TECHNICAL NOTE Nº IDB-TN-03005

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Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library

Grimaldi, Daniel.
Infrastructure's imprint: metro proximity and property development dynamics in São Paulo, Brazil / Daniel Grimaldi, Oscar A. Mitnik, Beatrice Zimmermann.
p. cm. - (IDB Technical Note ; 3005)
Includes bibliographical references.
1. Urbanization-Brazil. 2. Urban transportation-Brazil. 3. Land use, Urban-Brazil. 4. Urban impact analysis-Brazil. I. Mitnik, Oscar Alberto. II. Zimmermann, Beatrice. III. Inter-American Development Bank. Office of Strategic Planning and Development Effectiveness. IV. Title. V. Series.
IDB-TN-3005

http://www.iadb.org

Infrastructure's Imprint: Metro Proximity and Property Development Dynamics in São Paulo, Brazil*

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Abstract

How does the proximity to a metro station affect urban development in Latin America? While the literature assessing the causal impacts of transportation infrastructure has grown in recent years, only a few papers have focused on the effects of metro systems in Latin America and the Caribbean (LAC) region, and identifying the precise impacts of such investments is far from straightforward. We apply a Synthetic Difference-in-Differences (SDiD) approach to estimate the effects of the expansion of Line 5 of the *São Paulo* metro system in Brazil on land use and property features. Our results show positive impacts on constructed area, with a treatment effect that is half the magnitude of the average constructed area in untreated units in the pre-treatment period. Additionally, our findings indicate an increase in the number of properties around the stations, with a shift in property composition towards more commercial units. We also find a strong anticipation effect associated with the new metro infrastructure and dynamic impacts after the opening of the first metro station, with effects that increase over time.
JEL: R14, R40, R42.
Keywords: Land use, infrastructure investments, impact evaluation.

*The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the Inter-American Development Bank, its Board of Directors, or the countries they represent. This publication evaluates an expansion of the São Paulo metro system, which was partially financed through the IDB BR-L1227 project. We gratefully acknowledge the support of Daniel Torres Garcia and Ana Beatriz Monteiro, whose contributions helped make this evaluation possible. We also thank Victor Manuel Perez Martin for his valuable research assistance to this study.
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1 Introduction

How does the proximity to a metro station affect urban development processes in Latin America? While the justification for investing in public transport infrastructure is usually the necessity to improve connectivity in the city and everything that this entails, the answer to this question is not as straightforward as one would expect. Empirical research shows that the outcomes depend highly on local specificities, such as pre-existing land use patterns and distinct neighborhood characteristics, which vary widely across contexts (Cervero and Landis, 1997; Gibbons and Machin, 2005). In that sense, the tangible effects that these investments have on urban and socioeconomic patterns are much less clear than their direct objective.

Despite the increasing literature in recent years that has analyzed the causal impact of transport infrastructure, there are only a few studies that have focused on evaluating the effects of metro systems specifically in the LAC region (Vergel-Tovar, 2022; Yañez-Pagans et al., 2019). Given the significant role that local conditions play in shaping these outcomes, assessing the distinctive impacts within the LAC context is crucial for informing effective policy design and fostering learning for future urban development initiatives.

The vast majority of empirical studies carried out in LAC have been focused on investments in Bus Rapid Transit (BRT) systems (Perdomo Calvo et al., 2007; Rodríguez and Mojica, 2009; Bocarejo et al., 2013; Rodriguez et al., 2016), which while helpful, do not elucidate the effects of metro systems. Unlike BRT, metro systems are fixed, high-capacity infrastructures that tend to drive more substantial and permanent changes in urban density, land use, and property values (Suzuki et al., 2013). There are very few cases of impact evaluations of rail systems in the region (Asahi, 2016; Guerra, 2014), and sometimes these evaluations aggregate different types of infrastructure (Costa, 2018), which could hide the specific effects metro interventions may generate, considering that different types of rail infrastructure serve distinct urban functions and attract varying land use responses (Suzuki et al., 2013).

To contribute to this literature, we use a Synthetic Difference-in-Differences (SDiD) approach (Arkhangelsky et al., 2021) to estimate the effects of the Metro Line 5 expansion in *São Paulo*, Brazil, on land use and property features. As our basic setting for the analysis, *São Paulo* exemplifies the complex interplay between economic prosperity and spatial inequality of urban mega cities in developing countries, with a clear contrast between the peripheral districts and the more affluent downtown area.

Metro Line 5 was launched in the early 2000s. At that moment, it operated in isolation, without interconnections with the rest of the metro system. It had 6 stations, covering 8.4 km, from the southwest to the mid-south of *São Paulo*. The expansion of the line, announced in 2008, added 11 stations and 11.6 km to the line, including interconnections with Lines 1 and 2 in the city's central region. The first station of the extension opened in 2014, but the Line was only finished in 2019.

Leveraging the Line 5 expansion, we employ a SDiD approach to measure the effects of proximity to metro stations on urban development, using data on property features and metro stations aggregated to standardized areas (H3 cells).[1]. We define treatment units as cells that experienced a sizeable decrease in the distance to the nearest metro station (from more than 3 km to less than 2 km) due to the line expansion. Conversely, control areas are defined as those that were similar to the treated areas before the Line 5 expansion but whose distance to a metro station remained largely unchanged. The analysis spans from 1995 to 2020, enabling a detailed examination of the scenario before and after metro expansion.

Our estimates show a significant effect size of 0.50 in the properties constructed area. This result indicates that the treatment effect — the increase in constructed area attributable to proximity to metro stations — constitutes half the magnitude of the weighted average constructed area observed in untreated units during the pre-treatment period. Disentangling the mechanisms behind this effect, we show that the increase in the properties constructed area is mainly due to an increase in the number of properties around the stations, with an effect size equal to 0.24. Additionally, we observe a change in the composition of properties, with an increase in the number of commercial units. However, we find that the proportion of the total area occupied by commercial properties is unaffected, while the size of residential properties shows a slight increase. These results differ from those found by (Guerra, 2014) for Mexico City. The author shows that the density of properties around the station increases, but there is only little impact on

[1]We define those areas by using resolution 9 hexagonal H3 cells (with a side length of around 200 meters and an area of approximately 10,500 square meters). H3 cells are a hexagonal hierarchical geospatial grid system originally developed by Uber to analyze sub-areas of the world at different grid sizes ("resolutions"). For more details on H3 cells, see `https://h3geo.org/`.

commercial land use in downtown areas.

In addition, we detect a strong anticipation effect related to the expansion of the new metro line. We identify this effect between 2008 and 2014, the years leading to the opening of the first station on the newly extended metro line, showing an impact along the constructed area within the treatment zones. This finding means that owners and general real estate developers have considered the future gains of the announced metro line and launched real estate projects before the actual line expansion. This anticipation effect is also reflected in several other property-related metrics. We find an increase in the number of existing properties during this period, as well as in the proportion of commercial units. Furthermore, we show that the size of residential properties increased slightly, suggesting that the market anticipated the need for larger living spaces near metro facilities.

Lastly, our estimates show strong dynamic impacts after the opening of the first metro station, with effects strengthening over time. More precisely, proximity to the metro stations shows an increasingly positive and statistically significant effect on the built area over the periods following the opening of the first station. This growth is not only observed for the built area but is also reflected in other real estate variables. For instance, the effects on number of properties and the proportion of commercial properties also steadily grow over time. Lastly, an interesting evolution appears in the size of residential properties. After the initial growth associated with the anticipation effect, we observe a decrease in the size of the properties. Several factors may be behind these results, including property prices or demographics, and further research is needed to better understand these dynamics in this specific context.

The remainder of the paper is organized as follows. The next section introduces the study context. Section 3 describes the data while section 4 explains the methodology employed. In section 5, we present and discuss our estimates, and section 6 concludes the paper.

2 Study Context

São Paulo is the largest city in the southern hemisphere and Brazil's principal economic hub. However, its districts exhibit clear socioeconomic differences. According to the 2010 census, 45% of the households in the peripheral districts live on less than three minimum wages, heavily contrasting with the picture in the downtown area (DEINFO, 2010; IBGE, 2010b). Besides, peripheral regions have had much higher population growth rates in the last few years compared to the central districts. The end result is a metropolis where the population concentrates in the border regions while jobs are concentrated in the central districts (Dipro, 2010; Nakano, 2018).

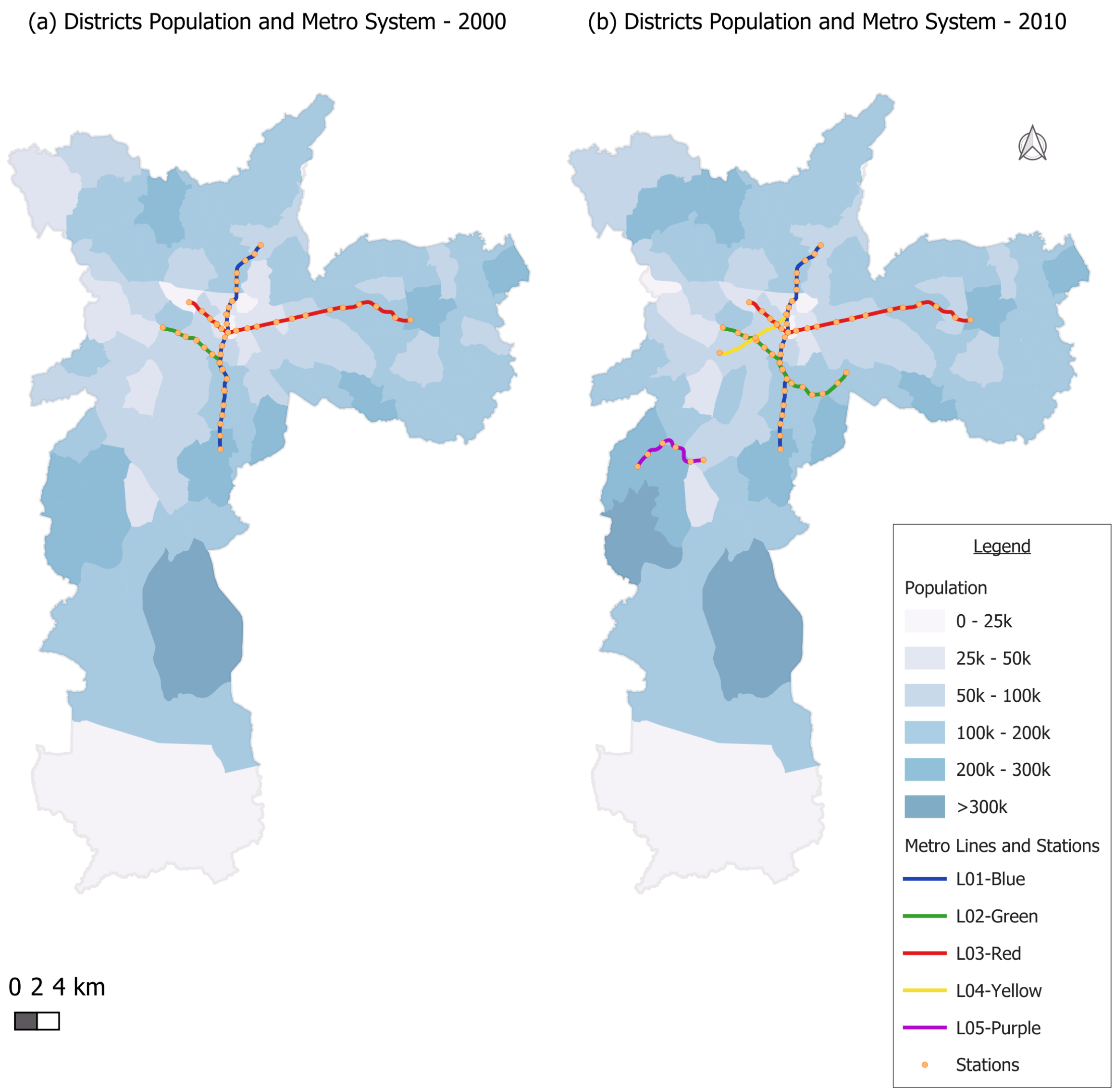
To solve these economic and geographic divides, *São Paulo* has developed an extensive public transportation system. Although the system includes metro and train lines, it primarily relies on an extensive bus network. Buses account, according to METRÔ (2021), for around 65% of the system's total demand (around 6,400 million passengers per year between 2017 and 2019). This heavy reliance on buses makes the system less efficient, considering the city's high congestion levels.

Having its first line launched in the last century, the metro structure has served only a few urban areas historically. In the early 2000s, *São Paulo*'s metro network had three lines, primarily serving the city's central and eastern districts (Figure 1 panel (a). At that moment, the system was responsible for transporting around 500 million passengers per year (METRÔ, 2002). However, this configuration left significant areas, particularly in the western and southern regions, without any metro service. These under-served areas, densely populated (with districts housing more than 200k persons) yet with no efficient option to connect with the main economic and social hubs, experienced considerable logistical and economic challenges.

Aiming to expand its coverage, Metro launched the first section of Line 5 in the south of the city in 2002. However, it did not achieve the expected volume of passengers mainly due to its poor integration with the existing network. The Line had 8.4 km and 6 stations (Figure 1 panel (b)), and it aimed to provide better transportation options for *Capão Redondo, Campo Limpo, Grajaú*, and surrounding cities residents. These regions have undergone recent urbanization and densification, serving primarily as commuter towns. Nevertheless, the metro system registered limited Line usage, with the route transporting only 74 million passengers in 2012 (METRÔ, 2013), representing approximately half the average ridership per kilometer of the other metro lines.

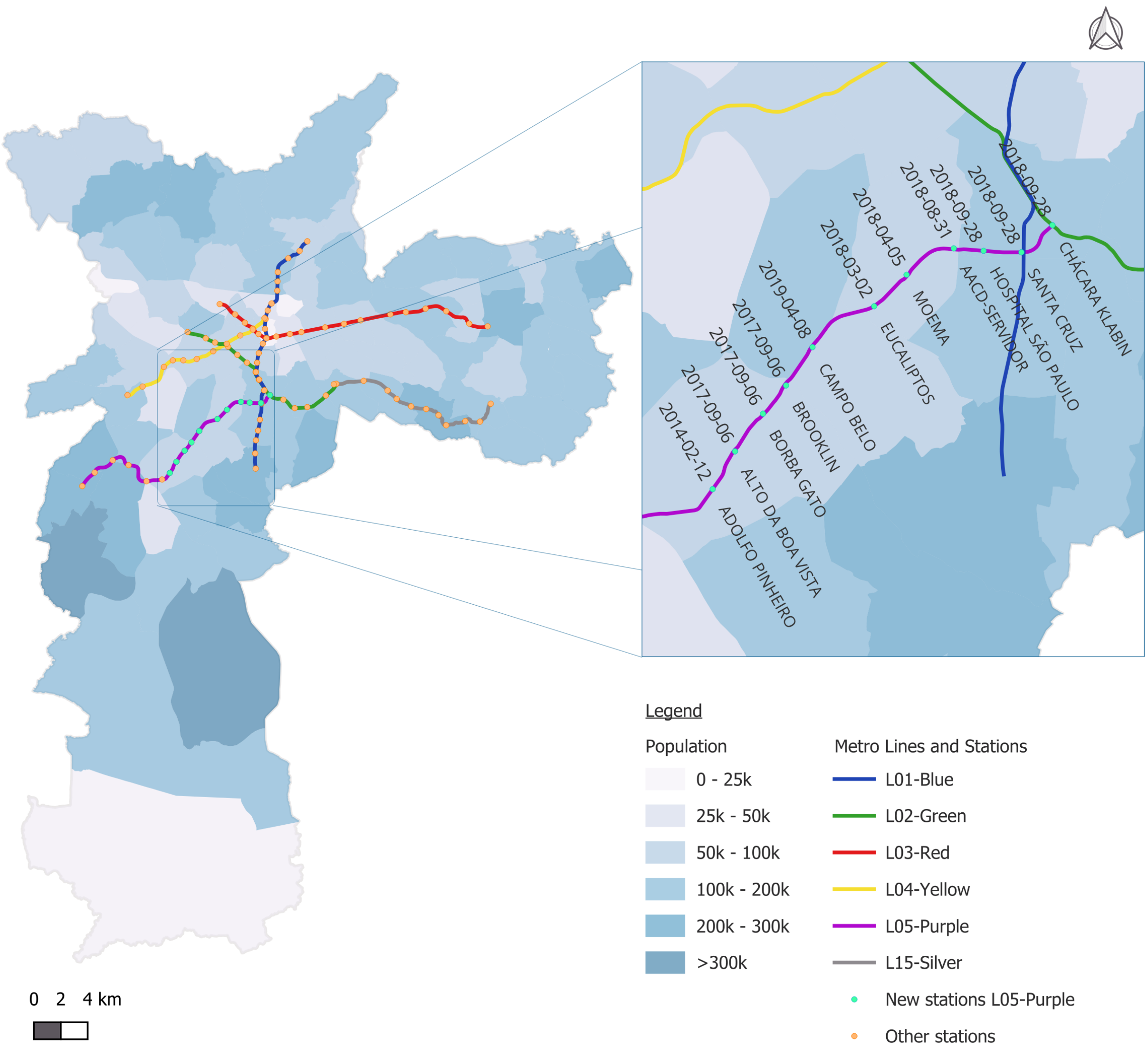
Under this scenario, the City announced in 2008 the expansion of Metro Line 5. The specific goal was to promote significant time savings for commuters in the southern parts of the city. According to the government, before the expansion, traveling from *Capão Redondo* to the city center (*Praça*

Figure 1: *São Paulo* Metro System Coverage and Districts Population: 2000 and 2010



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024) and from IBGE (2000 and 2010a)

Figure 2: Expansion of Metro Line 5 and Districts Population in 2022



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024) and from IBGE (2022). Population data is from Census preliminary results.

da Sé) typically took about 198 minutes using public transportation. The expansion project targeted reducing this travel time to approximately 144 minutes, a reduction of 38% (Schlindwein and Garbin, 2008).

The expansion of Metro Line 5 was effectively initiated in 2009. The infrastructure was planned to be delivered in phases, so station openings occurred at different moments. As Figure 2 shows, in 2014, the city delivered the first station of the expansion. After that, only in 2017 other stations were opened. In that year, the *Alto da Boa Vista, Borba Gato*, and *Brooklin* stations expanded the Line's reach, allowing access to both residential and commercial areas. The year 2018 marked the opening of five new stations, finally connecting Line 5 to the rest of the metro network through the stations *Santa Cruz* and *Chácara Klabin*. The expansion was completed with the opening of the *Campo Belo* station in April 2019, totaling an additional 11.6 km to the line and 11 new stations.

Upon completion, the extension transformed Line 5 from an isolated peripheral route into an important corridor. In 2019, the line transported 167 million passengers, i.e., it more than doubled its ridership compared to 2012 (METRÔ, 2021).

Leveraging the expansion described, we aim to examine the impact of metro station proximity on urban development. This extension, undertaken with substantial financial backing from international organizations such as the Inter-American Development Bank and the World Bank, provides a unique opportunity for assessing the broader impacts of metro accessibility on urban dynamics in the context of the LAC region. The detailed tracking of construction milestones combined with the availability of geo-referenced time series data on key outcomes provides an exceptional opportunity to empirically investigate the impacts of the project.

In this sense, this study is grounded in the rich tradition of location theory and urban spatial development, where seminal works by Alonso (1964), Mills (1972), and others have underscored the critical role of transit accessibility projects in urban land use and real estate dynamics. In summary, the location theory stresses the relationship between transit accessibility and land use decisions. It suggests that, as a consequence of the transit infrastructure, the interest in the surrounding areas increases. Also, due to higher flows of people, these areas may then result in a cluster of commercial activities, which may discourage residential uses due to the associated negative externalities. The final land configuration represents the equilibrium among all these forces, which cannot be clearly identified theoretically.

On the empirical front, isolating the causal impacts of such investments is a challenge since the specific positioning of public mass transit systems is usually not random. In that sense, the correlation between the transit route and the areas' geographical and socioeconomic aspects complicates direct comparisons with unaffected areas. To address this methodological challenge, quasi-experimental techniques have been applied in this area of study (Heblich et al., 2020; Bardaka et al., 2018), although the availability of quality data imposes restrictions on the wide use of these methods.

In our study, we employ an SDiD approach to identify the effects of the metro expansion on different measures of land use. We exploit all the details of the expansion's implementation to define our treatment and control zones. The next section provides a description of our data.

3 Data

We use an administrative dataset detailing property tax records as the key data source for our study, which we describe below.

3.1 Raw Data

The municipal tax registry (Prefeitura de São Paulo, 2022a) is an administrative dataset of information used for property tax evaluation (*IPTU* in Portuguese). It spans from 1995 to 2020 and holds detailed records of properties in *São Paulo*, linking each property to a specific parcel — a registered plot of land that serves as the basis for property evaluations. Besides allowing us to identify properties and their respective parcels at any given time, it lets us observe the temporal evolution of property attributes.

The dataset comprises information regarding several properties' physical attributes and also about the fiscal parameters used to compute the tax. Nevertheless, we are interested in this dataset mainly for its physical attributes, as the fiscal variable presented results from *ad hoc* government decisions, thus providing little to no value from an analytical standpoint.

The physical attributes comprise a broad set of variables, including the property location (street, number, neighborhood), the land and building area, construction year, number of floors, usage and construction types, and land type. Furthermore, each parcel contains precise geographical coordinates that provide accurate spatial location. With 75.5 million observations from 3.5 million unique properties associated with 1.6 million parcels, this dataset enables valuable insights into the temporal evolution of attributes of properties in the city.

However, an important feature of this dataset is its dependence on self-reported updates provided by property owners, which may generate data accuracy issues. According to the city administration, when the property suffers any modification, the legal owner or his representative has 60 days to update the information in the registry. Although this data collection method is widely used in these contexts, under-reporting and delayed reporting may become an issue. For example, owners may not report property updates due to the tax implications it may have. Or they may not report or delay the reporting because they are unaware of the registry rules. Nevertheless, we understand that in our context, these issues are of small magnitude. First, various legal activities, including property transactions and issuance or license renewals for commercial properties, require the property to have updated information in the city registry. In a highly dynamic city such as *São Paulo*, these interrelated processes help reduce substantial under-reporting risks. Furthermore, the city's regulatory layers and dense population make the probability of irregular constructions being reported to municipal authorities high, resulting in penalty fees on property owners. Consequently, this self-regulated process serves as a strong deterrent against under-reporting and delayed reporting of property modifications.

Even though we believe the issue is not sizeable, it is important to be aware of its implication for our identification strategy. While the application of SDiD helps to address some concerns, the robustness of our findings depends on three key assumptions.

The first is the assumption of consistency in reporting patterns. Specifically, our analysis assumes that any reporting pattern unfolds uniformly across the treated and control unit areas. Our second assumption is the randomness or non-systematic nature of reporting errors. We assume that these reporting anomalies are independent of treatment status or covariate influences. Finally, our third assumption is the temporal stability of reporting biases, meaning that we assume that reporting problems remain stable over time. If that is not the case and reporting patterns worsen or improve over time, it could bias our estimates.

Despite these considerations, we understand that the rich structure of this data allows for a detailed examination of property attributes over time.

3.2 Data Cleaning and Preprocessing

One important thing to mention is that the total number of parcels reported at the municipal tax registry is not fixed in time. It happens because the municipality of *São Paulo* creates new parcels to accommodate the city's expansion necessities. In fact, these newly created parcels concentrate a relevant share of the total newly constructed areas in the city. Intuitively, we can think of a new parcel as a plot of area where the municipality has just formally approved a new construction endeavor. As expected, more building work follows the initial one until most of the parcel's construction potential is exhausted. Naturally, we can always observe some changes in the properties' characteristics, but major construction work (such as new condos or major malls) becomes rare.

Using 1995 as the reference year, Figure 3 illustrates this behavior. The light blue line in Panel A shows the total newly constructed area added to the municipal tax registry (measured in square meters) per year since 1995, while Panel B shows the relative importance of this area within the city (as a ratio of the city's total constructed area). In contrast, the dark blue line shows the same measures, but limits the analysis for those perfectly balanced parcels - in this case, those which already existed in 1995. We can see that the importance of balanced parcels to the total newly constructed areas decreases rapidly, and by the 2000s their relevance to the city's expansions is basically residual.

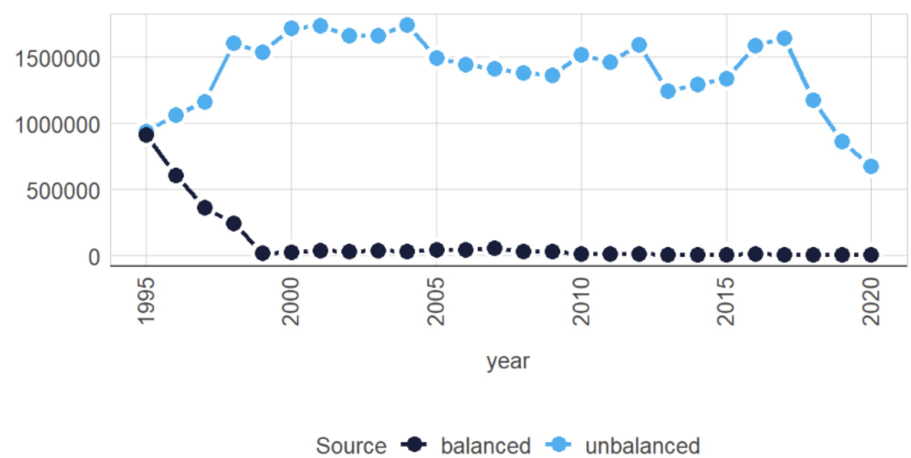
Thus, it seems inadequate to use parcel-year observations as our unit of analysis. First, because such a panel would be highly unbalanced. Worse still, if we confine our analysis to balanced parcels we would lose most of the information associated with the city's expansion and, thus, bias our results.

To avoid missing information from unbalanced parcels, we aggregate all information from the municipal tax registry using resolution 9 H3 Cells.[2] The major advantage of consolidating all data using this kind of grid system is that it allows us to build a perfectly balanced panel of cells. The advantage of using specifically the H3 Cells System, is that the centerpoint-distance between

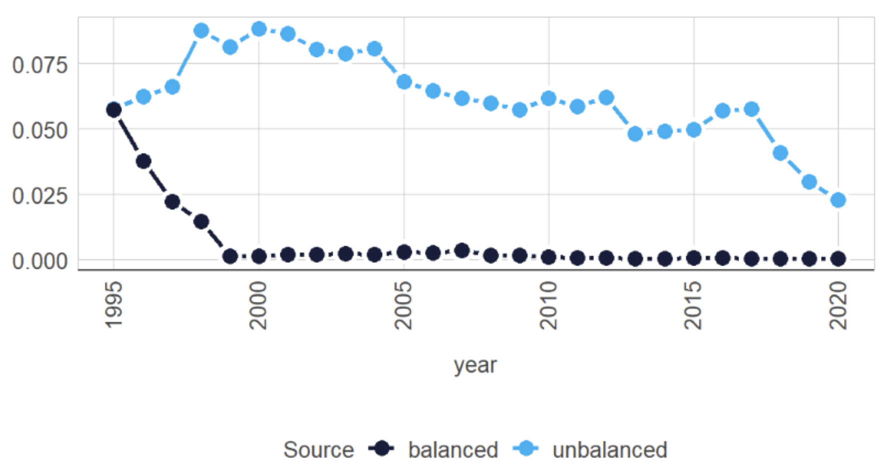
[2] See footnote 1 for more information on H3 cells and the resolution used in this paper.

Figure 3: The expansion of the city (comparing balanced and unbalanced parcels)

(a) Total New Area (square meters)



(b) Total New Area (share of total city's area)



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022a).

neighboring hexagons is always the same. Taking advantage of this feature, the distance between any points A and B can be summarized by the linear distance (in meters) between the centerpoints of their respective hexagons. By doing this, we are able to build a fairly uniform and easily implementable distance measure between cells – which is key since our treatment status depends on the distance between any given plot of land and the metro stations built during the Expansion of Metro Line 5.

4 Empirical framework

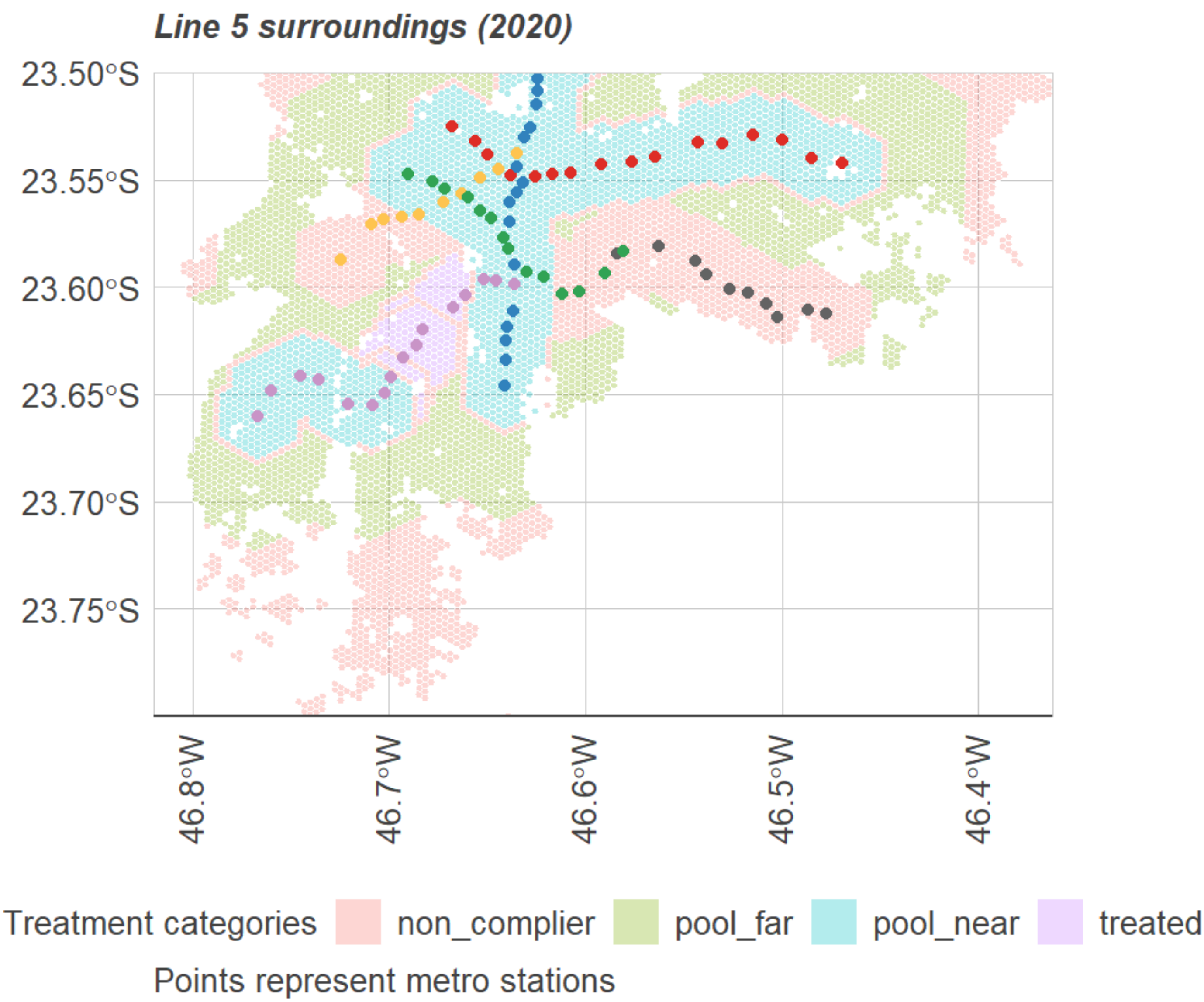
Having consolidated data into resolution 9 H3 cells, Figure 4 shows our classification of cells in the city of *São Paulo*. The colored points mark operational metro stations by 2020, with colors identifying specific metro lines (blue is Line 1; green is Line 2; red is Line 3; yellow is Line 4; purple is Line 5; and gray represents Line 15).

The key hypothesis to be tested is that the Metro Line 5 expansion should reduce overall transport times for a part of the city and, by doing this, produce a relevant change in the land use pattern. Intuitively, reduced travel times translate into better access to economic opportunities and amenities (Pereira, 2019; Pereira et al., 2019). Thus, we anticipate the affected areas should become more attractive for residential purposes. Conditionally on the real estate market having the capacity to respond to that stimulus, we can expect an increase in the urban density around the new metro stations. Finally, that higher density should support a demand boost for local commercial services.

Considering our proposed H3 Cells' grid system and our key hypothesis, Equation 1 shows how a typical Difference-in-Difference (DiD) approach could be used to identify the effects of the Metro Line 5 expansion. In this setting, i and t stand for, respectively, cells and years; α represents fixed effects; $Line5$ is a dummy variable equal to 1 for treated cells after the treatment and zero for the control regions; ε is the error term; and, finally, y represents outcomes associated with the expected increase in urban density.

$$y_{i,t} = \alpha_i + \alpha_t + \delta \; Line5_{i,t} + \varepsilon_{i,t} \quad (1)$$

Figure 4: H3 Cells Grid Around the Metro Line 5 Expansion



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024).

We consider five outcome variables, aggregated to the H3 cell level: *(i)* total constructed area, *(ii)* total number of properties, *(iii)* average size of residential properties, *(iv)* share of commercial properties, and *(v)* share of the total constructed area used by commercial properties. The standard errors are clustered at the H3 cell level. The parameter of interest is δ, which captures the impact of the Line 5 expansion on the treated areas of the city. If pre-treatment parallel trends hold unconditionally, the parameter δ can be easily estimated through a Two-Way Fixed Effect (TWFE) approach ($\hat{\delta}$).

Considering this basic setting, the first step to properly implement Equation 1 is to define the moment that marks the start of the treatment. In practical terms, travel time is only affected once metro stations become operational. However, economic agents (in our case, real estate developers and prospective house buyers) might anticipate future welfare changes. Thus, if we move the start of the treatment period too much ahead, we risk having contaminated baselines, which would bias our results. Thus, as a conservative approach, we use the year of the public *announcement* of Line 5 expansion (2008) as the first treatment year.

The second challenge to implement Equation 1 is to identify areas effectively treated by the Metro Line 5 expansion – *i.e.* those whose travel times are affected by the construction – and places that can serve as proper controls. To do that, every hexagon is classified according to its proximity to the closest metro stations using two key moments: *(i)* 2007, which represents the last year before the public announcement of the expansion of Line 5 and will serve as the end of the *ex ante* period; and *(ii)* 2019, which is the year when the last Line 5 metro station became operational.

Thus, we define as treated cells the ones where the distance to the closest metro station was above 3 km in 2007, but was reduced to less than 2 km due to the Line 5 expansion. In Figure 4, these areas are marked by the purple background. It is worth mentioning that even before the metro expansion those areas were not extremely far from the metro system – the average distance to the nearest metro stations right before the treatment was roughly 3.4 km (Figure 5) and the maximum distance was slightly above 6 km.

Control cells should be areas with two important characteristics: *(i)* before the Line 5 expansion, they had similar characteristics to those deemed treated; and *(ii)* that distance was not significantly reduced by Line 5 or any other metro expansions. To maximize potential comparability, we are especially interested in selecting controls with comparable *ex ante* distances to the subway system. Thus, we restricted our potential controls to those hexagons whose distance to the closest metro station in 2007 was between 3 and 6 km. These areas (called ”pool far”) are marked in Figure 4 by the green background.

It is important to mention there are two groups of cells in the municipality of *São Paulo* that are not considered in Equation 1. They are denominated Non-compliers and Pool Near in Figure 4. The former is marked by the red background in the Figure and it accounts for two types of regions. Firstly, we have those cells that during the entire period of analysis remain too far from the metro system (distance to the closest metro station is always above 6 km). Given the dynamics driving the city expansion, these areas tend to be isolated suburban areas, with a very different land use pattern from that observed for the treated region. Thus, the inclusion of these cells could hurt the comparability between treated and controls and lead to biased estimations. Secondly, we have cells whose distance to the metro system changed during the study period but not due to the expansion of Line 5 – basically, parts of the city that were affected by the expansions of Lines 4 and 15, which also took place after 2008. Intuitively, we can understand those areas as receiving an alternative treatment. Thus, since we aim to isolate the effects of the Line 5 expansion, we can not use them as either control or treated units.

The last group observed in Figure 4 is formed by cells that by 2007 were already closer (distance below 2 km) to an operational metro station – they are marked by the blue background. We can think of these areas as places that were already treated by the metro system before the expansion of Line 5. Again, their inclusion as controls could also bias our results. Neither these nor the H3 cells described in the prior paragraph are included as controls (or potential controls) in our empirical strategy.

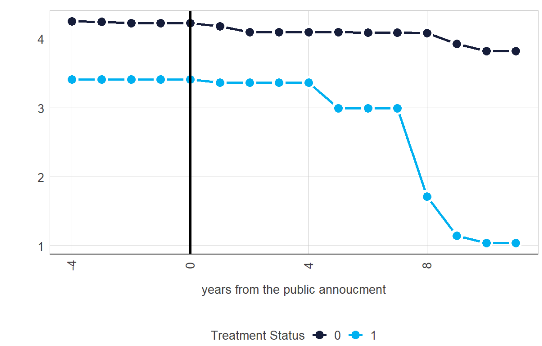
Figure 5 compares our treated and control areas before and after the treatment, and Table 1 shows the descriptive statistics for the whole sample and period for the two groups. Panel (a) of Figure 5 shows us the mean distance to the closest metro station, and it allows us to evaluate the exposure of both areas to the Metro Line 5 expansion. As expected, as new Line 5 Metro stations initiate their operations (starting 5 years after the announcement) the mean distance among treated cells decreases. At the end of the studied period, these cells are, on average, roughly 1 km away from the metro. Conversely, among the control regions, the mean distance is roughly 4 km during most of the period. Panels (b) and (c) shows how both groups evolve in terms of total number of properties and constructed area (two of our outcome variables). They suggest that the treated areas are becoming denser with time, and a change in slope seems apparent roughly six years after the announcement.

However, Figure 5 also indicates the presence of different trends between our treated and control groups – especially for the outcome variables. This suggests the key identification hypothesis for the estimation of $\hat{\delta}$ might not hold. Because of that, we use an alternative approach for the estimation of Equation 1, the Synthetic Difference-in-Differences (SDiD) method proposed by (Arkhangelsky et al., 2021). This method combines the logic of a DiD estimation, with that of synthetic controls. As Arkhangelsky et al.(2021) emphasize, SDiD is fundamentally a weighted DiD with more comparable units and periods contributing more to the estimated parameters. By putting more weight on more comparable units, SDiD is able to recover (conditional) pre-treatment parallel trends as a classical matching procedure would do, but with greater efficiency.

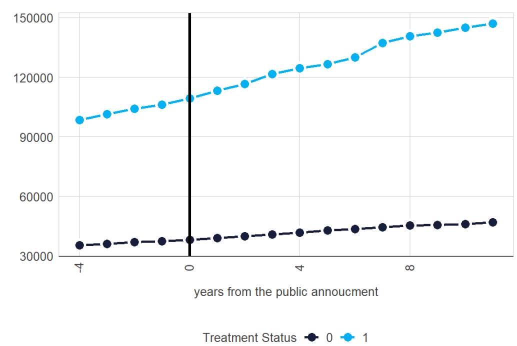
To evaluate the relative importance of time and units weights (respectively denoted by $\hat{\alpha}_t$ and $\hat{\omega}_i$) within the SDiD setting, we used two different estimators: *(i)* $\hat{\delta}_{sdid}$, which uses both weights and *(ii)* $\hat{\delta}_{sdid-\omega}$, which only uses $\hat{\omega}_i$. Using the total constructed area as outcome variable, Figure 6 shows how SDiD uses available information to build units weights. It is interesting to note that of the cells that are available as controls receive non-zero weights. Figures A1, A2, A3 and A4, in the Appendix show the same behaviour for the other outcome variables, which suggests our estimations are not highly dependent on any specific areas.

Figure 5: Visual inspection of treated and control groups

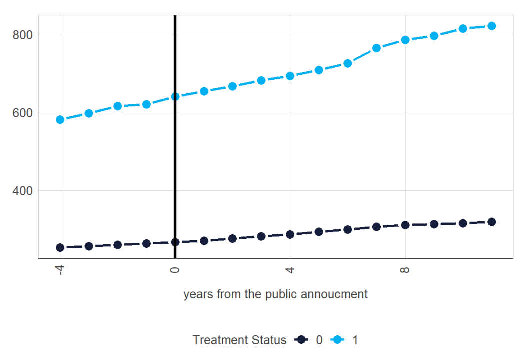
(a) Mean Distance to the closest metro station (km)



(b) Total constructed area (m^2)



(c) Total number of properties



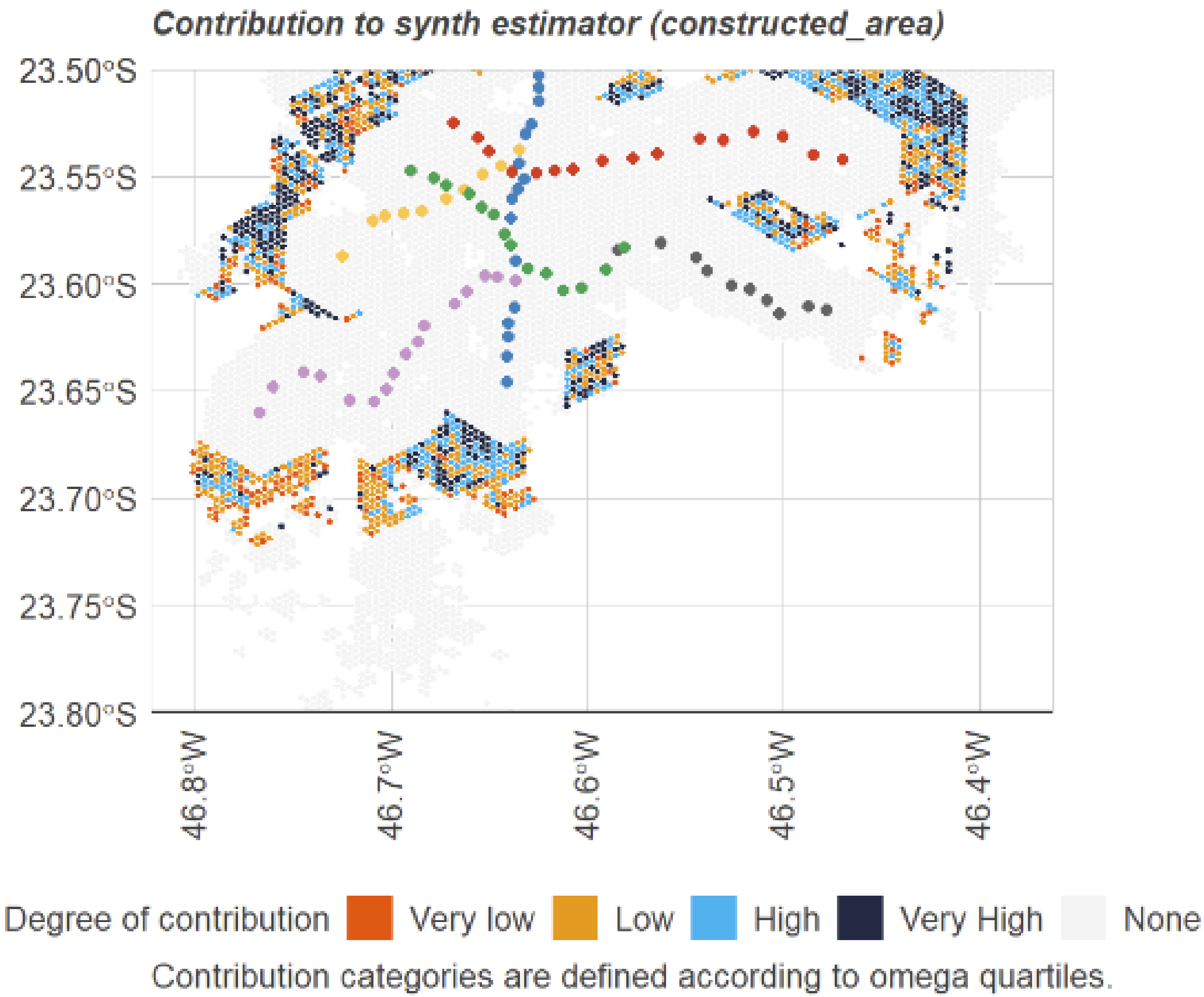
Note: Own elaboration, based on data from Prefeitura de São Paulo (2022a, 2022b and 2024).

Table 1: Summary Statistics

Variable	Whole sample	Control group (before)	Control group (after)	Treatment group (before)	Treatment group (after)
N	63,258	29,692	29,692	1,937	1,937
Distance to closest metro station (km)	4.88	5.41	4.54	4.07	2.84
	(1.95)	(2.38)	(1.26)	(0.91)	(1.24)
Total constructed area (m^2)	35,417.84	26,682.66	35,398.71	82,276.04	122,753.43
	(39,622.99)	(24,184.15)	(32,196.62)	(72,134.07)	(101,134.31)
Total number of properties	253.62	206.23	257.62	491.71	680.58
	(285.62)	(206.64)	(254.9)	(521.13)	(684.63)
Average size of residential properties (m^2)	143.98	130.58	150.39	181.63	201.3
	(443.06)	(112.76)	(630.98)	(101)	(158.64)
Share of commercial properties (%)	0.24	0.26	0.24	0.17	0.21
	(0.28)	(0.28)	(0.28)	(0.22)	(0.26)
Average size of commercial properties (m^2)	1,114.42	899.8	1,249.33	1,525.38	1,765.92
	(9,980.99)	(7,448.87)	(11,432.54)	(13,008.16)	(14,073.4)

Source: Own Elaboration.
Note: Whole sample t = 26 years; before t = 13 years; after t =13 years. Whole sample number of unique H3 cells = 2,433; Control group number of unique H3 cells = 2284; Treatment group number of unique H3 = 149. The values in the first row are averages and the values between parenthesis are standard deviations.

Figure 6: Units Contribution for SDiD: Total constructed areas (m^2)



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024).

5 Results

5.1 Main Results

Considering our key hypothesis, we expect the following results for areas affected by the Metro Line 5 expansion: *(i)* higher overall density, measured by an increase in the total constructed area and the number of properties within each cell; *(ii)* an increase in the share of properties dedicated to commercial use. We also investigate whether the expected increase in the number of properties is associated with a reduction in the mean size of those properties (both residential and commercial). This last pattern is usually observed in areas where use demand is high and total construction potential is a bidding constraint, forcing real estate developers to reduce average size.

Table 2 shows the main results from our estimations. As expected, it is possible to note significant increases in the total constructed area (roughly 50% increase, considering $\hat{\delta}_{SDiD}$), total number of properties (25%), and the share of commercial properties (13%). Despite that, we see no significant reduction in the mean size of properties. In fact, among those dedicated to residential use, the impact seems to be positive, but with a modest magnitude (4%).

These results indicate the Metro Line 5 expansion effectively induced an increase in urban density. They also suggest that the real estate market was able to meet the demand boost by increasing total construction area without the necessity to reduce the mean size of residences and commercial units.

Table 2: Main Results estimated for the Metro Line 5 Expansion

Estimator	Outcome	Cells	Periods	Effect	Effect size[1]	Std. Error	IC lower (95%)	IC upper (95%)
$\hat{\delta}$	Constructed Area (m^2)	2433	26	31761.35	0.93	3974.95	23970.45	39552.24
$\hat{\delta}_{SDiD}$		2433	26	16892.96	0.5	3523.89	9986.13	23799.79
$\hat{\delta}_{SDiD-\omega}$		2433	26	17209.93	0.5	4593.2	8207.25	26212.61
$\hat{\delta}$	Number of Properties	2433	26	137.48	0.53	20.22	97.84	177.11
$\hat{\delta}_{SDiD}$		2433	26	62.99	0.24	14.24	35.08	90.9
$\hat{\delta}_{SDiD-\omega}$		2433	26	63.67	0.24	22.63	19.32	108.02
$\hat{\delta}$	Size of Residential Properties (m^2)	2070	26	6.45	0.05	1.98	2.58	10.33
$\hat{\delta}_{SDiD}$		2070	26	5.19	0.04	1.73	1.8	8.58
$\hat{\delta}_{SDiD-\omega}$		2070	26	6.62	0.06	2.56	1.61	11.63
$\hat{\delta}$	Share of Commercial Properties (%)	2239	26	0.06	0.26	0.01	0.04	0.08
$\hat{\delta}_{SDiD}$		2239	26	0.03	0.13	0.01	0.01	0.04
$\hat{\delta}_{SDiD-\omega}$		2239	26	0.03	0.14	0.01	0.01	0.05
$\hat{\delta}$	Size of Commercial Properties (m^2)	2186	26	-93.8	-0.07	178.01	-442.7	255.1
$\hat{\delta}_{SDiD}$		2186	26	-192.42	-0.15	144.61	-475.85	91.02
$\hat{\delta}_{SDiD-\omega}$		2186	26	-219.14	-0.17	260.43	-729.58	291.31

[1] Effect size is equivalent to the estimated beta divided by the weighted average for the untreated units in pre-treatment periods.

5.2 Parallel Trends and Dynamic Effects

It is relevant to note that, even though overall statistical significance does not change across different estimators, the effect size dramatically changes once we apply SDiD unit weights. For total constructed area, the total number of properties and the share of commercial properties $\hat{\delta}_{SDiD-\omega}$ is roughly half of $\hat{\delta}$. This considerable difference raises the question of whether the basic DiD setting is able to provide unbiased results.

To answer this, it is crucial to validate the key identification assumption for both the DiD and SDiD approaches: pre-treatment parallel trends. To do so, we implement the dynamic version of Equation 1, by making the $Line5$ dummy equal to 1 for all treated units (despite the year) and interacting it with each α_t.

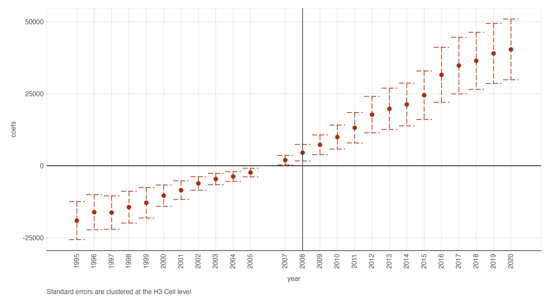
Figure 7 shows the results of this exercise for $\hat{\delta}$. For three of the five outcome variables, it is clear that pre-treatment parallel trends do not hold unconditionally. This indicates that without further adjustments, the control group was, even before the treatment, considerably different from the treated one. In this context, the basic DiD setting does not yield an unbiased estimation.

Figure 8 shows the same results, but for $\hat{\delta}_{SDiD-\omega}$. As suggested by Arkhangelsky et al. (2021), we can clearly see that the inclusion of SDiD weights is able to recover pre-treatment parallel trends, and, thus, lend credibility to the identifying assumption and to the estimated parameters.

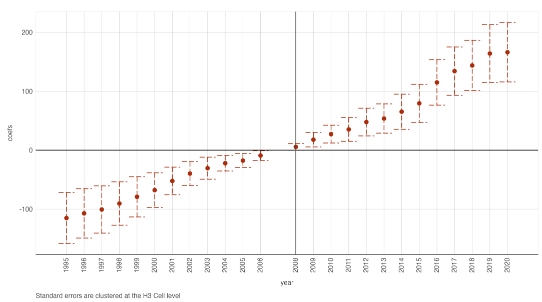
It is also relevant to note that our main results in terms of urban density arise roughly four years after the public announcement. As we can notice in Figure 5(a), at that moment the mean distance to the closest metro station was still stable, since no new Metro Line 5 station had been inaugurated. It reinforces the idea that economic agents anticipated the expected changes in transport accessibility, and the actual response to them happens before the delivery of the infrastructure expansion.

Figure 7: Dynamic Especification for DiD estimations

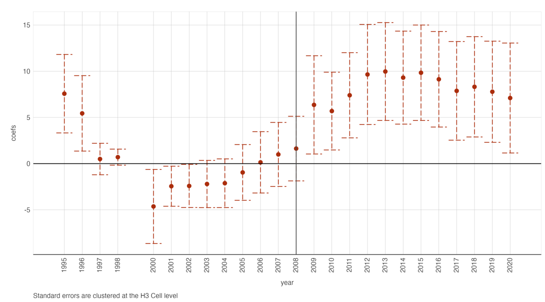
(a) Total constructed area (m^2)



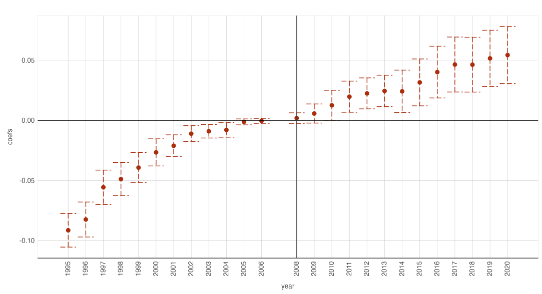
(b) Total number of properties



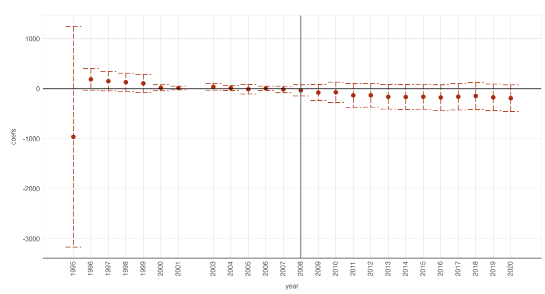
(c) Mean size of residential properties (m^2)



(d) Share of commercial properties (%)



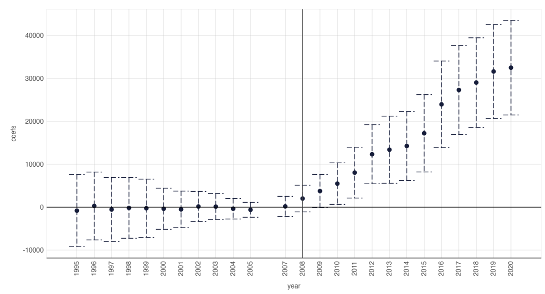
(e) Mean size of commercial properties (m^2)



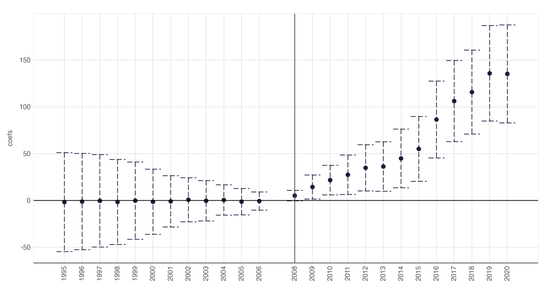
Note: Own elaboration, based on data from Prefeitura de São Paulo (2022a, 2022b and 2024).

Figure 8: Dynamic Especification for SDiD estimations

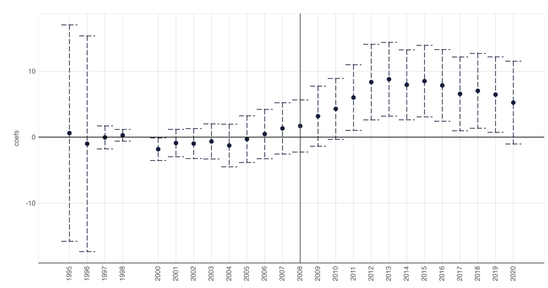
(a) Total constructed area (m^2)



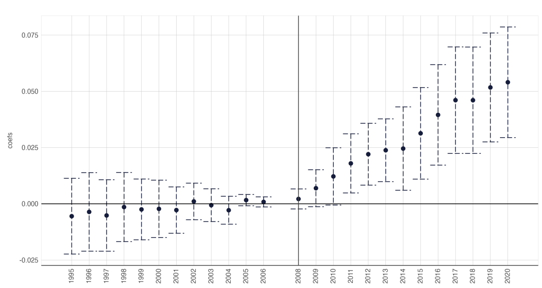
(b) Total number of properties



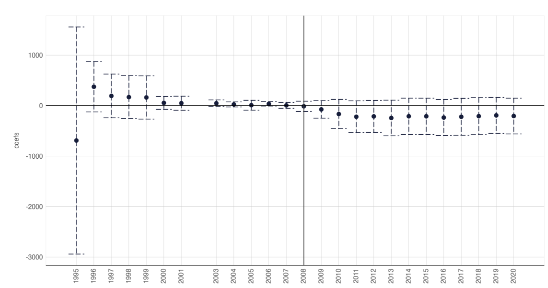
(c) Mean size of residential properties (m^2)



(d) Share of commercial properties (%)



(e) Mean size of commercial properties (m^2)



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022a, 2022b and 2024).

5.3 Placebo Treatment Effects

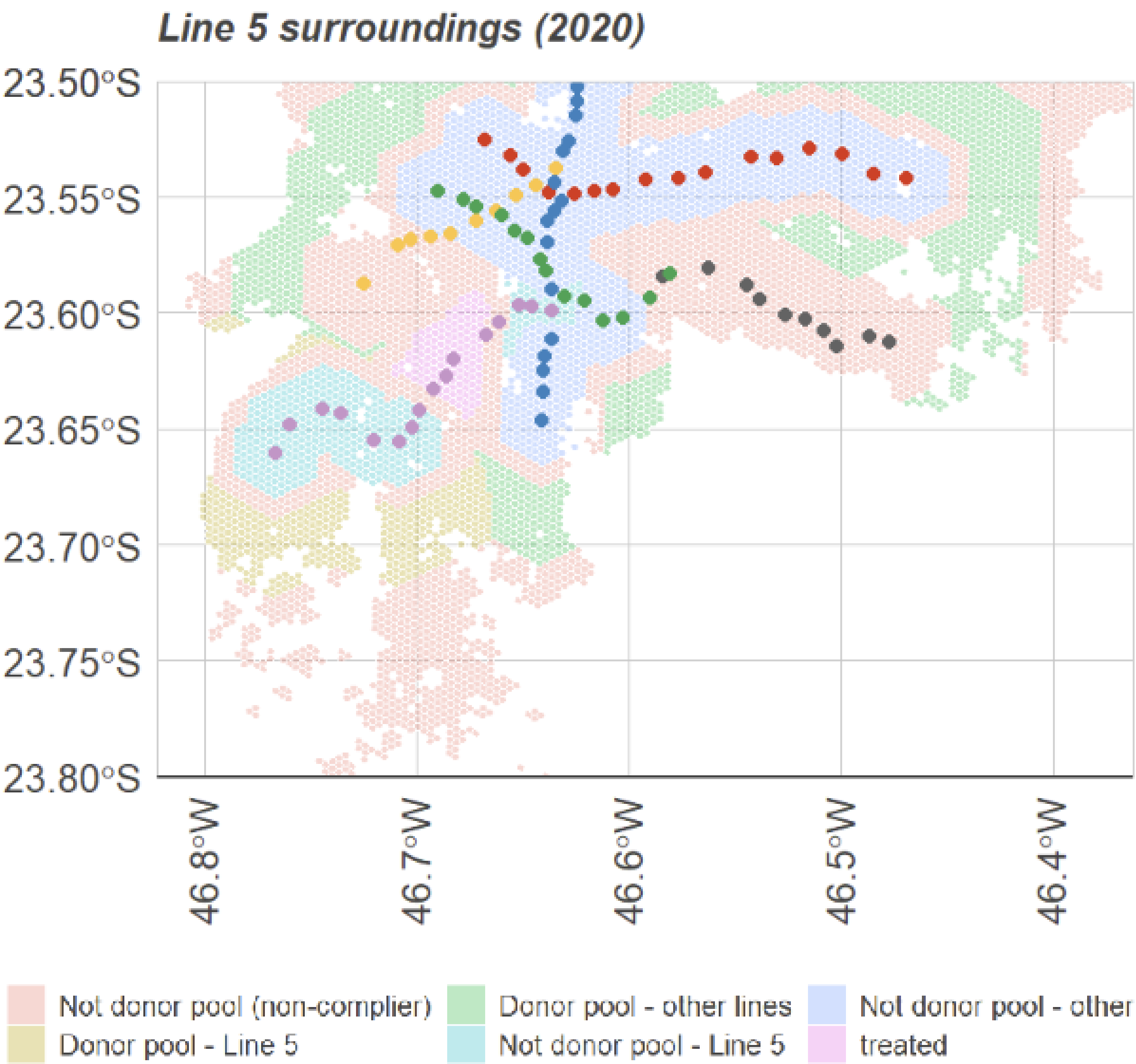
As Figure 4 shows, the expansion of Line 5 affects only a relatively small region in the southeast of *São Paulo*, while the control units spread throughout the entire city. Also, it is possible to conjecture that this specific region was already under the effect of the construction of the first phase of Line 5 - which took place in 2002. Thus, one could be worried that the previously observed results are mostly spurious and driven by specific economic growth forces that were already affecting the southeast area of the city even before the decision to expand Line 5.

To address those concerns, we implemented a placebo treatment effects analysis comparing cells that were in the same region of Line 5 (southeast of *São Paulo*), but not close to any metro station, to cells that were equally distant to the metro system, but in different parts of the city. To implement this analysis, we separated the original control group (”pool far”) into two new categories.

The first (denominated ”Donor Pool - Line 5” in Figure 9) serves as the treated group for the placebo estimation and comprises areas that *(i)* remained at a distance between 3 and 6 km from the closest metro station during the entire period, and *(ii)* had as the closest metro station one from Line 5. The second group (denominated ”Donor Pool - other lines” in the same figure) includes cells with comparable distance to the metro system but under the influence of different lines and, therefore, in other parts of the city.

If there had been any specific growth dynamic driving the expansion of construction in cells in the southeast of *São Paulo*, the replication of Equation 1 for our placebo treatment effects analysis should find similar impacts - at least in terms of signal and statistical significance if not magnitudes. However, as Table 3 shows, the coefficients from the placebo estimation are not statistically relevant, once we include the SDiD weights, and, in general the point estimates are opposite to what we observe in Table 3. This reinforces the idea that the results observed in 2 are driven by the Metro Line 5 expansion.

Figure 9: Grid Categorization for the Placebo Treatment Effects Analysis



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022a, 2022b and 2024).

Table 3: Main Results estimated for the Placebo Treatment Effects Analysis

Estimator	Outcome	Cells	Periods	Effect	Effect size	Std. Error	IC lower (95%)	IC upper (95%)
$\hat{\delta}$		2284	26	-3189.59	-0.11	767.09	-4693.08	-1686.1
$\hat{\delta}_{SDiD}$	Constructed Area (m^2)	2284	26	-302.56	-0.01	773.41	-1818.44	1213.32
$\hat{\delta}_{SDiD-\omega}$		2284	26	-732.96	-0.02	731.16	-2166.03	700.11
$\hat{\delta}$		2284	26	-19.43	-0.09	5.6	-30.4	-8.45
$\hat{\delta}_{SDiD}$	Number of Properties	2284	26	-6.61	-0.03	4.05	-14.54	1.33
$\hat{\delta}_{SDiD-\omega}$		2284	26	-6.82	-0.03	5.36	-17.32	3.69
$\hat{\delta}$		1930	26	0.42	0	2.99	-5.43	6.28
$\hat{\delta}_{SDiD}$	Size of Residential Properties (m^2)	1930	26	2.61	0.02	2.26	-1.81	7.03
$\hat{\delta}_{SDiD-\omega}$		1930	26	1.21	0.01	2.97	-4.61	7.03
$\hat{\delta}$		2094	26	-0.02	-0.07	0	-0.02	-0.01
$\hat{\delta}_{SDiD}$	Share of Commercial Properties (%)	2094	26	-0.01	-0.03	0	-0.01	0
$\hat{\delta}_{SDiD-\omega}$		2094	26	-0.01	-0.03	0.01	-0.02	0
$\hat{\delta}$		2041	26	-191.51	-0.29	109.98	-407.07	24.05
$\hat{\delta}_{SDiD}$	Size of Commercial Properties (m^2)	2041	26	-51.48	-0.08	31.62	-113.46	10.49
$\hat{\delta}_{SDiD-\omega}$		2041	26	-78.56	-0.12	40.13	-157.22	0.1

[1] Effect size is equivalent to the estimated beta divided by the weighted average for the untreated units in pre-treatment periods.

6 Conclusion

This paper quantifies the effects of the expansion of Line 5 of the *São Paulo* metro system in Brazil on land use and property features. This can help understand how the proximity to a metro station affects urban development in Latin America and the Caribbean. We use a Synthetic Difference-in-Differences (SDiD) approach to assure comparability between treated and control areas and show that the identification assumption of parallel trends holds once SDiD weights are used. Our results show positive impacts on constructed area, with a treatment effect that is half the magnitude of the average constructed area in untreated units in the pre-treatment period. Additionally, our findings indicate an increase in the number of properties around the stations, with a shift in property composition towards more commercial units. We also find a strong anticipation effect associated with the new metro infrastructure and dynamic impacts after the opening of the first metro station, with effects that increase over time.

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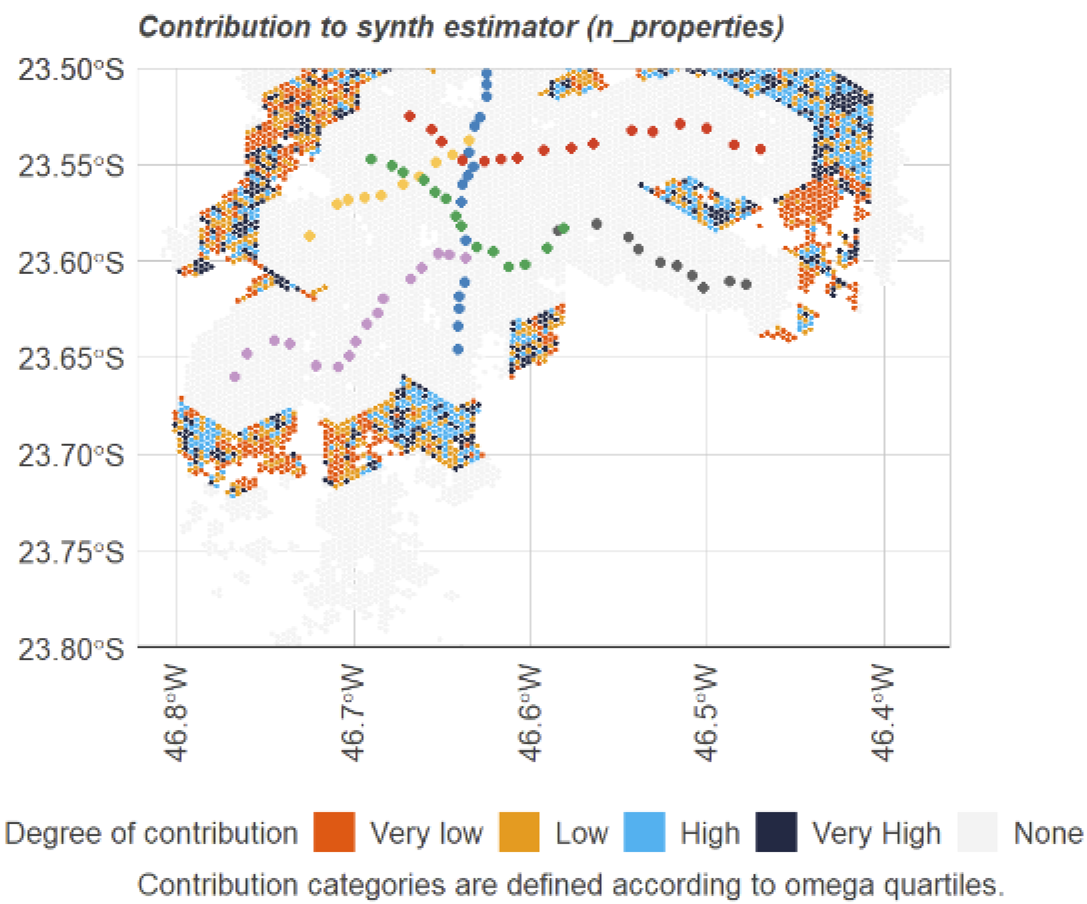
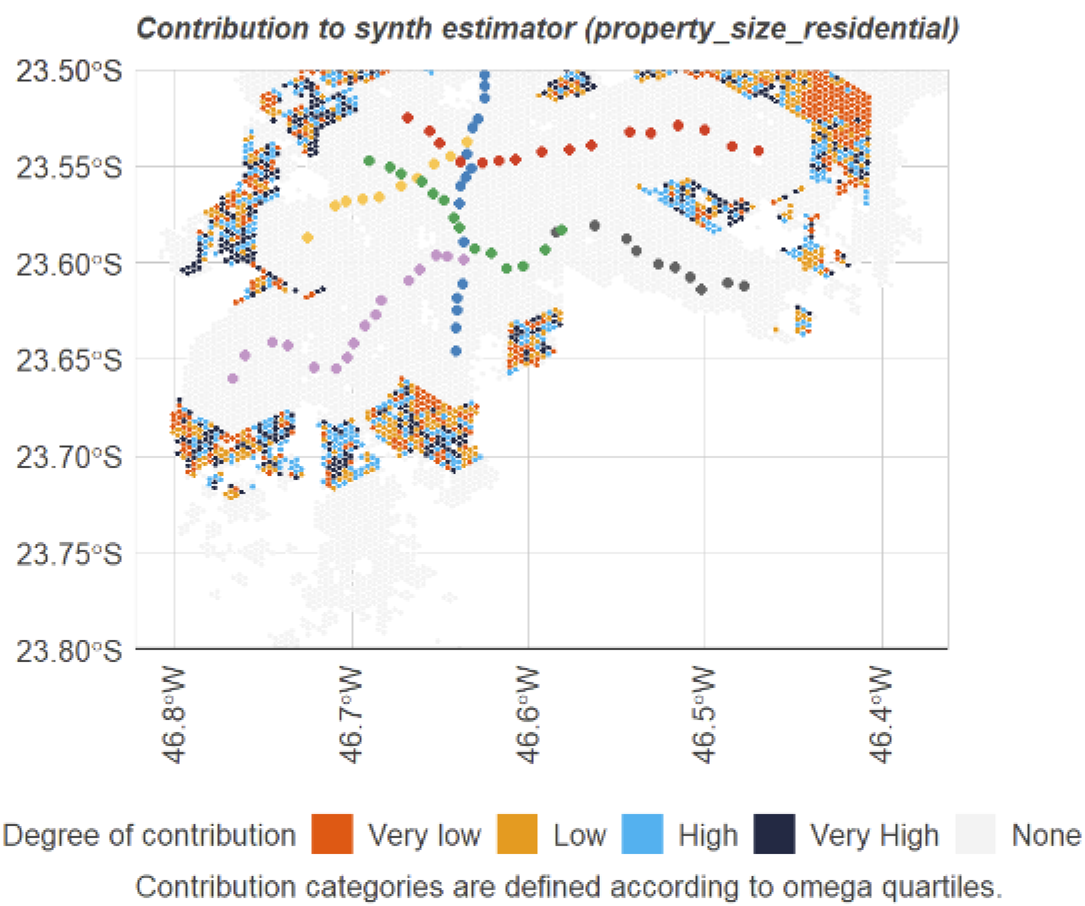
Appendix. Units' Weights for the SDID estimation

Figure A1: Units Contribution: Total number of properties



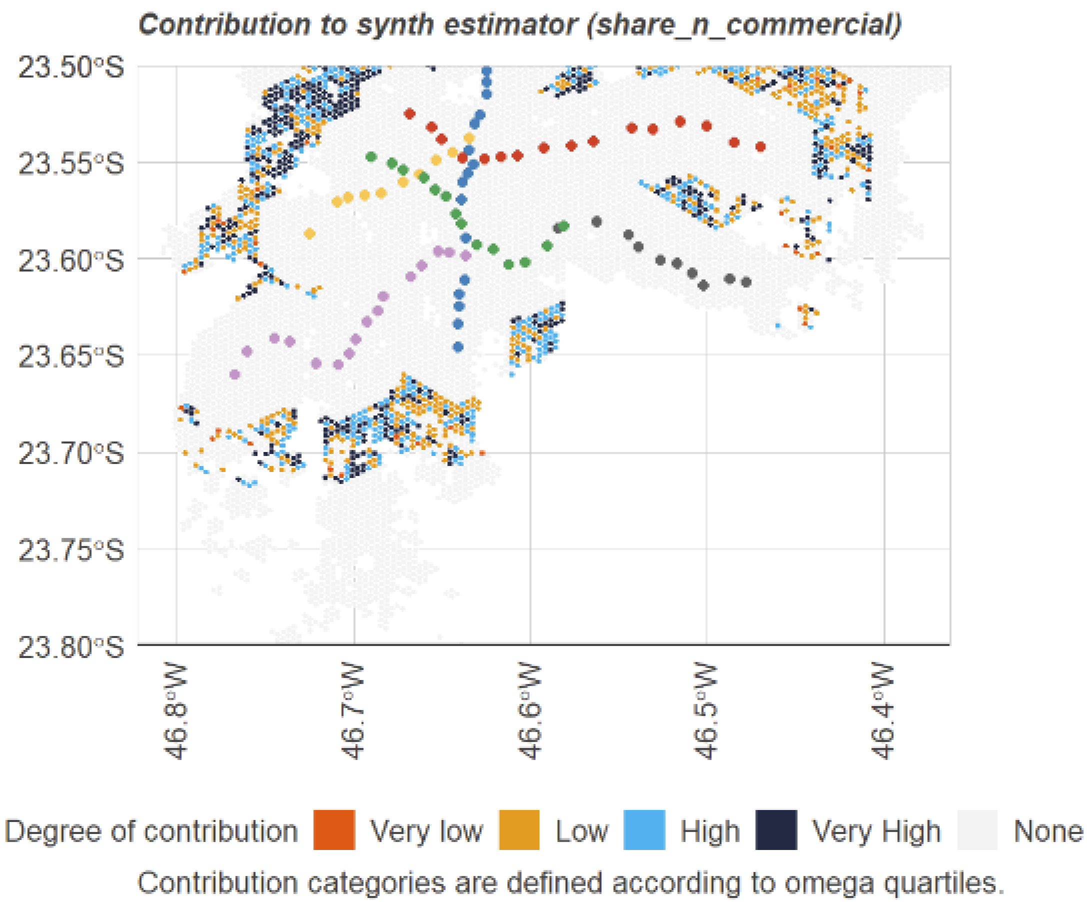
Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024).

Figure A2: Units Contribution: Mean size of residential properties



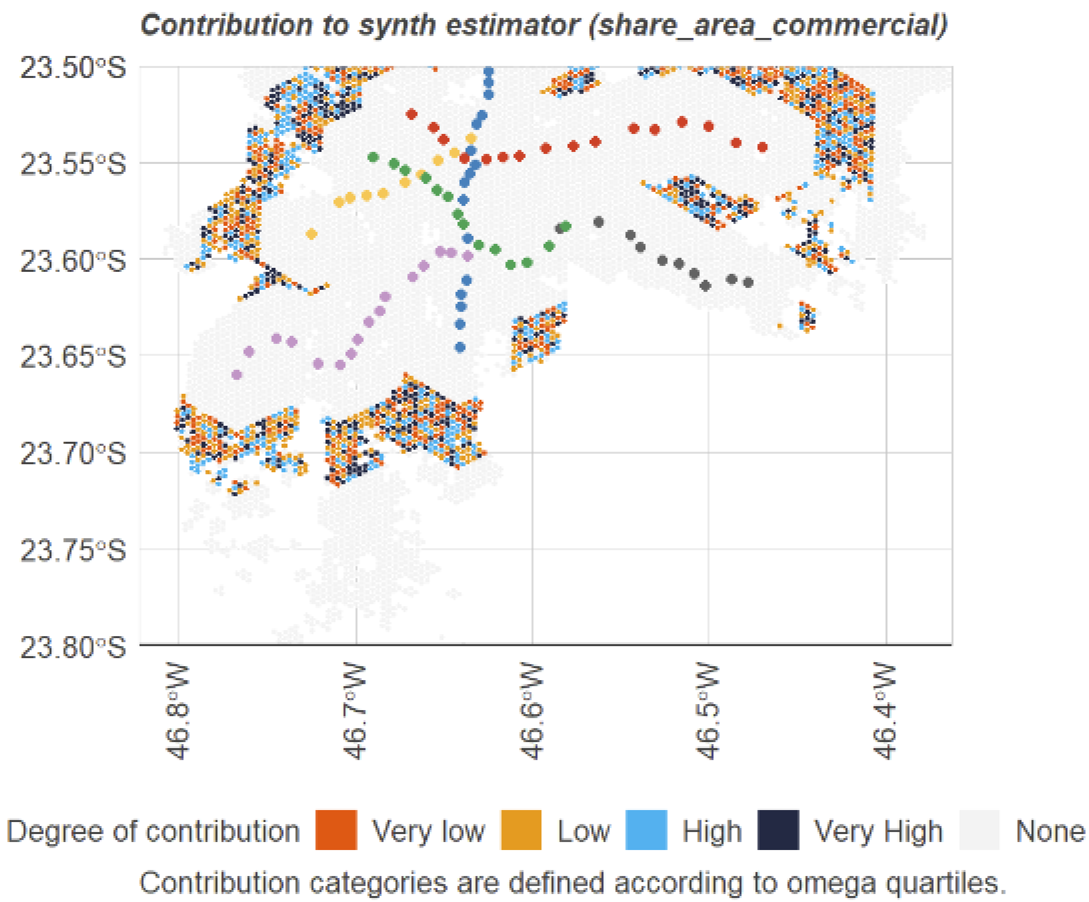
Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024).

Figure A3: Units Contribution: Share of commercial properties (%)



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024).

Figure A4: Units Contribution: Share of commercial area (%)



Note: Own elaboration, based on data from Prefeitura de São Paulo (2022b and 2024).