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The temporal sequence between gentrification and cycling infrastructure expansions in Montreal, Canada

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ABSTRACT

Increases in cycling infrastructure might be linked to gentrification. However, there is little empirical evidence investigating the existence and directionality of this possible relationship. This study examined the temporal sequence involved in the relation between gentrification and increases in the cycling infrastructure in Montreal, Canada. We analyzed changes in cycling infrastructure between 2006, 2011, and 2016, considering cyclist-only paths, multi-use paths, and on-street bike lanes. The Ding measure was used to identify gentrified census tracts (CTs) using census data. We implemented logistic regression models with and without geographically weighted regression specification at the CT level to test three scenarios; whether an increase in cycling infrastructure (2006–2011) was associated with subsequent gentrification (2011–2016); whether gentrification (2006–2011) was associated with subsequent increase in cycling infrastructure (2011–2016); or if these phenomena happened simultaneously (2011–2016). Increase in cycling infrastructure was not linked to subsequent gentrification, nor did these two phenomena happen simultaneously. However, gentrified CTs had a 44% greater chance of a subsequent increase in cycling infrastructure, with varying strengths of associations across the study area. When planning increases in cycling infrastructure, it is crucial to take an equity-based approach that underlying sociodemographic dynamics of urban CTs. To achieve this, cities need to engage in broad upstream community engagement, ensuring the inclusion of a diverse range of voices in the decision-making process.

1. Introduction

Many cities have expanded cycling networks, aiming to promote active living (Christiana, Bouldin, & Battista, 2021; Leger, Dean, Edge, & Casello, 2019; Rahman, Upaul, Thill, & Rahman, 2023), reduce automobile dependence and greenhouse gas emissions (Abubakar & Alshammari, 2023; Karimipour, Tam, Le, & Burnie, 2021; Kou, Wang, Chiu, & Cai, 2020; McQueen, MacArthur, & Cherry, 2020), or strengthen neighborhood social capital (Stroope, 2021). Prioritizing cycling infrastructure expansions in historically underserved neighborhoods can help reduce socio-spatial inequities in health (Uphoff, Pickett, Cabieses, Small, & Wright, 2013). Neighborhood improvements can also have unintended consequences such as gentrification. Gentrification is a process in which formerly lower-income neighborhoods experience investment and in-migration of increasingly affluent new residents (Tulier, Reid, Mujahid, & Allen, 2019) often resulting in increases in housing prices (Slater, 2013, p. 344; Smith, 1987). Thus, gentrification can lead to the displacement of long-term residents who cannot afford to stay, which in turn means they do not benefit from the investment in their neighborhood (Zuk, Bierbaum, Chapple, Gorska, & Loukaitou-Sideris, 2018). While the association between urban investment and gentrification has been extensively investigated (Zuk et al., 2018), little is known about the temporality of the association between increases in cycling infrastructure and gentrification. In other words, there is scant evidence on whether the development of cycling infrastructure precedes, follows, or occurs simultaneously with gentrification.

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The phenomenon of gentrification is a significant source of apprehension, eliciting concerns surrounding issues of urban inequity, among the general public and scholars (Mehdipanah, Marra, Melis, & Gelormino, 2018). Over the past two decades, the prevalence of gentrification has risen, serving as either a driver or an outcome of income inequality within urban regions (Chapple, 2017). Some authors have proposed, in theory and without empirical investigation, the possibility that the presence of cycling infrastructure may contribute to gentrification (Hoffmann, 2013), or alternatively, that the process of gentrification may attract further improvements in cycling infrastructure (Stehlin, 2015). Empirical evidence on the temporal association between the development of cycling infrastructure and gentrification is limited, primarily due to the designs of studies (Hirsch, Green, Peterson, Rodriguez, & Gordon-Larsen, 2017). However, existing research in North America indicates that cycling infrastructure is more commonly found in central cities, with a higher prevalence around college campuses and in gentrifying neighborhoods located near the urban core (Pucher, Buehler, & Seinen, 2011; Morrison, 2021).

In recent decades, many North American cities have made efforts to augment the quantity and quality of cycling infrastructure. Nonetheless, there persists a substantial degree of spatial variation and socioeconomic inequality in cycling infrastructure not only between cities and towns but also within different parts of a city (Pucher et al., 2011). Cycling infrastructure coverage, increased bike trips, better accessibility, and related health gains are unequally distributed, with equity-deserving groups benefiting less (Cunha & Silva, 2022). For instance, a study examining changes in cycling infrastructure across 29 cities in the United States highlighted the heterogeneity in investments based on neighborhood socioeconomic and demographic compositions (Ferenchak & Marshall, 2021). While downtown areas tend to have more cycling infrastructure, cities have unique socio-spatial configurations, leading to variations in the availability and equity of cycling infrastructure within and between cities based on their histories and structures (Ferenchak & Marshall, 2021).

Gentrification studies have largely overlooked changes in cycling infrastructure, focusing rather on total cycling infrastructure at one time period or have measured a directional relationship between gentrification and subsequent or simultaneous increases in cycling infrastructure, without fully investigating temporal directionality (Braun, 2019; Soria, Cohen, Molas y Molas, Rizk, & Wisambodhi, 2021). To address this knowledge gap, the present study aims to gain new insights into the direction of temporal sequences between gentrification and increases in cycling infrastructure by using longitudinal data in three time points, 2006, 2011 and 2016, in Montreal, Canada. Specifically, we examined the plausibility of three temporal scenarios via the following research question:

What is the temporal sequence between gentrification and increases in cycling infrastructure in Montreal, Canada, and how does it vary across census tracts (CTs)?

The rest of the article is structured as follows: In Section 2, a literature review and background research are provided to establish the connection between neighborhood change, gentrification, active transportation and cycling infrastructure. Section 3 presents the datasets for the case study conducted in Montreal, Canada and discusses the methodology for data analysis. The results of the analysis are presented through tables and maps in Section 4, where associations between changes in cycling infrastructure and gentrification in Montreal are reported. In Section 5, our findings are discussed and compared to the current literature. Lastly, in Section 6, the findings are summarized, and recommendations are made for future research that utilizes census and cycling infrastructure data to analyze association between increases in cycling infrastructure and gentrification process.

2. Literature review

2.1. Neighborhood change and gentrification

Neighborhood change can refer to any alteration in the characteristics of a neighborhood, including its access to urban facilities and services, its price, appearance, safety, political environment, and socioeconomic conditions (Delmelle, 2022). The direction and driving forces of neighborhood change can vary, with potential diverse effects on the community (Mallach, 2015). Gentrification can be considered a specific type of neighborhood change in which the socioeconomic and demographic makeup, built environmental characteristics, or housing prices might quickly change as a result of re-investment (Arreortua, 2016; Bhavsar, Kumar, & Richman, 2020; Schnake-Mahl, Jahn, Subramanian, Waters, & Arcaya, 2020).

Extensive research has been conducted to understand the drivers and consequences of gentrification (Cole, Mehdipanah, Gullón, & Triguero-Mas, 2021). Urban investment, in particular, plays a crucial role in initiating and fueling the process (Gale, 2019; Mehdipanah et al., 2018; Xiang et al., 2023). When investors and developers recognize the potential profitability of undervalued neighborhoods, they initiate processes that attract higher-income residents and bring about physical and social changes in the area. This investment-driven gentrification has raised concerns about social and economic inequalities, as well as the loss of affordable housing and community networks (Stehlin, 2015). It is also associated with the displacement of long-term residents who may not benefit from the resulting improvements (Mujahid et al., 2019; Zuk et al., 2018). Recently, a study used Airbnb data to identify association between gentrification and short-term residential spaces. The study emphasizes the importance of real estate market data, such as short-term rental data, for understanding gentrification, although the temporal relationship between gentrification and Airbnb remains uncertain (Rabiei-Dastjerdi, McArdle, & Hynes, 2022).

Gentrification measurements are varied, but often include key indicators relating to changes in the housing market, land use, and in demographic and socioeconomic composition (Firth, Fuller, Wasfi, Kestens, & Winters, 2020; Tulier et al., 2019). Housing market measures typically involve trends in property values, rental prices, and housing affordability (Chapple, Loukaitou-Sideris, Miller, & Zeger, 2022). By tracking these indicators over time, researchers can identify areas experiencing significant increases in housing costs, which may be indicative of gentrification processes. Additionally, measurements related to land use change focus on assessing alterations in the built environment, including the conversion of industrial or low-income housing areas into upscale residential or commercial spaces (Scott, 2019). This analysis provides insights into the physical transformations occurring within a neighborhood or city. Lastly, demographic and socioeconomic measurements involve examining changes in population composition, income levels, education, and employment patterns (Santos, Paciência, & Ribeiro, 2022). These measurements help capture shifts in the social fabric of an area, including potential displacement of long-time residents due to rising living costs and changes in neighborhood characteristics (Mujahid et al., 2019). In conclusion, there are many gentrification measures and each assesses one or more of the aspects of gentrification in the urban context. The Gentrification, Urban Interventions and Equity (GENUINE) dataset provides four commonly used measures of gentrification for all Canadian Census Metropolitan Areas (Firth, Thierry, Fuller, Winters, & Kestens, 2021).

2.2. Promoting equitable cycling infrastructure for sustainable and inclusive communities

Urban infrastructure plays a pivotal role in promoting active transportation as a sustainable mode of travel. Addition of bike lanes or sidewalks can signal increased investment in the neighborhood and contribute to a changing neighborhood (Rahman et al., 2023; Stroope, 2021). Such urban interventions not only support active transportation but also lead to increases in foot traffic, positively impacting local businesses and community development (Kornas, Bornbaum, Bushey, & Rosella, 2017).

The provision of dedicated bicycle lanes, separated from vehicular traffic, significantly enhances the safety and perceived comfort of cyclists (Jarry & Apparicio, 2021). Well-designed cycling infrastructure, including bike lanes and paths, increases cycling rates and encourages a shift from motorized transport to cycling for short to moderate distances. The accessibility and convenience of cycling can be further improved through bike-sharing programs and secure bike parking facilities (Eren & Katanalp, 2022; Padeiro, 2022). Cycling infrastructure like protected bike lanes appeals to inexperienced bicyclists, risk-averse individuals, women, people with children, people with disabilities, and younger and older cyclists, who are less likely to ride near motor vehicles (Dill, Goddard, Monsere, & McNeil, 2014; Garrard, Rose, & Lo, 2008; Winters & Teschke, 2010), which serves to mitigate existing inequities in cycling. However, uneven distribution of cycling infrastructure in urban areas may inadvertently contribute to gentrification, as highlighted by a recent study investigating the growing significance of urban platforms, such as bike sharing stations, in Vancouver, Canada, revealing that these stations play a role in creating a similar visual effect associated with gentrification in the area. This insight emphasizes the impact of gentrification on neighborhood appearances and underscores the involvement of bike sharing stations in this process (Leszczynski and Kong, 2023).

Equity considerations are crucial when implementing built environment interventions supporting active transportation, particularly cycling infrastructure (Ferenchak & Marshall, 2021; Hansmann, Grabow, & McAndrews, 2022; Padeiro, 2022). Addressing disparities in access to cycling infrastructure and resources is necessary to prevent exacerbating existing inequities. This can be done through considering 1) who is involved in decision-making related to new cycling infrastructure; 2) where interventions occur; and 3) how different population groups are impacted by these changes. For example, considering the perspectives and priorities of targeted communities in the planning and design processes, locating cycling infrastructure in underserved areas and implementing infrastructure and bike-sharing programs catering to diverse user needs can promote equity (Cunha & Silva, 2022; Doran, El-Geneidy, & Manaugh, 2021).

Few longitudinal studies have investigated how gentrification and investments in cycling infrastructure relate. A study conducted in Chicago and Portland between 1990 and 2010 found that cycling infrastructure improvements tended to occur in gentrifying neighborhoods or in pre-existing high-income neighborhoods, rather than in disadvantaged neighborhoods (Flanagan, Lachapelle, & El-Geneidy, 2016). Another study conducted in Los Angeles found a weak positive association between the extension of bikeways between 2010 and 2015 and neighborhood gentrification during the same period (Soria et al., 2021). A longitudinal study examining the change in bike lanes from 1990 to 2015 in Chicago, Minneapolis, and Oakland showed that gentrification predated cycling infrastructure change in Chicago, but that both happened simultaneously in Oakland. Furthermore, the new cycling infrastructure in Chicago and Oakland was predominantly implemented in high-income or in gentrifying neighborhoods (Braun, 2019). No previous study has been conducted regarding the association of increases in cycling infrastructure and gentrification in Montreal, Canada. However, in terms of socio-economic factors, a study conducted in Montreal aimed to examine the distribution of cycling infrastructure in different CTs over time and found that while access to cycling infrastructure was initially greater in CTs with more low-income populations, it became more evenly distributed over time. The study employed separate modeling approaches for different years, which could be seen as a combination of longitudinal and repeated-measure cross-sectional approaches, to measure the associations between cycling infrastructure and socio-economic factors at specific points in time (Houde, Apparicio, & Séguin, 2018). The investigation of temporal sequences between gentrification and cycling infrastructure holds significant scientific importance for cities seeking to invest in cycling infrastructure while mitigating gentrification's negative impacts. This research provides valuable guidance by allowing cities to strategically develop equitable cycling networks based on the observed order of these phenomena. By discerning whether gentrification precedes or follows the establishment of cycling infrastructure, policymakers and city planners can identify critical intervention points and prioritize investments in communities who need them most and promoting equitable development. By understanding the temporal association, cities can engage in inclusive consultations, considering the perspectives and interests of both long-term and short-term residents, and actively track stakeholder engagement to ensure a fair and informed decision-making process. Ultimately, this study will provide evidence on whether investments in cycling infrastructure contribute to gentrification-a currently debated issue in scientific literature.

3. Data and methods

3.1. Conceptual framing

It is challenging to determine how the development of new cycling infrastructure and gentrification may relate causally. In some cases, new cycling infrastructure might be a catalyst for gentrification by increasing property values, attracting new residents and businesses, and changing the neighborhood's character (Hoffmann, 2013). However, in other cases, gentrification might precede the development of new cycling infrastructure, with local authorities investing in cycling infrastructure as part of broader urban renewal strategies (Stehlin, 2015).

Fig. 1 illustrates the possible causal scenarios linking gentrification and increases in cycling infrastructure. Most existing literature has tested only one or two of these scenarios. We tested all three scenarios, that are, if increases in cycling infrastructure precede gentrification (cycling gentrification, Scenario 1), if gentrification predates increases in cycling infrastructure (gentrified cycling, Scenario 2), or if gentrification and increases in cycling infrastructure occur simultaneously (Scenario 3).

3.2. Study area

The study area for this retrospective longitudinal study encompasses a total of 689 CTs, including the Island of Montreal (533 CTs), adjacent cities of Longueuil, Brossard, and St Lambert (75 CTs) and Laval (81 CTs). These cities are associated with the INTErventions, Research, and Action in Cities Team (INTERACT), which is a pan-Canadian collaboration of interdisciplinary scientists, urban planners, and public health decision-makers working to advance research on the design of healthy and sustainable cities for all (Kestens et al., 2019). These areas were chosen due to their significant urbanization and diverse cycling infrastructure, making them ideal for analyzing increases in cycling infrastructure over time. Fig. 2 provides a visual representation of the study area and the distribution of CTs across the region.

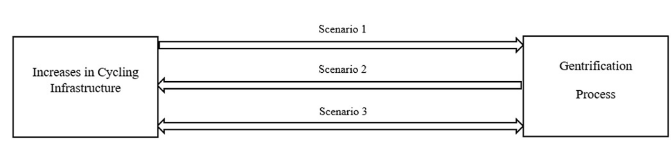

Fig. 1. Conceptual framework illustrating different scenarios linking gentrification and increases in cycling infrastructure in urban areas: 1) cycling infrastructure increases preceding gentrification, 2) gentrification preceding cycling infrastructure increases, and 3) simultaneous gentrification and cycling infrastructure increase.

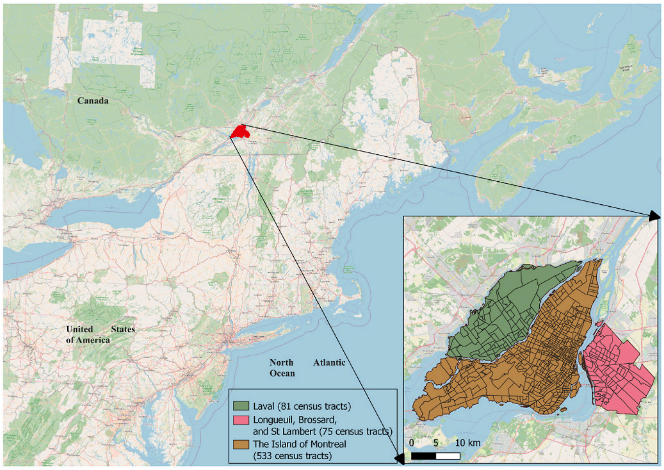

Fig. 2. Location of the study area, with census tracts serving as partitioning areas.

3.3. Data and variables

Gentrification status (gentrified v.s not gentrified) for 2006–2011 and 2011–2016 was assessed using Ding's measure (Ding, Hwang, & Divringi, 2016), as provided in GENUINE dataset (Firth et al., 2021). The Ding measure is a gentrification measure used to assess the gentrification status of CTs based on two conditions (Ding et al., 2016): 1) being below the CT median household income at the beginning of a period (e.g. qualifies as gentrifiable) and 2) experiencing an above-median increase in either gross rent or home value and in the proportion of university-educated residents at the end of the period (Ding et al., 2016). In this study, the CTs that were 'gentrifiable' (satisfying condition 1) were then dichotomized into either 'gentrified' if condition 2 was met (coded 1) and 'gentrifiable' but not gentrified' if it was not (coded 0). The Ding measure accounts both for housing (value) and socioeconomic (educational attainment) aspects of gentrification. However, it does not consider any land use changes, which are considered by some other gentrification measures (Cole et al., 2021; MacDonald & Stokes, 2020).

The GENUINE tool was created specifically to assess gentrification in Canada at the CT level, which is a finer geographical level than a neighborhood. The GENUINE tool assessed gentrification by modifying four existing gentrification measures that were previously used for analyzing census data in both the US and Canada (Firth et al., 2021). CTs are relatively small and stable areas with populations ranging from 2500 to 8000 people (with an average of 4000). In this study, they were chosen as the unit of analysis because they provide a detailed, local-level view of demographic and socioeconomic changes that are relevant to gentrification. It is worth noting that CTs are designed by a committee of local stakeholders and Statistics Canada to ensure that they follow permanent physical features and align with local neighborhood limits where possible. This ensures that CTs are representative of local areas and provide a reliable basis for analysis.

We used geocoded data on cycling infrastructure available for 2006, 2011, and 2016 (Houde et al., 2018). To build the cycling infrastructure dataset, the researchers used archival maps and open data, and constructed the cycling network in ArcGIS. The various cycling networks available in digital form for each of the areas were merged: the urban areas of Montreal and Longueuil, and the city of Laval. To reconstruct the cycling network for the three years (2006, 2011 and 2016) corresponding to the Statistics Canada census years, archival maps from various sources were employed, such as municipal services and Vélo Québec bike path guidebooks. The researchers listed seven types of infrastructure for these three years and grouped them into three categories for analytical purposes: cyclist-only bike paths, on-street bike lanes, and multi-use off-street paths. The continuity of the cycling network beyond street intersections was taken into account by extending the ends of the sections of bike path by 12 m, which corresponds to the average width of Montreal-area intersections. Two cartographical sources were used to validate the data on the cycling networks wherever possible. Complete details on the preparation of these data are provided by Houde et al. (2018).

We calculated the spatial relative and temporal CT-level index of cycling infrastructure as follows. For each census year, we first calculated the percentage of cycling infrastructure length by dividing the length of cycling infrastructure by the total length (kilometer) of roads within *i*-th CT. We computed a spatial relative index by calculating the ratio of the percent of cycling infrastructure in each CT to the mean percent of cycling infrastructure in the entire study region. This calculation was performed for all eligible (gentrifiable) CTs in each census year (t), as per Equation (1). Values greater than one indicate above-average prevalence of cycling infrastructure, and values less than one indicate below-average prevalence in a given CT, relative to the whole study region. We also calculated the temporal change between two consecutive census times (2006–2011, and 2011–2016) using the log-transformed ratio of relative measures for both periods (Equation (2)). This temporal change measure indicates if a given CT has experienced a larger (values above one) or smaller (values below one) increase in cycling infrastructure than the area as a whole. Doing so, we model substantial expansions in cycling infrastructure, i.e. an increase greater than the city's average (Sharifi, Nygaard, Stone, & Levin, 2021). A dichotomous variable was created to distinguish CTs with above-average increase (coded 1) from CTs with below-average increase (coded 0).

$$\text{Relative cycling infrastructure index } (\mathrm{i,t}) = \frac{Percentage\ of\ road\ length\ with\ cycling\ infrastructure\ (i,t)}{Mean\ Percentage\ of\ road\ length\ with\ cycling\ infrastructure\ (t)} \tag{1}$$

$$\text{Temporal cycling infrastructure change } (\mathrm{i}, \Delta_t) = \mathrm{Ln}\left(\frac{Relative\ \ cycling\ infrastructure\ \ (i,t)}{Relative\ \ cycling\ infrastructure\ (i,t-1)}\right) \tag{2}$$

where *i* indicates CT and *t* denotes time period.

Finally, we considered the 2011 CT population density as a control variable, as previous research has shown it is often a correlate of gentrification (Flanagan et al., 2016; Moos, 2014). All the data used in the study is freely accessible to the public through supplementary file 1, which is a geopackage file.

3.4. Methods

3.4.1. Descriptive analysis

Bivariate maps were created to illustrate how change in cycling infrastructure relates to the gentrification status of CTs.

3.4.2. Regression models

In order to test our three scenarios on the temporal association between gentrification and cycling infrastructure (Fig. 1), we developed four logistic regression models (two models for scenario 3), which estimated the association between these two processes globally (for the whole study region). As well, we fitted another set of logistic regression models under Geographically Weighted Regression (GWR) specification to examine if and how the associations vary spatially (MGWR, 2023).

The GWR approach is a statistical technique that allows us to explore how relationships between variables vary across different locations. Essentially, GWR is a type of regression analysis that takes into account the spatial context of the data being analyzed. This is important because relationships between variables may vary depending on where they are measured. For example, the relationship between change in cycling infrastructure and gentrification may be different in nature by local area. By locally adjusting regressions, using distance decay functions to weight observations inversely by distance, GWR allows us to examine local variations in associations and identify spatial patterns in the observed relationship that are not apparent when looking at the dataset as a whole.

When deciding whether to use GWR or regular logistic regression, it is important to consider the spatial nature of the data being analyzed. If there is reason to believe that relationships between variables may vary across different locations, GWR may be a more appropriate approach (Fotheringham, Yang, & Kang, 2017). However, if there is no spatial pattern in the data, regular logistic regression may be sufficient. In our case, it seems reasonable to use GWR since previous literature has shown a spatial pattern of both cycling infrastructure increases (Padeiro, Louro, & da Costa, 2019) and gentrification (Antunes, March, & Connolly, 2020).

Therefore, we fitted eight regression models in total, as summarized by Table 1, which describes the outcome, independent, and covariate variables for each of the three scenarios. Each regression model was fitted to CTs that were gentrifiable, thus excluding non-gentrifiable CTs (CTs with income levels above the median income of our study region at the beginning of each period) from the study. To study the connection between gentrification and transit-oriented development in cities, it is important to include gentrifiable neighborhoods in the regression models. This is known as the key eligibility factor (Padeiro et al., 2019).

Because our models exclude not gentrifiable CTs, and focus on gentrifiable CTs, the spatial pattern of the CTs under study is discontinuous, as illustrated in Fig. 3. Therefore, we used the golden search and adaptive bisquare spatial kernel in the binomial GWR models to optimize the bandwidth used for each regression model to obtain the lowest corrected Akaike Information Criterion (AICc) and avoid creating isolated CTs (a CT without a neighbor) (Oshan, Li, Kang, Wolf, & Fotheringham, 2019). AIC offers a quantitative means to evaluate and compare statistical models. Bisquare kernel has a similar but faster weighting decay as the Gaussian kernel. Using the bisquare weighting system allowed us to set a distance beyond which characteristics do not influence the regression results. This seems acceptable in the urban context where geographically distant CTs would not exhibit strong spatial dependency in terms of gentrification nor the amount of cycling infrastructure. We fitted GWR using MGWR 2.2 software developed by Spatial Analysis Research Center (SPARC) at Arizona State University (MGWR, 2023).

4. Results

4.1. Descriptive results

Fig. 3 shows the CT-level temporal association between gentrification and increases in cycling infrastructure for each of the three scenarios. For each scenario and corresponding regression model(s), CTs have been classified into one of four groups cross-classified by the status of gentrification and increase in cycling infrastructure. Specifically, CTs coded brown are gentrified CTs that experienced an above-average increase in cycling infrastructure relative to the entire study region. In fact, brown CTs in Fig. 3-1 (50/429 or 11.6%) indicate the prevalence of “cycling gentrification”, while those in Fig. 3-2 (87/416 or 20.9%) represent “gentrified cycling,” and those in Fig. 3 (75/429 or 17.5%) illustrate “simultaneous development”. The spatial pattern of gentrified cycling (Fig. 3-2) is distinct from that of the other two scenarios. This is because much of the cycling infrastructure development (brown CTs) is clustered around the center of the island. It is also worth mentioning that pale blue CTs, which indicate non-gentrified CTs that did not experience an increase in cycling infrastructure, constitute a considerable number of CTs in the study area, and could be flagged for future investments.

4.2. Results of regression models

We did not observe a significant association (95% CI crossing the null

Table 1
Summary of scenarios and corresponding regression models to identify the temporal directionality between the gentrification status and the increases in cycling infrastructure.

Specific scenario being tested	Regression model	Outcome variable*	Independent variables		Eligible sample of census tracts (CTs)
			Exposure	Covariate	
1- Increases in cycling infrastructure between 2006 and 2011 are associated with gentrification in the following 5-year period (2011–2016).	1- Cycling infrastructure- > gentrification	Gentrified between 2011 and 2016 (vs. not gentrified)	Cycling infrastructure temporal change between 2006 and 2011 (vs. null or negative change) (binary variable)	Population density (2011)	All CTs that were considered gentrifiable in 2011.
2- Gentrified CTs between 2006 and 2011 are associated with increases in cycling infrastructure in the subsequent 5-year period (2011–2016).	2- Gentrification - > cycling infrastructure	Cycling infrastructure temporal change between 2011 and 2016 (vs. null or negative change) (binary variable)	Gentrified between 2006 and 2011 (vs. not gentrified)	Population density (2011)	All CTs that were considered gentrifiable in 2006.
3- Gentrification and increases in cycling infrastructure happen simultaneously between 2011 and 2016.	3-1 Simultaneous association	Gentrified between 2011 and 2016 (vs. not gentrified)	Cycling infrastructure temporal change between 2011 and 2016 (vs. null or negative change) (binary variable)	Population density (2011)	All CTs that were considered gentrifiable in 2011.
	3-2 Simultaneous association	Cycling infrastructure temporal change between 2011 and 2016 (vs. null or negative change) (binary variable)	Gentrified between 2011 and 2016 (vs. not gentrified)		

* All outcomes are binary and all variables were measured at the level of the census tract.

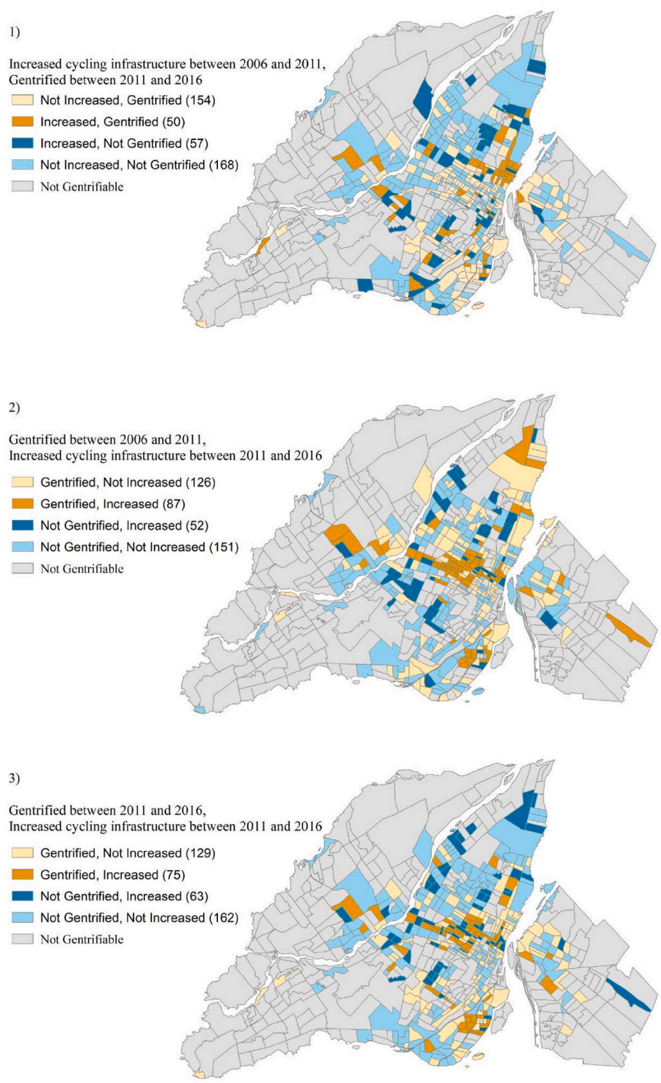

Fig. 3. Maps show the CT-level temporal relationships between gentrification status and increases in cycling infrastructure across two different periods. 1) Scenario 1 (Cycling Gentrification); 2) Scenario 2 (Gentrified Cycling); 3) Scenario 3 (Simultaneous relationship).

value) between an increase in cycling infrastructure (2006–2011) and gentrification in the subsequent period (2011–2016) (Table 2). We also did not observe conclusive associations for Models 3.1 and 3.2, which examined the simultaneous development of these two phenomena in the same period (Tables 2 and 3).

On the other hand, Model 2 showed significant associations between gentrification and cycling infrastructure over time, both in the locally-varying coefficient (GWR) and global models (Tables 2 and 3). CTs that underwent gentrification between 2006 and 2011 showed 44% higher odds of receiving more cycling infrastructure in the subsequent five years (2011–2016) than CTs that had not gentrified (Odds Ratio (OR) = 1.44, CI: 1.16–1.79). Fig. 4 depicts the results of the GWR, Model 2, displaying the association (OR) between gentrification from 2006 to 2011 and the subsequent increases in cycling infrastructure between 2011 and 2016. CTs with stronger associations tended to cluster around the city's central business districts. The local OR map also shows CTs that gentrified and did not experience an above-average increase in cycling infrastructure (CTs in yellow on the map). Since Moran's Index for GWR residuals is very close to zero, we can conclude that the spatial autocorrelation has been effectively accounted for in the regression model, thus validating its results (Table 3).

5. Discussion

Although some studies have investigated the association between the availability of cycling infrastructure and the gentrification status of urban neighborhoods (Braun, Rodriguez, & Gordon-Larsen, 2019; Pucher et al., 2011), few have examined the temporal association of these events i.e., which one precedes the other (Ferenchak & Marshall, 2021). In this study, we investigated whether the development of cycling infrastructure precedes, follows, or occurs simultaneously with gentrification. Each of the three scenarios was examined using logistic regression models with and without GWR specification, the latter evaluating how associations may vary spatially. Our findings reveal that gentrification in an earlier period was linked to increases in cycling infrastructure (gentrified cycling) in a later period in Montreal, as indicated by both GWR and logistic regression models. Nevertheless, the GWR model indicated that the relationship between gentrification and increases in cycling infrastructure was not consistent across all CTs. In particular, some CTs that had undergone gentrification from 2006 to 2011 did not see any increases in cycling infrastructure from 2011 to 2016, while others did. This highlights the utility of local spatial models for analyzing urban dynamics, including gentrification, as well as changes in the built environment, such as cycling infrastructure.

According to our results, the CTs located in the center of Montreal such as in the neighborhoods of Villeray, Rosemont - La Petite-Patrie, Plateau-Mont-Royal, and Parc-Extension, as well as areas in Verdun and the Sud-Ouest, which gentrified between 2006 and 2011, saw greater increases in cycling infrastructure between 2011 and 2016 than average. The arrival of new residents, as part of the process of gentrification in these neighborhoods may have led to a shift in preferences

Table 2
Results for global regression models 1-3.

Regression Models	Regression Model 1 Gentrified between 2011 and 2016 (vs. not gentrified)	Regression Model 2 Cycling infrastructure temporal change between 2011 and 2016	Regression Model 3.1 Gentrified between 2011 and 2016 (vs. not gentrified)	Regression Model 3.2 Cycling infrastructure temporal change between 2011 and 2016
Model specification	(OR (95% CI))	(OR (95% CI))	(OR (95% CI))	(OR (95% CI))
Intercept	0.91 (0.75–1.11)	0.48* (0.39–0.60)	0.91 (0.75–1.11)	1.00 (0.91–1.1)
Cycling infrastructure temporal change (5 year, 2006–2011)	0.99 (0.81–1.19)	N/A	NA	NA
Gentrified (5 year, 2006–2011)	NA	1.41* (1.14–1.75)	NA	NA
Cycling infrastructure temporal change (5 year, 2011–2016)	NA	NA	1.14 (0.94–1.39)	NA
Gentrified (5 year, 2011–2016)	NA	NA	NA	1.07 (0.97–1.18)
Population Density 2011	1.41* (1.14–1.75)	1.37* (1.11–1.67)	1.38* (1.12–1.70)	1.16* (1.05–1.27)
AICc	576.4	355.1	577.4	1215.6

Abbreviations: CI: Confidence Interval; OR: Odds Ratio.
NA indicates regression coefficients that are not relevant and thus not added to the regression models.
* Confidence interval crossing the null value of 1, thus indicating statistically conclusive result.

Table 3
Results for models 1–3 fitted under geographically weighted regression.

Regression Models	Regression Model 1 Gentrified between 2011 and 2016 (vs. not gentrified)	Regression Model 2 Cycling infrastructure temporal change between 2011 and 2016	Regression Model 3.1 Gentrified between 2011 and 2016 (vs. not gentrified)	Regression Model 3.2 Cycling infrastructure temporal change between 2011 and 2016
Model specification	(OR mean (95% CI))	(OR mean (95% CI))	(OR mean (95% CI))	(OR mean (95% CI))
Intercept	0.94 (0.77–1.15)	0.50* (0.40–0.63)	0.94 (0.77–1.14)	1.07 (0.73–1.56)
Cycling infrastructure temporal change (5 year, 2006–2011)	0.98 (0.79–1.22)	N/A	NA	NA
Gentrified (5 year, 2006–2011)	NA	1.44* (1.16–1.79)	NA	NA
Cycling infrastructure temporal change (5 year, 2011–2016)	NA	NA	1.16 (0.95–1.41)	NA
Gentrified (5 year, 2011–2016)	NA	NA	NA	1.04 (0.76–1.42)
Population Density 2011	1.39* (1.14–1.70)	1.35* (1.08–1.67)	1.36* (1.09–1.68)	1.16 (0.77–1.74)
Bandwidth	429 (427–429)	416 (414–416)	429 (427–429)	59 (54–57)
AICc	586.2	368.0	587.0	1149.6
Residuals' Global Moran's Index	−0.002	−0.002	−0.002	−0.001

Abbreviations: CI: Confidence Interval; OR: Odds Ratio.
NA indicates regression coefficients that are not relevant and thus not added to the regression models.
* Confidence interval crossing the null value of 1, thus indicating statistically conclusive result.

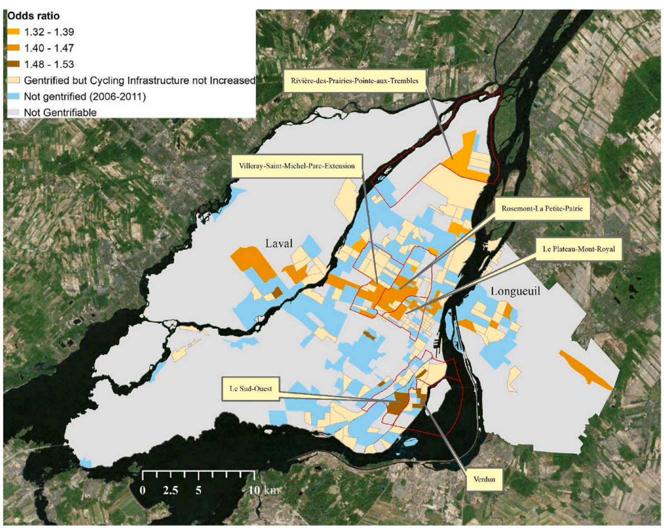

Fig. 4. Census-tract level associations between gentrification status (2006–2011) and increases in cycling infrastructure (2011–2016). Odds ratios are reported for CTs that gentrified between 2006 and 2011 and also experienced a temporal increase in cycling infrastructure between 2011 and 2016. Red-lined polygons represent urban agglomeration divisions used to designate significant urban census tracts (gentrified led to increased cycling infrastructure) on the main island of Montreal.

towards sustainable transportation options (Bruno, 2022). This, in turn, may have contributed to the growth of cycling infrastructure and a rise in cycling activity in the area. The ability of new residents to enact change in their neighborhood may be linked to collective efficacy, a form of social capital that includes both neighborhood social cohesion (i.e. mutual support and trust) and the collective capacity of community members to coordinate amongst themselves to achieve collective goals according to a set of principles. Past research has found that newcomers to gentrifying neighborhoods had a higher perception of collective efficacy, compared to individuals living in neighborhoods that did not gentrify (Steinmetz-Wood et al., 2017). In other words, newcomers in gentrifying neighborhoods are more confident in their ability to advocate for change, like new cycling infrastructure, as opposed to residents of non-gentrified areas.

Previous research examined the association between gentrification with subsequent increases in cycling infrastructure and the simultaneous association in Chicago, Oakland, and Minneapolis (Braun, 2019). In contrast to the US study, our study employed a distinct approach to measuring change in cycling infrastructure. Rather than comparing the absolute percentage of bike lanes between two time points, we used a relative index of cycling infrastructure change, which we believe offers a more relevant measure of change by comparing the change in a given area to the average increase across the study region. Using this index, a value larger than one indicates a change exceeding the average increase observed throughout the region, enabling us to better capture which areas benefited more than others. Moreover, while the US study focused on examining the association between gentrification and subsequent changes in cycling infrastructure, it did not test a possible opposite temporal sequence.

The absence of a link between cycling infrastructure expansion and subsequent gentrification suggests concerns regarding potential negative impacts of cycling expansions on gentrification may not be applicable in the Montreal region. This finding challenges the arguments made by critics who suggest that bike paths lead to gentrification (Hoffmann, 2013). This does not mean it is not at play in other contexts, where cycling infrastructure increases may lead to gentrification, and possibly other unintended consequences such as changes in neighborhood character, and displacement of long-term residents (Zuk et al., 2018). According to Hoffmann (2016), having bicycle infrastructure alone does not cause gentrification, as there are cases where bike facilities have not drastically changed the characteristics of their surrounding areas. However, bicycle infrastructure can easily become part of larger endeavors that aim to serve a more affluent and predominantly white demographic that is associated with upward mobility and creativity (Hoffman, 2016). It is also worth mentioning that increases in cycling infrastructure might be linked to gentrification over periods longer than 5 years, as investigated in this study. Consequently, we recommend conducting research with longer time horizons for future studies.

An urban system is a complex adaptive system that involves interactions between various components of the urban system and frequent adaptations of its networks (Nel, 2015; Nel, du Plessis, & Landman, 2018). This means that there are many factors to consider when planning cycling infrastructure, including the potential impact on the local community, and the need to ensure that all residents have equal access to transportation options. Cycling is often associated with higher-income individuals, but it is also an important mode of transportation in many lower-income communities. Research suggests that lower-income individuals are more likely to cycle out of necessity due to limited access to other forms of transportation, while higher-income individuals are more likely to cycle for recreation and exercise (Stein, 2011). The availability of bicycle infrastructure can also vary by neighborhood, with gentrified neighborhoods more likely to receive new infrastructure due to the preferences of new residents (Hoffman, 2016). This can create a complex relationship between cycling, income, and neighborhood change. As such, it is important for planners to consider the socio-demographics of cycling when designing and implementing new bicycle infrastructure. For a diverse cycling population, planners could seek community input to understand needs and preferences (Lock & Pettit, 2022). In all cases, planners should prioritize equitable access and usage, avoiding creating or reinforcing inequities in access to cycling infrastructure and in cycling use. Procedural equity, which focuses on the fairness of decision-making processes, plays a crucial role in ensuring distributional equity in the planning and implementation of cycling infrastructure. By incorporating procedural equity principles, such as community engagement, transparent decision-making, and inclusive participation, planners can reduce the risk of disproportionately benefiting certain groups or reinforcing existing disparities in access to cycling infrastructure (Cunha & Silva, 2023).

There are a number of limitations to this study. We only controlled for population density. Some studies have controlled for distance to the central business district as a confounder (Flanagan et al., 2016). However, it is worth mentioning that having different time periods in regression models (as in this research), the likelihood of bias owing to confounders decreases (Sharifi et al., 2021). Another limitation is that various measures (and definitions) of gentrification exist that could modify our results (Mujahid et al., 2019). In our study, we assessed CTs' gentrification statuses using the Ding measure that captures both the housing market dynamics and socio-demographic change relating to gentrification (Ding et al., 2016). Also, since each scenario had unique spatial and temporal boundaries, we opted to use a golden search strategy instead of the contiguous approach, which relies on neighboring borders. The golden search algorithm is used in the GWR approach to finding the optimal bandwidth parameter that minimizes the sum of squared errors in the GWR model, allowing for more accurate and localized spatial predictions (da Silva & Mendes, 2018). It is important to consider the significant time gap between the planning and implementation of cycling infrastructure, which makes it challenging for cities to react to changing socio-demographic needs. Research to help predict which areas could be on the path to gentrification would help cities make better informed planned decisions. Finally, to overcome the limitations of aggregated data analyses, future research can utilize individual-level data (Wong, 2009).

6. Conclusion

Because of the dependencies present in the urban system, built environment investments such as cycling infrastructure should be considered in relation to other neighborhood change dynamics, such as gentrification. This is particularly important as cities are increasingly aware of environmental inequities, and use various policies and built environment investments to increase equity and quality of life.

This research sought to respond to policymakers and city planners' needs for evidence on how to develop equitable cycling networks. By identifying whether gentrification precedes or follows new cycling infrastructure, policymakers and city planners can identify critical moments for intervention and prioritize investments in communities where they are most needed. Taking an equity approach to planning cycling infrastructure involves broad upstream community engagement to include a range of voices, a prioritization of investments where they are most needed and an evaluation of cycling intervention impacts to avoid worsening socio-spatial disparities in cycling infrastructure.

The study revealed that gentrified CTs in Montreal had a 44% higher likelihood of receiving a subsequent increase in cycling infrastructure that was larger than average compared to non-gentrified areas. However, spatial models showed that this relation was not true everywhere, underlining the usefulness of spatial models when studying urban dynamics.

Certainly, spatial models show various processes may be at play within a given city. This suggests additional factors beyond gentrification also influence the decision-making processes and resource distribution related to cycling infrastructure. Understanding these factors, such as urban planning policies, community dynamics, resident preferences, and advocacy group involvement, is also highly needed. Urban planning practices should incorporate an equity-based approach that takes the phenomenon of gentrification into account. Comprehensive assessments of infrastructure gaps, community consultations, and the integration of equity impact assessments can help ensure a fair distribution of cycling infrastructure resources. By recognizing the variations between gentrified and non-gentrified areas and within gentrified neighborhoods, researchers and urban planners can work towards fostering a more inclusive and equitable urban environment for all residents.

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Author statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yan Kestens reports financial support was provided by Canadian Institutes of Health Research.

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Appendix A. Supplementary data

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