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THE EFFECTS OF REMOTE WORK ON URBAN SPRAWL: 20 YEARS OF PRE-COVID DATA

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DEDICATION

I dedicate this to the current and future generations that will live with the consequences of the urban planning decisions of today.

FOREWORD

Cette thèse a été approuvé pour la rédaction en anglais.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS, INITIALS AND ACRONYMS

2SLS	Two-Staged Least Squares
AMM	Alonso-Muth-Mills model
APFO	Adequate Public Facilities Ordinances
CA	Census Agglomerations (Can.)
CBD	Central Business District
CMA	Census Metropolitan Areas (Can.)
CPI	Consumer Price Index
FE	Fixed Effects
GDP	Gross Domestic Product
GSS	Canadian General Social Survey
HH	Household
ICT	Information and Communication Technologies
MSA	Metropolitan Statistical Area (U.S.)
OLS	Ordinary Least Squares
PKT	Person-Kilometers Traveled
RMSE	Root-Mean-Square Deviation
TTB	Travel Time Budget
TSIV	Two-Sample Instrumental Variables model
UA	Urban Area (U.S.)
UGB	Urban Growth Boundary
USB	Urban Service Boundary
VKT	Vehicle Kilometers Traveled
VMT	Vehicle Miles Traveled

LIST OF SYMBOLS

y	Dependent variable
i	Entity (city)
t	Time period (census year)
β	Coefficient to be estimated
x_{it}	Vector of predictors for city i at time t
c_i	Entity-specific latent variable for city i
u_{it}	Idiosyncratic error for city i at time t
$\overline{x_\imath}$	Mean of the predictor for city i over time
u_{it}	Idiosyncratic error for city i at time t
$\overline{u_\imath}$	Average of the idiosyncratic error for city i over time

RÉSUMÉ

Cette étude examine les effets de la prévalence du travail à domicile sur les disparités dans les niveaux d’étalement urbain entre différentes villes et sur son évolution au sein des villes à travers le temps. Plus précisément, il examine si une augmentation du nombre de travailleurs à domicile est corrélée à une hausse des typologies de logements à faible densité, telles que les maisons unifamiliales et jumelées—et si les villes comptant davantage de travailleurs à domicile contiennent une plus grande proportion de ces types de logements par rapport aux autres villes. L'analyse est réalisée en appliquant des méthodes de panel à effets fixes sur un ensemble de données englobant 43 RMR et AR canadiennes sur une période allant de 2001 à 2021. Ceci est effectué en contrôlant les variables du modèle Alonso-Muth-Mills connues pour influencer l'étalement urbain : la population, le revenu, la rente agricole et les coûts de transport. L’une des principales conclusions de cette recherche révèle que, bien que les travailleurs à domicile résident principalement dans des zones métropolitaines plus denses, l’essor du travail à domicile est associé à une augmentation de l’étalement urbain. Cette étude contribue à la littérature sur l'urbanisme et les transports en fournissant un aperçu de la dynamique évolutive de l'étalement urbain dans le contexte de l'évolution des modes de travail, soulignant la nécessité de stratégies globales de planification urbaine qui répondent à ces nouvelles tendances.

Mots-clés:

Étalement urbain, travail à domicile, télétravail, Canada

ABSTRACT

This study investigates the effects of remote work prevalence on disparities in urban sprawl levels across different cities, and on its evolution within cities over time. Specifically, it examines whether an increase of remote workers correlates with a rise in low-density housing typologies, such as single-family and semi-detached homes—and whether cities with more remote workers contain a greater proportion of these types of housing compared to their counterparts. The analysis is conducted through the application of fixed-effects panel methods on a dataset encompassing 43 Canadian CMAs and CAs over a period spanning from 2001 to 2021. This is done by controlling for variables from the Alonso-Muth-Mills model known to influence sprawl: population, income, agricultural rent, and transportation costs. A key finding of this research reveals that, despite remote workers predominantly residing in denser, metropolitan areas, the rise of remote work is associated with an increase in sprawl. This study contributes to the urban planning and transportation literature by providing insights into the evolving dynamics of urban sprawl in the context of changing work patterns, highlighting the need for comprehensive urban planning strategies that address these new trends.

Keywords:

Urban sprawl, remote work, telecommuting, telework, Canada

INTRODUCTION

Urban sprawl, characterized by low-density development extending from the periphery of cities, is a matter of increasing concern throughout Canada. Between 2006 and 2016, 78% of new housing growth in Canada occurred in auto suburbs and exurbs, with these areas growing faster than the national average and accounting for 85% of the population growth in Census Metropolitan Areas (CMAs). Meanwhile, the proportion of CMA populations living in these areas increased from 73% to 75% (Gordon et al., 2018). Likewise, the urban footprint of CMAs, which includes buildings, roads, parking lots, parks and gardens, was 14 546 square kilometers in 2011, a 7.5% increase since 2001, and a colossal 157% increase since 1971 (Roberts et al., 2016). Considering the observed expansion of sprawl, it becomes imperative to explore its causes, especially given that this type of development often lacks the necessary infrastructure for sustainable growth, misallocates resources that could be more efficiently utilized elsewhere, and may result in a net deficit of private and social benefits after costs are accounted for (Carruthers & Ulfarsson, 2003; Burchell et al., 2002).

In order to explain the economic forces at work that generate sprawl, Mieszkowski and Mills (1993) proposed a popular framework based on the standard urban model developed by Alonso (1964), Muth (1969), and Mills (1967), also referred to as the AMM model. This model explains how housing densities adjust in response to land prices, population, income levels, and commuting costs. Land prices tend to decrease as one moves further away from employment centers, while transportation costs rise. Households weigh the trade-off between longer commutes and the affordability of land, which often translates to the ability to consume greater floor space. Consequently, reducing or eliminating commute times is expected to shift residential location preferences towards lower-density housing on the outskirts. Various forms of remote work, such as telework and home-based entrepreneurialism, offer the opportunity to dramatically reduce the costs of travelling to a workplace. It is this phenomenon that our study aims to explore in order to determine if a rise in remote work has the potential to stimulate the expansion of sprawl.

In the era of digital transformation, the concept of remote work is rapidly gaining traction, especially in economies with a strong tertiary sector such as Canada. When telework practices first appeared in the 70s, they were met with optimistic projections (Mokhtarian, 1990). However, in the subsequent decades, their widespread adoption was restricted by factors such as organizational, social, and financial constraints that limited necessary investments (Mohalik et al., 2019; Turcotte, 2010). In a dramatic turn of events, the onset of the COVID-19 pandemic acted as a catalyst, fast-tracking its adoption across different industries (Bartik et al., 2020; Leger, 2020). Consequently, the adoption of remote work has been speeding up and may induce a shift for many businesses and individuals, making remote work much more commonplace. This could impact critical economic dynamics related to the spatial organization of cities, such as employment locations, demand for transportation and housing space. Traditionally, cities have arisen and thrived due to agglomeration economies, where businesses and individuals benefit from being close to each other. If telecommuting reduces the importance of geographical proximity, it could radically transform the shape of future cities.

The literature pertaining to remote work’s impact on transportation is extensive yet inconclusive about its effects on urban sprawl, presenting conflicting forces that both consolidate urban centers and contribute to sprawl, without clear causality (Audirac & Fitzgerald, 2003). Additionally, studies on remote work's influence on residential location choices are limited, often focusing on the distance between homes and employers without specifying how it interacts with the urban form. The comprehensive longitudinal data from the Canadian census provides a unique opportunity to explore long-term trends related to remote work and fill this research gap. This study aims to enhance urban sprawl analysis by utilizing panel data modeling, a departure from the prevalent reliance on strictly cross-sectional city comparisons. Applying these techniques to a dataset of large Canadian cities allow for both simultaneous cross-city comparisons and time period analyses. These are crucial for more accurately determining the causal effects of remote work on urban sprawl.

Thus, the overarching objective of this thesis is to develop an explanatory model that investigates the relationships between remote work and urban sprawl in the Canadian context. The research question is centered around understanding the 'Between' effects, which focus on differences between cities, and the 'Within' effects, that examine changes within each city over time. This dual focus aims to offer a comprehensive view of the factors influencing urban sprawl. More specifically, the research question is divided into two parts:

- **Does the Increase in the proportion of remote workers in a city result in an increase in sprawl?**
- **Do cities that have a greater proportion of remote workers sprawl more than their counterparts?**

"Remote work" refers to tasks performed outside the primary workplace, such as working from home or in alternative locations like coffee shops. However, the Statistics Canada data used here only includes information on individuals who worked from home. For simplicity, the term "remote work" is used throughout this study.

In Chapter 1, the foundation of the thesis is laid by defining urban sprawl and discussing its consequences and causes. It delves into different models that explain the phenomenon, such as the AMM model, the Flight from Blight model (Mieszkowski and Mills, 1993), and the Phe & Wakely model (Phe & Wakely, 2000). Additionally, it explores various catalysts and constraints of sprawl that will aid in the selection of control variables.

Chapter 2 shifts focus to the central theme of the thesis. It begins by defining various aspects of remote work and examines the socio-demographic characteristics of remote workers and the incentives and frictions in adopting remote work. An important portion of the chapter is dedicated to exploring the relationship between remote work and travel patterns. This includes an analysis of commute distances, congestion, non-commute travel, transportation modes, residential and job locations and housing preferences.

Chapter 3, introduces the empirical basis of the thesis and outlines the selected theoretical framework. This chapter is instrumental in framing the research methodology, detailing the census, geographic, and temporal data used as dependent and explanatory variables. The descriptive statistics section provides an in-depth look at selected variables, setting the stage for analysis.

In Chapter 4, the methodology used to analyze the data are outlined. This includes a discussion of model selection, with a focus on the fixed effects (FE) models. The chapter also details the assumption tests for both cross-section and panel models, as well as the software and packages used for analysis.

Chapter 5 presents the results. It includes descriptions of the results from the cross-section model and FE models.

Finally, in Chapter 6, we interpret the results in the context of the research question. We analyze each variable in detail, offering explanations for the results and their policy implications. This comprehensive discussion synthesizes the findings, offering insights into how remote work might influence urban sprawl.

The conclusion wraps up the thesis, summarizing the key findings and their implications for the understanding of remote work's impact on urban sprawl. It also addresses the key methodological limitations and suggests areas for future research, drawing from the insights gained throughout the thesis.

CHAPTER 1

URBAN SPRAWL

This chapter delves into the complex concept of urban sprawl, examining its definition, causes, consequences, and measurement. It begins by highlighting the challenges in defining sprawl, distinguishing it from regular urban growth, and understanding its consequences. It next describes the most popular methods for measuring sprawl and serves to select an efficient and convenient dependant variable and geographic reporting unit to be used. The core of the chapter examines the causes of sprawl, outlining popular theoretical approaches like the AMM model from neoclassical economics and the flight-from-blight model, inspired by the Tiebout hypothesis (Tiebout, 1956). Finally, it extensively discusses factors influencing sprawl in comprehensive review of the literature in order to identify the crucial control variables for the study.

1.1 Defining sprawl

The lack of a concise and universally accepted definition of urban sprawl creates an important challenge within policy discussions and scientific literature. Without one, it is difficult to develop standardized indicators and quantify the presence of sprawl in a given area.

Numerous authors have emphasized the need to distinguish sprawl from regular growth patterns that unfold in undeveloped areas. They base their arguments on the premise that sprawl inherently results in negative externalities[1] that deserve close examination (Brueckner, 2000; Burchell et al., 2002; Downs, 1999; Ewing, 1997; Ewing et al., 2002). In light of this, many scholars opt to define sprawl through these negative consequences. This approach, however, poses several challenges. Accurately evaluating these externalities proves particularly challenging. Some externalities, like impacts on human health, are qualitative and necessitate exhaustive survey methods for precise assessment. Others, such as carbon emissions and heat island effects, demand exact on-site measurements in order to monetise their impacts for cost-benefit analysis. These phenomena may also exhibit non-linear relationships with urban

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[1] Negative externalities are harmful impacts from economic activities borne by the wider community and environment, not by the producers or consumers involved (Boudreaux & Meiners, 2019).

development, adding another layer of complexity to their analysis. More importantly, the different cultural and regulatory environments will create considerable variation across time and geographic areas for each chosen externality variable. For example, region-specific vehicle emission regulations influence the amount of atmospheric pollution resulting from sprawl. Varying research methodologies can further generate conflicting findings when assessing sprawl's effects. For example, Ewing (1997) initially presents “low accessibility’’ as one of two sole indicators of sprawl and proposes simple proxy variables such as Vehicle Miles Traveled (VMT) or average trip length to measure it. However, in a subsequent literature review paper, Ewing (2008) cited studies showing both a negative relationship between population density and VMT and a positive relationship between density and congestion, thereby rendering the net effect on travel costs ambiguous. Additional research, such as that by Glaeser & Kahn (2004), provide empirical evidence that average commute times increase with population density due to traffic congestion, disputing the notion that low density reduces accessibility. Another downside of using negative externalities as characteristics of sprawl is that weighing them against potential benefits can become a matter of political choice or personal preference. Given these complexities, formulating a universally applicable, easily measurable definition of sprawl becomes a daunting task, especially when consequences serve as defining criteria.

Others choose to view sprawl as the low-end on a continuum of urbanization, ranging from dense cores to sparse peripheries, that arises as the natural product of a city’s growth (Brueckner & Fansler, 1983; Glaeser & Kahn, 2004). This approach is useful because it reflects the interdependence between the elements of a city's spatial distribution. This accurately portrays how land-use allocation that occurs in areas at one extremity of a region's population density spectrum can influence outcomes at its opposite end, and vice-versa. The approach also considers sprawl as a continuous numerical variable rather than a categorical one, reducing subjectivity and limiting the potential for political interpretation. In this conceptualization, sprawl is not measured as an either-or state but is instead as a condition that exists on a scale of varying intensity. However, because these density gradients seem to arise naturally in the spatial distribution of cities, many proponents of this viewpoint tend to argue that sprawl is the result of an efficient market allocation of land, a claim that carries some degree of ideological weight. The ubiquity of population density gradients has been demonstrated empirically with data from 48 metropolitan regions in every continent, affirming the cross-geographical utility of this perspective (Bertaud & Malpezzi, 2003).

Despite the simplicity of using population density gradients to evaluate the degree of sprawl, several researchers contend that it is a multidimensional phenomenon and prefer instead to use a combination of distinct, yet interrelated, attributes to define and measure it (Ewing, 2008; Galster et al., 2001; Glaeser & Kahn, 2004; Maier et al., 2006; Torrens, 2006; Torrens & Alberti, 2000). It is often noted that these attributes will manifest themselves differently depending on the geographic area being studied, resulting in regional variations of sprawl patterns (Galster et al., 2001). Consequently, choosing the relevant dimensions to measure complicates research methodologies and the establishment of a comprehensive definition of the phenomenon.

This multidimensional perspective is further complicated by the reciprocal interactions among variables, making it challenging to ascertain whether they function as causes or outcomes of urban sprawl. This can lead to covert simultaneity biases, which are an important concern when constructing regression models. Certain variables, such as transportation costs and property taxes reciprocally impact urban form (Atkinson & Oleson, 1996; Geshkov & DeSalvo, 2012). Glaser and Khan (2004) identify two such self-perpetuating mechanisms. First, the decentralization of population and employment occurs in tandem. A spread-out population pulls employers from city centers, while decentralized employment further disperses the population, perpetuating the cycle. This type of path dependency has also been observed in other political decisions, such as the choice to build car-oriented infrastructure to serve dispersed communities, in turn encouraging more of the same type of urban expansion (Driscoll, 2014). Even local road networks tend to project their current characteristics upon future expansions. This means that the low road connectivity in suburban developments will favor the same sprawling patterns on neighboring land parcels (Barrington-Leigh & Millard-Ball, 2015). Another example of retroactivity has actually been noticed in the way a territory is politically structured. A sprawling metropolis may increase the number of local municipalities governing the region, which in turn enact legislation to limit their densification, therefore pushing future development further towards the periphery (Carruthers & Ulfarsson, 2002; Ulfarsson & Carruthers, 2006). Conversely, some relationships take the form of negative feedback loops that promote equilibrium. For example, a reduction in commuting costs can initially encourage expansive development on the city's periphery. The subsequent increase in urbanized land area will hinder transportation, leading to further increased commuting costs (Wassmer, 2008).

The perspective that sprawl is an evolving process, rather than a fixed state, aligns with the views of numerous scholars (Atkinson & Oleson, 1996; Galster et al., 2001; Siedentop & Fina, 2010; Torrens &

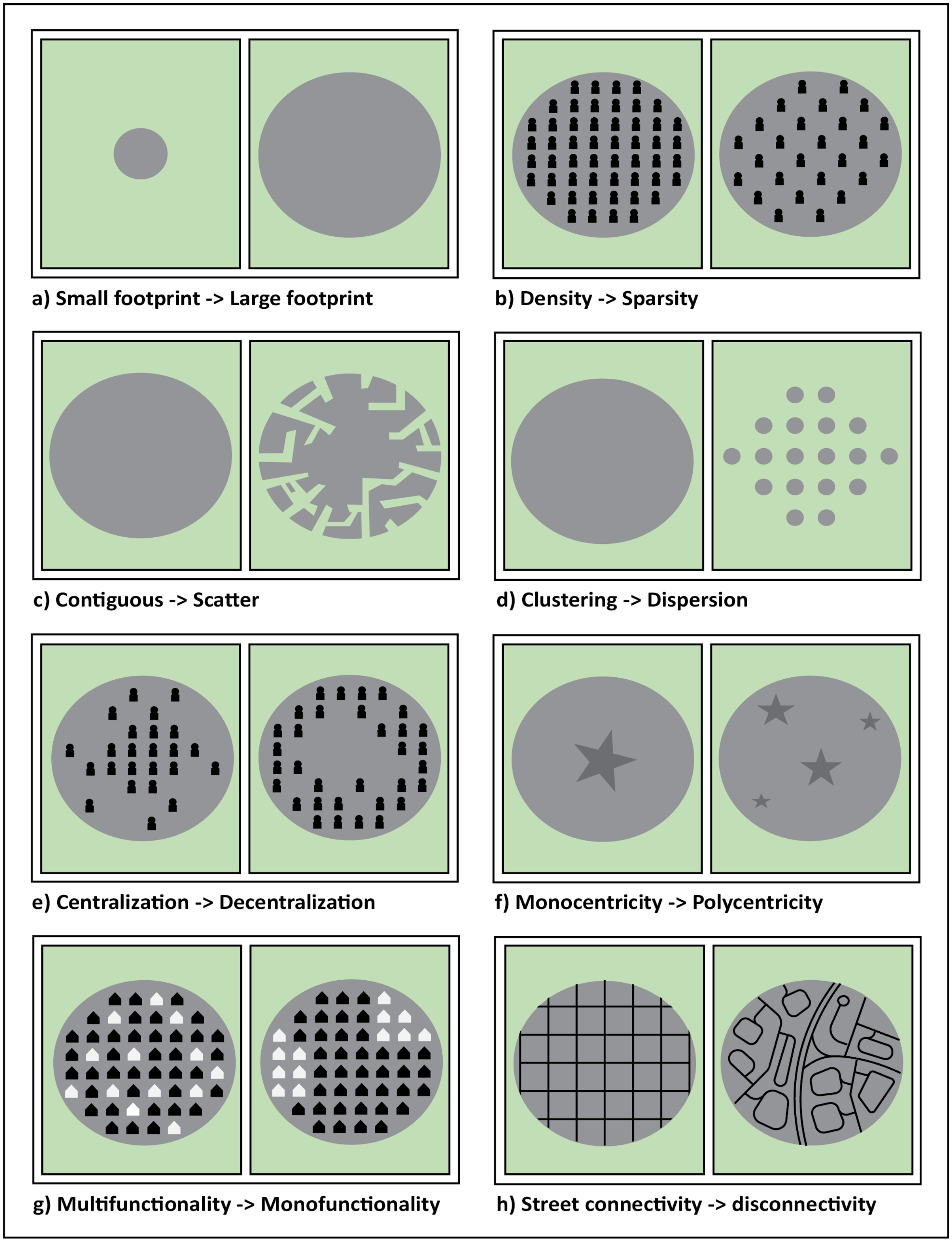
Alberti, 2000). This dynamic understanding allows for a richer analysis of urban sprawl. For instance, Burchell et al. (2002) highlight the importance of considering the direction and speed of urbanization as a defining variable for different types of sprawl; categorizing sprawl by its rate of expansion (increasing, decreasing or sustained). Incorporating a time component into the conceptual framework of sprawl reveals phenomena otherwise overlooked. Scattered developments have the potential for future infill, transforming what was once deemed undesirable sprawl into more compact forms (Peiser, 1989; Torrens, 2006). Conversely, neighborhoods that were initially compact but have declined over time may exhibit characteristics commonly associated with sprawl (Siedentop & Fina, 2010). Unlike cross-sectional views, which may obscure these details, a temporal lens reveals that fast-growing metropolitan areas not only expand over more land but do so with higher population densities. On the other hand, areas already characterized by high density tend to undergo urbanization more quickly while simultaneously experiencing notable decreases in density (Fulton et al., 2001).

Paulsen (2014) supports the perspective that urban sprawl should be considered a dynamic process. He argues for a longitudinal approach to measuring urban sprawl, highlighting the importance of employing panel models to capture the evolving nature of urban landscapes. This approach challenges the traditional reliance on cross-sectional measurements, which may not fully capture the historical development patterns and policy influences that are unique to each city.

1.2 Characteristics and measurement of sprawl

Urban sprawl encompasses various social and morphological phenomena observed across different scales. These phenomena primarily involve large spatial distances between individuals and activities in the urban landscape. Different authors have identified various characteristics of urban sprawl, each focusing on different observable aspects and scales. The following section aims to categorize contributions from various authors by thematic similarity, despite variations in terminology. Figure 1 offers a visual guide to the different dimensions of sprawl identified by these authors. For each dimension, the image on to the right denotes a more sprawling pattern. This section will help identify the dependant variable used in the regression model.

Figure 1 The characteristics of sprawl



a) Small footprint -> Large footprint

b) Density -> Sparsity

c) Contiguous -> Scatter

d) Clustering -> Dispersion

e) Centralization -> Decentralization

f) Monocentricity -> Polycentricity

g) Multifunctionality -> Monofunctionality

h) Street connectivity -> disconnectivity

Source : Gavin MacGregor

1.2.1 Footprint

The urban spatial extent of a city, also known as its "footprint," is defined as the surface area of urbanized land (see Figure 1a). It is most commonly used in studies based on the AMM model. Many researchers use a census-derived metric, defining contiguous census blocks as "urbanized" by employing population density thresholds (Brueckner & Fansler, 1983; Carruthers & Ulfarsson, 2002; Geshkov & DeSalvo, 2012; McGibany, 2004; Song & Zenou, 2006; Spivey, 2008; Ulfarsson & Carruthers, 2006; Wassmer, 2006, 2008). In the American context, these contiguous blocks are named “Urban Areas” (UAs). However, calibration is necessary for longitudinal analysis because the definitions of census blocks are inconsistent across time periods (Paulsen, 2012, 2013). Additionally, this approach overlooks more elusive forms of non-contiguous sprawl, prompting many researchers to favor more precise metrics of built-up area derived from satellite imagery. Built-up areas are characterized by impervious surfaces, such as roadways, parking lots, and rooftops (Soulard et al., 2016). Despite the high precision of satellite imagery, it comes with the drawback of reduced compatibility with census variables (Deng et al., 2008, 2010; Paulsen, 2012; Garcia-López, 2019). Some researchers prefer to mitigate the impact of excluding non-contiguous sprawl in their footprint metric by instead measuring a radius that approximates the distance from the city center to the periphery of the census-defined urbanized area (McGrath, 2005; Ke et al., 2009).

1.2.2 Sparsity

A characteristic frequently used to identify sprawl is density, or to be exact, its opposite, sparsity (See Figure 1b). It can be used to evaluate urban morphology, such as housing density, or assess social phenomena like population or employment density (Torrens & Alberti, 2000). The latter calculate the number of individuals or jobs per unit of area. Their accuracy depends on how the area's boundaries are defined and what types of land-uses are included. The easiest available measure, gross density, includes all land types, such as parks, water bodies, and mountains. In contrast, net density only considers areas with buildings and requires more time to calculate. Temporality is also an issue. In cross-section analysis, solely relying on population or employment density can misclassify declining areas, such as Detroit’s central residential districts, as sprawling (Siedentop & Fina, 2010).

Glaeser and Kahn (2004) criticized measures of density for social phenomena, arguing that different urban forms could yield identical density ratios—for instance, a skyscraper on an empty lot versus a tract of single-family homes. Galster et al. (2001) and Burchell et al. (2002) address this issue by focusing on housing density, defined as the number of residential units per area. When the calculations include commercial and industrial buildings, the term used is “development density”.

These metrics all provide an average value that fails to take into account how density is geographically distributed within a given region. This issue can be addressed by using alternative measures. These include the proportion of census blocks that are above or below the regional average density (Fallah et al.,2012); a Gini coefficient that evaluates the concentration of population across census tracts (Eidlin, 2010); or by examining changes in marginal density at the periphery, such as the amount of land consumed per net new housing unit built over a specific period (Paulsen, 2014). Torrens and Alberti (2000) propose using a non-linear function to calculate a region's population density gradient. However, this approach is highly sensitive to the chosen geographic parameters and the specific type of function used. It also proves challenging when comparing large cities to smaller ones that have steeper density gradient curves (Mieszkowski & Mills, 1993). Additionally, density gradients are not as smooth as often assumed; they feature jagged edges, smaller dips, and isolated peaks, challenging the conventional practice of estimating smooth density contours (Brueckner, 1986).

1.2.3 Scatter

The expression “scatter” can encompass various descriptors of urban morphology including: "fragmentation, leapfrogging, discontinuous development and piecemeal development” (Torrens and Alberti, 2000). Though terminology varies across literature, the concept of scatter boils down to the presence of unbuilt land interspersed among developed plots (See Figure 1c). Importantly, it is better viewed through a macro lens across an entire metropolitan area. Some areas may be discontinuous yet dense, while others may be contiguous but sparse.

Arribas-Bel et al. (2011) measure scattering as the quantity of individual patches of developed land, adjusted for population. Angel et al. (2012) instead calculate the U*rban Landscape Ratio* of built-up and open space within the metropolitan area. Galster et al. (2001) measure what they term “discontinuity” by considering a cell in a grid matrix as built-up if it exceeded certain housing or employment density thresholds, and then calculating the proportion of such cells within an UA. Jaeger & Schwick (2014) refine these concepts with the *Urban Permeation Unit*, which incorporates the percentage of built-up area and a weighted measure of distances between locations in a given region, termed "dispersion."

1.2.4 Dispersion

The concept of dispersion is similar in nature to scatter, but focuses on development patterns at a more localized level. It can be summarized as the distance between elements of the built environment at the local scale. The size of individual lots, floor-area ratios, and the arrangement of subdivisions and street grids directly influence this dimension of sprawl (See Figure 1d).

Some measure “land-use intensity” by calculating the median lot-size and floor-area ratios within the different neighborhoods of a metropolis (Knaap et al., 2007). Using satellite imagery, Angel et al. (2012) quantify “openness” as the average share of open space pixels within walking distance around each built-up pixel. Similarly, Burchfield et al. (2006) use the same calculation, but for pixels newly built-up during a specified timeframe. Others explicitly define dispersion as the mean distance between every possible pair of points in a built-up area (Jaeger et al., 2010).

Galster et al. (2001) utilize two distinct metrics to assess the degree of clustering and concentration in development, contributing to the overall understanding of dispersion. Clustered development, characterized by tightly packed nodes of activity, may reduce travel distances within each node but not necessarily affect commute lengths to other areas. It is quantified by averaging the density of features like housing within each grid cell of buildable land and then comparing it to the overall density across varying grid sizes. Concentration indicates the extent to which development is densely packed in specific areas rather than distributed across the urban landscape. Concentrated development can occur along extended roadways in a ribbon-development fashion, without necessarily reducing travel times. It is calculated by obtaining "The coefficient of variation of the density of housing units or employees among the grids of scale m in a UA" (Galster et al., 2001).

1.2.5 Decentralization

A high proportion of activity or population in the periphery rather than in or near the center of a metropolis signifies decentralization (See Figure 1e). Various calculations are employed to quantify this phenomenon. Arribas-Bel et al. (2011) utilize the percentage of population living outside the core city, while Baum-Snow (2007) relies on the log change in central city population between two time periods. Nelson et al. (2004) calculate the proportion of central-city to metropolitan-area development activity. However, these approaches come with a significant limitation: they depend on the administrative boundaries of the central city within a metropolitan area, which may not accurately capture changes in urban morphology or travel patterns. In the Canadian context, this issue is particularly problematic. Some core city boundaries, with the exceptions of Montreal, Toronto, and Vancouver, extend far beyond contiguous built areas to include agricultural tracts and, in the cases of Halifax and Hamilton, align with their respective CMA boundaries. To address this issue, Galster et al. (2001) adopt a more complex method. Their approach involves creating a spatial matrix to determine each cell's distance from city hall, which is then weighted by the number of housing units in each cell. The average sum of these weighted distances is calculated and standardized by the square root of the area of a UA.

1.2.6 Polycentricity

Polycentricity refers to a city with multiple centers that are located at a considerable distance from each other (See Figure 1f). Galster & al. (2001) identify high employment and population densities in geographic grid cells and combine contiguous cells falling within one standard deviation of these high-density areas. They then calculate the density of the combined area and designate cells within the grid that exceeded one standard deviation of this new area's density as activity centers.

It remains to be determined if polycentricity is truly a feature of sprawl, because multiple sub-centres could create density gradients that overlap, reducing the overall footprint. Spivey (2008) discovered evidence supporting this effect of polycentricity on urban footprints when making comparisons between cities. Likewise, when measuring the effects of AMM variables within cities across different time periods, Paulsen (2012) finds that they have a weaker influence on the footprint of cities that have more than one center.

1.2.7 Monofunctional land use

Areas characterized by very limited mixed land use due to single-use zoning are termed "monofunctional” (See Figure 1g). Some authors assess monofunctionality by calculating the percentage of the population within walkable distance from businesses, schools, and other institutions. They combine this analysis with an entropy-derived formula to evaluate the balance between employment and population at the metropolitan scale, as well as the balance between the number of land uses (Ewing et al., 2003; Knaap et al., 2007). Arribas-Bel et al. (2011) use Simpson's diversity index, while another approach involves Massey and Denton's exposure index (Galster et al., 2001). The latter also consider the proximity between different land uses, regardless of their degree of mixing, as a distinct dimension of sprawl. They calculate this using a modified version of White's index of spatial proximity.

1.2.8 Street disconnectivity

When travelling through a city, proximity between destinations depends more on the time it takes to get from origin to destination, rather than on actual physical distance. Sprawling cities commonly feature hierarchical road systems with pod-like subdivisions, gated communities, cul-de-sacs and fewer interconnected streets, which impede efficient transportation. Lower levels of street connectivity in sprawling cities often lead to longer, more circuitous routes for public transit and discourage active transportation by creating barriers to direct travel (See Figure 1h).

Arribas-Bel et al. (2011) use average commute distance as a proxy, which inadequately captures street connectivity due to its distortion by the size and density of a city. Ewing et al. (2003) propose a more straightforward approach that involves calculating average block length and size, and determining the percentage of blocks that meet the criteria for being small in a metropolitan area. In a similar approach, Knaap et al. (2007) divide the number of intersections in a neighborhood by the total number of cul-de-sacs and calculate the median distance between each pair of adjacent nodes on the street network. Others calculate their street connectivity index using four key criteria: mean nodal degree, dendricity, circuity, and sinuosity to capture network characteristics such as intersection density, route options, path efficiency, and street curvature (Barrington-Leigh & Millard-Ball, 2015).

1.2.9 Sparse housing typologies

Single-family homes are a defining feature of urban sprawl because they consume larger land areas compared to multi-family housing, leading to increased spatial expansion of cities. Turcotte (2018), Tanguay and Gingras (2012) and Young et al. (2016) calculate a sparse housing variable using the combined proportion of single-family, semidetached houses, and mobile homes in metropolitan areas. Turcotte (2018) identifies sparse neighborhoods in Canada as containing more than two thirds of these types of dwellings. In a related approach, Ortuño-Padilla & Fernández-Aracil (2013) use the proportion of the annual new construction dedicated to single-family homes.

These variables offer two principal advantages: they incorporate land use considerations and bypass the arbitrary classification of urbanized and built-up areas and choice of reporting unit. Therefore, they allow for the use of metropolitan area as reporting unit without the problem of over-bounding or under-bounding linked to other density measures. Additional strengths include consistent reporting across censuses and the utilization of a single data source for an entire study, and the fact they do not necessitate complex calculations. Furthermore, they are simple morphological variables easily recognized by both experts and non-experts as indicative of urban sprawl. However, this approach also has limitations, such as the inability to account for variations in lot or housing size and the inability to capture the spatial scattering of development.

1.3 The consequences of sprawl

Although it is beyond the scope of this thesis to evaluate all the impacts of sprawl, it is nonetheless important to overview a few of them in order to highlight the importance of studying this topic.

Sparse development may result in a number of advantages for society. This conclusion can be derived from the simple fact that single-family homes with large lots typical of sprawl are often the result of simple consumer preference that favors cheaper and larger homes (Burchell et al., 2002; Glaeser & Kahn, 2004). Certain authors point to research that indicates that suburban communities are less economically and racially segregated (Glaeser & Kahn, 2004). Others mention evidence that the smaller, more fragmented governance of these areas leads to greater citizen participation and influence in local decision-making (Burchell et al., 2002). Additional studies argue that lower density can sometimes contribute to the dispersion of air pollution, resulting in healthier neighborhoods (Bae & Richardson, 1994). To the extent that sprawl allows for the expansion of the labor and consumer markets of a city, it can be said to contribute to the prosperity of the economy (Bertaud & Malpezzi, 2003).

However, interest in the subject usually emanates from the desire to control or limit the various negative externalities and direct costs that can result from sprawl. Most of these are the result of simple geometric reality, sparse development requires a greater amount of infrastructure per capita. This inevitably reduces the cost-benefit ratio to provide public services to the population (Burchell et al., 2002; Carruthers & Ulfarsson, 2002; Ewing, 2008). A study of nine medium-sized Canadian cities demonstrates that the net population density in a census tract is responsible for 84% to 94% of its variation of road length per capita. This relationship follows a power law, meaning that road length per capita climbs dramatically at densities of 25 people per hectare or less, making road consumption a serious problem at lower densities (Cleveland et al., 2020). Sparse development with longer road networks and less connectivity does result in higher waste management costs (Lin & Kao, 2008). Moreover, additional asphalting required by longer roads and parking spaces reduce the impervious surface of the city which complicates stormwater management (Litman, 2011). In addition to increased infrastructure spending, sparse development raises the per capita cost of providing other public services, such as cultural, sports, and community facilities, policing, fire protection and municipal administration (Carruthers & Úlfarsson, 2008; Carruthers & Ulfarsson, 2003; Hortas-Rico & Solé-Ollé, 2010). Therefore, sprawl increases the average cost of delivering public services, resulting in inefficiencies and preventing the optimization of economies of scale.

Among the other negative consequences that are most commonly cited in the literature are the impacts on transportation and the loss of farmland and wildland. Repercussions on the environment are regularly included on the list, but these can generally be thought of as second-order effects of the previous two problems. Certain negative social outcomes, such as economic and racial segregation, are occasionally mentioned but remain contested (Burchell et al., 2002; Ewing, 2008).

1.4 The causes of sprawl: Theoretical framework

Two dominant theoretical approaches explain urban sprawl. The first stems from the bid-rent theory of neoclassical economics, while the second draws inspiration from the Tiebout hypothesis, focusing on fiscal and social perspectives.

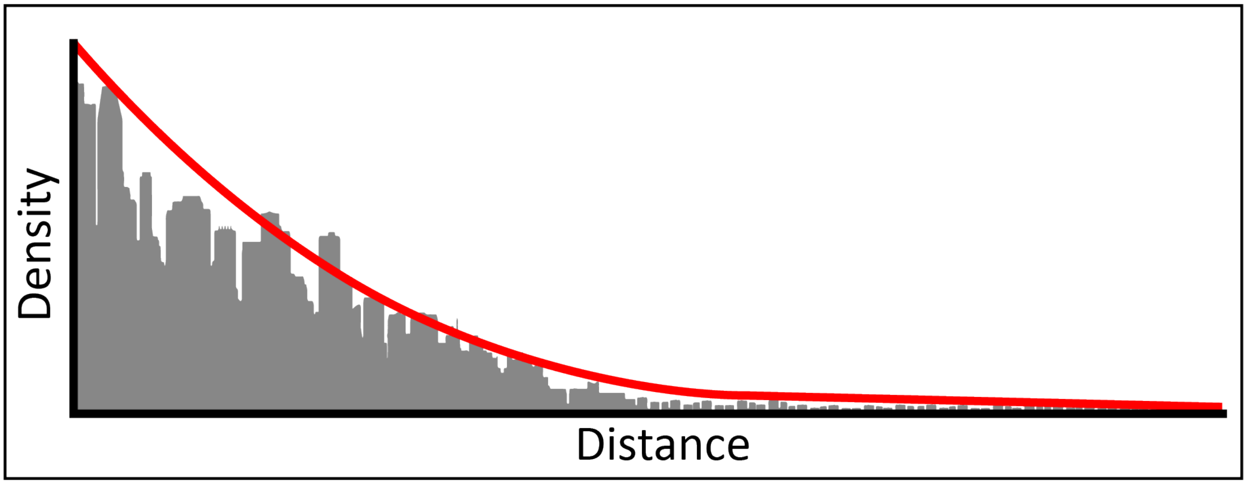
1.4.1 The Alonso-Muth-Mills model

The AMM model outlines the fundamental economic interactions that determine the shape of the urban form. It posits a constant, yet opposing, demand for land and proximity to employment. The model illustrates how households balance the trade-off between transportation and land costs in order to choose their ideal residential location. Demand for land is very high when it’s near employment opportunities, such as in a downtown area, while its supply remains limited. This increases its value, which in turn promotes the construction of high-density housing, allowing multiple individuals to divide the cost of each land parcel between themselves. Conversely, some households may prefer the city's outskirts, where land is more affordable. This choice enables them to acquire more housing space for the same price, or the same amount of space for a lower price, than in central areas.

Four essential inputs to the model can increase the surface area of urbanization. Higher population levels and increased household income both contribute to a greater demand for housing. Specifically, a rise in income tends to expand the city's boundaries but leads to lower population density. In contrast, population growth has the effect of both enlarging the city and/or increasing its density. Affordable agricultural land facilitates the acquisition of undeveloped lots that can be converted to residential use. Finally, lower transportation costs, primarily in the form of reduced travel times, makes more land accessible to employment centers and thus contributes to the city's territorial expansion (Alonso, 1964; Mills, 1967; Muth, 1969). Income's interaction with other model variables merits attention. Coupled with population growth, it amplifies demand for land consumption. Additionally, it influences the opportunity cost of travel by increasing the value of an individual’s time. In contrast, higher income enables easier procurement of private vehicles, potentially reducing travel durations (Glaeser & Kahn, 2004).

The model's market allocation process yields a population density gradient that diminishes as one moves outward from the city center, taking the form of a negative exponential distribution (see Figure 2). Cities with shallower gradients typically exhibit greater expansiveness and lower compactness, leading to increased sprawl. Conversely, cities with steeper gradients boast higher densities, even when their development spans a significant land area (Bertaud & Malpezzi, 2003). Upon close inspection, the density gradients do not follow a smooth curve; instead, they display a certain irregularity. This is likely a result of competing land use regulations across metropolitan areas affecting the traditional bid-rent curve (Brueckner, 1986; McMillen, 1994, 2004).

Figure 2 A simplified density gradient



Source: Gavin MacGregor

Mieszkowski & Mills (1993) argue that urban sprawl is a predictable outcome, representing the natural consequence of the density gradient’s lower end. This flattening of the gradient emerges from the spatial equilibrium conditions of the AMM model, indicating that sprawl is an inherent part of urban spatial structures as cities expand and evolve.

Despite its predictive qualities, the AMM model relies on a set of assumptions that have been criticized. These include a single city center where all employment is located, a uniform transportation system, and the homogeneity of households and production firms (Alonso, 1964; Mills, 1967; Muth, 1969). It has been noted that the monocentric view is rather limited and would only apply in the real world when certain conditions are met, such as low commuting rates. Thus, polycentric models have alternatively been suggested to reflect the complex spatial patterns of mixed land uses and multiple activity centers that are typical of most cities (Ogawa & Fujita, 1980). Others have tried to relax some of the model's assumptions so that it better approximates real-world conditions. One proposal is to set up a hierarchy of different centers of activity that not only provide jobs but also goods and services. Because the location of minor centers is related to a higher-order center, the population density gradient will maintain its negative exponential function in relation to the primary center, reflecting the monocentric model's description of the urban form (Papageorgiou, 2014). Some contend that the addition of smaller centers of activity does not affect the functioning of the AMM model's basic parameters (Zhang & Sasaki, 1997), or that its predictions will remain valid insofar as the main center has the highest amount of employment in the city (Bertaud & Malpezzi, 2003). This likely accounts for the model's demonstrated explanatory power in cities worldwide, even those in countries that have only recently adopted market-based land allocation (Bertaud & Malpezzi, 2003; Deng et al., 2008).

Paulsen (2012), has uncovered some empirical evidence suggesting that inputs to the model may react in slightly different ways when applied to a polycentric city. In comparison to monocentric cities, changes in population size had a comparatively lesser impact on the amount of land utilized. However, the impact of income levels on land use was almost twice as high. This is because the area of influence of their multiple centres of activity often overlap, resulting in the superimposition of density gradients, which in turn may reduce the city's urbanized surface and affect the income-to-land-area and population-to-land-area elasticities. Thus, the AMM model remains a valuable heuristic but its predictions must be nuanced as city structures become more complex.

1.4.2 Alternative models

Phe & Wakely (2000) propose an alternative spatial model that expands the traditional trade-off between housing space and proximity to employment. It redefines the trade-off as between housing status—affected by proximity to amenities, services, and desirable neighbors defined by ethnicity or wealth, along with cultural elements enhancing a location's appeal—and dwelling quality, encompassing the physical attributes that elevate a home's value. Despite being a more comprehensive approach, it requires a complex set of inputs that are difficult to quantify, which makes comparisons across cities challenging.

The second approach to explaining the advent of urban sprawl is rooted in the idea of Tiebout sorting, which theorizes that individuals prefer to live in communities that align with their fiscal and social preferences, including public goods and tax rates (Tiebout, 1956). Within this framework, often termed "Fiscalization of land-use", different fiscal or social factors attract or repel households to their optimal residential location. Since households with similar financial means and preferences will tend to aggregate together, these newfound communities can subsequently employ urban planning regulations to preserve their homogenous nature, effectively excluding households with differing socio-demographic characteristics (Fischel, 2005; Mieszkowski & Mills, 1993).

In the "flight from blight" model, local amenities, low residential density and public services act as pull factors towards suburbs (Kim et al., 2005; Bayoh et al., 2002; Fischel, 2005). Conversely, poverty, crime, and racial segregation push higher-income households away from inner cities (Brueckner, 2000; Burchell et al., 2002; Fischel, 2005). However, research by Glaeser and Kahn (2004) suggests that inner-city crime rates have a negligible effect on decentralization, with studies by Wassmer (2006) and Mieszkowski and Mills (1993) similarly downplaying the role of "flight from blight" factors such as racial tensions, poverty, or school desegregation in contributing to sprawl. In the Canadian context, the relevance of these factors is further diminished, attributed to the country's lower rates of violent crime and racial segregation compared to the United States (Gannon, 2001; Fong, 1996).

In terms of theoretical grounding, this research excludes sociological models like the "flight from blight" theory, mainly due to their limited applicability outside the U.S., and avoids the fiscalization of land-use framework, which focuses on less relevant, hard-to-measure variables. The Phe and Walkley model, demanding complex measures of amenities and abstract factors like social perception, is also not considered.

1.5 Catalysts and constraints of sprawl: Inputs to the AMM model

This section will identify key catalysts and constraints that can be viewed as the input variables to the theoretical framework of the AMM model. This will help define the explanatory independent variables to be considered for the study.

1.5.1 Geography

Geographic features and climate can impact the shape and expansion of cities in various ways. They can serve as obstacles that diminish street connectivity and escalate traffic congestion. They can also increase development costs, similar to the high agricultural land values' impact in the AMM model. For example, arid conditions necessitate reliance on municipal water systems, while steep terrain and water bodies introduce additional complexities to construction efforts.

Supporting this claim is the observation that when ranked by a population density metric, U.S. cities that are denser tend to be confined by steep topography, aridity, or public lands (Lang, 2002; Nelson & Sanchez, 2005). Moving from general observations to more detailed findings, the following studies attempt to better quantify this relationship. Two studies utilized aerial and satellite imagery with a similar metric of dispersion—the proportion of unused land around buildings—to compare geographic variables between cities in the US and internationally. Burchfield et al. (2006) found that elevation range at the urban fringe curbed sprawl due to steeper construction costs, while rough terrain promoted dispersed development. They also showed that extreme temperatures reduced housing demand, deterring sprawl, but found no significant impact from proximity to wetlands, public lands, or oceans. Angel et al. (2012) estimated a 12% increase in dispersion with every doubling of land area not limited by steep slopes or waterbodies, and a similar 12% rise with each doubling of the population using aquifers for water.

Paulsen (2014) found evidence indicating that geographic constraints—such as steep slopes, waterbodies, and protected land—led to increased infill development in previously urbanized census blocks, while simultaneously reducing density in new developments at the periphery. These effects were measured as changes within cities over a 20-year period. Saiz (2010) and Davidoff (2016) argue that geographic constraints correlate with stricter regulations and contribute to housing supply inelasticity by raising land values and limiting availability, while also stimulating housing demand and attracting educated individuals who favor regulation, explaining urban core intensification[2] and decreased greenfield development density.

The combined effect of attractivity and restricted land supply may lead to a difficulty in establishing relationships for certain geographic factors. For example, coastal proximity has not been found to significantly reduce the size of the footprint of cities, which may be attributed to the fact that these cities expand linearly along valuable oceanfront areas (Burchfield et al., 2006; Spivey, 2008).

1.5.2 Agricultural land prices

Although it is a foundational element of the AMM model, this variable yielded inconsistent results across multiple studies—manifesting in negligible effects, or absence of statistical significance (see Table 1). One challenge may arise from using average agricultural land prices from large regions, such as states, when comparing effects between cities. This may yield a non-linear relationship, where very high rates of urbanization can lead to an unexpected positive relationship due to the fact that large city footprints can reduce the availability of remaining agricultural land, inflating its price (McGibany, 2004).

Table 1 Agricultural land price to sprawl elasticities

Author(s)	Date	Agriculture	Sprawl variable	Elasticity[3]	Variance
Brueckner & Fansler	(1983)	County median	Footprint	-0.23	Between
McGrath	(2005)	State average	Footprint	-0.1	Between
Wassmer	(2006)	County mean	Footprint	not sig.	Between
Song & Zenou	(2006)	County median	Footprint	not sig.	Between
Spivey	(2008)	Sales per acre	Footprint	not sig.	Between
Wassmer	(2008)	County mean	Footprint	-0.05	Between
Ke et al.	(2009)	Sales per acre	Footprint	-0.01	Between
Geshkov & DeSalvo	(2012)	County mean	Footprint	-0.01	Between
Paulsen	(2012)	County mean	Footprint	not sig.	Within
Wassmer	(2002)	Sales per acre	Polycentricity	-0.1	Between

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[2] Intensification refers to development on previously urbanized land that increases population or employment density. This increase can be achieved either through infill, which involves developing vacant or underutilized parcels within existing urban areas, or by redeveloping a building to increase its floor-area ratio.

[3] Elasticity quantifies how much one variable changes in response to a 1% change in another variable. For instance, if the elasticity is 2, it means that a 1% increase in the x variable leads to a 2% increase in the y variable.

Furthermore, when evaluating changes within cities over time, fluctuations in land prices related to specific events can reduce the accuracy of the model. For example, Paulsen's 2012 study covered a period characterized by volatile land rent tied to the agricultural credit crises, potentially contributing to the lack of significance in the agricultural land price variable.

The use of different sprawl indicators shows some interesting results. When making comparisons between cities around the world, Angel et al. (2012) discovered that a country's agricultural contribution to GDP was positively associated with dispersion. This outcome could stem from the challenges in converting agricultural land to residential uses, leading to irregular development patterns. Alternatively, unique urbanization trends in more agrarian economies could explain this phenomenon, potentially rendering this finding less applicable for the comparison of Canadian cities.

When focusing on changes within cities over the period of 1977 to 1997, Wassmer (2002) showed that 1% increase in agricultural land prices were associated with 0.14% drop in retail sales in an MSA's outer regions, suggesting a decrease in polycentricity. Likewise, Pendall (1999) found that an MSA’s higher farmland productivity in 1982 led to lower population sparsity in its land that was newly developed by 1992.

1.5.3 Population demographics

The population variable consistently demonstrates the strongest effect on city footprints. In the nine studies highlighted in Table 2, all of the elasticities except one where superior to 0.5, indicating a strong population effect. This should come as an obvious conclusion; the size of a city is naturally the product of its population. However, the results are more complex when assessing its impact on different characteristics of sprawl.

In comparing American cities, Fulton et al. (2001) find that fast-growth metropolitan areas not only expand their footprint more substantially but also gain density, whereas slow-growing ones tend to lose density and do not increase their footprint as much. Corroborating these results, Ulfarsson & Carruthers (2006) estimated that a 1% increase in population corresponded with a 0.71% expansion in land area, and a 0.28% increase in density. Angel et al. (2012) found that cities with higher populations tend to exhibit less dispersion, with the share of open space in walking distance of built-up areas declining by 11% for every doubling of the population. Additionally, the more a city experienced population growth in the decade between 1990 and 2000, the more its dispersion declined in the same period. This aligns with the findings of Burchfield et al. (2006) which show that cities with faster, more predictable growth experienced less dispersed development due to intensification and decreased land speculation. On the other hand, Fallah et al. (2012) provided evidence that predictable growth patterns reduce the uncertainty within a city's housing market. This encourages development at the periphery, resulting in a net loss of population density.

Table 2 Population to sprawl elasticities

Author(s)	Date	Population	Sprawl variable	Elasticity	Variance
Brueckner & Fansler	(1983)	Population	Footprint	1.08	Between
McGrath	(2005)	Population	Footprint	0.76	Between
Wassmer	(2006)	Population	Footprint	0.9	Between
Song & Zenou	(2006)	Population	Footprint	0.52	Between
Ulfarsson & Carruthers	(2006)	Population	Footprint	0.71	Between
Spivey	(2008)	Population	Footprint	0.91	Between
Wassmer	(2008)	Population	Footprint	0.9	Between
Ke et al.	(2009)	10 year lag	Footprint	0.57	Between
Geshkov & DeSalvo	(2012)	Nb. of HH	Footprint	0.46	Between
Paulsen	(2012)	Population	Footprint	0.8	Within
Wassmer	(2016)	Population	Footprint	0.97	Within
Ulfarsson & Carruthers	(2006)	Population	Density	0.28	Between
Tanguay & Gingras	(2012)	Population	Sparse homes	-0.16	NA
Young et al.	(2016)	Population	Sparse homes	-0.09	NA

Together, these studies offer empirical evidence that growing populations place upward pressure on housing demand and land prices, thereby incentivizing both intensification and expansive development at the periphery. This results in a city's density gradient increasing vertically as well as horizontally over time. The cumulative impact of these countervailing effects should result in a net reduction in sparse housing. This assertion is supported by a twin set of studies that examined Canadian Metropolitan Areas (CMAs) during the periods 1986-2006 and 1996-2011. These studies demonstrated that a 1% increase in population is associated with a 0.16% and 0.09% decrease in the proportion of sparse housing, respectively (Tanguay & Gingras, 2012; Young et al., 2016).

1.5.4 Income

Consistent with the AMM model, income is significant and positively correlated with land area variables. Table 3 reports the results of eight studies that measured the income to land area elasticities. Despite the fact that most use household (HH) income variables, the size of the elasticities differ greatly. This is most likely due to different methods and model specifications.

Table 3 Income to sprawl elasticities

Author(s)	Date	Income	Sprawl variable	Elasticity	Variance
Brueckner & Fansler	(1983)	Average HH	Footprint	1.5	Between
McGrath	(2005)	Real personal	Footprint	0.33	Between
Wassmer	(2006)	Median HH	Footprint	0.57	Between
Song & Zenou	(2006)	Average HH	Footprint	0.72	Between
Spivey	(2008)	Median family	Footprint	-0.39	Between
Wassmer	(2008)	Per Capita	Footprint	1.1	Between
Ke et al.	(2009)	Average salary	Footprint	0.15	Between
Geshkov & DeSalvo	(2012)	Mean HH	Footprint	0.1	Between
Paulsen	(2012)	Median HH	Footprint	0.4	Within
Tanguay & Gingras	(2012)	Median HH	Sparse homes	0.65	NA
Young et al.	(2016)	Median HH	Sparse homes	0.24	NA

When examining the effects of income on other characteristics associated with urban sprawl, the evidence further supports the idea that housing space is a normal good, with households increasing their consumption as their income rises. Ortuño-Padilla and Fernández-Aracil (2013), Tanguay and Gingras (2012), and Young et al. (2016) provide evidence that income is positively associated with sparse housing typologies. Angel et al. (2012) observed that cities with higher GDP per capita exhibit more dispersed development patterns and that accelerated income growth amplifies this dispersion. Additionally, there is evidence that cities with higher wealth disparity have a greater share of their population living in low-density areas, possibly due to income segregation (Fallah et al. 2012).

Nonetheless, some authors have suggested that segmenting income categories more precisely could reveal a nonlinear relationship among variables such as footprint and sparsity (DeSalvo & Su, 2013). For example, a model produced by Wassmer (2008) indicated that cities with higher per capita incomes not only had larger footprints but also lower population density. However, the inclusion of very affluent households—those earning $100,000 or more—positively impacted urban density while reducing the land area. This may be due to the elevated opportunity costs associated with longer commute times in large, economically productive cities. These costs may lead wealthy individuals to locate in expensive high-rises at the city core.

1.5.5 Transportation costs

The travel behaviors of households can be attributed to two types of transportation costs: the monetary expenses and the time spent traveling. In his seminal paper on the AMM model, Mills (1967) emphasized that the opportunity cost of travel time is the most important of the two.

Hupkes (1982) and Schafer (2000) have argued that location choices are influenced by travel times rather than distance, suggesting that faster travel modes allow for increased distances from employment centers. Marchetti (1994) and Zahavi (1974) suggested that the average Travel Time Budget (TTB) of humans is consistent and stable across various times and places, indicating a universal tolerance for the amount of time allocated to daily travel. Despite variation at the individual level, including differences attributed to gender, vehicle ownership, income, employment status, lifestyle, and household size, this assumption holds true at the aggregate level (Ahmed & Stopher, 2014; Mokhtarian & Chen, 2004). This aggregate average tolerance for commute times suggests that urban expansion will be limited by the longest acceptable commuting distance, leading cities to densify through intensification when they grow beyond this commuting threshold. This theory informs the hypothesis that remote work, by reducing or eliminating travel times, can lead to the expansion of a city's footprint and a reduction in housing and population density. It also explains why large population centers with extensive urbanized areas will experience more densification in their cores.

Unfortunately, evaluating the impact of travel on urban development is complicated by the challenge of finding suitable proxies for transportation costs. In many of the studies examined in this review, the variables displayed unexpected signs, or lacked significance (Brueckner & Fansler, 1983; Spivey, 2008; Paulsen, 2012).

1.5.5.1 Travel time

Among the studies reviewed, average travel time was rarely included due to endogeneity issues related to its simultaneous relationship with two frequently used dependent variables: footprint and density. Larger urbanized land areas imply longer travel times, while higher density increases traffic congestion. This complexity escalates with census variables that aggregate travel times across different transportation modes—as each mode relates differently to physical distances—thereby complicating the association with the urban form. For these reasons, using this variable leads to multicollinearity issues and unexpected signs (Spivey, 2008; Paulsen, 2012).

A proposed workaround involves using congestion costs, which are expressed as a dollar amount associated with the volume of travel exceeding a specified threshold. Employing this method, Spivey (2008) revealed that cities with higher congestion costs tend to have smaller urban footprints, aligning with the expectations of the AMM model. However, this variable's unavailability for large datasets stems from the necessity of calculating it individually for each city.

Transportation infrastructure is the leading means by which cities can increase their commuting thresholds and further extend the range of their urbanization footprints. Two U.S. studies examining data from 1990 and 2000 indicated that cities located in regions with increased highway expenditures exhibit no significant discrepancies in the density of new developments or the magnitude of their footprints (Pendall, 1999; Geshkov & DeSalvo, 2012). However, Song and Zenou (2006), examining a larger dataset of American cities for the year 2000, identified an elasticity of 0.28 between footprints and per capita state transportation expenditures. Deng et al. (2008) and Ke et al. (2009) observed that, in Chinese cities, both the presence of highways traversing the center and the overall length of highways are associated with slight increases in the urban footprint, with elasticities below 0.1. Comparing European cities, Garcia-López (2019) found a similar elasticity with the expansion of the urban footprint from 1990 to 2012, while also indicating a small rise in dispersion. However, these studies do not take into account highway width. When focusing on changes within U.S. cities, Baum-Snow (2007) demonstrated that that each additional interstate highway added through their core between 1950 and 1990 led to a 18% decline of their central city population. Together, these findings illustrate that sprawl tends to be slightly higher in cities with extensive car infrastructure, with the greatest impact observed during the highway expansions of the mid-century.

1.5.5.2 Monetary costs

A regionally adjusted Consumer Price Index (CPI) for transportation acts as a direct indicator of the varying costs associated with transportation. These may include gas prices, airline and transit fares, as well as vehicle expenses and insurance. Increased public transportation CPI has been shown to considerably reduce the construction of new apartment floor space, but has not been a significant predictor of sparse housing development (Tanguay & Gingras, 2012; Ortuño-Padilla & Fernández-Aracil, 2013). McGrath (2005) uncovered that cities with higher private transportation CPI tend to have smaller urban footprints. These results suggest that inhabitants of sprawled areas are sensitive to the costs of driving, but remain unaffected by changes in transit fares. Nonetheless, improved transit accessibility does have a positive impact on densification.

Gas taxes and prices are among the transportation variables that seem to yield the best results when developing econometric models for the causes of sprawl. In comparing US cities, McGibany (2004) observed that while the price of gasoline did not significantly affect the extent of their urban footprints, a higher state gasoline tax was associated with a reduction in their size. Additionally, cities that had experienced an increase in gasoline taxes between 1986 and 1990 were also found to be smaller in extent. A similar study in Canada, covering 12 Census Metropolitan Areas (CMAs) from 1986 to 2006, discovered that a 1% increase in gasoline prices corresponded with a 0.18% reduction in average commute distance, and a 0.60% decrease in the prevalence of sparse housing (Tanguay & Gingras, 2012). A follow-up study evaluating 10 CMAs from 1996 to 2011 found more subdued associations: a 0.04% reduction in average commute distance and a 0.17% decrease in sparse housing (Young et al., 2016). A parallel study conducted in Spain identified a more pronounced relationship: a decrease of 0.73% in the construction of new single-family homes and an increase of 1.84% in the construction of new apartment units were observed (Ortuño-Padilla & Fernández-Aracil, 2013). These findings indicate that rising gas prices lead households to prefer denser housing and shorter commutes, a trend more pronounced in a European study focused on the production of new homes, suggesting rapid market response to these changing preferences. However, factors like improved fuel efficiency and higher disposable incomes may lessen gas price sensitivity over time, as evidenced by the reduction in elasticities in the second Canadian study.

Car ownership is considered as a primary contributor to urban sprawl (Glaeser & Kahn, 2004). Across Europe, it has been shown to be positively associated with more sparsely populated cities (Patacchini et al., 2009). However, in America, cities with sprawling footprints have demonstrated either insignificant relationships or very weak elasticities with respect to car ownership (Spivey, 2008; Wassmer, 2008). Additionally, broader metrics such as transit mode share or the number of cars owned per household tend to yield coefficients that are either statistically insignificant or indistinguishable from zero (Brueckner & Fansler, 1983; McGibany, 2004). This can be attributed to the limited variation in car ownership across American cities, leading to reduced effects and significance in cross-section models.

Low-cost parking also acts as a public subsidy to private vehicles that may encourage auto-centric development. Young et al. (2016) found that a 1% price increase in off-street parking reduced sparse housing stock by 0.12% and median commute distances by 0.05%.

1.6 Catalysts and constraints of sprawl: Other factors

This section delves into more fiscally and politically oriented determinants of sprawl. These are notably more challenging to measure compared to the inputs of the AMM model, especially when comparing across different cities. Given the inherent difficulties in quantifying these factors, this section does not intend to identify specific variables for inclusion in the regression model. Rather, it seeks to shed light on the unique characteristics and unseen influences of each city that impact the model's results, as captured by the error term.

1.6.1 Fragmented political jurisdictions

A centralized metropolitan government or planning agency can improve territorial coordination, leading to more efficient public transportation and higher population density targets. Many cities have also taken steps to combat the decline of their downtown areas by forming metropolitan governing bodies or annexing suburbs directly (Nelson et al., 2004). Conversely, increased political influence from suburban residents within these political institutions may coerce central districts into being more car-friendly, accommodating the needs of a more sprawled urban form. This discussion reveals a complex landscape where centralized governance may either exacerbate or mitigate the issues related to urban sprawl. Despite the theoretical possibilities, limited research has explored these relationships.

One aspect of governance that has received more attention is the impact of political fragmentation. Some studies incorporating political fragmentation as a control variable, such as those by Pendall (1999) and Burchfield et al. (2006), have not identified a significant impact. This could be due to the endogenous relationship between the number of governing bodies in a metro area and urban sprawl, where expansion and amalgamation of rural municipalities into urban areas might occur. When controlling for this, Ulfarsson & Carruthers (2006) estimated that a 1% increase in the number of municipal governments per capita led to a 0.67% decline in population and employment density and a minor 0.09% decrease in the extent of urban footprints. The decline in developed land area was likely an outcome of central municipalities annexing expansion areas. This evidence supports the hypothesis that rival municipalities may limit housing density to sustain property values, thereby pushing new development towards greenfields beyond the metropolitan periphery. In accordance with the Tiebout model, these fragmented jurisdictions influence sprawl through the adoption of local zoning and property tax laws that are unequally distributed in the metropolitan area. Some insight into this phenomenon can be gained from the following sections where we these policy tools are examined in more detail.

1.6.2 Fiscality

The impact of property taxes on population density is contingent upon whether one examines it from the standpoint of developers or consumers. In reaction to high property taxes, owners and developers might refrain from enhancing land parcels. Meanwhile, lower taxes might also encourage both developers and households to consume more land than they would in a state of market equilibrium, leading to reduced population density (Gihring, 1999). Conversely, high property taxes add to the costs of housing which can reduce floor space consumption and thereby increasing density (Brueckner & Kim, 2003). When comparing the impact of property taxes between different cities, Song and Zenou (2006) concluded that the net result of these countervailing effects is a 0.4 % reduction in footprint for every 1% tax increase. In a longitudinal study examining the effects of a 1% increase in property taxes within cities, Wassmer (2016) discovered varying impacts depending on the type of property taxed. Specifically, the study found an 8% expansion in the urban footprint for multifamily homes, a 4% decrease in footprint for commercial properties, and no significant change for industrial properties and single-family homes. This illustrates that individuals are less likely to invest in multifamily projects when taxes increase, whereas the effects are less clear for single family owners that face more complex trade-offs.

There is also evidence that municipal reliance on sales taxes incentivize suburban governments to draw retailers away from traditional business districts, fostering polycentric development (Wassmer, 2002). However, these findings are not quite helpful in the Canadian context, where municipalities predominantly depend on property taxes for income.

Sprawling development is incentivized when the local tax base does not fully cover the costs of infrastructure, such as transportation, waste and water management and other services. Pendall (1999) supports this, showing a correlation between increased reliance on property tax and slight rises in population density in newly developed areas. Burchfield et al. (2006) demonstrated that sprawl was more pronounced in cities that received higher state or federal transfer payments. Persky and Kurban (2003) also found that federal infrastructure subsidies modestly increased land conversion to residential use in suburban areas of the Chicago metropolitan area. Additionally, city-level governments rarely cover the full costs of building state and provincial roads, despite their impact on local transportation and urban expansion (Brueckner, 2000). These studies highlight how state and federal subsidies and investments reduce the tax burden on municipalities and encourage them to extend land consumption beyond the limits of their baseline fiscal capacities.

Other federal incentives, such as easier access to mortgages and financing options, increase the purchasing power of consumers, enabling them to acquire more land and floorspace (Green, 1999). Ideally, these subsidies could support denser housing initiatives, such as high-rises, but they often favor owner-occupied housing, which typically encourages the construction of sparser housing typologies (Voith et al., 2000; Voith & Gyourko, 1998, 2002). The location of government activities and contracted firms can further influence sprawl, with offices positioned outside central areas promoting decentralization, and vice-versa. For example, one study demonstrated that federal housing subsidies issued between 1989 and 1996 increased residential land use in the suburbs of Chicago by over 20%. In contrast, interventions aimed at revitalizing downtown areas reduced land consumption by only a small margin (Persky and Kurban, 2003).

1.6.3 Regulatory environment

1.6.3.1 Zoning

Zoning policies have a key influence on sprawl as local governments' interventions in land markets often skews property values and leads to sparser housing and higher costs (Knaap, 1998). Pendall (1999) found that MSAs with more land zoned for low-density had new developments that were sparser, as expected. Notably, land with building permit caps had an effect on sparsity that was more than twice as strong. Geshkov & DeSalvo (2012) compared the effects of regulations across 182 UAs. Due to data collection challenges, quantifying the precise effects of regulation intensity proved difficult. However, they found that the presence of lot-size restrictions, floor-area ratios, permit caps, density minimums, and impact fees all had the ability to either restrict or expand the urban footprint. Burchfield et al. (2006) found that cities incorporating larger peripheral areas into their jurisdiction experienced less dispersion, demonstrating that applying zoning to previously unregulated areas can mitigate sprawl.

Estimating zoning's impact on sprawl is challenging due to the endogeneity of zoning, which is influenced by and influences pre-existing land values. The homevoter hypothesis suggests households with higher property values support regulations preserving their home values (Fischel, 2005: p29-32). Similarly, Saiz (2010) observes that cities with geographic constraints, high land values, and growing populations tend to enact strict regulations, further indicating zoning's endogeneity. The studies presented in the preceding paragraph did not control for this endogeneity, which could influence the accuracy of their findings.

1.6.3.2 Urban containment policies

Governments employ diverse urban containment tools in their efforts to address sprawl. At the state level, Growth Management programs serve as policy instruments. Local governments, on the other hand, make use of urban containment strategies such as Urban Growth Boundaries (UGBs), greenbelts, Urban Service Boundaries (USBs), and other regulatory instruments; each serving distinct purposes and functions. Even within a single country or province, the implementation and design of these policies vary significantly, which can pose challenges for comparative analysis. These methods usually work in two ways: they either redirect development to already urbanized land or restrict development at the fringe.

In a comparison of 452 urban areas, Wassmer (2006) found that Statewide Growth Management programs were associated with smaller urban footprints. This association was only present if the program required cities to collaborate directly with the state, regional governance entities, or adjacent municipalities in formulating their policies. Additionally, the longer these programs were implemented, the more pronounced their effects became. However, areas with higher levels of sprawl often implement increased restrictions to mitigate its expansion, indicating that growth management strategies are inherently endogenous. Additionally, these plans frequently correlate with geographic factors, often as a result of ecological preservation initiatives (Howell-Moroney, 2008). To more effectively elucidate the effects of these plans, a longitudinal analysis that measures their impact within cities is necessary. In doing so, Paulsen (2013) determined that Statewide Growth Management programs led to declines in marginal land consumption only when they “mandated comprehensive plans by local governments and provided detailed guidance on the content of those plans.”

When opting for local or regional containment tools, synchronizing strategies across municipalities in an economic area and thoughtfully delineating perimeters are crucial to control development spillovers, manage growth effectively, and mitigate expansion pressures beyond set boundaries. (Pendall & Martin, 2002). Therefore, regional planning is essential to the deployment of the following policies, ensuring their effectiveness and alignment with intended goals.

UGBs consist of a perimeter within which development is constrained, typically designed to accommodate growth projected for a specific time period, often extending across multiple decades. They are also often paired with complementary zoning policies. While some find that cities with UGBs are not significantly correlated with smaller footprints (Pendall, 1999; Geshkov & DeSalvo, 2012), others find evidence that they are associated to lower levels of dispersion and polycentricity (Wassmer, 2002; Angel et al., 2012), as well as decreased exurban growth (Nelson & Sanchez, 2005).

UGBs limit sprawl with regulations whereas Greenbelts achieve the same purpose through the acquisition of undeveloped land or rights on agricultural land. Empirical research has shown that greenbelts effectively densify central urban areas and mitigate sprawl growth within their confines, yet they significantly heighten the risk of sprawl expansion beyond their boundaries (Pendall & Martin, 2002; Pourtaherian & Jaeger, 2022; Xie et al., 2020).

USBs are designated areas within which public infrastructure, such as sewer systems and water supply, is provided. The most commonly employed USB is the Adequate Public Facilities Ordinances (APFO). These are policies set by local authorities to ensure that public infrastructure can accommodate new developments. They often mandate that developers prove the availability or future provision of adequate facilities before receiving development approval. Pendall (1999) finds evidence that cities with larger areas of APFO-controlled land were associated with an increase in population density in their new developments, a result comparatively more successful than those employing UGBs.

1.6.3.3 Urban containment in Canada

Regional planning in Canada adopts a wide range of approaches across its provinces. In Quebec, regional planning bodies are established throughout the province, with specific efforts made for the cities of Quebec and Montreal, resulting in metropolitan plans adopted in 2012 and 2011, respectively (Act Respecting Land Use Planning and Development. RLRQ, c. A-19.1). However, high levels of municipal fragmentation have introduced political challenges, reducing the effectiveness of these plans (Han et al., 2023). In 1995, regional districts in British Columbia were empowered to collaboratively make land-use decisions, resulting in successful outcomes, including Vancouver's growth plan that successfully controlled urban sprawl. (Curran, 2003; Han et al., 2023). Ontario facilitated coordinated regional planning through the amalgamation of Ottawa in 2001 and the creation of a regional plan in 2006 for the Greater Golden Horseshoe (Han et al., 2023). In contrast, Alberta experienced mixed results in regional planning after the dissolution of Regional Planning Commissions in the mid-1990s, with Edmonton seeing some improvement after the establishment of the Capital Region Board in 2008, while Calgary did not see similar progress (Agrawal, 2016; Han et al., 2023; Taylor et al., 2014). Notably, provinces like Saskatchewan and Manitoba lack comprehensive regional planning mechanisms, with Saskatchewan's 2007 act suggesting but not mandating cooperation among municipalities, and Manitoba leaving regional planning to the discretion of municipalities. This policy has particularly impacted Winnipeg, leaving it as the only CMA with a population over 750,000 without a regional planning mechanism (Government of Saskatchewan, 2023; Province of Manitoba, 2004; Han et al., 2023).

While many cities aim to concentrate growth, their use of UGBs varies (Agrawal, 2016; Broderick, 2019; Taylor et al., 2014). Cities in British Columbia like Kelowna, Victoria, and Vancouver employ successful UGB initiatives (Curran, 2003). Notably, Ottawa added a UGB in 2003 to supplement its underperforming greenbelt (Broderick, 2019). Quebec mandates urban perimeters under the Act Respecting Land Use Planning and Development. Prairie cities generally lack UGBs; Winnipeg had an Urban Limit Line until 1986, but it is no longer in use (Broderick, 2019).

In terms of farmland protection, Quebec stands out with the most robust policy approach, with British Columbia and Ontario trailing closely. Conversely, Nova Scotia, New Brunswick, Manitoba, and Saskatchewan exhibit less stringent legislative measures. The frameworks in Newfoundland and Labrador, and Alberta are notably weaker (Connell, 2021). Highlighting significant greenbelt initiatives in Canada, the Oak Ridges Moraine Conservation Act of 2001 stands out for its impact on containing sprawl (Han et al. 2023). Equally noteworthy is the Greenbelt Act of 2005, credited for successfully curbing sprawl in Toronto according to Han et al. (2023). In contrast, the Ottawa National Capital Greenbelt established in 1950, struggled to contain sprawl within the first decade of its inception due to development jumping beyond its perimeter (Broderick, 2019).

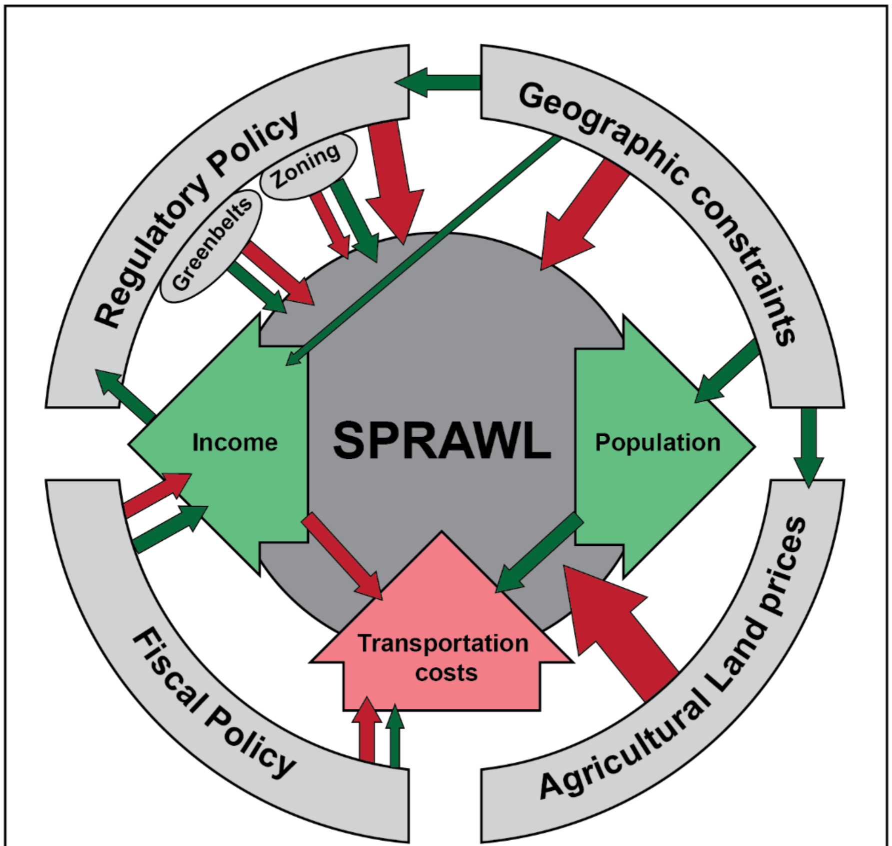
1.6.4 Flight from blight variables

Certain studies indicate that flight from blight variables have a weak impact on sprawl regression models. Central city poverty was found to have only a minimal impact on a UAs expansion, with a 1% increase in poverty correlating with a 0.3% increase in land area, while the effect of race was found to be negligible (Wassmer, 2006). A later study, using a different set of variables, corroborated these findings, indicating that a 1 % rise in poverty led to a 0.2 % increase in urban area size (Wassmer, 2008). In contrast, Bayoh et al. (2002) found evidence that factors such as school quality and crime rate have a significant influence on the choice of residential location in Ohio. Pendall (1999) revealed that U.S. counties with more Hispanic residents in 1980 grew denser in the subsequent decade, whereas non-Hispanic black population did not exert a significant effect.

Conversely, the monocentric AMM model posits that CBDs attract workers due to abundant employment opportunities. It follows that a vibrant CBD may decrease sprawl, as evidenced by findings that increases in CBD employment and job concentration in industries typically drawn to urban cores predicted reductions in urbanized areas (Burchfield et al., 2006; Wassmer, 2006).

1.7 Relationships between catalysts and constraints

Figure 3 The catalysts and constraints of sprawl



Source: Gavin MacGregor

Figure 2 encapsulates the observed relationships between sprawl's catalysts and constraints, as detailed in the preceding literature review section. Positive relationships are depicted with green arrows, whereas negative relationships are illustrated with red arrows.

Geographic features such as water and mountains restrict the availability of land for both agriculture and urban development. Their aesthetic appeal also attracts population growth, in particular with wealthy households who have higher residential mobility. To protect these ecologically significant ecosystems, policymakers often implement targeted regulations, which in turn contribute to rising land costs. Agricultural activities directly compete for housing development, subsequently limiting opportunities for sprawl by limiting available land.

Burgeoning population levels intensify the demand for housing, which consumes land and escalates transportation costs due to greater congestion. While higher incomes amplify the demand for land and housing, they also enable households to better manage rising transportation costs. Affluent households also tend to have more political clout and are more invested in protecting the value of their housing assets, which in turns leads to increased regulatory policies. Transportation costs act as a direct disincentive to land development, discouraging households from living far from employment centers and potentially mitigating sprawl. Fiscal measures significantly influence this intricate dynamic. Subsidies can manifest as investments in transport infrastructure or as easier access to housing financing, while land and gas taxes dictate how households allocate their income between housing and transportation.

Regulatory policy seeks to reduce sprawl, but their effectiveness remains open to debate. Some approaches like greenbelts and zoning have variable impacts, sometimes fostering leapfrog development or increasing lot sizes, while sometimes reducing land available for development. The complexity of these relationships, with various mutual directionalities and causal loops, highlight the importance of accounting for endogeneity bias and multicollinearity in modeling sprawl dynamics.

1.8 Chapter summary

This chapter offers a detailed exploration of the various factors contributing to urban sprawl, categorizing them into inputs for the AMM model and broader fiscal and political influences. Notably, it identifies a predominance of cross-sectional analyses, which, although informative for understanding the difference in the prevalence of sprawl across cities, reveal a gap in tracking its evolution within cities.

Brueckner (1987) discusses how the AMM model helps us understand and compare the structures of two theoretical types of cities; the closed-city case, in which people cannot leave the city in response to changes in the model, and the open-city case, where migration between cities is feasible and there's rivalry to attract inhabitants. He aptly points out that the two scenarios can coexist: migration is costly, both financially and psychologically, which consequently reduces its frequency. However, it does occur, as evidenced by the fluctuating populations of cities over time. Brueckner’s analysis provides the ideal framework for examining the empirical evidence discussed in this chapter of the literature review.

When holding all other variables constant, Brueckner (1987) explains that higher populations lead to both increased footprint and built density. The literature reviewed in section 1.5.3 supports this notion by providing evidence for the expansion of urbanization, reduction in dispersion, and intensification of development. Nonetheless, the net result of these concurrent effects appears to be a higher proportion of sparse housing.

Brueckner (1987) showed that cities experience increased density and reduced footprints due to elevated agricultural rents. However, in the open model, cities located in areas with high agricultural rents exhibit smaller footprints and lower populations but share the same density distribution as cities with lower agricultural rents. Both the closed and open model dynamics might simultaneously influence the outcomes, potentially explaining the inconclusive results observed in the urban development studies reviewed in section 1.5.2.

In the closed model, higher income lowers the core’s built density and enlarges the city's footprint as people move to the outskirts for larger housing. Conversely, in the open-city model, high incomes increase population, footprint, and density due to new residents and rising housing prices (Brueckner, 1987). Empirical findings from section 1.5.4 support both models, showing city expansion with increased income. However, despite rising land prices potentially intensifying density, higher incomes were shown to generally reduce development density.

Finally, a reduction in transportation costs should yield larger footprints and lower densities (Brueckner, 1987). By reducing these costs, remote work is expected to produce a rise in sprawl within cities.

CHAPTER 2

REMOTE WORK

This chapter explores the explanatory variable of interest in the present study, which measures the practice of remote work. Defining remote work is crucial for understanding the explanatory variable and assessing potential biases arising from its specification. The socio-demographic portrait and the frictions to adoption are discussed to better understand the profile and motivations of remote workers.

The main focus of this chapter is to review the literature that focuses on the relationship between remote work and travel patterns, including effects on commute distances, congestion, non-commute travel, and overall travel behavior. This section considers complex household interactions and aims to elucidate how remote workers relate to the concept of distance, which is vital in the AMM model. Additionally, the chapter investigates the impact of remote work on residential location choices and housing preferences, examining whether remote workers prefer locations and housing sizes for family proximity, lifestyle, or work-related reasons. This will complement our understanding of which aspects of the AMM model's trade-offs are significant to remote workers, be it distance or housing size. Finally, the chapter addresses the broader implications of remote work on urban form and job locations.

2.1 Defining remote work

There exist several conflicting definitions of the different types of remote work. Variation in descriptive criteria and inconsistent terminology has complicated policymaking, cumulative research, and comparisons between studies. For example, telecommuting is a subcategory of telework, but there is no established convention to distinguish the two terms. Even simple concepts such as “work” and “home” face classification issues. These ambiguities can not only confuse researchers and officials, but also respondents who are faced with survey questions that can be open to interpretation. Certain authors have made clear that this is an important source of bias for studies dealing with the theme of telework (Mokhtarian et al., 2005; Pratt, 2000). In the subsequent literature review, the classifications of "remote work," "telework," and "telecommuting" will be applied based on the criteria outlined in the following sections, rather than the definitions used in the individual articles. This will facilitate a consistent analytical framework for evaluating how each article's sample aligns with these specific definitions.

2.1.1 Remote Work

Remote work, while often associated with teleworking, encompasses a wider range of activities that can be conducted from home, including self-employment, moonlighting, and overtime hours (Mokhtarian, 1991a; Mokhtarian et al., 2005; Mokhtarian & Tal, 2013). It can also involve various types of work not requiring commuting, such as roles filled by agricultural workers, live-in domestic workers, and service occupations like plumbing and childcare. It can be considered as an umbrella term that encompasses home-based business owners, teleworkers and telecommuters. In this study, "remote work" refers to working from home, as per the Statistics Canada data, although it can also include other locations like coffee shops.

2.1.2 Home-based business operators

A home-based business operator is an individual who runs a business from their own home (Mokhtarian et al., 2005). These individuals are typically self-employed and may or may not require lots of time travelling on the road in order to reach a broad network of clients or suppliers. This type of business model allows for a great deal of flexibility and can include a wide range of activities, from consulting and freelance work to crafting, online retail, and professional services.

2.1.3 Telework

The initial definitions of telework in scientific literature centered on professional activities dependent on Information and Communication Technologies (ICT) (Mokhtarian, 1991a, 1991b). However, as ICTs became increasingly ubiquitous in the labor market, the term "telework" evolved to encapsulate more specific criteria such as workplace and employment conditions. Others elaborated on this, stating that telework involves the use of ICT to conduct work either partially or wholly outside a traditional office setting, in the framework of a formal employment relationship with a company (Graizbord, 2015). Employment arrangements also contribute to telework studies. Researchers sometimes exclude contract employees working from home because their travel patterns resemble business trips, despite the absence of a commute (Handy & Mokhtarian, 1995). Conversely, some researchers include these contract workers, arguing that their mobility patterns are more similar to those of traditional salaried employees than to non-commuters like the self-employed or agricultural workers (Mokhtarian et al., 2005).

2.1.4 Telecommuting

Telecommuting is a specific form of telework that more directly addresses the relationship between work and transportation (Nilles, 1988). It refers to the partial or total substitution of telecommunications for the commute to work, often with the assistance of computers. This definition necessitates additional criteria to evaluate its influence on mobility patterns. The impact of telecommuting on travel can be quite varied. A telecommuter may reduce travel by working at a location closer to home, such as a telecommuting center or café. Conversely, commuting can be entirely eliminated if work is performed at home all day. On some occasions, the commute may not be eliminated or reduced, but its timing can change if some work is performed at home and some at the office (Handy & Mokhtarian, 1995; Mokhtarian et al., 2005). Overtime hours worked at home are not considered telecommuting if the employee still commutes to the office for a regular shift.

2.1.5 Telemigration

Telemigration refers to the process where individuals work remotely from a different geographical location, often in a different country, than their employer or the main office. This is usually attributed to the outsourcing of entire departments to different countries such as India or the Philippines (Baldwin, 2019). However, in the context of this research, telemigration can also be considered a phenomenon where individuals choose to work from distant rural areas, away from large employment centers. This would mean a transfer of workers from the sphere of influence of metropolitan regions and moderately sized cities towards small villages or even cottages in the countryside. Thus, telemigration is by definition a category of remote work that is not captured by census data for CMAs and Census Agglomerations (CAs).

2.2 Socio-demographic characteristics of remote workers

Remote workers are very heterogeneous in their practices, but it is nevertheless possible to observe some particularities in their socio-demographic profiles that may influence their travel behaviors and housing preferences. The most comprehensive study on remote workers by Statistics Canada was conducted by Turcotte (2010), utilizing data from the 2008 General Social Survey (GSS). This survey, conveniently situated at the midpoint between 2001 and 2016, provides insight on individuals that conducted at least some of their paid work at home during the period of 2008. However, the full-time employees in the sample are primarily those who only work a few hours from home. Specifically, 67% of these employees spend less than 10 hours working from home, with their median remote work amounting to a single full-day shift. Therefore, the sample studied by Turcotte (2010) differs from the individuals categorized as remote workers in the Census—who are required to work at least half their time from home—that were used in our study.

Turcotte (2010) found that 19% of the workforce, including 60% of self-employed individuals and 11% of employees, engaged in some form of remote work. Despite remaining stable since 2001, the proportion of self-employed workers experienced a noticeable increase between 2006 and 2008, rising from 54% to 60%. Meanwhile, the rate of remote work among employees stayed consistent during this entire period. Unfortunately, the following statistics were evaluated solely for employees. More than half of this group occupied managerial or professional roles, a proportion nearly twice as large as that observed among regular office workers. Notably, the level of educational attainment within this group was high, with 54% holding a university degree—a figure that also doubles that of regular office workers. Consequently, a larger proportion of remote workers, compared to their office-bound counterparts, earned over $60,000 annually—52% as opposed to 25%. Regarding gender distribution, 10% of women worked from home, somewhat lower than the 12% observed among men. Those in the 35- to 54-year-old group were somewhat more likely to work from home than younger individuals. Finally, 13% of individuals with children under the age of 12 managed to conduct some of their work hours from home, in contrast to 10% among those who did not.

Several international studies corroborate this profile of older, experienced individuals with higher education levels, greater income, and employment in the tertiary sector, but not in retail (de Graaff, 2004; Duxbury & Higgins, 2002; Elldér, 2017; Haddad et al., 2009; Helminen & Ristimäki, 2007; Jiang, 2008; Muhammad et al., 2007; Global Workplace Analytics & Flexjobs, 2017; Ravalet & Rérat, 2019).

2.3 Incentives and frictions to the adoption of remote work

Understanding the motivations for adopting remote work can help understand if residential location choices are caused by telework, or if people work remotely because of their current place of residence.

Numerous studies have explored the factors that either encourage or hinder the adoption of remote work. Avoiding work interruptions and enhancing personal and family life emerge as the primary motivations for telecommuting, while avoiding traffic congestion is a lesser but still relevant factor (de Graaff, 2004;

Haddad et al., 2009; Mokhtarian & Salomon, 1994). In one Finnish study by Helminen & Ristimäki (2007), only 8% of teleworkers mentioned a long commute as the primary motive for teleworking. In Taipei, financial considerations and home space availability significantly influence the decision to adopt telecommuting, with the cost of commuting having a relatively inelastic impact (Yen, 2000). Koeplinger (2007) showed that among many employees of Fortune 500 companies, telecommuting is generally viewed as a lifestyle choice rather than a necessity driven by external constraints such as distance from the office; this geographic flexibility is particularly appealing to employers for recruitment purposes. An interesting finding among the results of Koeplinger (2007) was that geography were not necessarily a priority for employees, but were very important for employers. Business leaders see telecommuting as an excellent way to recruit the best candidates, without having to be subject to spatial constraints.

As a result of the COVID-19 pandemic, telework became a mandatory practice for many companies and individuals who had not previously engaged in such arrangements, effectively diminishing the barriers to its adoption. At the height of the first wave of the pandemic, Canada saw its labor market reach a work-from-home rate of 39% (Chowhan et al. 2021). These numbers approach the predictions made by Deng et al. (2020) and Dingel and Neiman (2020) regarding the feasibility of remote work in Canada and the U.S., respectively. Deng et al. estimated that 38.9% of Canadian jobs could be performed from home, while Dingel and Neiman calculated that 37% of U.S. jobs are suitable for remote work. These estimations were derived from analyses of the types of industries and professions present in each labor market. Consequently, the prevalence of remote work is accelerating and is likely to instigate a lasting transformation in certain industries. Going forward, some companies may not only consistently offer working from home as an option, but may also mandate it, making remote work a standard practice of their employment arrangements. Bartik et al. 2020 observed that more than one third of companies believed that working from home will remain more common in their business after the COVID-19 crisis. While the option of working from home has become more widely available, there has been a corresponding increase in demand for it; 59% of those who worked from home during COVID-19 say they would like to telework as much as possible in the future (Brenan 2020). This situation highlights the urgency of studying the impacts of remote work the spatial structures of cities.

2.4 Relationship between remote work and travel patterns

According to Salomon & Mokhtarian (2007), four types of relationships exist between remote work and travel: substitution, complementarity, modification, and neutrality. "Substitution" involves replacing one element with another, such as exchanging commuting time for more work or leisure time. “Complementarity” refers to a situation where the presence of one element does not eliminate another, but may actually enhance it. For instance, the invention of the telephone increased, rather than reduced, travel by facilitating virtual human connections that eventually led to physical encounters. The unexpected increase in travel despite advancements in telecommunications designed to reduce it is commonly referred to as the “rebound effect”. The term "Modification" denotes a bidirectional relationship where one element can both reduce and increase the other; if these changes offset each other, the modification may appear as "neutrality." "Neutrality" implies that the demand for one element remains unchanged despite variations in another. These four relationships are the first-order effects of remote work adoption, and can be measured directly (Salomon & Mokhtarian, 2007).

Remote work influences household travel behavior by affecting factors such as trip frequency, distance, scheduling, mode choice, and travel chain configuration (Mokhtarian, 1991b). These behavioral changes can subsequently impact residential location choices through altered interactions with urban destinations. Spatial anchoring occurs when households opt to live near destinations that they frequently visit to reduce commuting costs. Activities that require regular and planned trips, like commuting and shopping, strengthen this attachment to specific locations (Elldér, 2014). By reducing or eliminating travel costs outright, remote work can shift household preferences concerning the distance from key destinations. The primary focus of this thesis paper is to estimate this second-order effect of remote work adoption and its predicted impact on land-use changes. Although third-order effects associated with changes in social values and norms warrant consideration, they fall outside the scope of the present study.

To accurately estimate the impact of remote work on transportation patterns, several key factors need to be taken into account. First, it is essential to consider the effects of remote work on travel behavior for all members of a household, not just the individual who is telecommuting. Second, the types of destinations to which travel occurs must be evaluated comprehensively, encompassing work-related and non-work-related locations. Third, analyses should span longer periods, such as months or years, to capture more persistent trends and to account for long-term behavioral changes. Lastly, the frequency with which telecommuting occurs can significantly affect travel patterns, and must be taken into consideration.

2.4.1 Relationship to commute distance

Considering that the sociodemographic profile of remote workers—marked by higher income, education, and age—is associated with longer work-to-home distances, these variables were used as controls in all the studies mentioned in the following sections. While this adjustment diminished the disparity, findings still reveal that remote workers have longer work-to-home distances than regular office workers (Helminen & Ristimäki, 2007; Muhammad et al., 2007; Ravalet & Rérat, 2019; Zhu, 2013). The estimates for each study vary considerably, ranging from a 3.1% increase in commute distance for Dutch telecommuters in 2002 (Muhammad et al., 2007), to a 23.9% longer total commute distance for Americans in 2009 (Zhu, 2013). This considerable variation in estimates can be attributed to the unique commuting behaviors in Europe compared to America, with Canadian patterns likely mirroring those of the American context. However, there is evidence in both continents that the influence of remote work on commute distances manifests over the long term, as these distances tend to increase with time (Ravalet & Rérat, 2019; Zhu, 2013). Therefore, households may not relocate further from employment centers until several years after adopting remote work.

There is some evidence that the increased frequency of remote work reduced sensitivity to commute times, leading to longer work-to-home journeys (de Vos et al., 2018). Household dynamics also seem to play a role; Zhu (2013) estimated that although one partner's telecommuting status in dual-earner households does not significantly affect the other's work-to-home distance, but it does extend the household's overall work-to-home distance. This suggests that these dual-income households did not take advantage of their situation by relocating closer to the commuter's place of employment. While both Zhu (2013) and Jiang (2008) examined U.S. data from around 2001 to understand gender dynamics within dual-earner households, their findings diverged. Zhu found no gender differences in the impact of telecommuting on residential choices. In contrast, Jiang argued that in dual-earner households, women who telecommuted tended to adapt to their partners' workplace locations, resulting in these women experiencing longer commutes.

These studies provide evidence in support of the "substitution theory," suggesting that remote workers often choose residences farther from their workplaces due to lower commuting needs. Even after adjusting for sociodemographic factors like income and education, the evidence shows that the relationship not only persists but also strengthens over time and with increased frequency of telecommuting. However, it is important to note that causality is not always clear in the studies mentioned;

the adoption of remote work can be a result of residential choices just as much as residential locations can be influenced by remote work status. Additionally, the explanatory power of the studies mentioned in this section was weak, meaning that remote work was far from being the most important influence on work-to-home distances.

2.4.2 Impact on congestion

Early U.S. data, stemming from the 1988 "State of California Telecommuting Pilot Project", revealed that telecommuting reduced travel during the morning rush hour by 73% and in the afternoon by 54% (Kitamura et al., 1991). A subsequent pilot program in 2010, which involved a larger participant pool, demonstrated that while off-peak trips did not change significantly, teleworking each day reduced rush-hour trips by 1.98 per individual. Specifically, for rush hour trips made on the highway, there was a reduction of 0.72 trips per teleworker per day (Lari, 2012). Lower peak travel times were also observed in Seoul, where telecommuters are of a lower income class than those in America. When they did commute, it was done during off-peak hours in a slightly higher proportion than that of both full-time and part-time office workers (Kim, 2017).

Two studies used one-day travel survey data from the Canadian GSS offer further insights on how different remote arrangements influence travel schedules. Remote workers were categorized into three groups: those who worked exclusively from home, those who worked both at home and at a workplace, and a combination group that included working from home, elsewhere, and at a workplace. The self-employed were excluded from the sample. The first study, using 2005 data, found that while individuals working solely from home showed no significant change in morning peak trips compared to commuters, they did exhibit a statistically significant reduction in afternoon peak travel. The other two categories of remote workers exhibited travel reductions during both morning and afternoon peak hours (Lachapelle, Tanguay & Neumark-Gaudet, 2018). The second study, using 2010 data, showed a universal decline in afternoon rush hour travel across all groups, with reductions between 4% and 6%. Only the combination group experienced a significant reduction in morning rush hour travel. Notably, all types of telecommuters saw a significant uptick in travel between peak hours, with increases ranging from 10% to 14%, indicating a rebound effect (Tanguay & Lachapelle, 2019).

A complementary insight to this phenomenon can be found in the analysis of the 1991 "Caltrans Statewide Travel Survey". It classified remote workers as telecommuters or home-based business operators and compared their mean trip rates to those of commuters. In the morning peak, telecommuters averaged 0.5 trips, home-based business operators 1 trip, and regular workers 1.1 trips. During the afternoon peak, telecommuters and regular workers both averaged 1.4 trips, while home-based business operators only made 1 trip (Henderson & Mokhtarian, 1998). Another study suggested that while part-day telecommuters were more likely to align their travel with peak hours for trips related to shopping and leisure, full-day telecommuters mostly traveled outside of this time period (Asgari et al., 2019). Thus, the type of remote worker influences travel times, suggesting different levels of flexibility in adjusting their transportation schedules.

These studies demonstrate that remote work has the potential to reduce peak-hour traffic, particularly during afternoon commutes. However, the impact varies based on the type of remote worker, leading to different patterns of travel reduction. By reducing congestion, remote workers have the potential to influence the transportation costs for their entire community. Therefore, their relationship with sprawl extends not only from the direct consequence of choosing to reside further from urban centers but also through the indirect effects on the entire city's transportation costs. However, because the reduction in travel is not consistent across both peak periods, high congestion costs persist in the morning.

2.4.3 Relationship to non-commute travel

For clarity, all trips not related to commuting or work will be labelled as "miscellaneous trips" in the following section. Many of the studies reviewed found that telecommuting and the operation of home-based businesses resulted in an increase in these miscellaneous trips, both at the individual and the household level, suggesting a rebound effect (Budnitz et al., 2020; e Silva & Melo, 2017; Henderson & Mokhtarian, 1998; Kim, 2017; Kim et al., 2015; Koenig et al., 1996; Saxena & Mokhtarian, 1997; Zhu, 2012).

When analyzing the specific interactions within households, Kim (2017) uncovered evidence that this increase in miscellaneous travel was caused by long-term behavioral changes in travel patterns when the household head telecommutes regularly. Their study suggests that this could be caused by an uptick in activity enabled by a flexible work schedule, or by shifts in household employment dynamics due to the partner telecommuting. Kim et al. (2015) also provided evidence that when an automobile is not used for commuting, it can be redirected to use for other types of trips. Research by e Silva & Melo (2017) supports this analysis. They found that telecommuting frequency positively affected the amount of weekly car travel, indicating a potential reallocation of trips among household members. Interestingly, they found that the net effect of telecommuting frequency on single-earner households was an increase in overall travel, attributed to the inability to redistribute tasks. For dual-earner households, there was no net change in travel, as the reduction in commuting is balanced by the increase in miscellaneous trips.

Research focusing on individual behaviors has sometimes confirmed this equilibrium in travel patterns (Henderson & Mokhtarian, 1998; Budnitz et al., 2020), despite others indicating a net reduction in overall travel (Koenig et al., 1996; Saxena & Mokhtarian, 1997; Lachapelle, Tanguay & Neumark-Gaudet, 2018). Some studies have also identified a net reduction in travel, attributed to individuals partaking in less leisure activities and eliminating their work-related travel on days they telecommute (de Graaff, 2004; Paleti & Vukovic, 2017). These findings highlight that the observed rebound effect in travel patterns is primarily a result of the reallocation of travel among household members rather than an increase in activities undertaken by individuals. However, Mokhtarian et al. (1995) suggested that travel surveys used in these often result in an underreporting of short-distance walking trips conducted near the home, adding nuance to these findings.

Zhu (2012) found that, in addition to increasing the frequency of certain miscellaneous trips, an individual's telecommuting expanded the distance and duration of these trips, especially for shopping and business purposes. On the other hand, Asgari et al. (2019) reported that when comparing telecommuters with regular office workers, there was no significant difference in the distances they are willing to travel from home for miscellaneous trips. Henderson & Mokhtarian (1998) noted that despite having a similar trip rate as other remote workers, Home-based business operators spend the least amount of time on daily travel, suggesting that their journeys are generally shorter and closer to home. Their research also indicates that this group of remote workers is the most complex, exhibiting considerable diversity in travel patterns when segmented according to their respective industries.

Together, these studies suggest that remote work has a complementary effect on travel, stimulating both miscellaneous trips and journeys by other household members. This could result from various factors: shifts in residential and work locations, changes in vehicle availability, increased home responsibilities, more flexible activity schedules, and changes in economic status associated with adopting remote work. Mokhtarian (1998) outlined how these changes in behavior might affect latent and induced travel demand, echoing the principles of the "law of constant travel time and travel rates" identified by Hupkes (1982) and Marchetti (1994). According to this principle, households tend maintain a consistent travel time budget;

therefore, if commuting is reduced, they will reallocate the freed-up time to other activities or use it to access better housing locations. In summary, the studies highlighted show that telecommuter households are relocating farther from employment hubs but engage in equal or greater amounts of miscellaneous travel, predominantly by car. This indicates that telecommuting might be extending household travel to areas more reliant on vehicles, potentially increasing sprawling forms such as strip developments and malls. However, this pattern may not apply to certain home-based business owners that depend on proximity to customers or suppliers.

2.4.4 Relationship to mode of transportation

The use of various transportation modes influences the tolerance for travel distances, affecting the spatial anchoring of households. Some research suggests that working from home on a given day spurred active transportation (Lachapelle, Tanguay & Neumark-Gaudet, 2018). However, the type of remote worker may influence this pattern, as demonstrated by Henderson and Mokhtarian (1998). They find that home-based entrepreneurs specifically engaged in more walking and cycling, likely due to their higher level of education. They also find that this group used public transportation more frequently, while the opposite is true of telecommuters. Additionally, e Silva & Melo (2017) revealed that telecommuting's impact on travel behavior differed by household income structure. In single-income households, telecommuting increased travel across all modes, particularly cars. In dual-income households, only car travel increased, likely due to vehicle sharing among household members. Budnitz et al. (2020) offered a different perspective, suggesting a modest decline in car ownership among teleworking households. This difference may arise from the distinction between car usage and ownership. Telecommuters might use cars as frequently as traditional commuters but own fewer, perhaps due to more efficient vehicle sharing within households or reliance on other transportation modes.

2.4.5 Relationship with residential location

Three hypotheses offer explanations for the location preferences of remote workers. First, some individuals opt to work from home in order to live in areas where land costs are lower or in order to locate closer to family and friends. Second, some choose remote work to balance work-life commitments, rather than to evade daily commutes, and therefore maintain similar locational preferences as commuters. Last, some view remote work as a short-term remedy for long commutes but are not inclined to move to a different area (Ettema, 2010). Changing residential location is a long-term decision with high transaction costs more difficult to reverse than the decision to remote work. Minor adjustments in travel behavior therefore are not likely to motivate short or even mid-run relocation (Helling & Mokhtarian, 2001).

An evaluation of the 2008 Canadian GSS by Turcotte (2010) revealed that employed individuals residing in CMAs demonstrated a higher propensity to engage in remote work compared to those in smaller cities and rural regions, with a notable difference observed among employed individuals but not among the self-employed. Specifically, 12% of employed individuals in CMAs reported working from home, in contrast to 8% in CAs and 9% in rural areas. Although most studies reviewed primarily focused on travel dynamics, some include variables that provide information on the type of location where the remote workers reside. Ravalet & Rérat (2019) found no significant relationship between telecommuting and the propensity to live in a specific residential location, whether core city, isolated city, suburban, or rural. However, variables such as the business sector in which individuals are employed, their employment status, and flexibility in work hours were predictive of telecommuting. Interestingly, while living in rural or isolated cities was not associated with a higher likelihood of telecommuting in 2010, this association became significant for partial telecommuting in 2015, but not for high frequency telecommuting. In contrast, the British study conducted by e Silva & Melo (2017) found that one-worker households that were located in sparse areas telecommuted more frequently, although the effect was small. However, two-worker households living in the London central area or other areas with high employment density were associated with higher telecommuting frequency, even if they had longer commutes, indicating that high congestion may play a role in the adoption of telecommuting.

Ellen & Hempstead (2002) specifically measured the location choices of more than 50,000 American households surveyed in 1997. Controls for socio-demographic characteristics and the different employment sectors of each metropolitan area were used to take into account the fact that remote workers are tied to specific sectors of activity that are more prevalent in larger cities. The analysis revealed that there was no connection between rural and suburban locations and remote work that was statistically significant at the 5% level. This absence of a relationship remained consistent even when focusing on high-frequency remote workers who logged more than 20 hours per week remotely. However, when the latter group lived in a metropolitan area, they had a 64% chance of living in a sparse area (of less than 350 people per square mile), as opposed to a 68% for commuters. This difference was deemed statistically significant, indicating that these high-frequency remote workers preferred dense areas. One possible explanation is that ICT infrastructure was less developed in 1997, making it difficult for remote workers to locate in rural areas. This reality supports the theory that dependency paths of past urban development and existing road networks guide new residential development and ICT infrastructure, which in turn influence the spatial distribution of remote workers (Larson & Zhao 2017; Feitelson & Salomon, 2000).

Two other studies focus on the 2002 data from a national Dutch travel survey specifically to determine the residential location preferences of telecommuters. Muhammad et al. (2007) found evidence of two fundamentally different types of telecommuters. They revealed a small yet significant overrepresentation of telecommuters in rural and inner-city areas, and an underrepresentation in suburban locations, compared to commuters. Older, middle-income, and high-income telecommuters were the ones most likely to reside in the rural areas, and low-income telecommuters were predominantly found in inner-city areas. After controlling for income, age, and household status, regression analysis showed a positive and statistically significant association between telecommuting and rural locations, compared to commuting. However, other locations showed no statistical significance. Despite this relationship, life cycle stages continued to be the primary factors explaining location choices. Lastly, their analysis indicated that telecommuting status did not significantly affect the probability of moving to a different area. If they did intend to relocate, they showed a preference for an environment similar to their current one. Ettema (2010) revisited the same dataset using a latent class discrete choice framework which improved the estimation of relocation probability and residential preferences. This demonstrated that a longer commute distance did not have a significant influence on a Dutch households' motivation to relocate. In dividing the sample based on likelihood to relocate, telecommuting was not significantly associated with the group more inclined to move. However, when the model was limited to just telecommuters, longer commutes were associated with a decreased preference for relocation. These findings suggest that, based on their sociodemographic profile, showed a preference for either lively central districts or quiet rural areas. They were less inclined to compromise on suburban living, which often involves a trade-off between urban amenities and larger homes. Additionally, their reduced transportation costs likely increase the opportunity cost of moving to a different area, contributing to greater residential inertia.

The fact that remote workers fall into distinct groups, some gravitating towards dense urban environments and others towards rural areas, might obfuscate the identification of a significant linear relationship between remote work and population density. This is particularly true when utilizing a macroscopic perspective that fails to distinguish the varying densities within the metropolitan area itself. Nevertheless, a prevailing trend suggests that they are more likely to be located in densely populated areas with employment sectors conducive to remote work. This predilection may be especially pertinent for home-based entrepreneurs who require proximity to a large client base. Even when Ellen and Hempstead (2002), controlled for employment sectors, intensive telecommuters still tended to be situated more frequently in dense metropolitan areas

Kim et al. (2012) presents interesting evidence for the fact that employers may benefit from remote work more than the remote workers themselves. This is due to the fact that it is rather the places of employment which offer the option of teleworking which are more likely to located on the outskirts, in the centers of secondary activities. In this case it is the employer rather than the teleworker who reaps the benefits of substituting travel time for telework. It facilitates the expansion of the geographical scope of their employment area, allowing them to locate further away and benefit from less expensive land costs.

2.4.6 Relationship with housing

A more straightforward way to assess how remote work may impact sprawl is by examining the housing preferences associated with this practice.

A few travel surveys have included questions that facilitated the exploration of this theme. A random sample of 1877 U.S. teleworkers conducted by “Telework America” revealed that teleworkers occupied an average of 500 more square feet of housing space than commuters (Nilles, 2000). Similarly, a survey of 460 Taipei residents found a positive relationship between larger room sizes in a dwelling and a favorable attitude towards adopting telework (Yen, 2000). In a study focusing on metropolitan Seoul, where the population is generally less affluent than in American or European cities, teleworking still predicted a higher likelihood of living in a detached house and a lower likelihood of residing in an apartment (Kim et al., 2012). These provide evidence of a consistent pattern of housing choices and attitudes across different cultures.

Another two reviewed studies explored these preferences in more detail. Qin et al. (2021) utilized data from the 2011 Netherlands Time Use Survey to analyze the relationship between telecommute frequency, measured in hours per week, and housing typology. They revealed that compared to living in flats, residing in detached, semi-detached, and townhouses positively predicted the number of telecommuting hours, with the strongest prediction associated with semi-detached homes. No significant prediction was found for other types of housing. They also found that the number of rooms in a residence was associated with a greater probability of telecommuting.

Moos & Skaburskis (2008), using 2001 Canadian census data, found that in the thirteen major CMAs, despite unique historical factors and housing types, homeworkers are more likely to reside in single-family, suburban homes. Specifically, the odds were 2.4 times higher for couples where both partners worked from home, 2 times higher when the primary income was from remote work, and 1.2 times higher when remote work contributed to secondary income. When controlling for socio-demographic characteristics, these households also had more rooms compared to commuter households. Remote work also predicted occupancy in a single-family home more strongly than factors like age, immigration status, and household size. Importantly, the study excluded individuals working less than half their hours from home, thereby omitting the majority of teleworkers who work only 1-1.5 days per week. These detailed results are even more useful considering that they directly measure the Canadian context.

2.5 Chapter summary

Audirac & Fitzgerald (2003) identify two major schools of thought regarding the relationship between ICT and urban form. The first is that of “deconcentration”. This approach is based on neoclassical economic theories, such as the AMM model, and places great emphasis on substitution phenomena. The second is that of restructuring, which emphasizes the complementarity of ICTs and transport. In the latter, urban growth is then guided by the effects of transport demand induced by ICT. Agglomeration economies operate on location choices and urban centrality persists. The literature does not yet clearly elucidate which of these dynamics opposing dynamics yield a net result on the urban form. The following paragraph attempts to sum up the overarching picture that emerges from the review of literature on remote work in order to better understand how current contributions answer the question of if remote work causes sprawl.

The general sociodemographic profile of remote workers often aligns with a suburban lifestyle, yet this group exhibits considerable diversity. While the primary motivation behind adopting remote work does not seem to be the reduction of travel times, evidence strongly suggests an impact on travel patterns, including longer commute distances when travel is necessary, decreased travel during peak hours, a rebound in miscellaneous travel, and increased vehicle sharing within households. Over time, remote work may influence shifts in residential locations, though such changes manifest gradually. The preference of remote workers regarding their living environment remains ambiguous; while some might relocate further from their workplaces, it is not definitively clear whether they opt for denser urban settings or larger, more suburban homes. However, a tendency towards larger homes and single-family dwellings is noted. From an employer’s perspective, remote work facilitates access to a broader talent pool and enables relocation to more affordable areas, potentially encouraging polycentric urban development. Despite these observations, it remains unclear from the literature whether remote work contributes to urban sprawl. The various secondary effects observed, such as reduced congestion, employer relocation, and increased car usage for non-commute travel, could influence sprawl, yet direct measures are essential for a conclusive understanding.

CHAPTER 3

VARIABLES AND DATA

3.1 Theoretical framework and research question

The primary objective of this research is to explore the causes of urban sprawl, with a specific focus on how reduced transportation costs, stemming from the rise of remote work, influence the evolution and levels of urban sprawl across different cities, and within individual cities.

The study is anchored in urban economic theory, particularly the AMM model, which underscores the importance of factors such as population, income, agricultural rent, and transportation costs in shaping the density gradient of cities. Consequently, the control variables for this research have been chosen to reflect these key inputs of the AMM model. They are obtained from nationally comparable census data, while agricultural costs are sourced from a standardized national database. Transportation costs, a critical component of the AMM model, pose a challenge in terms of data availability, as well as measurability. Ideally, the perceived opportunity costs of travel times would be the ideal variable to be included. However, as is evidenced by section 1.5.5 of the literature review, this variable is notoriously difficult to measure and presents endogeneity problems due to the negative feedback loop produced by the interaction of sprawl and congestion. The study uses average travel times as a variable where feasible, although it does not delve into the evaluation of transportation infrastructure investments or of congestion costs, due to the lack of standardized data. The cost of gasoline is included as a proxy for transportation costs, given its perceptibility to drivers and availability in national databases.

To accurately measure urban sprawl within the scope of this research, the chosen response variable is the proportion of sparse homes. This decision is informed by several key considerations. First, while the ideal input for the AMM model would be the built-up land area, the data available from various Canadian national databases presents significant quality issues across different time periods. For instance, there are prevalent measurement errors in older land use files, leading to overestimations of built-up areas. These inaccuracies often arise from the inclusion of natural features such as water bodies, hills, or non-contiguous agricultural lands. Additionally, in some instances, the data is only available for specific years, like 2001 and 2011, limiting its usability for a comprehensive analysis. Secondly, focusing on a housing-related variable is particularly relevant in the context of remote work. Remote workers may have preferences for larger homes, and the proportion of sparse homes serves as an indicator of this trend. This aspect of housing aligns well with the study's emphasis on understanding how remote work influences urban sprawl. Furthermore, the proportion of sparse homes can effectively proxy for various facets of urban sprawl while maintaining simplicity and ease of accessibility in census data. Lastly, it has the advantage of reducing the bias that arises due to the choice of spatial reporting unit associated with more commonly used measures of density (Cutsinger et al., 2005; Lang, 2002). This variable, therefore, strikes a balance between relevance and practicality for the study.

The research question is centered around understanding both the 'Between' effects – how differences between cities impact the dependent variable, and the 'Within' effects – how changes in the explanatory variable over time influences the dependent variable, for the average city. In order to assess these effects, the research question is divided into two parts:

- **Does the Increase in the proportion of remote workers in a city result in an increase in sprawl?**
- **Do cities that have a greater proportion of remote workers sprawl more than their counterparts?**

Four hypotheses allow us to identify what can be observed to improve our understanding of the phenomenon:

- The decreased sensitivity to distance enables remote workers to locate farther from urban cores.
- Remote workers prefer larger dwellings because they require a workspace at home.
- These combined preferences for greater distances from the urban core and larger homes lead to an increased association between remote workers and sprawling development patterns.
- This will vary across cities based on initial shares of remote work, extent of sprawl and the distinct evolution of both.

Future sections of the thesis will examine the selected variables for econometric modeling in greater detail, providing justification for the chosen model in alignment with the research objectives and theoretical foundations.

3.2 Geographic reporting unit and temporality

"Geographical observations were conducted across 43 Canadian cities, encompassing 34 Census Metropolitan Areas (CMAs) and 9 of the largest Census Agglomerations (CAs)[4]. Data were collected for every census from the period of 2001 to 2021 to provide an overview of the evolution of homeworking and urban sprawl over two decades. For simplicity, both CMAs and CAs will be referred to as “cities” in the following sections.

Using CMAs and CAs as spatial units offers several advantages. Firstly, they provide clear and well-defined geographic boundaries that follow the same definition and that are not influenced by arbitrary political divisions. This ensures consistency and comparability across different regions. Furthermore, they tend to exhibit relative stability over different time periods, which is crucial when using panel data. By considering commuting flows, CMAs and CAs capture the economic interdependencies between residential areas and employment centers, facilitating an examination of the spatial implications of remote work. Finally, the data is readily available in the Canadian census, and does not require any geographic transformation. However, the use of CMAs and CAs has a notable limitation in that they do not consider isolated rural areas that may be attractive to remote workers that are no longer geographically bound to urban labor markets. This exclusion could underestimate the extent of urban sprawl in areas beyond the metropolitan regions. Therefore, it is impossible to measure the effect of Telemigration in the present study.

The cities of Red Deer and Abbotsford-Mission were removed because they consistently were identified as outliers with high-leverage values with large Cook distances in all the models[5]. This is most likely due to the fact that these cities contain almost no remote workers and had unusually high levels of sprawl. Abbotsford-Mission was particularly problematic because it is the city with the highest proportion of

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[4] CMAs and CAs are defined by Statistics Canada as "consisting of one or more adjacent municipalities centered around a population center, referred to as the core. A CMA must have a total population of at least 100,000, with 50,000 or more residing in the core. A census agglomeration must have a core population of at least 10,000. To be included in the CMA or CA, other adjacent municipalities must demonstrate a high level of integration with the core, as measured by commuting flows derived from previous census place of work data. Specifically, at least 50% of the employed labour force living in within the CMA or CA boundaries must work in the core" (Statistics Canada, 2014).

[5] High leverage points are observations with extreme values for predictor variables, potentially distorting the regression line's slope, whereas Cook's distance measures an observation's overall influence on the fitted values, combining both its leverage and the size of its residual to assess its impact on the regression model's predictions.

sparse homes, but also the only city that had a negative number of remote workers after the adjustment for agricultural workers was applied (details of this adjustment in section 3.3.2).

3.3 Variables

Sociodemographic variables were obtained from Statistics Canada Census data sets spanning two decades (Statistics Canada, 2001, 2006, 2011, 2016, 2021). Population and age data are collected from the short form of the census, which covers the entire Canadian population. Data for income, housing type, commute time and remote work variables are derived from the long form (Questionnaire 2B) of the census for the years 2001, 2006, 2016 and 2021. For 2011, data comes from the National Household Survey (NHS) a similar questionnaire with some differences in terms and classification of information. In 2001 and 2006, Questionnaire 2B data is gathered from a random sample representing 20% of the population. The NHS sample size is increased to 30% for that year. In cases where the non-response rate reaches or exceeds 25% for a category, all data is deleted for the voluntary census of that year. In 2016, Statistics Canada reintroduces the detailed questionnaire (2B) with mandatory participation, using a sample size of 25%.

3.3.1 Dependent variable: sparse housing

Following the definition outlined by Turcotte (2008) and used by Tanguay and Gingras (2012) and Young et al. (2016), this variable represents the proportion of occupied private dwellings classified as single-family, semi-detached and moveable dwellings (which includes mobile homes, houseboats and railroad cars) and is obtained from the 100% sample of census data. Statistics Canada defines single-family homes as “single dwellings that are completely isolated on all sides, including single dwellings linked to other dwellings below ground. Included are bungalows, split levels, two-storey single-family homes built by conventional methods or prefabricated”. Semi-detached homes are defined as “One of two dwellings attached side by side (or back-to-back) to each other, but not attached to any other dwelling or structure (except its own garage or shed). A semi-detached dwelling has no dwellings either above it or below it, and the two units together have open space on all sides”. Considering that the vacancy rate for Canadian cities varies around an average of 1.9% to 3.8% during the study period (Statistics Canada, 2023), and that this variable only considers occupied dwellings, it is possible that the proportion is slightly underestimated for cities with a large stock of sparse homes, and overestimated for cities with a lower stock.

These sparse housing types are more likely to feature backyards, have a larger geographic footprint, and are often located in suburban or peripheral areas. These characteristics make them a more reliable indicator for urban sprawl compared to population density, as the boundaries of CMAs often include undeveloped and agricultural lands which can bias measurement[6]. Although this indicator combines housing types representing various socio-economic statuses, its sole purpose is to measure built-up density.

3.3.2 Explanatory variable of interest: Percentage of remote workers in the workforce

This variable is calculated as a percentage of remote workers in the labor force of employed individuals aged 15 to 64[7]. Self-employed or unpaid workers for a household member's company or professional practice are included, as well as people who held a job a job but were absent due to sickness, disability, family, vacation, or a strike. Respondents who changed jobs over the year had to consider only the one they worked at during the census reference week. The most-worked place of employment was to be reported by those with several jobs. In order to be classified as a remote worker, a respondent must have answered ‘’Worked at home’’ to the long form census question #42: ‘’At what address did this person usually work most of the time?’’. The formulation ‘’most of the time’’ is open to the respondent’s interpretation and may exclude certain part-time remote workers. However, it is possible to assume that respondents who spend at least half of their work hours at home are considered remote workers. This also implies that respondents who do commute 49% of the time or less may be considered remote workers.

In order to refine the Remote Work variable, a transformation was implemented to exclude agricultural workers. The rationale for this is that agricultural workers that live on their own farms have specific spatial

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[6] Census based metropolitan regions can upwardly bias certain sprawl indicators as they usually include large tracts of rural land at the fringe, which may upwardly bias sprawl indicators (Cutsinger et al., 2005; Lang, 2002). For example, many CMAs with smaller populations exhibit boundaries of comparable size to those with larger populations. This phenomenon can be attributed to the relatively lower congestion levels in the smaller CMAs, thereby increasing the catchment area of their commuter flows which Statistics Canada uses are used to define their boundaries. For this reason, the population density of smaller CMAs is considerably underestimated when using density indicators, which divides the population or employment by the land area.

[7] The employed are persons having a job or business, whereas the unemployed are without work, are available for work, and are actively seeking work. Together the unemployed and the employed constitute the labor force. Persons not in the labor force are those who, during the reference week, were unwilling or unable to offer or supply labor services under conditions existing in their labor markets, which includes persons who were full-time students currently attending school (Statistics Canada, 2021

constraints as they are tied to the large tracts of agricultural land they operate on, resulting in considerable land consumption and a residential location on the urban periphery. Consequently, such circumstances give rise to a strong correlation between them and land use patterns that may be attributed to sprawl; however, it is essential to note that farmland does not truly epitomize sprawl in practice. The calculation involved subtracting the number of respondents classified in the occupation of "Natural resources, agriculture and related production occupations, except management" from the total number of respondents who worked from home. This also includes middle managers, supervisors, workers, and laborers involved in agriculture, harvesting, landscaping, mining, fisheries, forestry and related production occupations. However, the non-agricultural job descriptions in this list are typically performed on-site in rural or natural areas well beyond the boundaries of CAs or CMAs. Therefore, the proportion of remote workers is expressed as: (Remote workers – Natural resource and agricultural workers) / Population*100.

While this exclusion may lead to the possibility of omitting farmhands and other workers who do not reside on the land they work on, the error incurred from excluding agricultural workers is significantly smaller compared to the error introduced by including them. The individuals classified under the aforementioned occupations represent only 1.4% of the total population of the dataset. However, according to Turcotte (2010), 48% of agricultural workers engage in remote work, which is the highest rate among all professions.

In Abbotsford and Red Deer, there are only a few hundred remote workers alongside a notable presence of agricultural or natural resource workers. Therefore, the above transformation leads to an underestimate of the prevalence of remote work in these cities, which was apparent by their consistent identification as outliers in the initial models. For this reason, they were excluded from the dataset.

The hypotheses in section 3.1 collectively suggest that the prevalence of remote work is anticipated to be associated with an increase in sparse homes.

3.3.3 Control variables

3.3.3.1 Population

This variable refers to the number of individuals whose permanent address falls within the boundaries of the CMA or CA. This variable doesn't include individuals who have secondary homes in the city, which also play a role in shaping the urban landscape. Following the AMM model, we expect that larger populations and greater growth will be associated with more sprawl when measuring effects within cities. However, because larger cities tend to have higher density cores, we expect a negative relationship with sparse housing when measuring between-city effects.

3.3.3.2 Median household income

Statistics Canada defines this variable as the sum of income receipts from various sources for all members of the household, before accounting for income taxes and deductions, during the entire reference year. This variable is specifically chosen over other income categories because the household, as a collective entity, plays a crucial role in determining residential location decisions and the level of housing consumption. To ensure accurate comparisons, the variable is computed in real terms in 2021 dollars using the annual average Canadian Consumer Price Index (CPI). Additionally, the variable is lagged by one year in the census, meaning it reflects the declared revenue amounts from the year prior to the census. This lag serves a beneficial purpose in this study, as it helps account for the time required for residential location decisions to take effect. Following the AMM model, higher incomes are expected to be associated with sprawl in both the within and between city measurements.

3.3.3.3 Commute times

In the Canadian census data, there are notable limitations and variations in the travel time statistics across different years. For the years 2001 and 2006, there are no statistics available for travel time. However, commute distance data is available for these years, though it does not serve as an ideal measure of transportation costs due to the varying time taken for long distances depending on the mode of travel. In 2011, the census introduced a median travel time variable, but this data was only aggregated at the Census tract level, not at the broader CMA or CA levels. Furthermore, in 2016, the nature of the travel time variable was altered to a categorical format, which hinders the ability to make direct comparisons across all the time periods.

Despite these challenges, for the years 2016 and 2021, where the categorical variable is available, it was included in cross-section models. This variable, is defined by Statistics Canada the “commuting duration for the employed labour force aged 15 years and over in private households with a usual place of work or no fixed workplace address” and is categorized into four time-intervals: 15 minutes, 30 minutes, 45 minutes, and 60 minutes. In alignment with Marchetti's theory, the analysis focused on the proportion of the active population with a commuting duration exceeding 45 minutes. This approach was adopted to examine the impact of high transportation costs as a deterrent to urban sprawl. In accordance the AMM model, this variable is expected to yield a negative association with sprawl in both the within and between city analysis.

3.3.3.4 Gas price

This variable was created by calculating annual averages from the monthly average retail prices for regular unleaded gasoline at self-service filling stations, using data available from Statistics Canada (Statistics Canada, n.d.). All prices are adjusted to 2021 dollars by using the annual average Canadian Consumer Price Index, and are expressed as cents per litre. To account for the time required for prices to influence residential location decisions, a one-year lag is incorporated. Statistics Canada typically selects the largest cities in each province as reference points for their gas price data, therefore when data is absent, the available price from the closest city within the same province is used as a substitute. Consequently, this approach may result in an upward bias in gas prices for smaller cities, as larger urban centers generally have higher fuel prices compared to smaller ones. This variable is expected to be negatively associated to the sprawl variable in both within and between city analysis.

3.3.3.5 Farmland value

The variable representing agricultural land prices is obtained from the Historic FCC Farmland Values Report 1985-2022 (Farm Credit Canada, 2023). The average value and sales price of benchmark properties are used to calculate average values per acre. These properties are chosen by the FCC to be representative of the observed agricultural regions. The variable incorporates a one-year lag to account for land development time, as well as being adjusted to 2021 dollars by using the annual average Canadian Consumer Price Index (CPI).

However, it is important to note a limitation of this variable. In cases where a city was surrounded by multiple agricultural regions, each with its own distinct farmland price per acre, an average price across these regions was calculated. This averaging method, while necessary, may reduce the precision of the data for cities bordering multiple agricultural areas. Additionally, the averaging of prices across large regions may not accurately reflect the agricultural land prices in proximity to cities. In particular, the variable may underestimate prices in prime agricultural areas near waterbodies, which often host large cities. Furthermore, it does not consider the amount of arable land contiguous to urban development, meaning cities with less agricultural land near their borders are less influenced by the price of agricultural land compared to cities entirely surrounded by such land. It is also important to mention that Kamloops (2000-2011), Kelowna (2000-2016) and St John's (entire study period) have no such values. In order to create a balanced panel, the values for Kamloops and Kelowna were estimated. The estimation process involves utilizing the "Historic national average % change in farmland values" table from the report, specifically focusing on the percent change data for British Columbia. By considering the available prices for these two cities, it becomes possible to assess the accuracy of the calculation for the NA values. The Kelowna estimate is off by 0.2%, whereas the Kamloops estimates are off by 4.8%, 9.7% and 14.1%. The farmland prices for the city of St. John's were obtained from Pictou-Antigonish, which is the easternmost farmland region of Nova Scotia. This variable is expected to be negatively associated with sprawl in both within and between city measurements.

3.3.3.6 Geographic constraints

This variable represents the percentage of land within a 25 km range of the city center[8] that is difficult to develop due to the presence of waterbodies or extreme slope gradients. The city hall of a given city is used as the center point to calculate a 25 km buffer in QGIS[9]. For CMAs comprised of multiple distinct cities with their own respective center, the city hall for the largest city was used.

Slope and water files were obtained from Canada’s Open Government data portal (Government of Canada, 2013). Following Saiz (2010), waterbodies were included by using the 2011 Lakes and Rivers and Coastal Waters shapefiles. Only water bodies with a surface area greater than 10 square kilometers were kept for analysis, thereby removing small ponds and narrow streams. The polygons were then converted to a 250 X 250-meter pixel raster file and counted within the buffers using the QGIS zonal statistics tool. Slope

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[8] A 25 km radius was used to strike a balance among various methods and to adjust for the smaller urban footprints of Canadian cities compared to those in the American and global studies. Saiz (2010) limited the analysis to land within a 50km radius of the central city, Angel et al. (2010) use a radius calculated as four times the size of the city's urbanized area as of the first year in the dataset, while Paulsen (2014) focused on the entire metropolitan area without specifying a radius. Paciorek (2013) additionally subtracted the land with a slope greater than 15% from the total land area of each MSA's component counties to derive a measure of developable land.

[9] This was done using the ESPG: 3347 - NAD83 Statistics Canada Lambert projection for all cities but St John’s, which used EPSG: 32621 WGS 84 / UTM zone 21N in order to reduce warping.

calculations were performed using the Canadian Digital Elevation Model 1945-2011 (CDEM), provided by Natural Resources Canada (NRCan)[10]. The GDAL slope tool in QGIS 3 was utilized to convert the CDED files into Geotiff raster format, enabling the calculation of slope as a percentage using Horn's formula. Only pixels containing slopes equal to or greater than 15% were retained for further analysis. This threshold was selected based on previous research that examined the effects of topography on urban development (Angel et al., 2010; Paciorek, 2013; Paulsen, 2014; Saiz, 2010). This variable will only be present in the between analysis and is expected to yield a negative relationship with sprawl.

3.4 Descriptive statistics

Table 4 Descriptive statistics

Variable	Variance measure	Mean	SD	Min	Max	Expected sign
Sparse housing	overall	63.8	10.3	32	80.4	
(%)	between		10.2	37.5	76.9	Y
	within		1.8	-6.3	8.1	
Remote Work	overall	3.7	1.6	0	7	
(% in workforce)	between		1.5	0	6.6	-
	within		0.4	-1.1	1.3	+
Population	overall	537,339	996,414	60,264	5,928,040	
	between		1,000,688	65,382	5,326,788	-

---

[10] The CDEM dataset uses a base resolution of 0.75 arc-seconds in the North-South direction, and between 0.75 and 3 arc-seconds in the East-West direction. To ensure consistency in units, each CDEM file was reprojected to ESPG: 3347 - NAD83 Statistics Canada Lambert, converting the horizontal unit from degrees to meters.

	within		95,040	-643,891	601,253	+
Median HH Income *($ per household)*	overall	74,186	10,860	53,388	111,382	
	between		9,864	55,225	97,663	+
	within		4,728	-13,771	15,844	+
Gas price *(cents per litre)*	overall	119.15	10.3	94.3	140.1	
	between		6	105.1	128.8	-
	within		8.4	-24.8	12.7	-
Farmland value *($ per acre)*	overall	5,922.27	8,940	472	69,689	
	between		8,069	884	50,555	-
	within		3,995	-27,548	19,134	-
Geographic constraints *(% in 25km radius)*	overall	16.8	17.8	0	65	
	between		17.8	0	65	-
	within		0	0	0	

Source: Statistics Canada

Table 4 displays the different descriptive statistics for the variables. The dataset is comprised of 43 cities and 4 time periods, for a total of 172 observations. The "overall" measure calculates statistics for the entire dataset without accounting for the panel structure. This provides the mean, standard deviation, and the range of values observed across all 172 observations.

The "between" measure focuses on comparisons between different cities, while omitting the effect of time. The statistics for each variable are calculated using the mean of the four time periods for each city. Therefore, this measure reports the range and standard deviation of $\bar{x}_i$, indicating how much these cities differ from one another.

Finally, the "within" measure examines variability within each city, ignoring differences between cities. It examines how individual observations for each time period diverge from their respective city's mean, calculated as x_{it} - $\bar{x}_i$. Consequently, the range reports the minimum and maximum deviations from the city-means across the dataset. To calculate the standard deviation, these values are squared and summed, then divided by the total number of observations minus one (171), facilitating comparisons between the dispersion of "within" statistics and those of the "between" and "overall" measures.

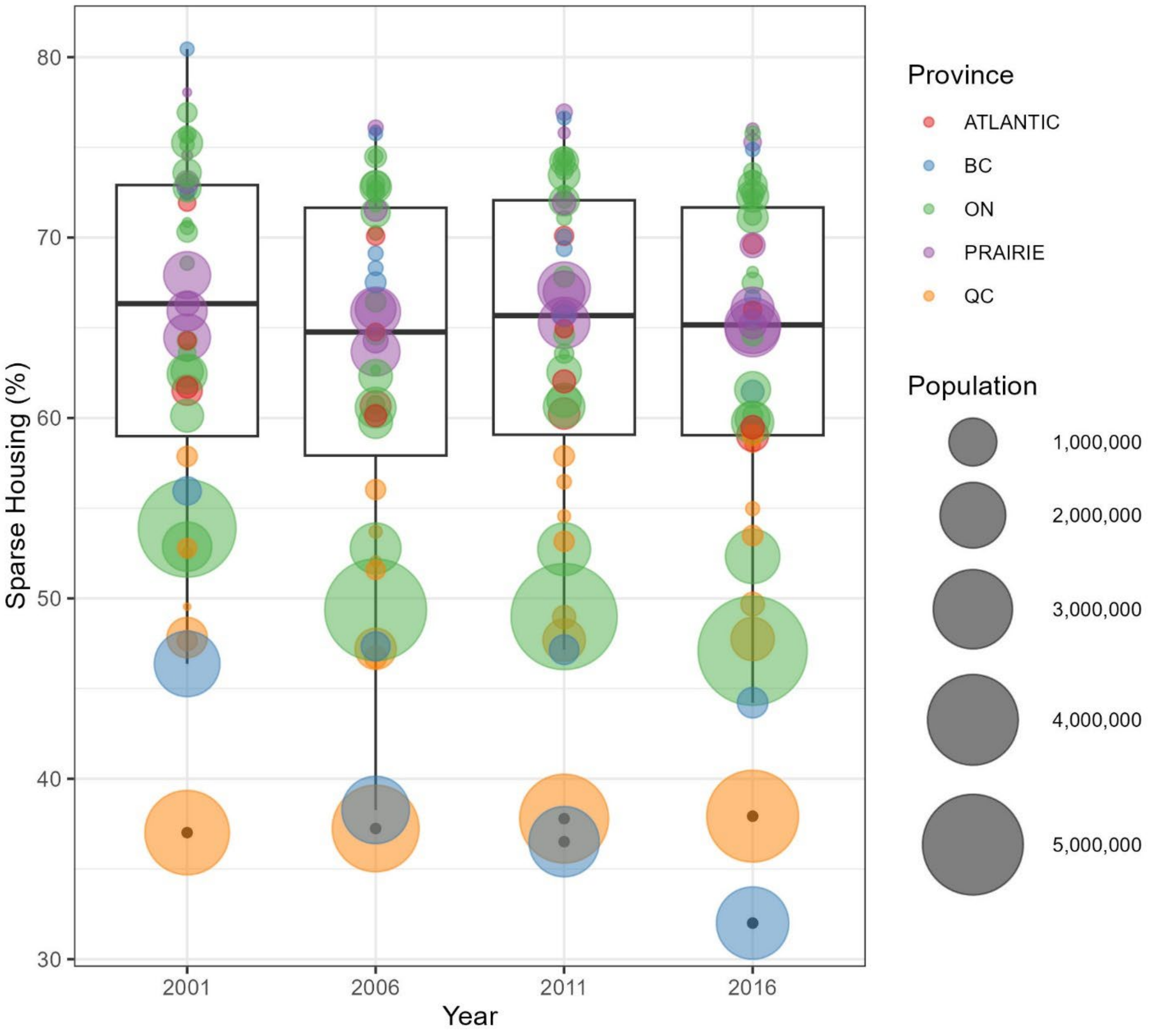
3.4.1 Sparse housing

Table 4 shows that the diversity in the proportion of sparse homes across the dataset is high, as indicated by the range extending from 32% to 80.4% and the standard deviation of 10 percentage points (SD = 10.3).

The variation between cities (SD = 10.2) closely matches the overall variation, whereas the variation within cities is markedly smaller (SD = 1.8). This suggests that differences in sparse housing are much more pronounced between cities than within them over the observed periods. As depicted in Figure 4, the mean value of sparse housing over the 15-year period exhibits little change, remaining close to the dataset's mean of 63.8%. Nonetheless, it traces a slight downward trajectory, suggesting an increase in the intensification of development over time.

Further analysis of Figure 4 reveals certain patterns. As expected, the smallest cities are located in the upper quartile, likely due to their reduced CBDs. Many medium-sized cities from Ontario, also occupy the upper half of the distribution. Membership in the Golden Horseshoe planning region does not seem to influence the distribution of Ontarian cities either, with five greenbelt cities in the upper half and four in the lower half. The lower quadrant is predominantly occupied by cities from Quebec, highlighting a provincial disparity. The three largest cities are situated in the lower quartile, supporting the notion that higher populations foster a greater proportion of dense development. Meanwhile, the major prairie cities, which are also large population centers, are grouped near the mean, converging towards it as time progresses.

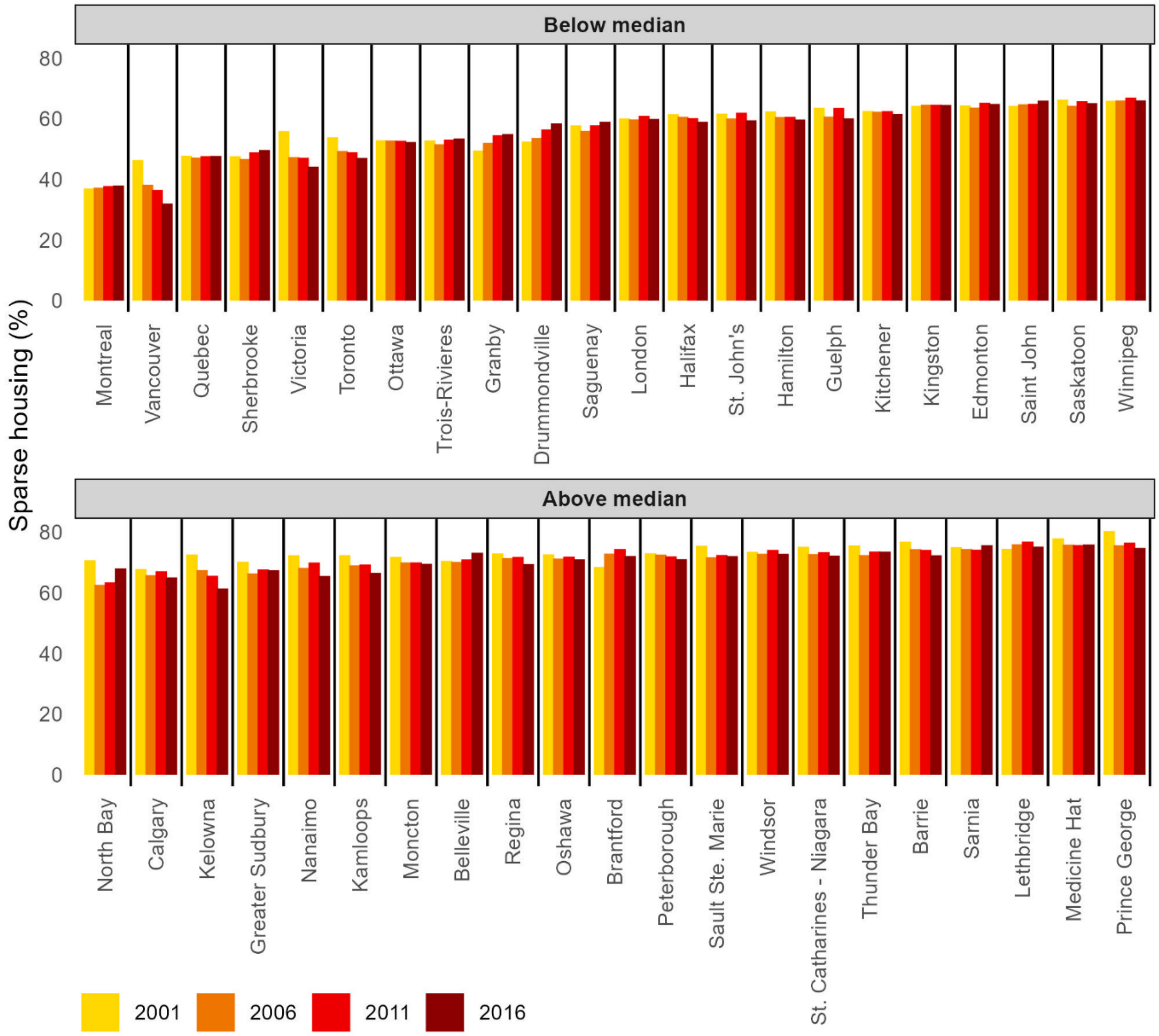
Figure 4 Evolution of sparse housing



Source: Statistics Canada

Figure 5 provides a more detailed picture of each individual city, highlighting the stark difference in within-city and between-city variation. A fair number of cites experienced a sharp decrease in the proportion of sparse housing between 2001 and 2006. This trend is particularly pronounced in British Columbia, where cities such as Vancouver, Victoria, and Kelowna exhibit substantial declines, but it also extends to Toronto. These steep declines signal an urban development characterized by marked intensification within a short period of time. Moreover, most cities experience a slow but steady decline in the sparse housing, indicating a broader shift towards denser urban living. Despite being in the lowest quartile, the cities in Quebec provide an exception to the densification trend. Notably within the cities of Sherbrooke, Granby, and Drummondville, which all display the highest increases in sprawl among the dataset.

Figure 5 Proportion of sparse housing across cities

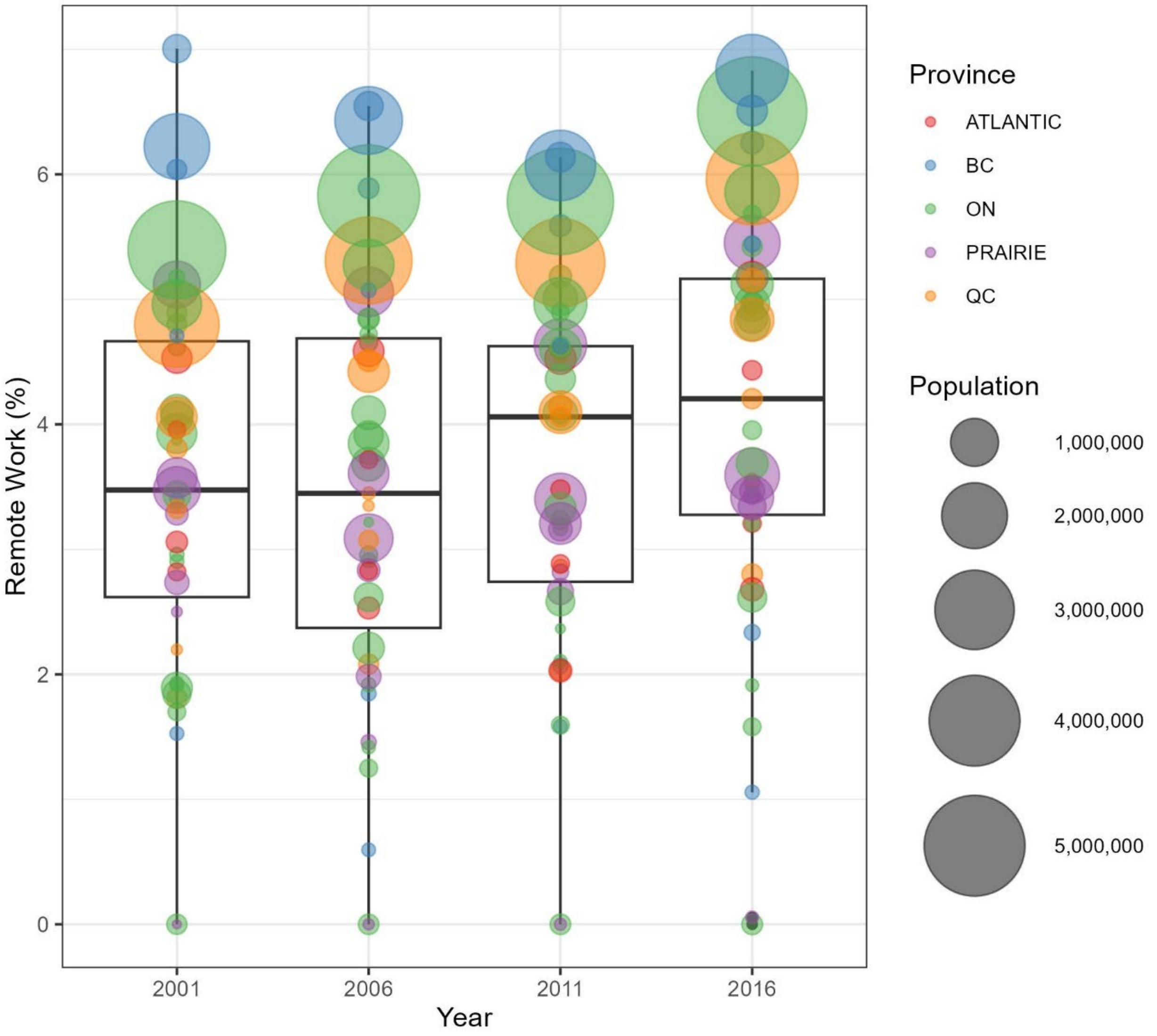


Source: Statistics Canada

3.4.2 Remote work

The “overall” statistics in Table 4 show that the percentage of individuals working from home ranges from 0% to 7%, with a mean of 3.7%. Considering this small range of values, the standard deviation of 1.6 percentage points (SD = 1.6) suggests sizeable degree of variability in the proportion of individuals working from home. However, most of this variation is to be found between cities (SD = 1.5), whereas variation within cities is relatively low (SD = 0.4). Figure 6 presents an almost mirror image to that of the evolution of sparse housing.

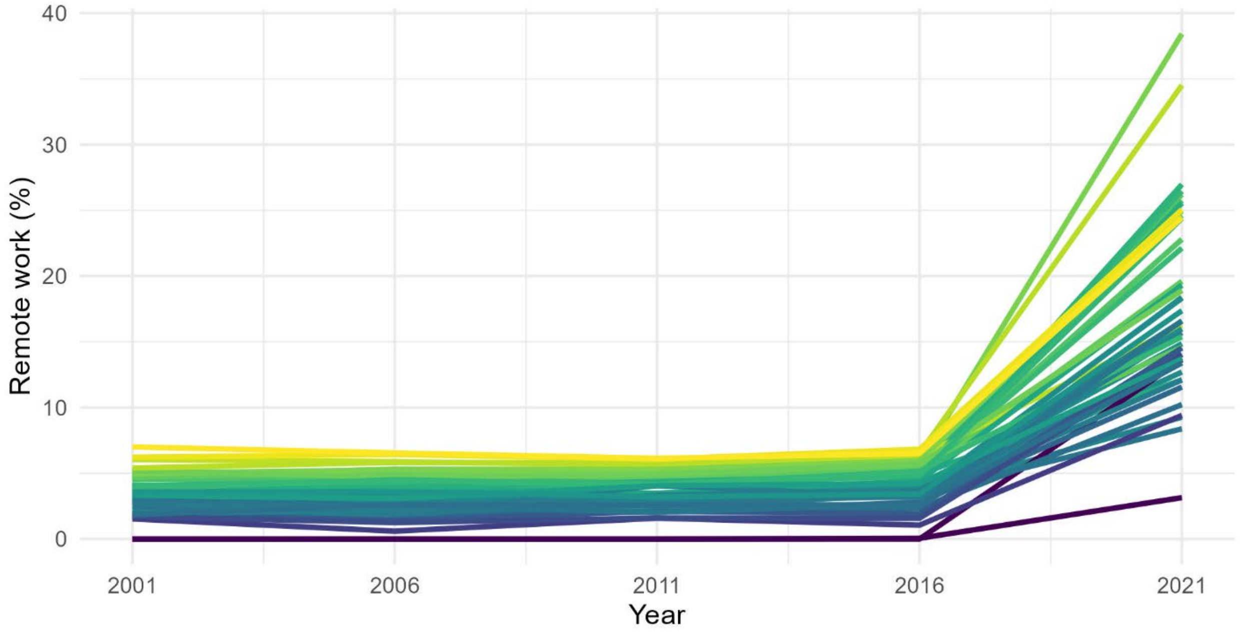
Figure 6 Evolution of Remote work



Source: Statistics Canada

As expected, figure 6 shows that the biggest cities are found in the upper half, while the smallest cities occupy the lower half, indicating that remote workers gravitate towards larger urban centers. Prairie cities, which were originally centered around the mean in 2001, have gradually descended towards the lower quartile. Calgary, however, is a notable exception, as it remains in the upper quartile throughout the entire time period. The distribution across provinces is much more heterogeneous, with no province clustering in a particular quartile. Figure 6 also shows a gradual increase of remote work adoption over time, with a notable upward shift of the mean starting in 2011.

Figure 7 Evolution of Remote work with COVID-19 pandemic years



Source: Statistics Canada

Figure 7 illustrates the evolution of the proportion of remote workers over time, incorporating data from the 2021 census. Each line represents one individual city, and the color scale is based on their mean remote work value for the 2011 to 2016 period. This figure highlights how the prevalence of remote work and the rankings among cities underwent considerable changes due to the COVID-19 pandemic's impact. Cities previously known for high remote work rates did not necessarily maintain their leading positions, and those with low rankings did not consistently remain at the bottom. The combined effects of this shift in ranking and dramatic surge in remote work represents a structural break that will inevitably bias the estimation of within-city variation, motivating the exclusion of 2021 in the panel model (see the discussion on non-stationarity in Baltagi, 2021: p337-339).

3.4.3 Control variables

3.4.3.1 Population

Table 4 reveals that population figures vary considerably in the overall dataset (mean = 537,339; SD = 996,414), with an even more substantial difference between cities (SD = 1,000,688) but much less variability within cities over time (SD = 95,040). The smallest observation in the dataset is Granby, which had a population of 60,264 in the year 2001. The largest is Toronto, with a population of 5,928,040 in 2016.

3.4.3.2 Median household income

Table 4 shows that income has an overall mean of 74,186$ and a standard deviation of 10,860, with between-city variation (SD = 9,864) again surpassing within-city variation (SD = 4,728), reflecting economic disparities across cities more than economic changes over time. Notably, almost every city has displayed income growth over the fifteen-year time period.

3.4.3.3 Gas price

Table 4 indicates that Gas Price has an overall mean of 119.2 cents with relatively low variability (SD = 10.3), but the within-city variation (SD = 8.4) is almost as dispersed as the between-city variation (SD = 6.0), suggesting that gas prices fluctuate greatly over time. The minimum yearly average price for regular unleaded gasoline is of 94.29 cents per litre, while the maximum is 140.12 cents. The resulting range is of 45.83 cents. Its important to consider that gas prices were only available for 14 of the 43 cities investigated in this study, representing 32% of the dataset. Since the gas prices of these cities were copied into their closest geographic relatives in order to obtain prices for all observations, this means that the distribution of the variable has been fairly leveled for the dataset. Thus, the true variability across time and geography is not adequately represented in this variable.

3.4.3.4 Farmland values

Table 4 shows that agricultural land values per acre range from $472 to $69,689, a colossal difference of $69,217. The lowest values are found in the Prairies around cities like Regina and Saskatoon, whereas the coast of British Columbia boasts the most expensive values. Vancouver, Nanaimo and Victoria are thus located in proximity of the richest agricultural land of the country. The overall mean of $5,922 and a high standard deviation of 8,940, shows extreme variation across the dataset, especially between cities (SD = 8,069). Although lower, within-city variation is still considerable at $3,995. It is important to note that Abbotsford, which had the highest farmland value per acre of all Canadian CMAs and CAs was considered an outlier and thus removed from the dataset.

3.4.3.5 Geographic constraints

As noted in Table 4, the geographic constraints variable is the only one that does not have within-city variation, as the natural landscape does not change over time. The proportion of land occupied by a constraint range from 0 to 65%, with a mean of 17.8 %. The standard deviation of 17.8 percentage points indicates a high variability, the presence of the Rocky Mountains around the western cities being the biggest influence on regional differences.

3.4.3.6 Commute Times

Commute times are not included in Table 4 for the simple reason that this variable was only available for the periods of 2016 and 2021, and was subsequently not retained for the within-city analysis.

CHAPTER 4

METHODOLOGY

4.1 Model selection

4.1.1 Cross-section models

To investigate the between-city impact of the variables for individual census, we first run cross-sectional Ordinary Least Squares (OLS) regression for each year, including 2021. The primary objective of this analysis is to observe the year-by-year effects in order to determine if certain periods were more influential than others, and to compare the effects between cities. It also serves to examine the data for 2021 in order to assess the effects of the pandemic, and to test the commute time variable for 2016 and 2021. This multiple cross-sectional analysis compares the effects of each independent variable on urban sprawl across cities, for each given year. However, since this approach is limited to city-to-city comparisons, it fails to account for how changes in the variables within each city affects urban sprawl over time. Therefore, it cannot discern whether the greater prevalence of remote workers in certain types of cities is due to reasons unrelated to this analysis, such as the presence of economic opportunities aligned with their work practices, or whether it is the remote workers themselves who are driving changes in urban form due to their specific lifestyles. Consequently, panel regression models are employed to analyze the temporal evolution of sprawl.

4.1.2 Panel model setup

Given the available time sequence, we can investigate how changes in the predictors influenced the response variable, providing clearer insights into the causality of these relationships. The 2021 year is excluded from the panel analysis as the pandemic adds too much variation in the remote work variable that is not consistent with the previous years. This creates an important structural break that would lead to biased and inconsistent estimates if included in the panel models (Baltagi, 2021: p337-339). The data can be considered a macro panel, as it is composed of a moderate number of entities collected over long periods of time, in this case 20 years. It is also a balanced panel; each city appears in every time period.

4.1.3 Fixed effects models

Panel data offer several benefits, including the ability to take advantage of the increased variability offered by an enlarged dataset for more efficient estimation, to examine how the dependent variable responds to changes in predictors over time, and to remove the unobserved invariant characteristics—specific to cities or time periods—that cause endogeneity (Baltagi, 2021: p 6-9). Omitted variable bias arises when the error term of a model includes unobserved factors that affect the response variable and that are correlated with the predictors, leading to potentially incorrect estimations. Due to the complexity involved in calculating variables for regulatory environments, fiscal policies, and the broader dynamics of transportation, these city characteristics were not incorporated into the models. Nonetheless, existing literature suggests a correlation between these factors and certain predictors used in this study. This association is further substantiated by a Hausman test which indicated a significant relationship between the model's error terms and the predictors (see Appendix C). It should be emphasized that while certain of these unmeasured characteristics may have remained constant over time, there is a possibility that they have undergone at least some degree of change during the 20-year period under observation.

A popular way to address this problem of unobserved heterogeneity is with a one-way error component model, which can be written as:

$$y_{it} = \beta x_{it} + c_i + u_{it} \tag{1}$$

Where :

- y is the dependent variable.
- i is the entity (city).
- t is the time period (census year).
- β are the coefficients to be estimated.
- x_{it} is a vector of predictors for city i at time t.
- c_i is the entity-specific latent variable for city i.
- u_{it} is the idiosyncratic error for city i at time t.

This approach decomposes the error term into two components: the first is the idiosyncratic error (u_{it}), unique to each observation and varying across both cites and time periods; the second is the latent variable (c_i), specific to each city but constant over time. The latter represents the unobserved heterogeneity that can be accounted for with a type of one-way error component model named the fixed effects (FE) model (Baltagi, 2021: p 16; Wooldridge, 2002: p 251-252).

The main feature of the FE model is its ability to remove the unobserved heterogeneity (c_i), which ensures reliable estimates for the coefficients. However, we then estimate only the changes that occur within entities over time. The conventional method for accomplishing this is by executing a "within" transformation to the data. In our case, this is done by taking the average value of a variable over time within each city and then subtracting this average from the variable's value in each respective time period. This procedure, known as “time-demeaning,” effectively eliminates the influence of characteristics that remain constant over time, including the unobserved time-invariant heterogeneity (Wooldridge, 2002: p267-269). This can be written as:

$$y_{it} - \overline{y_i} = \beta(x_{it} - \overline{x_i}) + (u_{it} - \overline{u_i})$$

(2)

Where:

- y_{it} is the dependent variable for city i at time t.
- y_i is the average of the dependent variable for city i over time.
- β is the coefficient to be estimated.
- x_{it} is a vector of predictors for city i at time t.
- $\overline{x_i}$ is the mean of the predictor for city i over time.
- u_{it} is the idiosyncratic error for city i at time t.
- $\overline{u_i}$ is the average of the idiosyncratic error for city i over time.

This has removed all time-invariant elements from equation (1), including the latent variable (c_i). The transformed data can then be pooled and estimated with OLS (Woolridge, 2002: p267-269). This is the technique employed in the *plm* package for R, used to calculate our models (Croissant & Givanni, 2018).

In order to estimate the average between-city variation over the entire time period, it is also possible to estimate a “time” FE model that instead removes variables that vary in time, but remain constant across cities. This can represent economic shocks, policy implementations or historical events that would affect all cities in equal measure, at a given period in time. One example in the context of this research is the changes in the national interest rate, which affect the housing market. The Time-FE approach employs a mean-centering technique, and its coefficients are interpreted as differences between cities, as opposed to changes over time within cities (Kropko & Kubinec, 2020).

The FE model faces limitations due to its exclusive focus on variations within clusters, reducing the variance of the predictors and potentially overlooking significant relationships, particularly when the variable of interest, such as remote work, shows limited variation over time (Hill et al., 2020; Mummolo & Peterson, 2018). Additionally, the omitted variables that cause unobserved heterogeneity are not necessarily time-invariant. For example, the regulatory and fiscal environments are susceptible to change. This makes the evaluation of both a within-city and between-city model more advantageous as it offers a comprehensive picture, capturing both within and between city variations and overcoming the FE model's limitations in assessing time-invariant variables (Bell et al., 2019; Bell & Jones, 2015).

4.2 Assumption tests

4.2.1 Tests for OLS models

For each dataset in the OLS models, the Variance Inflation Factor (VIF) consistently showed values below a threshold of five for all predictors, indicating no concerns of multicollinearity. Residual normality was affirmed across datasets through various methods, including Shapiro-Wilk test as well as histogram and Q-Q plot visualizations. Each dataset demonstrated homoscedasticity of residuals, supported by p-values from the Breusch-Pagan test consistently above the 0.05 threshold and visual inspection of the data (See appendix A).

Cook's Distance analysis revealed some influential data points in each dataset, with varying percentages of observations exceeding the 4/n threshold and fewer surpassing higher thresholds of 8/n. Fox (2019) endorses a prudent approach to setting numerical thresholds, emphasizing the importance of visual examination. His work advocates maintaining data points in analysis if these outliers are not data errors, but rather unusual observations that are part of the natural variation of the dataset. Cook distances and leverage values were plotted for each time periods to identify of outliers (see appendix B).

Table 5 Outliers and influential observations

Year	4/n obs.	Influential observations at 4/n	Outliers identified at 8/n
2001	13.95%	Granby, Guelph, Kelowna, Moncton, Ottawa, St-Catharines-Niagara	Ottawa
2006	9.30%	Guelph, Kelowna, Moncton, Nanaimo	-
2011	9.30%	Medicine Hat, Prince George, Vancouver, Victoria	Vancouver
2016	18.60%	Guelph, Kelowna, Medicine Hat, Prince George, Vancouver, Victoria, St-Catharines-Niagara, St John's	Prince George

Source: Author's calculations

Table 5 presents the results of this analysis. The total percentage of cities exceeding the 4/n threshold is noted; however, none of these were confirmed as outliers in the plots. The cities identified as outliers through visual examination were all recorded at the 8/n level. The analysis shows that although cities such as Guelph, Kelowna, and Prince George consistently emerge as influential observations, the majority of influential cities vary across different time periods. Additionaly the standard 4/n threshold does not seem to translate into strong outliers upon visual inspection of the plots, indicating it may not be adequate for this dataset. Although robust regression diminishes the influence of outliers without necessitating their removal, the aim of this research is to develop a model that captures the general trend in the data, including the effects of outliers. This inclusion is based on the premise that outliers are not mere anomalies, but rather indicators of a distinct phenomenon. Considering that the outliers exceeding the 8/n threshold vary across different time periods, and given the unrealistic possibility of excluding major cities such as Vancouver and Ottawa, these outliers were retained. Consequently, a robust regression framework was not employed in this analysis.

4.2.2 Tests for panel models

Several tests were conducted to validate the assumptions and model choices. First, a Breusch-Pagan Lagrange Multiplier test was used to compare pooled OLS with FE and indicated significant differences across units. This result suggests a panel effect and supports the use of FE. Similarly, a Chow test for the "poolability" of the data concluded that the coefficients are not stable across the panel, further recommending FE. The aforementioned Hausman test showed evidence of correlation between the error term and the predictors, thereby rejecting the use of classic random effects model. Results from two F test indicate evidence for effects that vary within entities but are common across time, and for effects that are common across entities but vary with time. This validates the use of both City-FE and Time-FE models. However, a Breusch-Pagan Lagrange Multiplier applied to the case FE model instead suggests that there is no significant evidence of effects that are consistent across cities and vary over time. This finding implies that the time FE approach might not be essential for removing case-invariant unobserved heterogeneity (see appendix C).

To adhere to the assumptions of the FE models, it is necessary to ensure there is no multicollinearity among the predictors, this was ensured by the previous VIF tests applied to each cross-section. Furthermore, the error terms must be independent of the predictors for each time period, exhibit homoscedasticity, and lack serial correlation that can potentially lead to underestimated standard errors (Wooldridge, 2010: p300-307). Following recommendations by Baltagi et al, (2009), an Angrist–Newey test was used to assess the validity of FE assumptions and found that the within specification applies. An Augmented Dickey-Fuller Test, applied to the variable of sparse homes, showed that the data is stationary, which is essential to ensure consistency of the models (Baltagi, 2021: p94). A Breusch-Godfrey/Wooldridge test and Wooldridge's test revealed the presence of serial correlation, consistent with the literature review that identifies sprawl as a phenomenon driven by path dependencies. Finally, a Breusch-Pagan test indicated homoscedasticity of residuals, supporting the assumption of constant variance across time in the idiosyncratic errors. However, the p-value for this test was of 0.09, and visual inspection of the plotted residuals did suggest patterns of non-constant variance and the lower and upper-end of the graph for a few observations (See appendix C). These findings highlight challenges of serial correlation, and potential heteroscedasticity, calling for the use of panel-robust standard errors (Wooldridge, 2002, p. 55-58). Thus, a model was calculated using *vcovHC* function for R and specifying for the Arellano method (Arellano, 1987). The use of robust standard errors not only corrects for the violated assumptions but also serves as a diagnostic tool to identify any underlying issues in model specification, as indicated by the presence of any disparity between robust and classical standard errors (King and Roberts, 2015). Due to the uncertain nature of the heteroscedasticity, and considering that the robust standard errors closely resembled the classic standard errors, robust standard errors were applied in the City-FE model. It is noteworthy that there is only a slight change in the standard errors of this model when employing a robust specification.

Nonetheless, this subtle adjustment is sufficient to elevate the significance of the remote work variable from a p-value of 0.07 to 0.03, making it significant once the robust standard errors are applied.

Following Fox (2019), outliers were also identified in the panel models using two criteria. The first, formulated as (2k+2)/n, where k is the number of predictors and n denotes the size of the dataset, flagged Vancouver, Montreal, Greater Sudbury, and Medicine Hat, while the second, 3(k/n), only identified Vancouver. This indicates Vancouver's unique characteristics, particularly under the stricter second criterion. For the same reasons as with the cross-section models, these outliers were not removed from the dataset (see appendix C).

CHAPTER 5

RESULTS

5.1 Cross-section models

The cross-sectional analysis is presented in Table 6. In these models, the regression coefficient is interpreted as the percent point change in the proportion of sparse homes for each unit variation in a given predictor, observed across cities. *Population*, *income*, *gas price* and *farmland values* are log transformed to facilitate interpretation. The F-Statistics indicate that all models are statistically significant. The adjusted R-squared values, ranging from 0.652 to 0.713 across the years, denote a good fit, indicating that a substantial proportion of variance in the share of sparse homes is explained by the models.

The *population* variable consistently shows a significant negative relationship with the proportion of sparse homes across all years. *Household median income* is significantly positive in all years except 2016, implying a positive association with the proportion of sparse homes. *Gas price* generally presents a negative coefficient, suggesting an inverse relationship with sparse homes, except in 2006 where it is not significant. *Farmland value* is not significant in any of the census years. *Geographic constraints* are only significant in 2001, and are positive, contrary to expectations. Considering that this predictor is time-invariant, the change in significance and sign can only be due to the model specifications, and not the variable itself. The proportion of *remote workers* is significant in 2016 and 2021 only, and is negative, also contrary to expectations. The proportion of commuters that travel for over 45 minutes does not show significance in the models where the variable is included. Additionally, the sign unexpectedly reverses in 2021. The *remote work* and *commute distance* variables also display an exceptionally high level of standard error, indicating that they offer imprecise estimates of the variation in the proportion of sparse homes between cities.

These results underlie the importance of using a panel approach in sprawl analysis. This is evidenced by inconsistent signs for *farmland values* and *commute times*, as well as inconsistent significance in more than half of the variables. Moreover, the results cast doubts on the inclusion of *farmland* and *geographic* variables, as well as confirm that that the *commute time* variable is not useful for cross-city comparisons.

Table 6 Cross-section OLS models

	Dependent variable: Proportion of sparse homes (%)				
	(2001)	(2006)	(2011)	(2016)	(2021)
Population (log)	**-0.061*****	**-0.058*****	**-0.065*****	**-0.064*****	**-0.051****
	(0.010)	(0.011)	(0.011)	(0.013)	(0.014)
Household median income (log)	**0.384*****	**0.332*****	**0.309*****	0.149	**0.427*****
	(0.072)	(0.091)	(0.081)	(0.084)	(0.110)
Gas Price (log)	**-0.553*****	-0.497	**-0.544***	**-0.586****	**-0.506*****
	(0.136)	(0.256)	(0.219)	(0.176)	(0.138)
Farmland Value (log)	-0.017	-0.012	0.017	0.013	-0.003
	(0.013)	(0.012)	(0.015)	(0.015)	(0.013)
Geographic constraints (%)	**0.110***	0.060	-0.018	-0.022	0.037
	(0.054)	(0.061)	(0.059)	(0.054)	(0.058)
Remote work (%)	-1.067	-1.291	-1.572	**-1.807***	**-0.627****
	(0.710)	(0.808)	(0.922)	(0.770)	(0.220)
Commute over 45 minutes (%)				0.125	-0.047
				(0.183)	(0.231)
Intercept	-0.264	0.069	0.655	2.605	-1.110
	(1.098)	(1.996)	(1.623)	(1.412)	(1.281)
Observations	43	43	43	40	39
R^2	0.754	0.726	0.704	0.706	0.716
Adjusted R^2	0.713	0.680	0.654	0.642	0.652
Residual Std. Error	0.055 (df = 36)	0.058 (df = 36)	0.061 (df = 36)	0.057 (df = 32)	0.058 (df = 31)
F Statistic	18.431*** (df = 6; 36)	15.895*** (df = 6; 36)	14.248*** (df = 6; 36)	10.986*** (df = 7; 32)	11.171*** (df = 7; 31)

*p<0.05 **p<0.01 ***p<0.001

Standard errors in parenthesis

5.2 Fixed Effects models

The results for the fixed effects models are presented in Table 7. The time fixed effects model (Time-FE) removes effects consistent across cities for each census year— and evaluates the average impact of a predictor's one-unit increase between cities, relevant for all time periods. The classic fixed effects model (City-FE) eliminates city-specific time-invariant effects— and estimates the within-city effect, represented as the average impact of a predictor's one-unit increase over time, applied to all cities. Population, income, gas price and farmland values are log transformed to facilitate interpretation.

Table 7 Fixed-Effects models

	Dependent variable:	
	Proportion of low-density homes	
	(Time-FE: *Between*)	(City-FE: *Within*)
Population (log)	**-0.062*****	**0.085***
	(0.005)	(0.037)
Household median income (log)	**0.298*****	-0.044
	(0.038)	(0.039)
Gas Price (log)	**-0.510*****	**-0.113*****
	(0.086)	(0.025)
Farmland Value (log)	0.001	**-0.017****
	(0.006)	(0.006)
Geographic constraints (%)	0.028	
	(0.027)	
Remote Work (%)	**-1.339*****	**0.737***
	(0.383)	(0.341)
Observations	172	172
R^2	0.712	0.313
Adjusted R^2	0.696	0.053
Log-likelihood	255.65	479.99
F Statistic	66.680*** (df = 6; 162)	11.315*** (df = 5; 124)

** $p<0.05$ **$p<0.01$ ***$p<0.001$*
Standard errors in parenthesis

The F-statistics reveal that each model is highly significant. The adjusted R-square values demonstrate that the City-FE model (Adjusted R-square = 0.053) has considerably less explanatory power compared to the Time-FE model (Adjusted R-square = 0.696). This predominant between-city effect is explained by the greater variation across cities for most of the variables. Because the between-city variance is greater, this suggests that city-specific factors or policies play a more important role in influencing sparse housing than the variables included in the model. The individual intercepts for each city are found in appendix D, and demonstrate an elevated amount of variation, that somewhat follows the distribution of sparse homes across cities observed in figure 5. This suggests that a large portion of the variation in the model can be attributed to between-city effects or unobserved variables

5.2.1 Time-FE: Between-city variation

The Time-FE model closely approximates the results from the cross-sectional analysis, apart from the *remote work* variable which emerges as highly significant. The *geographic constraints* variable does not gain significance in the panel approach. Isolating the within-city effects produces some interesting outcomes. *Population* remains highly significant, but its coefficient reverses sign and is now positive. *Median income* also reverses sign but loses significance. *Gas price* retains significance and sign, but its marginal effect is somewhat weakened. *Farmland value* is now highly significant and has a negative impact on the proportion of sparse housing.

In the results for the Time-FE model (Table 7), the coefficient for *population*, at -0.062, is highly significant and negative. This suggests that, ceteris paribus, a city with a 1% larger population than its counterparts tend to have a 0.06 percentage point lower proportion of sparse housing. The coefficient for *household median income* is positively significant at 0.298, indicating that cities with a 1% higher median income than others are associated with a 0.30 percentage point higher proportion of sparse housing. The *gas price* variable, with a significant negative coefficient of -0.510, implies that cities with gas prices 1% higher than the rest of the dataset are typically associated to a 0.51 percentage point lower proportion of sparse housing. *Farmland value* lacks significance, indicating no substantial difference in the proportion of sparse homes for cities located in areas with more expensive farmland. *Geographic constraints* are not significant, meaning cities in more constrained areas are not significantly different than the ones in areas with less constraints. Lastly, the *remote work* variable, with a significant and negative coefficient of -1.339, demonstrates that cities with a proportion of remote workers that is one percentage point higher than others will be associated with a 1.34 percentage point lower share of sparse housing. The strengths of these coefficients exhibit only minor differences compared to the OLS models. Furthermore, the significance of each variable remains largely consistent, with the notable exception of the *remote work*, which demonstrates a higher level of significance in the Time-FE effects model.

5.2.2 City-FE: Within-city variation

In the City-FE model (Table 7), the *population* variable is highly significant, with a positive coefficient of 0.085, meaning a 1% increase in population is associated with a 0.08 percentage point increase in sparse housing. *Household median income* is not significant. The *gas price* variable is highly significant, with a negative coefficient of -0.113, implying that a 1% increase in gas prices leads to a 0.11 percentage point decrease in the proportion of a city's sparse housing. *Farmland value* is significant, with a negative coefficient of -0.017, suggesting a 0.02 percentage point decrease in the share of sparse housing for each 1% increase in farmland value for an average city. Finally, *remote work* has a positive coefficient of 0.737, indicating an increase of 0.73 percentage points of sparse housing when the proportion of remote workers increases by 1% over time.

CHAPTER 6

DISCUSSION

6.1 Interpretation of the model coefficients

6.1.1 Population

When examining the disparities between cities, the *population* coefficient is highly significant and negative for the Time-FE model. This finding aligns with the cross-sectional analysis, wherein the stability of the coefficients across all census years demonstrates the persistent negative influence of population size on sparse housing. This demonstrates that larger population centers have denser development. In contrast, when observing the differences in time periods for the average city, the coefficient for population remains highly significant, but its sign is now positive. This indicates that as a city's population expands, the increase in sparse homes has outpaced the increase in other housing types during the study period.

Research using sparse housing as the dependent variable suggests that population growth exerts upward pressure on both housing demand and land prices. This pattern had a dual impact on density gradients, promoting intensification at the urban core as well as encouraging expansion at the fringe (Young et al. 2016; Ortuño-Padilla & Fernández-Aracil, 2013; Wassmer, 2008).

6.1.2 Income

Cities with a higher *median household income* tend to have a larger proportion of sparsely distributed housing. This observation is supported by the analysis of the between-city effects in the Time-FE model, as well as cross-sectional analysis. The implication is that in cities where households possess greater purchasing power, there is a higher consumption of housing, leading to an increased presence of sparsely distributed housing. This trend is consistent with housing space being a normal good. It is interesting to note that the significance of the income variable vanishes for the 2011 and 2016 OLS models, potentially due to an undersupplied housing market driving up prices and increasing pressure for denser development.

On the other hand, the within-city effects show that an increase in the median income of a given city does not significantly alter the proportion of sparse housing on the market. This could be attributed to the non-linear relationship of income, which arises from the opportunity costs associated with transportation for high-earners. Because their time is worth more, high-earners will prefer to pay more to remain near centers of activity, such as downtowns (DeSalvo and Su in 2013). It could also be attributed to the countervailing effects of income on the density of cities that exhibit both open-city and closed-city dynamics simultaneously, as illustrated by Brueckner (1987). Despite greater housing consumption, the increase in land prices due to a highly competitive market and positive migratory flows leads to increased building densities.

6.1.3 Transportation costs

The *commute time* variable was not significant in the cross-sectional models. This may be due to the complexity of modeling in the largest metropolitan areas, which not only have large footprints and high levels of congestion but also exhibit the highest levels of density. Furthermore, these urban centers provide a wide range of transportation options, resulting in varied commuting times. This diversity adds complexity to the task of assessing the impact on urban form.

In every model tested, the variable representing *gas prices* consistently exhibits a negative and statistically significant coefficient, as anticipated. This negative correlation suggests that higher gas prices may be associated with reduced sparse home occupancy due to increased commuting expenses, as observed by Tanguay & Gingras (2012), Ortuño-Padilla & Fernández-Aracil (2013) and Young et al. (2016). When examining the coefficients in the FE models, a notable difference is observed between the between estimation (-0.510) and the within estimation (-0.113). This discrepancy is understandable, given the greater variation in data across different cities compared to within cities.

However, the reliability of the gas price variable was further compromised by the lack of data for numerous cities, necessitating the use of the nearest available data point from adjacent cities. These coefficients are thus biased, and should not be used to make predictions about the precise effects of gas prices on sprawl.

6.1.4 Agricultural land values and geographic constraints

Geographic constraints and *farmland value* are never significant in the cross-section models or the between-city effects component of the Time-FE model. This reveals that there is no substantial difference in the proportion of sparse homes for cities located in areas with higher greenfield development costs, compared to others.

Some explanations can be posited for this finding. One possibility is that the impact of these costs is too small to be picked up by the model, and therefore is susceptible to type II error. Additionally, the value of farmland, especially when proximate to the expanding fringes of a rapidly developing city, may not be adequately captured by the regional average land prices used in our variable. This oversight, coupled missing values for certain cities, might introduce biases, thereby diminishing the statistical significance of this variable.

Furthermore, the actual size of cities varies significantly, which suggests that a uniform 25km threshold for geographic constraints might not accurately represent the real pressure that they exert on urban form. For instance, cities like Kelowna or Kamloops, despite being heavily enclaved by steep topography, still have plenty of room to develop due to their relatively small size. Moreover, the distribution of the geographic variable is skewed towards lower values, suggesting that these constraints are not a predominant issue for most cities.

Because the geography of a city is time-invariant, its role in restraining sprawl as a city evolves over time cannot be measured with the within effect component of the City-FE model. However, it does show that as the agricultural prices of a given city increase, sprawl is reduced, confirming the predictions of the AMM model.

6.1.5 Remote work

Remote work is the key variable of interest in this study. The between-city effects of the Time-FE model indicate that remote workers are significantly and negatively associated with sparse housing. This outcome suggests that, once controlling for other key factors, remote work is more associated to dense cities, as opposed to sprawled ones, contrary to expectations.

When comparing data at the city level, the between estimator is often used to capture the impact of numerous unobserved dynamics that are not directly measured but influence the outcomes. These dynamics could be complex social behaviors, political conditions, or economic trends. Among these unobserved factors, employment opportunities serve as a notable example. Large cities, known for their higher density, also exhibit a stronger presence in the creative and knowledge economy sectors that tend to attract remote workers. Furthermore, as shown by Turcotte (2010), many of the remote workers are home-based business operators. Despite their remote working status, these individuals often travel as much as regular workers. Their tendency to gravitate towards large urban centers can be attributed to the higher concentration of clients or suppliers in these areas, further reinforcing the observed association between remote work and urban density. Others, who practice Telemigration, may opt for rural settings, and are not detected by any of these models that only consider urban and suburban populations. These differences make it challenging to identify a clear relationship between remote work and population density, especially when analyses do not distinguish between different densities within a metropolitan area.

The within estimation of the City-FE model reveals a positive relationship, indicating that an increase in a city's remote worker population over time correlates with a higher proportion of sparse homes. Notably, the coefficient is very strong for this variable, compared to others. This finding aligns with Moos & Skaburskis (2008), who demonstrated a preference for single-family homes among remote worker households.

The combined results of the City-FE and Time-FE show that while there is a higher concentration of remote workers in dense cities, the increase in remote workers in a given city leads to a reduction in its overall density. Consequently, remote workers tend to prefer residing in the suburbs of major cities rather than in smaller urban areas. This suggests that for the average remote worker, migrating towards smaller cities for a quieter, more natural setting might not be the ideal choice. Instead, remaining in a metropolitan area and moving to the suburbs appears to be a more logical option. This is especially true for part-time remote workers, who, despite enjoying increased flexibility in choosing where to live, still need some proximity to their place of employment due to their partial spatial anchoring.

It is important to note that it is too early to observe any significant potential effects of remote work on sprawl locations, given the study period and the fact that the pandemic occurred in March 2020.

6.1.6 Unobserved variables

Unobserved variables are contained in the error term. These factors include; the attitudes and opinions of the local populations and governing bodies, property and sales taxes, infrastructure investments and homeownership subsidies, local zoning, as well as urban containment policy. Although some may be specific to entire CMAs or CAs, many of these factors will influence urban development at smaller municipal or neighborhood scales, complicating their detection. Furthermore, many are not time-invariant or case-invariant, meaning their effects are not purged from the models. Federal subsidies and interest rates are case-in variant, and therefore have no impact on models. To investigate the impact of various provincial urban planning legislative frameworks on sprawl, including containment policies, the study initially incorporated a dummy variable for the province in both the cross-section and panel models. However, the inclusion of this variable did not alter the outcomes, and it only proved to be significant when Quebec was selected as the reference category, indicating that it is the only province that differs from the rest of the country. It might be inferred that the distinct characteristics of Quebec, such as its strong farmland protection measures, play a role. However, as demonstrated in Figure 5, cities within Quebec have the lowest incidence of low-density housing units. Remarkably, it is in these very cities that there has been an increase in the proportion of such housing types over the study period. This finding suggests that the observed phenomenon may not be directly related to regulatory measures. Instead, it appears to be more likely influenced by historical development patterns.

6.2 Policy recommendations

In light of the increasing prevalence of remote work and its implications for urban planning and sprawl, governments should adopt a pre-emptive strategy, aimed at preparing for future shifts in the spatial structure of cities, rather than focusing on immediate effects. In the realm of urban planning, this holds particularly true, as the built environment often requires years, if not decades, to adjust and respond to evolving social behaviors. Additionally, the literature in section 2.4.1 suggests that changes in residential location only manifest after long periods of remote work adoption.

Despite the potential of telemigration, remote workers continue to concentrate around major urban centers, as demonstrated by between-city analysis. Consequently, it is foreseen that larger cities may bear a more substantial brunt compared to their smaller counterparts. This shift has the potential to fuel the expansion of sprawling conurbations. In particular, such growth presents challenges for CMAs comprised of diverse fragmented administrative entities that will increasingly compete for highly mobile residents. Enhanced regional coordination will be imperative to properly plan growth and infrastructure distribution. Provinces should consider expanding the powers granted to regional administrative and planning institutions in order to properly anticipate for this.

Urban containment policy warrants substantial reconsideration. The prevalence of telecommuting, in particular, facilitates the circumvention of greenbelts and encourages development just beyond UGBs, where land costs are lower and accessibility to the city by car during off-peak hours is convenient. By pushing development further out, these policies complicate city access via active transportation due to the substantial distances necessary to traverse protected land parcels on foot or bicycle. Revising urban containment policies to limit development beyond an hour's drive from the city during off-peak times can decrease amenities accessibility for remote workers, reducing the attractiveness of such areas. Additionally, hard containment strategies could be replaced by fiscal measures, such as taxing the redevelopment of agricultural land, which may be less susceptible to circumvention by locating just beyond the fringe of a hard containment boundary. However, it is essential to ensure the continued protection of sensitive natural areas under hard containment measures.

Remote work tends to increase miscellaneous travel, necessitating efforts to enhance the walkability and transit orientation of suburbs through zoning reforms and initiatives like smart growth. This entails improving the permeability of suburban road networks for active transportation and repurposing shopping centers into compact mixed-use commercial hubs designed to provide a pedestrian-friendly environment, thus promoting more active forms of transportation.

Given the compounded effects of reduced office space and the relocation of companies and individuals away from central business districts, downtown cores must be planned differently to accommodate this shift. Prioritizing residential zoning and adaptive reuse of office spaces can address evolving work patterns and alleviate the housing crisis facing many cities. Such measures are crucial for the survival of downtown businesses, as the disappearance of their clientele could pose significant challenges.

Anticipated shifts in transportation networks include a more even distribution of commute times and reduced reliance on center-oriented radial transit systems. Additionally, the trend of remote work could prompt offices and commercial establishments to relocate to areas with lower land rents. This relocation trend has the potential to drive cities toward polycentric development and necessitate the establishment of more intricate transportation networks. These changes may lead to a decline in overall transit usage, affecting the agency’s ability to generate funding, thereby placing the onus of investment on federal and provincial governments to reconfigure the networks to adjust to new mobility patterns. Circumferential lines for suburb-to-suburb transport and redesigned bus routes that prioritize feeder trips towards a structural network, as opposed to servicing downtown routes, are recommended adjustments.

The elimination of commuting altogether presents opportunities for the redistribution of city populations, stimulating growth in smaller regional cities and altering regional hierarchies. This may foster a more equitable distribution of populations within and across cities. Small cities and regional governments should proactively anticipate these changes, particularly in areas with limited planning resources and challenges in controlling development. It is imperative to enhance the protection of natural resources against development, recognizing their appeal to full-time remote workers lacking spatial anchoring.

CONCLUSION

This thesis comprehensively examines a timely issue: the impact of remote work on the dynamics of urban sprawl. The research, set within the context of growing telecommuting trends, poses a critical question: How does the shift towards remote work influence urban development patterns, particularly sprawl? Theoretically, it bridges urban planning and labor dynamics, offering insights into how work modalities can contribute to reshaping cities. Practically, understanding this relationship informs policy decisions in urban development and transportation planning.

Inspired by the AMM model, this study employs key variables such as population size, household income, transportation costs, agricultural land value, and the percentage of remote workers to ascertain the distribution of low-density housing types across various cities. It utilizes a dataset of 43 Census Agglomerations and Metropolitan Areas from the census years of 2001, 2006, 2011, and 2016, employing longitudinal and cross-sectional techniques, notably fixed-effects panel modeling. This approach analyzes both the cross-sectional variance across the cities and the temporal changes within each city over the studied years. Therefore, it aims to understand if an increase in remote workers leads to more sprawl and if cities with more remote workers sprawl more than others.

This study reveals that although larger cities tend to be denser, population growth positively influences the expansion of sparse housing. A comparison between cities indicates that higher median household incomes correlate with a greater proportion of sparse housing, suggesting a preference among wealthier households for more space. However, within cities, an increase in median income does not significantly alter the proportion of sparse housing, pointing to complex dynamics within housing markets that involve both increased housing consumption and rising land prices. Furthermore, an increase in gas prices is consistently associated with a decrease in the occupancy of sparse homes, indicating that higher commuting costs discourage living in less densely populated areas.

The key findings of this study reveal important insights into the dynamics of remote work and urban sprawl. The between-city analysis—which focuses solely on the differences in variables among different cities, without considering changes over time—indicated a negative correlation between remote work and sparse housing, suggesting a preference among remote workers for denser, metropolitan areas—a finding contrary to initial expectations. On the other hand, within-city analysis examines changes within the cities that occur over time, averaging the findings to understand the general trend. This analysis unveiled that an increase in the prevalence of remote work resulted in an uptick in sparse housing within a city, suggesting a preference for sparser housing types and neighborhoods among remote workers. Taken together, these findings suggest that remote workers prefer suburban areas within large metropolitan regions, underscoring a desire for some proximity to large employment markets, despite the flexibility that remote work offers. This will be especially true of the part-time remote workers and home-based business operators, that retain a certain level of spatial anchoring to large centers of activity and employment. However, remote workers will also prefer living in the less dense areas of these metropolitan regions. Therefore, while remote workers may continue to converge towards large metro areas, they are more likely to choose to locate in sparser peripheries due to reduced commuting needs. This suggests that areas with the highest potential for further sprawl are the suburbs of large metropolitan regions.

These insights underscore the importance of considering the impact of remote work on urban development and city densification efforts moving forward, and carry important implications for urban planning, housing policy, and transportation management in the post-COVID era. Cities and governments are urged to rethink regional planning practices and urban containment regulations, and to reevaluate transit strategies to better serve peripheries, while also promoting flexible housing solutions to anticipate and accommodate the influx of remote workers to suburban areas, as well as the potential decline in activity in core districts.

In terms of methodology, this study highlights the importance of employing models that account for both within-city and between-city effects in the analysis of urban sprawl. The results demonstrate that various variables exert differing impacts depending on whether the analysis involves a cross-sectional or longitudinal dataset. Longitudinal data proves essential for establishing causality and comprehensively capturing the phenomenon of sprawl as a complex and dynamic process.

However, the study encounters several limitations that are important to consider for accurate interpretation of its findings. First, the requirement of strong exogeneity is critical for panel models to yield accurate causal inference (Wooldridge, 1997). There is a risk of biased and inconsistent estimates due to omitted variables, such as fiscal or regulatory measures, that are not time or city invariant and which might correlate with the predictors. Additionally, although FE models are adept at handling time-invariant unobservable traits, they face challenges in accounting for time-varying unobserved heterogeneity (Hill et al., 2020). Another notable limitation for panel data is cross-section dependence, especially evident in macro panel data where occurrences in one city might influence or relate to those in another. For example, there is likely to similarities in the cities within the Toronto Conurbation that are collectively influenced by policies like the Greater Golden Horseshoe plan and the Ontario Greenbelt. Moreover, estimates derived from panel models are susceptible to being diminished due to measurement inaccuracies, a factor that demands meticulous attention in the framework of the current research due to the gas price and agricultural land price variables being constructed with incomplete data. The Remote Work variable aggregates multiple types of work practices and cannot detect the effect of remote workers that choose to leave cities entirely, surely underestimating this effect. Furthermore, using percentages as a dependent variable introduces complications, as they are bounded by 0 and 100 and thus exhibit a sigmoidal relationship[11] rather than a linear one. However, the dependent variable range in this study falls within 20% to 80%, mitigating this issue to some extent.

It is recommended that future studies extend their scope to include more rural areas, which would provide insights into the phenomenon of telemigration and its potential to reshape non-urban landscapes. Additionally, distinguishing between different types of remote work, such as telecommuting and home-based business operations, could offer a nuanced view of how each category specifically influences urban form. Investigating the frequency of remote work is another critical area, as it could reveal varying degrees of urban impact based on how often individuals work remotely. Furthermore, incorporating a wider range of sprawl-related variables would enhance our understanding of the intricate dynamics influencing urban development in the context of remote work. This multi-faceted approach will contribute significantly to our knowledge of urban evolution in the digital age, facilitating more effective urban planning and policy-making.

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[11] A sigmoidal relationship describes a specific kind of pattern between two variables, where the relationship curve resembles the shape of an "S".

APPENDIX A

NORMALITY TESTS

Shapiro-Wilk normality test: OLS 2001

- W = 0.98864
- p-value = 0.9423

Shapiro-Wilk normality test: OLS 2006

- W = 0.98412
- p-value = 0.8069

Shapiro-Wilk normality test: OLS 2011

- W = 0.98693
- p-value = 0.8992

Shapiro-Wilk normality test: OLS 2016

- W = 0.98842
- p-value = 0.9375

Shapiro-Wilk normality test: OLS 2021

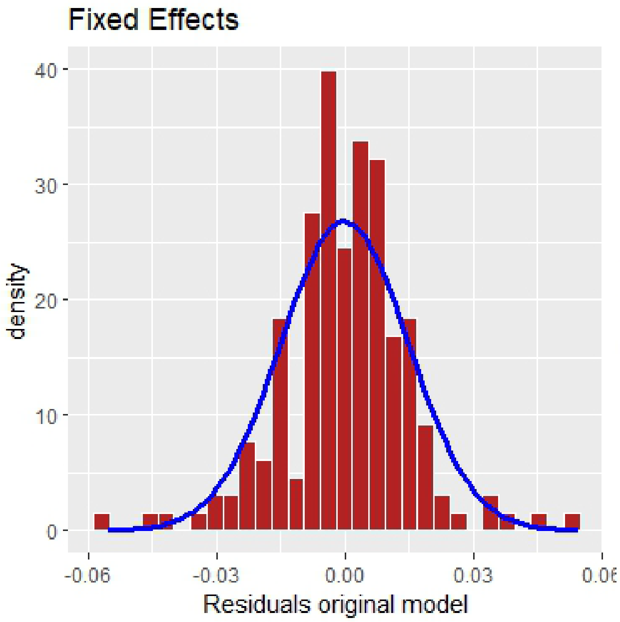
- W = 0.98684
- p-value = 0.9032

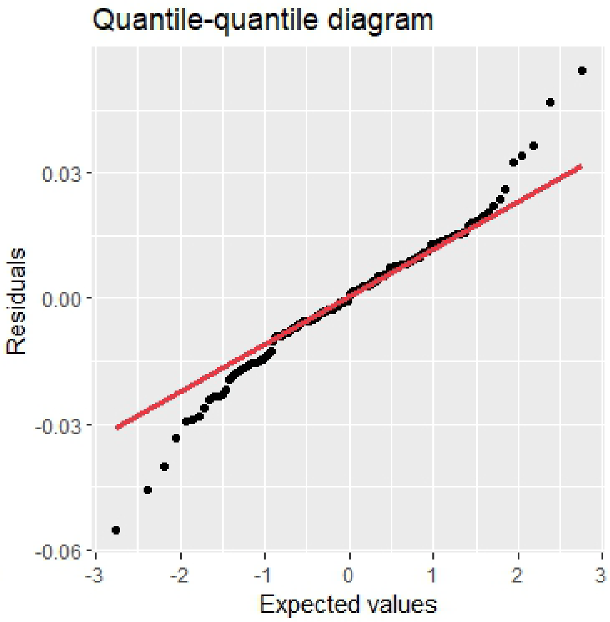
Shapiro-Wilk normality test: FE-Model

- W = 0.96766
- p-value = 0.0004923
- alternative hypothesis: residuals are not from a normal distribution.
- The Shapiro-Wilk test indicates that the residuals are not normally distributed.

Robust Jarque Bera Test for the normality of residuals: FE-Model

- X-squared = 46.317
- df = 2
- p-value = 8.756e-11
- alternative hypothesis: residuals are not from a normal distribution.
- The Jarque Bera test indicates that the residuals are not normally distributed.

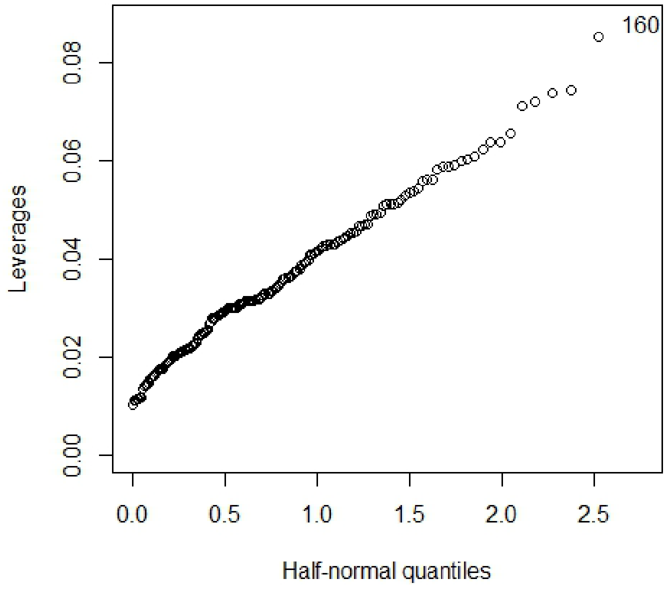


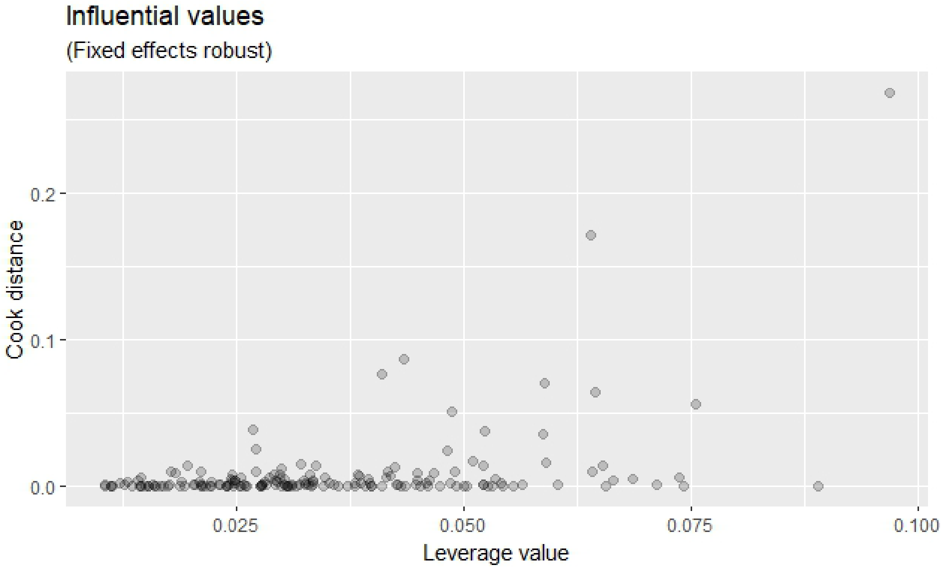


APPENDIX B

OUTLIERS TESTS

High Leverage values for panel dataset





APPENDIX C

PANEL MODEL ASSUMPTION TESTS

Breusch-Pagan Lagrange Multiplier test

- Models = Pool vs. FE
- F = 41.302,
- df1 = 41, df2 = 124,
- p-value <2.2e-16
- alternative hypothesis: significant effects
- The result of the Breusch-Pagan Lagrange Multiplier test is that there is evidence of significant differences across units = panel effect.

Chow test for the poolability of the data

- Models = Pool vs. FE
- F = 41.302
- df1 = 41, df2 = 124
- p-value < 2.2e-16
- alternative hypothesis: unstability.
- The coefficients are not stable, fixed effects is recommended.

Hausman test for fixed effects versus random effects model

- Models = FE vs. RE
- chisq = 116.01,
- df = 5,
- p-value < 2.2e-16
- alternative hypothesis: one model is inconsistent
- The result of the Hausman test is that there is evidence of correlation between the error term and the predictors. Do not use random effects.

Breusch-Pagan Lagrange Multiplier Test - time effects

- Model = FE case
- chisq = 0.99382,
- df = 1,
- p-value = 0.3188
- alternative hypothesis: significant effects
- The result of the Breusch-Pagan Lagrange Multiplier test indicates no evidence of effects that are common across entities but vary with time. Do not use case fixed effects.

F test for time effects

- Model = FE case
- F = 4.2793, df1 = 3,
- df2 = 162,
- p-value =0.006153
- alternative hypothesis: significant effects
- The result of the F test indicates evidence for effects that are common across entities but vary with time.

F test for individual effects

- Model = FE
- F = 40.397,
- df1 = 42, df2 = 124,
- p-value <2.2e-16
- alternative hypothesis: significant effects
- The result of the F test indicates evidence for effects that are vary within entities but are common across with time.

Angrist–Newey test for fixed effects assumptions

- Model = FE
- chisq = 53.34,
- df = 55,
- p-value = 0.5383
- alternative hypothesis: within specification does not apply
- The result of the Angrist–Newey test indicates that the within specification applies.

Breusch-Godfrey/Wooldridge test for serial correlation in panel models

- Model = FE
- chisq = 28.185,
- df = 4,
- p-value = 1.144e-05
- alternative hypothesis: serial correlation in idiosyncratic errors.
- The result of the Breusch-Godfrey/Wooldridge test indicates the presence of serial correlation.

Wooldridge's test for serial correlation in FE panels

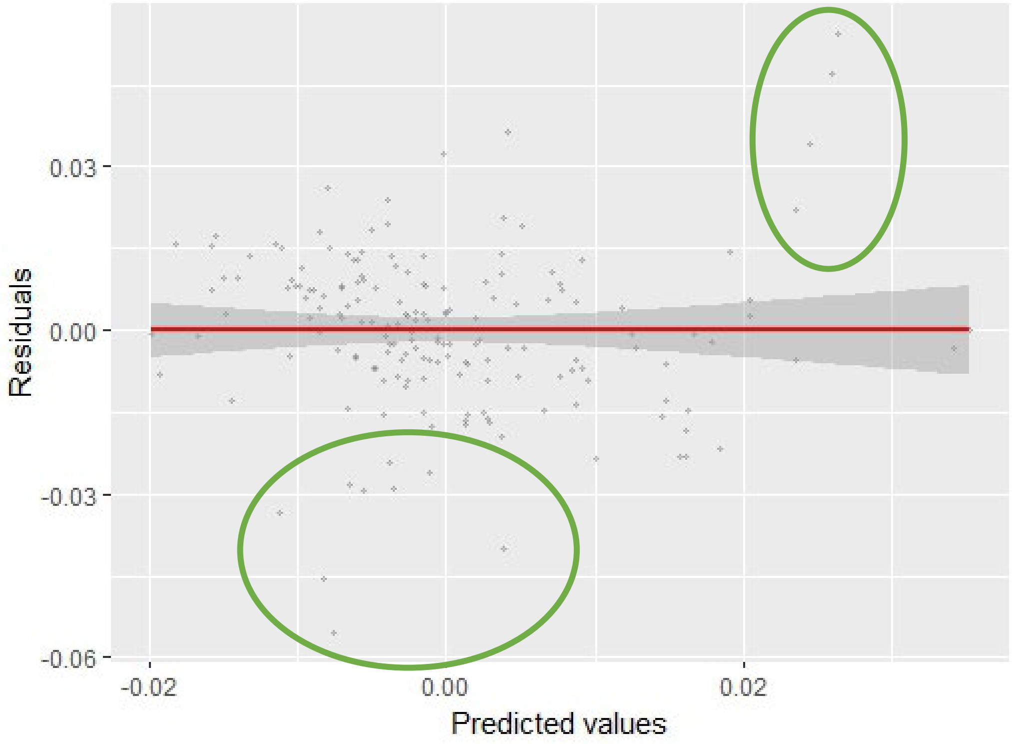
- Model = FE
- F = 12.536,
- df1 = 1, df2 = 127,
- p-value = 0.0005588
- alternative hypothesis: serial correlation.
- The result of the Wooldridge test indicates the presence of serial correlation.

Augmented Dickey-Fuller Test for stochastic trends

- Variable = low-density homes (%)
- Dickey-Fuller = -5.9804
- Lag order = 1
- p-value = 0.01
- alternative hypothesis: stationary.
- The result of the Dickey-Fuller test indicates that the data is stationary.

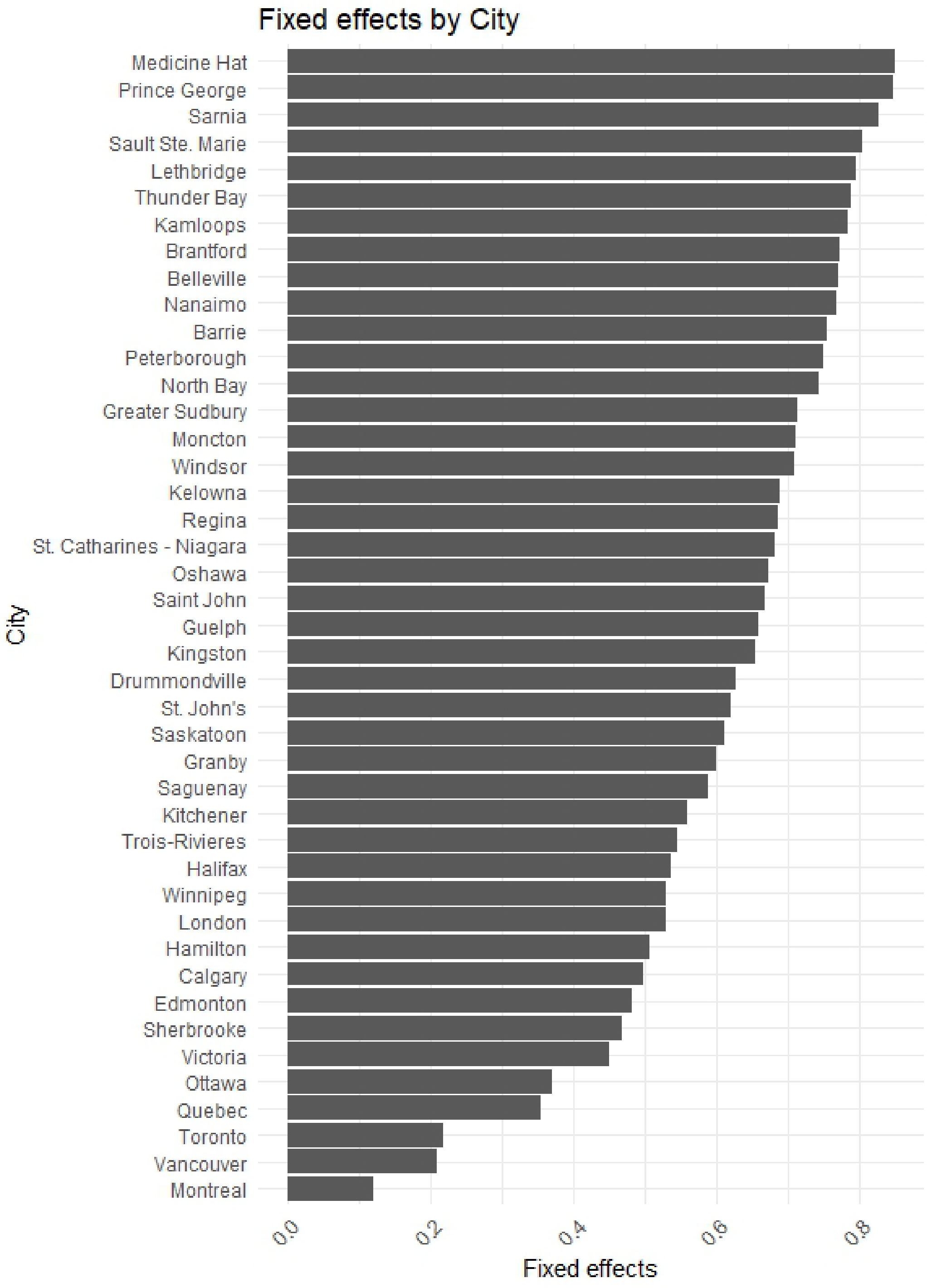
Breusch-Pagan test for homoscedasticity of residuals

- Model = FE
- BP = 10.7,
- df = 6,
- p-value = 0.0981
- alternative hypothesis: heteroscedasticity of residuals.
- The Breusch-Pagan test indicates



APPENDIX D

CITY-FE INTERCEPTS



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