that local governments may lack sufficient autonomy in budget allocation and political decision-making. Although this paper attempts to evaluate the role of autonomy in growth dynamics while controlling for factors affecting the institutional development of municipalities, the measures related to expenditure autonomy fail to yield conclusive results, even when a more flexible timeframe is used (see the Online Appendix). This is not uncommon in the literature, as real autonomy is notoriously difficult to measure. While this study aimed to model expenditure-based decentralization, these measures were significantly constrained by data availability—both autonomy in expenditure decisions and municipal independence were only available from 2002 onward. Municipal independence may have been affected by class imbalance, as only 5% of municipalities in the sample had been fully certified.

The fact that revenue decentralization appears to enhance growth and

convergence, while expenditure autonomy does not, highlights some of the limitations of Colombia's fiscal structure. Despite the country's decentralization efforts over the past three decades, by 2018, municipal budgets still relied on central government transfers for more than two-thirds of their funding. As discussed in Section 2, this reliance imposes strict limits on how local governments can allocate these resources. Even when municipalities are certified and granted greater discretion, most expenditures must be directed toward education or health, which can partly overlook the preferences of the local population. This is in line with Richard Bird (2012) view that Colombia's model is more consistent with one of delegation of responsibilities rather than of actual transfer of powers. Consequently, the strong effect of revenue-based decentralization on growth dynamics may suggest that, under strict expenditure rules, municipalities benefit from expanding the pool of available resources that are not subject to supervision from national and departmental governments.

Similar findings have been reported in other empirical studies. For instance, Gemmell *et al*. (2013) find that in OECD countries, which tend to show greater decentralization of spending responsibilities than of revenue powers, efficiency gains from decentralization occur when revenue more closely matches expenditure autonomy. From the perspective of fiscal federalism, this may result from increased scrutiny by local populations on public spending. While the issue of public engagement in expenditure oversight is beyond the scope of this investigation, it undoubtedly presents an interesting avenue for further research to reinforce the generally positive outcomes of revenue decentralization while providing insight onto the real effect of expenditure autonomy.

Furthermore, segmenting the results into three distinct subperiods (see the Online Appendix) reveals clear differences in the pace of convergence among Colombian municipalities over the decades, as well as a waning effect of fiscal decentralization. During the periods 1997–2003 and 2004–2010, the beta

convergence rate was approximately 2% per year. Although the convergence rate increases significantly during the 2011–2017 period, coinciding with the end of the 2000s commodity super cycle, this increase does not appear to be driven by fiscal decentralization as the estimated effect during this period is weak and not statistically significant. The timing of this rise in convergence suggests that, even in the absence of effective decentralization—understood as the devolution of fiscal and policy decision-making authority to subnational governments—an expansion in the pool of resources transferred from the central government can have a growth-enhancing effect, particularly in poorer municipalities. Nevertheless, the inability to accurately measure the degree of autonomy in expenditure decisions, combined with the statistically insignificant convergence result in the 2010s, leaves important questions unanswered regarding the mechanisms through which decentralization may influence territorial development.

The data reveal heterogeneity in the convergence patterns across administrative regions (see the Online Appendix). Although differences in convergence rates — with regions such as the Caribbean and Pacific converging faster than the Andean — can be explained by the lower initial income levels of municipalities within those regions, differences in the effects of fiscal decentralization measures (see Table 3) suggest varying levels of public capital productivity. These differences may stem from confounding factors that, due to data availability constraints, were not directly evaluated within this paper's methodological framework. For instance, productive public capital is determined not only by revenue and expenditure dynamics but also by the quality of budget execution, local institutions, and public works. In particular, corruption reduces the productivity of public capital by lowering the quality of public projects and diverting funds toward less productive investments, which in turn can affect municipalities' ability to develop alternative revenue sources.

An important insight from this study is the divergence in income dynamics depending on the level of geographic aggregation. While our analysis shows strong evidence of income convergence at the municipal level, trends at the departmental level reveal the opposite pattern—at least during the last two decades. A simple correlation between initial departmental GDP per capita in 2000 and subsequent growth indicates that wealthier departments have grown faster than poorer ones, and the dispersion of departmental income levels has remained virtually unchanged since 2006. This contrast illustrates a form of Simpson's Paradox, in which aggregate trends at a higher level of analysis mask or even reverse patterns observed at a more disaggregated level. This seems to suggest that convergence among municipalities is taking place within departments, but this intra-departmental convergence is not sufficient to shift the broader trend of inter-departmental divergence. These findings indicate that the choice of geographic scale in empirical analyses is not a trivial methodological issue—it fundamentally shapes the conclusions we can draw about the spatial effects of decentralization and growth.

This distinction is particularly important because much of the existing literature on regional inequality and income convergence in Colombia has focused on the departmental level. This focus has largely been driven by data limitations: while GDP data at the department level are available consistently over time, estimates of income at the municipal level have historically been scarce or unreliable.[11] As a result, earlier work—such as that by Cárdenas and Pontón (1995)—was forced to examine convergence at the level of departments, which are not the primary units of fiscal policy implementation in Colombia. In contrast, municipalities are the institutional core of the country's decentralization policy: they are

[11] Estimates of local economic activity for Colombia that have been used repeatedly by the empirical literature follow the methodology proposed by Sánchez and Núñez (2000). Roughly, the official departmental GDP reported by DANE is distributed according to each municipality's share of total tax revenues. The use of information on tax revenues, which at the local level is capturing mostly property taxes, weighs more heavily on regions with larger formal economies and better administrative capacity.

responsible for the provision of most public goods. By enabling analysis at the municipal level through the use of satellite data and machine learning techniques, this paper offers a more accurate lens through which to assess the effectiveness of fiscal decentralization. It shows that when municipalities are empowered with fiscal autonomy, convergence can and does occur—even if such patterns are obscured at more aggregated levels.

While this study provides valuable insights into Colombian growth dynamics, it is important to highlight some important limitations. First, per capita value-added growth is predicted using remote sensing data, which may introduce errors when estimating growth regressions due to satellite saturation, resolution, and differences in light-generating processes. Although there is no easy way around this, estimates for local per capita income could be refined using more precise and granular data sources. One approach to achieve this is by incorporating more advanced neural network structures, such as Convolutional Neural Networks, to process larger volumes of remote sensing data, including daytime satellite images. Although computationally intensive, this method—which has been successfully applied in growth studies—, is crucial for capturing complex patterns like urban agglomerations, building materials, crops, and other economic activities, all of which can enhance model accuracy.

Additionally, this paper does not fully address certain structural aspects of income convergence, particularly concerning the public sector's role. For instance, the paper assumes that all government spending generates productive public capital. However, this assumption may not hold due to variations in development levels, institutional quality, and external factors such as spillover effects and the externalities of public capital. While some of these factors are accounted for in growth regressions, others require more precise measures of cross-municipal conditions and administrative capacity.

8. Conclusions

This paper presents the first systematic attempt to assess the impact of fiscal decentralization on inter-municipal income convergence in Colombia. The most robust model specification yields an annual convergence rate of 4.1%. This suggests that it would take approximately 30 years for the poorest municipality in the year 2000 to close half of its income gap with a rich municipality such as Bogotá, and about 24 years for a municipality in the 25th percentile of the income distribution in the year 2000 to close the same gap. Most measures of fiscal decentralization included in the analysis are positively and significantly associated with municipal income growth and convergence. These findings lend support to a central hypothesis of fiscal federalism theory: that more decentralized administrations are better equipped to identify local preferences and, as a result, provide more effective and productive public goods. Within the framework of the neoclassical growth model, an increase in productivity—combined with lower barriers to capital and labor mobility—can lead to faster convergence, allowing municipalities to narrow per capita income disparities more rapidly.

Although this paper identifies relatively high rates of cross-municipal convergence, it does not explain why significant municipal differences persist. It is crucial to continue studying this topic by investigating the effects of technological change and diffusion on convergence, inter-municipal migration patterns, the impact of violence on service delivery, and other variables that may be widening cross-municipal disparities.

References

Akai, N., & Sakata, M. (2002). Fiscal decentralization contributes to economic growth: Evidence from state-level cross-section data for the United States. *Journal of Urban Economics*, *52*(1), 93–108. https://doi.org/10.1016/S0094-1190(02)00018-9

Barro, R. J. (2015). Convergence and Modernisation. *The Economic Journal*, *125*(585), 911–942. https://doi.org/10.1111/ecoj.12247

Barro, R. J., & Sala-i-Martin, X. (1992). Convergence. *Journal of Political Economy*, *100*(2), 223–251. https://doi.org/10.1086/261816

Beyer, R., Yao, J., & Hu, Y. (2022). Measuring Quarterly Economic Growth from Outer Space. *IMF Working Papers*, *2022*(109), 1. https://doi.org/10.5089/9798400211553.001

Bird, R. (2012). Fiscal Decentralization in Colombia: A Work (Still) in Progress. *International Center for Public Policy*, *paper1223*. https://ideas.repec.org/p/ays/ispwps/paper1223.html

Boadway, R., & Tremblay, J.-F. (2012). Reassessment of the Tiebout model. *Journal of Public Economics*, *96*(11–12), 1063–1078. https://doi.org/10.1016/j.jpubeco.2011.01.002

Bonet, J., & Meisel, A. (1999). La convergencia regional en Colombia: Una visión de largo plazo 1926-1995. *Fedesarrollo*, *XXIX*(1), 69–106.

Cárdenas, M., & Pontón, A. (1995). Growth and convergence in Colombia: 1950–1990. *Journal of Development Economics*, *47*(1), 5–37. https://doi.org/10.1016/0304-3878(95)00003-8

Chen, X., & Nordhaus, W. D. (2011). Using luminosity data as a proxy for economic statistics. *Proceedings of the National Academy of Sciences*, *108*(21), 8589–8594. https://doi.org/10.1073/pnas.1017031108

Del Granado, F. J. A., Martinez-Vazquez, J., & McNab, R. M. (2018). Decentralized Governance, Expenditure Composition, and Preferences for Public Goods. *Public Finance Review*, *46*(3), 359–388. https://doi.org/10.1177/1091142116639127

Faguet, J.-P., & Sánchez, F. (2014). Decentralization and access to social services in Colombia. *Public Choice*, *160*(1–2), 227–249. https://doi.org/10.1007/s11127-013-0077-7

Filippetti, A., & Sacchi, A. (2016). Decentralization and economic growth reconsidered: The role of regional authority. *Environment and Planning C: Government and Policy*, *34*(8), 1793–1824. https://doi.org/10.1177/0263774X16642230

Galvis-Aponte, L. A., Galvis-Larios, W., & Hahn-de-Castro, L. W. (2017). *Una revisión de los estudios de convergencia regional en Colombia*. Banco de la República. https://doi.org/10.32468/dtseru.264

Galvis-Aponte, L. A., & Meisel-Roca, A. (2010). *Persistencia de las desigualdades regionales en Colombia: Un análisis espacial*. Banco de la República. https://doi.org/10.32468/dtseru.120

Garman, C., Haggard, S., & Willis, E. (2001). Fiscal Decentralization: A Political Theory with Latin American Cases. *World Politics*, *53*(2), 205–236. https://doi.org/10.1353/wp.2001.0002

Gemmell, N., Kneller, R., & Sanz, I. (2013). Fiscal Decentralization and Economic Growth: Spending Versus Revenue Decentralization. *Economic Inquiry*, *51*(4), 1915–1931. https://doi.org/10.1111/j.1465-7295.2012.00508.x

Gennaioli, N., La Porta, R., Lopez De Silanes, F., & Shleifer, A. (2014). Growth in regions. *Journal of Economic Growth*, *19*(3), 259–309. https://doi.org/10.1007/s10887-014-9105-9

Henderson, J. V., Storeygard, A., & Weil, D. N. (2012). Measuring Economic Growth from Outer Space. *American Economic Review*, *102*(2), 994–1028. https://doi.org/10.1257/aer.102.2.994

Hodler, R., & Raschky, P. A. (2014). Regional Favoritism*. *The Quarterly Journal of Economics*, *129*(2), 995–1033. https://doi.org/10.1093/qje/qju004

Hooghe, L., Marks, G., & Schakel, A. H. (2010). *The rise of regional authority: A comparative study of 42 democracies* (1. publ). Routledge.

Hu, Y., & Yao, J. (2022). Illuminating economic growth. *Journal of Econometrics*, *228*(2), 359–378. https://doi.org/10.1016/j.jeconom.2021.05.007

Islam, N. (2003). What have We Learnt from the Convergence Debate? *Journal of Economic Surveys*, *17*(3), 309–362. https://doi.org/10.1111/1467-6419.00197

Jean, N., Burke, M., Xie, M., Davis, W. M., Lobell, D. B., & Ermon, S. (2016). Combining satellite imagery and machine learning to predict poverty. *Science*, *353*(6301), 790–794. https://doi.org/10.1126/science.aaf7894

Keola, S., Andersson, M., & Hall, O. (2015). Monitoring Economic Development from Space: Using Nighttime Light and Land Cover Data to Measure Economic Growth. *World Development*, *66*, 322–334. https://doi.org/10.1016/j.worlddev.2014.08.017

Khachiyan, A., Thomas, A., Zhou, H., Hanson, G., Cloninger, A., Rosing, T., & Khandelwal, A. K. (2022). Using Neural Networks to Predict Microspatial Economic Growth. *American Economic Review: Insights*, *4*(4), 491–506. https://doi.org/10.1257/aeri.20210422

Kyriacou, A. P., Muinelo-Gallo, L., & Roca-Sagalés, O. (2015). Fiscal decentralization and regional disparities: The importance of good governance. *Papers in Regional Science*, *94*(1), 89–108. https://doi.org/10.1111/pirs.12061

Lessmann, C., & Seidel, A. (2017). Regional inequality, convergence, and its determinants – A view from outer space. *European Economic Review*, *92*, 110–132. https://doi.org/10.1016/j.euroecorev.2016.11.009

Li, X., & Zhou, Y. (2017). A Stepwise Calibration of Global DMSP/OLS Stable Nighttime Light Data (1992–2013). *Remote Sensing*, *9*(6), 637. https://doi.org/10.3390/rs9060637

Ligthart, J. E., & Van Oudheusden, P. (2015). In government we trust: The role of fiscal decentralization. *European Journal of Political Economy*, *37*, 116–128. https://doi.org/10.1016/j.ejpoleco.2014.11.005

Lozano-Espitia, L. I., & Julio-Román, J. M. (2015). *Fiscal decentralization and economic growth: Evidence from regional-level panel data for Colombia.* Banco de la República. https://doi.org/10.32468/be.865i

Maldonado, A. (2011). Descentralización territorial en Colombia: Situación y perspectivas de política. *Friedrich-Ebert-Stiftung*, 24.

Martínez, L. R. (2025). Natural Resource Rents, Local Taxes, and Government Performance: Evidence from Colombia. *Review of Economics and Statistics*, 1–10. https://doi.org/10.1162/rest_a_01324

Martinez-Vazquez, J., Lago-Peñas, S., & Sacchi, A. (2017). The Impact of Decentralization: A Survey. *Journal of Economic Surveys*, *31*(4), 1095–1129. https://doi.org/10.1111/joes.12182

Martinez-Vazquez, J., & McNab, R. M. (2003). Fiscal Decentralization and Economic Growth. *World Development*, *31*(9), 1597–1616. https://doi.org/10.1016/S0305-750X(03)00109-8

Michalopoulos, S., & Papaioannou, E. (2013). Pre-Colonial Ethnic Institutions and Contemporary African Development. *Econometrica*, *81*(1), 113–152. https://doi.org/10.3982/ECTA9613

Michalopoulos, S., & Papaioannou, E. (2014). National Institutions and Subnational Development in Africa *. *The Quarterly Journal of Economics*, *129*(1), 151–213. https://doi.org/10.1093/qje/qjt029

Oates, W. E. (1974). Fiscal Federalism. *American Political Science Review*, *68*(4), 1777–1778. https://doi.org/10.2307/1959998

Oates, W. E. (1999). An Essay on Fiscal Federalism. *Journal of Economic Literature*, *37*(3), 1120–1149. https://doi.org/10.1257/jel.37.3.1120

Pérez-Sindín, X. S., Chen, T.-H. K., & Prishchepov, A. V. (2021). Are night-time lights a good proxy of economic activity in rural areas in middle and low-income countries? Examining the empirical evidence from Colombia. *Remote Sensing Applications: Society and Environment*, *24*, 100647. https://doi.org/10.1016/j.rsase.2021.100647

Perry, G., García, E., & Jiménez, P. (2014). State Capabilities in Colombian Municipalities: Measurement and Determinants. *Banco de Desarrollo de América Latina*. https://scioteca.caf.com/handle/123456789/762

Phan, D. H. (2023). Lights and GDP relationship: What does the computer tell us? *Empirical Economics*, *65*(3), 1215–1252. https://doi.org/10.1007/s00181-023-02377-y

Pinkovskiy, M., & Sala-i-Martin, X. (2016). Lights, Camera … Income! Illuminating the National Accounts-Household Surveys Debate *. *The Quarterly Journal of Economics*, *131*(2), 579–631. https://doi.org/10.1093/qje/qjw003

Prest, A. R., & Musgrave, R. A. (1959). The Theory of Public Finance. *The Economic Journal*, *69*(276), 766. https://doi.org/10.2307/2227672

Prud'homme, R. (1995). The Dangers of Decentralization. *The World Bank Research Observer*, *10*(2), 201–220. https://doi.org/10.1093/wbro/10.2.201

Ramírez, J. M., Bedoya, J. G., & Díaz, Y. (2016). Geografía económica, descentralización y pobreza multidimensional en Colombia. *Fedesarrollo*.

Rodriguez-Pose, A., & Ezcurra, R. (2010). Does decentralization matter for regional disparities? A cross-country analysis. *Journal of Economic Geography*, *10*(5), 619–644. https://doi.org/10.1093/jeg/lbp049

Sacchi, A., & Salotti, S. (2014). The Effects of Fiscal Decentralization on Household Income Inequality: Some Empirical Evidence. *Spatial Economic Analysis*, *9*(2), 202–222. https://doi.org/10.1080/17421772.2013.833343

Thornton, J. (2007). Fiscal decentralization and economic growth reconsidered. *Journal of Urban Economics*, *61*(1), 64–70. https://doi.org/10.1016/j.jue.2006.06.001

Tiebout, C. M. (1956). A Pure Theory of Local Expenditures. *Journal of Political Economy*, *64*(5), 416–424. https://doi.org/10.1086/257839

ONLINE APPENDIX

"Carrying the Weight of Autonomy? Growth and Spatial Inequality Among Municipalities in Colombia"

Carlos F. Holguín-Isaza & Carlos A. Mesa-Guerra

This online appendix includes seven items: (1) Appendix A offers complementary information and descriptions of the variables used through this study, emphasizing the data sources and methods used in variable transformation. (2) Appendix B summarizes the prevalence of satellite bottom saturation across different departments represented in the sample. (3) Appendix C includes a detailed diagram of the neural network workflow used to generate predictions of municipal VA shares. (4) Appendix D registers the first-stage relationship between the instruments and endogenous variables used in the convergence regressions of Table 2. (5) Appendix E registers the determinants of growth for three-year intervals. (6) Appendix F registers the convergence rate across seven-year periods within the sample. (7) Appendix G exhibits the beta convergence rates across regional subsamples.

Appendix A: Main Data Sources

This appendix describes the main variables and data sources used in this study. All municipal variables were joined into a single panel encompassing fiscal, production and sociodemographic information using a unique municipality and year identifier. Data source integrity was maintained for most variables within the main dataset with very few exceptions, which will be mentioned in this section.

A. Remote Sensing

Raw data of NTLs usually comes from two sources. (1) The Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) publishes annual nightlight cloud-free composites from 1992 to 2013, spanning -180 to 180 degrees longitude and -65 to 75 degrees latitude at a resolution of 30 arc second grids. Each pixel (approximately 1 square kilometer) in the luminosity grid is assigned a digital number (DN) representing its luminosity that ranges from 0 to 63 (DMSP Operational Linescan System (OLS), 2023). (2) The Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) has produced publicly available nightlight data since 2013, this suite offers greater accuracy and resolution when compared to the DMSP-OLS, allowing it to record a greater array of surface phenomenon (NOAA NPP VIIRS, 2023).

Since NTLs come from two main sources and there are even multiple satellites associated with each program, inter-calibration and harmonization between both DMSP-OLS and NPP-VIIRS programs is paramount to create data points that can be practically compared across multiple years. Li *et al*. (2018) offers a solution to this problem by

calibrating and harmonizing NTLs information from 1992 to 2018. Their approach follows three steps: (i) they composite the annual VIIRS monthly data, (ii) they qualify the relationship between VIIRS and DMSP data in the year 2013 (this is the only year in which both programs overlap) using a Sigmoid function and creating a DMSP-like VIIRS dataset, and (iii) they generate a consistent dataset by integrating the calibrated DMSP data with the DMSP-like VIIRS data. This dataset has been made publicly available by the authors.[12]

To account for urban and rural dynamics that may fall outside the scope of night-time lights, yearly municipal estimates of land coverage were incorporated using publicly available land use data from the MapBiomas 1.0 collection. Mapbiomas is a multinational project for processing and classifying daylight images from Landsat series 4,5,6,7,8, and 9, creating annual continental mosaics of land coverage for 1985 onwards. MapBiomas uses a Random Forest classifier trained over stable samples of land coverage which didn't suffer drastic changes throughout the 38 years of the series. These mosaics offer rich information for 34 classification categories including urban infrastructure, mining, agriculture, silvopastoral, palm crops, between others with a map resolution of 30 square meter tiles. These estimates have been validated by an external institution using a stratified random sampling.

B. Fiscal and GDP estimates

A broad array of fiscal indicators and budgetary executions is published annually for all Colombian municipalities by the National Planning

[12] This dataset can be downloaded from https://figshare.com/articles/dataset/Harmonization_of_DMSP_and_VIIRS_nighttime_light_data_from_1992-2018_at_the_global_scale/9828827

Department (DNP for its acronym in Spanish), with information ranging from 1984 onwards. All revenue sources are expressed in current prices and are reported by local authorities. The dataset encompasses most sources of municipal public revenue including total and current municipal income and tax revenue. Specific local taxes such as the industry and commerce tax, the gasoline surtax and the property tax are also discriminated within the dataset, allowing for different measures of fiscal decentralization to be computed.

GDP estimates are available at the departmental level from the DANE. These are crucial for estimating the relationship between nightlights and real GDP. Since fiscal indicators are only available from 1984 onwards and my nightlights data is only available from 1992 onwards, this study will only consider the GDP information from 1993 onwards. Furthermore, due to constrains in the granularity of GDP estimates before 1991 for departments previously classified as "National Territories", the study will only consider GDP estimates for departments which territorial status didn't change with the 1991 constitution[13]. All monetary variables are expressed in constant 2015 prices and are deflated using department specific CPI produced by the DANE for all year between 1985 and 2022.

C. Socio-demographic Characteristics, Geography and Natural Resources

Official population estimates are annually projected by the DANE from national censuses conducted roughly every 12 years (1993, 2005 and 2018), these datasets are publicly available for the complete study timeframe.

[13] These departments are: Amazonas, Arauca, Casanare, Guainía, Guaviare, Putumayo, San Andrés, Providencia y Santa Catalina, Vaupés and Vichada.

To account for human capital, the national censuses offer information on years of schooling for all Colombian municipalities in 1993, 2005 and 2018. Years of schooling is widely used in the growth literature as it offers a measure for evaluating the general literacy of the working population while other measures focus only on the educational performance of current students which may not make part of labor force and therefore of the growth dynamics within each municipality. To obtain yearly estimates, a linear interpolation of the years of schooling for each municipality was performed between census years.

A wide array of institutional controls is also included as a way of accounting for observed heterogeneities within municipalities. The Center for Development Studies (CEDE, for its acronym in Spanish) offers a comprehensive collection of official municipal registries encompassing five main chapters: State Capacity, Conflict and Violence, Education, Government, Health and Services, and Agriculture. Following Perry *et al.* (2014), institutional controls were selected based on their demonstrated effectiveness as predictors of state capacity within Colombian municipalities. These variables were grouped into three broad categories: (1) Financial Capacity: measuring the percentage of total expenditure in investment which can be obtained from the municipal budgetary executions from the DNP, (2) Fiscal Capacity: which include self-generated revenue per capita and operational expenditure per capita, (3) Physical Capacity: which include the number of education facilities per capita and the number of teachers per student as a proxy for the number of public officials, both variables can be obtained from the panel on Education published by the CEDE. Given Colombia's prolonged civil conflict, violence has played a significant role in shaping municipal capacities (Cárdenas *et al.*, 2011). Accordingly, variables were selected to

capture incidences of conflict targeting both specific individuals (e.g., number of displacement occurrences) and the broader population (e.g., number of terrorist attacks and anti-personnel mines). All variables on violence and conflict are registered by the CEDE using the number of occurrences of each type of violence registered by the Unique Registry of Victims.

Information on the municipal production of hydrocarbon and precious metals, as well as the royalties perceived from these industries, were obtained from administrative registries of the Ministry of Mines and the DNP respectively. Geographical control variables like the municipal total area and distance from departmental capital were calculated with a Geographical Information System (GIS) using the 2018 geostatistical framework provided by the DANE. Finally, information on municipal living conditions was obtained from the national censuses of 1993, 2005, and 2018.

Appendix B: Bottom-Coding in Colombian Departments

Table A1. Bottom-Coded Municipalities Per Year and Department

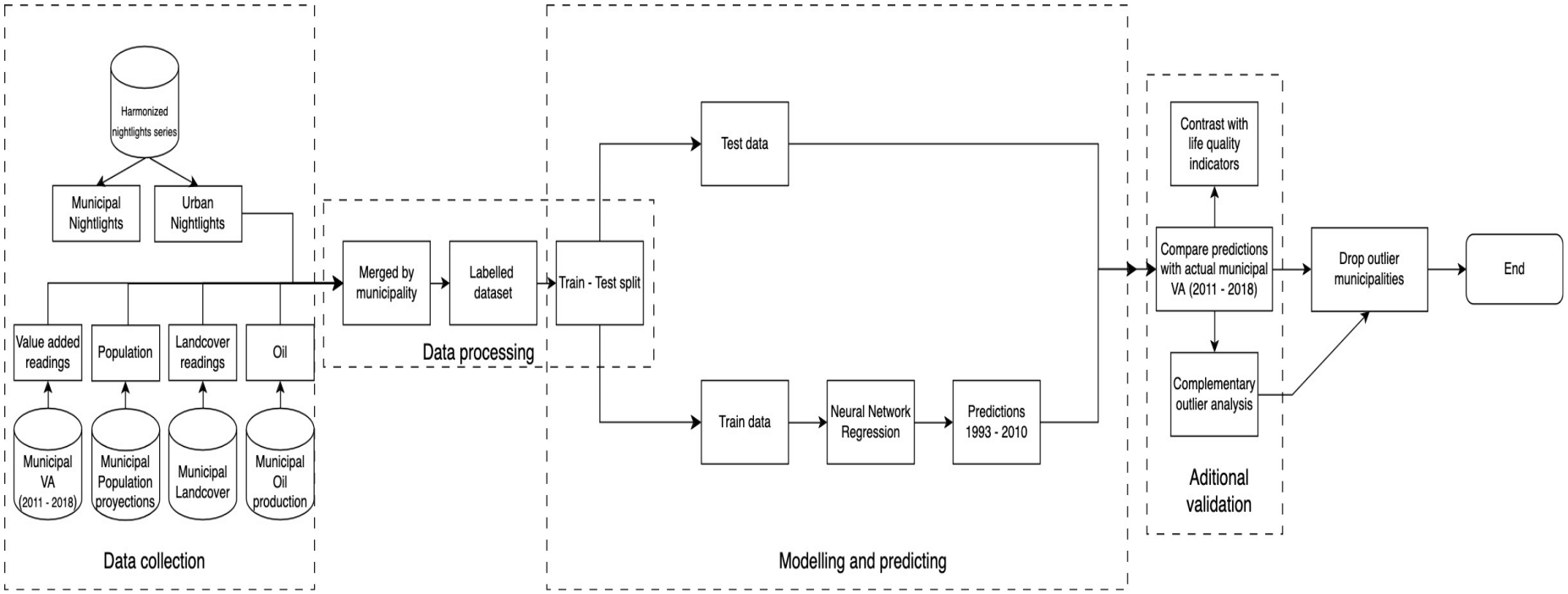
Department	(1) Mean	(1)/(4) Yearly average	(2) Min	(3) Max	(4) Municipalities
Antioquia	2.2	1.8%	1	3	122
Atlántico	0	0.0%	0	0	23
Bogotá D.C.	0	0.0%	0	0	1
Bolívar	1	2.3%	1	1	44
Boyacá	3.9	3.3%	1	12	119
Caldas	1	3.7%	1	1	27
Caquetá	2.4	17.1%	1	6	14
Cauca	3	7.9%	1	7	38
Cesar	0	0.0%	0	0	25
Córdoba	0	0.0%	0	0	30
Cundinamarca	1.6	1.4%	1	3	114
Chocó	2	13.3%	1	4	15
Huila	1.4	3.8%	1	2	37
La Guajira	0	0.0%	0	0	15
Magdalena	0	0.0%	0	0	30
Meta	1.5	5.8%	1	3	26
Nariño	3.8	6.8%	1	10	56
Norte de Santander	1.6	4.0%	1	3	40
Quindío	0	0.0%	0	0	12
Risaralda	0	0.0%	0	0	14
Santander	3.9	4.9%	1	14	77
Sucre	0	0.0%	0	0	26
Tolima	1.4	3.0%	1	3	47
Valle del Cauca	0	0.0%	0	0	42

Note: The table presents the average number of municipalities within each department that have a DN sum equal to 0, the minimum and the maximum. The total number of municipalities are those considered within the sample.

Columns (2) and (3) show the minimum and maximum number of municipalities with a DN sum equal to 0 throughout the timeframe of the sample. For instance, Antioquia had on average 2.2 municipalities —from a total of 122 included in the sample— with sever bottom coding on a yearly basis; in the best year it had only 1 municipality with sever bottom coding and in the worst year it had 3 municipalities with the issue. Caquetá and Chocó have on average more than 10% of their municipalities bottom-coded on a yearly basis; these departments were dropped from the sample.

Appendix C: Neural Network Workflow

Figure A1. Neural Network Workflow



Source: Authors' elaboration.

Appendix D: Decentralization and Economic Growth: Instrumental Variable Regressions

Table A2: First-Stage Results

	(2)			(3)			(4)		
	Log Current PC VA	Log Locally raised own revenues	Interaction PC VA x FD	Log Current PC VA	Log Autonomy on expenditure decisions	Interaction PC VA x FD	Log Current PC VA	Log non-earmarked tax revenues	Interaction PC VA x FD
Lag Per Capita VA	0.905***	-0.152***	-2.704***	0.921***	0.338***	4.185***	0.887***	0.055	0.482
	(0.005)	(0.022)	(0.363)	(0.006)	(0.022)	(0.369)	(0.006)	(0.035)	(0.567)
Lag Fiscal Decentralization	0.365***	0.472*	-1.192	0.171***	-0.217	-4.736**	0.400***	-0.060	-11.992***
	(0.038)	(0.251)	(4.103)	(0.031)	(0.142)	(2.312)	(0.034)	(0.275)	(4.460)
Interaction Lag PC VA x Lag FD	-0.024***	0.002	0.592**	-0.011***	0.030***	0.566***	-0.026***	0.046***	1.433***
	(0.002)	(0.016)	(0.261)	(0.002)	(0.008)	(0.138)	(0.002)	(0.017)	(0.282)
Cadastral Updates	0.000	-0.007***	-0.117***	0.000	-0.012***	-0.199***	-0.000	-0.014***	-0.237***
	(0.000)	(0.001)	(0.014)	(0.000)	(0.002)	(0.029)	(0.000)	(0.001)	(0.019)
Exogenous Transfers	-0.006**	-0.052***	-0.851***	-0.006	0.237***	3.800***	-0.003	0.052***	0.821***
	(0.002)	(0.011)	(0.181)	(0.004)	(0.019)	(0.310)	(0.002)	(0.011)	(0.186)
Obs	13,725	13,725	13,725	7,105	7,105	7,105	13,710	13,710	13,710
SW F-statistic	1711.31	602.33	600.49	24.79	24.27	24.17	1725.86	705.65	718.46
Shea Partial R-square [Partial R-Square]	0.57 [0.90]	0.45 [0.41]	0.45 [0.42]	0.04 [0.89]	0.03 [0.14]	0.03 [0.12]	0.56 [0.90]	0.48 [0.51]	0.48 [0.52]

Standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: All regressions include controls accounting for population density, the Euclidian distance to the departmental capital measured in Kilometers, latitude, oil production measured as number of barrels produced in a given year, the number of educational facilities per 100,000 students, the number of teachers per 10,000 students, the number of homicides per 100,000 people, the number of terrorist occurrences per 100,000 people, the number of antipersonnel mine occurrences per 100,000 people, the departmental inflation rate, the number of displaced individuals received by the municipality in a given year, and the number of displaced individuals expulsed by the municipality in a given year. All included variables were transformed into a logarithmic scale.

Table A2 (Continued)

	(5)			(6)		
	Log Current PC VA	Log Locally raised own revenues	Interaction PC VA x FD	Log Current PC VA	Log Autonomy on expenditure decisions	Interaction PC VA x FD
Lag Per Capita VA	0.890*** (0.057)	-0.036 (0.027)	-1.317*** (0.444)	0.943*** (0.004)	0.003*** (0.001)	0.052*** (0.018)
Lag Fiscal Decentralization	0.437*** (0.039)	0.225 (0.229)	-3.511 (3.694)	0.589 (0.361)	1.088*** (0.032)	4.082*** (0.607)
Interaction Lag PC VA x Lag FD	-0.028*** (0.002)	0.010 (0.014)	0.614*** (0.232)	-0.034 (0.022)	-0.007*** (0.002)	0.740*** (0.040)
Cadastral Updates	0.000 (0.000)	-0.011*** (0.001)	-0.183*** (0.019)	-0.000 (0.000)	-0.000 (0.000)	-0.001 (0.001)
Exogenous Transfers	-0.007*** (0.003)	-0.161*** (0.013)	-2.631*** (0.213)	-0.001 (0.003)	-0.004*** (0.001)	-0.056*** (0.020)
Obs	13,728	13,728	13,728	8,703	8,703	8,703
SW F-statistic	409.92	274.45	279.46	20437.64	854.40	874.70
Shea Partial R-square [Partial R-Square]	0.26 [0.90]	0.20 [0.20]	0.20 [0.21]	0.89 [0.89]	0.79 [0.91]	0.79 [0.91]

Standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: All regressions include controls accounting for population density, the Euclidian distance to the departmental capital measured in Kilometers, latitude, oil production measured as number of barrels produced in a given year, the number of educational facilities per 100,000 students, the number of teachers per 10,000 students, the number of homicides per 100,000 people, the number of terrorist occurrences per 100,000 people, the number of antipersonnel mine occurrences per 100,000 people, the departmental inflation rate, the number of displaced individuals received by the municipality in a given year, and the number of displaced individuals expulsed by the municipality in a given year. All included variables were transformed into a logarithmic scale

Appendix E: Convergence Dynamics at Longer Time Intervals

Table A3. Determinants of Growth (Three-year intervals)[14]

Dependent variable: Yearly per capita VA growth rate						
	(1)	(2)	(3)	(4)	(5)	(6)
Ln (VA pc municipality)	-0.008***	-0.033***	-0.037***	-0.035***	-0.039***	-0.022***
	(0.001)	(0.003)	(0.015)	(0.004)	(0.005)	(0.002)
Ln (Locally raised own revenues)		0.203***				
		(0.035)				
Ln (Va pc municipality) x Ln (Locally raised own revenues)		-0.013***				
		(0.002)				
Ln (Autonomy on expenditure)			0.161			
			(0.162)			
Ln (VA pc municipality) x Ln (Autonomy on expenditure)			-0.010			
			(0.010)			
Ln (non-earmarked tax revenues)				0.138***		
				(0.027)		
Ln (VA pc municipality) x Ln (non-earmarked tax revenues)				-0.009***		
				(0.002)		
Ln (Transfer independence)					0.203***	
					(0.049)	
Ln (VA pc municipality) x Ln (Transfer independence)					-0.013***	
					(0.003)	
Municipal independence						0.029
						(0.314)
Ln (VA pc municipality) x Municipal independence						-0.001
						(0.019)
Obs	5,784	3,977	1,830	3,974	3,977	2,177
Estimation	OLS	IV	IV	IV	IV	IV
R-squared	0.36	0.38	0.47	0.38	0.38	0.45

[14] Note that growth rates are expressed per year, in other words they express the average level of growth within three-year periods: 1993 – 1995, 1996 – 1998, 1999 – 2001, 2002 – 2004, 2005 – 2007, 2008 – 2010, 2011 – 2013, 2014 – 2016, 2017 – 2019.

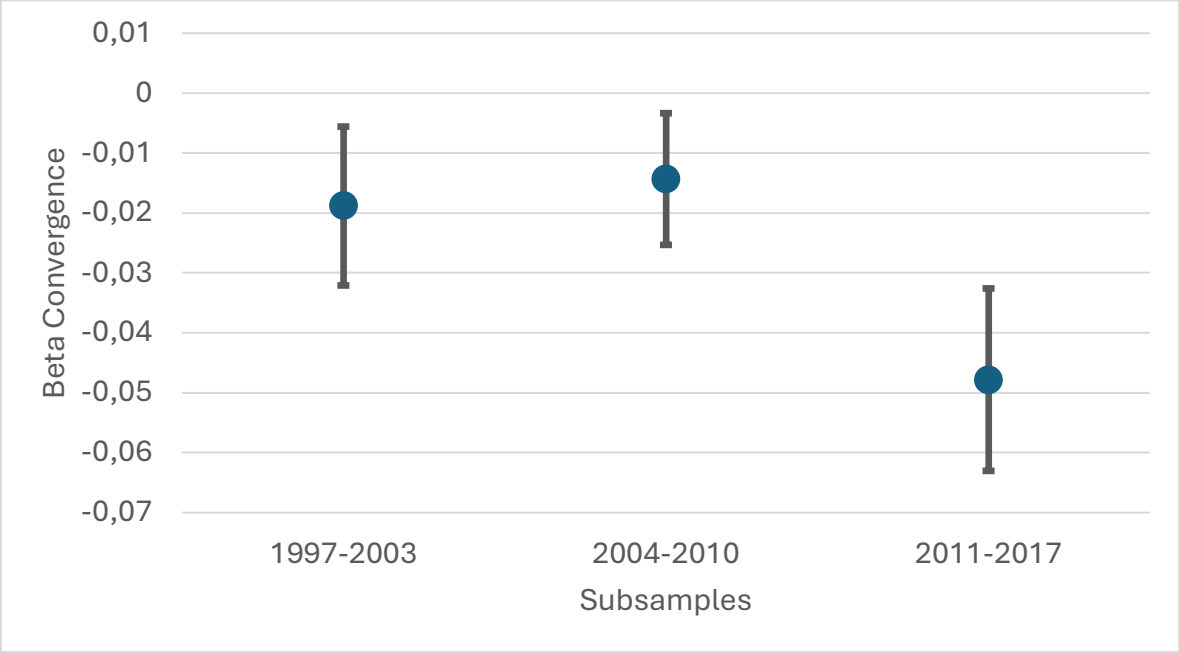
AR F-statistic	NA	27.21	19.73	26.54	26.05	22.20
Hansen J-statistic	NA	1.081	2.472	2.329	0.329	4.272
[p-value]		[0.582]	[0.291]	[0.312]	[0.849]	[0.062]

Standard errors in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.0$

Note: All regressions include controls accounting for population density, the Euclidian distance to the departmental capital measured in Kilometers, latitude, oil production measured as number of barrels produced in a given year, the number of educational facilities per 100,000 students, the number of teachers per 10,000 students, the number of homicides per 100,000 people, the number of terrorist occurrences per 100,000 people, the number of antipersonnel mine occurrences per 100,000 people, the departmental inflation rate, the number of displaced individuals received by the municipality in a given year, and the number of displaced individuals expulsed by the municipality in a given year. All included variables were transformed into a logarithmic scale.

Appendix F: Convergence Dynamics Across Seven-Year Subsamples

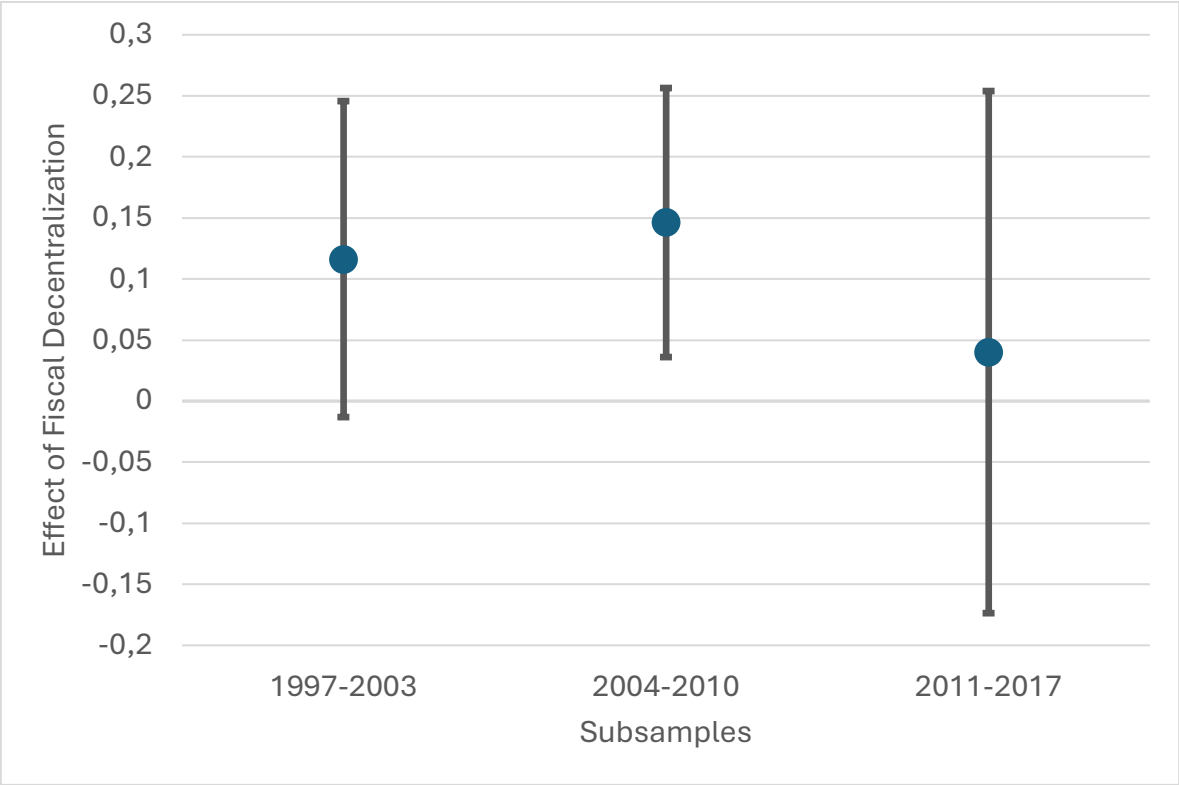
Panel A: Beta Convergence



Source: Authors' calculations using predictions from a machine learning model trained on data from Li *et al* (2018), DANE, Mapbiomas, and DNP.

Note: Vertical bars represent 95% confidence intervals. A negative convergence coefficient implies convergence.

Panel B: Effect of Fiscal Decentralization

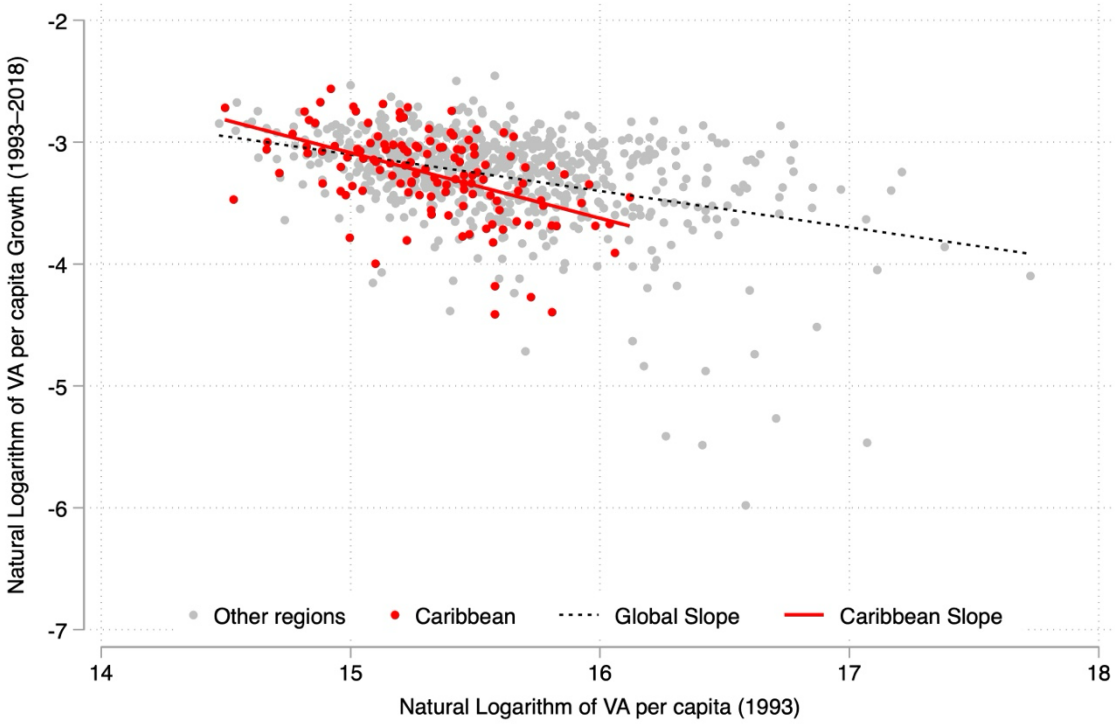


Source: Authors' calculations using predictions from a machine learning model trained on data from Li *et al* (2018), DANE, Mapbiomas, and DNP.

Note: Vertical bars represent 95% confidence intervals.

Appendix G: Beta Convergence Rates Across Regional Subsamples

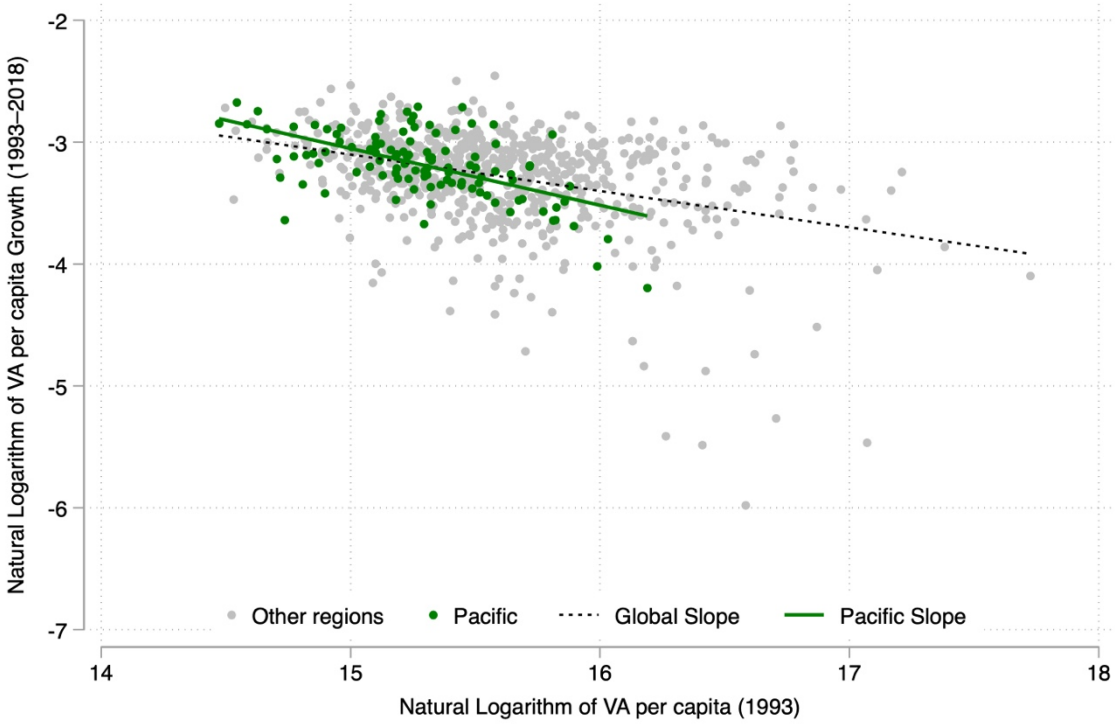
Figure A 3.1 Beta Convergence Caribbean Region



Source: Authors' calculations using predictions from a machine learning model trained on data from Li and Zhou (2017), DANE, Mapbiomas, and DNP.

Note: Beta convergence is estimated using the annual growth rate of value added per capita between 1993 and 2018 (y-axis) and the logarithm of value added per capita in 1993 (x-axis). The negative relationship indicates beta convergence: municipalities with higher initial income levels in 1993 experienced lower growth rates.

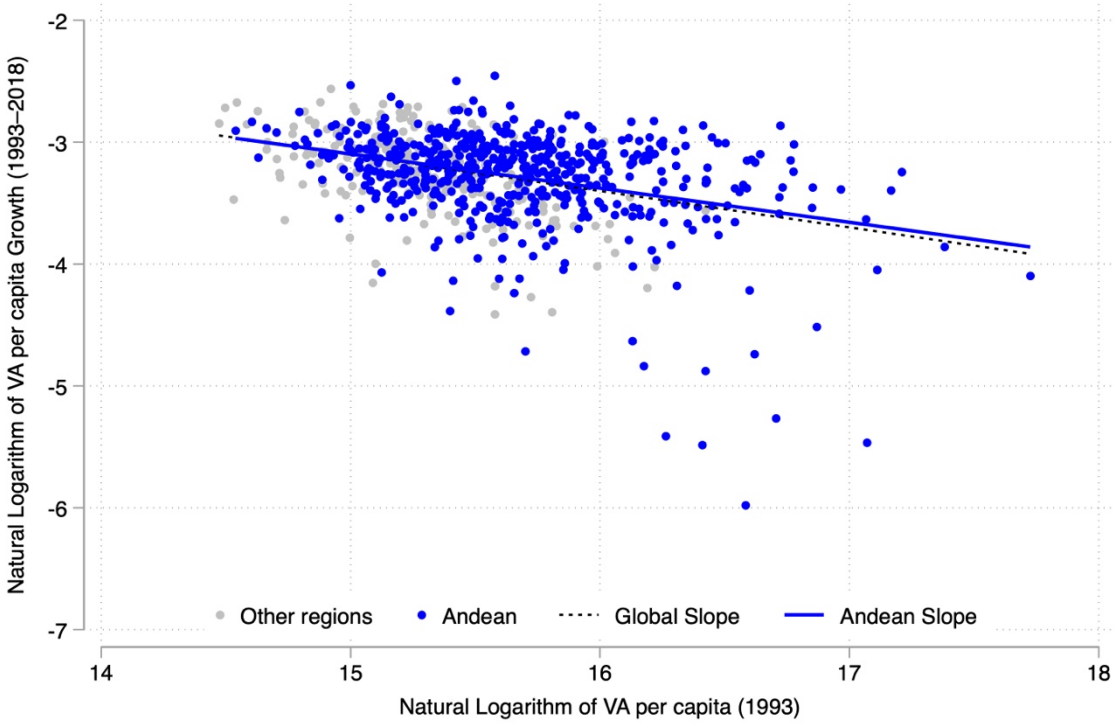
Figure A 3.2 Beta Convergence Pacific Region



Source: Authors' calculations using predictions from a machine learning model trained on data from Li and Zhou (2017), DANE, Mapbiomas, and DNP.

Note: Beta convergence is estimated using the annual growth rate of value added per capita between 1993 and 2018 (y-axis) and the logarithm of value added per capita in 1993 (x-axis). The negative relationship indicates beta convergence: municipalities with higher initial income levels in 1993 experienced lower growth rates.

Figure A 3.3 Beta Convergence Andean Region



Source: Authors' calculations using predictions from a machine learning model trained on data from Li and Zhou (2017), DANE, Mapbiomas, and DNP.

Note: Beta convergence is estimated using the annual growth rate of value added per capita between 1993 and 2018 (y-axis) and the logarithm of value added per capita in 1993 (x-axis). The negative relationship indicates beta convergence: municipalities with higher initial income levels in 1993 experienced lower growth rates.