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**Urban Sprawl: Land-Use, Travel Behaviours, and Emissions
in Ireland**

Thesis presented by

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Author Declaration

“This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.”

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Date: 05/09/2023

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Abstract

Land-use configurations determine the distribution and intensities of human activities across space while transport infrastructure determines the ability of goods, services, and people to travel across this space. Considering this relationship, it is important to understand how these mechanisms interact, but also how they can contribute to efforts to achieve sustainability in regional development while also positively benefitting local economies and social fabrics. By directly influencing regional time-space geographies, land-use configurations influence the efficiency with which finite resources, like land, are used while also defining local and regional connectivity, considerations which are directly related to economic, environmental, and social outcomes. In this regard, land-use developments in the Republic of Ireland have historically been characterised by urban sprawl, a developmental form which creates spatially segregated human settlements characterised by car-centric transport networks. Evidence suggests that these patterns inefficiently (and therefore unsustainably) use natural resources, like land, but also increase regional time-space geographies, characteristics known to influence economic, environmental, and social outcomes for individuals, households, and regions.

Using Geographical Information Systems (GIS), econometric techniques, and network analysis methods, this research investigates the economic, social, and environmental dimensions of regional development across Ireland and Europe. Using refined built and social environment data, nationally comprehensive Census data, and highly disaggregated spatial scales, this thesis provides substantial contributions to regional science by undertaking six empirical analyses. These investigations focus on four principal research questions, namely: 1) How do land-use configurations contribute to efforts to achieve sustainability in regional development across Ireland and Europe? 2) Can the incorporation of opensource data improve our understanding of land-use configurations and their ability to contribute to sustainability efforts? 3) What is the relationship between built and social environments, individual socio-demographics, trip-specific concerns, and travel mode choices when commuting and during school-runs? 4) How do land-use configurations and transport infrastructure provision impact the environmental degradation attributable to travelling when shopping?

From a land-use perspective, I show that regions which minimise time-space geographies and incorporate higher levels of land-use mixing utilise land, infrastructure, and natural resources, like space, more efficiently than alternative regions. This is because more people and human activities are accommodated within smaller spatial scales, thereby reducing the spatial extents of developments, and by extension, the levels of natural landscape destruction attributable to

human settlements. In addition to this, more compact developmental forms face lower development costs, increased market/amenity accessibility, and strengthened social fabrics – producing positive economic and social outcomes. From a transport perspective, these areas reduce the implicit costs associated with regular public and active transport use by reducing required travel times and distances, heightening the competitiveness and convenience associated with these modes. I argue that these characteristics positively contribute to altering regional transport hierarchies away from excessive car-use, and therefore prompt reductions in travel-related environmental degradation.

I conclude this research by highlighting how land-use and transport policies can be coordinated around environmental goals whilst not compromising economic and social objectives within regional development. In this regard, I provide specific policymaking recommendations surrounding the use of these instruments to increase the efficiency and sustainability of land-use configurations while also catalysing shifts away from excessive car-use in favour of more sustainable alternatives. Of these, the principal recommendation is that future developmental proposals should prioritise maximizing the efficiency of existing man-made settlements and infrastructure prior to outward expansion. In urban areas, this relates to prioritising greater land-use mixing and vertical expansion, while in rural areas, this more so relates to reducing time-space geographies through multi-modal transport investment, initiatives which may stimulate the emergence of polycentric developmental patterns. Similarly, initiatives which alter regional transport hierarchies by reducing the implicit costs of public and active transport relative to cars are recommended. I end by highlighting the limitations of this work while also providing directions for future research.

Chapter 1: Introduction

1.1 Regional Development: The Nexus Between Land-Use Configurations and Travel Behaviours

Regional planning has been defined as the coordination of residential settlements, transport and utility infrastructure, and economic development which seeks to balance national objectives with local conditions (Rogers, Castree and Kitchin, 2013). From a land-use perspective, this development is a spatiotemporal phenomenon whereby land-use distributions determine the locations and intensities of human activities and therefore the degree of time-space isolation faced by individuals, localities, and regions (Reynolds-Feighan, 2003; Button, 2010; Giuliano, 2012; Gao *et al.*, 2020). From a transport perspective, regional development is also spatiotemporal whereby land-use configurations determine the concentration and provision of infrastructure that facilitates the movement of goods, services, and people across space (Travisi, Camagni and Nijkamp, 2010). In this context, transport infrastructure can be viewed as a reactive mechanism which regulates the spatial disadvantages associated with the geographical distribution of settlements and human activities (Button, 2010; Vega and Reynolds-Feighan, 2016). It does this by defining the accessibility of economic and social opportunity (i.e., jobs and amenities) and inter-regional connectivity, phenomena which can influence the environmental, economic, and social outcomes associated with regional development (Button, 2010; Trannoy, 2011).

This thesis has two overarching focuses: 1) The relationships between land-use configurations and transport infrastructure provision (and by extension land-use and transport policies), and 2) how land-use configurations and transport infrastructure provision influence environmental, economic, and social outcomes within regions. Directly inspired by policymaking initiatives like *Project Ireland 2040* and the *United Nations Sustainable Development Goals*, this research provides highly refined insights on how regional planning (from a land-use and travel behaviour perspective) has contributed to efforts to achieve sustainability in development across Irish and European regions, a key policy concern since the beginning of the twentieth century (European Environmental Agency [EEA], 2006, 2015; OECD, 2018b, 2022). I analyse how policymakers can ensure the economic, environmental, and social vitality of future regional development, issues that are investigated across six empirical chapters which address the following research questions:

- [1] How do land-use configurations contribute to efforts to achieve sustainability in regional development across Ireland and Europe?
- [2] Can the incorporation of opensource data improve our understanding of land-use configurations and how these configurations can contribute to sustainability efforts?
- [3] What is the relationship between built and social environments, individual socio-demographics, trip-specific concerns, and travel mode choices when commuting and travelling to school?
- [4] How do land-use configurations and transport infrastructure provision influence the environmental degradation attributable to travelling when shopping?

Regional development across much of the Global North has been characterised by urban sprawl. This is often attributed to an increased demand for suburban lifestyles as a result of rising incomes and the commercialisation of private cars in the post-WW2 era (Weilenmann, Seidl and Schulz, 2017). This shift in developmental paradigms paired with advances in transport technologies provided individuals and firms with greater flexibility surrounding location decisions. Specifically, these changes reduced the costs associated with travel, subsequently allowing agents to avail of cheaper and more abundant land in peripheral areas without compromising urban lifestyles and economic opportunities, creating a landscape characterised by residential (and commercial) dispersion while also spawning a culture of inward commuting from peripheral areas (Nechyba and Walsh, 2004).

As a developmental form, urban sprawl is characterised by low settlement densities, segregated land-use, and limited multi-modal transport accessibility (Jaeger, Bertiller, Schwick and Kienast, 2010; Jaeger, Bertiller, Schwick, Cavens, *et al.*, 2010). Low settlement densities increase the spatial expanse of regions, thereby increasing required travel distances, while land-use segregation dislocates residential areas from places of interest, increasing the need for transport modes which can flexibly accommodate individual travel needs within isolated localities and disjointed regions (De Vos *et al.*, 2021; O’Riordan *et al.*, 2022). As a result, the demand for private cars has consistently increased over time at the expense of alternative (and

arguably more sustainable) transport modes, like public and active transport, because of their relative inability to bridge the rising spatial gaps between residential areas and places of economic and social interest in sprawling landscapes (Reynolds-Feighan, 2003; Giuliano, 2012; Wu *et al.*, 2021).

The onset of urban sprawl catalysed changes in travel behaviours by increasing the demand for private cars. This stimulated negative feedback loops as transport infrastructure and service investment became increasingly focused around accommodating private cars. In Ireland, the results of this shift have been dramatic, something evidenced by the fact that national transport infrastructure is still characterised by inadequate rail-based transport, inefficient and unreliable bus services, low levels of regular active travel, and disproportionately high levels of regular car-use when compared to other European countries (Reynolds-Feighan, 2003; Bielenberg and Ryan, 2012; Giuliano, 2012; Eakins, 2015; OECD, 2022). These phenomena have created unique problems on two fronts. From a land-use perspective, the prevalence of urban sprawl has increased the costs of regional development and exacerbated the level of natural landscape destruction attributable to human settlements (Zhang and Zhao, 2017), as illustrated in **Chapters 3, 4, and 5**. From a transport perspective, urban sprawl (and the subsequent neglect of multi-modal transport infrastructure) has heightened the severity of travel-related environmental degradation by increasing regular car-use, but evidence suggests these trends may also negatively contribute to regional economic and social objectives (Ewing, 1997; Reynolds-Feighan, 2003; Millward and Spinney, 2011), something explored across **Chapters 6, 7, and 8**.

In an Irish context, urban sprawl, suburbanisation, and the subsequent shifts in travel behaviours appear to have emerged as extreme manifestations of global trends (European Environmental Agency [EEA], 2006; OECD, 2018b, 2022). From the post-WW2 years to the late-1990s, regional policymaking coordination and control in the realm of land-use and transport was absent, creating a policymaking landscape characterised by localised territorial politics (Moore-Cherry and Tomaney, 2019). The general result of this was that localities and regions would expand in an uncoordinated manner unless governments intervened – which they rarely did on account of the prevalence of private lobbying in the land-use management sector (Winston, 2007; OECD, 2018b; Williams and Nedović-Budić, 2020). Therein emerged the contemporary problems associated with regional development in Ireland. That is, isolated urban centres, unbalanced regional growth, an effectively unimodal transport infrastructure, and an inefficient use of natural resources, like land (European Environmental Agency [EEA],

2006; OECD, 2018b; Department of Transport, 2022). The consequences of these phenomena have created individual- and regional-level divergence in economic, environmental, and social outcomes, something borne out in numerous statistics describing disparities in regional economic growth (OECD, 2018a), social fabrics (OECD, 2013, 2018a), and environmental degradation (O’Riordan *et al.*, 2022; OECD, 2022).

From an economic perspective, between 2000-2016, Gross Domestic Product (GDP) per capita within Ireland’s most prosperous regions (The Southern and Eastern region) increased by 74% while in the Border, Midland, and Western region, it increased by only 11% (OECD, 2018a). Similarly, there are significant disparities in the accessibility of jobs, education, and leisure amenities, as well as substantial differences in income-levels, across these two regions – disparities known to negatively impact social mobility, individual wellbeing, and are the direct result of unbalanced regional development¹ (OECD, 2018a). Environmentally, between the 1930s and the 1990s, the population of the Greater Dublin Area (Ireland’s capital city) doubled but its spatial expanse quadrupled, indicating an inefficient use of natural, finite resources (i.e., space) when expanding (Winston, 2007, p. 62). Furthermore, the proportion of people travelling by car for everyday travel has increased from 44% to 76% since 1980 (Winston, 2007, p. 66; Central Statistics Office [CSO], 2022; C. O’Driscoll *et al.*, 2022b). In this realm, quantifying the environmental damage (i.e., emissions) of this shift is difficult. However, Alam *et al.*, (2017) demonstrate that although improved fuel efficiency and technology reduced the levels of environmental degradation attributable to car-use, it was not enough to offset those generated by a growing passenger fleet. Subsequently, travel-related emissions have persistently increased since 1990, with private cars contributing to ~95% of this, suggesting that these problems will only worsen unless car-use can be reduced. Clearly then, these changes have exacerbated the environmental degradation attributable to regional development and travel behaviours. But international evidence also suggests that changes of this nature can also damage local social fabrics, economies, and the subjective wellbeing of individuals (Mouratidis, 2018b, 2018a).

1.2 Contributions of This Thesis

Each of the empirical chapters presented in this thesis is characterised by a considerable data collection effort, whereby significant contributions to existing literature stem from the use of

¹ For instance, the OECD report, *Cities and Regions at a Glance*, states how the Southern and Eastern region ranks in the top 20% of OECD regions in terms of employment outcomes while the Border, Midland, and Western region ranks in the bottom 20% of OECD regions. For more information, see: OECD, (2018a).

spatially comprehensive data at highly disaggregated spatial scales. This builds upon a global push to increase our collective understanding of urban and regional morphology by blending the data and social sciences. In an Irish context, this push was embodied by Minister For Transport Eamon Ryan, who called for research which elevated our knowledge of land-use configurations and patterns across Ireland while also improving the datasets used when assessing these developments (Ryan, 2023). Contributing to this effort, each empirical chapter in this thesis uses data from *OpenStreetMap*, *The Property Price Register*, *National Deprivation Indices*, and the *2016 Irish Census*, while the spatial scales allow me to analyse travel behaviours and land-use configurations at sub-neighbourhood and municipality levels. In an Irish context, this corresponds to spatial units consisting of 18,641 (Small Areas) and 3,409 (Electoral Divisions) localities, while in a European context, this scale consists of standardised 1km x 1km (and 2km x 2km) grids across 28 city-regions. When analysing individual travel behaviours in the Republic of Ireland, I place 1,597,789 people within these 18,641 and 3,409 spatial units. This depth in scope and scale improves our understanding of the spatially heterogeneous interrelationships between individual socio-demographics, built and social environments, trip-specific concerns, and travel behaviours along the urban-rural continuum, while also providing more refined insights into the sustainability and efficiency of land-use configurations across European city regions and the Republic of Ireland as a whole. The academic contributions specific to each empirical chapter are outlined below.

Chapter 3 is the first of six empirical chapters in this thesis. The objective of this chapter is to assess land-use distributions and their spatial pattern across the Republic of Ireland. Land-use mixing is the empirical instrument employed as it offers a robust instrument for measuring land-use mixing/segregation, a key metric for policymakers concerned with developmental sustainability and the relative efficiency of land and infrastructure use. **Chapter 3's** principal contribution to existing literature is that it presents visualisations of land-use patterns and configurations through high-quality cartography. But it also provides a replicable methodology for merging traditional land-use data sources (The CORINE Land Cover) and more refined opensource data, like that from OpenStreetMap. The maps presented in this chapter illustrate how both datasets classify land-use and their subsequent strengths and weaknesses, but they also present estimates of land-use mixing and compare cross-dataset differences in these estimates at highly disaggregated spatial scales, answering numerous calls in existing literature (Druga and Minár, 2018; Ahrens and Lyons, 2019; Gao *et al.*, 2020; Strollo *et al.*, 2020; Calka, 2021; Fleischmann and Arribas-Bel, 2021; Arribas-Bel, 2022). The principal finding of this

chapter is that the CORINE Land Cover fails to distinguish unique land-uses at refined spatial scales, a problem which can be improved by incorporating OpenStreetMap data. This adds to the growing body of literature indicating that opensource data can be used to elevate our understanding of development configurations (Haklay, 2010; Fan *et al.*, 2014; Patias *et al.*, 2021), thereby allowing us to make inferences regarding the sustainability and efficiency of land and infrastructure use across the Republic of Ireland, inferences which have direct implications for regional land-use policies.

Chapter 4 investigates land-use configurations, and the subsequent patterns in their distribution, across Irish metropolitan areas. Using theories of regional expansion embedded in urban economics alongside the historical context of the Irish planning system, this research endeavours to explain why different patterns of land-use configurations emerge. This chapter uses land-use mixing as its empirical instrument, given its prominence within the regional development and urban planning literature, and use this instrument to make inferences regarding the sustainability and efficiency of land and infrastructure use. There is a growing literature which analyses regional development in Ireland. This literature investigates issues like labour markets (Crowley *et al.*, 2021), metropolitan governance (Moore-Cherry and Tomaney, 2019; Clifford *et al.*, 2022), population dynamics (J. O’Driscoll *et al.*, 2022), retail landscapes (C. O’Driscoll *et al.*, 2022a, 2022b), and travel behaviours (Vega and Reynolds-Feighan, 2008; O’Riordan *et al.*, 2022). I contribute to this literature by combining data-driven approaches to morphological assessments and theory-driven approaches to explaining these morphologies, thereby improving our fundamental understanding of regional development structures (Correia, Moore and Goodwin, 2021; Arribas-Bel, 2022). The principal finding of this chapter is that land-use mixing generally peaks in central areas and tends to decrease as distances from hubs increase and that these estimates are highly volatile in urban cores. This allows me to analyse the interrelationships between regional economic and environmental outcomes, settlement patterns, and policymaking instruments like zoning laws – key concerns in existing literature (Boustan, 2012; Gould Ellen and O’Regan, 2012; Jargowsky, 2012; McDonald and McMillen, 2012; Song and Stevens, 2012).

Chapter 5 is a case-study which assess the added value of using opensource data in urban morphological research. Specifically, I merge the most prominent traditional land-use dataset (The CORINE Land Cover) and the most prominent Volunteered Geographical Information dataset (OpenStreetMap) and quantify the degree of land-use mixing within the Functional Urban Areas of 28 European capital cities. Specifically, I produce estimates of land-use mixing

across 162,037 localities (using a spatial scale consisting of standardised 1km x 1km grids) and compare cross-dataset and cross-city differences in these estimates, and the patterns inherent in their distribution, through high-quality cartography. Cross-country research into land-use configurations is typically limited by a lack of adequate and comprehensive spatial data, despite the opportunities provided by opensource data to address this issue (Badoe and Miller, 2000; Adolphe, 2001; Arribas-Bel, 2014, 2022; Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021). I contribute to this literature by developing data-driven classifications of land-use developments that provide a better understanding of settlement patterns and structures (Correia, Moore and Goodwin, 2021; Arribas-Bel, 2022). But I also provide a replicable methodology for incorporating this data into future regional studies. This allows me to evaluate the strengths and limitations of discipline-standard methodologies, while also offering improved empirical instruments for future research that provide more spatially-comprehensive insights into the sustainability and efficiency of land-use developments (Druga and Minár, 2018; Ahrens and Lyons, 2019; Calka, 2021). The principal finding of this chapter is that the incorporation of opensource data can enhance our understanding of built environments because of their ability to distinguish unique land-uses within otherwise homogenous urban fabrics, findings that are consistent across European city-regions – thereby justifying the use of opensource data in future regional research (Haklay, 2010; Mobasheri, Zipf and Francis, 2018; Patias *et al.*, 2021; Biljecki, Shin and Lee, 2023).

Chapter 6 investigates the interrelationships between individual socio-demographics, built and social environments, trip-specific considerations, and commute mode choices. The incorporation of spatial data that are typically segregated across studies constitutes a significant contribution to existing literature as it allows me to examine the relative influence different features of residential areas have on travel behaviours (Guerra *et al.*, 2018; Eldeeb, Mohamed and Páez, 2021; Guerra, Li and Reyes, 2022). The spatial data employed here captures land-use characteristics, area-level deprivation, transport infrastructure provision and area-quality indicators, alongside nationally comprehensive socio-demographic data from the 2016 Irish Census. This data facilitates the analysis of these relationships for 235,936 workers across 3,409 localities spanning the urban-rural continuum, allowing me to extend the comprehensiveness of the spatial scope typically employed in transportation studies (Guerra *et al.*, 2018; Cheng, Yan and Gao, 2020; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022). I use Generalised Structural Equation Modelling to facilitate the investigation of these interrelationships simultaneously within a Tiebout Sorting-Spatial Mismatch theoretical

framework (Ewing, Hamidi and Grace, 2016; Gim, 2018; De Vos *et al.*, 2021). This addresses concerns that traditional modelling structures (i.e., Multinomial Logit Regression) cannot account for the confounding nature of these variables and that generally, the inter-relatedness of socio-demographics, residential environments, and travel considerations remains poorly understood (Ahrens and Lyons, 2019; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022). One key finding of this work is that areas which reduce time-space geographies and provide high-quality multi-modal transport infrastructure exhibit greater levels of public and active transport use when compared to other areas, an effect which is independent of socio-demographic considerations.

Chapter 7 addresses concerns that the relationships between residential environments, destination environments, and travel mode choices requires greater understanding, particularly outside of a commuting context (Ding, Cao and Wang, 2018; Ton *et al.*, 2019; Wang *et al.*, 2021; Jeong, Lee and Gim, 2022). I employ a nationally comprehensive Census dataset of students engaged in secondary education as well as highly disaggregated spatial data capturing land-use configurations, transport infrastructure, and social environments in residential and school locations. The spatial scale used consists of 18,641 localities within the Republic of Ireland and enables me to effectively distinguish between residential and school environments. By doing this, I answer calls for greater research into the potentially heterogenous effects of residential and destination (school) environments on travel behaviours (Ding, Cao and Wang, 2018; Wang *et al.*, 2021; Jeong, Lee and Gim, 2022). Specifically, I investigate the travel behaviours of 297,968 students residing along the urban-rural continuum using a Generalised Structural Equation Modelling framework, adding a national perspective to an otherwise regionally-segmented literature (Broberg and Sarjala, 2015; Curtis, Babb and Olaru, 2015; Ermagun and Samimi, 2015; Lee, Vojnovic and Grady, 2018; Charreire *et al.*, 2021; Jacob *et al.*, 2021; Loraamm and Mustain, 2022). One key finding of this work is that landscapes which reduce regional time-space geographies exhibit greater odds of public and active transport use relative to cars (effects which are stronger in residential areas) and that increases mode-specific infrastructure (i.e., roads) provision are associated with greater odds of mode-specific (i.e., cars) use, relative to alternative modes.

Chapter 8 presents a counterfactual analysis of the environmental degradation attributable to travelling when shopping. A key issue within this literature constitutes investigating the economic, environmental, and social outcomes attributable to the location of major retail centres (Dennis, Marsland and Cockett, 2002; Määtä-Juntunen *et al.*, 2011; Erdin and Akbas,

2019). I contribute to this literature by investigating the travel-induced environmental degradation associated with regional retail landscapes across Irish city-regions (Määttä-Juntunen *et al.*, 2011; Rasouli and Timmermans, 2013; Ahmad and Hiyasat, 2017). Specifically, I apply central place and gravity frameworks to analyse the environmental degradation attributable to travel behaviours using Origin-Destination matrices. To do this, commuting data from the 2016 Irish Census is adapted to proxy the preferred mode of travel when shopping and thereafter used to quantify the hypothetical CO₂ emissions attributable to travelling from 18,641 residential areas to the most attractive regional retail centre, of which there are 103 across the five Irish city-regions. The highly disaggregated spatial scale and comprehensive transport network data (stemming from OpenStreetMap) used in this research facilitates investigations into how this degradation relates to surrounding land-use configurations. One key finding of this work is that travel-related emissions are highest at retail centres located in fringe areas and areas characterised by poor multi-modal transport accessibility, something attributable to increased car-use.

1.3 Structure of The Thesis

Chapter 2 reviews existing literature on the economic, environmental, and social dimensions of regional development as well as the relationship between land-use configurations and travel behaviours. This chapter describes key theoretical frameworks based in urban economics, transport economics, quantitative geography, and human geography while also providing background on the relationship between land-use and transport policies, something supplemented by a historical account of regional development patterns in Ireland and Europe. Finally, this chapter evaluates the environmental, economic, and social inefficiencies attributable to current developmental forms and illustrates how policymakers can alleviate these problems.

Chapter 3 is the first empirical chapter of this thesis. I present visualisations of land-use mixing across the Republic of Ireland using two unique datasets: The CORINE Land Cover and OpenStreetMap. Cross-dataset differences in land-use mixing estimates are visualised using a spatial typology distinguishing between areas exhibiting low and high levels of land-use mixing alongside areas exhibiting relatively low and high cross-dataset differences in land-use mixing. This chapter is published as: O'Driscoll, C., Crowley, F., Doran, J. and McCarthy, N. (2023) 'Measuring land-use mixing across the Republic of Ireland: source data comparisons', *Journal of Maps*, 19(1), pp. 1–7. doi: 10.1080/17445647.2023.2214165.

Chapter 4 is the second empirical chapter of this thesis. This chapter assesses patterns of land-use mixing within and across Irish metropolitan areas. I assess the sustainability and efficiency of land and infrastructure use in these city-regions and discuss how these configurations may be influenced by policymaking mechanisms. This chapter is published as: O'Driscoll, C., Crowley, F., Doran, J. and McCarthy, N. (2023) 'Land-use mixing in Irish cities: Implications for sustainable development', *Land Use Policy*, 128(5), pp. 1–7. doi: 10.1016/j.landusepol.2023.106615.

Chapter 5 is the third empirical chapter of this thesis. This chapter investigates whether the incorporation of opensource land-use data can enhance the datasets used to analyse the sustainability and efficiency of land-use configurations across Europe. I compare land-use mixing estimates generated from the CORINE Land Cover dataset and a combined CORINE-OpenStreetMap land-use catalogue. Thereafter, I evaluate each dataset's relative robustness and assess policymaking mechanisms that can facilitate shifts away from unsustainable and inefficient land-use development. This chapter is under consideration for publication in *European Urban and Regional Studies*.

Chapter 6 is the fourth empirical chapter of this thesis. This chapter investigates the interrelationships between socio-demographics, residential built and social environments, trip-specific concerns, and commute mode choices. I employ Generalised Structural Equation Modelling to measure the interrelationships between these variables using individual-level data from the 2016 Irish Census on 235,936 workers across the Republic of Ireland alongside spatially disaggregated built environment, social environment, and transport infrastructure data. This chapter is published as: O'Driscoll, C., Crowley, F., Doran, J. and McCarthy, N. (2023) 'How the relationship between socio-demographics, residential environments, and travel influence commuter choices', *Regional Studies*, pp. 1–18. doi: doi.org/10.1080/00343404.2023.2199779.

Chapter 7 is the fifth empirical chapter of this thesis. This chapter investigates the interrelationships between individual socio-demographics, residential built and social environments, school-location built and social environments, trip-specific concerns, and travel mode choices on school-runs using a Generalised Structural Equation Modelling framework. I use individual-level Census data for 297,968 students across the Republic of Ireland, spatially disaggregated land-use and transport infrastructure data, alongside random-effects which proxy

for safety concerns surrounding travel routes. This chapter is under consideration for publication in *The Journal of Transport Geography*.

Chapter 8 is the sixth empirical chapter of this thesis. This chapter examines how location-effects influence hypothetical travel-related emissions and travel mode choices when shopping in Ireland's five major city-regions. I adapt commuting data from the 2016 Irish Census and use retail and residential location data to estimate hypothetical travel-related emissions within a multi modal transportation network. This chapter is published as: O'Driscoll, C., Crowley, F., Doran, J. and McCarthy, N. (2022) 'Retail sprawl and CO2 emissions: Retail centres in Irish cities', *Journal of Transport Geography*, 102(6), pp. 1-12. doi: 10.1016/j.jtrangeo.2022.103376.

Chapter 9 presents the conclusions of this research by compiling the key findings of the different empirical chapters within this thesis. I also provide policymaking recommendations, a discussion on the limitations of this research and detail an agenda for future research.

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Chapter 2: Literature Review

This chapter provides background on the extant literature which informs later empirical chapters and describes the wider conceptual frameworks in which this thesis operates. Given the interdisciplinary nature of this research, this review is structured as a disciplinary overview of how economists, geographers and planners typically analyse the themes within this thesis. *Section 2.1* outlines the relevant theoretical and empirical approaches to analysing regional development from the perspective of urban, regional, and transport economics. *Section 2.2* outlines the relevant theoretical and empirical approaches to assessing regional development patterns from the perspective of urban, economic, and quantitative geography, paying particular attention to the empirical opportunities and challenges associated with using opensource data. Finally, *Section 2.3* outlines the relevant approaches to analysing regional development from the perspective of regional/urban planning. It does this by detailing the historical context of regional development patterns and urban sprawl in Ireland and Europe while also describing how policymaking mechanisms shape these developmental patterns.

2.1 Regional Development: An Economics Perspective

A key concern within urban and regional economics is how supply, demand, institutional, technological, and spatial considerations influence development patterns and growth trajectories. A general framework for assessing this problem is that of the regional product lifecycle, which details how value-creation changes as technology and the spatial characteristics of areas evolve (Dong *et al.*, 2017; Juraschek *et al.*, 2018). Value-creation is typically assessed in the context of output and growth, whereby variables like industrial composition, human/social capital, and labour market fluidity take on high degrees of theoretical and empirical significance (Glaeser, 2011). But also implicit (and more relevant to the research conducted in this thesis) is the fact that technology (especially that pertaining to transport) is a key determinant of regional spatial structures and the subsequent location decisions of economic agents (Dieleman and Wegener, 2004; Arnott, 2012; Green, 2012; Knowles, Ferbrache and Nikitas, 2020). In this context, evidence suggests that rapid improvements in transport technologies (i.e., the commercialization of private cars) extended the spatial boundaries of regions by significantly reducing travel costs, thereby significantly altering regional spatial structures and the location decisions of individuals/firms (Button, 2010; Holz-Rau and Scheiner, 2019). This is what allowed regional value-creation to shift from industrial cityscapes and move toward modern service-based economies and associated developmental patterns (Dieleman and Wegener, 2004; Knowles, Ferbrache and Nikitas,

2020). Although a rather generic framework, the regional product lifecycle paradigm offers important insights into the role of land-use and transport in shaping economic outcomes, but additional frameworks provide more nuanced insights into these phenomena.

2.1.1 Monocentric Regional Spatial Structures

Regional spatial structures illustrate the distribution of economic and social activities within given territories. Subsequently, they offer unique insights into the various mechanisms which might influence the location decisions of economic agents (i.e., individuals and firms), but also offer indications as to how different economic or social variables might impact expansion/development patterns (Anas, Arnott and Small, 1998; Nechyba and Walsh, 2004; Dominguez, Sierra and Ballesteros, 2021). Perhaps the most significant framework in this context stems from Von Thünen's theory of land-use which posits that transport costs are the most significant variable in influencing location decisions (Wartenberg and Hall, 1966). In this model, transport costs define the spatial extent of regions, meaning location decisions within these boundaries are a function of a land-owner's return on investment in the land and transport costs, something usually approximated by distances from urban centres (Wartenberg and Hall, 1966; Peet, 1970; Beckmann, 1972). Subsequently, if transport costs reduce (say, because of technological advances), regional boundaries expand, something which may prompt changes in location decisions (Evans, 1983; Parr, 2015b, 2015a; Walker, 2022). The context in which Von Thünen's theory of land-use was developed meant there was little consideration given to the role of urban systems and that the urban-rural divide was largely a binary demarcation (Samuelson, 1983; Parr, 2015a). But rapidly evolving transport technologies and changing developmental landscapes prompted revisions in this framework, revisions which led to the development of monocentric (and polycentric) theories of land-use and regional expansion.

Monocentric theories of land-use investigate how supply and demand constraints affect development patterns (Alonso, 1964; Muth, 1969; Mills, 1972; Evans, 1983). They generally argue that changes in population, income, transport technology, and land values determine urban structures, and that regional expansion occurs homogeneously around a singular regional core (Alonso, 1964; Evans, 1983; Brown, 1993; Paulsen, 2012). Like Von Thünen, the key focus of these theories is how the location decisions of economic agents are shaped by land values and transport costs. The theoretical logic is that the value of/demand for land and space incrementally decreases with distances from these regional hubs whereby the magnitude of the increment is determined by transport technologies (i.e., travel times) (Evans, 1983; Oueslati, Alvanides and Garrod, 2015). Subsequently, land is allocated to the highest bidder, a

framework which reflects how different agents (i.e., households and firms) face different trade-offs between the travel costs induced by location decisions and the accessibility of economic and social opportunity, trade-offs often referred to as ‘accessibility premiums’ (Guy, 1998; Oueslati, Albanides and Garrod, 2015; Weilenmann, Seidl and Schulz, 2017; Erdin and Akbas, 2019). Within these frameworks, transport technologies and infrastructure determine the ability of regions to expand horizontally or vertically, whereby these accessibility premiums can be approximated to the amenity value of different locations, a value which differs depending upon the agent (Ahlfeldt and Pietrostefani, 2019). For instance, households usually value minimising land rents whereas firms usually value the benefits associated with agglomeration (Evans, 1983; Arnott, 2012; Green, 2012; Hanushek and Yilmaz, 2012).

From a land-use perspective, these theories indicate that unique land-uses will value the costs/benefits associated with location decisions differently. Specifically, agricultural land-uses normally require economies of scale/scope, residential land-uses generally value low land-rents, while industrial/commercial land-uses typically value market access and proximity to major urban centres/infrastructure (Evans, 1983; Arnott, 2012; Green, 2012). As a consequence, these theories predict that agricultural land-uses will concentrate in peripheral areas, industrial/commercial land-uses will concentrate in urban centres, and residential land-uses may disperse/concentrate anywhere in between (Arnott, 2012; Green, 2012). This implies that monocentricity will result in the concentration of economic opportunity in-and-around regional hubs with residential areas uniformly dispersing around said hub – spawning inward commuting from peripheral areas (Paulsen, 2012). But it also suggests that the clustering and mixing of land-uses will decrease with distances from regional cores, thereby accounting for reductions in the demand for space, but also partially explaining why and how settlement patterns like suburbs² emerge (Nechyba and Walsh, 2004; Carruthers and Úlfarsson, 2008; Jaeger, Bertiller, Schwick and Kienast, 2010).

2.1.2 Polycentric Regional Expansion

As regions grow over time and transport technologies continue to evolve, the supposition that regional expansion revolves around a singular hub has been questioned. The emergence of “edge cities” in certain contexts has created spatial dynamics where there are multiple

² Suburbs are the settlement pattern which emerges as a result of suburbanisation. Suburbanisation is defined by the physical spread of residential areas beyond traditional urban cores, whereby peripheral expansion rates exceed those of urban centres (Rogers, Castree and Kitchin, 2013). They can be generally characterised by low settlement densities and high degrees of land-use segregation (Nechyba and Walsh, 2004; Weilenmann, Seidl and Schulz, 2017; Albouy *et al.*, 2019).

economic hubs within regions, also known as polycentric regions (Nechyba and Walsh, 2004; Wang, Derudder and Liu, 2019). From a theoretical perspective, polycentricity of this nature can occur for many reasons. It is largely attributable to changes in land rents and transport costs to such an extent that the traditional locational advantages associated with historical urban centres diminish, but it can also occur if regional horizontal expansion becomes impossible, thereby prompting increases in vertical expansion (Anas, Arnott and Small, 1998; Tabuchi, 2011; Persky and Wiewel, 2012). In the case of the former, a dispersion of economic activities is incentivized and cluster formations can emerge, while for the latter densities will increase in areas deemed most valuable to populations, firms, and industries (Anas, Arnott and Small, 1998; Nechyba and Walsh, 2004; Tabuchi, 2011; Persky and Wiewel, 2012). This emphasis on the attractiveness of locations provides direct linkages to theories of spatial mismatches which explicitly analyse the reasons behind why regional investment/development is unevenly distributed across space (Zenou and Boccard, 2000; Nechyba and Walsh, 2004; Tyndall, 2017; Picard and Zenou, 2018; Aïkous *et al.*, 2023; Dubé *et al.*, 2023).

Theories of polycentricity conclude that *truly* polycentric regions eliminate the need for inward commuting to traditional regional cores if an equilibrium between residential dispersion and the provision of economic opportunity (i.e., jobs) is found, and thus create efficiency out of decentralised developmental forms like urban sprawl (Gordon, Kumar and Richardson, 1989; García-Palomares, 2010; Anas, 2012; Gordon and Richardson, 2012). This is because these areas create alternative destinations for economic and social activity, catalysing increases in the self-sufficiency of peripheral developments (García-Palomares, 2010; Anas, 2012; Gordon and Richardson, 2012; Tsai, 2015). The economic logic is regional expansion usually commences with residential dispersion, but is eventually accompanied by commercial/job decentralisation, whereby businesses vacate central areas because the net benefits associated with being centrally located are eliminated (Tabuchi, 2011). Subsequently, the dispersion of employment centres and residential areas becomes symmetrical, potentially reducing the negative externalities associated with regional development, particularly those related to travel and land-use if these developments are accompanied by increasing settlement/population densities (Anas, 2012; Gordon and Richardson, 2012; Persky and Wiewel, 2012).

2.1.3 Spatial Mismatches and Tiebout Sorting: The Relationship Between Socio-Demographics and Regional Spatial Structures

The previous sections illustrate how economic theories can help us understand the location decisions of different economic agents from the perspective of land-rents and transport costs.

However, these theories implicitly assume that regional expansion, investment, and development occurs homogenously and evenly around one (monocentric) or many (polycentric) urban centre(s) (Anas, Arnott and Small, 1998; Nechyba and Walsh, 2004). Regional expansion, human activities, and associated transport infrastructure is known to distribute unevenly across space. Although this can simply be the result of geographical phenomena like morphological considerations (Aïkous *et al.*, 2023; Dubé *et al.*, 2023), spatial mismatch theories argue that uneven spatial distributions of investment and development is more-so related to socio-demographic considerations (Zenou and Boccoard, 2000; Nechyba and Walsh, 2004; Tyndall, 2017; Picard and Zenou, 2018; Aïkous *et al.*, 2023; Dubé *et al.*, 2023).

Spatial mismatch theories imply that regional investment and development will concentrate in areas characterised by relative affluence in what is normally observed as a recursive relationship (Nechyba and Walsh, 2004; Button, 2010). Over time, this can create spatial imbalances in the quality of local infrastructure and may warp the spatial distribution of commercial and residential decentralisation (Samuelson, 1954; Tiebout, 1956; Hanushek and Yilmaz, 2007; Shen, 2017; Picard and Zenou, 2018; Bastiaanssen, Johnson and Lucas, 2022). Subsequently, this may create imbalances in the accessibility of economic and social opportunity across different socio-demographic cohorts, imbalances which may disproportionately favour relatively affluent areas (Glaeser, Kahn and Chu, 2001; Travisi, Camagni and Nijkamp, 2010; Guerra *et al.*, 2018; Guirao, Casado-Sanz and Campa, 2018; Guerra, Li and Reyes, 2022). Therefore, relatively deprived areas may receive less infrastructure investment, may find it disproportionately difficult to access economic (and social) opportunity locally, and may subsequently lag behind more affluent regions/localities in terms of economic and social growth (Chen and Vickerman, 2017; Tyndall, 2017; Curl, Clark and Kearns, 2018). Over time, this may create social exclusion and hinder social mobility, especially if economic and social opportunities are not accessible by multiple modes³ (Nechyba and Walsh, 2004; Boustian, 2010; Giuliano, 2012; Tyndall, 2017; Guirao, Casado-Sanz and Campa, 2018; Picard and Zenou, 2018; Allen and Farber, 2019).

These negative feedback loops stem from a tension between regional expansion and population distributions. Clearly, individuals, households, and firms value different location

³ This can create transport poverty. Transport poverty is the accumulation of socioeconomic and transport accessibility disadvantage whereby the social mobility of relatively deprived persons is hindered as a direct consequence of inaccessibility to amenity and employment destinations (Ewing *et al.*, 2016; Allen and Farber, 2019).

characteristics, but the amenity value of locations for all users is heavily linked to transport infrastructure (Ahlfeldt and Pietrostefani, 2019). Considering this, if development and investment concentrates in-and-around highly affluent and high-growth areas, this will be reflected in population/activity distributions whereby relatively deprived populations become disproportionately affected (Button, 2010; Green, 2012; Curl, Clark and Kearns, 2018). This phenomenon is illustrated by models of population ‘sorting’, which argue that individuals’ preferences regarding the consumption of public goods (like land-use configurations and transport infrastructure) manifest through residential locations, whereby the decision to move (or not to move) becomes analogous to willingness to pay⁴ (Samuelson, 1954; Tiebout, 1956). In other words, people of shared socio-demographic status are assumed to share similar tastes and preferences in public good provision and are also assumed to have similar socioeconomic (i.e., employment) aspirations (Nechyba and Walsh, 2004; Hanushek and Yilmaz, 2007, 2012, 2013). This in turn leads to people of shared socio-demographic status to typically cluster in the same *types* of residential areas because they generally seek the same *types* of employment (Nechyba and Walsh, 2004). However, mobility is key, and the ability of individuals to realise these preferences is highly sensitive to the accessibility of travel-related resources and employment opportunities, something obviously linked to regional land-use configurations and transport infrastructure provision⁵ (Curl, Clark and Kearns, 2018; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022).

These models of residential location (and by extension regional development) have their roots in the history of racism and segregation (Boustan, 2010). Evidence suggests that the clustering and sorting of different population cohorts today stems from advances in transport technologies in the post-WW2 era; advances which allowed relatively affluent populations to acquire a rural residence but maintain an urban lifestyle⁶, thereby reducing their sensitivity to the accessibility

⁴ A Tiebout model of regional development is similar to mono- and poly-centric theories of development in that they all operate within a general equilibrium framework (i.e., location decisions change with incentives). But the latter assume that these decisions stem from trade-offs between land-rents and transport costs while the former assume that these decisions stem from public good provision and the accessibility of employment (Hanushek and Yilmaz, 2007, 2012, 2013).

⁵ One interesting conclusion of these models is that feedback loops become established once population cohorts settle in specific areas, prompting development patterns to become more aligned with residents’ tastes in preferences (Samuelson, 1954; Tiebout, 1956). Here, if development policies and practices are not aligned with these preferences, people will relocate to areas whose policies do align with these preferences, something which negatively impacts local policymakers and politicians (Garcia-Lopez, Nicolini and Roig, 2020).

⁶ Often quipped as a ‘Flight from Blight’, urban sprawl has been historically linked with sorting mechanisms which reflect middle- and upper-class desires to leave central areas in response to rising social stress in cities. This process led to reductions in property values, thereby facilitating greater intensities of sorting.

of local opportunities (Boustan, 2010; Button, 2010; Giuliano, 2012; Curl, Clark and Kearns, 2018; Walks, 2018). Conversely, relatively deprived cohorts could not avail of these advancements, so they remained sensitive to the accessibility of opportunities and therefore tended to cluster in residence in-and-around major economic and employment hubs (Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022). Considering this, the historical concentration of economic activity within urban centres, and the naturally high levels of connectivity within these areas, may have maintained a coincidental balance between socio-demographic sorting and the accessibility of opportunity (Thomas *et al.*, 2018).

However, increasing patterns of residential and commercial decentralization indicate that this is changing as firms/industries are increasingly vacating central areas in favour of more abundant (and cheaper) land in regional peripheries (Travisi, Camagni and Nijkamp, 2010; Guerra *et al.*, 2018; Guirao, Campa and Casado-Sanz, 2018; Guirao, Casado-Sanz and Campa, 2018; Guerra, Li and Reyes, 2022). This is problematic because these areas exhibit lower levels of accessibility and connectivity than central areas, something which may disproportionately impact vulnerable populations (Wassmer, 2002; Frenkel and Ashkenazi, 2008; Holz-Rau and Scheiner, 2019). Although the decreasing monetary costs of car-ownership (and subsequent use) may alleviate this problem by allowing relatively deprived cohorts to improve their accessibility to economic and social opportunity (Gordon and Richardson, 2012), increased car-use implies increasing the severity of travel-related externalities, like congestion, creating environmental and social issues, while also increasing the implicit costs of travel (Credit and Arnao, 2022; OECD, 2022). Subsequently, this may not fix the issues vulnerable populations face, rendering improvements in multi-modal transport networks and infrastructure vital (Tyndall, 2017; Curl, Clark and Kearns, 2018; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022; OECD, 2022). This is further supported by evidence suggesting that a disproportionately high proportion of these modes' ridership comes from relatively disadvantaged populations, illustrating the importance of land-use and transport policies in mitigating the adverse consequences associated with sorting, spatial mismatches, and regional development more generally (Reynolds-Feighan, 2003; Button, 2010; Giuliano, 2012; Tyndall, 2017; Ibraeva *et al.*, 2020; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022).

2.2 Regional Development: A Geography Perspective

2.2.1 Regional Spatial Structures and Geography: Central Place Theory and Spatial Interaction Models

A key concern within human and urban geography is the interrelationship between human mobility and regional spatial structures, an interrelationship which provides insights into how towns, regions, and cities grow, alongside the development patterns which follow (Huang *et al.*, 2020; Schlöpfer *et al.*, 2021). Central Place Theory is the dominant theoretical paradigm in this realm and it focuses on how different agents (i.e., households and firms) have heterogeneous location preferences (Mulligan, 1984; Guy, 1998). The core idea is that because economic activity is unevenly distributed across space, a hierarchy of locations will emerge as some locations (i.e., Central Business Districts) become more *central* to a region's activities than others (Mulligan, 1984; Clarkson, Clarke-Hill and Robinson, 1996). In this framework, settlements that are more central (i.e., higher-level) are assumed to offer more diverse, comprehensive, and luxurious types of economic activities/goods/services than peripheral (i.e., lower-level) settlements, and will therefore have larger catchment areas (Mulligan, 1984). This suggests that depending on the type of goods/services/activities agents require, they will only travel to the nearest available settlement to attain these, rendering distance and travel thresholds (i.e., catchment areas for different order goods/services) highly significant determinants of regional spatial structures (Clarkson, Clarke-Hill and Robinson, 1996; Dennis, Marsland and Cockett, 2002; Parr, 2015a). Therefore, central and peripheral locations can be distinguished according to whether they only serve local or regional populations, whereby people are assumed to travel further (but less frequently) to central locations and are assumed to not travel far (but more frequently) to lower-order locations⁷ (Dennis, Marsland and Cockett, 2002).

The main implications of this work are that regional spatial structures and the concentration of human activities are principally shaped by travel distances and travel thresholds (i.e., catchment areas) (Dennis, Marsland and Cockett, 2002). Evidence of the relative hierarchy of locations has been found across retail, agglomeration, and human mobility literature, illustrating that this hierarchy can exert major centralising effects which may exacerbate existing, or create new, imbalances across regions in economic, social, and

⁷ This theoretical framework is usually applied in a retailing context whereby settlements are assumed to represent shopping destinations. Here, higher-order shopping destinations sell more expensive and luxurious goods (i.e., High Streets) and subsequently attract much larger populations, whereas lower-order shopping destinations sell convenience goods (i.e., grocery stores) and subsequently mainly attract local populations (Clarkson, Clarke-Hill and Robinson, 1996; Guy, 1998; Dennis, Marsland and Cockett, 2002). Accordingly, this framework is often used to assess various 'retail location' problems.

environmental outcomes (Zandiatashbar and Hamidi, 2018; Hamidi and Zandiatashbar, 2019; Schlöpfer *et al.*, 2021; Kopczewska and Kopczewski, 2022). However, this also implies that location decisions and hierarchies are dependent on the accessibility of transport infrastructure/networks (Zandiatashbar and Hamidi, 2018; Schlöpfer *et al.*, 2021). Considering this, alternative theoretical approaches have emerged which stress the importance of variables related to the relative attractiveness of specific locations in defining locational hierarchies as opposed to just distance (Guy, 1998; Dennis, Marsland and Cockett, 2002; Erdin and Akbas, 2019). Principle of these are Spatial Interaction Models (also known as Gravity Models), which argue that agents' location decisions are a function of destination attractiveness and distance-decay effects (Clarkson, Clarke-Hill and Robinson, 1996). Not only does this acknowledge the complexity of regional location hierarchies (i.e., mono- and poly-centricity), but it also provides a framework for assessing how this trade-off relates to variables like land values and the emergence of agglomerations/clusters within regions (Clarkson, Clarke-Hill and Robinson, 1996; Taylor, Hoyler and Verbruggen, 2010; Huang *et al.*, 2020). Applying these theories to a land-use context suggests that a larger diversity of land-uses will concentrate in more central (or more attractive) areas, as this is where the competition/demand for space is most fierce, and that this will diminish with distance (Mulligan, 1984; Clarkson, Clarke-Hill and Robinson, 1996; Dennis, Marsland and Cockett, 2002).

2.2.2 Time-Space Geographies: Land-Use Configurations, Transport Infrastructure, and Subsequent Behaviours

Land-use distributions determine the location and intensity of human activities and therefore the degree of time-space isolation faced by individuals, localities, and regions (Hägerstrand, 1970; Reynolds-Feighan, 2003). Time-space geographies is a concept used to describe the spatial expanse of regions, the efficiency of transport networks and infrastructure, and is explicitly linked to required travel distances/times and subsequently, regional spatial structures (Hägerstrand, 1970). From a landscape perspective, developments can either expand horizontally or vertically. The former increases time-space geographies and reduces settlement densities while the latter reduces time-space geographies and increases settlement densities, *ceteris paribus*. Outward expansion increases the spatial demands of regional development, and by extension the levels of natural landscape destruction attributable to such developments (Nechyba and Walsh, 2004; Kwan, 2013; Millward, Spinney and Scott, 2013). This can negatively impact the realm of travel as outward regional expansion can reduce regional connectivity and accessibility to multi-modal transport infrastructure, changes associated with

increased car-use, arguably to the point of dependency, prompting increases in unsustainable travel (Martínez, 2008; Button, 2010; Travisi, Camagni and Nijkamp, 2010; Millward, Spinney and Scott, 2013; Ewing *et al.*, 2016; Chen and Vickerman, 2017; Guirao, Casado-Sanz and Campa, 2018; White, 2018). Subsequently, a long line of literature supports claims that more compact development forms (like those related to “X-minute cities”) have greater environmental, social, and economic benefits relative to those associated with more dispersed forms, like urban sprawl⁸ (Newman and Kenworthy, 1996; Dieleman and Wegener, 2004; Badland and Schofield, 2005; OECD, 2018b; Jain and Tiwari, 2019; Tikoudis *et al.*, 2022).

Interrelated with land-use configurations is the travel behaviours of people within areas and how these behaviours change depending on different individual-specific and area-based variables. In this context, individuals’ socio-demographic characteristics are typically regarded as exogenous variables that proxy for tastes and preferences (Ding *et al.*, 2017, 2018; Gim, 2018; Cheng *et al.*, 2019). Accordingly, variables like gender and household structures typically relate inconsistently across regions/nations, something largely attributable to differences in cultural/social norms⁹ (Vega and Reynolds-Feighan, 2008, 2009; Travisi, Camagni and Nijkamp, 2010). Conversely, variables like age, education attainment, trip-specific considerations (i.e., travel times), and socioeconomic status generally exhibit intuitive relationships with travel behaviours (Vandenbulcke, Steenberghen and Thomas, 2009; García-Palomares, 2010). For instance, car-use generally peaks in middle-ages, improvements in socioeconomic status, and education attainment typically prompt increased car-use, and larger required travel distances/times are associated with greater car-use (Button, 2010; García-Palomares, 2010; Travisi, Camagni and Nijkamp, 2010; Curl, Clark and Kearns, 2018; Walks, 2018; Allen and Farber, 2019).

⁸ Socially, more compact developmental forms facilitate increased social interactions and strengthen social fabrics, variables which positively spill-over into individual health and wellbeing (Jacobs, 1961; Glaeser and Gottlieb, 2006; Glaeser, 2011; Mouratidis, 2018b). Economically, compactness is associated with greater abilities to facilitate agglomeration and clustering, while also allowing firms/regions to retain proximity (accessibility) to competitors and labour markets (Porter, 2003; Zandiatashbar and Hamidi, 2018; Hamidi and Zandiatashbar, 2019). These variables significantly contribute to growth trajectories by facilitating increased knowledge exchange and network interactions, thereby stimulating innovation and competition (Glaeser, Kahn and Chu, 2001; Glaeser and Gottlieb, 2006; Gordon and Richardson, 2012; Hamidi and Zandiatashbar, 2019; O’Leary, Doran and Power, 2022).

⁹ In Ireland, evidence suggests that females are more likely to commute by car than males, an imbalance seemingly caused by demographic and location effects (Carroll *et al.*, 2020). In Germany, evidence suggests that women are less likely to use cars than males, something attributable to a hierarchy in household economic and social roles whereby the mode preferences of males are prioritised (Chidambaram and Scheiner, 2020). In China, evidence suggests that these roles are reversed whereby the travel behaviours of males is determined by female partners (Guan and Wang, 2019).

But these variables are also clearly subject to individual- and/or household-level considerations (Zolnik, 2012; Deka, 2013). At a household level, evidence suggests that the behaviours of parents directly influence those of children, something usually assessed through the prevalence of ‘generational habits’ (Pooley, 2010; Yang, Abbott and Schlossberg, 2012; Curtis, Babb and Olaru, 2015; Chakrabarti and Joh, 2019). Despite this, evidence suggests that land-use configurations and transport infrastructure provision exert a stronger influence over travel behaviours than socio-demographic variables at the individual and household level, and that it is these built environment configurations which shape generational habits to begin with (Vandenbulcke, Steenberghen and Thomas, 2009; Jun, 2012; De Vos, 2016; Zhao, Bentlage and Thierstein, 2017; Guerra *et al.*, 2018; Ton *et al.*, 2019; Gan *et al.*, 2021). This suggests that variables like accessibility, connectivity, compactness, and mixed-use are highly significant determinants of travel behaviours and by extension the environmental degradation attributable to regional development (Pooley and Turnbull, 2005; Vandenbulcke *et al.*, 2009; Lin and Chang, 2010; Wilson *et al.*, 2010; Van Goeverden and De Boer, 2013; Curtis, Babb and Olaru, 2015). In this context, evidence consistently shows that if places of interest and residential areas are closer together, and if regional transport infrastructure facilitates efficient multi-modal travel, increases in public and active transport use will occur (Millward, Spinney and Scott, 2013; O’Riordan *et al.*, 2022).

2.2.3 Quantitative Geography and Regional Development: The Modifiable Areal Unit Problem and Opensource Data

Spatial analysis mainly concerns investigations into the distribution of, and association between, variables within a given study area. The research in this thesis focuses on the distribution of human settlements and activities while also investigating how these considerations impact population distributions, human behaviours, and various economic, social, and environmental outcomes. But assessing these patterns is fraught with difficulties, namely the Modifiable Areal Unit Problem (MAUP). The MAUP occurs when analyses of spatial phenomena (i.e., land-use configurations) create results which are sensitive to the scale at which these phenomena are analysed (Openshaw, 1984; Dark and Bram, 2007). Generally, spatial units are delineated according to administrative boundaries or uniform grids (Fleischmann and Arribas-Bel, 2021). Both methods involve superimposing morphologically arbitrary spatial units across study areas and may subsequently fail to reflect the true economic, social, and environmental contexts of the study area (Openshaw, 1984; Dark and Bram, 2007; Fleischmann and Arribas-Bel, 2021). This can create uncertainties regarding whether the

geographical units employed accurately reflect the relationships under study¹⁰ (Openshaw, 1984; Dark and Bram, 2007; Kwan, 2012).

Within existing literature, the most common way of addressing this is by replicating the analysis using multiple spatial scales, something which facilitates a direct examination of the sensitivity of results to spatial scales (Openshaw, 1984). But this can raise concerns related to scaling; that is, the rationale behind choosing specific levels of spatial disaggregation over others. Regional science is a discipline dedicated to enhancing our understanding of the relationship between places and people, while also seeking to assess the impacts of different policymaking initiatives across space (Hägerstrand, 1970; Reynolds-Feighan, 2003; Cerin *et al.*, 2007; Manaugh and Kreider, 2013). To acquire a nuanced understanding of the former requires research at spatially disaggregated levels, while the latter implies that findings should be accrued at spatial scales which are meaningful to local, regional, and national policymakers (i.e., administrative units). Therefore, assessing these problems requires the use of spatial scales which accurately reflect communities, localities, and municipalities – areas usually associated with Local Administrative Units. In an Irish context, these correspond to Electoral Divisions and Small Areas, of which there are 3,409 and 18,641 respectively. Electoral Divisions constitute the smallest administrative unit within the state, while Small Areas capture localities hosting between 80-120 households, thereby allowing this research to provide insights at local and regional levels (Central Statistics Office [CSO], 2016).

The most important advance in studying regional development through the lens of land-use configurations and transport infrastructure has arguably come from the development of mapping technologies and Geographical Information Systems more generally (Heywood, Cornelius and Carver, 2006). These methodological advances have allowed researchers to elevate our understanding of spatial phenomena like regional development patterns, land-use distributions, transport infrastructure, alongside how these relate to travel behaviours and the accessibility of opportunity. But they have been somewhat restricted by data limitations whereby technological advances had not yet made refined land-use, infrastructure, and network data readily available (Cervero and Radisch, 1996; Cervero and Kockelman, 1997; Badoe and Miller, 2000; Adolphe, 2001; Skonhoft and Solem, 2001; Arribas-Bel, 2014). However, recent

¹⁰ Importantly, methods of delineating spatial units using more fluid boundaries (i.e., breaks in natural landscapes) are emerging, but they are not yet operational at large scales, rendering administrative units (and uniform grids) the most effective units to use when assessing spatial phenomena (Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021; Arribas-Bel, 2022).

advancements in data science and the increasing availability of Big Data have re-defined the data landscape available to applied researchers. These advancements have provided unprecedented depth and refinement in data catalogues (like those concerning land-use composition and transport networks), but have also facilitated improvements in network analysis and remote sensing techniques (Thériault *et al.*, 1999; Badoe and Miller, 2000; Heywood, Cornelius and Carver, 2006; Rey *et al.*, 2011; Batty, 2012; Arribas-Bel, 2014; Reis, Silva and Pinho, 2016). Similarly, improvements in the quality and availability of opensource data have allowed scholars to analyse spatial phenomena at highly disaggregated spatial scales while also enhancing the depth and refinement of land-use, infrastructure, and population data across space (Rey *et al.*, 2011; Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021).

The opensource data most frequently employed in this thesis stems from OpenStreetMap. OpenStreetMap is the world's largest Volunteered Geographical Information (VGI) dataset, and a long line of international literature argues that its quality (i.e., accuracy) is comparable in quality (if not better in certain contexts (Fleischmann and Arribas-Bel, 2021)) to that of more traditional data sources, like the CORINE Land Cover in a land-use and transport infrastructure context (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018). However, because these data are volunteered, its quality and accuracy tend to decrease in peripheral and rural areas due to the diminishing number of contributors in these areas (Haklay, 2010; Fan *et al.*, 2014). In an Irish context, these conclusions are also reached by Cipeluch *et al.*, (2010) and Mooney, Corcoran and Winstanley, (2010), suggesting that there are no unique risks associated with using these data in an Irish context. Indeed, Herfort *et al.*, (2023) in the most recent global assessment of the quality and completeness of OpenStreetMap land-use data confirm how land-use data sourced from OpenStreetMap is comparable in accuracy to more authoritative datasets (i.e., CORINE, Urban Atlas, Global Human Settlement) while also exceeding 80% in the completeness of its coverage in urban areas within an Irish and European context, justifying its use in regional-focused research. Another attractive quality of OpenStreetMap land-use data is that it classifies land-use according to function, a characteristic which distinguishes it from other datasets (i.e., The CORINE Land Cover, The Urban Atlas, and The Global Human Settlement) that classify land-use according to form (Mobasheri, Zipf and Francis, 2018; Herfort *et al.*, 2023). This is important because a growing body of evidence suggests that datasets which focus on function instead of form offer unique opportunities to enhance our understanding of land-use configurations by providing fine-grain

insights into land-use compositions (Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Fleischmann and Arribas-Bel, 2021; Singleton and Arribas-Bel, 2021; Arribas-Bel, 2022). From a transport perspective, infrastructure, network, and node data is only partially volunteered in OpenStreetMap as it is largely sourced directly from national institutions (e.g., (Road Safety Authority [RSA], 2021; Transport Infrastructure Ireland [TII], 2023)), hence explaining its wide use in existing literature (e.g., Vega and Reynolds-Feighan, (2016)).

2.3 Regional Development In Europe and Ireland: A Planning Perspective

2.3.1 Land-Use Configurations Across European Regions: Urban Sprawl and Compact Development

Regional development and expansion can take numerous forms. Historically, many regions had one economic/urban hub and limited transport technologies required that all development and expansion revolved around this hub (Oueslati, Albanides and Garrod, 2015; Tikoudis *et al.*, 2022). But rapid advances in transport technologies (especially the commercialisation of private cars) in the mid-twentieth century provided greater flexibility to planners by reducing regional transport costs. Not only did this facilitate greater levels of outward expansion, but it also led to a departure from traditional planning paradigms (that created compact industrial cityscapes) and a shift toward the development of modern cityscapes characterised by service economies and widespread expansion (Ewing, 1997; Nechyba and Walsh, 2004; Winston, 2007). In this regard, numerous different types of developmental patterns emerged in the post-WW2 years but the most prominent of these was urban sprawl, a developmental pattern generally characterised by high-degrees of land-use segregation, low residential densities, and limited multi-modal transport infrastructure/use¹¹ (Jaeger, Bertiller, Schwick and Kienast, 2010; Jaeger, Bertiller, Schwick, Cavens, *et al.*, 2010; Jaeger and Schwick, 2014). The emergence of urban sprawl is attributed to the commercialisation of private cars because this increased the demand for road space, but it was also accompanied by an infatuation toward visions of The American [Suburban] Dream, prompting increases in the demand for suburbanisation (Freilich and Peshoff, 1997; Razin, 1998; Pendall, 1999; Blanchard *et al.*, 2003; Pooley and Turnbull, 2005; Bielenberg and Ryan, 2012; Kullmann, 2015). This shift has been long-lasting as many city-regions within OECD countries still exhibit symptoms of (or

¹¹ Broadly speaking, alternative developmental patterns to urban sprawl (i.e., leapfrog development) only marginally differ in these characteristics, and urban sprawl is the developmental paradigm most relevant to an Irish context, hence why these alternatives are not expanded upon further in this thesis.

are largely characterised by) sprawling developmental patterns (European Environmental Agency [EEA], 2006; OECD, 2018b).

Urban sprawl, as experienced across Europe, took place in a context where city-regions had one historical urban centre, meaning regional expansion usually revolved around said centre (European Environmental Agency [EEA], 2006). But expansion patterns and their associated investment were unevenly distributed across space, creating problems that were compounded by the typically self-interested nature of local planners and property developers, alongside the usually uncoordinated nature of local, regional, and national planning frameworks (Oueslati, Albanides and Garrod, 2015; Tikoudis *et al.*, 2022). In this context, a growing body of evidence suggests that sprawling developmental patterns negatively contribute to economic, social, and environmental objectives. From a planning perspective, this manifests as a land-use and transport policy issue as sprawling developmental patterns have high spatial demands because they prioritise outward regional expansion. Paired with the low-density nature of these developments, this increases natural resource consumption and exacerbates the levels of natural landscape destruction attributable to regional planning. Furthermore, these characteristics limit the ability of populations to regularly use public and active transport, prompting increases unsustainable travel behaviours (European Environmental Agency [EEA], 2006, 2015; OECD, 2018b, 2022).

Planning literature¹² that favours urban sprawl primarily argues that it constitutes a single stage within a larger regional expansion building cycle (Sultana and Weber, 2014). The underlying logic is that the creation of low-density settlements through peripheral expansion and residential dispersion may eventually subside as these areas mature (i.e., when they reach a point when further horizontal expansion becomes impossible). The maturation of areas is implied to be followed by increases in densities, thereby enhancing the efficiency of infrastructure use (Atkinson-Palombo, 2010; Sultana and Weber, 2014). However, implicit in these arguments is that settlements will eventually evolve into polycentric structures. This is a

¹² A smaller body of economics literature advocate urban sprawl as the bastion of consumer preference and economic efficiency (Gordon and Richardson, 1997, 2012; Anas, 2012). By offering affordable and spacious housing, suburbanisation can provide a safety net for young families who are priced-out of inner-cities by predatory rental practices (Gordon and Richardson, 1997; Razin, 1998; Picard and Zenou, 2018; Albouy *et al.*, 2019). However, evidence suggests that although urban sprawl *once* facilitated an unmet demand for affordable, low-density residential areas, this is not necessarily the case anymore (Ewing, 1997; Nechyba and Walsh, 2004; Boustan, 2010; Ewing *et al.*, 2014).

problem because insufficient decentralisation efforts, paired with extensive peripheral expansion, have thwarted the ability of European city-regions to become polycentric (and by extension self-sufficient) (Batten, 1995; Nechyba and Walsh, 2004; Tsai, 2015; OECD, 2018b; Schlöpfer *et al.*, 2021; Clifford *et al.*, 2022).

Although more compact developmental forms (i.e., polycentric developments) produce positive economic, environmental, and social outcomes, this transition has not occurred, something largely attributable to the fact that prevailing paradigms and instruments facilitate uncontrolled expansion across peripheries and uncoordinated regional development more generally (Oueslati, Alvanides and Garrod, 2015; Tsai, 2015). Subsequently, modern developmental landscapes are not only characterised by excessive natural landscape destruction, but also unsustainable travel behaviours and inequities in the accessibility of opportunity (Nechyba and Walsh, 2004; Ewing *et al.*, 2014; OECD, 2018b). This has forced policymakers to acknowledge that even if urban sprawl is one component of a natural regional expansion business cycle, it is too late to let this natural cycle unfold as the pressing climate crisis requires immediate transformative action (Paterson, 2000; Feitelson and Rotem, 2004; Goetz, 2013; Albouy *et al.*, 2018; OECD, 2018). This has prompted policymaking initiatives to shift toward emphasizing the importance of compactness, land-use mixing, and multi-modal connectivity when configuring future developments; a shift which has seen some positive economic, environmental, and social outcomes across global city-regions (European Environmental Agency [EEA], 2006, 2015; Giffinger and Suitner, 2015; Government of Ireland, 2018; OECD, 2018b; Derudder *et al.*, 2022; Ouweland, van Oort and Cortinovis, 2022; The United Nations, 2022).

2.3.2 Regional Development and Urban Sprawl in Ireland

Although the booming American and European economies of the post-WW2 era saw a rapid shift in developmental paradigms toward those favouring urban sprawl, the struggling Irish economic and political system was not able to fully adapt until the 1990s with the advent of the Celtic Tiger, providing a uniquely Irish context for the implementation of urban sprawl (Freilich and Peshoff, 1997; Reynolds-Feighan, 2003, 2016; Bielenberg and Ryan, 2012; Kullmann, 2015; Vega and Reynolds-Feighan, 2016). However, the unique relationship between regional development and Ireland not only has a temporal dimension, whereby Ireland sought to catch-up with European and American regional planning practices, but also a political dimension. This stems from Ireland's intense history of localised, territorial politics surrounding land usage and management, an issue which became compounded at this time due

to a lack of coordination between local, regional, and national objectives for development and growth (Scott, 2006; Winston, 2007; Moore-Cherry and Tomaney, 2019; Williams and Nedović-Budić, 2020). Indeed, Ireland consistently faltered in the implementation of strategic regional land-use planning between 1960-2010 (Albrechts, Healey and Kunzmann, 2003; Winston, 2007; Gkartzios and Scott, 2009; Williams and Nedović-Budić, 2020), whereas in Europe, strategic regional planning began to gain political weight from the 1980s onward, somewhat stabilising this uncontrolled expansion in many regions, hence explaining why shifts in developmental paradigms may emerge at different intervals across different countries/regions (Williams and Shiels, 2002; Albrechts, Healey and Kunzmann, 2003; Winston, 2007; Williams and Nedović-Budić, 2020).

In a comprehensive overview of Ireland's (economic) history during this timeframe, Bielenberg and Ryan, (2012) highlight how although these dimensions of regional development proved somewhat unique to Ireland, the manifestation of urban sprawl, and subsequent regional planning practices, in Ireland was consistent with global experiences. That is, urban sprawl, in an Irish context, created developmental landscapes characterised by large degrees of land-use segregation, low settlement densities, and limited multi-modal transport accessibility/use, something largely typified by suburbanisation and the persistent development of one-off housing (Reynolds-Feighan, 2003; European Environmental Agency [EEA], 2006, 2015; Bielenberg and Ryan, 2012). This naturally increased the spatial demands of regional development, thereby increasing the habitat destruction attributable to regional planning, but it also created lasting economic and social consequences (OECD, 2018b).

For instance, between the 1930s and 1990s, Dublin, like the other Irish cities, expanded via the outward dispersal of its population, leading to a decline in urban density. During this period, the Greater Dublin Area's (Ireland's capital city) population doubled, but its spatial expanse quadrupled (Winston, 2007, p. 62). This increased the per-capita costs of infrastructure, utility, and essential service provision, but it also led to a greater concentration of resources within these areas (Reynolds-Feighan, 2003). This created disproportionate disparities in investment, accessibility to employment, and social mobility between the five major cities and the rest of the country, as well as similar disparities along the East-West divide more generally whereby the East of Ireland is typically more heavily invested in and subsequently more prosperous¹³

¹³ This naturally has distinct impacts on migration patterns and population distributions. For instance, during this time there was a parallel, but sporadic, in-migration to city areas, as rural residents and workers sought greater economic and social opportunities. However, in general, these phenomena failed to balance, creating

(European Environmental Agency [EEA], 2006; Commins and Nolan, 2010, 2011; Cafferkey and Caulfield, 2012; Ahern, Vega and Caulfield, 2016; Rock, Ahern and Caulfield, 2016; Vega and Reynolds-Feighan, 2016; OECD, 2018a). But urban sprawl in Ireland took place in the context of an inefficient transport network and a virtually non-existent strategic transport planning framework (Winston, 2007). Paired with the fact that these developmental forms isolate residential areas from places of economic and social interest, it is clear why these developments have prompted increased car-use at the expense of more sustainable alternatives (Winston, 2007; De Vos *et al.*, 2021; O’Riordan *et al.*, 2022). Indeed, the proportion of people travelling to work by car went from 44% in 1980, to 62% in 2002¹⁴, and reached 76% in 2022 (Central Statistics Office [CSO], 2022), something which has exacerbated the environmental degradation associated with travel (by worsening the severity of negative externalities like congestion) but also compounded the problems associated with regional development in Ireland more generally (Reynolds-Feighan, 2003; Vega and Reynolds-Feighan, 2008; Crowley *et al.*, 2021; O’Riordan *et al.*, 2022).

Subsequently, planners today are grappling with the fact that the highly centralised and monocentric nature of regional development in Ireland has created regional landscapes which negatively contribute to economic, environmental, and social objectives. It is now clear that these centralisation effects prompted an uneven spatial distribution of investment and development, creating new (and exacerbating existing) spatial inequalities (OECD, 2018b, 2018a). Attempts to alleviate these problems emphasize the importance of policymaking coordination at local, regional, and national levels, a coordination which will facilitate the effective implementation of place-based policies (Reynolds-Feighan, 2003). In this context, there is a growing recognition that these policies can facilitate a natural spatial dispersion of economic and social activities because they improve cross-regional connectivity, thereby providing a springboard to achieve more balanced and sustainable regional development (Reynolds-Feighan, 2003; Government of Ireland, 2018; Department of Transport, 2022; OECD, 2022).

concerns regarding regional shrinkage in these under-invested areas (Hourihan, 1982, 1992; Kelly *et al.*, 2013; O’Driscoll *et al.*, 2022).

¹⁴ This is perhaps unsurprising considering that 15% of the population reported living further than 20 minutes away from public transport in 2002 relative to the less than 5% typically reported across Europe (Winston, 2007, p. 66; Bielenberg and Ryan, 2012).

2.3.3 Interdisciplinary Perspectives on Sustainable Regional Development, Land-Use Policies, and Transport Policies

The sustainable and efficient use of natural resources (i.e., space) is critical to future regional development proposals. Subsequently, multiple frameworks can be adopted when assessing the sustainability of land-use configurations. Ecologically, land-use sustainability involves minimising waste and pollution while maximizing the availability of natural resources within urban areas (van den Bergh and Nijkamp, 1991; Gibbs, Deutz and Proctor, 2005). In this regard, evidence suggests that land-use mixing of any variety is more environmentally desirable than land-use segregation due to reductions in wasted natural, and man-made, resources when developing¹⁵ (Gibbs, Deutz and Proctor, 2005). Socially, evidence suggests that local environments exert a distinct influence on individuals' wellbeing, happiness, and quality of life (OECD, 2013; Tomaney, 2017; McDougall *et al.*, 2021). Specifically, this literature argues that areas characterised by high residential densities and developmental compactness facilitate greater levels of social interaction and greater accessibility to amenities and jobs by reducing required travel distances (Mouratidis, 2018b, 2018a, 2021). Moreover, if people in these areas can easily access greenspace, there will be synergistic benefits to wellbeing and health by encouraging regular exercise (i.e., active travel) while also enhancing feelings of place attachment, belonging, and wellbeing (Jacobs, 1961; Glaeser, 2011; Jones *et al.*, 2021; McDougall *et al.*, 2021; Mouratidis, 2021). Economically, evidence suggests that increased proximity (and accessibility) to competitors and labour markets is generally conducive to economic growth, particularly in the context of modern service economies (Glaeser, Kahn and Chu, 2001; Glaeser and Gottlieb, 2006; Gordon and Richardson, 2012; Zandiatashbar and Hamidi, 2018; Hamidi and Zandiatashbar, 2019). Subsequently, evidence suggests that built environments characterised by mixed-use, multi-modal transport accessibility, and compactness facilitate economic growth and the emergence of strong agglomeration and cluster economies. They do this by improving the labour forces' ability to access economic and social opportunity by reducing required travel distances, expand the labour force pool available to employers by enhancing regional connectivity, and reduce the cost of infrastructure provision

¹⁵ This research is typically based within Industrial Ecology research (a literature which attempts to consolidate economic, social, and environmental objectives in regional development from the perspective of firms/industries). Here, empirical measures investigating these relationships are principally related to *The Triple Bottom Line*, which measures the economic, social, and environmental performance of regions/firms (Gibbs, Deutz and Proctor, 2005; Deutz and Gibbs, 2008; Caradonna, 2014). But they can also be found across urban morphology literature (Zhang, Ghosh and Park, 2023)

(and operation) by increasing developmental efficiencies¹⁶ (Ciscel, 2001; Glaeser and Gottlieb, 2006; Rice, Venables and Patacchini, 2006; Picard and Zenou, 2018).

Therefore, land-use policies which focus on increasing residential/settlement densities and mixed-use can abate the environmental degradation attributable to urban sprawl, and regional development more generally, while also enhancing social cohesion and facilitating economic growth (Newman and Kenworthy, 1996; Dieleman and Wegener, 2004; Badland and Schofield, 2005; OECD, 2018b; Jain and Tiwari, 2019; Tikoudis *et al.*, 2022). Furthermore, these policies reduce regional time-space geographies, thereby increasing regional connectivity, suggesting that these landscapes can prompt shifts towards greater sustainable (i.e., multi-modal) travel at the expense of car-use (Vandenbulcke, Steenberghen and Thomas, 2009; Millward, Spinney and Scott, 2013; O’Riordan *et al.*, 2022). This paradigm aligns with the work of Jacobs (1961), who argued that local time-space geographies fundamentally influence economic, environmental, and social outcomes, and the principle determinant of these geographies are land-use configurations and transport infrastructure. Subsequently, research and praxis have become increasingly invested in assessing built environment variables known to impact time-space geographies, namely population/settlement densities, land-use mixing, land-use concentration and diversity, and also required travel times/distances (Cervero and Kockelman, 1997; Song, Merlin and Rodriguez, 2013; Jain and Tiwari, 2019; Qiao *et al.*, 2019; Eldeeb, Mohamed and Pérez, 2021; Faccini *et al.*, 2021).

There are two approaches to analysing the spatial distribution of land-use configurations. On the one hand, integral measures primarily measure area-wide proportional shares of land-use categories, the most prominent of which include The Balance Index, Relative Entropy, and The Herfindahl-Hirschman Index. The Balance Index is designed to assess land-use segregation or the evenness of land-use patterns across space, and is usually employed in literature analysing segregation and regional job-housing balances (Song, Merlin and Rodriguez, 2013). The Herfindahl-Hirschman Index is designed to measure the concentration of singular land-uses within spatial units, and is typically employed in literature investigating urban agglomerations and clusters (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; O’Leary, Doran and

¹⁶ Over time, these characteristics may boost the attractiveness of these areas, stimulating increases in property market values (Zandiatashbar and Hamidi, 2018; Hamidi and Zandiatashbar, 2019). An important trade-off and policy consideration here is the potential pricing-out of small businesses and relatively deprived populations, which may thwart the accessibility of opportunity if regional multi-modal transport infrastructure is inadequately, and inequitably, distributed (Tyndall, 2017; Curl, Clark and Kearns, 2018; Wang, Derudder and Liu, 2019; Bourke *et al.*, 2022; Guerra, Li and Reyes, 2022).

Power, 2022; Zhang, Ghosh and Park, 2023). Relative Entropy measures land-use diversity as the degree of land-use mixing within a given spatial unit relative to the number of land-uses within said unit (rendering it analogous to Shannon's Diversity Index (Shannon, 1948)), and is usually employed in investigations of regional development patterns (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Zhang, Ghosh and Park, 2023). On the other hand, divisional measures mainly quantify the degree of (dis)similarity between land-use compositions and configurations within neighbouring spatial units, the most prominent of which include the Atkinson Index and Dissimilarity Index (Song, Merlin and Rodriguez, 2013). The Atkinson Index measures severe imbalances in land-use distributions (or other variables) relative to a single land-use class (or other parameters) and is often employed in assessments of inequality (Song, Merlin and Rodriguez, 2013). The Dissimilarity Index measures the degree of (dis)similarity of land-use patterns across neighbouring spatial units, and is most often employed in studies of urban form, regional boundaries, and zoning (Zhang, Ghosh and Park, 2023). A review of these measures by Song, Merlin and Rodriguez, (2013) illustrates how many of these measures are generally correlated in their results and all are subject to the Modifiable Area Unit Problem. This means that the use of any individual empirical indicator for assessing land-use configurations is dependent upon the spatial scale of analysis, the number of land-uses analysed, and the specific research question (Song, Merlin and Rodriguez, 2013; Patias *et al.*, 2021)..

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Chapter 3: Land-Use Mixing Across The Republic of Ireland

Land-use configurations determine the locations and intensities of human activities, meaning they can contribute to achieving sustainability in future regional development by influencing the degree of natural landscape destruction attributable to human activities. Depending on the spatial context of developments, landscapes characterised by land-use segregation and low settlement densities may have larger spatial demands than more compact and mixed-use settlements. This implies that natural resources like space may be used inefficiently as regions expand outward, thereby negatively contributing to sustainability efforts. Suburban developments often face this criticism, but in rural areas characteristics like land-use segregation may constitute the presence of agricultural or natural landscapes, emphasizing the need for morphological studies which provide refined insights surrounding land-use configurations within wider spatial contexts. Here, I create a spatial typology which distinguishes between areas exhibiting low and high levels of land-use mixing (relative entropy) across the Republic of Ireland using a dataset consisting of CORINE Land Cover and OpenStreetMap data. Figure 3.1 presents a visualisation of the comprehensiveness of both CORINE and OpenStreetMap datasets, compares entropy estimates for both datasets, and illustrates cross-dataset disparities in relative entropy estimates. I end by discussing the role of opensource data in future regional research.

3.1 Introduction

Land-use distributions determine the locations and intensities of human activities, rendering them fundamental to human geography, regional development, and environmental sustainability (Gao *et al.*, 2020). This links development topographies to population distributions, the accessibility of economic (i.e., jobs) and social (i.e., leisure amenities) opportunity, and the availability of natural resources. Because land is a finite natural resource, perpetual regional expansion is impossible, illustrating the need to use these resources efficiently and subsequently minimise the environmental damage attributable to regional development (Nechyba and Walsh, 2004). Efficiency in this context relates to the fact that regional expansion necessitates a trade-off between the extent of natural landscapes and the configurations of human settlements. In this case, settlements are typically more efficient when densities are high and landscapes are multi-purpose, but also more generally when local physical time-space geographies are low (Heck *et al.*, 2018; Hersperger *et al.*, 2018). This rationale follows a long line of urban planning literature which argues that sustainable land-use configurations approximate those which accommodate the maximum number of people

and activities within the smallest horizontal space (Jacobs, 1961; Ewing *et al.*, 2014). Therefore, it is important to enhance our understanding of the characteristics of land-use developments and human settlements more generally. As a result, I assess land-use configurations across the Republic of Ireland at highly refined spatial scales and quantify the degree of land-use mixing (relative entropy) across Ireland's Electoral Divisions (ED).

Urban sprawl is often described as a developmental pattern which inefficiently utilises natural resources because it prioritises land-use developments characterised by low residential densities, segregated land-use, and large local time-space geographies (Ewing, 1997; Reynolds-Feighan, 2003; OECD, 2018). In these landscapes, the spatial demands of regional development increase alongside the costs associated with infrastructure and essential service provision (Carruthers and Úlfarsson, 2008; Ewing *et al.*, 2014). But there are also negative consequences in other realms, particularly those pertaining to travel behaviours, subjective wellbeing, and even economic growth as humans and their settlements become separated from economic and social activities (Mouratidis, 2021; OECD, 2022; O'Driscoll *et al.*, 2023a). Furthermore, from a land-use perspective, evidence suggests that urban sprawl is not only inefficient in its use of resources, but also unsustainable due to its excessive spatial expansion (OECD, 2018). Ireland's history of regional development is characterised by urban sprawl and suburbanisation, but also a general lack of strategic land-use and transport planning at regional and national levels, highlighting its importance as a case study for this area of research (Scott, 2006; Williams and Nedović-Budić, 2020). This is further illustrated by Ahrens and Lyons (2019), who observe that 'urban land expansion in Ireland is among the highest in Europe' (Ahrens and Lyons, 2019, p. 1).

I focus on the physical form of regional developments, their relationships at different spatial scales, and to a lesser extent how these have evolved over time. Specifically, I investigate three broad aspects of urban and regional morphology by explicitly analysing urban/regional tissue configurations, land-use configurations, and the presence of natural (landscape) features (Zhang, Ghosh and Park, 2023). A wide interdisciplinary literature has placed major emphasis on the importance of these aspects in influencing economic, social, and environmental outcomes for individuals, households, and regions. (European Environmental Agency [EEA], 2006; Ewing and Cervero, 2010; Brooks, 2012; OECD, 2018). One common principle across this literature concerns the benefits associated with mixing diverse land-uses within spatial units. As a result of this, land-use mixing has become a centrepiece in global land-use policies, with a growing body of evidence suggesting that policies which focus on increasing settlement

densities and land-use mixing have been found to abate the environmental degradation attributable to urban sprawl by increasing the efficiency, and subsequent sustainability, of land and infrastructure use (Newman and Kenworthy, 1996; Dieleman and Wegener, 2004; Badland and Schofield, 2005; Ewing and Cervero, 2010; Chen and Song, 2020; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021).

I follow existing literature by operationalising land-use mixing as the diversity of land-uses present within spatial units relative to the number of observed land-uses in these units (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Zhang, Ghosh and Park, 2023). Considering this, I employ the relative entropy metric. Relative entropy measures the diversity of land-uses within spatial units using the proportion of space occupied by different land-use types as well as the number of land-use types within a given spatial unit (Duncan *et al.*, 2010; Song, Merlin and Rodriguez, 2013; Mavoa *et al.*, 2018; Eldeeb, Mohamed and Páez, 2021). This explicitly measures land-use mixing, and as a result, facilitates inferences into the relative efficiency of land and infrastructure use because low levels of land-use mixing imply high levels of land-use segregation, characteristics which may negatively contribute to regional environmental objectives by increasing the spatial demands of human settlements (Ewing, 1997; Song, Merlin and Rodriguez, 2013; Mavoa *et al.*, 2018; OECD, 2018; O'Driscoll *et al.*, 2023b). But to gain meaningful insights at local levels, the datasets and spatial scales used must be able to map spatially disaggregated land-use pockets defined by their purpose of use and function (Song, Merlin and Rodriguez, 2013).

Studies analysing land-use configurations typically employ the CORINE Land Cover dataset due to its comprehensive classification of land-use across Europe, and many use relative entropy to measure land-use mixing (Ton *et al.*, 2019; Eldeeb, Mohamed and Páez, 2021; O'Driscoll *et al.*, 2023b). While CORINE is famous for the comprehensiveness of its coverage, its focus on mapping land-use forms means it fails to distinguish unique land-use functions across otherwise homogenous urban fabrics (O'Driscoll *et al.*, 2023b). OpenStreetMap remedies this by mapping land-use according to function. OpenStreetMap is the world's largest Volunteered Geographical Information (VGI) dataset, and evidence suggests its land-use data is highly accurate at a global scale, particularly in urban areas (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018). But due to the volunteered nature of the information, its reliability and accuracy will decrease in rural and sparsely populated areas (Haklay, 2010). In an Irish context, these conclusions regarding the datasets strengths and weaknesses were also made by Cipeluch *et al.*, (2010) and Mooney, Corcoran and Winstanley,

(2010), supporting the use of such data in this research context. Considering this, I exploit the ability of OpenStreetMap to provide highly refined land-use data and incorporate this data into this research. To address OpenStreetMap quality concerns, I merge this data with CORINE Land Cover data, a dataset renowned for its European-wide comprehensiveness and quality (Copernicus Land Monitoring Service, 2021), when OpenStreetMap is unable to classify land in an area. This allows us to analyse land-use configurations across the Republic of Ireland using highly refined data and highly disaggregated spatial scales. But I go further by explicitly comparing how datasets which prioritise land-use function versus land-use form produce sometimes conflicting relative entropy estimates, thereby elevating our understanding of local heterogeneities in land-use configurations across the urban-rural continuum, something called for across international literature (Ton *et al.*, 2019; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021; Gan *et al.*, 2021).

Cartographically, I build upon a wide body of literature which presents visualisations of the multifunctionality of land across highly disaggregated spatial scales (Druga and Minár, 2018; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021), while also answering calls for greater research which analyses land-use configurations across diverse national geographies at local levels (Druga and Minár, 2018; Ahrens and Lyons, 2019; Gao *et al.*, 2020; Strollo *et al.*, 2020; Calka, 2021). Specifically, I use the administrative level of Electoral Divisions (EDs) from the 2016 Irish Census as the spatial scale, which are Ireland's Local Administrative Units 2 (LAU2) that account for 3,409 localities (Central Statistics Office [CSO], 2016). To address concerns that spatial analyses which employ administrative units are highly sensitive to the Modifiable Area Unit Problem, I replicate this study in **Appendix 1 (A1)** using Ireland's Small Areas, which are the smallest geographical spatial unit within the 2016 Irish Census (Central Statistics Office [CSO], 2016). Nested within EDs, the 18,641 Small Areas across Ireland are areas of population consisting of between 80-120 dwellings (Central Statistics Office [CSO], 2016).

Section 3.2 details the data and methodology used in this analysis. *Section 3.3* illustrates the results and their implications. *Section 3.4* concludes the analysis by highlighting the policymaking implications of this work while also illustrating the study's limitations and potential avenues for future research.

3.2 Data and Methods

3.2.1 Data

The base of Figure 3.1 comes from shapefiles provided by the Central Statistics Office (CSO) and Ordnance Survey Ireland (OSI) (Central Statistics Office [CSO], 2016; Ordnance Survey Ireland [OSI], 2016). The CSO shapefile features ungeneralised ED boundaries for the 2016 Irish Census, which are the smallest administrative areas in the State, and capture 3,409 localities (Central Statistics Office [CSO], 2016). This shapefile is then clipped using the OSI sea boundary shapefile to mitigate the base Census shapefile's omission of important facets of Ireland's land mass, like the Shannon Estuary (Ordnance Survey Ireland [OSI], 2016). Northern Ireland is not analysed here and is therefore only included in outline format to increase cartographic accuracy.

We adopt Electoral Divisions as the spatial scale to uncover local heterogeneities in land-use configurations which may be hidden at larger, more commonly employed spatial scales, like the NUTS3 regions, of which there are only eight in Ireland (Boarnet and Sarmiento, 1998; J. O'Driscoll *et al.*, 2022). From a policymaking perspective, this approach aligns with the objectives of *Project Ireland 2040* (Ireland's strategic planning framework) to provide greater clarity on how local policymakers can enhance the efficiency of land and infrastructure use in pursuit of sustainable regional development (Government of Ireland, 2018; O'Driscoll *et al.*, 2023b). In this regard, although spatial units like Small Areas can provide greater spatial disaggregation, and can subsequently analyse these configurations in greater detail, the smallest administrative unit in the state is the Electoral Division. Therefore, policymaking recommendations may be compromised at lower levels (i.e., Small Areas) if conflicting results within administrative areas emerge, hence the use of Small Areas in a robustness check (Boarnet and Sarmiento, 1998; J. O'Driscoll *et al.*, 2022).

Our land-use dataset combines the CORINE Land Cover dataset and OpenStreetMap data. I exploit OpenStreetMap's thoroughness in classifying land-use according to function and rectify it with CORINE's comprehensive land-use classification system based upon form, a combination which creates nationally comprehensive, fine-grain land-use classification catalogue. Because land classified by function offers more nuanced insights into land-use configurations than that classified by form, I use OpenStreetMap as the principal dataset and the CORINE to complete the dataset so all land in the study area is classified. Alternative datasets to CORINE exist in other countries, and are usually centrally administered (Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021). But, in Ireland CORINE is the best

available land-use dataset due to the comprehensiveness of its coverage across the Irish land mass, hence its use here. Furthermore, a large body of international, and Irish, literature suggests that OpenStreetMap data is highly accurate, mitigating concerns surrounding data quality (Cipeluch *et al.*, 2010; Haklay, 2010; Mooney, Corcoran and Winstanley, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018). But I go further by also allowing for overlap in the classification of land-uses across the dataset, which reduces the risk that land-uses are mis-identified.

In cases where additional datasets are available which can enhance our understanding of land-use configurations, they should be employed (Fleischmann and Arribas-Bel, 2021). Of particular importance here is the incorporation of data which captures the verticality of land-use developments, something I cannot explicitly capture here. A viable proxy for this may be the incorporation of population density statistics. But, as detailed further in **Chapter 4**, zoning laws within Irish urban centres have created a developmental landscape characterised by mono-use developments and a general lack of vertical development beyond three-or-four stories, rendering this limitation not as significant as in other spatial contexts (Dublin City Council, 2022; Department of Housing Local Government and Heritage, 2023). Therefore, I leave this undertaking, and a subsequent analysis of these patterns, to future research.

3.2.2 Dataset Construction

CORINE Land Cover data is imported into Quantum Geographic Information Systems (QGIS) where it is clipped to the adjusted ED boundary file to only include observations within the Republic of Ireland. This dataset identifies 18,872 unique land-use polygons. Each polygon is then dissolved according to aggregated land-use categories and then intersected with the ED boundary file, creating a dataset consisting of 10,544 polygons. I group land-use types into seven broad groups in line with existing literature (Gao *et al.*, 2020; Calka, 2021). Table 3.1 below illustrates these land-use categories for the CORINE dataset.

To acquire a comprehensive catalogue of OpenStreetMap land-use polygons, I collect every polygon across the Republic of Ireland identified by QGIS's QuickOSM plugin as characterising land-use. This query identified 395,835 unique land-use polygons. Polygons are then aggregated into broad categories of land-use. To account for potential identification errors present in this data, scope for overlap in these categories is allowed, particularly in those dedicated to public space. Due to the novelty of using OpenStreetMap data within this research context, no precedent exists to guide my aggregation process. Consequently, I roughly follow previous aggregations of the CORINE dataset (Calka, 2021) by basing the aggregation on the

official CORINE class 2 and class 3 nomenclature¹⁷. Table 3.2 below illustrates these aggregated land-use categories for the OpenStreetMap dataset.

We then collect all non-overlapping features from both shapefiles whereupon differences are merged with the OpenStreetMap data. This creates a land-use dataset which combines all the information from the CORINE and OpenStreetMap data for the Republic of Ireland. This merge results in a dataset containing 411,889 land-use pockets, whereby aggregated land-use categories are adjusted to construct a consistent metric which incorporates elements from each shapefile. Thereafter, this shapefile is dissolved according to newly aggregated land-use categories, creating a shapefile containing 36,337 unique land-use polygons. Finally, this dataset is intersected with the ED boundary file, facilitating the calculation of the proportion of space each land-use category occupies within every ED. Table 3.3 below details the aggregated land-use categories when the CORINE and OpenStreetMap datasets are combined.

¹⁷ An alternative guide for land-use classification is Clark and Scott, (2013), who create relative entropy measures using self-aggregated land-use classes.

Table 3.1: CORINE Land Cover Categories

Continuous Urban Fabric (1)	Discontinuous Urban Fabric (2)	Industrial and Commercial Land (3)	Agricultural Land (4)	Public Green Land (5)	Wilderness and Forests (6)	Coastal and Wetlands (7)
Continuous UF (Code 111).	Discontinuous UF (Code 112).	Industrial and Commercial (Code 121). Transport (Codes 122-124). Mine, Dump and Construction (Codes 131-133).	Arable land (Code 211). Plantations (Code 222) Pastures (Code 231). Hetero. Agri. Land (Codes 242, 243).	Green Areas (Codes 141, 142)	Forests (Codes 311-313). Herbaceous Vegetation (Codes 321, 322, 324). Greenfields/Brownfields (Codes 333, 334).	Beaches (Codes 331, 332). Inland Wetlands (Codes 411, 412, 421). Maritime Wetlands (Code 423). Inland Waters (Codes 511, 512). Marine Waters (Codes 521-523).

Table 3.2: OpenStreetMap Land Cover Categories

Commercial (1)	Retail (2)	Residential (3)	Industrial (4)	Public Urban (5)	Public Rural (6)	Agriculture (7)	Religious (8)
Commercial.	Retail.	Residential. Garden. Flowerbed. Farmyard.	Industrial. Railway. Garages. Military. Quarry/Construction. Landfill/Brownfield.	Trees/Flowerbeds. Grass. Village Green. Common/Park. Recreational Ground.	Public Urban (5). Woods/Forests/Cutline. Nature Reserve. Grassland/Meadow. Greenfield. Sand/Rocks/Scree/Shingle. Shrub/Scrub/Heath/Fell. Aquaculture/Salt Pond.	Allotments. Plant Nursery. Greenhouse. Orchard. Farmyard. Farmland. Meadow.	Religious. Graveyard. Cemetery.

Table 3.3: Combined OSM and CORINE Land Cover Categories

Commercial (1)	Retail (2)	Residential (3)	Industrial (4)	Public Urban (5)	Public Rural (6)	Agri (7)	Religious (8)	Unidentified Cont. UF (9)	Unidentified Discont. UF (10)	Unidentified Coast/Wet (11)
OSM1.	OSM2.	OSM 3.	OSM 4. CORINE 3.	OSM 5. CORINE 5.	OSM 6. CORINE 5. CORINE 6.	OSM 7. CORINE 4.	OSM 8.	CORINE 1.	CORINE 2.	CORINE 7.

3.2.3 Measuring Relative Entropy

There are two approaches to analysing the spatial distribution and concentration of unique land-uses. On the one hand, integral measures primarily measure area-wide proportional shares of land-use categories, the most common of which include The Balance Index, Relative Entropy, and The Herfindahl-Hirschman Index. The Balance Index's principal use concerns measuring the existence of balance (in terms of space occupied) between multiple land-uses within spatial units, the Herfindahl-Hirschman Index measures the concentration of singular land-uses within spatial units, while Relative Entropy measures the diversity of land-uses within spatial units (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Zhang, Ghosh and Park, 2023). On the other hand, divisional measures mainly quantify the degree of (dis)similarity between land-use compositions/configurations within neighbouring spatial units (Song, Merlin and Rodriguez, 2013). Because the results produced by individual measures within each category (i.e., Integral and Divisional) are highly correlated, the choice of any single indicator is usually dependent on the geographic scope of the analysis¹⁸. Integral measures are more suitable for this research given their emphasis on proportional shares and distributions of unique land-use classes, yet both are still susceptible to the Modifiable Area Unit Problem due to their dependency on geographical boundary specification (Song, Merlin and Rodriguez, 2013; Druga and Minár, 2018). Further, because this analysis principally investigates area-wide land-use shares as opposed (dis)similarities in land-use distributions, an integral measure is appropriate, and following existing literature, I employ the relative entropy metric (Bhatta, Saraswati and Bandyopadhyay, 2010; Mavoa *et al.*, 2018; Eldeeb, Mohamed and Páez, 2021; Jeong, Lee and Gim, 2022).

Relative entropy measures the relative mixing of land-use types across pre-defined spatial boundaries. Higher levels of relative entropy (measured on a 0-1 continuous scale) indicate greater land-use mixing, something linked to greater levels of efficiency in land and infrastructure use in urban areas but can also reflect the concentration of agricultural or natural landscapes in rural areas. This illustrates the importance of considering the wider spatial context of land-use configurations when analysing concepts like developmental sustainability, but it also highlights the importance of understanding the mathematical properties of the metric (Song, Merlin and Rodriguez, 2013; Zhang and Zhao, 2017; Eldeeb, Mohamed and Páez, 2021).

¹⁸ For an in-depth discussion on this topic, see: Song, Merlin and Rodriguez, (2013).

The relative entropy metric is analogous to Shannon's Diversity Index and quantifies the degree of land-use mixing and diversity within a given spatial unit, relative to the number of land-uses within said unit (Shannon, 1948; Song and Knaap, 2004; Mavoa *et al.*, 2018). Relative entropy for a given spatial unit can be calculated as outlined in Equation 3.1, where E_j reflects the relative entropy score of area j . P_{kj} reflects the summed proportions of land types k within area j .

$$E_j = (-1) \times \sum_{k=1}^{K-1} \frac{P_{kj} \ln(P_{kj})}{\ln(K)} \quad (3.1)$$

In extreme scenarios, relative entropy reaches 0 when there is no mixing of land-uses within a specified spatial unit. In other words, there is only one land-use occupying that unit. Whereas relative entropy can reach 1 when land-use types are distributed equiprobably within a given spatial unit. This property implies that if the denominator is not standardised (i.e., by being $\ln(k)$ instead of $\ln(K)$), measurement bias occurs and relative entropy estimates are not comparable across spatial units because identical scores can be achieved in numerous ways (Hajna *et al.*, 2014). This weakens the explanatory power of the metric significantly as inferences into problems like developmental sustainability become hazardous (Hajna *et al.*, 2014). Once standardised, relative entropy can only reach a score of 1 when *all* possible land-use classes are distributed equally across a spatial unit and lower values consistently imply lower levels of land-use mixing.

Another property of the relative entropy metric is its symmetry, meaning that it treats all land-use classes homogenously by only tracking the overall level of mixing within the areal unit and not how specific land-use classes interact. This is important because when analysing land-use configurations in the context of travel behaviours, understanding what type of land-use classes are mixed is necessary (Hess, Moudon and Logsdon, 2001). This is not a problem in this research context because I use land-use mixing as an instrument to gauge the efficiency of regional development. In other words, the primary concern is whether spatial units exhibit high levels of *any* land-use mixing or high degrees of land-use segregation.

3.2.4 Cartographic Visualisation

Placed atop a light blue-magenta background, Figure 3.1 contains three distinct sections. Northern Ireland is included in outline format, rendering the Republic of Ireland land mass the primary focus. The Republic of Ireland land mass is presented according to Electoral Division

boundaries. The coordinate system used to visualise this data is the Irish Transverse Mercator (EPSG: 2157).

The first section of Figure 3.1, on the top-left, illustrates the choropleth of land-use polygons collected from the CORINE Land Cover dataset and that from the OpenStreetMap dataset as described in *Section 3.2.1*. Here, OpenStreetMap's thoroughness in urban areas relative to that of CORINE is evident while CORINE's national comprehensiveness is apparent. However, OpenStreetMap's relatively sparse classification of land-uses in more rural areas is also evident.

The second section, the bottom left, displays the relative entropy estimates for each Irish ED when using the CORINE Land Cover dataset alone and the relative entropy estimates for each Irish ED when using the combined CORINE-OSM dataset. Relative entropy cannot be estimated using the OpenStreetMap dataset alone because it does not comprehensively classify land across the study area. In these maps, although it is evident that cross-dataset relative entropy estimates are similar in many cases (as evidenced by the frequency distribution in the legend), the Functional Urban Areas of the five major city regions see significant changes.

The principal component of Figure 3.1 is presented on the right half. Specifically, it denotes the principal legend, which is constructed according to equal interval measures, and provides regional contextual points and boundaries by illustrating where city centres are located and the scale of Electoral Divisions. This map also presents visualisations of cross-dataset differences in relative entropy estimates, thereby explicitly showing how different relative entropy estimates are across the two datasets. This is supplemented by inset shapefiles which highlight these differences in urban core areas, whereby "core" is defined according to OECD definitions (Dijkstra, Poelman and Veneri, 2019), and also frequency distributions which describe the share of areas falling within each category of differences. In this regard, positive values on Figure 3.1 indicate that relative entropy estimates are higher when using the CORINE-OSM dataset while negative values indicate that relative entropy estimates are lower when using the CORINE-OSM dataset, all relative to the estimates produced using the CORINE dataset alone.

Our chosen colour schemes accommodate natural inclinations to associate darker colours with larger values and lighter colours with smaller values, while also accommodating colour-blind readers by avoiding red-green combinations (Schiewe, 2019; Calka, 2021; C. O'Driscoll *et al.*, 2022; J. O'Driscoll *et al.*, 2022; O'Driscoll *et al.*, 2023b). In this regard, I implement a viridis colour ramp on maps displaying relative entropy scores. I adopt a three-dimensional colour

scheme to illustrate the results of Figure 3.1 because these span positive and negative values. Specifically, I adopt a three-dimensional dark magenta, grey, and green-cyan colour hue.

3.3 Results and Discussion

3.3.1 Relative Entropy and The CORINE Land Cover Dataset

Lighter colours indicate lower levels of relative entropy and by implication lower levels of land-use mixing in developments. When analysing these trends using the CORINE Land Cover dataset, high levels of relative entropy (land-use mixing) concentrate in the West of Ireland and the Midlands, suggesting that land-use configurations in these areas are diverse in their composition and well mixed. Noticeably, relative entropy scores in-and-around city regions (Dublin in particular) are quite low, indicative that land-use configurations in these areas are relatively homogenous and not well mixed. In both cases, these results go against a large body of evidence which suggests that, in-and-around urban centres characterised by monocentric expansion (as in Ireland), land-use mixing will peak due to a concentration of human activities in these areas and the inverse relationship between the demand for space and distance from these urban centres¹⁹ (Mavoa *et al.*, 2018; OECD, 2018). Also, rural and coastal areas should be where land-use mixing is less frequent due to the prevalence of agricultural and natural landscapes in these areas. The lack of theoretical or empirical evidence supporting these results suggests possible issues with the underlying data. In this case, Table 3.1 shows that the CORINE Land Cover places greater emphasis on classifying natural/rural land-uses relative to urban land-uses (something reflected the land-use classification names), and that may partly explain these results.

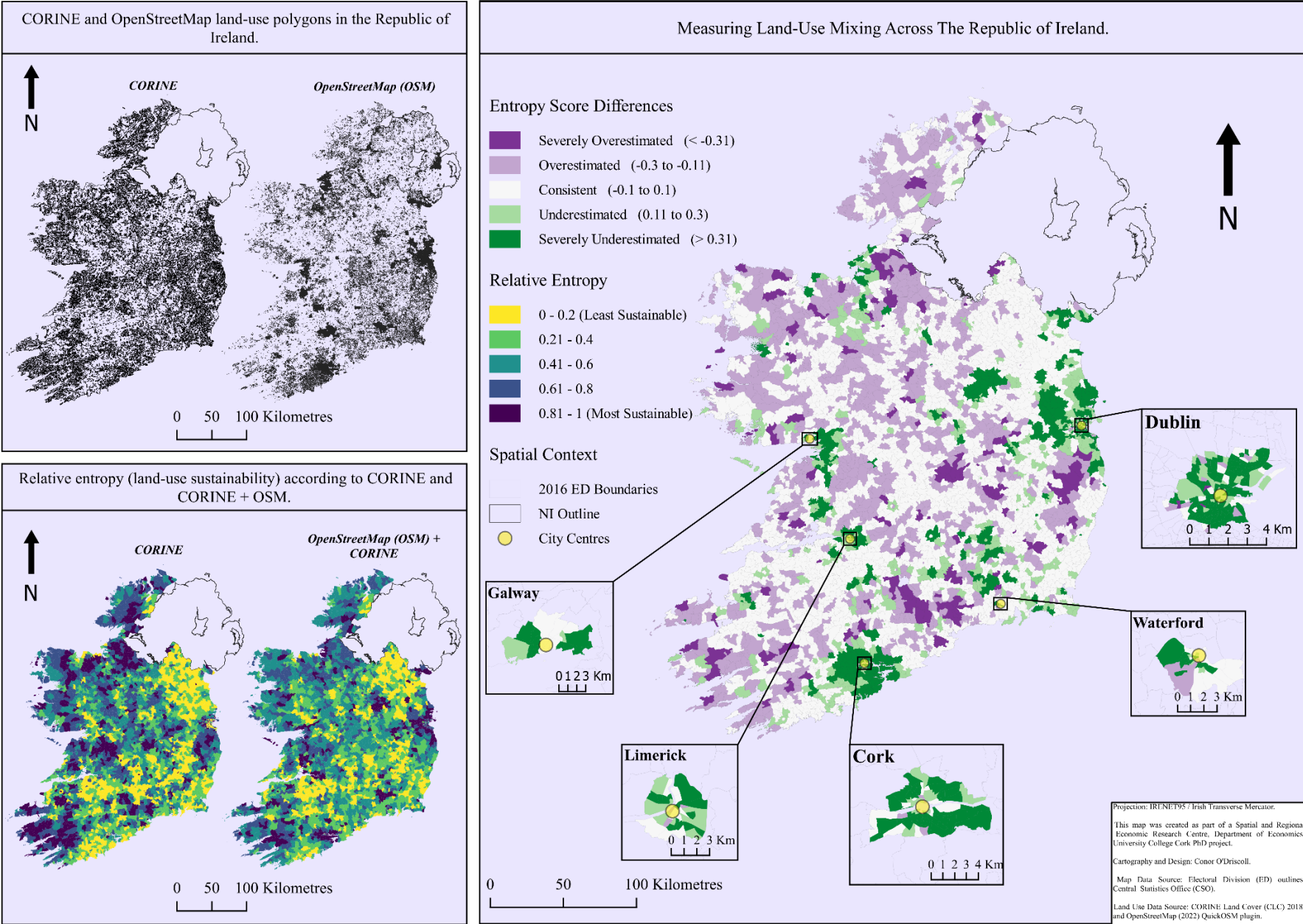
3.3.2 Relative Entropy and The CORINE-OSM Dataset

As before, lighter colours indicate lower levels of relative entropy and by implication lower levels of land-use mixing in developments. When analysing these trends using the CORINE-OSM dataset, high levels of relative entropy (land-use mixing) concentrate in-and-around the five major city-regions in Ireland. The relative entropy estimates produced by this dataset are more theoretically consistent and align with a wide body of literature. Specifically, high levels of relative entropy (land-use mixing) concentrating in-and-around urban areas can be explained by concentrations in human activities and settlements, thereby producing a diverse landscape

¹⁹ This evidence stems from urban economics which argues that, in regions characterised by monocentric regional expansion, population densities will incrementally decrease as distances from CBDs increase. In a land-use context, the conclusions are analogous as the demand for space by multiple land-uses decreases as distances from CBDs increase, lowering instances of land-use mixing as fewer land-uses occupy increasing amounts of space (i.e., agriculture) (Arnott, 2012; Green, 2012).

from a land-use perspective, while low levels of relative entropy naturally concentrate in more peripheral areas because of an increase in the concentration of natural and agricultural landscapes. High levels of relative entropy outside of major urban centres possibly illustrate the limitations associated with OpenStreetMap. Rural/coastal land-use pockets are primarily incorporated through the CORINE alone due to a lack of comprehensiveness in OpenStreetMap, something which may artificially identify more unique land-uses per area, thus giving the illusion of mixed-use developmental forms. In this case, Table 3.2 shows that OpenStreetMap is more thorough in its classification of urban land-uses while also maintaining a high degree of refinement in its classification of rural land. While this thoroughness allows us to gauge the composition of land-use developments more accurately in urban centres, OpenStreetMap's lack of comprehensiveness in rural areas may be inflating the relative entropy estimates of rural areas. However, it is outside the scope of this research to formally test these inferences.

Figure 3.1: Measuring Land-Use Mixing Across The Republic of Ireland



3.3.3 Implications for Policymakers

Tables 3.1, 3.2, and 3.3 illustrate the comprehensiveness of the CORINE dataset and its potential to assess land-use configurations across large geographies. However, also evident is that CORINE lacks thoroughness in distinguishing land-uses within urban environments, a characteristic which I find produces inaccurate (i.e., low) relative entropy estimates. OpenStreetMap is shown to remedy this by providing more insightful land-use classifications in urban areas but is restricted in its ability to comprehensively classify land across the study area, illustrating the complementarity of both datasets when analysing land-use configurations in the context of regional development as well as their limitations.

Figure 3.1 depicts cross-dataset differences in relative entropy estimates. Across urban centres, relative entropy scores are typically low when using the CORINE Land Cover dataset, but high when using the CORINE-OSM dataset²⁰. This may suggest that discipline-standard datasets like the CORINE cannot adequately distinguish urban land-uses due to their focus on land-use forms and therefore may underestimate the level of land-use mixing in these environments, something which may significantly impact policies surrounding developmental sustainability. Somewhat surprisingly, Figure 3.1 indicates that the CORINE Land Cover dataset produces higher relative entropy estimates in rural areas relative to the CORINE-OSM dataset. This finding may be linked to the fact that the CORINE dataset is more heavily weighted towards documenting rural land-use categories, thereby possibly creating a bias in land-type counts, but formally testing this inference remains outside the scope of this research.

Considering this, I argue that in urban areas, relative entropy may be higher than typically accounted for whereas it may be lower than typically accounted for in peripheral and rural areas. In and around cities, this may create problems as local heterogeneities in the efficiency of land and infrastructure use are hidden due to an inability to differentiate unique urban land-uses by focusing on land-use form. Similarly, in regional peripheries (i.e., suburbs), this may create problems by understating how inefficient these developmental patterns are in land and infrastructure use. These problems are clearly related to data quality and illustrate the need to improve the source-data used in analyses pertaining to land-use configurations. I align myself with a large literature in urban morphology which argues that this data is of a higher quality

²⁰ One possible cause of this result may be that, as shown across Tables 3.1, 3.2, and 3.3, the land-use classes within the datasets increase, thereby providing more opportunities for mixing relative to a dataset with fewer classes. As illustrated further in **Chapter 5**, we found that maintaining a consistent number of land-use classifications did not significantly impact our results.

when OpenStreetMap is included because of its ability to identify unique land-uses across otherwise homogenous urban fabrics (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018). However, further improvements in this data could be gained by explicitly capturing the verticality of land-use developments.

Low relative entropy scores in rural areas are not concerning because these areas exhibit an increased concentration of agricultural and natural land, rendering low scores unsurprising. But considering that regional expansion necessitates trade-offs between the destruction of natural landscapes and the creation of human settlements, it is important that we can effectively distinguish land-uses at highly refined spatial scales so excessive spatial expansion can be mitigated. In this regard, I argue that the inclusion of opensource data into studies of land-use configurations and regional development can elevate our understanding surrounding the efficiency of developmental patterns by explicitly focusing on land-use functions over land-use forms. Furthermore, this allows researchers to track changes in land-use configurations along the urban-rural continuum more effectively, thereby enhancing our understanding of urban-suburban-rural boundaries.

3.4 Conclusions

This chapter presents visualisations of the levels of relative entropy across the Republic of Ireland whereby relative entropy is used to gauge the efficiency of land and infrastructure usage. I use two land-use classification datasets (The CORINE Land Cover and OpenStreetMap) and compare the relative entropy estimates of each. By comparing the measurements of discipline-standard datasets with those of opensource data, we gain inferences into the strengths and weaknesses of these data, but I also enhance existing knowledge of land-use configurations, and how they contribute to sustainability efforts, through the use of highly refined data.

Our principal finding is that in urban areas, discipline-standard datasets like the CORINE Land Cover fail to distinguish between unique land-uses at refined spatial scales because they measure land-use forms. I argue that this produces low relative entropy estimates due to an inability to distinguish between unique land functions across otherwise homogenous urban fabrics. In rural areas, these estimates may be artificially high due to a disproportionate weighting in the number of rural land-use classes, thereby providing greater opportunities (theoretically) for increased land-use mixing. I argue that this might explain why relative entropy estimates produced by the CORINE Land Cover go against a wide body of theoretical

and empirical evidence, but I am unable to formally test this claim. Considering this, and following a long line of literature in urban morphology, I argue that the inclusion of opensource data in investigations of land-use configurations (and investigations into the efficiency and sustainability of developmental patterns more generally) will allow researchers to enhance their understanding of land-use configurations and how they can contribute to efforts to achieve sustainability in development (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018; O'Driscoll *et al.*, 2023b).

One limitation of this research is that I cannot capture the verticality of land-use developments. Considering this, future research could elevate the data used in this type of research by explicitly capturing land-use verticality. At smaller spatial scales, data capturing population densities may be viable proxies, but in this analysis, the spatial units are too large to gain meaningful insights into the heterogeneities of development intensity within spatial units. Furthermore, as justified in **Chapter 4**, omitting building verticality data in an Irish context is not as consequential relative to other geographical contexts due to Ireland's history of mono-use, single story development. Relatedly, I do not formally test the quality of OpenStreetMap data in this analysis, but instead rely upon the findings in a long line of urban morphology literature which demonstrates its high-quality. Although not a serious limitation to this analysis, future research may benefit from deeper investigations into the contribution opensource data can make in urban research. Specific questions may test data quality and reliability, as in Fan *et al.*, (2014); Arsanjani *et al.*, (2015); Mobasheri, Zipf and Francis, (2018), or the conditions in which such data is unreliable.

Another limitation is that, despite the robustness check in **Appendix 1 (A1)**, which replicate the analysis at alternative spatial scales, these results may still be sensitive to the Modifiable Area Unit Problem. In this context, future research should explore the ability to incorporate regional and structural weights into relative entropy metrics, and morphological studies more generally, thereby acknowledging regional heterogeneities in developmental patterns and possibilities. One possible direction may involve the manipulation of Location Quotients and Distance Weights, thereby accounting for spatial autocorrelation in land-use configurations but also heterogeneities in regional morphology. Finally, research which compares the insights provided by discipline-standard and opensource datasets should be employed across wider geographies to investigate how opensource data can elevate our collective understanding of regional development and how this development can relate to economic, environmental, and social vitality.

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Chapter 4: Land-Use Mixing in Irish Cities: Implications for Sustainable Development

Land-use configurations are explicitly related to the outcomes of numerous economic, social, and environmental policies. Depending on the spatial context of developments, landscapes characterised by land-use segregation and low settlement densities may have larger spatial demands than more compact and mixed-use settlements. This implies that natural resources like space may be used inefficiently as regions expand outward, thereby negatively contributing to sustainability efforts. This chapter assesses the efficiency of land and infrastructure usage within Irish metropolitan areas using relative entropy (i.e., land-use mixing) as an empirical instrument. I find that land-use configurations across Irish metropolitan areas are characterised by low levels of land-use mixing and by extension, inefficient land-use developments. I discuss these findings in the context of decades of urban sprawl in Ireland and illustrate how these developmental trends have thwarted efforts to achieve the objectives laid out in the *United Nations Sustainable Development Goals* pertaining to enhancing the sustainability of regional development.

4.1 Introduction

In 2022 it took society 7 months and 28 days to expend all the natural resources Earth could sustainably replenish within one year, a historic turning point which is known as “overshoot day” (Global Footprint Network, 2022). With the passing of “overshoot day” so early in the calendar year, and in the context of the global climate crisis, policymakers must reflect upon the instruments which can reduce the environmental degradation attributable to human activities. The United Nations’ seventeen Sustainable Development Goals provide insights on, and guidance in using, these instruments (The United Nations, 2022). Of these seventeen goals, three are directly related to land-use planning, the management of human settlements, and natural resource usage. Understanding how to improve outcomes in these areas is inextricably linked to measuring societal usage of land and infrastructure. In this chapter I focus on assessing the efficiency and subsequent sustainability of land-use developments across metropolitan areas in the Republic of Ireland. A long line of urban planning literature argues that sustainable land-use developments which efficiently use natural resources like space approximate those which accommodate the maximum number of people and activities within the smallest horizontal space (Jacobs, 1961; Ewing *et al.*, 2014). Subsequently, relative entropy (land-use mixing) is the empirical instrument used.

Land is a finite resource which determines the locations and intensities of human activities (Gao *et al.*, 2020). As a result, land-use configurations significantly influence economic, environmental, and social outcomes within and across regions, illustrating its importance as an instrument in regional planning (Gao *et al.*, 2020). Although sustainability as a broader concept employs many, often competing, perspectives, some policymaking instruments like those pertaining to land-use configurations have the potential to harmonize multiple agendas (Mori and Christodoulou, 2012; Song, Merlin and Rodriguez, 2013). For instance, evidence suggests that land-use configurations characterised by mixed-use and compactness can produce positive economic, environmental, and social outcomes, and are thus one of the components which positively contribute to sustainability efforts in these realms (European Environmental Agency [EEA], 2006; OECD, 2018).

This analysis of the efficiency of land and infrastructure use (i.e., land-use consumption) employs land-use mixing as the empirical indicator. In this context, efficiency relates to the fact that regional expansion necessitates a trade-off between the destruction of natural landscapes and the development of human settlements. Therefore, settlements are typically more efficient when densities are high and landscapes are multi-purpose, but also more generally when local physical time-space geographies are low (Heck *et al.*, 2018; Hersperger *et al.*, 2018). These settlements are also more sustainable because they reduce the habitat degradation attributable to regional developments while also strengthening local economies and social fabrics (OECD, 2018; Jain and Tiwari, 2019; Tikoudis *et al.*, 2022). Conversely, developments characterised by low residential densities and segregated land-use can have excessive spatial demands, and therefore may inefficiently utilise land and infrastructure, something which can thwart efforts to achieve sustainable regional development from an economic, environmental, and social perspective (Nechyba and Walsh, 2004; O’Riordan *et al.*, 2022).

Global policymaking frameworks have increasingly recognised the need to minimise habitat destruction and maximize the efficiencies of existing infrastructure when undertaking regional development. This is epitomised through the *United Nations Sustainable Development Goals*, but also *Project Ireland 2040*, the planning framework guiding regional development across the Republic of Ireland. Globally, regions have failed to achieve this and have also failed to minimise the environmental degradation attributable to regional development due to excessive spatial expansion and the persistent development of low-density, spatially segregated landscapes (European Environmental Agency [EEA], 2006; OECD, 2018, 2022). From this

perspective, one component needed to achieve land-use sustainability is to maximize the efficiency of land-use developments, something approximate to accommodating the greatest number of people in the smallest space. In this paradigm, greater spatial demands translate to greater damage, both directly (through increased levels of natural landscape destruction) and indirectly (by increasing physical time-space geographies and reducing local accessibility and connectivity). Therefore, research typically focuses on analysing the relative mixing of land-uses within areas, whereby higher levels of mixing are implicitly associated with greater levels of developmental compactness and lower spatial demands (Vega and Reynolds-Feighan, 2008; Song, Merlin and Rodriguez, 2013; Jain and Tiwari, 2019; Eldeeb, Mohamed and Páez, 2021).

There is a growing body of literature which analyses regional development in Ireland. This literature investigates issues such as labour markets (Crowley *et al.*, 2021; Rijnks, Crowley and Doran, 2022), metropolitan governance (Moore-Cherry and Tomaney, 2019; Clifford *et al.*, 2022), population dynamics (J. O'Driscoll *et al.*, 2022), retail landscapes (C. O'Driscoll *et al.*, 2022b, 2022a), and travel behaviours (Vega and Reynolds-Feighan, 2008, 2009; O'Riordan *et al.*, 2022; O'Driscoll *et al.*, 2023a). I contribute to this growing literature by analysing the degree of land-use mixing across metropolitan areas within the Republic of Ireland, thereby analysing one component necessary to achieve developmental sustainability while also providing a broader understanding of the consequences associated with historical regional development configurations in Ireland.

Section 4.2 provides a background to the literature concerning the relationship between land-use developments and regional economic, social, and environmental outcomes. *Section 4.3* describes the data and methodology used throughout this analysis. *Section 4.4* illustrates the results. *Section 4.5* discusses the implications of these results and concludes the analysis with a discussion surrounding future research directions and the limitations associated with this work.

4.2 Background To The Literature

Land-use configurations determine the location and intensity of human activities. From this perspective, land-use configurations primarily influence regional economic, social, and environmental outcomes by 1) determining how efficiently land and infrastructure are utilised by influencing the tension between horizontal and vertical expansion (Reynolds-Feighan, 2003; Ahlfeldt and Pietrostefani, 2019; Gao *et al.*, 2020); 2) influencing the spatial distribution of populations, employment opportunities, leisure amenities, and the subsequent strength of

community social fabrics (Mouratidis, 2018, 2021; J. O'Driscoll *et al.*, 2022; O'Driscoll *et al.*, 2023a); and 3) dictating the levels of habitat destruction attributable to regional development by influencing developmental spatial demands (Nechyba and Walsh, 2004; O'Driscoll *et al.*, 2023b; Zhang, Ghosh and Park, 2023). However, land-use considerations also spill-over into realms relating to travel behaviours, labour market mobility, social exclusion, and unemployment, all by defining regional time-space geographies and relative accessibility and connectivity within and across localities (Reynolds-Feighan, 2003; Arnott, 2012; Kaza and Knaap, 2012; Ewing *et al.*, 2014).

From a travel behaviour perspective, evidence suggests that land-use configurations determine the competitiveness and efficiency of transportation modes and subsequently influence travel behaviours (Button, 2010; Millward, Spinney and Scott, 2013; OECD, 2018, 2022). Environmentally damaging behaviours, like car-use, can be encouraged when land-use configurations increase regional time-space geographies because this reduces local connectivity and accessibility by increasing required travel distances (Vega and Reynolds-Feighan, 2008, 2009; OECD, 2018; O'Riordan *et al.*, 2022). This happens because private cars are highly flexible to the needs of individuals whereas active travel and public transport become increasingly inconvenient and unreliable as required travel distances increase (Button, 2010; de Palma and Fosgerau, 2011; Giuliano, 2012; Hickman, 2018). Evidence in this realm suggests that the relationship between land-use configurations and travel behaviours (particularly vehicle miles travelled and travel mode choices) is strongest, and most significant, for built environment characteristics pertaining to the accessibility of destinations (i.e., developmental compactness), the diversity of land-uses within localities, and the number of accessible destinations within localities (i.e., land-use mixing at spatially disaggregated scales) (Ewing and Cervero, 2010; Gim, 2012, 2013; OECD, 2018, 2022)²¹. This suggests that increases in characteristics like land-use mixing, something associated with increased developmental compactness and population densities, compound to reduce required travel distances and catalyse shifts in travel behaviours. Therefore, while specific relationships can be small for *individual* variables, it is apparent that complimentary variables (i.e.,

²¹ For instance, Ewing and Cervero (2010) report that elasticities in the relationship between individual variables pertaining to land-use configurations and VMT range between -0.22 and 0. These same variables are shown to display positive elasticities when related to public and active transport use, indicative of their collective ability to catalyse shifts in travel behaviour (Ewing and Cervero, 2010).

developmental compactness, land-use mixing, and population densities), can interact to significantly influence travel behaviours (Ewing and Cervero, 2010; OECD, 2018).

The interpretation of sustainability differs depending on whether it is analysed from a social, economic, or environmental perspective. And although land-use configurations alone cannot achieve sustainability in all these realms, they can be used as a mechanism to harmonize the goals of typically competing agendas (European Environmental Agency [EEA], 2006, 2015; Glaeser, 2011; OECD, 2013, 2018; Mouratidis, 2021). Take for instance, the relationship between economic, environmental, and social policy in a regional development context. One key concern of social policy is to provide equity in the accessibility of economic and social opportunities (i.e., jobs, housing, and leisure amenities) to all population cohorts. One tangible way to achieve this is by improving accessibility and reducing time-space geographies. From an economic perspective, a key concern involves fostering balanced regional growth and maintaining low unemployment. One tangible way to achieve this is to increase market accessibility and density. From an environmental perspective, a key consideration concerns minimising the levels of habitat degradation attributable to regional development by utilising natural resources efficiently. One tangible way to achieve this involves reducing horizontal expansion when developing. In all these realms, evidence suggests that by reducing time-space geographies (i.e., by increasing accessibility and connectivity), the risks of regional social stress decline and community social fabrics strengthen (Mouratidis, 2021); the accessibility of economic and social opportunities increase, thereby boosting regional economies (Tyndall, 2017; Heuermann and Schmieder, 2019; Bastiaanssen, Johnson and Lucas, 2022); land and infrastructure are used more efficiently because horizontal spatial expansion is reduced, thereby reducing the environmental costs associated with regional development (Nechyba and Walsh, 2004; Jaeger *et al.*, 2010; Guerra *et al.*, 2018; O’Riordan *et al.*, 2022).

Historical regional development patterns across many developed countries can generally be characterised by land-use segregation and low residential densities (OECD, 2018). Ireland is no different, but unlike many of these countries, Ireland has historically faltered in coordinating regional development with national planning frameworks, something which appears to have exacerbated the consequences of urban sprawl and has more generally thwarted the ability of land-use policies to act as an instrument to achieve sustainability in development (Winston, 2007; Williams and Nedović-Budić, 2020). Coupled with zoning laws which failed to punish (tax) inefficient land-use and uncoordinated development proposals brought on by intense localised territorial politics, this lack of policymaking coordination has culminated in decades

of uncontrolled urban sprawl, uneven regional development, and inefficient land and infrastructure usage (Reynolds-Feighan, 2003; European Environmental Agency [EEA], 2006; OECD, 2018; Moore-Cherry and Tomaney, 2019).

Ireland's developmental trends have had predictable consequences. Decades of urban sprawl have created spatially segregated, low density landscapes; characteristics which increase the time-space geographies of regional developments and may negatively impact local environments, economies, and social fabrics (Curl, Clark and Kearns, 2018; Allen and Farber, 2019; Mouratidis, 2021; O'Driscoll *et al.*, 2023a). For instance, between 1930-1990 the population of the Greater Dublin Area doubled while the spatial expanse of this same area quadrupled, a growth rate unmatched in the other major urban centres in Ireland, while as of 2016, at least 70% of the Irish population use cars as their primary mode of transport because the regular use of alternative modes appears to be impractical and difficult, something I attribute to rising required travel distances and local time-space geographies (Winston, 2007; C. O'Driscoll *et al.*, 2022b). While these changes have obviously increased the habitat destruction and environmental degradation (i.e., travel-related emission outputs) associated with regional development, they have also created landscapes whereby the accessibility of economic and social opportunities has been reduced. This is compounded by Ireland's monocentric (i.e., Dublin-centred) regional development profile as disproportionately large volumes of developmental resources concentrate in-and-around the capital city (Reynolds-Feighan, 2003).

Project Ireland 2040 is Ireland's national planning framework which seeks to remedy these issues by coordinating national and regional planning around the objectives of the *United Nations Sustainable Development Goals*. From a land-use perspective, the goals of this framework are to reduce the geographical expansion attributable to regional development while also improving local and regional connectivity (Government of Ireland, 2018). In other words, the framework seeks to increase the efficiencies of existing infrastructure and land through increases in developmental compactness and mixed-use (O'Riordan *et al.*, 2022). While these initiatives are broadly being implemented across all Irish regions, there are also mechanisms which seek to align local considerations with these broader objectives. For instance, the framework seeks to ease zoning restrictions around the integration of residential-commercial-leisure land while also restricting the approval of single-use developments (Government of Ireland, 2018; Dublin City Council, 2022). Complimenting this, are the framework's objectives to empower local policymakers in developmental decision making, thereby allowing local

decisionmakers to allocate developmental resources according to local needs. Although the results of these initiatives will not be evident for several years, evidence suggests that these initiatives will positively contribute to efforts aimed at achieving sustainability in development by catalysing the creation of landscapes characterised by efficient infrastructure and land use, high connectivity, and balanced regional growth (Glaeser, 2011; Been *et al.*, 2014; Moore-Cherry and Tomaney, 2019; Clifford *et al.*, 2022; OECD, 2022).

4.3 Data and Methods

I assess the physical characteristics of land-use developments within Irish metropolitan areas. This analysis builds upon international evidence which argues that developments that facilitate high levels of land-use mixing utilise natural resources like land more efficiently because their inherent compactness mitigates the degree of habitat destruction attributable to regional development (Reynolds-Feighan, 2003; OECD, 2018; Jain and Tiwari, 2019). Ireland's developmental landscape is characterised by monocentric expansion and unbalanced regional development/growth, characteristics shared by many European countries, meaning that the results, and the general implications therein, have international relevance (European Environmental Agency [EEA], 2006; OECD, 2018). I measure land-use mixing within localities using the relative entropy metric. Relative entropy quantifies the mixing of distinct land-use types within pre-defined geographical spaces (Song, Merlin and Rodriguez, 2013). The logic for using this metric is that increases in relative entropy correspond to increases in land-use mixing, something associated with compact developmental forms and developmental forms which positively contribute to regional economic, environmental, and social objectives more generally (Jain and Tiwari, 2019; Eldeeb, Mohamed and Páez, 2021).

To strengthen the global transferability of the results, the OECD definition of Functional Urban Areas are used to define city-region boundaries (Dijkstra, Poelman and Veneri, 2019). Functional Urban Areas are constructed at the OECD level according to regional population densities and the spatial distribution of employment opportunities, rendering their configurations consistent across OECD member states (Dijkstra, Poelman and Veneri, 2019). The spatial scale used are Ireland's Small Areas (SA). SAs contain between 80-120 dwellings and provide 18,641 localities to analyse (Central Statistics Office [CSO], 2016). This level of spatial disaggregation facilitates investigations into local development patterns across metropolitan areas and aligns with *Project Ireland 2040's* objectives to strengthen our understanding of the drivers of developmental patterns at sub-regional levels (Government of Ireland, 2018). To address concerns that the results in this analysis are sensitive to the

Modifiable Area Unit Problem, this analysis is replicated at the Electoral Division (ED) level. There are 3,409 EDs in Ireland and they constitute the smallest administrative unit in the state (Local Administrative Unit 2). Internationally, these units are equivalent to the European commune, and thus enhance the transferability of this research to European regions. This replication is presented in the **Appendix 2 (A2)**.

The land-use dataset employed consists of a combination of the 2018 CORINE Land Cover and 2022 OpenStreetMap land-use data. CORINE Land Cover is the discipline standard dataset used to analyse the configurations of developmental forms and comprehensively classifies land-use across Europe according to landscape characteristics (i.e., Continuous Urban Fabric, Discontinuous Urban Fabric, Industrial/Commercial, Agricultural, Public Green Space, Wilderness). OpenStreetMap consists of Volunteered Geographical Information (VGI) data which classifies land according to function (i.e., Commercial, Retail, Residential, Industrial, Public Green Space, Agriculture, and Religious). OpenStreetMap is the world's largest Volunteered Geographical Information (VGI) dataset, and evidence suggests its land-use data is highly accurate at a global scale, particularly in urban areas (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018). But due to the volunteered nature of the information, its reliability and accuracy will decrease in rural and sparsely populated areas (Haklay, 2010). In an Irish context, these conclusions regarding the datasets strengths and weaknesses were also made by Cipeluch *et al.*, (2010) and Mooney, Corcoran and Winstanley, (2010), supporting the use of such data in this research context. Therefore, whilst not comprehensive in its coverage, OpenStreetMap arguably provides a greater level of depth in areas it does cover because it captures unique land functions (i.e., Retail, Commercial, and Residential) within otherwise homogenous urban fabrics. The merging of this data with nationally comprehensive and high-quality CORINE data produces a dataset which is not only nationally comprehensive in its classification of land-use, but also highly refined in its insights. This facilitates meaningful investigations into local-level heterogeneities in horizontal²² land-use developments (Badoe and Miller, 2000; Adolphe, 2001; Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021).

Relative entropy is the principal metric used in existing literature to assess land-use diversity. Alternative metrics, such as The Balance Index or Herfindahl-Hirschman Index are complementary in that The Balance Index assess the degree of balance which exists between

²² Importantly, the data is limited in that it does not consider vertical mixing.

land-use distributions while the Herfindahl-Hirschman Index is principally concerned with the spatial concentration of singular land-uses (Song, Merlin and Rodriguez, 2013). However, Relative Entropy is the only metric employed in existing literature which explicitly measures land-use diversity using the proportionate share of space allocated to different land-use types *and* the number of land-use types within a region, hence its use here (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Zhang, Ghosh and Park, 2023). Relative entropy for a given spatial unit can be calculated as outlined in Equation 4.1, where E_j reflects the relative entropy score of area j . P_{kj} reflects the summed proportions of land types k within area j .

$$E_j = (-1) \times \sum_{j=1}^{k \geq 2} \frac{P_{kj} \ln(P_{kj})}{\ln(K)} \quad (4.1)$$

The relative entropy for each Small Area is calculated by summing the proportionate shares of space each land-use type²³ takes up relative to the number of land-use types within the region. Higher levels of relative entropy (measured on a 0-1 continuous scale) indicate greater land-use mixing, something linked to greater levels of efficiency in land and infrastructure use in urban areas but can also reflect the concentration of agricultural or natural landscapes in rural areas. In extreme scenarios, relative entropy reaches 0 when there is no mixing of land-uses within a specified spatial unit. In other words, there is only one land-use occupying that unit. Whereas relative entropy can reach 1 when land-use types are distributed equiprobably within a given spatial unit. This property renders it important to hold the number of land-use types counted within each area constant. In other words, the number of land-uses counted per spatial unit is held at the number of total classes in the dataset. Otherwise measurement bias occurs as identical scores can be achieved in numerous ways (Hajna *et al.*, 2014). Not standardising the counts weakens the explanatory power of the metric significantly as comparing scores across spatial units becomes impossible (Hajna *et al.*, 2014). Once these counts standardised, relative entropy can only reach a score of 1 when *all* possible land-use classes are distributed equally across a spatial unit and lower values consistently imply lower levels of land-use mixing.

²³ The final land-use catalogue consists of the following land-use classifications: 1. Commercial Land; 2. Retail Land; 3. Residential Land; 4. Industrial Land; 5. Public Urban Land; 6. Public Rural Land; 7. Agricultural Land; 8. Religious Land; 9. Unidentified Continuous Urban Fabric; 10. Unidentified Discontinuous Urban Fabric; 11. Unidentified Coastal/Wetlands.

Another property of the relative entropy metric is its symmetry, meaning all land-use classes are treated homogenously by only tracking the overall level of mixing within the areal unit and not how specific land-use classes interact. This is important because when analysing land-use configurations in the context of travel behaviours, understanding what type of land-use classes are mixed is necessary (Hess, Moudon and Logsdon, 2001). This is not a problem in this research context because land-use mixing is used as an instrument to gauge the efficiency of regional development. In other words, the primary concern is whether spatial units exhibit high levels of *any* land-use mixing or high degrees of land-use segregation.

The results are presented using two maps. One visualises the relative entropy scores of Irish city regions at the metropolitan level, whereby metropolitan areas refer to OECD definitions of Functional Urban Areas, while the other visualises these results exclusively within the cores of these areas, whereby cores refer to urban centres with a minimum population of 50,000 people with a density of 1,500 people per square kilometre (Dijkstra, Poelman and Veneri, 2019). Ireland has five Functional Urban Areas: Dublin, Cork, Galway, Limerick, and Waterford.

4.4 Results

Figure 4.1 below presents a visualisation of relative entropy in each Small Area within Irish metropolitan areas. These metropolitan areas capture city centres and their surrounding commuter belts. From a land-use perspective, core areas produce the highest relative entropy scores meaning they exhibit higher levels of land-use mixing and subsequently higher levels of efficiency in infrastructure and land usage, findings which align to those presented in international literature (Arnott, 2012; Green, 2012; Patias *et al.*, 2021). Conversely, commuter belts generally have lower relative entropy scores, and subsequently lower levels of land-use mixing in developments. A consistent pattern emerges whereby relative entropy scores tend to decrease with distances from urban centres, confirming *a priori* expectations (based on international literature) that urban sprawl creates land-use developments which inefficiently utilise land and infrastructure and have excessive spatial demands by segregating developmental landscapes (Prud'homme and Lee, 1999; Ewing *et al.*, 2014). Subsequently, I argue that urban sprawl, as experienced in Ireland, has thwarted efforts to achieve sustainable land-use developments as infrastructure and land are currently inefficiently utilised. In other words, horizontal growth is excessive. One concern with spatial analyses of this nature relates to the sensitivity of results to changes in spatial units. To address these concerns, this analysis follows existing literature by replicating this study in **Appendix 2 (A2)** at an alternative spatial

scale (Electoral Divisions) and produces similar results (Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021).

Figure 4.1: Relative Entropy Scores in Small Areas within Irish Metropolitan Areas

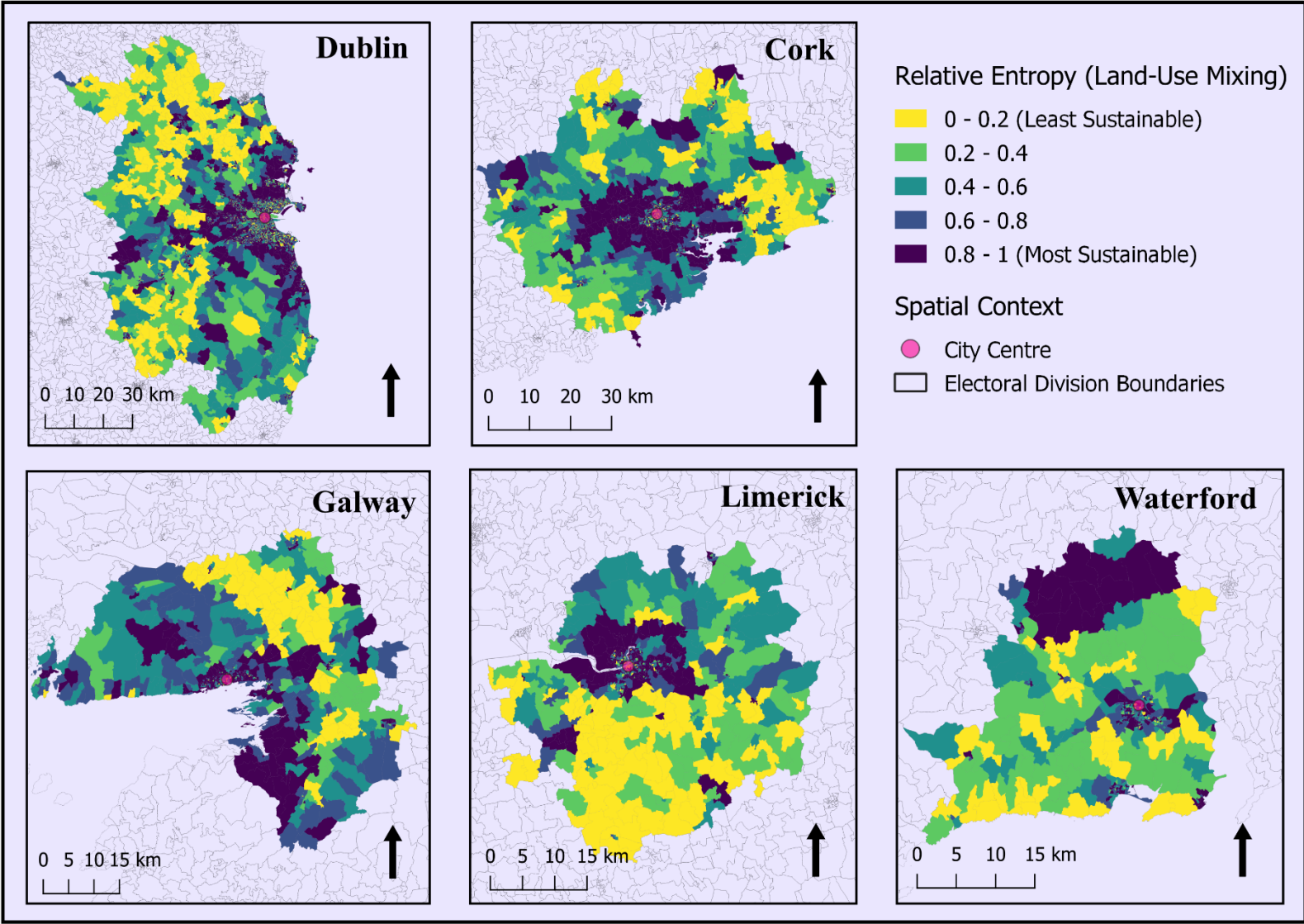


Figure 4.2 presents a visualisation of relative entropy in each Small Area within Irish city cores. Here, a unique pattern to that presented in Figure 4.1 is observed. In city cores, substantial variability is found in the relative mixing of land-uses. Because these results are specific to urban cores, this variability cannot necessarily be the result of misguided regional expansion (i.e., urban sprawl), perhaps explaining the lack of evidence showing a relationship between relative entropy and distances from city centres. Rather, this variability is likely the result of locality-specific considerations, such as zoning regulations, site suitability, and resource allocation (i.e., the distribution of employment hubs). For example, two of the most prominent Small Areas coloured green in Dublin correspond to a national park and a port, obviously explaining their low entropy scores. However, this is clearly the exception to the rule. But historical urban morphology also clearly plays a role. From a historical perspective, proximity to major natural amenities significantly influenced the formation of major urban centres (Glaeser, 2011). This was no different in Ireland, as all five major cities are situated in-and-around major ports and developed in a monocentric style (Reynolds-Feighan, 2003; Moore-Cherry and Tomaney, 2019). These findings fit into a wider body of international literature which suggest that the efficiency of land and infrastructure use within cities is largely independent of city sizes, which arguably supports the suggestion that volatility in relative entropy most likely stems from disparities in local-specific planning and zoning considerations (Moore-Cherry and Tomaney, 2019; Lemoy and Caruso, 2020, 2021). These findings are not as apparent when this analysis is replicated using an alternative spatial scale (see **Appendix 2 (A2)**), something possibly attributable to the fact that larger spatial units can mask local heterogeneities in land-use configurations.

Relative entropy scores in Galway (and Waterford to a lesser extent) illustrate that this high degree of variability may not necessarily be the default outcome. Consistently high relative entropy scores in these cities highlight consistency in the configuration of local land-use developments (and by deduction, local land-use policies). In this context, high variability in Cork, Dublin, and Limerick may highlight how a lack of coordination in local land-use policies and possibly restrictive zoning laws within these urban centres has created cityscapes characterised by inefficient and inconsistent land-use developments. Figure 4.2 suggests that land-use developments in Ireland's major cities are inefficient in their use of space, possibly because of historically restrictive/inadequate policymaking mechanisms, and therefore negatively contribute to achieving sustainability in Irish regional development.

Figure 4.2: Relative Entropy Scores in Small Areas within Irish City Cores

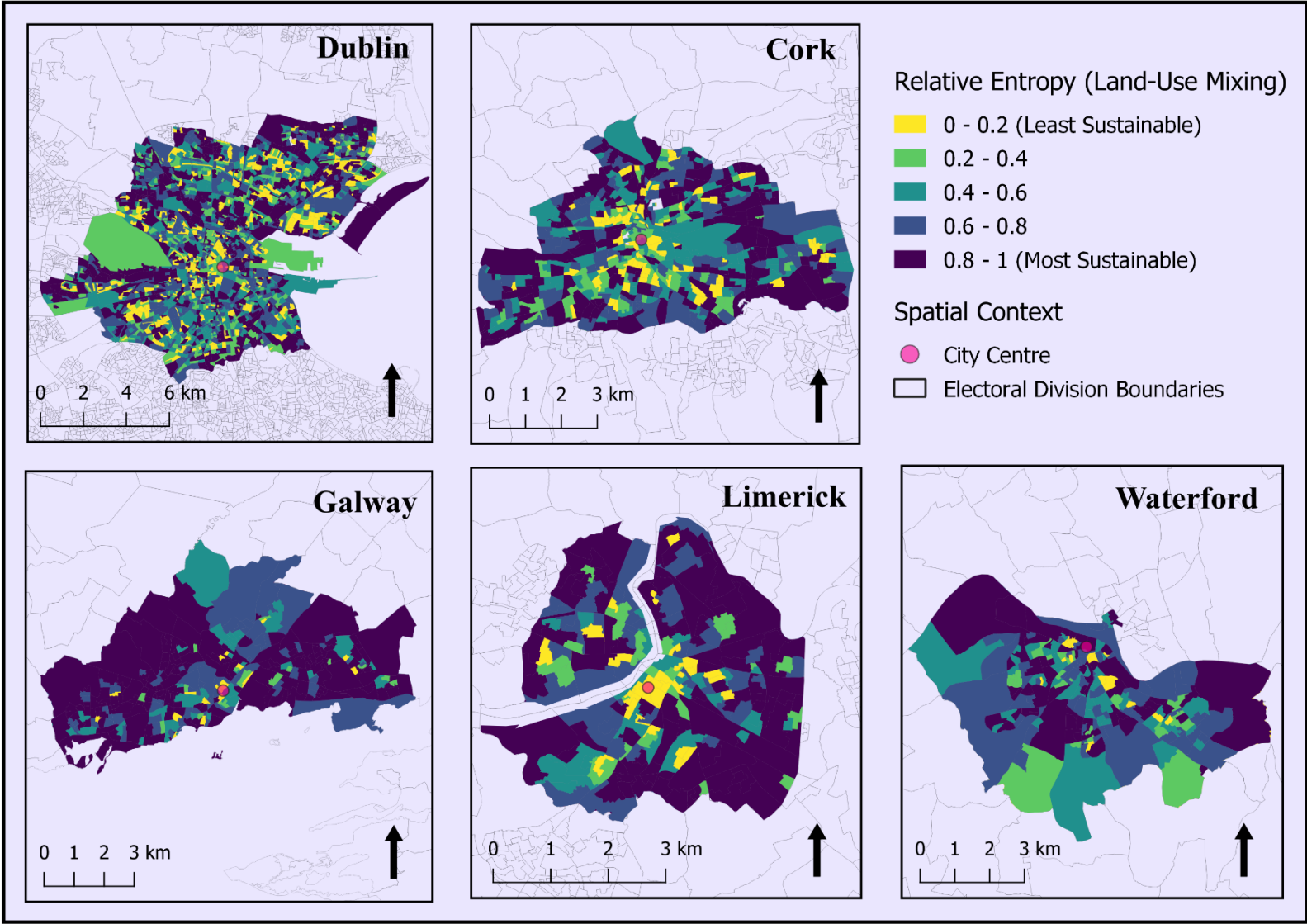


Figure 4.1 illustrates a pattern whereby land-use mixing decreases as Small Areas get further away from city cores, something found in other geographical contexts (Tikoudis *et al.*, 2022). This confirms *a priori* expectations about the inefficiency of land-use configurations outside of urban centres due to decades of urban sprawl (Ahrens and Lyons, 2019). Subsequently, I interpret the results of Figure 4.1 to suggest that historical regional development in-and-across Irish metropolitan areas has created landscapes characterised by inefficient land and infrastructure use, something supported in **Appendix 2 (A2)**. Considering the global evidence which suggests that city regions are homothetic in land, meaning city size is independent to the parsimony of land and infrastructure use (Lemoy and Caruso, 2020, 2021), international city regions characterised by sprawling developmental patterns may display similar results, illustrating the need for future research into land-use configurations across global metropolitan areas.

Figure 4.2 illustrates the high variability in land-use mixing across different urban localities. This may not necessarily be the result of urban sprawl *per se* because that is related to dispersed development in peripheral areas. Therefore, these findings be the result of other mechanisms, like zoning regulations or the poor coordination of local land-use policies (Moore-Cherry and Tomaney, 2019). The interpretations from Figure 4.1 can be extended to argue that, in an international context, regardless of city sizes, the rigidity of zoning and the competency of local/regional planning may serve as a fundamental determinant of the spatial expanse of regions. Whilst analysing the intricacies of how historical land-use patterns relate to zoning regulations and policymaking coordination is outside this article's scope, the results nonetheless suggest that land-use developments in Irish metropolitan areas and city cores are generally characterised by inefficiency in infrastructure and land usage, characteristics which negatively contribute to sustainability efforts.

Finally, to further support the inferences made above, Figure 4.3 and Table 4.1 below detail land-use counts per Small Area ('totallandtype') as well as the proportion of Small Areas which fall into each category of relative entropy scores. Land-use counts are distributed normally across metropolitan areas (i.e., a majority of Small Areas accommodate between 4-6 land-uses), indicating that the classification catalogue proposed aligns with the theoretical expectations of monocentric expansion when concerned with land-use. In other words, the land-use classification system used effectively captures land-use distributions along an urban-rural continuum whereby relatively few locations will host a high number of land-use classes (i.e., CBDs) while relatively few locations will also host a low number of land-use classes (i.e.,

rural areas), with most locations in-between will host a wide variety of land-uses (Evans, 1983; Green, 2012). However, as mentioned previously, relative entropy calculations standardise land-use counts so these distributions hold no bearing on relative entropy scores.

Figure 4.3: Distribution of Land-Use Counts ('totallandtype') Per Small Area By City Region

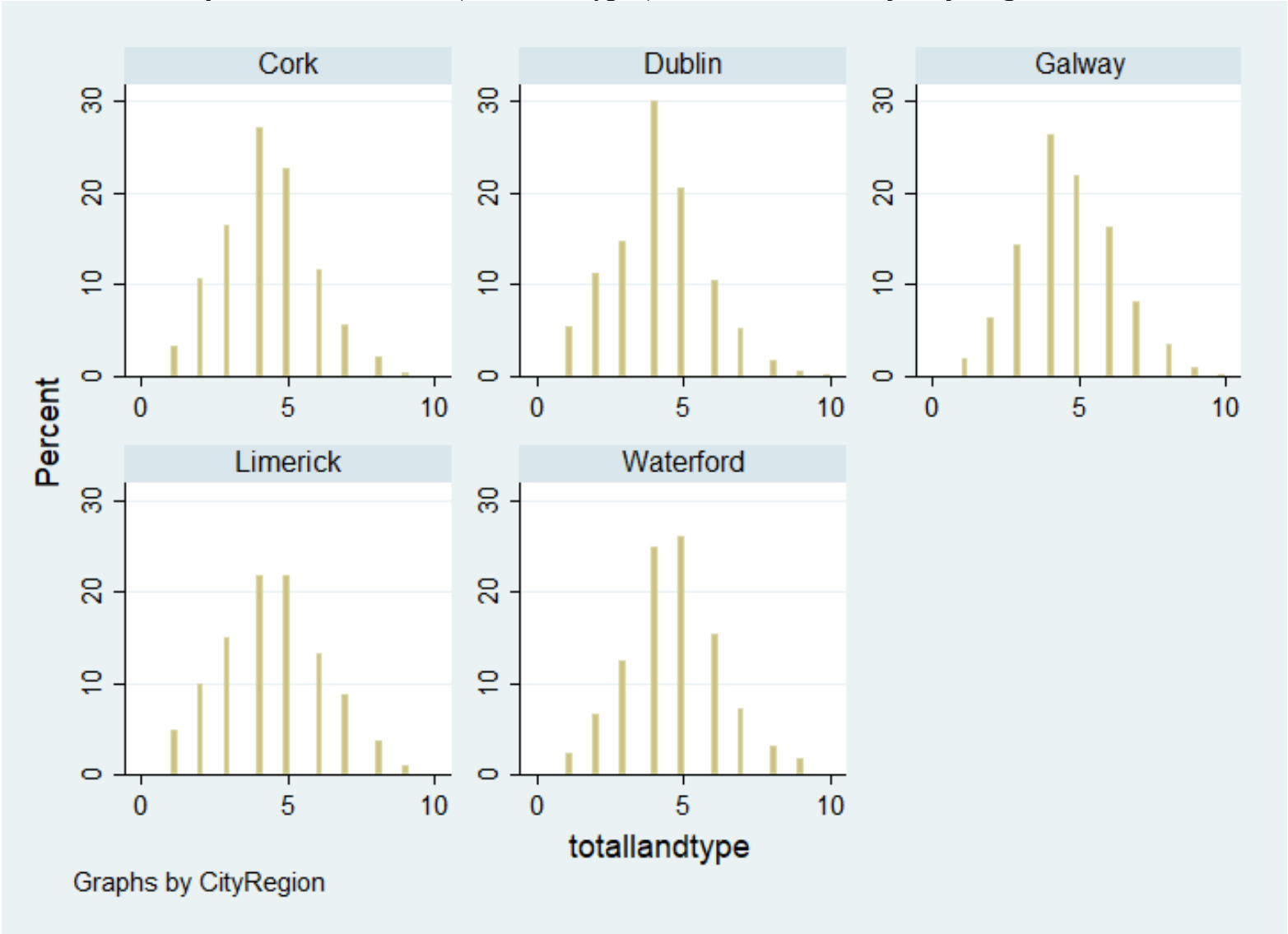


Table 4.1 provides an alternative perspective on the results presented above by illustrating the proportion of areas characterised by different levels of land-use mixing. These show that generally, a substantial proportion of Small Areas are characterised by high-levels of land-use mixing with no clear pattern emerging in the other categories. The former finding is unsurprising given the study areas consist of Functional Urban Areas – areas with significant levels of urbanisation. The latter however is interesting because theoretical expectations suggest that the distribution of scores in all city regions should roughly follow a linear pattern whereby the proportion of Small Areas corresponding to lower score categories should be lowest and the proportion of Small Areas corresponding to higher score categories should be highest. Once again, this is because the nature of these areas is predominantly urban and highly developed (i.e., suburban commuter belts), leaving fewer opportunities for predominately agricultural, rural, or natural landscapes to emerge.

Table 4.1: Percentage of Small Areas which fall into each relative entropy category

	Dublin	Cork	Galway	Limerick	Waterford
Relative Entropy (0-0.2)	17.6%	15.9%	13.6%	21.5%	13.6%
Relative Entropy (0.2-0.4)	14.5%	14.4%	9.7%	15.4%	19.8%
Relative Entropy (0.4-0.6)	18.8%	19.8%	19.9%	17.1%	22.6%
Relative Entropy (0.6-0.8)	20.3%	20.1%	24.2%	17.4%	20.3%
Relative Entropy (0.8-1.0)	28.8%	29.8%	32.6%	28.6%	23.7%

4.5 Discussion and Conclusions

Our analysis illustrates how decades of urban sprawl in Ireland has created metropolitan landscapes characterised by monocentric urban areas surrounded by suburban commuter belts which inefficiently utilise land and infrastructure, something evidenced by consistently low relative entropy scores. At the city-centre level, the results suggest that land-use developments within urban centres may be uncoordinated and that efforts to achieve efficiency in land and infrastructure usage have possibly been thwarted by restrictive zoning and inefficient resource allocation in past decades. While the focus of the analysis is Irish metropolitan areas and cities, evidence suggests that the fundamental implications of these results are transferrable to global geographies due to the observed consistencies in the relationships between city sizes, population distributions, and land-use configurations (Lemoy and Caruso, 2020, 2021; Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Patias *et al.*, 2021; Tikoudis *et al.*, 2022); variables which constitutes one key component to achieving sustainability in regional development. This is further supported by global evidence indicating that the underlying data

and methodology employed in this study shows consistent strength and transferability to diverse contexts, something particularly true for Volunteered Geographical Information (VGI) datasets like OpenStreetMap as they have been found to significantly elevate our understanding of land-use configurations across metropolitan areas (Cipeluch *et al.*, 2010; Haklay, 2010; Mooney, Corcoran and Winstanley, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018; Biljecki, Shin and Lee, 2023).

From a land-use perspective, sprawling suburbs are characterised by low residential densities, land-use segregation, and large time-space geographies whereby time-space geographies refer to required travel distances and horizontal regional expansion (Nechyba and Walsh, 2004). This type of development reduces the efficiency of local and regional infrastructure by increasing the spatial demands attributable to regional development, something which also worsens the habitat destruction attributable to human activities (Ye and Titheridge, 2017; Dunning and Lord, 2020). Economically, these inefficiencies obviously raise the costs associated with regional development, but socially, these inefficiencies may also heighten risks of social exclusion and unemployment, compounding the negative externalities associated with regional development (OECD, 2013, 2018; Ye and Titheridge, 2017; Zhang and Zhao, 2017). City centres can provide suitable templates for achieving efficiency in land and infrastructure use, something highlighted in international literature, but these areas may be thwarted by restrictive policymaking mechanisms and a possible lack of coordination between local land-use developments in the past, something alluded to in Moore-Cherry and Tomaney, (2019). This may explain why land-use developments across Irish city cores exhibit a high variability of land-use mixing, particularly areas in Dublin, Cork, and Limerick, characteristics which may subsequently induce increased levels of horizontal expansion.

Inefficient land-use within cities and metropolitan areas presents unique problems. At the metropolitan level, increased horizontal expansion results in the depletion of natural resources like land, particularly that pertaining to natural habitats. Perpetual spatial expansion is impossible. Therefore, increasing the efficiency of land-use configurations by seeking to accommodate the maximum number of people and activities within the smallest space is a key ingredient needed to attain sustainability in regional development. While many mechanisms influence the effects of this expansion, the tension between horizontal and vertical expansion is one component. Analysing land-use mixing allows researchers to investigate these (in)efficiencies and thus provide a meaningful contribution to discussions around achieving sustainability in development. Currently, Irish land-use developments inefficiently use these

resources, something which can cause significant environmental (and economic) damage. At both the city and metropolitan level, policies which promote mixed-use developments offer tangible mechanisms to increase the efficiency of regional development in Ireland by reducing regional time-space geographies, but the effectiveness of such measures hinges on the degree of coordination between regional land-use, transport, economic, and social policies.

Although relative entropy provides a robust measure of land-use mixing, as shown in Song, Merlin and Rodriguez (2013), it has some limitations. Relative entropy fails to consider heterogeneities in regional morphology and fails to capture the influence of neighbouring spatial units on relative entropy scores. Furthermore, it also neglects a location's place along the urban-rural continuum, a key consideration when considering the theoretical rationale of regional expansion and location decisions more generally (Evans, 1983; Anas, Arnott and Small, 1998; Green, 2012; Oueslati, Albanides and Garrod, 2015). Therefore, future research should endeavour to enhance measures of land-use mixing by explicitly incorporating regional structural weights, spatial proximity weights, and distance weights. This will allow researchers to circumvent issues associated with the Modifiable Area Unit Problem, but it will also serve to combat additional limitations in this analysis, such as that related to the lack of data on building verticality.

Urban landscapes in Ireland are largely characterised by mono-use developments which inefficiently use the verticality of developments to increase efficiency in infrastructure and land-use (Winston, 2007; Moore-Cherry and Tomaney, 2019). But global cities are heterogenous in this respect, with some having developmental paradigms prioritising this intensity more than others (i.e., London, Paris, or New York). As a result, future research should endeavour to enhance the datasets used to make such calculations to account for the square footage of developments, as they are currently not available in an Irish context unless researchers use population densities as proxies, which may be appropriate in certain contexts. This will allow researchers to acquire more nuanced insights into global land-use configurations within cities, something which can be supplemented by explicitly accounting for distances to regional cores and cities, as in Lemoy and Caruso, (2020, 2021).

When analysing the sustainability of regional development, land-use configurations are only one component of the analysis. Future research should conceptualise metrics which synergise the analysis of social, economic, and environmental sustainability. Considering this, interesting avenues to pursue could involve quantifying the economic and social costs associated with

different types of developments to enhance our understanding of the interrelationships between these sometimes conflicting realms. Relatedly, researchers should endeavour to link land-use configurations to individual socio-demographic considerations. This will allow researchers to probe whether socio-demographic mechanisms, like Tiebout Sorting, influence the temporal evolution of land-use configurations, and the subsequent sustainability and efficiency of developmental patterns. Theoretically, land-uses and Tiebout Sorting mechanisms share an interesting relationship because of the expectation that residents, through voting patterns, shape the direction of local development (Tiebout, 1956). Relatedly, researchers can use additional workhorse theories of urban economics, like those related to the location decisions of economic agents, to explain land-use configurations and their evolution over time.

Finally, policymakers must recognise that a win-win solution to sustainability may not exist, and that trade-offs in the economic and/or social realm may be necessary to achieve sustainability in development. At a rudimentary level, simple trade-offs which stem from developmental decisions such as the location of new infrastructure are highly important in determining the effectiveness of land-use and transport policies as instruments which can be used to achieve these goals.

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Chapter 5: Incorporating Opensource Data into Land-Use Sustainability Metrics: A Case Study of European Capital Cities

Recent advancements in data science have provided opportunities to improve the source data used to assess land-use configurations, yet few studies utilise this data. Using land-use mixing as the empirical instrument, I quantify relative entropy in standardised 1km x 1km grids across 28 European city regions to gauge the level of land-use mixing present within cities. This facilitates investigations into the distribution of land-use across space, something explicitly linked to regional environmental, economic, and social outcomes. I compare relative entropy estimates collected from the CORINE Land Cover dataset with those from a land-use catalogue comprised of CORINE and OpenStreetMap data. The objective of this case study is to evaluate the extent to which OpenStreetMap data can be used to assess land-use configurations within a monocentric and polycentric regional development framework. In this regard, I find that the CORINE dataset often produces results which are inconsistent with theoretical expectations, relative to the estimates produced by a combined CORINE-OpenStreetMap catalogue. While also making inferences into the relative sustainability and efficiency of land-use developments within these city regions, I also argue that traditional datasets like the CORINE Land Cover may overestimate the degree of land-use mixing within spatial units by measuring urban form instead of function.

5.1 Introduction

Land and space are finite natural resources, meaning perpetual horizontal expansion is impossible. A key issue in regional planning is that these resources should be used efficiently, as wasteful developmental patterns negatively contribute to efforts to achieve sustainability in development (Nechyba and Walsh, 2004). Efficiency in this context usually relates to a development's ability to accommodate a large number of people and activities within a relatively small space, thereby reducing the physical time-space geographies of regions and the costs associated with expansion and development (Bryan *et al.*, 2016; Heck *et al.*, 2018; Hersperger *et al.*, 2018). One way to tackle this issue involves reducing required travel distances within regions, something directly related to developmental compactness, but more so relevant to the distribution of land-uses across space (Reynolds-Feighan, 2003; Zhang and Zhao, 2017; O'Riordan *et al.*, 2022). In this context, evidence suggests that developmental forms characterised by compactness, high settlement densities, and mixed land-use boost the efficiencies of land-use configurations by reducing regional spatial demands, subsequently reducing the natural landscape destruction attributable to human activities (OECD, 2018;

Motieyan, Kaviari and Mostofi, 2022). Considering this, I assess the sustainability and efficiency of land-use configurations across European capital cities by measuring relative entropy (i.e., land-use mixing) within metropolitan areas using a highly refined land-use dataset. Specifically, this case study incorporates opensource land-use data into a study of urban morphology and assess whether this data can provide unique insights into land-use distributions.

Relative entropy is the most common metric used in the literature to assess land-use mixing because of its mathematical elegance and attractive properties which explicitly allow it to measure levels of land-use diversity and segregation, both within and across spatial units, using the proportionate share of space used by each land-use class alongside the number of observed land-use classes counted (Song, Merlin and Rodriguez, 2013; Eldeeb, Mohamed and Páez, 2021; Motieyan, Kaviari and Mostofi, 2022). The rationale behind such a metric follows the work of (Jacobs, 1961) by arguing that land-use mixing can significantly influence regional economic, environmental, and social outcomes, rendering it vital to policymakers and academics alike. In this context, land-use mixing is cited as a tangible instrument to mitigate the damage and costs associated with prevailing developmental patterns like urban sprawl (Song, Merlin and Rodriguez, 2013; Mavoa *et al.*, 2018; Im and Choi, 2019, 2020; Sass and Porsse, 2021).

A historical bottleneck in regional science research has been the lack of adequate spatial data to evaluate the impact of different developmental patterns on phenomena like economic growth, environmental sustainability and social vitality (Badoe and Miller, 2000; Adolphe, 2001; Arribas-Bel, 2014; Mansury, Anantsuksomsri and Tontisirin, 2021; Östh, Türk and Huang, 2022). The first significant advance in alleviating this problem came from the collection and mapping of data from supranational institutions like the OECD. However, the adaptability of this data to differing spatial contexts was limited to administrative boundaries, restricting the scope of spatially-oriented urban research (Batty, 2012; Fleischmann and Arribas-Bel, 2021; Singleton and Arribas-Bel, 2021). Recent advances in data science offer significant opportunities to broaden this scope by demonstrating how Volunteered Geographical Information (VGI) datasets are highly accurate, particularly in metropolitan areas, and should therefore be used in tangent with traditional, institutionally sourced data to improve our understanding of urban morphology (Haklay, 2010; Biljecki, Shin and Lee, 2023). Considering this, I create a land-use classification catalogue comprised of OpenStreetMap and CORINE Land Cover data to measure land-use mixing across European cities, an effort which constitutes

a case study in merging discipline-standard and opensource data. In general, this work contributes to debates within regional and urban studies by visualising the multifunctionality of land-use across small geographical spaces using two datasets at a uniquely disaggregated spatial scale (Druga and Minár, 2018; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021), thereby allowing us to make two distinct contributions to regional and urban science.

Firstly, this research builds on the work of Fleischmann and Arribas-Bel, (2021) and Arribas-Bel, (2022), who have established a research agenda to develop data-driven classifications of land-use developments that provide a better understanding of regional development structures (Correia, Moore and Goodwin, 2021; Arribas-Bel, 2022). This data-driven focus stems from new opportunities provided by opensource data that enable researchers to circumvent data inadequacies within urban studies (Badoe and Miller, 2000; Adolphe, 2001; Arribas-Bel, 2014; Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Correia, Moore and Goodwin, 2021). Typically, European-based studies measuring land-use mixing only adopt the CORINE Land Cover dataset (or its sister Urban Atlas dataset) to classify land-use (Schwarz, 2010; Druga and Minár, 2018; Ahrens and Lyons, 2019; Eldeeb, Mohamed and Páez, 2021). I go further by creating a land-use classification catalogue which combines the strengths of the discipline-standard CORINE Land Cover dataset and OpenStreetMap data, while also comparing relative entropy estimates produced by each. Supplementing this, the strengths and limitations associated with these datasets are discussed alongside directions which will allow future research to improve upon these limitations.

Secondly, studies investigating the configurations of land-use developments are typically conducted at a local level whereby singular regions are the focus of study (Ton *et al.*, 2019; Eldeeb, Mohamed and Páez, 2021). Few studies elevate this research to cross-country comparisons of regions (see Lemoy and Caruso, (2020, 2021) for exceptions), largely due to data and spatial scale limitations (Ton *et al.*, 2019; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021; Gan *et al.*, 2021). I contribute to this literature by providing a cross-country analysis of regional land-use patterns using consistent and highly disaggregated spatial units and regional boundaries, directly facilitating cross-country comparisons of land-use mixing within city regions, a variable known to directly influence economic, environmental, and social outcomes (Druga and Minár, 2018; Ahrens and Lyons, 2019; Calka, 2021).

Empirically, this is a data case study that focuses on incorporating one opensource dataset into regional science. Specifically, the most renowned institutional land-use dataset in Europe is

merged with the largest global VGI dataset to assess whether novel insights around land-use configurations can be attained. The first of these is the discipline-standard 2018 CORINE Land Cover dataset and the second is a combination of CORINE Land Cover and OpenStreetMap data. This combination utilizes the strengths of both datasets, specifically CORINE's comprehensive coverage and OpenStreetMap's fine-grain scale, while also mitigating the limitations associated with both individual datasets. Using these data, relative entropy estimates are calculated and cross-dataset differences in these estimates are presented. Small differences in relative entropy estimates suggests that OpenStreetMap may not provide many new and meaningful insights into the degree of land-use mixing across European cities whereas large differences possibly indicate that source-data improvements may be needed in future research. To ensure cross-country comparability, a consistent spatial scale is employed across the city regions under study. Specifically, a 1km x 1km grid within 28 cities is used, providing 162,037 spatial units.

Section 5.2 details a literature review surrounding land-use mixing, regional development, and the importance of incorporating opensource data into regional science literature. *Section 5.3* provides insights into the datasets used throughout this analysis, the study area, and the methodological framework. *Section 5.4* presents the results. *Section 5.5* concludes the analysis by discussing the implications of the results, whilst also providing direction for future research and addressing this study's limitations.

5.2 Background To The Literature

5.2.1 Regional Development in Europe: Monocentric Regional Expansion and Urban Sprawl

Monocentric theories of regional development posit that regional economic activity concentrates in-and-around singular urban/economic hubs (Muth, 1969; Mills, 1972; Evans, 1983). Regional development revolves around this hub because of its attractiveness as an economic and social outlet, a dynamic which produces an inverse relationship between land rents and distances from urban centres (Evans, 1983). Traditionally, this inverse relationship has reflected the increasing travel costs associated with travelling from peripheral areas to urban centres (Evans, 1983), but it can also be linked to the demand for space, something approximate to building/population densities. Land rents become cheaper as distances from urban cores increase, implying that fewer individuals/firms can acquire higher volumes of land at further distances from urban cores because demand is relatively low (Guy, 1998; Weilenmann, Seidl and Schulz, 2017; Erdin and Akbas, 2019; Garcia-Lopez, Nicolini and

Roig, 2020). But if the demand for land increases, so too does the price, suggesting that more individuals/firms can only acquire lower volumes of land as distances from cores decrease (Evans, 1983; Oueslati, Albanides and Garrod, 2015). Or, in other words, building/population densities increase. From a land-use perspective, this suggests that singular land-uses (i.e., residential, agricultural, and natural landscapes) will account for larger volumes of space as distances from hubs increase, thereby reducing levels of land-use mixing, while also implying that the demand for specific land-uses concentrates in these peripheries (Nechyba and Walsh, 2004; Ewing *et al.*, 2014; Weilenmann, Seidl and Schulz, 2017; Albouy *et al.*, 2019; DiBartolomeo and Turnbull, 2021). In this case, achieving high degrees of mixed-use (i.e., efficiency in land and infrastructure use) within urban cores can positively contribute to sustainability efforts by preserving natural landscapes in peripheries despite the subsequently low relative entropy scores in these areas (Ewing *et al.*, 2014; Lemoy and Caruso, 2020, 2021).

Accordingly, this theory produces a scenario whereby particular land-uses will have different desirable location characteristics whereby typically urban land-uses will crowd alternative uses out of urban centres due the high competition for space, leaving relatively cheaper and more abundant land free in peripheral areas for alternative uses (i.e., residential suburbs and agriculture) (Lafourcade and Thisse, 2011). From a land-use mixing and perspective, this implies that there is no one-size-fits-all approach to interpreting metrics like land-use mixing, because depending on a location's place along the urban-rural continuum, low scores may not indicate any deficiencies. However, it remains an important framework for assessing land-use configurations because horizontal expansion is generally not desirable if it can be avoided. Therefore, metrics like land-use mixing can be employed within an urban economics theoretical framework to assess whether *urban* boundaries and peripheries have excessive spatial extents (Anas, Arnott and Small, 1998).

Regional development in Europe since WW2 has been typified by urban sprawl. In this context, regions expand around singular urban cores whereby as distances from these cores increase residential densities decrease and land-use segregation increases (Hosseini and Hajilou, 2019; Qiao *et al.*, 2019; Strollo *et al.*, 2020; Faccini *et al.*, 2021). A key problem with the manifestation of these developmental patterns is that they are guided by inefficient land-use within urban cores, thereby forcing increases in the spatial expanse of urban areas and their subsequent boundaries (European Environmental Agency [EEA], 2006; OECD, 2018). This compounds problems associated with other traits of these developmental forms, like the dislocation of residential areas from places of interest, as land becomes increasingly segregated

due to increasing regional time-space geographies (i.e., required travel distances) (Hosseini and Hajilou, 2019; Motieyan, Kaviari and Mostofi, 2022; O’Riordan *et al.*, 2022). For instance, from a travel behaviour perspective, increases in regional time-space geographies and land-use segregation are positively associated with increased car-use, whereas from an economic perspective, these characteristics increase the costs of infrastructure and service provision, rendering low-density, spatially expansive regions relatively inefficient on multiple fronts (Dieleman and Wegener, 2004; Badland and Schofield, 2005; Huang *et al.*, 2020; C. O’Driscoll *et al.*, 2022; O’Riordan *et al.*, 2022).

An important element of this debate is whether regions are still developing around a singular urban hub. The emergence of “edge cities” in certain contexts has created spatial dynamics where there are multiple economic hubs within regions, also known as polycentric regions (Nechyba and Walsh, 2004). Theoretically, polycentric regions divide once-monocentric regions into multiple parts, whereby each part has a corresponding economic hub that development revolves around, something which may facilitate greater efficiency in regional development by creating a landscape akin to cluster settlements (European Environmental Agency [EEA], 2015). For instance, polycentric regions theoretically eliminate the need for inward commuting from hinterlands to regional cores if an equilibrium between residential dispersion and the provision of economic opportunity (i.e., jobs) is found (García-Palomares, 2010). This is because these areas create alternative destinations for economic and social activity, catalysing increases in land-use mixing, developmental compactness, and a dispersal of human activities to locations that are closer to residential areas, further reducing local time-space geographies (García-Palomares, 2010; Tsai, 2015).

However, realising this has been challenging for two main reasons. Firstly, decentralised urban sprawl, as experienced in Europe, is a phenomenon where peripheral expansion/growth rates exceed those of core areas (Tsai, 2015; OECD, 2018). This is a problem because it implies that the development of peripheral greenfield sites is taking precedent over the re-development of existing settlements and infrastructure, making it difficult to benefit from economies of scale in development. But secondly, peripheral developments have generally been unable to provide competitive levels of economic opportunity, thereby catalysing inward commuting (Nechyba and Walsh, 2004). Collectively, this has inhibited the creation of relatively self-sufficient developments characterised by compactness and mixed-use and persists in facilitating the creation of commuter belt suburbs (Vega and Reynolds-Feighan, 2008, 2009). Polycentricity is tangential to this chapter because the spatial boundaries are representative of monocentric

areas, whereby boundaries are defined according to population densities *and* the extent to which people work in the relevant regional core (Dijkstra, Poelman and Veneri, 2019). Therefore, relative entropy estimates are expected to generally follow a monocentric pattern meaning the mixing of unique land-use classes decreases with distances from urban cores, partly reflecting the reduced demand for space in these areas but also reflecting increases in land-use segregation and decreases in settlement densities.

5.2.2 Land-Use Mixing and Regional Development

In a regional development context, there are three broad uses for land: Artificial land (i.e., man-made settlements), Non-Artificial land (i.e., natural habitats), and Agriculture. In this context, the spatial costs of human settlements are disproportionately borne by natural habitats, meaning that the inefficient use of land by humans leads to disproportionate increases in natural landscape destruction (Heck *et al.*, 2018). For instance, the CORINE Land Cover change maps illustrate that since 1990, a significant proportion of land-use developments have been related to agriculture and human settlements. Although this implies that these occurred at the expense of natural landscapes, there is some regional variation in the trends. For instance, in the Scandinavian countries, a substantial chunk of natural landscapes were preserved and expanded (Copernicus Land Monitoring Service, 2021). One key element of sustainability in land-use relates to this trade-off between natural and man-made landscapes, or in other words, how the spatial demands of human settlements impacts local environments (Zhang and Zhao, 2017). Human settlements characterised by low building densities and land-use segregation (i.e., the historical manifestation of urban sprawl across much of the Global North) have higher spatial demands than areas characterised by land-use mixing and compactness because they increase regional time-space geographies (Reynolds-Feighan, 2003).

From this perspective, land-use configurations directly influence the economic and environmental costs of regional development by defining the relative efficiency of land and infrastructure usage (Zhang and Zhao, 2017). Accordingly, maximizing the efficiency of existing settlements prior to initiating outward expansion offers a tangible mechanism to mitigate the levels of habitat destruction attributable to human settlements. Specifically, evidence suggests that land-use mixing and compactness are development traits which can positively contribute to these efforts by reducing required travel distances, something which allows for the integration of multiple land-uses within singular areas (Jacobs, 1961; Pojani and Stead, 2015; Bryan *et al.*, 2016; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021). More simply, the maximum number of people can be accommodated within the smallest space,

increasing developmental efficiencies and reducing the spatial demands of human settlements (Dieleman and Wegener, 2004; Badland and Schofield, 2005; Zhang and Zhao, 2017; Huang *et al.*, 2020). This is particularly important in urban centres and cities (i.e., areas which host the greatest concentration of artificial landscapes) because they have a greater capacity to achieve economies of scale and density in both infrastructure and land usage, effects which may slow rates of outward horizontal expansion (Takayama, 2020).

Considering this, land-use mixing, while not unambiguously related to urban sustainability, can be used as an indicator to gauge the relative efficiency of land and infrastructure usage, one of many key considerations when investigating the sustainability of land-use configurations (Eldeeb, Mohamed and Páez, 2021). Whilst multiple instruments exist to assess land-use configurations, relatively few explicitly measure land-use diversity and mixing as described above. For instance, The Balance Index's principal use concerns measuring the existence of balance (in terms of space occupied) between multiple land-uses within spatial units, the Herfindahl-Hirschman Index measures the concentration of singular land-uses within spatial units, while Relative Entropy measures the diversity of land-uses within spatial units (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Zhang, Ghosh and Park, 2023). A review of these measures by Song, Merlin and Rodriguez, (2013) illustrates how many of these measures are generally correlated, and the use of any metric depends largely on the spatial scale of analysis and the number of land-use classes employed. Spatially, most measures are subject to the Modifiable Area Unit Problem if administrative spatial boundaries are used (Song, Merlin and Rodriguez, 2013; Patias *et al.*, 2021). The principal remedy for this problem is to undertake analyses at multiple spatial scales (as done in **Chapters 3, 4**, and **Appendix 1**), through the use of standardised grids, or in certain contexts it can be possible to construct spatial weights (i.e., Location Quotients) to correct for the influence of proximity on developmental patterns (Chen and Song, 2020).

When examining land-use configurations to gauge the sustainability of developmental patterns, different metrics are recommended depending on the research question. Analyses into the segregation of residential land requires a different metric (Balance or Dissimilarity Index) to investigations into the relative mixing of land-use classes (see Song, Merlin and Rodriguez, (2013) for greater details on these nuances). However, when analysing the relative mixing of more than two land-use classes across highly disaggregated spatial scales, relative entropy is explicitly recommended as an appropriate measure (Song, Merlin and Rodriguez, 2013), and is also the measure typically used across urban studies, hence its use here (Mavoa *et al.*, 2018;

Eldeeb, Mohamed and Páez, 2021). Relative entropy measures the mixing of unique land-use classes across pre-defined spatial units whereby higher levels of relative entropy correspond to greater levels of land-use mixing, and by extension possibly greater levels of developmental sustainability (Mavoa *et al.*, 2018; Chen and Song, 2020; Im and Choi, 2020).

5.2.3 The Integration of Opensource Data into Regional Science

Traditionally, studies assessing land-use developments and their influence on phenomena like travel behaviours (Cervero and Radisch, 1996; Cervero and Kockelman, 1997) and economic activity (Skonhoft and Solem, 2001) have been hindered by data limitations whereby technological advances had not yet made adequate land-use classification data available (Badoe and Miller, 2000; Adolphe, 2001; Arribas-Bel, 2014). Recent technological advancements have re-defined the data landscape available to applied researchers and have provided unprecedented depth and refinement in data catalogues, such as those concerning land-use composition, enhancing the capabilities of morphological, geographical, and urban science (Badoe and Miller, 2000; Arribas-Bel, 2014). In a land-use and urban development context, this advancement has elevated the capabilities of scholarship through improvements in remote sensing technologies (Rey *et al.*, 2011; Reis, Silva and Pinho, 2016) and Geographic Information Systems more generally (Heywood, Cornelius and Carver, 2006; Batty, 2012), allowing researchers to gain more nuanced insights into built environment configurations and urban development patterns (Arribas-Bel, 2022).

The CORINE Land Cover is the standard dataset used to classify land-use within European literature because it comprehensively classifies land across Europe²⁴ (Schwarz, 2010; Druga and Minár, 2018; Ahrens and Lyons, 2019). However, land-use classifications stemming from the CORINE Land Cover can arguably be improved upon by incorporating opensource data which provide finer-grain land-use classifications (Reis, Silva and Pinho, 2016). For instance, when classifying urban land-use, the CORINE dataset generally produces two unique land-use classes: Continuous Urban Fabric and Discontinuous Urban Fabric²⁵ (Copernicus Land Monitoring Service, 2021). This contrasts heavily with, for instance, OpenStreetMap, which generally produces at least three: Residential, Retail, and Commercial. Even by the names of

²⁴ The Urban Atlas is a sister dataset to the CORINE and provides comprehensive land-use classifications across European city regions. These classifications are close to identical to those provided by the CORINE dataset.

²⁵ The Urban Atlas does slightly better here by explicitly dividing “Discontinuous Urban Fabrics” into four unique categories (1. Discontinuous dense urban fabric; 2. Discontinuous medium density urban fabric; 3. Discontinuous low density urban fabric; 4. Discontinuous very low density urban fabric) but still encounters the same issue in that one cannot explicitly identify unique land uses, such as residential or retail land.

these classes, it is clear that greater insights can be acquired through OpenStreetMap data. This is because The CORINE (and its sister Urban Atlas) focus on classifying land according to tissue fabrics and urban form, whereas VGI datasets like OpenStreetMap prioritise function and use. Subsequently, recent research has analysed the efficacy of OpenStreetMap in creating large-scale land-use catalogues and has found that its accuracy and reliability is comparable to administrative data, particularly in urban areas, hence its use in this case study (Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018; Patias *et al.*, 2021). Whilst not adequately comprehensive to replace datasets like CORINE, it is apparent that in the areas OpenStreetMap does cover, it can provide superior insights through greater refinement in land-use classifications (Patias *et al.*, 2021).

5.3 Data and Methods

5.3.1 Study Area

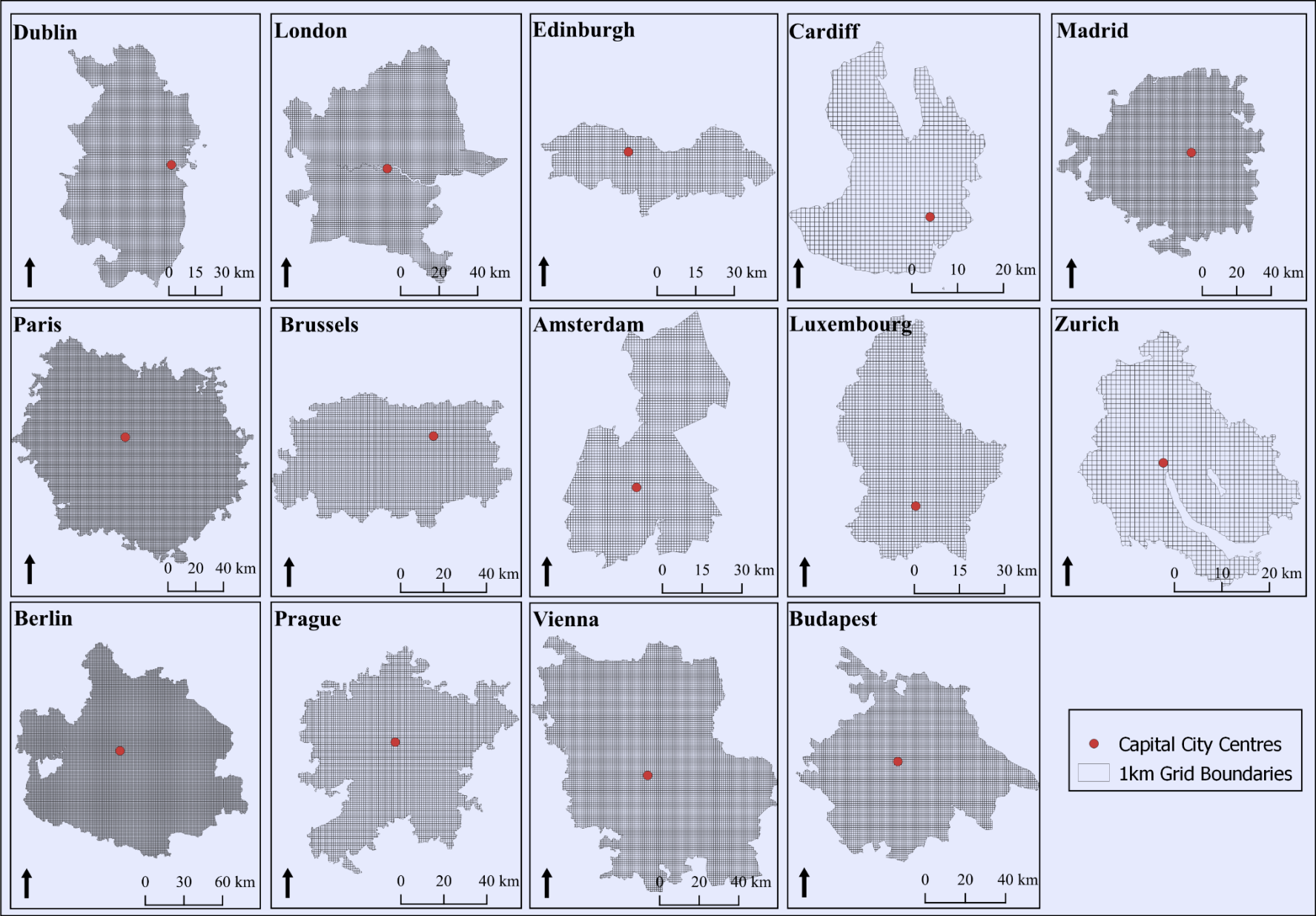
The land-use characteristics of capital cities from 28 European countries are assessed here. Capital cities are chosen because they represent the centre of urban expansion within countries. Therefore, these cities are likely to have the most pronounced developmental forms and patterns relative to minor cities. The city regions retained in this analysis include Dublin, London, Edinburgh, Cardiff, Madrid, Paris, Brussels, Amsterdam, Luxembourg, Zurich, Berlin, Prague, Vienna, and Budapest. Readers can find the results for an identical analysis conducted in Belfast, Lisbon, Rome, Athens, Warsaw, Ljubljana, Vilnius, Riga, Tallinn, Helsinki, Stockholm, Oslo, Copenhagen, and Reykjavik in **Appendix 3 (A3)**.

To facilitate cross-country comparisons between cities, regional boundaries are limited to those of Functional Urban Areas (FUA), as defined by the OECD, which incorporate urban cores and commuting zones in what are broadly defined as metropolitan areas (Dijkstra, Poelman and Veneri, 2019). Additionally, the spatial units of analysis employed are denoted through a 1km x 1km grid²⁶. Figure 5.1 below illustrates the extent of the capital cities' Functional Urban Area and the scale of the spatial units. It contextualises the FUA boundaries through the input of a city centre point, represented by the centroid of urban cores²⁷.

²⁶ **Appendix 4 (A4)** replicates this analysis with a spatial scale consisting of 2km x 2km grids, a sensitivity analysis which directly addresses concerns relating to the Modifiable Area Unit Problem.

²⁷ City centres follow the OECD definition of "urban cores", as detailed by Dijkstra, Poelman and Veneri, (2019).

Figure 5.1: Inset Maps Detailing The Functional Urban Areas of Our Capital Cities



5.3.2 Data

The data employed combines land-use data from the 2018 CORINE Land Cover dataset and OpenStreetMap to create a comprehensive and thorough land-use catalogue for capital cities. The high-quality of both datasets is well established in the literature (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasher, Zipf and Francis, 2018; Biljecki, Shin and Lee, 2023). Subsequently, formal checks of this quality are not undertaken here, but results are presented and discussed in the context of these dataset's strengths and limitations. Cross-dataset relative entropy scores are compared to gauge whether the incorporation of opensource data yields new insights concerning land-use configurations and distributions (Bhatta, Saraswati and Bandyopadhyay, 2010; Eldeeb, Mohamed and Páez, 2021). The European scope of analysis employed facilitates assessments into whether the insights found in **Chapter 3** and **4** are specific to Ireland or whether there is a wider international context to some of these issues. If so, this illustrates the need for a greater emphasis on the incorporation of open data in urban science.

For the CORINE dataset, every land-use polygon in the European Union is collected. Land-use types are aggregated into broad classifications in line with existing literature (Gao *et al.*, 2020; Calka, 2021), alongside the CORINE class 2 and 3 nomenclature. These include: 1. Continuous Urban Fabric; 2. Discontinuous Urban Fabric; 3. Industrial and Commercial Land; 4. Agricultural Land; 5. Public Green Space; 6. Wilderness and Forests; 7. Coastal Areas and Wetlands. Because the CORINE Land Cover comprehensively classifies land across Europe, it provides an adequate foundation to build a more refined land-use classification catalogue. **Chapter 3** provides a more detailed discussion on how these classifications are constructed.

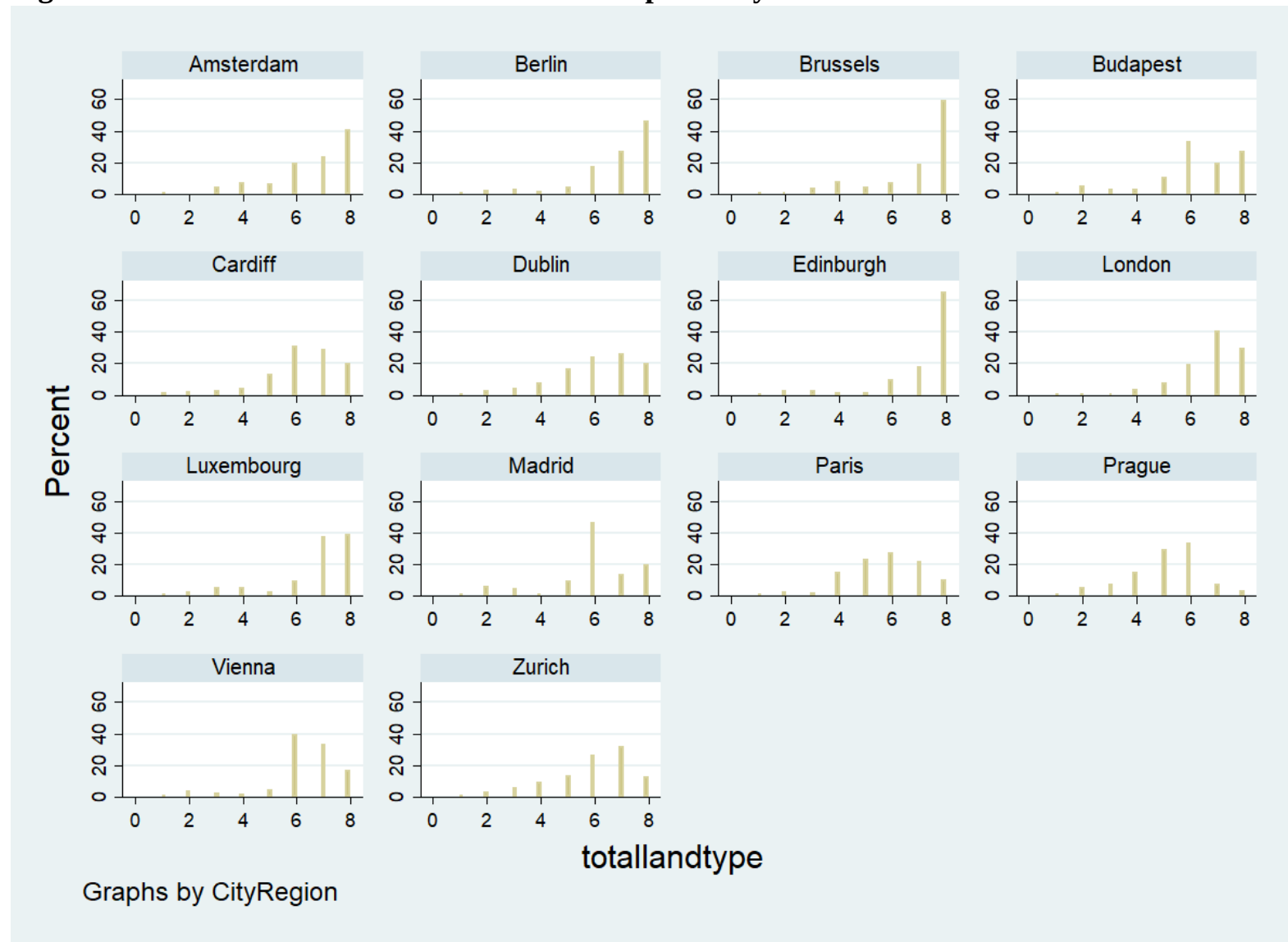
The OpenStreetMap land-use catalogue is comprised of every land-use polygon collectable via Quantum Geographic Information Systems (QGIS) QuickOSM plugin which lay within the Functional Urban Area boundaries of the capital cities. No precedent exists to guide this aggregation of OpenStreetMap land-use classes. However, where possible I follow previous classifications of the CORINE Land Cover dataset (Calka, 2021) and alternative country-specific datasets (Clark and Scott, 2013). The OpenStreetMap catalogue consists of 1. Commercial Land; 2. Retail Land; 3. Residential Land; 4. Industrial Land; 5. Public Urban Land; 6. Public Rural Land; 7. Agricultural Land; and 8. Religious Land. **Chapter 3** provides a more detailed discussion on how these classifications are constructed.

Although the CORINE Land Cover data is comprehensive in its coverage, it is not particularly thorough in distinguishing unique land-use classes in urban areas because it focuses on classifying land according to form. Therefore, when constructing the combined CORINE-OSM land-use catalogue, OpenStreetMap data is the main source while CORINE serves as a supplementary input when OpenStreetMap is unable to classify land. Specifically, I create a difference layer whereby CORINE Land Cover data is only kept in areas where OpenStreetMap data are absent. This allows me to exploit OpenStreetMap's strengths of providing highly refined land-use data in urban areas while the CORINE Land Cover classifies any remaining land-use pockets. The final catalogue consists of the following land-use classifications: 1. Commercial Land; 2. Retail Land; 3. Residential Land; 4. Industrial Land; 5. Public Urban Land; 6. Public Rural Land; 7. Agricultural Land; 8. Religious Land.

This classification builds upon the classification catalogue proposed in **Chapter 3**. The key differences are that “Class 9: Unidentified Continuous Urban Fabric” is now classed as “Commercial Land”, “Class 10: Unidentified Discontinuous Urban Fabric” is now classed as “Residential Land”, and “Class 11: Unidentified Coastal/Wetlands” is now classed as “Public Rural Land”. This follows the official CORINE documentation as Continuous Urban Fabrics principally relate to Central Business Districts (and similar types of environments), Discontinuous Urban Fabrics specifically relate to urban areas whereby residential land is a significant component, and Coastal/Wetlands refer to public land in predominately rural settings (Copernicus Land Monitoring Service, 2021). This also addresses concerns that relative entropy scores are highly sensitive to the number of land-use classes identified. Although, this issue is further remedied through the standardisation of the number of land-uses identified within each spatial unit, something discussed below.

Figure 5.2 below visualises the distribution of land-use counts per spatial unit across the capital cities within this study. Here, it is apparent that land-use distributions are comparable across the city regions in this analysis, justifying comparisons between levels of land-use mixing and subsequent inferences into the efficacy of land-use policies and regional development in later sections.

Figure 5.2: Land-Use Count Distribution Per Capital City



5.3.3 Methodological Approach

Land-use configurations can be assessed through multiple paradigms. An urban planning framework in the spirit of Jacobs, (1961) is adopted to assess these configurations. In other words, land-use configurations are assessed according to their relative diversity in form and function. In this context, relative entropy is the most commonly employed metric but alternatives exist, such as The Balance Index, The Dissimilarity Index, and The Herfindahl-Hirschman Index. Song, Merlin and Rodriguez, (2013) showed how the results produced by these metrics tend to be highly correlated, and all of them generally have the same limitations with respect to the Modifiable Area Unit Problem, so the choice of metric should be determined by the specific research question. In this regard, relative entropy is best suited because it assesses land-use mixing within spatial units using the share of space each land-use takes up alongside the number of observed land-uses within the region (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Zhang, Ghosh and Park, 2023).

Relative entropy measures the relative mixing of land-use types across pre-defined spatial boundaries. Higher levels of relative entropy (measured on a 0-1 continuous scale) indicate greater land-use mixing, something linked to greater levels of efficiency in land and infrastructure use in urban areas but can also reflect the concentration of agricultural or natural landscapes in rural areas. This illustrates the importance of considering the wider spatial context of land-use configurations when analysing concepts like developmental sustainability, but it also highlights the importance of understanding the mathematical properties of the metric (Song, Merlin and Rodriguez, 2013; Zhang and Zhao, 2017; Eldeeb, Mohamed and Páez, 2021). Higher levels of relative entropy are associated with greater land-use mixing and subsequently greater efficiency and sustainability in developmental forms (Jaeger, Bertiller, Schwick and Kienast, 2010; Jaeger, Bertiller, Schwick, Cavens, *et al.*, 2010; Cao, 2016; Zhang and Zhao, 2017; Mavoa *et al.*, 2018; Luan and Fuller, 2019). Relative entropy for a given spatial unit can be calculated as

$$E_j = (-1) \times \sum_{j=1}^{k \geq 2} \frac{P_{kj} \ln(P_{kj})}{\ln(K)} \quad (5.1)$$

Whereby E_j reflects the relative entropy score of area j . k represents land types and P_{kj} reflects the summed proportions of land types k within area j . In extreme cases, relative entropy can appear as 0 only when a given spatial unit consists of a singular land-use and facilitates no mixing of land-use classes. Whereas relative entropy can appear as 1 when land-use classes are

distributed equiprobably (For example, an area made up of three land-use classes where each have a 33.33% share). This property implies that if the denominator is not standardised (i.e., by being $\ln(k)$ instead of $\ln(K)$), measurement bias occurs and relative entropy estimates are not comparable across spatial units because identical scores can be achieved in numerous ways (Hajna *et al.*, 2014). This weakens the explanatory power of the metric significantly as inferences into problems like developmental sustainability become hazardous (Hajna *et al.*, 2014). Once standardised, relative entropy can only reach a score of 1 when *all* possible land-use classes are distributed equally across a spatial unit and lower values consistently imply lower levels of land-use mixing.

Another property of the relative entropy metric is its symmetry, meaning that it treats all land-use classes homogenously by only tracking the overall level of mixing within the areal unit and not how specific land-use classes interact. This is important because when analysing land-use configurations in the context of travel behaviours, understanding what type of land-use classes are mixed is necessary (Hess, Moudon and Logsdon, 2001). This is not a problem in this research context because I use land-use mixing as an instrument to gauge the efficiency of regional development. In other words, the primary concern is whether spatial units exhibit high levels of *any* land-use mixing or high degrees of land-use segregation.

Like **Chapters 3 and 4**, when presenting the results, I opt for cartographic visualisation. This allows me to visually contextualise the scale and scope of the analysis, and explicitly make cross-country comparisons on the levels of land-use mixing within spatial units, a variable directly related to regional economic, environmental, and social outcomes. Cartographic visualisation supplemented with the presentation of descriptive statistics enables a direct comparison between the results generated using the two land-use catalogues. This not only directly enables inferences to be made into the value of opensource data in this research context, but it also facilitates cross-country comparisons in land-use developments and their relative efficiency and subsequent sustainability. Colour schemes are chosen to accommodate natural inclinations that associate darker colours with larger values and lighter colours with smaller values, while also avoiding red-green colour combinations (Schiewe, 2019; Calka, 2021; J. O'Driscoll *et al.*, 2022).

5.4 Results

Below are a series of maps which illustrate the relative entropy of each 1km² grid within the European Functional Urban Areas under study. Figure 5.3 presents visualisations of relative entropy scores calculated using the CORINE Land Cover dataset and Figure 5.4 presents

visualisations of relative entropy scores calculated using the combined land-use catalogue. Figure 5.5 presents the absolute cross-dataset differences in relative entropy scores.

5.4.1 Relative Entropy Using CORINE Land Cover

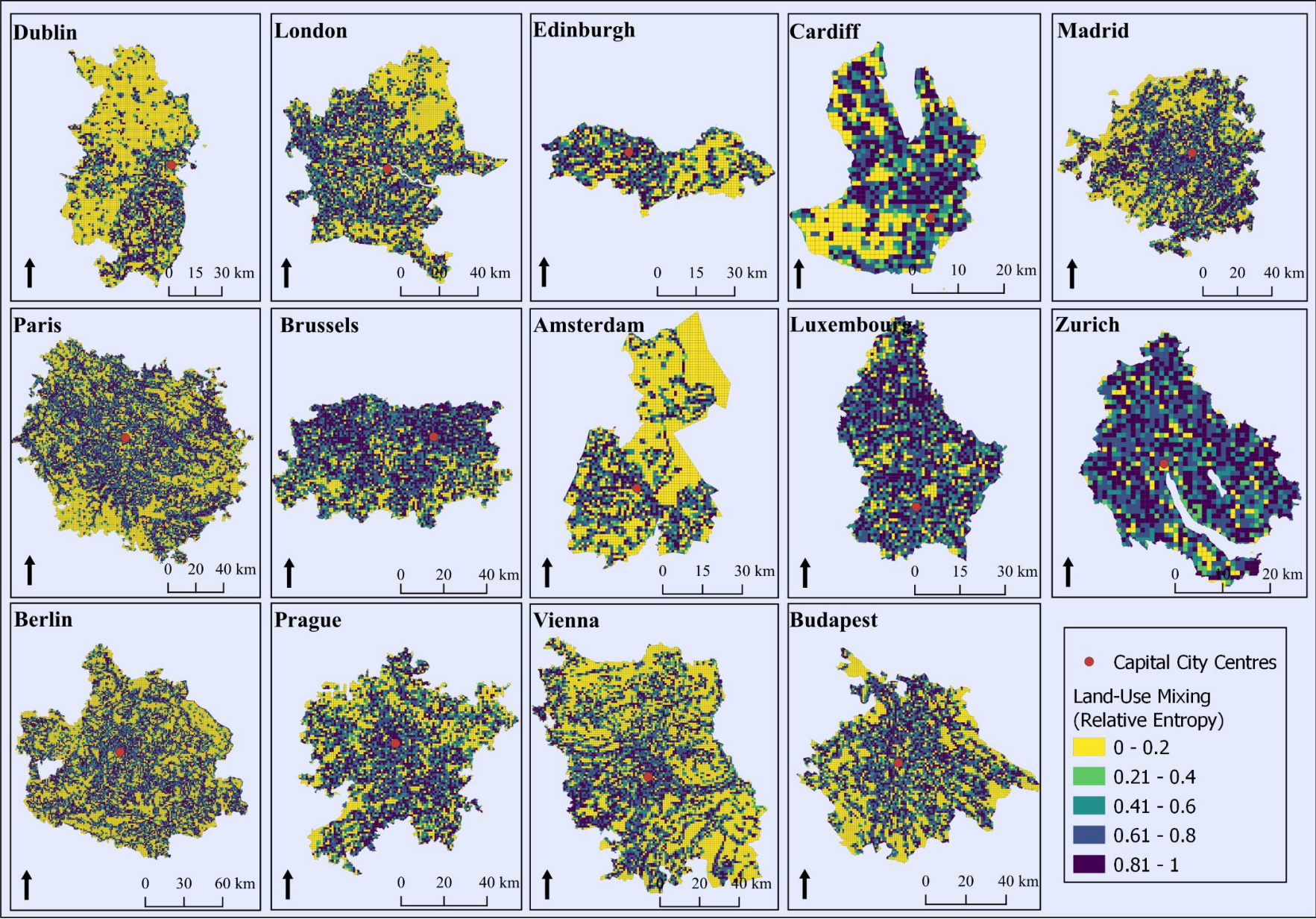
Figure 5.3 below displays the relative entropy scores obtained from CORINE Land Cover data. Darker colours correspond to higher levels of relative entropy, and therefore suggest higher levels of efficiency and sustainability in land-use developments. Across the metropolitan areas, high relative entropy scores generally concentrate in-and-around urban cores, but the theoretically expected relationship between distance and relative entropy, or in other words, distance and land-use configurations, is not obvious except in parts of Madrid and Vienna, a finding also present in **Appendix 3 (A3)** and **Appendix 4 (A4)** (Lemoy and Caruso, 2020, 2021). *A priori*, relative entropy is expected to decrease as distances from urban cores increase due to reductions in settlement densities (as well as increased clustering of singular land-uses) and a subsequent increase in required travel distances, a key consideration for determining the efficiency and sustainability of artificial land and infrastructure usage (Evans, 1983; Ewing *et al.*, 2014; OECD, 2018; Schlöpfer *et al.*, 2021).

When administrative spatial scales are used, as is typically the case in this literature, results of this nature can arguably be partially explained by the fact that relative entropy does not distinguish between different types of land-use combinations (Brown *et al.*, 2009; Song, Merlin and Rodriguez, 2013). So, as distances from urban cores increase, retail and commercial land-uses may be substituted for, say, greenspace and agricultural land, while maintaining consistent relative entropy scores, something further supported by the consideration that the size of administrative spatial units is explicitly linked to this distance (Batista e Silva, Gallego and Lavallo, 2013). However, because a spatial scale significantly more disaggregated than administrative scales is used and the fact that the extent of the spatial units are independent of distances to urban cores, this rationale is weakened as it implies perfect trade-offs in the spatial extents of unique land-use classes. Furthermore, the number of land-uses counted within each spatial unit is held constant, so high levels of land-use mixing can only occur if *every* land-use is observed in any given spatial unit and their distribution is close to equiprobable (Hess, Moudon and Logsdon, 2001; Brown *et al.*, 2009). Therefore, these results run contrary to a substantial body of literature, results which I argue stem from data inadequacies (Lemoy and Caruso, 2020, 2021).

Relatedly, there is considerable volatility in relative entropy scores both inside and outside urban cores across the dataset. In this context, volatility may result from land-use segregation within city regions stemming from clustering phenomena which produce areas like Central Business Districts, national parks, or commuter belts. However, it could also suggest a lack of coordination between local development strategies culminating to form uncontrolled and inefficient horizontal urban expansion patterns, something which aligns with historical manifestations of urban sprawl in monocentric regions across Europe (European Environmental Agency [EEA], 2006; OECD, 2018). However, it could also be indicative of inadequate and restrictive zoning laws which may morph the developmental landscape, something particularly evident in an Irish context (Moore-Cherry and Tomaney, 2019).

Across regional peripheries consistently high levels of land-use mixing are generally reported, particularly in parts of London, Madrid, Paris, Brussels, Berlin, Prague, and Budapest. While this could be representative of the emergence of polycentric regions whereby phenomena such as retail and residential sprawl converge and create new regional hubs (Sultana and Weber, 2014; Wang, Derudder and Liu, 2019), the lack of moderate relative entropy scores in these areas may illustrate weaknesses in the source data as the distinguishing of different land-use configurations at small spatial scales becomes difficult. In other words, the CORINE's focus on classifying land according to urban form may be masking local-level nuances in land-use configurations, something which can be potentially remedied through the use of data which classifies land according to function.

Figure 5.3: Relative Entropy in European City Regions Using The CORINE Land Cover Dataset



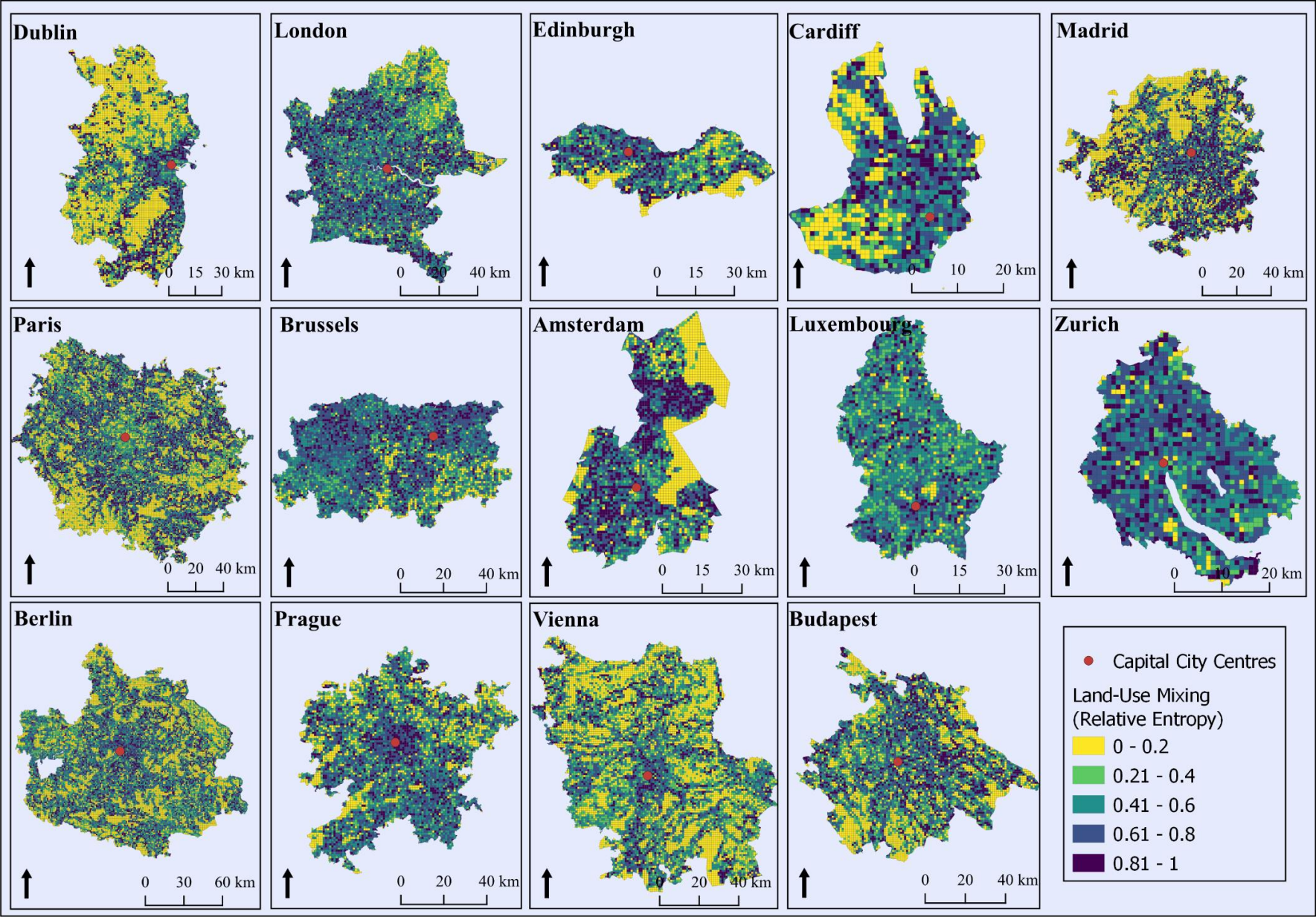
5.4.2 Relative Entropy Using OpenStreetMap and CORINE Land Cover

Figure 5.4 below displays relative entropy scores using the combined CORINE-OpenStreetMap land-use dataset. Generally, higher relative entropy scores concentrate in-and-around urban cores (i.e., the immediate surrounding area of city centre points), suggesting that urban centres across Europe are generally characterised by high levels of land-use mixing and that as a result, these areas are also likely to exhibit relatively higher settlement densities. Unlike before, the theoretically expected inverse relationship between distances from urban cores and relative entropy scores is more apparent across cities, particularly Dublin, Madrid, and Prague²⁸, something also illustrated in **Appendix 3 (A3)**, indicating that these insights may be more robust than those produced using the CORINE dataset alone.

With this dataset, significant volatility in relative entropy scores occurs outside of urban cores more so than within cores. This makes the theoretically expected inverse relationship between distances from urban cores and relative entropy less apparent, particularly in parts of Madrid, London, Paris, Brussels, Berlin, and Prague where clusters of high-entropy areas are present, indicative of areas characterised by high levels of land-use mixing and developmental compactness. As before, this may be indicative of the emergence of polycentric areas, and in this particular case this is intuitive because these cities are global, and some mega, cities. However, the ability to identify the extents of these clusters is easier when using the combined catalogue as evidenced by greater diversity in relative entropy scores across spatial units, indicating that heterogeneities in small-scale land-use configurations can be identified. Within core areas, there is greater consistency in relative entropy scores and scores are generally higher. This is indicative of land-use developments characterised by efficient land and infrastructure use, a finding generally more difficult to identify when using the CORINE Land Cover data alone, something I attribute to the lack of refined land-use classes within urban centres.

²⁸ In Amsterdam, significant clusters with low relative entropy scores represent port areas while similar areas in Dublin correspond to mountainous regions.

Figure 5.4: Relative Entropy in European City Regions Using The Combined Land-Use Dataset



5.4.3 Comparing The Scores

Figure 5.5 below displays the absolute differences in relative entropy scores between the combined land-use catalogue and that of the CORINE land-use catalogue. Here, dark colours reflect extreme disparities in the estimates, suggesting possible imprecision through either overestimation or underestimation, while lighter colours suggest relative consistency. In most cities, both datasets produce significantly different estimates in many spatial units.

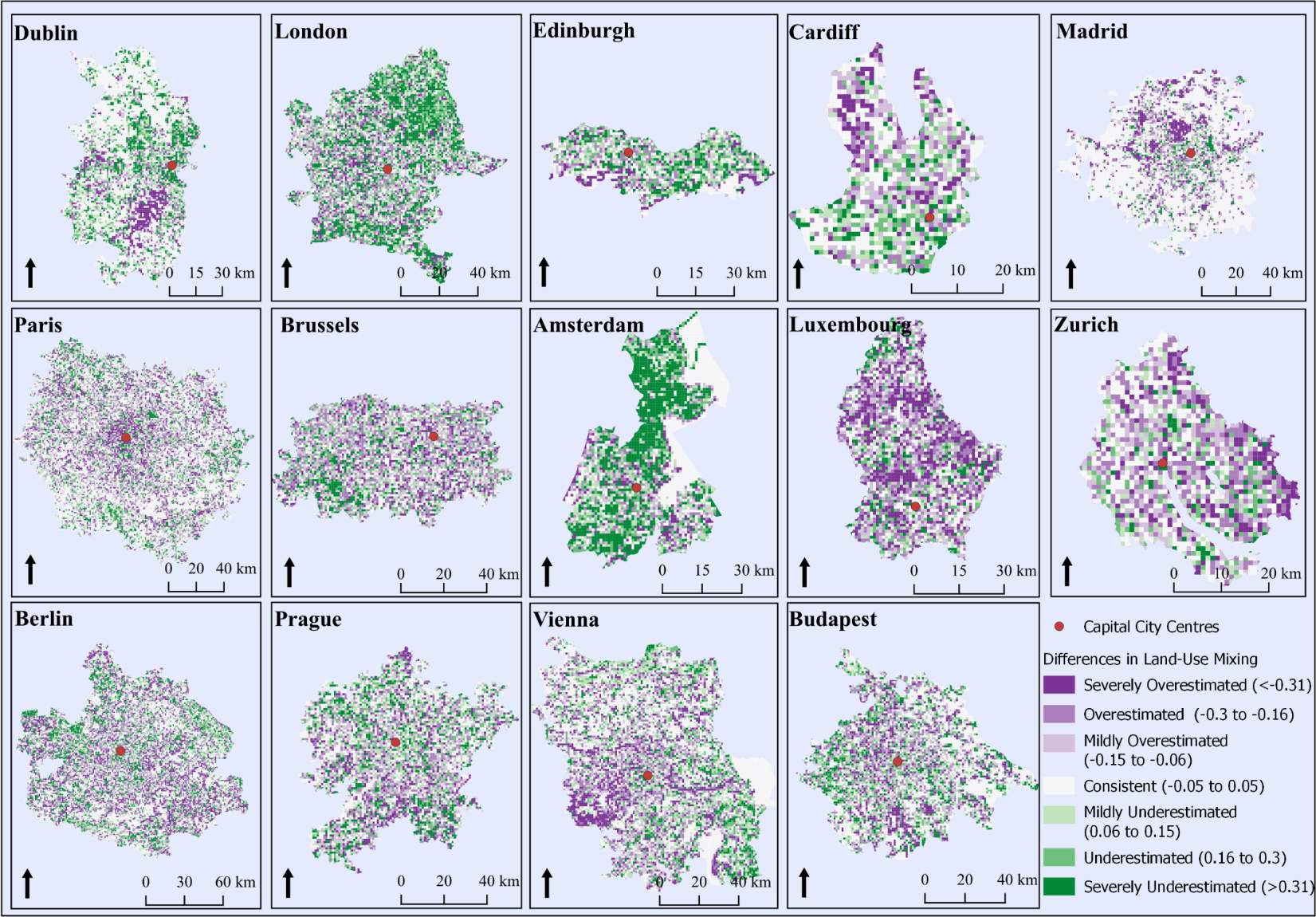
I posit that because the combined CORINE and OpenStreetMap land-use catalogue produce more theoretically robust results (which align with empirical literature), the combined land-use catalogue produces more accurate estimates. This argument is complimented by the fact that the land-use catalogues themselves contain a similar number of unique land-use classes, meaning if the underlying data are equally as insightful, they should produce similar relative entropy estimates, something further supplemented by the large literature which demonstrates the high quality of the data (Haklay, 2010; Mobasheri, Zipf and Francis, 2018; Biljecki, Shin and Lee, 2023). Considering this, these results suggest that in certain contexts, the CORINE Land Cover data may underperform as an empirical instrument, but OpenStreetMap may also underperform depending on the context the data are used. Evidence shows OpenStreetMap data to have the highest quality in urban areas, hence its use in this research (Haklay, 2010; Mobasheri, Zipf and Francis, 2018; Biljecki, Shin and Lee, 2023).

Generally, there appears to be no discernible pattern between cross-dataset differences in relative entropy estimates and distances to urban cores, something displayed in the aforementioned maps but empirically supported through low correlation scores. Supplementing this, many spatial units display consistent relative entropy scores, indicative that the data are equally as insightful and by implication, of equal quality. Subsequently, instances where relative entropy estimates obtained from the combined dataset exceed those obtained from the CORINE dataset may occur due to the CORINE's coarseness in land-use classification, particularly for land relating to human activities like residential, commercial, retail, and industrial land. This is particularly evidenced in parts of London, Paris, Brussels, Berlin, and Prague, whereby possibly emerging polycentric areas are identified but difficult to distinguish using just the CORINE Land Cover dataset. On the other hand, instances where relative entropy estimates obtained from the combined dataset are lower than those obtained from the CORINE dataset may occur because of CORINE's disproportionate weighting of land-use classes for rural/natural landscapes. In other words, there are more land-use categories for rural and natural landscapes, something which may produce artificially higher relative entropy scores, an issue

not encountered by the combined dataset due to a balance in urban-rural land-uses. This is particularly apparent in mountainous and coastal areas surrounding Dublin, Zurich, and Vienna.

Consistency in metric scores across datasets can be indicative of the relative robustness of the underlying data and their subsequent results. Therefore, Figure 5.5 suggests that when using the CORINE dataset alone to classify land, the subsequent metrics may imprecisely assess land-use configurations due to its focus on classifying land according to form. This is particularly problematic in urban centres and areas characterised by high intensities of human activities as it is in these areas where economies of scale and density can be most easily exploited by planners when undertaking regional development. I argue that this imprecision is evidenced by the significant disparities in relative entropy estimates when using alternative datasets, a finding supported in **Appendix A3 (A3)**. In general, this suggests that land-use catalogues which explicitly incorporate opensource data may provide greater insights into the heterogeneity in land-use configurations, particularly at smaller spatial scales, something attributable to their ability to provide fine-grain land-use classifications by focusing on classifying land according to function.

Figure 5.5: Cross-Dataset Differences in Relative Entropy Estimates In European City Regions



5.4.4 Statistical Comparisons

To supplement these inferences, Figures 5.6, 5.7, and 5.8 below display frequency distributions of relative entropy scores, as well as cross-dataset differences between scores, across all cities analysed in this research. These distributions provide some helpful insights and support for the claims and conclusions presented in this chapter while also strengthening the robustness of the results presented in Figures 5.3, 5.4, and 5.5.

Supplementing the insights provided in Figure 5.3, Figure 5.6 demonstrates that a significant proportion of spatial units across all 28 cities analysed in this chapter (and **Appendix 3**) are characterised by a low degree of land-use mixing, a finding which goes against a substantial international literature (European Environmental Agency [EEA], 2006; OECD, 2018; Lemoy and Caruso, 2020, 2021). However, Figure 5.6 also sheds light on the nuanced finding that many cities also share a U-shaped distribution in relative entropy scores when the CORINE dataset is used to generate these scores (i.e., grids display either low or high relative entropy scores with fewer in between). This supports previous assertions that CORINE struggles to classify land-use at highly refined scales, creating results which only distinguish between landscape forms. In other words, the coarse classification by form is masking nuances in land-use configurations. Relatively few city regions follow the theoretically expected distribution of relative entropy scores; Luxembourg and Tallinn being notable exceptions.

Figure 5.6: Relative Entropy Distributions in European City Regions Using The CORINE Land Cover Dataset

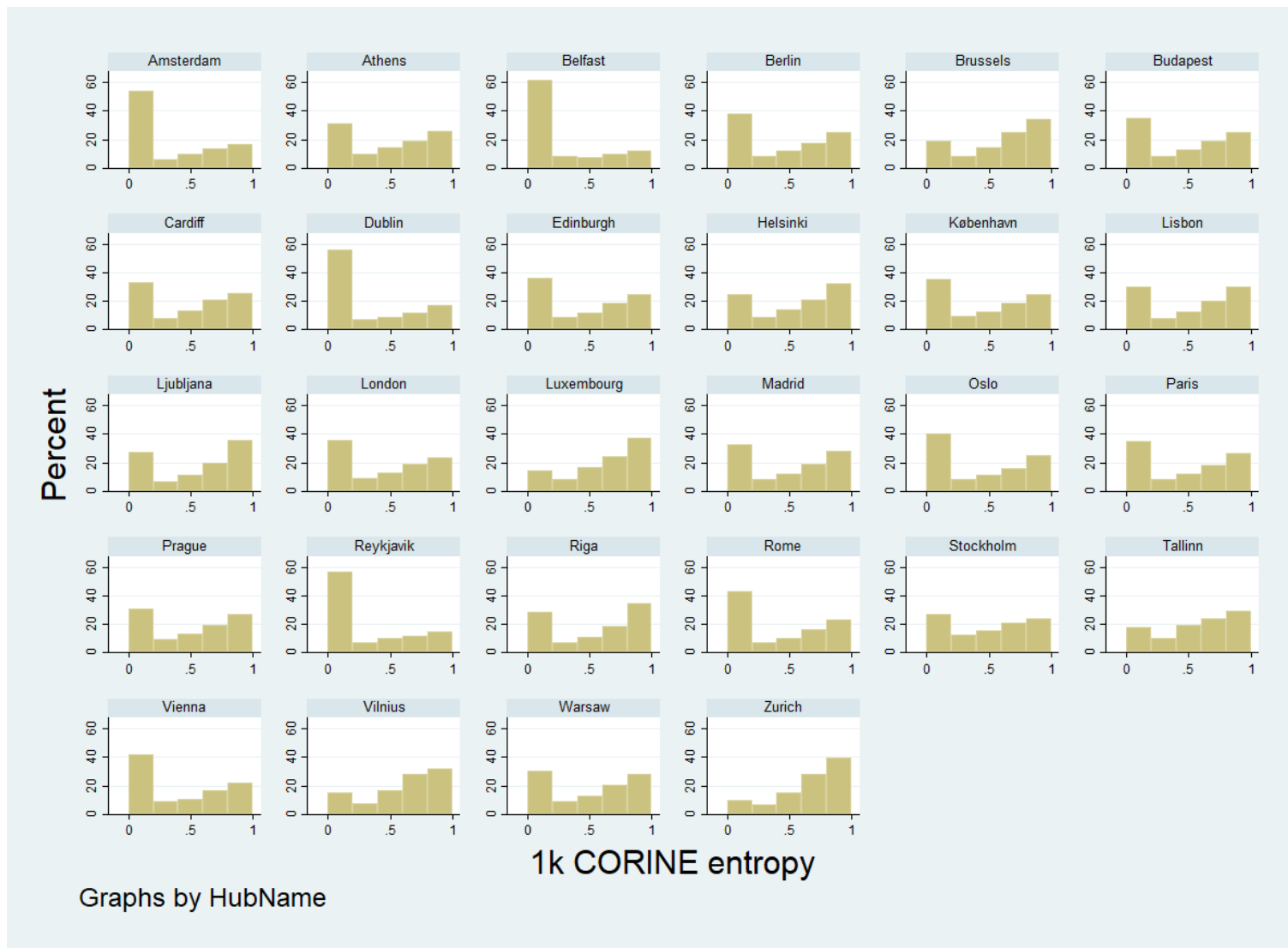


Figure 5.7 demonstrates a clear departure as no clear pattern in relative entropy distributions emerges across the 28 city regions analysed in this chapter (and **Appendix 3**). Here, it is apparent that land-use mixing scores are distributed much more evenly across spatial units when OpenStreetMap data is incorporated into these calculations, suggesting that OpenStreetMap can assist The CORINE Land Cover data in classifying land-uses at highly refined scales, thereby mitigating some of the issues associated with classifying landscapes according to form (Fleischmann and Arribas-Bel, 2021). Furthermore, the distributions in Figure 5.7 also better align with theoretical expectations regarding land-use mixing and configurations in city-regions. This is because, theoretically, many regions are assumed to be comprised of concentric rings of development (i.e., urban, suburban, and rural areas), which are implied to have distinct land-use configurations. Although in practice one would expect these rings to deviate in size in this particular case because the research is concerned with Functional Urban Areas, theoretically it is not wholly unsurprising that these relative entropy scores are more evenly distributed because it implies relatively evenly (spatially) distributed rings of development (Evans, 1983; Green, 2012).

Figure 5.7: Relative Entropy Distributions in European City Regions Using The Combined Land-Use Catalogue

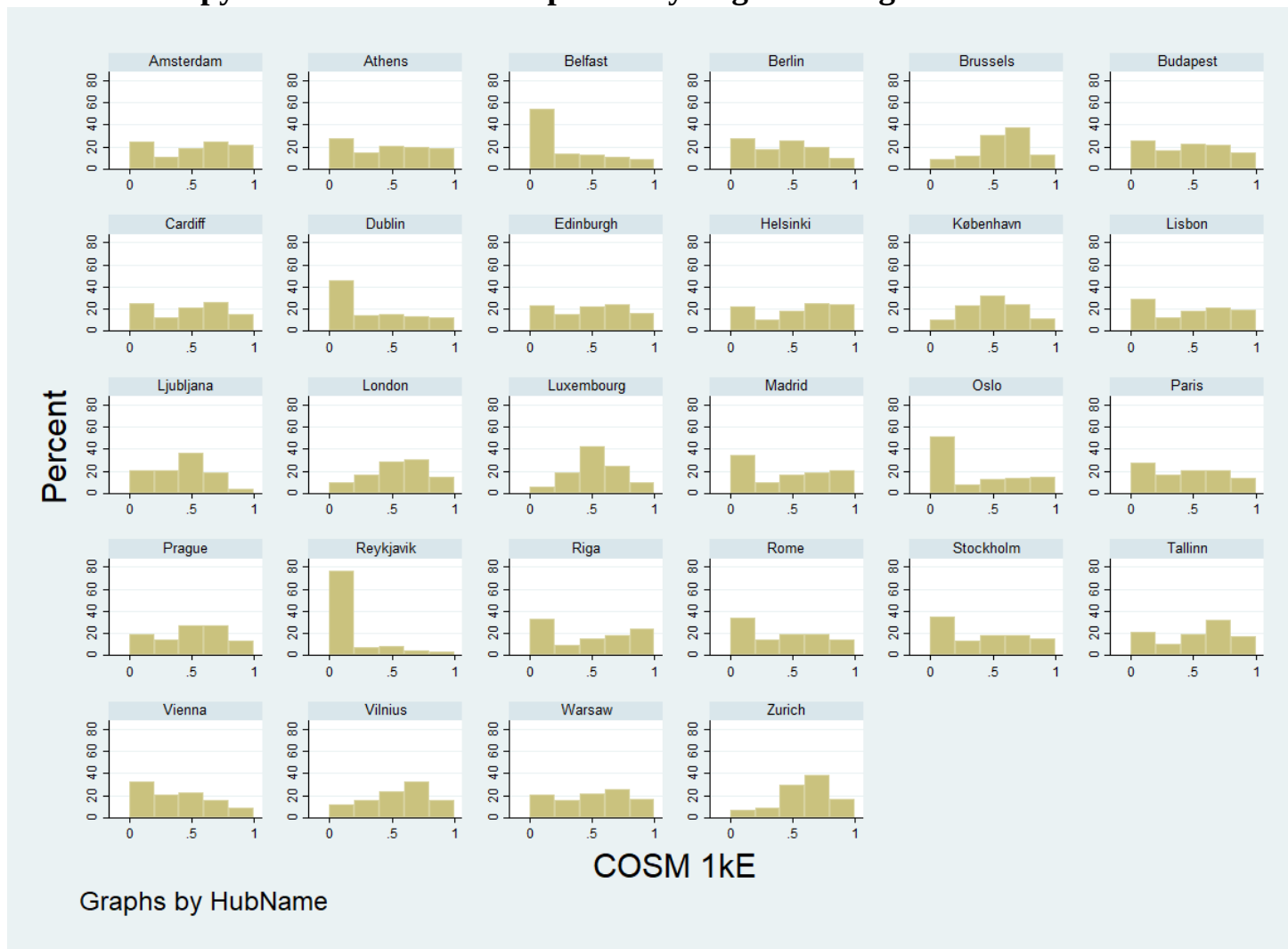
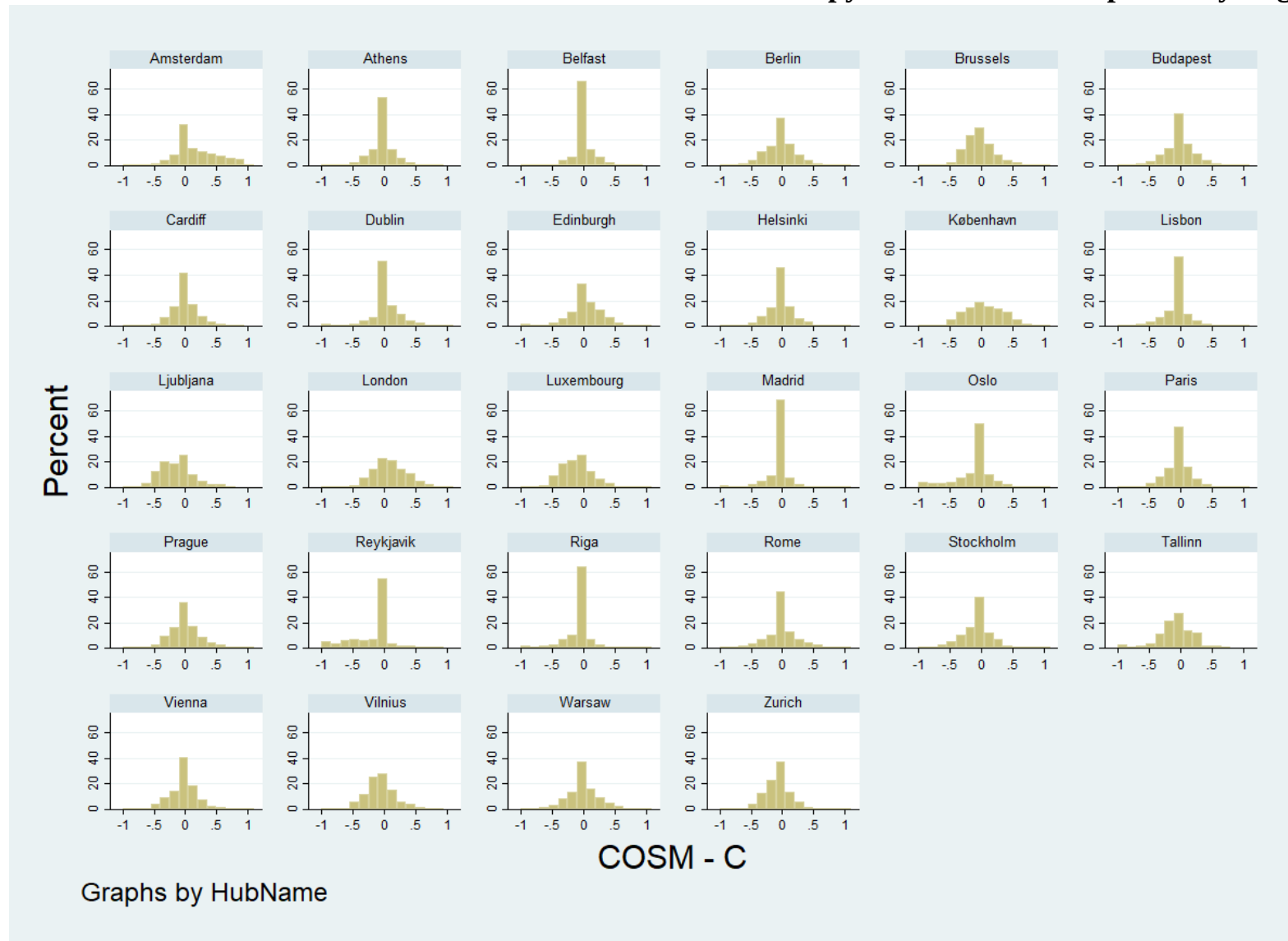


Figure 5.8 compares the distribution of cross-dataset differences in relative entropy scores across the 28 city regions analysed in this chapter (and **Appendix 3**). In each city, a substantial proportion of spatial units display similar relative entropy scores across both datasets, which ultimately supports the fact that both data are of high-quality and provide useful insights into our understanding of land-use configurations. However, there is a somewhat wide, and normal-like, variation and distribution in these differences (i.e., many cross-dataset differences in relative entropy are negligible, with relatively fewer at extreme ends of the distribution), generally indicating that no single dataset is clearly superior to the other in its evaluation of land-use mixing but still supporting a wide body of literature which argues that opensource data, like OpenStreetMap can positively contribute to studies of urban morphology (Haklay, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasher, Zipf and Francis, 2018).

Figure 5.8: Distributions of Cross-Dataset Differences in Relative Entropy Estimates In European City Regions



5.5 Discussion and Conclusions

This chapter uses land-use mixing (i.e., relative entropy) as an instrument to assess land-use configurations within the metropolitan areas of 28 European capital cities. High relative entropy scores typically cluster in-and-around urban cores, and depending on the dataset used, can generally be expected to decrease as distances from these cores increase. This implies that land-use developments within European urban cores facilitate the highest level of land-use mixing, a result which aligns with theoretical expectations. But this also suggests that these land-use developments may offer suitable templates for pursuing sustainable and efficient future development (OECD, 2018; Garcia-Lopez, Nicolini and Roig, 2020).

Also evidenced is that discipline-standard land-use catalogues may struggle to identify departures in historical regional development patterns. The combined land-use catalogue can distinguish between heterogeneous land-use configurations at highly disaggregated spatial scales more effectively than the CORINE Land Cover dataset alone due to its emphasis on function over form. These results indicate that this may provide improved insights into the prevalence of emerging polycentricity within regions, while also highlighting where urban regions may inefficiently utilise land and infrastructure. In these instances, there must be greater emphasis placed on developmental proposals which seek to minimise regional time-space geographies and those which aim to maximise the use of existing infrastructure prior to initiating outward expansion. In other words, policies which reduce horizontal expansion. The results of these initiatives will help preserve natural landscapes and minimise the spatial demands of human settlements (Cho and Rodriguez, 2015; Zhang and Zhao, 2017; O’Riordan *et al.*, 2022). From a land-use perspective, this may also reduce the degree of volatility in relative entropy scores found in regional and urban peripheries, as the dispersal of human activities and settlements concentrates in smaller areas, something also possible through the creation of polycentric areas (OECD, 2018).

This chapter provides a case study of the contributions opensource data can make to studies focusing on assessing land-use configurations, a contribution which a long line of literature predicts will be positive (Arribas-Bel, 2014; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasher, Zipf and Francis, 2018; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021). From a practical perspective, combining data like CORINE with opensource data allows researchers to create more insightful land-use classifications, thereby broadening the scope and potential impact of research. When using the CORINE Land Cover dataset to calculate relative entropy,

as in Figure 5.3, the results can lack a strong theoretical foundation and can go against empirical evidence relative to those acquired from a combined land-use classification catalogue, as in Figure 5.4. When comparing the results from both datasets, as in Figure 5.5, relative entropy estimates are highly sensitive to the underlying dataset, which I argue is theoretically and empirically more robust when it includes both CORINE and OpenStreetMap data. **Appendix A4 (A4)** also shows how these insights are not necessarily subject to the size of the spatial units, this analysis is replicated using spatial scale consisting of 2km x 2km grids, mitigating concerns surrounding the Modifiable Area Unit Problem. Furthermore, Figures 5.6-5.8 illustrate how these inferences are empirically robust while also supporting evidence which argues that land-use configurations and regional development patterns within European (and perhaps global) city-regions are homothetic and independent of city/region sizes, something which firmly illustrates the importance of land-use policies in shaping future development in more sustainable and efficient ways (Lemoy and Caruso, 2020, 2021).

This work contributes to debates within urban studies calling for the advancement of abilities to analyse and understand built environment configurations (Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021; Arribas-Bel, 2022). From an academic perspective, I provide guidance on how to elevate the insights provided by land-use classification catalogues through the incorporation of opensource data. From a policymaking perspective, this case study argues that the metrics typically used to quantify the efficiency and sustainability of land-use developments across Europe may produce imprecise results due to the inability of institutionally sourced data, like the CORINE Land Cover dataset, to distinguish between different types of (urban) land-uses at highly disaggregated spatial scales.

Future research should endeavour to probe deeper into the contribution opensource data can make in urban research. Specific questions may further test data quality and reliability, as in Fan *et al.*, (2014); Arsanjani *et al.*, (2015); Mobasheri, Zipf and Francis, (2018), but a more fruitful avenue may be to investigate the conditions in which such data is unreliable. Secondly, as pointed out by Lemoy and Caruso, (2020, 2021), sustainability is a much broader concept than just land-use, and phenomena like population densities, transport networks, and the economic and social viability of developmental forms are important considerations. Future research should seek to incorporate these elements into future analyses concerning the sustainability and efficiency of land and infrastructure use. Thirdly, metrics like relative entropy are sensitive to the Modifiable Area Unit Problem. While I endeavoured to partially

address this through the use of spatial scales consisting of standardised grids, other mechanisms to perhaps address this more meaningfully could involve the use of more fluid and natural boundaries for spatial units, like rivers and road junctions as suggested by Fleischmann and Arribas-Bel, (2021), or through the use of structural and spatial weights in the relative entropy calculations, as in Chen and Song, (2020). Finally, our understanding of regional built environments will significantly benefit from research which explicitly incorporates the intensities (i.e., verticality) of these environments and how this may impact the developmental sustainability, alongside research which explores the temporal evolution of human settlements and how this influences developmental outcomes, as signalled in (J. O'Driscoll *et al.*, 2022).

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Chapter 6: The relationships between socio-demographics, residential environments, travel considerations, and commute mode choice in Ireland

Individual socio-demographic characteristics influence the composition of residential environments, employment considerations, and transport-dedicated resources; all of which influence individual travel behaviours. To analyse these interrelationships, I employ Generalised Structural Equation Modelling using individual-level data from the 2016 Irish Census on workers across the Republic of Ireland alongside highly spatially disaggregated residential built and social environment data. This allows me to consider the non-linear relationships between multiple variables known to influence travel behaviours and provide direction for future policymaking. I find that, regardless of socio-demographic compositions, increased developmental compactness and infrastructure quality is associated with increased public and active travel.

6.1 Introduction

Like an Alonso-Muth-Mill model of residential location, location decisions in a Tiebout model operate within a General Equilibrium whereby location decisions change with incentives (Hanushek and Yilmaz, 2012). But unlike Alonso-Muth-Mill models, which frame location decisions as a trade-off between land-rents and travel costs, Tiebout models posit that these location decisions stem from tastes and preferences surrounding the provision of public goods (Tiebout, 1956; Alonso, 1964; Evans, 1983; Arnott, 2012). Because these preferences are clearly subject to budget constraints, this implies that individuals with shared preferences (and constraints) may produce similar decisions when pertaining to residence and workplace locations, creating possibilities for sorting. Sorting of this nature, although stemming from individual tastes and preferences, can also stem from socioeconomic considerations, like household mobility and employment considerations, creating landscapes whereby location decisions are delineated along socio-demographic lines (Nechyba and Walsh, 2004). Subsequently, this can spawn social exclusion through socioeconomic segregation and potentially create spatial mismatches in the accessibility of economic opportunity (Nechyba and Walsh, 2004; Lenaerts, Allroggen and Malina, 2022). Historically, this sorting primarily took the form of relatively deprived persons clustering in residence in-and-around urban cores, but decades of urban sprawl has reduced the relative costs of peripheral living, potentially altering existing sorting dynamics, something compounded by the also-changing spatial distribution of employment opportunities (Travisi, Camagni and Nijkamp, 2010). Considering this, I analyse how individual socio-demographics, residential built and social environments,

and travel considerations are related while also investigating how these interrelationships influence commute mode choices across the Republic of Ireland.

Sprawling developments catalyse increased car-use at the expense of alternative transport modes through land-use segregation and inefficient geographical expansion (Nechyba and Walsh, 2004). Environmental consequences aside, this can exacerbate social exclusion by inducing car dependency if relatively deprived persons are unable to access economic opportunities locally, something which can worsen the travel-related burdens of already strained households (Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022). Consequently, when analysing the implications of regional development patterns on transport accessibility, researchers should consider the relationship between transport policies and land-use. Whilst circular in their relationship, coordinated efforts can alleviate the risk of social exclusion by encouraging developments which facilitate the integration of multi-modal transport networks, the mixing of residential and employment centres, and the minimising of required travel distances (Button, 2010; Curl, Clark and Kearns, 2018; Thomas *et al.*, 2018; Allen and Farber, 2019).

Often quipped as spawning a ‘flight from blight’, urban sprawl has been linked with sorting mechanisms which once reflected middle- and upper-class desires to leave cities in response to rising social stress (Nechyba and Walsh, 2004; Boustan, 2010). In this context, spatial mismatch hypotheses suggest that combined residential and commercial decentralisation is what disconnects populations from economic opportunities by reducing relative accessibility (Picard and Zenou, 2018; Lenaerts, Allroggen and Malina, 2022). This can happen because commercial decentralisation generally concentrates around relative prosperity and connectivity, creating accessibility inequities (Nechyba and Walsh, 2004; Guirao, Casado-Sanz and Campa, 2018; Picard and Zenou, 2018). In a sprawling context, these inequities can be exacerbated because peripheries are generally characterised by segregated land and limited alternative transport accessibility. In other words, required travel distances and local time-space geographies increase. As a result, I adopt a spatial mismatch framework to analyse commute mode choices and how these choices relate to socio-demographics, the social and physical characteristics of residential environments, and travel considerations.

This research makes three contributions to existing literature. Firstly, I incorporate data that are typically segregated across studies, something which allows me to examine the relative influence different features of residential areas have on travel behaviours. For instance, when

analysing the built environment's influence on commute mode choices, research typically focuses on either land-use metrics (Ton *et al.*, 2019) or population measures (Guerra, Li and Reyes, 2022), and seldom both (see Guerra *et al.*, (2018) for an exception). Similarly, comprehensive multi-modal transport network data is usually lacking, with studies generally only employing road networks and seldom attempting to distinguish between the networks of multiple modes (Guerra, Li and Reyes, 2022). Furthermore, few studies explicitly measure the underlying attributes of residential environments, like the quality of existing infrastructure and the underlying social circumstances of areas (Lee, Vojnovic and Grady, 2018; Eldeeb, Mohamed and Páez, 2021). The first contribution stems from the synergy of different built environment indicators into one analysis. By doing this I answer calls by Guerra *et al.*, (2018) who explicitly note how data availability on built environments restricted their analysis of travel behaviours, while numerous other authors call for greater quantification of the built environment determinants of travel behaviours (Ton *et al.*, 2019; Eldeeb, Mohamed and Páez, 2021; Gan *et al.*, 2021; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022).

Secondly, I extend the scope of analysis typically employed in transportation studies. Ordinarily, studies analysing travel behaviours are confined to metropolitan areas due to a lack of data available at other spatial scales (Guerra *et al.*, 2018; Cheng, Yan and Gao, 2020; Guerra, Li and Reyes, 2022). This ability to use a nationally representative sample comprised of 235,936 individuals residing across 3,409 localities allows me to investigate inter-regional disparities in travel behaviours and their social and physical environmental drivers, something only before attempted by Bastiaanssen, Johnson and Lucas, (2022). This answers calls by Ahrens and Lyons, (2019), who determine that '...link[ing] census data on commuting flows between small areas to administrative data...' offers exciting avenues for future research (Ahrens and Lyons, 2019, p. 12) and Wu *et al.*, (2021) who call for the incorporation of more geographically diverse datasets when analysing travel behaviours.

Typically, studies employ a single-equation framework, like multinomial regression, when analysing travel behaviours (Guerra *et al.*, 2018; Ton *et al.*, 2019; Eldeeb, Mohamed and Páez, 2021; Gan *et al.*, 2021). However, this framework risks collapsing a multi-stage decision into a single equation (Ewing, Hamidi and Grace, 2016; De Vos *et al.*, 2021). I analyse the interrelationships between socio-demographic characteristics, residential environments, and travel considerations, alongside how these interrelationships influence commute mode choice. This requires a methodological framework capable of testing multiple interrelated hypotheses simultaneously (Ewing, Hamidi and Grace, 2016; Gim, 2018; De Vos *et al.*, 2021).

Accordingly, the final contribution of this research stems from the use of a novel Generalised Structural Equation Modelling (GSEM) framework which facilitates the use of categorical and binary response variables, a capability which has allowed GSEM to outperform traditional Structural Equation Modelling structures when analysing travel behaviours (Yin, Zhang and Shao, 2020).

Empirically, a stratified random sample from the 2016 Place of Work, School, or College Census of Anonymised Records (POWSCAR) dataset is used. These data are derived directly from the 2016 Irish Census and cover all persons working in the Republic of Ireland. Subsequently, it captures individual socio-demographic and commute characteristics, but is supplemented by data which accounts for the built and social characteristics and residential environments of Electoral Divisions (ED), of which there are 3,409 in Ireland. This allows links to be made between individual travel behaviours to socio-demographic characteristics, local built and social environments, and travel considerations. Specifically, it allows me to model the determinants of commute mode choice for 235,936 individuals, across 3,409 localities, using five mode choice options – Walking, Cycling, Buses, Trains/Trams, and Cars/Motorbikes/Vans.

Section 6.2 documents a comprehensive literature review surrounding the determinants of travel behaviours. *Section 6.3* describes the data and methodology used throughout. *Section 6.4* presents the results and *Section 6.5* discusses their implications. I conclude the analysis in *Section 6.6* by investigating the policy implications of this work while also highlighting this study's limitations and future research avenues.

6.2 Background To The Literature

6.2.1 Travel Behaviour

Travel is a good/service typically characterised by derived demand, whereby journeys serve as a means to an end (Button, 2010; Cheng *et al.*, 2019). When commuting, this relates to how individuals travel between their home and workplace. In this context, private cars generally exhibit characteristics of normal goods due to their flexibility and reliability (hence explaining positive relationships between car-use and income typically found in extant literature) whereas public transport is typically perceived as an inferior good due to negative perceptions of service quality (Friedrich and Quinet, 2011; Giuliano, 2012). Therefore, unlike typical goods, the monetary costs associated with travel may not influence mode-use as strongly as factors pertaining to reliability, convenience, and quality (Button, 2010). This implies that commute

mode choices may be highly sensitive to land-use and transport policy instruments (Vandenbulcke *et al.*, 2009; Button, 2010).

A substantial body of evidence suggests that individual socio-demographic considerations distinctly influence travel behaviours (Nechyba and Walsh, 2004; Vandenbulcke, Steenberghen and Thomas, 2009). However, evidence suggests that these behaviours are sensitive to other considerations, like the physical characteristics of residential environments. For instance, reducing required travel distances is associated with reduced car-use due to the heightened competitiveness, convenience, and efficiency of alternative modes (Button, 2010; Millward, Spinney and Scott, 2013; O’Riordan *et al.*, 2022). From a land-use perspective, this involves increasing developmental compactness, while from a transport perspective, this involves allocating more resources to the provision of multi-modal transport infrastructure (Gim, 2012). The efficacy of these policy instruments is determined by the spatial distribution of infrastructural investment, something historically linked to local socio-demographic compositions, and subsequently, phenomena like Tiebout Sorting (Nechyba and Walsh, 2004; Boustan, 2010).

6.2.2 Socio-Demographics and Travel Behaviours

When considering travel mode choices, individuals’ socio-demographic characteristics are typically regarded as exogenous variables that proxy for tastes and preferences (Ding *et al.*, 2017, 2018; Gim, 2018; Cheng *et al.*, 2019). In this context, variables like gender and household structures typically relate inconsistently across regions/nations (Vega and Reynolds-Feighan, 2008, 2009; Travisi, Camagni and Nijkamp, 2010)²⁹. Despite these inconsistencies arguably stemming from differences in cross-country cultural/social norms, these contrast with variables like age and socioeconomic status which generally exhibit intuitive relationships with travel behaviours (Vandenbulcke, Steenberghen and Thomas, 2009; García-Palomares, 2010). For instance, car-use generally peaks in middle-ages, while improvements in socioeconomic status catalyse increased car-use (Reynolds-Feighan, 2003; Button, 2010; García-Palomares, 2010; Giuliano, 2012; Curl, Clark and Kearns, 2018; Allen and Farber, 2019).

Although these considerations often hold high explanatory power over individual travel behaviours, individuals do not operate in a vacuum. Evidence suggests that larger family units typically travel greater distances, subject to residential environment characteristics (Commins

²⁹ In Ireland, evidence suggests that females are less likely to commute actively than males, favouring cars instead, an imbalance seemingly caused by demographic and location effects (Carroll *et al.*, 2020).

and Nolan, 2011; Ermagun and Levinson, 2016). For larger family units (i.e., households with children), this suggests that the ability/need to trip-chain (i.e., combining the trips of multiple individuals) significantly influences the travel behaviours of parents and children, thereby intertwining behaviours across individuals (Commins and Nolan, 2011; Ermagun and Levinson, 2016). Trip-chaining is a travel option typically reserved for private cars due to their flexibility, convenience, and reliability³⁰. Subsequently, depending on the characteristics of residential environments and required travel distances, public and active transport may be inconvenient, unreliable, and too costly, thereby increasing car-use (Curl, Clark and Kearns, 2018).

Individuals typically have ordinal preferences regarding their consumption of goods and services (Samuelson, 1954). While in a travel behaviour context, these preferences manifest through mode choices, in a broader regional development context these preferences (when pertaining to the consumption of public goods, like land-use configurations and transport infrastructure) can be deduced through residential locations (Tiebout, 1956). Here, the decision to move (or not to move) becomes somewhat analogous to willingness to pay in economies characterised by high levels of human mobility (Samuelson, 1954; Tiebout, 1956). Although high levels of mobility is symptomatic of society in the developed world, the ability of individuals to realise these preferences is highly sensitive to the accessibility of travel-related resources and employment opportunities, something obviously linked to socio-demographic considerations, but also to regional land-use configurations and transport infrastructure provision (Curl, Clark and Kearns, 2018; Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022). In other words, individuals can only realise their preferences for residential (and workplace) locations if places of interest (i.e., places where individuals can avail of economic and social opportunities) are accessible, something clearly linked to local time-space geographies (Reynolds-Feighan, 2003).

6.2.3 Built Environments and Travel Behaviours

Regional development is a spatiotemporal process characterised by the expansion of urban areas whereby rural/semi-rural areas are integrated into urban infrastructures (Travisi, Camagni and Nijkamp, 2010). This links the topography of regional developments to economic, social, and environmental outcomes by defining the severity of the disadvantages associated with separation from regional cores (Button, 2010; Trannoy, 2011; Vega and Reynolds-Feighan,

³⁰ While this has historically been the case, the commercialisation of cargo-bikes may change this landscape.

2016). Historically, this topography has been defined by monocentric expansion and urban sprawl across much of Europe, whereby land-use developments are characterised by low residential densities, high degrees of land-use segregation, and widespread car-use (Reynolds-Feighan, 2003; Vega and Reynolds-Feighan, 2008, 2009, 2016; Weilenmann, Seidl and Schulz, 2017).

Evidence increasingly points to aspects pertaining to the built environment, such as land-use mix, transport infrastructure provision, and infrastructural quality, as important features influencing commuting decisions (Ewing and Cervero, 2010; Guerra *et al.*, 2018; Ton *et al.*, 2019; Gan *et al.*, 2021). But urban sprawl has also resulted in population dispersions characterised by relatively affluent populations residing in peripheral areas and commuting to employment hubs, whilst relatively deprived populations tend to live and work in the same localities³¹ (Nechyba and Walsh, 2004; Button, 2010). Over time, regional infrastructure investment has become increasingly concentrated in areas characterised by relative affluence. This creates spatial imbalances in the quality of local infrastructure and may warp the spatial distribution of commercial decentralisation, something particularly evident in Ireland through uneven regional growth (Vega and Reynolds-Feighan, 2016), but may also distort the spatial expanse of regions more generally by concentrating development resources in particular locations (Button, 2010; Dubé *et al.*, 2023).

Subsequently, because land-use and population distributions determine the provision and accessibility of regional transport infrastructure, the consequences associated with spatially segregated, sprawling developments may be compounded by spatial mismatches in the provision of infrastructure and the accessibility of jobs (Nechyba and Walsh, 2004; Button, 2010). Spatial mismatch hypotheses conclude that regional investment is inequitably distributed across space and that residential/commercial decentralisation coupled with inadequate public/active transport networks disconnects populations from employment opportunities (Nechyba and Walsh, 2004; Vega and Reynolds-Feighan, 2009, 2016). In a sprawling landscape, the quality of local infrastructure and the accessibility of employment will be lower in relatively deprived areas, heightening sensitivities to the inter-connectedness of localities and the relationship between land-use configurations and transport infrastructure/service provision (Curl, Clark and Kearns, 2018). In other words, if services are not available locally, access to distant services may be prevented by inadequate transport

³¹ **Appendix 5 (A5)** presents the spatial distribution of socio-demographic deprivation and mode-use.

infrastructure, a scenario whose severity hinges on the transport infrastructure accompanying development patterns (Curl, Clark and Kearns, 2018; Guerra *et al.*, 2018).

Spatially segregated, low-density settlements increase regional time-space geographies (i.e., required travel distances) and reduce the efficiency and effectiveness of public and active transport (Vega and Reynolds-Feighan, 2016). Accordingly, evidence suggests that land-use induced challenges to employment accessibility can be mitigated by increasing the accessibility and efficiency of public and active travel (Millward, Spinney and Scott, 2013; Tyndall, 2017). Improved transport accessibility is positively associated with regional economic performance and reduces the risk of social exclusion regardless of local socio-demographic compositions, thereby abating land-use induced accessibility inequities (Heuermann and Schmieder, 2019; Bastiaanssen, Johnson and Lucas, 2022).

6.2.4 Travel Considerations, Social Environments, and Travel Behaviours

The physical configurations of residential environments clearly exert a distinct influence on required travel distances. Mixed-use landscapes exhibit higher levels of accessibility to local employment opportunities than areas characterised by land-use segregation and low residential densities (Friedrich and Quinet, 2011; Giuliano, 2012; OECD, 2018). Urban sprawl has resulted in relatively affluent populations developing an inward-commuting culture over longer distances, while relatively deprived populations usually reside near their workplace, meaning relatively affluent populations typically exhibit larger commute distances (Curl, Clark and Kearns, 2018; OECD, 2018; Thomas *et al.*, 2018; Guerra, Li and Reyes, 2022; O'Driscoll *et al.*, 2022b)³².

Evidence suggests that variables concerning travel considerations, like trip durations, can influence (and potentially restrict) travel behaviours and that these variables are explicitly linked to Tiebout Sorting mechanisms (Vega and Reynolds-Feighan, 2009; Chen and Vickerman, 2017). If infrastructure and regional investment is disproportionately concentrated in suburban peripheries, it implies that although travel distances to urban centres and employment opportunities may be larger, the existing infrastructure will be of a higher quality (Vega and Reynolds-Feighan, 2016). But this also suggests that while relatively deprived populations may face shorter travel distances, local infrastructure may be inadequate (Boustan,

³² Considering that 75% of the Irish population commute by car, this suggests that there is a significant amount of environmental (and economic) damage attributable to daily commuting through travel-related emission outputs and their associated externalities, like congestion (O'Driscoll *et al.*, 2022b, 2022a; O'Riordan *et al.*, 2022).

2010; Giuliano, 2012). Therefore, if the employment opportunities relatively deprived populations cluster around re-locate to suburban areas, these populations may need to adapt their travel behaviours or re-locate their residence to avail of new opportunities (Curl, Clark and Kearns, 2018; Guerra, Li and Reyes, 2022).

Because peripheries are inherently inaccessible by public and active transport in a sprawling landscape, this can force trade-offs between affordable housing and transport needs, heightening the risks of transport poverty³³, social exclusion, and unemployment (Hu and Schneider, 2017; Curl, Clark and Kearns, 2018). Therefore, socioeconomic exclusion can be conceptualised as a problem of accessibility, whereby economic and social outcomes are directly influenced by the usability of regional transport infrastructure (Tyndall, 2017; Picard and Zenou, 2018). This implies that socio-demographics directly influence travel behaviours through individual preferences, alongside mode convenience and reliability, while also indirectly influencing these behaviours through the consequences of Tiebout Sorting. This connects socio-demographic considerations to the underlying qualities of residential environments and the relative accessibility of employment opportunities, mechanisms directly linked to travel behaviours (Bastiaanssen, Johnson and Lucas, 2022; Guerra, Li and Reyes, 2022; Lenaerts, Allroggen and Malina, 2022).

6.2.5 Theoretical Model

Figure 6.1 below builds upon the literature reviewed in previous sub-sections by synergizing the conceptual framework. The model proposed in this research posits that socio-demographics distinctly influence the physical and social characteristics of residential environments, travel considerations and commute mode choices through Tiebout Sorting mechanisms. These relationships are presented as arrows which stem from Socio-Demographics and point toward the other elements of the model, while the specific variables captured within each category are outlined in Table 6.1 below.

The variable group corresponding to Socio-demographics are exogenous variables within this research context, hence the lack of arrows leading to Socio-Demographics in Figure 6.1. These variables share a direct relationship with the types of built environments people reside in and the underlying social characteristics of these environments through Tiebout Sorting mechanisms, mechanisms illustrated through arrows stemming from Socio-Demographics in

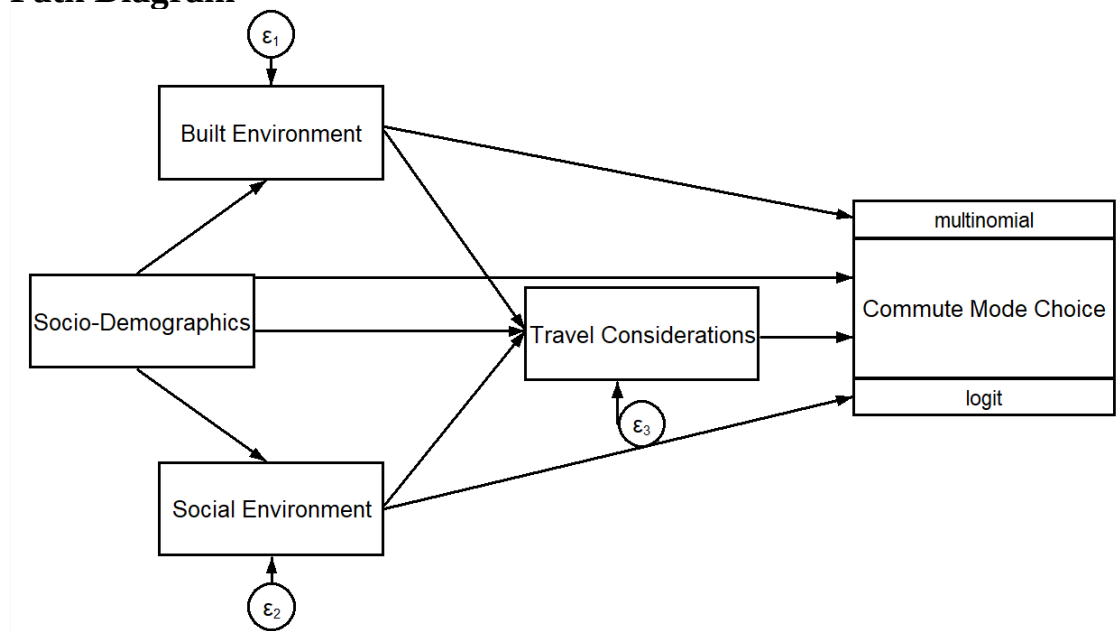
³³ Transport poverty is the accumulation of socioeconomic and transport accessibility disadvantage whereby the social mobility of relatively deprived persons is hindered due to the inaccessibility of amenity/employment destinations (Allen and Farber, 2019).

Figure 6.1 (Nechyba and Walsh, 2004; Boustan, 2010). This builds upon Cheng *et al.*, (2019) who investigate the interrelationships between individual socio-demographics, household considerations, trip purpose, and the frequency of mode-use.

Our Tiebout Sorting-Spatial Mismatch theoretical framework suggests that relatively deprived populations typically live and work in the same locality while relatively affluent populations usually do not (Nechyba and Walsh, 2004; Boustan, 2010; Tyndall, 2017; Guerra, Li and Reyes, 2022). This implies that relatively deprived populations may have shorter travel distances. Because travel distances define the mode choice-sets available to individuals, shorter travel distances imply larger choice sets. However, this conceptual framework also suggests that infrastructural investment may disproportionately concentrate in areas characterised by relative affluence (Nechyba and Walsh, 2004; Vega and Reynolds-Feighan, 2016). This may leave relatively deprived areas with lower quality transport infrastructure which reduces the efficiency and feasibility of public and active transport (Curl, Clark and Kearns, 2018; Allen and Farber, 2019, 2020). Subsequently, the inherent quality of infrastructure and the wider social environment will influence travel behaviours by defining the efficiency of travel and the mode choice set available to individuals. In other words, because relatively deprived populations will typically live and work in the same locality, they may use public and active transport more regularly than relatively affluent populations, but low-quality transport infrastructure may counteract this. This provides the rationale for the arrows stemming from the variable group corresponding to Social Environment and ending in the variable groups corresponding to Travel Considerations and Commute Mode Choice in Figure 6.1.

Advancing the work of Idris *et al.*, (2015), who analyse the interrelationships between psychological considerations, the appraisal of transport services, and travel mode choices, I posit that the physical characteristics of built environments, like developmental compactness, directly influence travel behaviours by defining local time-space geographies, influences which are represented by arrows stemming from the variable group corresponding to Built Environment and leading to the variable groups corresponding to Travel Considerations and Commute Mode Choice in Figure 6.1. From a travel behaviour perspective, this suggests that areas characterised by compactness and mixed-use will facilitate greater levels of public and active travel than areas characterised by land-use segregation and low residential densities (O’Riordan *et al.*, 2022).

Figure 6.1: Generalised Structural Equation Model Visualised Through A Path Diagram



6.3 Data and Methods

6.3.1 Data

I use individual-level data from the Place of Work, School, or College Census of Anonymised Records (POWSCAR) from the 2016 Irish Census. This provides detailed information on individuals' socio-demographic and commuting characteristics. I also incorporate regional infrastructure data inclusive of transport networks, land-use metrics, and area quality indicators derived from *OpenStreetMap*, *The 2018 CORINE Land Cover* index, *The Teljeur et al. (2019) 2016 Deprivation Index*, and *The Property Price Register (2016)*. This data measures the individual determinants of travel behaviours based on socio-demographic, built and social environment characteristics, and travel considerations.

POWSCAR comprises of 3,058,607 individuals. Given the focus of research lays on commuting behaviour within the Republic of Ireland, the sample includes only those who(se) 1) Live and work in the Republic of Ireland; 2) Are gainfully employed; 3) Do not report null values for key variables; 4) Are of working age (20-65); or 5) Employment does not entail primarily mobile/tele work. From this potential sample of 1,299,821 individuals, a 20% (235,936 individuals) stratified randomly selected sample with proportionate weighting of individuals within each socio-demographic cohort is used. The sample is consistent with the wider dataset and all 3,409 Electoral Divisions (residential areas) are accounted for.

I develop a categorical variable to represent commute mode choice. The base choice set, as laid out within the Census, captures ten options (1. Not a Worker; 2. Walk; 3. Bike; 4. Bus; 5. Train/Tram [i.e., DART and LUAS]; 6. Private Motorcycle/Scooter; 7. Drive Private Cars; 8. Private Car Passenger; 9. Van; 10. Other Including Lorries)³⁴. Individuals opting for 1 and 10 are removed due to their non-working status or likely mobile nature of employment. Thereafter, conceptually identical choices are combined. The final choice category specification is: 1. Walk; 2. Bike; 3. Bus; 4. Train/Tram; 5. Private Motorised, as explained in *Section 6.3.2*.

The other variables are placed into four groups: Socio-Demographics, Travel Considerations, Built Environments, and Social Environments. The variables representing socio-demographics capture each person's age, sex, socioeconomic group, and household composition. Household composition and socioeconomic group categorise the household structure of individuals' and the socioeconomic group individuals belong to. I argue that these variables appropriately proxy individual-level tastes/preferences and facilitate investigations into Tiebout Sorting mechanisms. Travel considerations are conceptualised as journey durations in minutes and whether people live and work in the same locality at the Electoral Division (ED) and Small Area (SA) level³⁵. Importantly, there is no explicit variable measuring trip distance available in the 2016 Census.

The built environment variables comprehensively capture the physical characteristics of residential environments by accounting for land-use, population, and transport infrastructure while also proxying for their underlying quality using property market values. Specifically, *CORINE* classifies each residential ED according to its majority land-use classification. This was calculated in *ArcGIS* whereby EDs are characterised according to the 2018 *CORINE* land-use class which covers the largest share of ED land. *Residence Area Type* measures the degree of urbanisation per residential county expressed as population counts³⁶. To capture transport infrastructure provision and the relative accessibility of said infrastructure, I incorporate network access nodes. *Road* and *Active* represent the logged length of roads and active travel

³⁴ The DART is a commuter train network, and the LUAS is a tram line situated in Dublin. A van is a private commercial vehicle which carries goods and industrial equipment.

³⁵ Small Areas are the smallest spatial unit in the Irish Census. There are 18,641 Small Areas in the Republic of Ireland.

³⁶ Ewing and Cervero, (2010), highlight how variables like population density typically display weak associations with travel behaviours once land-use characteristics are controlled for and should be treated as a mediating variable. Following this, they explicitly state its inclusion to be unnecessary, hence its exclusion here. However, also worth noting is that when population density is included in this model, there are significant multicollinearity problems as population density is highly correlated with Built and Social Environment variables. These problems are identified through correlation matrices.

infrastructure per ED³⁷, allowing investigations into the relationship between mode-specific (i.e., road) infrastructure provision and mode-specific (i.e., car) use. Supplementing these are measures which account for transit node provision, like *Bus Stops* and *Rail Stops*, which count the number of bus and rail stops within each ED³⁸. Finally, local infrastructural quality is measured by logging the average property price (for properties sold between 2015-2017) per ED. Here, the logged average house price per ED is assumed to be positively correlated with the provision of high quality infrastructure, and subsequently subject to spatial mismatches (Allen and Farber, 2020; Guerra, Li and Reyes, 2022). Although property prices may be a somewhat crude measure for this context, given their correlation with other variables (i.e., urbanisation and population densities), this arguably further justifies its use in this specific context as it explicitly captures heterogeneities in morphology, population distributions, and a location's context along the urban-rural continuum.

To capture the social environments of residential areas, I use *Deprivation*, which is a area-based index capturing the underlying social circumstances of localities through employment levels, socio-demographic characteristics, and car-ownership levels aggregated across Electoral Divisions (Teljeur *et al.*, 2019). *Deprivation* is specified in quintiles whereby a score of 1 represents the least deprived 20% of EDs and a score of 5 represents the most deprived 20% of EDs. This proxies for the relative socioeconomic prosperity of localities and is therefore related to spatial mismatches and Tiebout Sorting mechanisms. Table 6.1 defines these variables in the context of the path diagram presented in Figure 6.1, while also presenting descriptive statistics, a method of presentation which is common practice in existing literature (Ding and Lu, 2016; Cheng *et al.*, 2019).

³⁷ This network data is calculated in Quantum Geographical Information Systems and measures the length of the network within each ED, a measure which is subsequently logged. The road network accounts for every publicly accessible road available in the QuickOSM QGIS plugin whereas the active network captures a combination of roads with low speed limits and every walkable/cyclable surface available in the same plugin. More information can be found in **Chapter 8**.

³⁸ The Irish train network is not nationally comprehensive and principally serves to connect major cities with limited access outside these areas. There is only one tram network across Ireland, and that is in Dublin. Subsequently, bus is the only nationally comprehensive Irish public transport network.

Table 6.1: Key Variables Used

Variables	Proportion of Sample (%) /Mean	Variable Definition within Modelling Framework
Commute Mode Choice (n =235,936)		
Means of Travel		A categorical variable denoting the proportion of the POWSCAR sample which utilise each travel mode when commuting. The Census defines Means of Travel as the travel mode that is used to cover the longest part of the trip.
Walk	9.69%	
Bike	3.42%	
Bus	6.28%	
Train/Tram	3.97%	
Private Motorised	76.64%	
Socio-Demographics (n = 235,936)		
Sex	0.48	A binary variable denoting the sex of individuals in the POWSCAR sample (1 = Male).
Age		A categorical variable denoting the age range of individuals in the POWSCAR sample.
20-29	17.37%	
30-39	31.87%	
40-49	27.09%	
50-59	18.98%	
60-64	4.68%	
Household Composition		
Single Person	11.54%	A categorical variable denoting the household structure of individuals in the POWSCAR sample.
Single Parents	4.75%	
Two Parent Households	73.02%	
Other	10.69%	
Socioeconomic Group		A categorical variable denoting the socioeconomic group of individuals in our POWSCAR sample.
Employers / Professionals	45.80%	
Non-manual	30.30%	
Manual (semi) skilled	17.55%	
Unskilled and Agriculture	3.34%	
Other (Incl. Farmers)	3.01%	
Built Environment Factors (n = 3,409)		
Residence Area Type		A categorical variable denoting the population-based characteristics of the residential county of individuals in the POWSCAR sample.
Rural Area	26.91%	
Urban Area [UA] (0-999 people)	4.71%	
UA (1,000-4,999 people)	7.93%	

UA (5,000-49,000 people)	23.21%	A categorical variable denoting the landscape characteristics of the residential Electoral Divisions of individuals in the POWSCAR sample.
UA (50,000-499,999 people)	9.52%	
UA (>500,000 people)	27.71%	
Land-Use (CORINE)		
Res Continuous Urban Fabric [UF]	7.90%	
Res Discontinuous UF	65.87%	
Rural Land	26.23%	
Rail Stops ED	0.27	A count variable denoting the number of rail stops per residential ED.
Bus Stops ED	10.31	A count variable denoting the number of bus stops per residential ED.
Log Road Length ED	10.34	A continuous variable denoting the logged length of road infrastructure per residential ED.
Log Active Length ED	9.85	A continuous variable denoting the logged length of active travel infrastructure per residential ED.
Log House Price ED	12.10	A continuous variable denoting the logged mean house price per residential ED.
Social Environment Measures (n = 3,409)		
Deprivation ED		A categorical variable denoting the deprivation quintile (1-5) of every residential ED.
1 (Least Deprived)	3.25%	
2	24.50%	
3	36.60%	
4	25.23%	
5 (Most Deprived)	10.42%	
Travel Considerations (n = 235,936)		
Journey Minutes	27.51	A continuous variable denoting the commute length of every individual in the POWSCAR sample.
Same Res-Work ED	0.11	A binary variable denoting whether people live and work in the same ED (1 = Yes).
Same Res-Work SA	0.02	A binary variable denoting whether people live and work in the same SA (1 = Yes).

6.3.2 Econometric Modelling

Using STATA 17, this research employs a series of Generalised Structural Equations to estimate the relationships between socio-demographics, built and social environment configurations, and travel considerations, while also investigating how these variables (and the interrelationships therein) influence commute mode choices. The key benefit of Generalised Structural Equation Modelling is its inherent flexibility whereby any variable/data structure can be accounted for, correlated, and constrained, but more generally facilitates the investigation of multiple interrelated hypotheses simultaneously (Ewing, Hamidi and Grace, 2016; Gim, 2018; De Vos *et al.*, 2021). Generalised Structural Equation Modelling (GSEM) facilitates this by allowing me to evaluate the relationships between different mediating variables. It does this by evaluating theoretical models with data through the use of path diagrams, a methodological practice which explicitly allows researchers to evaluate numerous empirical and theoretical relationships within the data (Idris *et al.*, 2015; Ewing, Hamidi and Grace, 2016; Gim, 2018).

The path diagram related to this research (Figure 6.1 above) postulates that socio-demographics are the main exogenous variables in the model³⁹. These factors directly influence residential built and social environments, travel considerations, and commute mode choice. This follows a Tiebout Sorting theoretical framework by suggesting that although built and social environment configurations (alongside travel considerations) directly influence travel mode choices, socio-demographics are what influence the infrastructural make-up and area-level deprivation of these environments (Acker, Witlox and Wee, 2007; Ding *et al.*, 2017). By assuming relationships between these mediating variables, I can partly account for residential self-selection by capturing the indirect effect of personal characteristics on commute mode choice via residential built and social environments (Mokhtarian and Cao, 2008; Ding *et al.*, 2017, 2018). Therefore, this model tracks how individual, environmental, and travel considerations influence travel behaviours while also investigating how these considerations interact.

This modelling framework simultaneously accounts for endogenous and exogenous categorical and continuous variables which are interrelated (Golob, 2003; Acker, Witlox and Wee, 2007;

³⁹Variables within a GSEM framework can take an endogenous and exogenous structure simultaneously. The state of any given variable in any given relationship is best gauged according to path diagrams (Figure 6.1). But in general, any variable with an arrow stemming from it is deemed exogenous in that particular relationship, while any variable with an arrow leading into it is deemed endogenous in that particular relationship.

Idris *et al.*, 2015; Ding *et al.*, 2017; Cheng *et al.*, 2019; Yin, Zhang and Shao, 2020). I follow existing literature by employing the Maximum Likelihood method to estimate the GSEM (Golob, 2003; Ding *et al.*, 2018; Cheng *et al.*, 2019; De Vos *et al.*, 2021). Specifically, the specification builds upon that detailed by Cheng *et al.*, (2019), who posit that a GSEM which includes no latent variables takes the generic form of:

$$y = By + \Gamma x + \zeta \quad (6.1)$$

Where y is column vector of n dependent variables, x is a column vector of m independent variables, B is a matrix ($n \times n$) of direct relationships, Γ is a matrix ($n \times m$) of regression coefficients, and ζ is a column vector of error terms (Cheng *et al.*, 2019).

Goodness-of-fit tests for traditional Structural Equation Models, such as the Root Mean Square Error of Approximation (RMSEA), are not applicable in this context due to the generalised structure of response variables (Yin, Zhang and Shao, 2020). This renders comparisons between the Akaike Information Criterion (AIC) and Schwarz Bayesian Information Criterion (SBIC) scores of alternative modelling structures as the principal robustness test for the modelling structure (Hooper, Coughlan and Mullen, 2008; Ding *et al.*, 2017, 2018; Gim, 2018; Cheng *et al.*, 2019; Yin, Zhang and Shao, 2020; De Vos *et al.*, 2021). In this regard, I evaluate four alternative modelling specifications which can describe the relationships in the data, whereby the best fitting model is determined according to AIC and SBIC scores (Golob, 2003; Gim, 2018; De Vos *et al.*, 2021). This approach illustrates that the proposed modelling specification (Figure 6.1) best describes the relationships within the data, something corroborated by results produced using alternative econometric techniques (i.e., Multinomial Logit Regression) that are consistent with the findings presented in this chapter (Golob, 2003; Gim, 2018; De Vos *et al.*, 2021). Specifically, **Appendix 6 (A6)** demonstrates consistent coefficients when the key elements of this model are estimated using a standard spatially disaggregated Multinomial Logit framework and highlights how the modelling structure produces the lowest (i.e., best) AIC and SBIC scores relative to alternative specifications.

The primary dependent variable is commute mode choice (1. Walk; 2. Bike; 3. Bus; 4. Train/Tram; 5. Private Motorised). This generalised response variable takes a Multinomial Logit structure, meaning it must satisfy the assumption of the Independence of Irrelevant Alternatives (IIA). To satisfy IIA, each option within the choice-set must be independent. Following established literature, AIC and SBIC scores were used to analyse the efficacy of the

dependent variable specification (Guerra *et al.*, 2018), while Hausman tests analysed the validity of assuming IIA. The optimal specification of the dependent variable emerged as previously outlined in *Section 6.3.1*. The other variables are specified as a mix of continuous and binary variables, with many serving as independent and dependant variables simultaneously depending on the specific relationship within the path diagram presented in Figure 6.1⁴⁰.

6.4 Results

Table 6.2 presents the results of the marginal effects derived from the GSEM estimation on the relationships between socio-demographic considerations, built and social environments, and travel considerations. Table 6.3 illustrates the results of the marginal effects derived from the same GSEM estimation on the influence of socio-demographics, built and social environments, and travel considerations on commute mode choice. Within the GSEM models, commute mode choice is estimated using a Multinomial Logit structure, but other categorical dependent variables (Residence Area Type, Land-Use (CORINE), and Deprivation) are treated as continuous variables. When response variables are polytomous (Commute Mode Choice), coefficients are presented as the Marginal Effects at Means derived from odds ratios. All other response variables are treated as continuous variables, meaning they reflect the Marginal Effects at Means derived from linear regression. For clarity positive and negative coefficients which are statistically significant are highlighted green (positive) and red (negative). All other coefficients are left black.

6.4.1 Tiebout Sorting and Travel Behaviours

The model described in Figure 6.1 implies that populations are roughly distributed according to Tiebout Sorting mechanisms. That is, relatively deprived populations will live and work within the same locality so that local time-space geographies can be minimised, while relatively affluent populations will disperse in residence to peripheral areas and commute inward (Nechyba and Walsh, 2004; Vega and Reynolds-Feighan, 2016). Accordingly, the key relationship is whether the relative deprivation of localities shares a direct relationship with living and working in the same locality. Columns II-III in Table 6.2 show that one-unit

⁴⁰ A correlation matrix of the variables are presented in **Appendix 6 (A6)**. The correlation coefficients are sufficiently low to not raise multicollinearity concerns.

increases in deprivation are associated with increased instances of workers living and working in the same locality at the ED and SA level.

When analysing the spatial distribution of different socioeconomic cohorts, the relationships between most socio-demographic variables and residential built and social environment variables are significant at the 1% level. Male workers typically live in more urbanised areas and areas which are associated with greater levels of socioeconomic affluence relative to female workers⁴¹ (Table 6.2, Columns IV-V and X-XI). Gender shares a somewhat ambiguous relationship with commute durations in that male workers typically have longer commutes, but inconsistently relate to living and working in the same locality – a characteristic obviously linked to commute durations (Table 6.2, Columns I-III). I interpret this to be the consequence of a trip duration variable which is insensitive to the mode used when commuting. Older workers usually reside in urban areas (Table 6.2, Column V), and usually live and work in the same locality (Table 6.2, Columns II-III), a locality which is generally relatively affluent (Table 6.2, Column XI). The built and social characteristics of residential environments become more significantly associated with household structures as household structures become more complicated, and by extension, individual travel behaviours become more intertwined (Table 6.2, Columns IV-XI). There is no significant relationship observed between individual socioeconomic groups and the physical characteristics of built environments (Table 6.2, Columns IV-IX). However, advances in individual socioeconomic groups (i.e., moving from Non-Manual to Employers/Managers) is associated with increased affluence in residential areas (Table 6.2, Columns X-XI), reduced instances of workers living and working in the same locality (Table 6.2, Columns II-III), and longer commute durations (Table 6.2, Column I).

Theoretically, Tiebout Sorting mechanisms should exert different environmental influences on different socio-demographic cohorts because socio-demographics proxy for group tastes and preferences surrounding the built and social characteristics of residential environments (Tiebout, 1956; Nechyba and Walsh, 2004). Subsequently, these mechanisms are explicitly linked to local infrastructure provision, land-use configurations, and the accessibility of employment – characteristics which directly influence travel behaviours (Tyndall, 2017; Curl, Clark and Kearns, 2018; Guerra, Li and Reyes, 2022). This inference is strengthened upon analysing the relationships between the physical and social characteristics of residential

⁴¹ In 2016, it was reported that 62% of households with two partners were dual earners. However, in single-earner households, 72% of the workers were male (Central Statistics Office [CSO], 2016). Considering the sample used in this research consists of workers, this may explain this somewhat counterintuitive finding.

environments and travel considerations. Although the relative deprivation of localities insignificantly affects trip durations, an outcome which is not sensitive to mode choice, it positively influences the number of people living and working in the same locality (Table 6.2, Columns II-III), a consideration clearly linked with reduced travel burdens (Table 6.2, Column I).

Complimenting these insights are results highlighting how increases in socioeconomic status are associated with increased likelihoods of using rail-based transit and private cars relative to alternatives (Table 6.3, Columns IV-V), while increases in the relative deprivation of localities is associated with increased likelihoods of public and active transport use relative to cars (Table 6.3, Columns I-V). This suggests that because more relatively deprived workers tend to live and work in the same localities that these populations are more inclined to avail of public and active travel (Table 6.3, Columns I-III).

Table 6.2: The Marginal Effects of Socio-Demographic Changes on Residential Environment Characteristics and Travel Considerations

Travel Considerations				Built Environment							Social Environment
	Journey Minutes	Same Res-Work ED	Same Res-Work SA	CorineED	Res-Area Type	Roads	Active	Bus Stops	Rail Stops	House Prices	Deprivation
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)	(X)	(XI)
Socio-Demographics											
Sex (Male =1)	2.8707*** (0.1600)	-0.0107*** (0.0022)	0.0058*** (0.0007)	-0.0661*** (0.0039)	0.2399*** (0.0103)	-0.0500*** (0.0069)	0.0981*** (0.0081)	1.4728*** (0.1470)	0.0626*** (0.0181)	0.0891*** (0.0043)	-0.0415*** (0.0151)
Age	-0.9653*** (0.0645)	0.0078*** (0.0012)	0.0031*** (0.0003)	0.0344*** (0.0035)	-0.0860*** (0.0082)	0.0398*** (0.0056)	0.0153** (0.0059)	-0.1789* (0.0968)	0.0396*** (0.0100)	0.0062* (0.0035)	-0.1868*** (0.0131)
Household Composition											
Other	Base			Base							Base
Single Person	2.0391*** (0.3779)	0.0192*** (0.0064)	-0.0038** (0.0018)	0.0193 (0.0142)	-0.3286*** (0.0275)	0.2971*** (0.0303)	0.1976*** (0.0292)	-2.2454*** (0.3785)	-0.1227*** (0.0426)	-0.1707*** (0.0150)	0.3050*** (0.0560)
Single Parent	1.5408*** (0.3420)	0.0269*** (0.0071)	-0.0035** (0.0017)	0.1654*** (0.0237)	-0.4488*** (0.0388)	0.4250*** (0.0424)	0.3238*** (0.0420)	-2.2793*** (0.5392)	-0.2292*** (0.0766)	-0.2278*** (0.0221)	0.1342 (0.0914)
Two Parent Homes	2.6087*** (0.2690)	-0.0160*** (0.0054)	-0.0055** (0.0012)	0.3291*** (0.0246)	-1.1466*** (0.0441)	0.4315*** (0.0402)	-0.1176*** (0.0382)	-6.1119*** (0.5028)	-0.3220*** (0.0706)	-0.3060*** (0.0191)	-0.4669*** (0.0838)
Socioeconomic Group											
Other (Incl. Farmers)	Base			Base							Base
Employers/Professionals	4.463*** (0.3570)	-0.2082*** (0.0083)	-0.1233*** (0.0060)	-0.0553*** (0.0096)	0.4373*** (0.0285)	-0.2853*** (0.0183)	-0.0748*** (0.0240)	1.387*** (0.2826)	0.0558** (0.0244)	0.2151*** (0.0139)	-0.4997*** (0.0393)
Non-Manual	1.297*** (0.3335)	-0.1615*** (0.0080)	-0.1220*** (0.0060)	-0.0581*** (0.0084)	0.3232*** (0.0236)	-0.2420*** (0.0141)	-0.0977*** (0.0205)	0.2739 (0.2300)	0.0075 (0.1765)	0.0551*** (0.0101)	0.0473 (0.0324)
Manual (Semi) Skilled	-0.5249 (0.3487)	-0.1520*** (0.0089)	-0.1227*** (0.0060)	0.0090 (0.0092)	-0.0159 (0.0277)	-0.0987*** (0.0152)	-0.1578*** (0.0246)	-1.973*** (0.4161)	0.0807* (0.0460)	-0.1267*** (0.0124)	0.3729*** (0.0419)
Unskilled/Agri	-0.6849* (0.4045)	-0.0981*** (0.0109)	-0.1097*** (0.0065)	-0.1694*** (0.0156)	0.5064*** (0.0419)	-0.0960*** (0.0280)	0.1949*** (0.0341)	1.804*** (0.5307)	0.0618 (0.0502)	0.0353* (0.0180)	0.9031*** (0.0659)
Social Environment											
Deprivation	-0.1419 (0.0940)	0.0183*** (0.0022)	0.0013*** (0.0002)	NA	NA	NA	NA	NA	NA	NA	NA
Built Environment											
CorineED	0.1343 (0.3514)	-0.0421*** (0.0074)	0.0008 (0.0011)	NA	NA	NA	NA	NA	NA	NA	NA
Res-Area Type	-0.7312*** (0.1798)	-0.0018 (0.0036)	-0.0064*** (0.0005)	NA	NA	NA	NA	NA	NA	NA	NA
Roads	0.0565** (0.0252)	0.0572*** (0.0062)	-0.0012 (0.0009)	NA	NA	NA	NA	NA	NA	NA	NA
Active	0.0883***	0.0173***	0.0003	NA	NA	NA	NA	NA	NA	NA	NA

	(0.1440)	(0.0026)	(0.0006)								
Bus Stops	1.599*** (0.2963)	-0.0021*** (0.0004)	-0.0000* (0.0000)	NA	NA	NA	NA	NA	NA	NA	NA
Rail Stops	0.7329** (0.3480)	0.0101*** (0.0030)	0.0011*** (0.0003)	NA	NA	NA	NA	NA	NA	NA	NA
House Prices	0.1009 (0.1223)	-0.0164** (0.0065)	-0.0015 (0.0010)	NA	NA	NA	NA	NA	NA	NA	NA

*** denotes 1% Significance ** denotes 5% Significance * denotes 10% Significance. Standard Errors are clustered around residential EDs in the GSEM prior and are presented here in brackets.

6.4.2 Built Environments, Trip Durations, and Commute Mode Choices

Considering the relationship between socio-demographics and the built and social characteristics of residential environments, it is important to analyse the effect these environments have on travel considerations and commute mode choice. In this context, there is no significant relationship found between the physical characteristics of residential environments and journey durations (Table 6.2, Column I). I interpret this to be the consequence of a trip duration variable which is insensitive to the mode used when commuting. Similarly, the results do not extract meaningful relationships between the number of workers living and working in the same locality and urbanisation or transport infrastructure provision (Table 6.2, Columns II-III), something which may be attributable to the increasing size of the spatial units (Electoral Divisions) as distances from urban areas increase (i.e., providing greater opportunity to live and work in the same area), but future research should probe this issue further. However, residential property market values are found to negatively influence the number of workers living and working in the same locality, supporting previous results that the relative deprivation of residential areas is positively associated with workers living and working in the same localities (Table 6.2, Columns II-III). As highlighted within the theoretical model (Figure 6.1), residential built environments do not influence residential social environments, meaning the model reports N/A values.

Table 6.3 shows how decreases in the continuity of urban fabrics (i.e., increases in land-use segregation), are associated with lower likelihoods of active and public travel but higher likelihoods of car-use (Table 6.3, Columns 1-V). Similarly, increases in the populations within, and the urbanisation of, residential counties are associated with increased public and active travel and lower car-use (Table 6.3, Columns I-V). Additionally, living and working in the same locality is found to increase the likelihood of walking and reduce the likelihood of using cars; effects which vary by spatial scale (Table 6.3, Columns I and V).

While these variables are explicitly related to the land-use configurations of residential environments, intrinsic to these compositions is the accompanying transport infrastructure. In this context, active transport infrastructure provision produces results contrary to *a priori* expectations in that increased active transport infrastructure provision insignificantly influences the likelihood of using any mode (Table 6.3, Columns I-V)⁴². However, the

⁴² I interpret this to be the result of imprecise data as road networks with low-speed limits are partially used to proxy for footpaths because walkable and cyclable surface layers within OpenStreetMap do not comprehensively cover the study area, rendering approximations necessary.

provision of road networks significantly affects all modes at the 1% level, illustrating how increased road network provision reduces the likelihood of walking, cycling, and bus-use, whilst increasing the likelihood of car-use (Table 6.3, Columns I-III, and V). Also evident is that transit node provision positively influences the likelihood of using public transport (Table 6.3, Columns III and IV). Increases in bus stop provision are associated with lower likelihoods of car-use and insignificantly impact alternative mode-use, whilst increases in rail stop provision increase the likelihood of walking, reduce the likelihood of bus-use, and insignificantly affect alternative mode-use. These results detail how increased transport network provision is associated with increased likelihoods of people using these modes, a relationship that is particularly strong between road network provision and car-use.

The model also tests whether infrastructure provision alone is enough to stimulate changes in travel behaviours. To test this, I analyse infrastructural quality through the lens of property markets. Increased property market values within localities is associated with increased likelihoods of public and active transport use relative to cars (Table 6.3, Columns I-V). While this may imply that the quality of transport infrastructure may distinctly influence travel behaviours, part of this effect could be attributable to confounding variables, like population densities. Nonetheless, when comparing these results with the infrastructure provision variables, I argue that the quality of infrastructure may share a stronger association with travel behaviours than infrastructure provision itself. For modes other than cars, building infrastructure on its own may not be sufficient to attract greater alternative transport users because the infrastructure that is built must be of a high quality. Future research may wish to test this claim with more comprehensive data capturing transport infrastructure quality.

Table 6.3: Marginal Effects Socio-Demographic, Residential Built and Social Environment, and Travel Consideration Changes on Commute Mode Choices

	Means of Travel				
	Walk	Bike	Bus	Rail	Private Motor
	(I)	(II)	(III)	(IV)	(V)
Socio-Demographics					
Sex (Male = 1)	-0.0049*** (0.0012)	0.0180*** (0.0009)	-0.0039*** (0.0008)	0.0016*** (0.0004)	-0.0108*** (0.0018)
Age	-0.0097*** (0.0006)	-0.0024*** (0.0002)	-0.0099*** (0.0006)	-0.0038*** (0.0003)	0.0260*** (0.0010)
Household Composition					
Other	Base				
Single Person	-0.0269***	-0.0078***	-0.0099***	-0.0030**	0.0477***

	(0.0039)	(0.0018)	(0.0026)	(0.0012)	(0.0059)
Single Parent	-0.483*** (0.0041)	-0.0200*** (0.0017)	-0.0135*** (0.0026)	-0.0058*** (0.0013)	0.0878*** (0.0061)
Two Parent Households	-0.0599*** (0.0035)	-0.0128*** (0.0014)	-0.0221*** (0.0020)	-0.0056*** (0.0010)	0.1005*** (0.0048)
Socioeconomic Group					
Other (Incl. Farmers)	Base				
Employers/Managers	-0.0095*** (0.0031)	0.0054*** (0.0017)	-0.0024 (0.0028)	0.0074*** (0.0017)	-0.0008 (0.0051)
Non-Manual	0.0152*** (0.0029)	0.0063*** (0.0018)	0.0186*** (0.0028)	0.0093*** (0.0017)	-0.0495*** (0.0051)
Manual (Semi) Skilled	-0.0093*** (0.0032)	0.0042** (0.0018)	0.0002 (0.0028)	-0.0036** (0.0015)	0.0084 (0.0053)
Unskilled/Agri	0.0281*** (0.0036)	0.0116*** (0.0021)	0.0248*** (0.0031)	0.0018 (0.0022)	-0.0664*** (0.0063)
Built Environments					
CorineED	-0.0243*** (0.0031)	-0.0069*** (0.0013)	-0.0093*** (0.0021)	-0.0108*** (0.0014)	0.0514*** (0.0051)
Res-Area TypeED	0.0111*** (0.0016)	0.0082*** (0.0007)	0.0115*** (0.0016)	0.0035*** (0.0010)	-0.0346*** (0.0028)
RoadsED	-0.0199*** (0.0029)	-0.0100*** (0.0011)	-0.0156*** (0.0025)	-0.0034** (0.0015)	0.0489*** (0.0049)
ActiveED	-0.0031 (0.0020)	0.0012 (0.0009)	0.0019 (0.0015)	0.0003 (0.0011)	-0.0004 (0.0034)
Bus Stops ED	0.0000 (0.0001)	0.0000 (0.0000)	0.0007*** (0.0001)	0.0001* (0.0000)	-0.0009*** (0.0003)
Rail Stops ED	0.0028* (0.0016)	0.0002 (0.0005)	-0.0034*** (0.0008)	0.0023*** (0.0003)	-0.0020 (0.0025)
House Prices ED	0.0299*** (0.0048)	0.0102*** (0.0015)	0.0080*** (0.0021)	0.0133*** (0.0019)	-0.0616*** (0.0070)
Social Environments					
Deprivation ED	0.0096*** (0.0010)	0.0009** (0.0003)	0.0015*** (0.0005)	-0.0004 (0.0004)	-0.0117*** (0.0016)
Travel Considerations					
Journey Minutes	-0.0010*** (0.0000)	-0.0002*** (0.0000)	0.0012*** (0.0000)	0.0006*** (0.0000)	-0.0005*** (0.0000)
Same Res-Work ED	0.0921*** (0.0033)	0.0120*** (0.0014)	-0.0155*** (0.0045)	-0.0189*** (0.0047)	-0.0697*** (0.0073)
Same Res-Work SA	0.0600*** (0.0037)	-0.0018 (0.0036)	0.0139 (0.0088)	0.0033 (0.0083)	-0.0754*** (0.0135)

*** denotes 1% Significance ** denotes 5% Significance * denotes 10% Significance. Standard Errors are presented here in brackets.

6.4.3 Robustness Checks

Several robustness checks were conducted to ensure the validity of these results. Principal of those is the evaluation of the theoretical model presented in Figure 6.1 above. I propose four alternative modelling specifications using the same key variable groups (Socio-Demographics, Built/Social Environments, and Travel Considerations). I do not consider omitting any individual group entirely because each hold significant empirical and theoretical justification

for inclusion. Consequently, I primarily test whether model goodness of fit improves (according to AIC and SBIC scores) when relationships between the variables (i.e., arrows in the path diagram) are removed. More information on these alternative specifications can be found in **Appendix 6 (A6)**. I also use a Multinomial Logit specification which provides an alternative econometric framework to test these relationships. I find support for the results as the Multinomial Logit produces similar marginal effects to those of the GSEM in Table 6.3 (**See Appendix 6 (A6)**). I test for multicollinearity in the variables using a correlation matrix which failed to identify issues relating to multicollinearity (**See Appendix 6 (A6)**). The efficacy of the use of specific independent variables is tested by omitting each from the modelling framework and comparing AIC and SBIC scores. Additionally, alternative variables to Deprivation (proportion of local populations reliant on social welfare), House Prices (gross median household incomes per ED) are incorporated into the model alongside additional variables like population density. In all cases, AIC and SBIC scores indicate that the variables employed in this analysis produce a model with superior fit.

6.5 Discussion and Implications

The first stage of the model employed in this research examines the relationship between socio-demographics, the characteristics of residential environments, and travel considerations. From a demographic perspective, the key finding is that more complicated household structures generally reside in environments characterised by lower levels of active and public transport infrastructure, high degrees of land-use segregation, and that fewer commuters in these households live and work in the same locality. From a socioeconomic perspective, greater numbers of relatively deprived populations tend to live and work in the same locality and that people residing in these localities typically face shorter commuting times. This suggests that relatively affluent cohorts reside peripherally and commute inward for work, whilst relatively deprived populations typically live and work locally, possibly due to their reliance on the accessibility of local employment opportunities. This inference is supported through the relationships found between commute mode choice, individual socioeconomic status, and the relative deprivation of localities, whereby people residing in relatively deprived areas are more likely to travel via public and active transport relative to cars, and that these people generally live and work in the same locality.

The second component of the model investigates how residential environments influence travel considerations and commute mode choices. Increases in the segregation of urban fabrics and lower degrees of urbanisation deter public and active transport use at the expense of cars.

Complementing these patterns are findings that living and working in the same locality significantly increases active travel and public transport use. These results suggest that regardless of the socio-demographic composition of localities, areas which minimise required travel distances encourage greater transit-use and active travel. I interpret this to be the result of increases in the efficiency of public and active transport infrastructure/services.

Larger road networks are found to adversely affect active and public transport use, while increased transit node provision increases the likelihood of using transit. These results echo existing literature by showing that greater mode-specific transport infrastructure provision increases mode-specific use (Millward, Spinney and Scott, 2013). However, this is only really the case for cars and roads, as building infrastructure on its own negligibly, but positively, impacts the likelihood of travelling via transit and does not significantly influence the likelihood of travelling actively. There is a stronger relationship between infrastructural quality and the likelihood of using public and active transport as increases in local infrastructure quality significantly increase the likelihood of using public and active transport. This implies that increased public and active transport use is only significantly related to the provision of high-quality infrastructure, and that providing infrastructure alone may be insufficient.

These results align with global policymaking objectives. To meet the targets laid out by the United Nations Sustainable Development Goals relating to regional development, land-use developments must be coordinated around compactness and mixed-use. These developments reduce regional spatial demands and utilise existing infrastructure more efficiently (Eldeeb, Mohamed and Páez, 2021; O'Driscoll *et al.*, 2023). This increases multi-modal accessibility (and subsequently regional connectivity) by reducing the spatial expanse of developments (Gim, 2012; Zhang and Zhao, 2017; O'Riordan *et al.*, 2022). These initiatives have been shown to reduce the environmental degradation attributable to travel behaviours and also facilitate economic growth by increasing the accessibility of economic opportunity (Chen and Vickerman, 2017; Heuermann and Schmieder, 2019). This research adds to the evidence base supporting these frameworks by showing how the coordination of land-use and transport policies around mixed-use and compactness offers robust mechanisms to reduce the environmental degradation, economic inefficiencies, and social exclusion attributable to regional development.

6.6 Conclusions

This research investigates the distinct influences socio-demographics, built and social environments, and travel considerations have in determining commute mode choices, and the interrelationships therein. To do this, it employs Generalised Structural Equation Modelling to assess these interrelationships across the Republic of Ireland. Considering these findings, I discuss planning mechanisms which can work harmoniously to increase regional connectivity, reduce social exclusion, and facilitate shifts towards greater sustainable transport use.

The principal finding of this work is that the associations between residential environments, travel considerations, and commute mode choice typically reported in existing literature are possibly inflated by Tiebout Sorting mechanisms. I find that these mechanisms directly influence the types of environments people reside in and their subsequent travel behaviours. Overall, relatively deprived populations tend to live and work in the same locality and are subsequently more likely to use public and active transport. However, there is also no significant relationship found between the physical characteristics of built environments and socio-demographic characteristics. This implies that built and social environments in residential areas exert a distinct influence on travel behaviours, thus suggesting that regardless of socio-demographic composition, areas characterised by higher levels of mixed-use and compactness are generally associated with increased likelihoods of using public and active transport. Additionally, transport infrastructure provision alone only positively affects the likelihood of car-use, whereas increases in infrastructural quality are associated with increased likelihoods of using public and active transport. This suggests that public and active transport use may be particularly sensitive to infrastructural quality, and that infrastructure provision alone may not be sufficient to encourage greater use, a finding which suggests that the implicit costs associated with transport (i.e., service quality) are a stronger predictor of mode choice than the monetary costs (Button, 2010).

These results illustrate that those residing in extremely deprived areas are highly sensitive to the accessibility of economic opportunities. Should employment centres continue to decentralise and become inaccessible by modes other than cars, people residing in relatively deprived areas may be forced into car-use to avail of economic opportunities (Tyndall, 2017; Allen and Farber, 2019; Bastiaanssen, Johnson and Lucas, 2022). This exacerbates the risk of creating transport poverty and social/economic exclusion because of land-use and transport policy configurations. Considering this, the development of planning frameworks centred around accessibility and mixed-use appear to be tangible instruments which can mitigate these

problems. Specifically, evidence suggests that these increase regional connectivity, reduce the risks of socioeconomic exclusion, and alleviate the environmental degradation attributable to land-use and transport policies (Millward, Spinney and Scott, 2013; Guerra *et al.*, 2018; Eldeeb, Mohamed and Páez, 2021). This joint focus can limit the creation of spatial mismatches in economic accessibility by keeping places of interest accessible via multiple modes (Tyndall, 2017; Bastiaanssen, Johnson and Lucas, 2022).

There are numerous directions future research could take in this realm. Travel behaviour research generally operates in the framework of the four-stage model (and more recently, dynamic models). In this context, this chapter focused on one of these stages, mode choice, but future research could build upon this work by investigating these problems in the context of the other stages (trip-generation, trip-frequency, and trip-distribution). Particularly fruitful avenues in this regard may investigate why people travel to-and-from different Origin-Destination pairs and how that might relate to socio-demographic characteristics and/or land-use configurations. This chapter is principally concerned with the determinants of travel mode choices for commuting, and is therefore too restrictive for an analysis of, say, trip-generation, which is best suited to multi-purpose travel in a time-series setting (McNally, 2008; McNally and Rindt, 2008). Furthermore, this research could not access data on the travel mode alternatives available to individuals within the dataset. Otherwise, alternative modelling structures such as the Nested Logit could be employed (within or independently of a Structural Equation framework). This is important because some individuals/locations will not be able to access the entire choice set available (i.e., because rail access nodes might be too costly to access or too far away). Considering this, it is important to elevate our understanding of how individuals adjust their behaviours to changes in the available choice sets.

This analysis calls for improvements in the quality of land-use data/metrics when analysing travel behaviours. Particularly pertinent is a call for studies which improve upon the limitations of this study by incorporating: 1) more thorough land-use classification data and land-use configuration metrics and 2) more comprehensive measures of public transport service quality, more precise measures of infrastructural quality, and a more comprehensive mode choice set which accounts for trip-chaining. Also important is the incorporation of travel distance variables, as relying on duration variables alone produces biased estimates given its independence of travel mode used. In other words, future research should endeavour to avoid scenarios where variables equate 10-minute walks to 10-minute drives. Empirically, this will likely involve the incorporation of opensource datasets, the innovative use of land-use

classification metrics, and the mapping of transit schedules/services (alongside congestion effects). Finally, future research could incorporate temporal population dynamics, such as shrinkage, into travel behaviour literature.

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Chapter 7: Travel Behaviours and Built Environments On The School-Run

School-runs are one of a few staple trips within global households. Like commuting, the consistency of school-runs across households presents unique opportunities for policymakers to facilitate shifts away from excessive car-use because of their sensitivity to land-use and transport policies; opportunities that stem from the derived nature of the demand for these trips. This research employs Generalised Structural Equation Modelling to analyse the determinants of travel behaviours of secondary school students across the Republic of Ireland. But it specifically focuses on the relationships between individual socio-demographics, the built and social characteristics of residential and school locations, trip-specific considerations, and travel mode choices. I find that landscapes which reduce local time-space geographies (i.e., required travel distances) are associated with significantly increased odds of using active and public transport over cars (effects which are stronger in residential areas) and that increased mode-specific infrastructure (i.e., roads) provision is consistently associated with increased mode-specific (i.e., cars) use.

7.1 Introduction

A global consequence of sprawl-centred development has been a general inability to access important destinations, such as leisure amenities, schools, and workplaces by transport modes other than cars. This is because land-use and transport policies have created a landscape characterised by high-degrees of land-use segregation and limited alternative transport accessibility, characteristics which have increased the time-space geographies of global regions (Nechyba and Walsh, 2004; Ewing *et al.*, 2014). In an Irish context, sprawl and suburbanisation characterise most of the developed landscape in what are extreme manifestations of global developmental trends (European Environmental Agency [EEA], 2006; OECD, 2018; Ahrens and Lyons, 2019; Charmes, Rousseau and Amarouche, 2020). For instance, Winston (2007, p. 62) document how between the 1930s-1990s, the population of the Greater Dublin Area (Ireland's capital city) doubled but its spatial expanse quadrupled, a trend also mirrored in the other Irish metropolitan areas. This is complemented by Ahrens and Lyons (2019, p. 1), who note how between 1990-2012, urban land expansion in Ireland was among the highest in Europe. These phenomena have served to increase the time-space geographies of Irish regions to such an extent that travel behaviours have radically changed, whereby as of 2022, 76% of the Irish population use cars as their primary travel mode (Driscoll *et al.*, 2013; Central Statistics Office [CSO], 2022; O'Driscoll *et al.*, 2022). More specifically, the Irish National Travel Survey estimates that 19% of all household trips are explicitly designated as

companion/escort and education-specific journeys; the principal characteristics of the school-run (Central Statistics Office [CSO], 2016). Subsequently, I analyse the interrelationships between individual socio-demographics, built and social environments, travel considerations, and the travel mode choices of students across the Republic of Ireland.

School-runs constitute a consistent trip in the routine of households globally. Unlike typical goods, travel in this context is usually characterised by derived demand whereby travel serves as a means to reach an end destination, such as school (Button, 2010). As a result, the demand for travel (and subsequent decisions, like mode choice) may not necessarily be dictated by monetary costs, but instead implicit costs. Captured here are variables like distance/duration, but also perceptions of mode-specific quality, reliability, safety, and convenience – variables directly influenced by land-use and transport policies (Vandenbulcke, Steenberghen and Thomas, 2009; Button, 2010; Giuliano, 2012). But research into the relationship between travel behaviours, land-use configurations, and transport infrastructure typically focus on workers when commuting, something largely attributable to a lack of data for alternative demographics which provide statistically meaningful insights across the urban-rural continuum. In this context, disentangling the environmental effects on travel behaviours from individual tastes and preferences has proved challenging due to self-selection phenomena potentially biasing results (Schwanen and Mokhtarian, 2005; Acker, Witlox and Wee, 2007; Mokhtarian and Cao, 2008; Ding *et al.*, 2017). But analysing travel behaviours in a school-run context presents unique opportunities because children, in an agency context, hold no direct influence over residential locations, because it is parents who make these decisions; implying a degree of independence between travel-related preference and residential/school locations (Kim, Horner and Marans, 2005; Broberg and Sarjala, 2015; Fatmi, Chowdhury and Habib, 2017). As a result, this research can make three distinct contributions to existing literature.

My first contribution stems from my ability to analyse travel behaviours outside of a workplace commute context. Analysing travel mode choices from the perspective of school-runs provides a broader perspective on the interrelationships between individual socio-demographics, built and social environments, and travel behaviours (Broberg and Sarjala, 2015; Curtis, Babb and Olaru, 2015; Ermagun and Samimi, 2015; Ton *et al.*, 2020). With the exception of Driscoll *et al.*, (2013) who briefly touch on the issue, no research tackles this problem in an Irish context, illustrating the need for greater research. However, this research goes further by undertaking a substantial data collection effort which allows us to incorporate nationally-comprehensive variables characterising built and social environments alongside transport networks and

infrastructure within residential and destination environments, a typically-cited limitation within travel behaviour research (Liu *et al.*, 2018; Ko, Lee and Byun, 2019; Ton *et al.*, 2020; Yang *et al.*, 2021; Jeong, Lee and Gim, 2022).

My second contribution answers calls for a greater level of spatial and demographic depth when analysing travel behaviours. In this regard, a nationally comprehensive Census dataset of secondary school students is paired with highly disaggregated spatial data and scales which span the urban-rural continuum (Cheng, Yan and Gao, 2020; Wang *et al.*, 2021; Basu, Sevtsuk and Li, 2022). Not only does this add a national perspective to an otherwise regionally-segmented literature (Lee, Vojnovic and Grady, 2018; Nasri and Zhang, 2019; Charreire *et al.*, 2021; Basu, Sevtsuk and Li, 2022), it also facilitates investigations into the differing relationships between residential environments, destination environments, and travel mode choices, a common directive for future research (Ding, Cao and Wang, 2018; Ton *et al.*, 2019; Wang *et al.*, 2021; Jeong, Lee and Gim, 2022). Furthermore, this explicitly addresses concerns that improved understanding of travel behaviours can only be achieved through analyses across consistent geographies using consistent data, thereby eliminating confounding cultural and geographical influences (Pojani and Boussauw, 2014; Basu, Sevtsuk and Li, 2022).

My third contribution builds upon typical limitations presented within the research design of travel research. The use of Generalised Structural Equation Modelling in this context allows me to investigate hierarchical cross-sectional data which are interrelated (Rabe-Hesketh, Skrondal and Pickles, 2004, 2005; Nasri and Zhang, 2019). This capability allows me to isolate unobserved heterogeneities in mode choices across localities as well as control for the interrelated nature of the variables, thereby partially controlling for self-selection phenomena (Mokhtarian and Cao, 2008; Ding and Cao, 2019; Nasri and Zhang, 2019). But it also allows me to consider the influence of parental perceptions on the safety of local infrastructure and travel routes on school-runs, another key limitation of existing research (Deka, 2013; Ermagun and Samimi, 2015; Ermagun and Levinson, 2016).

Empirically, the Place of Work, School, or College Census of Anonymised Records (POWSCAR) dataset is derived directly from the 2016 Irish Census and covers all students studying in the Republic of Ireland. This captures individual socio-demographic, and travel characteristics, but is paired with built and social environment data clustered within highly disaggregated spatial units which comprehensively cover the urban-rural continuum. The chosen spatial scale for this analysis is Small Areas, of which there are 18,641 in Ireland. This

scale allows for the distinguishing between residential and school locations because only 1.67% of students within the sample share a residential and school Small Area. This allows me to model the interrelationships between socio-demographics, the physical and social characteristics of residential and school environments, trip-specific considerations, and the travel mode choices of 297,968 Irish secondary school students using mode choice options capturing active, public, and private motorised transport.

Section 7.2 documents a literature review surrounding the determinants of student travel behaviours. *Section 7.3* describes the data and methodology used. *Section 7.4* illustrates the results. *Section 7.5* discusses their implications. *Section 7.6* concludes the analysis while highlighting this study's limitations and avenues for future research.

7.2 Background To The Literature

7.2.1 Travel Behaviours And Households

Travel behaviours are intertwined across individuals within households. This is commonly evidenced through trip-chaining, whereby members of the same household share journeys and transportation modes (Commins and Nolan, 2010, 2011; Ermagun and Levinson, 2016). As a result, parental behaviours and preferences clearly influence those of children and their licence to travel independently. This inheritance of preferences (or formation of generational habits) is often attributed to the nesting of individuals within households and the subsequent convergence of tastes and preferences (McDonald, Deakin and Aalborg, 2010; Clark and Scott, 2013; Ermagun and Samimi, 2015). But a wide body of evidence suggests that children develop travel-related habits at a young age; habits which are also sensitive to built and social environment considerations. The problem is that the longer they hold onto these habits, the more challenging they are to break (Lin and Chang, 2010; Mitra and Buliung, 2015; Ermagun and Levinson, 2016).

Excessive car-use is typically cited as the most damaging travel-related habit because of its excessive environmental damage and its creation of negative externalities (European Environmental Agency [EEA], 2006; OECD, 2018, 2022). But putting these aside, excessive car-use by children is explicitly linked to a sluggish development of social skills and independent growth (Yang, Abbott and Schlossberg, 2012) and is also one factor which can contribute to growing obesity levels across the western world – considerations which have been particularly motivating for past research into youth travel behaviours (McDonald, Deakin and Aalborg, 2010; Henne *et al.*, 2014; Silva *et al.*, 2014; Easton and Ferrari, 2015; Hollein *et al.*,

2017). Thus, if children are raised being driven in cars, they may resist change in later life, as ingrained habits may outweigh any environmental characteristics which would otherwise influence travel behaviours, creating problems for both current and future generations (Pojani and Boussauw, 2014; Mitra and Buliung, 2015; Jacob *et al.*, 2021).

Considering this problem, research suggests that delaying (and if possible preventing) habitual car-use can positively alter future perceptions of alternative modes while also inducing physical health benefits (Lin and Chang, 2010; Curtis, Babb and Olaru, 2015; Focas, 2016; Kar *et al.*, 2017; Zhang, Yao and Liu, 2017). Specifically, increased exposure to public and active travel increases independent mobility, incidental physical activity, and allows for the independent development of perceptions surrounding residential environments and travel modes, something which may encourage greater multi-modal travel in later life (Zhao and Kaestner, 2010; Yang, Abbott and Schlossberg, 2012; Van Goeverden and De Boer, 2013; Pojani and Boussauw, 2014; Broberg and Sarjala, 2015; Zhang, Yao and Liu, 2017). Pair this with evidence which suggests that globally students (both boys and girls) typically acquire independent mobility around the ages of 12-14 (i.e., upon entering Middle School) and it is apparent that policymakers have a significant opportunity to shape the travel behaviours of future generations by configuring regions which free individuals/households from car dependency (Curtis, Babb and Olaru, 2015; Easton and Ferrari, 2015; Ermagun and Samimi, 2015; Ermagun and Levinson, 2016).

7.2.2 Travel Behaviours and Built and Social Environments

Despite the benefits associated with shifting travel behaviours away from excessive car-use in favour of public and active transport, car-use is still increasing across the western world at the expense of public and active transport, regardless of whether trips are conducted by adults or children for work, school, or leisure (Ferrari and Green, 2013; Curtis, Babb and Olaru, 2015; O'Driscoll *et al.*, 2022). In an Irish context, cars are being increasingly adopted for shorter trips, yet travel times are also consistently increasing (Central Statistics Office [CSO], 2016). For people residing in urban areas, this most likely relates to the fact that the development of new, and improvement of existing, transport infrastructure for modes other than cars have been historically neglected, reducing the viability of alternative modes even for short trips (Reynolds-Feighan, 2003; Vega and Reynolds-Feighan, 2008; O'Riordan *et al.*, 2022). But for people residing in rural areas, this is most likely attributable to the prevalence of unabated residential and commercial decentralisation since 1950, creating development landscapes characterised by urban sprawl and large local time-space geographies (O'Driscoll *et al.*, 2022;

O'Driscoll, Crowley, Doran and McCarthy, 2023; O'Driscoll, Crowley, Doran and McCarthy, 2023b).

Evidence suggests that the characteristics of built/social environments at trip origins and destinations can influence travel behaviours in similar ways (Lee *et al.*, 2011; Zhao, Bentlage and Thierstein, 2017; De Vos, Mouratidis, *et al.*, 2021). Evidence consistently shows that developmental forms which minimise local time-space geographies (i.e., required travel distances) and provide adequate multi-modal transport infrastructure discourage car-use in favour of increased active and public transport use due to the heightened competitiveness and convenience of these modes (Boussauw, Neutens and Witlox, 2012; Nahlik and Chester, 2014; Broberg and Sarjala, 2015; Curtis, Babb and Olaru, 2015; Mitra and Buliung, 2015; Christiansen *et al.*, 2017; Neves and Brand, 2019; Lee, 2020). This is especially important given the wide body of evidence which suggests that the built environment mechanisms that impact adult travel behaviours (i.e., land-use characteristics and infrastructure provision) are the same mechanisms which impact the travel behaviours of children, (Boussauw, Neutens and Witlox, 2012; Deka, 2013; Henne *et al.*, 2014; Ermagun and Levinson, 2016; Guerra, Li and Reyes, 2022). Therefore, if essential destinations like schools (or places of interests like leisure amenities), are closer to residential areas and if transport infrastructure facilitates efficient multi-modal travel, evidence suggests that increased public and active transport use will occur (Millward, Spinney and Scott, 2013; Spinney and Millward, 2013; O'Riordan *et al.*, 2022; O'Driscoll, Crowley, Doran and McCarthy, 2023a).

However, as discussed earlier, in a school-run context a student only has independent mobility subject to parental approval. In this context, parental perceptions of these environments, and the routes travelled therein, become important especially if trying to encourage shifts in habitual behaviour. Of these perceptions, the extant literature identifies perceptions related to route safety and infrastructure quality as the most important (Olvera, Plat and Pochet, 2003; Vandenbulcke *et al.*, 2009; McDonald, Deakin and Aalborg, 2010; Yang, Abbott and Schlossberg, 2012; Clark and Scott, 2013). Here, if parental confidence in transport infrastructure quality is absent, increased car-use by children (i.e., through trip chaining) is virtually guaranteed (Wilson *et al.*, 2010; Pojani and Boussauw, 2014; Ermagun and Samimi, 2015; Rothman *et al.*, 2015). This illustrates the linkages between individual-level and household-level travel behaviours but also highlights how these behaviours can be influenced by built/social environmental considerations (Commins and Nolan, 2011; Ermagun and Levinson, 2016). Therefore, depending on land-use and transport infrastructure configurations,

parents may be more willing to use public and active transport instead of cars, an effect which may spill-over to younger children (Noland and Kunreuther, 1995; Clark and Scott, 2013; Pojani and Boussauw, 2014; Neves and Brand, 2019).

7.2.3 Theoretical Model

Figure 7.1 below synergises the conceptual framework discussed in the previous subsections through a path diagram which presents the theoretical model employed in this analysis. Straight arrows indicate direct relationships between variables. Rectangular boxes represent observed variables while circular shapes represent latent variables. The principal argument of this model is that individual socio-demographics, the built and social characteristics of residential and school environments, travel considerations, and underlying destination-specific concerns (like those relating to travel routes), all directly influence travel mode choices on school-runs, arguments which build upon existing literature (Mitra and Buliung, 2015; Ding *et al.*, 2017, 2018; O’Riordan *et al.*, 2022). Figure 7.1 presents the aggregated groupings of variables while the variables belonging to each group are outlined and described in a later table (Table 7.1).

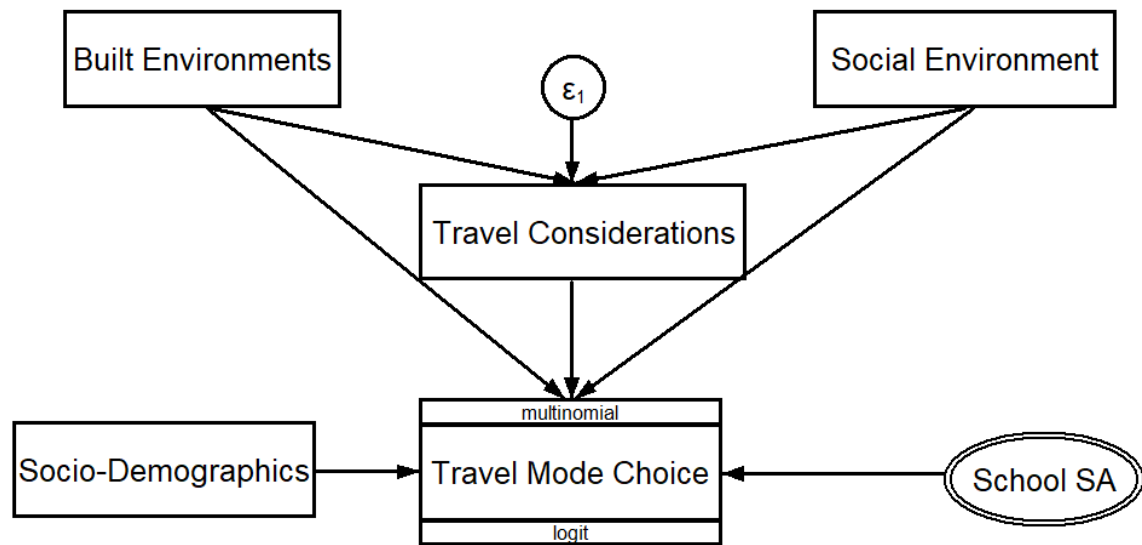
The first component of the model argues that the variable group corresponding to Socio-Demographics directly influences travel mode choices through tastes and preferences. This stems from the body of global evidence which suggests that students acquire independent mobility around the ages of 12-14, thereby allowing them to theoretically realise their travel-related preferences (Wilson *et al.*, 2010; Pojani and Boussauw, 2014; Curtis, Babb and Olaru, 2015; Easton and Ferrari, 2015; Ermagun and Samimi, 2015; Mitra and Buliung, 2015; Ermagun and Levinson, 2016). However, this component of the model also assumes that Socio-Demographics do not directly influence the characteristics of residential or school environments. This assumption follows a line of literature which argues that parents/workers/adults are the principal decisionmakers within households, particularly pertaining to residential locations and that, although children influence these decisions indirectly, the children/students themselves have no direct input (Kim, Horner and Marans, 2005; Fatmi, Chowdhury and Habib, 2017). Empirically, this is partially supported by results which show that 97% of the sample under study maintained the same residential location as in the previous Census, a timeline (5-years) in which many cohorts would have graduated from primary to secondary school – thus providing the opportunity to directly influence residential locations on account of changing schools. This provides the rationale for the arrow stemming from the variable group corresponding to Socio-Demographics and ending in the variable group corresponding to Travel Mode Choice in Figure 7.1.

The second component advances the work of Idris *et al.*, (2015), who analyse the interrelationships between psychological considerations, the appraisal of transport services, and travel mode choices, by positing that the physical characteristics of built environments directly influence travel behaviours by defining local time-space geographies. This component goes on to argue that trip-specific considerations directly influence travel mode choices by defining available choice sets. In this context, evidence suggests that variables like travel time define the feasibility of modes like walking and cycling (Millward, Spinney and Scott, 2013; Idris *et al.*, 2015; Tyndall, 2017). These influences are represented by arrows stemming from the variable groups corresponding to Built Environment and Social Environment and ending in the groups corresponding to Travel Considerations and Travel Mode Choice, but also the arrows stemming from the variable group corresponding to Travel Considerations and ending in the group corresponding to Travel Mode Choice within Figure 7.1.

The final component of the model argues that any residual effects on individual Travel Mode Choices can be captured through a latent variable denoted by the unique Small Area identifier for every student's school. This is feasible because only 1.67% of the sample share a residential and school Small Area⁴³ and because the previous components of the model comprehensively extract individual socio-demographics, built and social environment data, and trip-specific considerations as exogenous variables on Travel Mode Choice for both residential and school locations. As a result, I argue that any residual effects are most likely related to travel routes, as those remain the only consideration not explicitly captured and which evidence suggest exert a distinct influence on travel mode choices (Ermagun and Samimi, 2015; Mitra and Buliung, 2015; Christiansen *et al.*, 2017; Sun, Ermagun and Dan, 2017). This approach advances the work of Ding and Cao, (2019) and Higuera-Mendieta *et al.*, (2021) who explicitly advocate the incorporation of both origin and destination effects when analysing travel behaviours. This provides the rationale for the arrows stemming from the variable School SA and ending in Travel Mode Choice within Figure 7.1.

⁴³ There are 732 post-primary schools in The Republic of Ireland spread across 18,641 Small Areas, a figure sourced directly from the Department of Education (Department of Education, 2016).

Figure 7.1: Path Diagram Describing The Generalised Structural Equation Modelling Framework



7.3 Data and Methods

7.3.1 Data

This research uses individually disaggregated Place of Work, School, or College Census of Anonymised Records (POWSCAR) data derived directly from the 2016 Irish Census. These data provides statistics on individuals' socio-demographic, household, and school-run travel details. But also incorporated is data pertaining to local residential environments which capture transport infrastructure, land-use metrics, and infrastructural quality indicators. These data are derived from *OpenStreetMap* (2021), *The 2018 CORINE Land Cover Dataset*, *The Property Price Register* (2016), and *The Teljeur et al. (2019) 2016 Deprivation Index*.

POWSCAR comprises of 3,058,607 individuals. I focus on student travel behaviours within the Republic of Ireland, so these data are filtered whereby only those who(se) 1) Live and go to school in the Republic of Ireland; 2) Are full-time students in secondary school; 3) Report complete information for key variables; 4) education attendance is not home-based, are included in the sample. This filtering reduces the sample to 297,968 secondary school (i.e., the Irish equivalent of Middle and High School) students. The spatial scale employed are Small Areas (SA). SAs offer the highest level of spatial resolution in Ireland and facilitate meaningful investigations into local environmental heterogeneities in travel behaviours. Approximating areas covering between 80-120 households, these 18,641 spatial units are an appropriate scale to distinguish between residential and school environments.

This analysis develops the following categorical variable to represent travel mode choices⁴⁴ during school-runs: 1. Walking; 2. Cycling; 3. Buses; 4. Trains/Trams; 5. Private Motorised. The other variables are categorised into five groups: individual socio-demographics, built environments, social environments, school locations, and travel considerations. Socio-demographics capture each student's sex, socioeconomic group, and each students' household structure/composition⁴⁵. Travel considerations are captured by journey durations in minutes and whether people live and go to school within the same locality at two spatial scales: Small Areas and Electoral Divisions (ED)⁴⁶.

From a built environment perspective, I employ measures of land-use mixing (i.e., relative entropy⁴⁷) something which serves as a proxy for developmental compactness (O'Driscoll, Crowley, Doran and McCarthy, 2023; O'Driscoll, Crowley, Doran and McCarthy, 2023b), while also characterising each Small Area according to their predominant landscape characteristics – as classified by the 2018 CORINE Land Cover dataset. But this research also incorporates variables accounting for transport infrastructure provision and quality. Specifically, *Road* and *Active* measure the logged length of roads and active transport infrastructure within each Small Area⁴⁸. *Bus Stops* and *Rail Stops* count the number of bus and rail nodes per Small Area. *Bus Routes* and *Rail Routes* count the number of transit routes which service each Small Area. Collectively, these act as an indicator of service quality. Finally, local infrastructural quality is measured by logging the average property price (for properties sold between 2015-2017) per SA. In this context, the logged average house price per SA is assumed to be positively correlated with the provision of high quality infrastructure (Allen and Farber, 2020; Guerra, Li and Reyes, 2022).

⁴⁴ The Census defines mode choice as the main mode of travel used throughout the journey. This means we are unable to account for multi-modal trips within this analysis.

⁴⁵ For data protection reasons, age variables are unavailable for student cohorts. Additionally, we cannot identify the relationships between individuals within the dataset (i.e., parent and child). As a result, we cannot incorporate variables like parental education levels and income but also cannot distinguish between escort and non-escort journeys.

⁴⁶ Electoral Divisions are the smallest administrative spatial unit in an Irish context and capture 3,409 unique municipalities.

⁴⁷ Relative entropy (E) measures the level of mixing across unique land-use classes (k) within pre-defined spatial units (j) and is calculated as: $E_j = (-1) \times \sum_{k=1}^K \frac{P_{kj} \ln(P_{kj})}{\ln(K)}$. Information on the data used to make such calculations can be found in **Chapters 3, 4, and 5**.

⁴⁸ This network data is calculated in Quantum Geographical Information Systems and measures the length of the network within each ED, a measure which is subsequently logged. The road network accounts for every publicly accessible road available in the QuickOSM QGIS plugin whereas the active network captures a combination of roads with low speed limits and every walkable/cyclable surface available in the same plugin. Information on the data used to generate transport networks can be found in **Chapter 8**.

Social environments are captured through the *Teljeur et al. (2019) 2016 Deprivation Index*. This deprivation index is stratified across five quintiles and captures the underlying social circumstances of localities through employment levels, socio-demographic characteristics, and car-ownership levels (Teljeur *et al.*, 2019). Subsequently, it proxies for the relative socioeconomic prosperity of localities. The descriptive statistics associated with these variables are outlined below in Table 7.1.

Table 7.1: Key Variables Used

Variables	Mean Prop (%)	Variable Description
Means of Travel	Bus	A categorical variable denoting the proportion of the POWSCAR sample which utilise each travel mode when travelling to school.
Walk	20.6%	
Bike	2.11%	
Bus	29.52%	
Train/Tram	1.67%	
Private Motorised	46.09%	
Socio-Demographics (n = 297,968)		
Sex	0.5	A binary variable denoting the sex of individuals in the POWSCAR sample (1 = Male).
Household Composition	Two-Parent Home	A categorical variable denoting the household structure of individuals in the POWSCAR sample.
Single Parent Households	19.28%	
Two Parent Households	78.77%	
Other	1.95%	
Socioeconomic Group	Non-Manual	A categorical variable denoting the socioeconomic group of individuals in the POWSCAR sample.
Employers/Professionals	44.52%	
Non-Manual	22.69%	
Manual (Semi) Skilled	13.15%	
Unskilled and Agri	2.68%	
Other (Incl. Farmers)	16.96%	
Travel Considerations (n = 297,968)		
Journey Minutes	19	A continuous variable denoting the journey length of every individual in the POWSCAR sample.
Same Res-School ED	0.21	A binary variable denoting whether people live and go to school in the same ED (1 = Yes).
Same Res-School SA	0.01	A binary variable denoting whether people live and go to school in the same SA (1 = Yes).
Built Environments (n = 18,641)		
CORINE Classification	Discontinuous UF	A categorical variable denoting the landscape characteristics of the residential Small Areas of individuals in the POWSCAR sample.
Continuous Urban Fabric [UF]	1.15%	
Discontinuous UF	38.83%	
Rural Areas	60.02%	
Land-Use Mix (Entropy)	0.55	A continuous variable (on a 0-1 scale) documenting the levels of land-use mixing per residential SA.
Log Road Networks	8.00	A continuous variable denoting the logged length of road infrastructure per residential SA.

Log Active Networks	7.17	continuous variable denoting the logged length of active transport infrastructure per residential SA.
Bus Stops	0.36	A count variable denoting the number of bus stops per residential SA.
Rail Stops	0	A count variable denoting the number of rail stops per residential SA.
Bus Routes	2	A count variable denoting the number of bus routes which service each residential SA.
Rail Routes	0	A count variable denoting the number of rail routes which service each residential SA.
Log House Prices	12.05	A continuous variable denoting the logged mean house price per residential SA.
Social Environments (n = 18,641)		
Relative Deprivation	3	A categorical variable denoting the deprivation quintile (1-5) of every residential SA.
1 (Least Deprived)	20.1%	
2	20.3%	
3	19.7%	
4	20.4%	
5 (Most Deprived)	19.5%	

7.3.2 Econometric Modelling

This chapter investigates how individual- and environmental-level variables influence the travel mode choices of secondary school students during school-runs. To do this, I explicitly model: 1) the relationship between individual socio-demographics and travel mode choices, 2) the relationship between the built and social characteristics of residential and school environments and travel mode choices, 3) the relationship between these considerations and trip-specific considerations (i.e., journey minutes), and 4) the relationship between trip-specific considerations and travel mode choices.

These data are clearly hierarchical whereby individual students are nested within school Small Areas. To account for this, I incorporate random effects through a latent variable which capture the unobserved heterogeneities in individual travel behaviours across school Small Areas (Rabe-Hesketh, Skrondal and Pickles, 2004, 2005). The empirical model comprehensively captures the influence of built and social environments (at both residential and school locations), alongside tastes and preferences, on travel behaviours in a school-run context. Therefore, I argue that the latent variable primarily captures unobserved differences in parental perceptions of safety surrounding required travel routes to reach destinations, a key consideration found in existing literature which this chapter cannot explicitly measure, also explaining why a latent variable capturing unobserved effects in residential Small Areas is excluded (Deka, 2013; Ermagun and Samimi, 2015; Ermagun and Levinson, 2016).

Variables within a GSEM framework can take an endogenous and exogenous structure simultaneously. The state of any given variable in any given relationship is best gauged according to path diagrams (Figure 7.1). In general, any variable with an arrow stemming from it is deemed exogenous in that particular relationship, while any variable with an arrow leading into it is deemed endogenous in that particular relationship. The path diagram related to this research (Figure 7.1 above) postulates that socio-demographics, built environments, social environments, and school small area (latent) are the main exogenous variables in the model.

To investigate these relationships, this chapter employs a Generalised Structural Equation Modelling (GSEM) framework using STATA 17. This is because GSEM facilitates the investigation of multiple interrelated hypotheses simultaneously while also allowing for the incorporation of random effects within hierarchical cross-sectional data and polytomous response variables (Bhat, 2000; Ewing, Hamidi and Grace, 2016; Ding *et al.*, 2017, 2018; Gim, 2018; De Vos, Cheng, *et al.*, 2021). Following existing literature, I employ the Maximum Likelihood method to estimate the GSEM (Golob, 2003; Ding *et al.*, 2018; Cheng *et al.*, 2019; Yan *et al.*, 2019; De Vos, Cheng, *et al.*, 2021), whereby the generic modelling structure takes the form of:

$$y = By + \Gamma x + \xi + \zeta \quad (7.1)$$

Where y is column vector of n dependent variables, x is a column vector of m independent variables, B is a matrix ($n \times n$) of direct relationships, Γ is a matrix ($n \times m$) of regression coefficients, ξ represents the latent variable effects, and ζ is a column vector of error terms (Grace, 2006; Cheng *et al.*, 2019).

This research cannot use goodness-of-fit tests traditionally applied to Structural Equation Models (i.e., the Root Mean Square Error of Approximation (RMSEA)) due to the polytomous nature of the key response variable (travel mode choice). Subsequently, when evaluating the efficacy of the model specification I compare the Akaike's and Schwartz Bayesian Information Criterion (AIC and SBIC) scores of alternative modelling structures to those of the proposed modelling configuration (Figure 7.1) (Hooper, Coughlan and Mullen, 2008; Ding *et al.*, 2017, 2018; Gim, 2018; Cheng *et al.*, 2019; Yin, Zhang and Shao, 2020; De Vos, Cheng, *et al.*, 2021). Specifically, I evaluate the AIC and SBIC scores of two alternative models which may also reasonably describe the relationships within the data, whereby the model which produces the lowest AIC and SBIC scores is retained, something further discussed in **Appendix 7 (A7)**

(Golob, 2003). This approach illustrates that the model proposed in Figure 7.1 best describes the relationships in the data by producing the lowest AIC and SBIC scores. To test the validity of employing a hierarchical modelling structure, I measure the Intraclass Correlation Coefficient and find that when all individual-level and environmental-level variables are included in the model, there is still significant clustering within the data at the school Small Area level, justifying this approach. Finally, to evaluate the robustness of the results, I replicate this analysis using alternative econometric techniques (Multinomial Logit Regression), a replication analysis which produces results that are consistent with those presented in Section 7.4, as **Appendix 7 (A7)** shows.

Categorical dependent variables in a GSEM framework (i.e., travel mode choice) assume a Multinomial Logit structure, meaning they are subject to the Independence of Irrelevant Alternatives (IIA), which requires that each alternative within a choice set is independent (Skrondal and Rabe-hesketh, 2003; Long and Freese, 2014). The efficacy of the mode choice set (1. Walk, 2. Bike, 3. Bus, 4. Train/Tram, 5. Private Motorised) is evaluated through Hausman tests (Long and Freese, 2014), and the variable specification retained is best according to these tests. Typical modelling structures fail to acknowledge how multilevel data compound the liability of IIA by inducing additional dependence (i.e., spatial dependence) between individuals nested within Small Areas, something GSEM accounts for in this study, further justifying the use of GSEM (Bhat, 2000; Mokhtarian and Cao, 2008; Oud and Folmer, 2008; Ding *et al.*, 2018).

7.4 Results

Table 7.2 presents the results associated with the Generalised Structural Equation Model. It demonstrates the relationships between socio-demographics and travel mode choices; the relationships between residential environments, travel considerations, and travel mode choices; and the relationships between school-location effects and travel mode choices. The GSEM framework incorporates two types of response variables. Specifically, Columns I-III are interpreted through linear regression (as in regular Structural Equation Models), while Columns IV-VIII are interpreted through Multinomial Logit Regression, meaning they correspond to odds ratios whereby coefficients > 1 are equivalent to positive values while coefficients < 1 are equivalent to negative values. For clarity positive and negative coefficients which are statistically significant are highlighted green (positive) and red (negative). All other coefficients are left black.

7.4.1 Socio-Demographics and Travel Mode Choices

The proposed model argues that socio-demographic considerations exert a distinct influence on travel mode choices. Boys are found to face higher odds of travelling actively or via transit than girls, particularly for cycling and rail-based transit. But household structures becoming more complicated (i.e., moving from a single-parent house to a two-parent household) is associated with significantly increased odds of children using cars relative to alternatives. Furthermore, improvements in socioeconomic status (i.e., moving from a household characterised by “Manual (Semi) Skilled Labour” to “Employers/Professionals”) is associated with significantly reduced odds of active travel and transit-use relative to cars.

This insight holds when analysing social environments, whereby the relative deprivation of residential localities is negatively associated with journey durations, positively associated with living and going to school in the same locality, and positively associated with the odds of actively travelling. Similarly, increases in residential property market values reduce the odds of active travel. But increases in residential property market values are also associated with shorter travel durations and inconsistently relate to living and going to school locally. This may relate to the journey durations variable not being mode-specific, meaning a ten-minute walk and a ten-minute drive are treated as identical within the model.

7.4.2 Residential Environments, Travel Considerations, and Travel Mode Choices

The model also argues that residential built environments exert a distinct influence over trip-specific considerations. In this context, increases in land-use mixing (and by extension developmental compactness) lead to lower travel times while increases in land-use mixing is also positively associated with the number of people living and going to school in the same locality⁴⁹. Increased road network provision in residential areas is associated with increased travel times as well as less instances of living and going to school in the same area, while increased active transport infrastructure is associated with shorter travel times and increased instances of living and going to school in the same locality, albeit the effects are significantly weaker than those pertaining to road network provision. There is no meaningful relationship found between the provision of public transport infrastructure and travel considerations,

⁴⁹ The finding that increases in the segregation of urban fabric (CORINE) is associated with increased instances of living and going to school in the same locality is possibly explained by the fact that Small Areas tend to increase in size as distances from major urban centres increase.

something which may be partially explained by the journey minutes variable being insensitive to the mode used when travelling.

Also investigated is how these characteristics influence travel mode choices. Table 7.2 shows that increases in land-use mixing and developmental compactness are associated with increased odds of active travel relative to car-use but also reduced odds of transit-use relative to cars. Increases in mode-specific transport infrastructure (i.e., roads) in residential areas is associated with increased odds of mode (i.e., car) use across all mode-infrastructure pairs. Regarding transit, the coefficients relating to rail infrastructure are generally weaker than those concerning buses, perhaps because the bus network is nationally comprehensive, while the rail network is not. As property market values increase within residential areas, an indicator of infrastructure quality, the odds of cycling and using rail-based travel relative to cars increase, but the odds of car-use relative to other modes also increase, suggesting that infrastructure quality may not influence student travel behaviours as significantly as infrastructure provision (i.e., accessibility).

Finally, I investigate the relationship between travel considerations and travel mode choices. Living and going to school in the same locality is associated with significantly increased odds of active and public transport use relative to cars, considerations that are clearly linked to journey durations. This suggests that smaller regional time-space geographies (i.e., shorter required travel distances) increase the odds of public and active transport use⁵⁰.

7.4.3 School Environments and Travel Mode Choices

The next component of the model analyses the influence of school-location characteristics on travel considerations. When pertaining to school locations, variables concerning built and social environments share similar relationships to when they relate to residential environments. For instance, students who go to school in relatively deprived areas, and areas with low property market values, face shorter travel times. Additionally, school environments which reduce local time-space geographies (i.e., by increasing land-use mixing and reducing required travel distances) are associated with shorter travel times and increased instances of living and going to school in the same locality. Increased transport network provision at school locations is also associated with shortened travel times, but inconsistently relates to whether students live in that area.

⁵⁰ The finding that longer journeys are associated with increased odds of transit-use over cars-use is interpreted as being the result of the journey minutes variable not distinguishing between travel modes.

Students who attend schools in relatively deprived areas face increased odds of walking relative to car-use. But relative to other alternatives, their odds of using cars are highest, something also reflected through the property market variable. Increases in the continuity of urban fabrics and land-use mixing in school locations is also associated with increased active travel relative to car-use, but inconsistently relates to transit-use. Increases in the provision of mode-specific transport infrastructure (i.e., roads) at school locations is associated with increased mode (i.e., cars) use relative to all other mode-infrastructure pairs. Like in residential environments, this relationship is strongest between roads and cars. Rising infrastructural quality in school locations (i.e., property market values) is associated with increased odds of cycling and rail-based transit relative to car-use but reduced odds of walking and bus-use relative to car-use.

The final component of the model posits that because all plausible built and social environmental influences on travel behaviour are directly captured within the model, residual variance can be explained by random effects pertaining to school locations. Subsequently, these coefficients are interpreted as principally relating to parental concerns surrounding travel routes. These unobserved effects significantly influence the odds of utilising public and active transport.

Table 7.2: The Relationships Between Socio-Demographics, Residential/School Environment Characteristics, Travel Considerations, and Mode Choices								
Travel Considerations				Travel Mode Choice				
	Journey Minutes	Same Res-School ED	Same Res-School SA	Walk	Bike	Bus	Rail	Car
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)
Socio-Demographics								
Sex (Male =1)	NA	NA	NA	1.1062*** (0.0132)	11.652*** (0.5292)	1.0491*** (0.0127)	1.4275*** (0.0584)	Base
Household Composition								
Other	NA	NA	NA			Base		
Single Parent	NA	NA	NA	0.8900*** (0.0369)	0.7714*** (0.0716)	0.9296* (0.0401)	1.0499 (0.1345)	Base
Two Parent Homes	NA	NA	NA	0.6368*** (0.0261)	0.6146*** (0.0561)	0.7692*** (0.0324)	0.8115* (0.1027)	Base
Socioeconomic Group								
Other (Incl. Farmers)	NA	NA	NA			Base		
Employers/Professionals	NA	NA	NA	0.6621*** (0.0118)	0.8293*** (0.0629)	0.7033*** (0.0114)	0.9389 (0.0539)	Base
Non-Manual	NA	NA	NA	0.8561*** (0.0158)	0.8949** (0.0425)	0.8912*** (0.0154)	1.0823 (0.0693)	Base
Manual (Semi) Skilled	NA	NA	NA	1.1311*** (0.0240)	1.0770 (0.0608)	1.0921*** (0.0217)	1.3331*** (0.1062)	Base
Unskilled/Agri	NA	NA	NA	1.4243*** (0.0517)	1.2925*** (0.1225)	1.3846*** (0.0495)	0.9883 (0.1589)	Base
Residential Social Environment								
Deprivation	-0.0587*** (0.0088)	0.0063*** (0.0002)	0.0014*** (0.0000)	1.0285*** (0.0022)	1.0248*** (0.0052)	0.9913*** (0.0021)	0.9845** (0.0064)	Base
Residential Built Environment								
CORINE SA	0.8500*** (0.0692)	0.0998*** (0.0021)	0.0037*** (0.0007)	0.6657*** (0.0106)	0.6329*** (0.0260)	0.8645*** (0.0165)	0.7041*** (0.0359)	Base
Relative Entropy SA	-0.6037*** (0.0802)	0.1137*** (0.0025)	0.0096*** (0.0008)	1.1174*** (0.0229)	0.09897 (0.0467)	0.7919*** (0.0161)	0.9405 (0.0545)	Base
Roads	1.5965*** (0.0268)	-0.1012*** (0.0008)	-0.0034*** (0.0002)	0.4487*** (0.0040)	0.4937*** (0.0109)	0.9162*** (0.0064)	0.7081*** (0.0174)	Base
Active	-0.1011*** (0.0149)	0.0070*** (0.0004)	0.0009*** (0.0001)	1.0846*** (0.0072)	1.0930*** (0.0189)	0.9922** (0.0033)	0.9314*** (0.0151)	Base
Bus Stops	-0.0366 (0.0227)	0.0010 (0.0007)	0.0049*** (0.0002)	1.0657*** (0.0061)	1.0727*** (0.0115)	1.0432*** (0.0059)	1.0563*** (0.0137)	Base
Rail Stops	0.4071** (0.1656)	-0.0177*** (0.0052)	0.0003 (0.0017)	1.0121 (0.0396)	0.9025 (0.0804)	1.0516 (0.0480)	1.7127*** (0.0893)	Base
Bus Routes	-0.1289*** (0.0064)	0.0003* (0.0002)	0.0005*** (0.0000)	1.0504*** (0.0064)	1.0224*** (0.0027)	1.0315*** (0.0018)	0.9901** (0.0038)	Base
Rail Routes	-0.0980*** (0.0248)	0.0091*** (0.0007)	0.0009*** (0.0002)	1.0341*** (0.0016)	1.0480*** (0.0131)	1.0062 (0.0064)	1.3237*** (0.0140)	Base
House Prices	-0.7698*** (0.0403)	0.0071*** (0.0012)	-0.0024*** (0.0004)	0.9159*** (0.0109)	1.1524*** (0.0326)	0.9639*** (0.0095)	1.3936*** (0.0470)	Base
Destination Social Environment								
Deprivation	-0.0916*** (0.0085)	-0.0008*** (0.0002)	-0.0005*** (0.0000)	1.0100** (0.0041)	0.9522*** (0.0066)	0.9980 (0.0104)	0.9492*** (0.0147)	Base
Destination Built Environment								
CORINE SA	-2.1582*** (0.0569)	0.1003*** (0.0018)	0.0050*** (0.0005)	0.9128*** (0.0243)	1.0427 (0.0456)	1.6929*** (0.1147)	0.4470*** (0.0476)	Base

Relative Entropy SA	-0.3735*** (0.0961)	0.0221*** (0.0030)	-0.0085*** (0.0009)	1.0139*** (0.0490)	1.9265*** (0.1332)	0.8402 (0.0896)	1.1818 (0.1917)	Base
Roads	-0.2634*** (0.0333)	0.0168*** (0.0010)	0.0107*** (0.0003)	0.8163*** (0.0118)	0.6935*** (0.0160)	1.1159*** (0.0374)	0.5330*** (0.0266)	Base
Active	-0.1661*** (0.0210)	0.0135*** (0.0006)	-0.0006*** (0.0002)	1.0671*** (0.0101)	1.1097*** (0.0189)	0.9439*** (0.0194)	0.9213** (0.0331)	Base
Bus Stops	-0.0056 (0.0136)	-0.0072*** (0.0004)	-0.0012*** (0.0001)	1.0383*** (0.0068)	1.1077*** (0.0084)	0.9739 (0.0165)	1.0416* (0.0243)	Base
Rail Stops	-0.2722*** (0.0737)	-0.0105*** (0.0023)	0.0007 (0.0007)	1.1010** (0.0449)	0.5633*** (0.0536)	1.1030 (0.1216)	1.7519*** (0.2456)	Base
Bus Routes	0.2183*** (0.0025)	-0.0020*** (0.0000)	-0.0000 (0.0000)	0.9988 (0.0013)	1.0138*** (0.0016)	1.0134*** (0.0034)	1.0060 (0.0043)	Base
Rail Routes	-0.1009*** (0.0203)	-0.0014** (0.0006)	-0.0008*** (0.0002)	1.0062 (0.0098)	1.1062*** (0.0119)	1.0098 (0.0260)	1.2981*** (0.0441)	Base
House Prices	2.4059*** (0.0412)	-0.0437*** (0.0013)	-0.0023*** (0.0004)	0.9005*** (0.0160)	1.5682*** (0.0446)	0.7987*** (0.0338)	1.9694*** (0.1284)	Base
Travel Considerations								
Journey Minutes	NA	NA	NA	1.0228*** (0.0007)	0.9846*** (0.0017)	1.1158*** (0.0006)	1.1242*** (0.0014)	Base
Same Res-School ED	NA	NA	NA	5.7002*** (0.2204)	1.7796*** (0.0655)	0.1967*** (0.0047)	0.1370*** (0.0330)	Base
Same Res-School SA	NA	NA	NA	6.1546*** (0.0942)	2.0268*** (0.2785)	0.8313* (0.0861)	3.7890 (3.9269)	Base
Unobserved Effects								
M1[school SA code]	NA	NA	NA	2.7182 (Constrained)	2.0101*** (0.1606)	0.0487*** (0.0062)	43.849*** (8.0500)	Base

*** denotes 1% Significance ** denotes 5% Significance * denotes 10% Significance. Standard Errors are presented here in brackets.

7.4.4 Robustness Checks

Several robustness checks are conducted to ensure the validity of the results. Principal of those is the evaluation of the theoretical model presented in Figure 7.1 above. I propose two alternative modelling specifications using the same key variable groups (Socio-Demographics, Built/Social Environments, Travel Considerations, and School Small Area [Latent]). I do not consider omitting any individual group entirely because each hold significant empirical and theoretical justification for inclusion. Consequently, I primarily test whether model goodness of fit improves (according to AIC and SBIC scores) when relationships (i.e., arrows in the path diagram) are removed. In this regard, **Appendix 7 (A7)** demonstrates how the model proposed in Figure 7.1 produces the lowest AIC and SBIC scores, rendering it the best model to describe the relationships within the data. I also test the robustness of the results by collecting relative risk ratios from a spatially disaggregated Multinomial Logit Regression analysing the relationship between socio-demographics, the built and social characteristics of residential and school environments, travel considerations, and travel mode choices. These results, shown in **Appendix 7 (A7)**, are consistent with those provided above, enhancing the robustness of the analysis. The other variables are subject to correlation matrices which test for multicollinearity. These results are available in **Appendix 7 (A7)** and do not highlight any issues. The efficacy

of the use of specific independent variables is tested by omitting each from the modelling framework and comparing AIC and SBIC scores. Additionally, alternative variables to Deprivation (proportion of local populations reliant on social welfare), House Prices (gross median household incomes per ED) are incorporated into the model alongside additional variables like population density. In all cases, AIC and SBIC scores indicate that the variables employed in this analysis produce a model with superior fit.

7.5 Discussion and Implications

The first stage of the model analyses how socio-demographic considerations impact the travel mode choices of students. More complicated household structures and increases in socioeconomic status are associated with increased odds of car-use relative to all other modes. I interpret this to possibly be the result of increased trip-chaining within these types of households, but it could also relate to the fact that less complicated household structures, such as single-parent households, may have less travel-related resources, meaning students are obliged to travel independently, as suggested by Mitra & Buliung, (2015). Therefore, if parents in these households use cars more frequently, this may spill-over to children and manifest in greater trip-chaining and subsequently, greater car-use by students. This is corroborated by variables pertaining to the relative deprivation of residential environments and residential area property market values, as increases in deprivation are associated with reduced odds of car-use while increases in property market values are associated with increased odds of car-use.

Overall, land-use configurations in residential areas and school locations exert consistent effects on travel mode choices. In both cases, land-use developments characterised by mixed-use are associated with increased odds of active travel relative to car-use. This suggests that greater active travel can be encouraged by reducing local time-space geographies as this will reduce required travel distances, findings generally corroborated by the travel consideration variables, as well as evidenced in a wide body of literature (Vega and Reynolds-Feighan, 2008; OECD, 2018; O’Riordan *et al.*, 2022).

Infrastructure provision shares no meaningful relationship with trip-specific considerations except that active travel infrastructure provision is associated with shorter trip durations. This lack of consensus may suggest that these factors are dependent on case-by-case circumstances, something which can be remedied through data which precisely identifies household and school locations and specified routes. However, the model consistently shows that increases in mode-specific infrastructure (i.e., roads) is associated with increased odds of mode use (i.e.,

cars) in both residential and school locations, effects that are stronger in residential areas. In both cases, this relationship is strongest between roads and cars. Increased active and public transport infrastructure provision positively influence the odds of using *all* types of public and active transport. This suggests that if mode-specific infrastructure is inaccessible, in residential areas especially, students are significantly less likely to avail of these modes or complimentary modes, perhaps due to convenience, but also possibly due to safety concerns, results consistent with existing literature (Ermagun and Samimi, 2015). In this context, accessibility to public and active transport appears to be a key catalyst in shifting travel behaviours away from car-use during school-runs. This may be because increased accessibility to this infrastructure reduces required travel distances to the network, perhaps positively impacting perceptions of safety and convenience. Finally, I analyse how the underlying qualities of school environments influenced travel mode choices. There is significant variation associated with the odds of mode choices depending on the unobserved effects attributable to school-locations. I argue that because I have explicitly captured all built and social environment considerations which may plausibly influence mode choices, this variation may be best explained by travel route considerations, principally those relating to infrastructural safety and convenience.

While it is evident that individual socio-demographics will always influence travel behaviours to some extent, policymakers can use land-use and transport policies to catalyse shifts away from car-use. For example, increases in land-use mixing and developmental compactness can be achieved through the easing of zoning regulations and restricting one-off residential developments, thereby reducing pressures to expand horizontally. But it can also be achieved by prioritising investment in existing infrastructure prior to outward regional expansion, or through the coordination of area-based policies which restrict distances between residential areas and places of interest. Complimenting this, if infrastructure is accessible, the odds of using active and public transport significantly increase. Here, policies surrounding sustainable transport hierarchies, like those which reduce road space for cars in favour of public and active transport, hold significant potential because they can re-define the competitiveness of public and active transport, thereby altering the implicit costs associated with travel.

7.6 Conclusions

This chapter investigates the distinct influences socio-demographics, built and social environments, and travel considerations have in determining travel mode choices and the interrelationships therein. Thereafter, policymaking mechanisms which can facilitate shifts away from excessive car-use are evaluated by discussing these relationships when pertaining

to both residential and school environments. To do this, Generalised Structural Equation Modelling is employed to assess these interrelationships across the Republic of Ireland.

This chapter produces many major findings. Firstly, social environments exert a distinct influence on the travel behaviours of children, something attributable to parental behaviours and the resources available to households. For instance, students living in relatively deprived areas, students living in households characterised by simpler household structures (i.e., single-parent houses), and students of lower socioeconomic statuses are associated with increased odds of active travel relative to car-use. In other words, individuals/households with possibly limited or strained travel-related resources are significantly less likely to use cars and are more likely to live closer to essential destinations, like schools. Secondly, landscapes which reduce regional time-space geographies are associated with significantly increased odds of using active and public transport over cars, effects which are stronger in residential areas, something I interpret to be the result of increased modal competitiveness and convenience. Thirdly, increased mode-specific infrastructure provision (i.e., roads) is consistently associated with increased odds of mode (i.e., car) use. This relationship is strongest between roads and cars, whereby increased road network provision generally reduces the odds of using all alternative modes. But public and active travel are complimentary, explaining the finding that providing infrastructure for one (i.e., walking) generally positively influences the odds of using another (i.e., bus). This suggests that developments which make car-use more convenient may experience disproportionate decreases in public and active transport use.

These results suggest that there is significant scope for policymaking intervention in the realm of land-use and transport which can positively contribute to facilitating shifts away from car-use during school-runs. Although some of the mechanisms which influence school-run travel behaviours stem from individual- and household-specific considerations, others are principally associated with the accessibility of infrastructure and travel distances. In this context, land-use configurations are especially important because they define local time-space geographies, and therefore significantly influence the viability of regular active and public transport use. Considering this, landscapes which reduce required travel distances and facilitate greater levels of land-use mixing (i.e., characteristics which facilitate living, working, and going to school in the same locality) can catalyse shifts away from car-use because these landscapes increase local connectivity while also increasing the efficiency, reliability, and convenience of regular public and active transport use.

Future research could improve upon these efforts in numerous ways. Travel behaviour research generally operates in the framework of the four-stage model (and more recently, dynamic models). In this context, this chapter focused on one of these stages, mode choice, but future research could build upon this work by investigating these problems in the context of the other stages (trip-generation, trip-frequency, and trip-distribution). Particularly fruitful avenues in this regard may investigate why people travel to-and-from different Origin-Destination pairs and how that might relate to socio-demographic characteristics and/or land-use configurations. This chapter is principally concerned with the determinants of travel mode choices for commuting, and is therefore too restrictive for an analysis of, say, trip-generation, which is best suited to multi-purpose travel in a time-series setting (McNally, 2008; McNally and Rindt, 2008). Furthermore, this research could not access data on the travel mode alternatives available to individuals within the dataset. Otherwise, alternative modelling structures such as the Nested Logit could be employed (within or independently of a Structural Equation framework). This is important because some individuals/locations will not be able to access the entire choice set available (i.e., because rail access nodes might be too costly to access or too far away). Considering this, it is important to elevate our understanding of how individuals adjust their behaviours to changes in the available choice sets.

Furthermore, data which allows for the nesting of individuals within households and within residential/destination environments will be highly effective in distinguishing the explicit relationship between parental behaviours and child behaviours. Similarly, the ability to precisely link origins to destinations via actual travelled routes will provide more refined insights into the influence of route considerations on travel mode choices, and behaviours more generally. This will also further address a limitation here in that researchers could more easily capture the generalised costs of travel (and the cost of alternative modes available to individuals). Particularly fruitful avenues to pursue may involve investigating the effect of initiatives which reduce the explicit costs of travel (i.e., changes in Irish Bus Pass fares) in shifting behaviours. Finally, this model implies that there is a transport hierarchy on school-runs whereby children will either walk or take a car, and seldom use alternatives. In this context, future research should explore the influence of novel micro-mobility technologies (i.e., e-bikes and e-scooters) on these decisions and whether they can further contribute to facilitating shifts away from car-use.

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Chapter 8: Retail Sprawl and CO2 Emissions: Retail Centres in Irish Cities

The concept of sustainable retail development implies that retail centres should serve their communities economically and socially, while not degrading local environments. However, existing literature finds that retail centres often create negative externalities, something which impacts the ability of regional cores and peripheries to develop and grow sustainably. International evidence shows that transport emissions have been exacerbated by existing planning architecture, notably retail parks. This type of retail sprawl has resulted in commercial centres shifting from high streets to suburban areas, worsening congestion levels and environmental degradation. This chapter examines how location-effects influence travel-related emissions and travel mode choice when shopping in Ireland's five major administrative city regions. I adapt commuting data from the 2016 Irish Census and use retail and residential location data to estimate hypothetical travel-related emissions within a multi-modal transportation network incorporating cars, buses, cycling, and walking. This analysis is performed at the Small Area level for Ireland's five major cities and their surrounding commuter belts. The results show that retail centres generating the most travel-related emissions tend to be found outside city cores, in the fringe areas of built-up city environments, and that these retail centres are generally only accessible to car users. This supports theories suggesting that accessibility-centred development is the best option to combat the ill effects of sprawl, and that car dependency worsens the environmental degradation associated with regional development.

8.1 Introduction

Urban sprawl is a by-product of haphazard, rapidly expanding urban development (Nechyba and Walsh, 2004). Due to the heterogenous nature of urban areas, and the complicated relationships between development indicators and their environment, refining this definition further can be problematic (Ewing, 1997; Ewing *et al.*, 2014). However, sprawled developments are commonly characterised by low residential densities, low multi-modal accessibility, and segregated land (OECD, 2018). But urban sprawl can also refer to areas which experience spatial expansion rates greater than that of population growth, something which generally decreases settlement densities over time and increases travel-related emission outputs by increasing required travel distances (Song and Sohn, 2007). With evidence suggesting that sprawl in all forms contributes to environmental degradation (European Environmental Agency [EEA], 2006), this research focuses on a particular dimension of urban sprawl; namely *retail sprawl*, and its relationship with travel-related emission outputs. Retail

sprawl refers to the urban exodus of firms in favour of cheaper and more abundant land in peripheral areas (Wassmer, 2002). It specifically relates to the consequences of businesses moving to suburbs (Frenkel and Ashkenazi, 2008; Vandenbulcke *et al.*, 2009) and was initially characterised by strip-mall development, whereby commercial developments were usually situated parallel to roads, but it has since outgrown this characterisation due to the scale of modern retail parks (Department of Housing Planning Community and Local Government, 2012).

Theoretically, this research extends traditional central place frameworks which usually analyse the economic consequences of locating away from central locations to an emissions-minimising context (Erdin and Akbas, 2019). I test these locations' environmental merits by analysing whether centrally located retail environments offer optimal locations to minimise carbon impacts (Dennis *et al.*, 2002). Complimenting this, is the incorporation of gravity framework theories (Luo and Wang, 2003; Rasouli and Timmermans, 2013), whereby I use retail centres' physical footprints to proxy the retail environment's perceived attractiveness as a shopping destination. Methodologically, I broaden the investigative scope of retail location modelling by gauging the environmental impacts associated with travelling to retail centres while also analysing how this relates to retail centre locations. Specifically, I incorporate variables capturing travel mode choices, residential locations, retail centre locations, retail centre sizes, travel network data, and mode-specific emission estimates to examine the environmental consequences associated with sprawling retail environments and induced travel behaviours.

International literature has addressed many sprawl-related problems. Specific investigations surrounding how land-use (Oueslati *et al.*, 2015), transport networks (Lee, 2020), government incentives (Wassmer, 2002; Carruthers and Úlfarsson, 2008), retail location (Kristoffersson *et al.*, 2018), and regional property markets (Öner, 2017) affect urban development have been conducted worldwide. This research questions whether centrally located retail centres can reduce the environmental degradation associated with travelling for leisure. Specifically, the objective is to quantify the hypothetical emission outputs generated when travelling to peripheral retail centres relative to their centrally located counterparts. This analysis fits into an established body of literature addressing the environmental consequences associated with retail location (Suarez *et al.*, 2004; Scott and He, 2012; Suárez-Vega *et al.*, 2012). It adopts a central place and gravitational theoretical lens, primarily because of the pivotal role policymaking plays within these frameworks, but also because of their proven robustness

(Dolega *et al.*, 2021; Schlöpfer *et al.*, 2021). Geographic Information Systems (GIS) facilitates this analysis by showing how hypothetical emissions, transportation networks, residential locations, retail centre size, and retail locations are related and the hypothetical emission patterns emerging therein.

There have been numerous calls within existing literature to develop more holistic models of retail development. Määttä-Juntunen *et al.*, (2011) and Ahmad and Hiyasat, (2017) explicitly call for research investigating the alleviation of the ‘...consequences of unplanned retail service distribution in the city on its investors and users’ (Ahmad and Hiyasat, 2017, p. 36), and emphasise the need to ‘...pay attention to the location of workplaces and commuting, which may also strongly affect the traffic flow and shopping preference’ (Määttä-Juntunen *et al.*, 2011, p. 353). This chapter answers these calls, and contributes to global retail policymaking, by modelling retail development in terms of minimising hypothetical emissions from a multi-modal perspective, including cars, buses, cycling, and walking. This multi-modal approach fills numerous research gaps, as many studies tend to focus exclusively on the car (Määttä-Juntunen *et al.*, 2011; Kristoffersson *et al.*, 2018), occasionally investigating walking (Roig-Tierno *et al.*, 2013; Eldeeb *et al.*, 2021), cycling (Giorgi *et al.*, 2017), and transit (Hay, 2005; Cheng *et al.*, 2007; Rao and Pafka, 2021), with no study cross-comparing these modes simultaneously using the same geographical scope as here.

Section 8.2 provides a review of the literature surrounding urban and retail sprawl. Section 8.3 describes the data and methodology used throughout this analysis. Section 8.4 illustrates the results and discusses their implications. Section 8.5 concludes the analysis while also highlighting this study’s limitations and future research avenues.

8.2 Background To The Literature

8.2.1 Urban Sprawl

The rapid industrialisation experienced across the developed world post-WW2 forever changed commuting patterns as cars became more affordable, incomes steadily rose, and the desire for suburbanisation increased (Paterson, 2000; Pooley and Turnbull, 2005). Residential decentralisation created new markets for businesses to exploit (Sultana and Weber, 2014), resulting in a commercial expansion from cities, eventually leading to widespread retail sprawl. Currently, retail sprawl is most prominent in urban peripheries, where public and active transport accessibility is limited, thereby encouraging greater car-use when travelling to these areas (Knowles *et al.*, 2020; Eldeeb *et al.*, 2021). Considering this, retail sprawl can exacerbate

the environmental degradation associated with car-use by increasing required travel distances, something which may increase congestion and travel-related emission outputs (Focas, 2016). Furthermore, because suburbs have been found to grow in popularity with their size (Glaeser *et al.*, 2001), these effects have worsened over time as residential and retail sprawl continue to occur, thereby linking regional development configurations and environmental degradation (Frenkel and Ashkenazi, 2008; OECD, 2018).

The economic theory of sprawl stems from central place theories which state that changes in population, income, transport technology, and land values are fundamental determinants of urban structure (Evans, 1983). These models argue that population density decreases incrementally as distances from Central Business Districts (CBD) increase, whereby expansion patterns are uniform and revolve around a singular regional hub (Evans, 1983; Oueslati *et al.*, 2015). I strengthen this theoretical approach by incorporating gravity theories which argue that accounting for a location's perceived attractiveness can determine expansion patterns, infrastructure distribution, and subsequent developmental forms (Kristoffersson *et al.*, 2018; Erdin and Akbas, 2019; Schlöpfer *et al.*, 2021). In a retail context, evidence suggests that these environments get more attractive with size, irrespective of distances from urban cores (Glaeser *et al.*, 2001; Kristoffersson *et al.*, 2018). But also important here is the relative ordering of goods/services sold at these sites (i.e., luxury or normal goods). In this context, luxury good/service providers are deemed to have a larger catchment area than providers of normal goods, but facilitate reduced trip frequencies (Dolega, Pavlis and Singleton, 2016; Dolega *et al.*, 2021). Combining these concepts allows researchers to analyse circumstances when a retail environment's attractiveness may exceed that of CBDs for travellers, and thereby catalyse shifts in shopping destinations (Nechyba and Walsh, 2004).

Adapting these theories to the suburban and car boom of the mid-twentieth century shows how urban sprawl may be a by-product of traditionally monocentric regions expanding to the point where peripheral areas become more attractive places for economic/social activity than CBDs, but still falling short of polycentricity. Considering how in a sprawling landscape these peripheries are typically inaccessible by public and active transport, this necessitates increased car-use and subsequently exacerbates the travel-related emissions attributable to regional development (Ewing *et al.*, 2014; Focas, 2016; Holz-Rau and Scheiner, 2019). These developmental trends can be explained by haste attempts to meet the demand of rapidly emerging markets chasing the 'American Dream', as the provision of public and active transport infrastructure was neglected in growing suburbs (Ewing *et al.*, 2014; Knowles,

Ferbrache and Nikitas, 2020). This underscores the role policymaking plays in influencing the environmental outcomes of regional development (Razin, 1998; Pendall, 1999).

Specifically, increased car-use in the twentieth century was met with increased road construction as road space demand began to outpace supply (Pooley and Turnbull, 2005). The resulting congestion problems which emerged in population centres was initially believed to be the fault of transit, ultimately strengthening car-friendly policymaking and weakening alternative transport provision (Pooley and Turnbull, 2005). This happened despite the fact that this increased congestion was attributable to increased instances of inward commuting from hinterlands via car which subsequently increased traffic (Pooley and Turnbull, 2005). Over time, this has intertwined urban sprawl and car-use as public and active transport investment continues to be inadequate across many countries, in Ireland especially, thereby illustrating how developmental forms have negatively contributed to sustainability efforts in regional development (Vandenbulcke *et al.*, 2009).

8.2.2 Sprawl and Negative Externalities

Suburbanisation, congestion alleviation, and compact developments have seldom been able to realise their theoretical potential because globally inefficient policymaking enables negative externalities, like travel-related emissions, to emerge unaddressed and subsequently underpriced (Paterson, 2000). Specifically, congestion (and the subsequent environmental degradation) in cities increases because of the attraction of central places and from an inability to access these areas via public and active transport (Holz-Rau and Scheiner, 2019). In this context, urban structures are intimately linked to commuting costs to-and-from CBDs. If travel is underpriced (by not internalising externalities), then cities can spread beyond optimal levels (Anas, Arnott and Small, 1998). While this creates problems in travel by increasing time-space geographies, it can also distort land values whereby land-uses related to transport are underpriced, subsequently prompting more space to become dedicated to travel-related uses (Anas, Arnott and Small, 1998). City dwellers tend to have excess accessibility opportunities due to the high connectivity of these areas while suburbanites tend to lack similar opportunities due to limited public and active transport infrastructure, exposing imbalances in the mode choice set available to different populations (Holz-Rau and Scheiner, 2019). Given that technology and car-use have been found to evolve in unison, it is unsurprising that technology has been unable to balance the externalities associated with excessive travel behaviours. In other words, green technologies, particularly when pertaining to private cars, do not necessarily create net positives (Paterson, 2000; Määttä-Juntunen *et al.*, 2011).

The cost of public services is negatively related to population/settlement densities and positively related to the spatial extent of developed land, making sprawl a relatively more expensive form of development than more compact urban forms (Carruthers and Úlfarsson, 2008; Ewing *et al.*, 2014; OECD, 2018). Sprawl exacerbates travel-related emissions by catalysing increased car-use while also increasing the per-capita costs of infrastructure and service provision (Nechyba and Walsh, 2004). Low settlement densities also worsen the levels of habitat destruction attributable to regional development by increasing the spatial expanse of regions (Nechyba and Walsh, 2004). These negative externalities outweigh the positives urban sprawl produces, as these tend to be individualistically centred, often revolving around private transport, embodying the environmental unsustainability characterising twenty-first century development (OECD, 2018). Therefore, if the primary cost of sprawl can be surmised by its spatial demands, measures countering these demands should be used to alleviate these effects (Song and Sohn, 2007).

Increased transport accessibility and reduced local time-space geographies can alleviate some sprawl-related problems. This is because improvements in multi-modal transport accessibility and reductions in time-space geographies (i.e., required travel distances) necessitate greater levels of land-use mixing, improvements in the efficiency of land and infrastructure usage, and greater multi-modal infrastructure investment (Ewing, 1997; Vandenbulcke *et al.*, 2009; Kono *et al.*, 2012; Lee, 2020; Yang *et al.*, 2020). Relatedly, evidence suggests that highway driving is more environmentally damaging than city driving (OECD, 2018; Holz-Rau and Scheiner, 2019) and that there may be a positive relationship between regional accessibility, subjective wellbeing, and the sustainability and efficiency of land and infrastructure use (Song and Sohn, 2007; Öner, 2017; Zhang *et al.*, 2020). Therefore, by addressing issues related to transport accessibility and local connectivity, policymakers can abate the environmental degradation attributable to regional development and subsequent travel behaviours while also positively contributing to regional economic and social objectives.

8.2.3 Retail Sprawl and CO₂ Emissions

Retail sprawl encapsulates regional development as a spatial economic issue (Nechyba and Walsh, 2004). Given the fixed costs associated with retail park establishments, it is surprising that retail sprawl has advanced more rapidly than the understanding of it. Environmentally, these centres clearly produce externalities, something potentially exacerbated as distances from urban cores increase if unsustainable travel behaviours (i.e., excessive car-use) are encouraged (Erdin and Akbas, 2019; Holz-Rau and Scheiner, 2019), possibly highlighting some of the

hidden costs associated with commuter belt living (Song and Sohn, 2007). Internalising these externalities has been found to alleviate retail park establishment by disincentivizing their location far from population centres and incentivizing developers to consider locations with multi-modal transport infrastructure, effects which ultimately serve to reduce the environmental damage attributable to regional expansion (Feitelson and Rotem, 2004; Carruthers and Úlfarsson, 2008; OECD, 2018).

Historically, retail location analyses have employed multiple theoretical lens' (Clarkson *et al.*, 1996; Suarez *et al.*, 2004; Suárez-Vega *et al.*, 2012). While individually, many of these theories have been contested as outdated (Ahmad and Hiyasat, 2017; Dolega *et al.*, 2021), when combined, central place and gravitational models constitute the most robust conceptual framework for analysing retail location from a sustainability perspective. This is primarily because they capture some of the central tenets of travel behaviour, like distance and the perceived attractiveness of destinations (Clarkson *et al.*, 1996; Dennis *et al.*, 2002; Dolega *et al.*, 2021). This research extend central place modelling by incorporating theoretical principles embedded within gravity frameworks by assuming that perceived attraction and the time spent travelling determine destination choices. I calibrate this by weighting the size of retail environments over the time it takes to travel there from each possible origin within the travel threshold, thereby identifying the retail centre that people residing in each Small Area will hypothetically visit.

Arguably the most important advance in studying sprawl has come from adopting mapping software (GIS) to aid in understanding the phenomenon whereby retail sprawl is typically conceptualised as a problem of accessibility and incentives (Cheng *et al.*, 2007; Määttä-Juntunen *et al.*, 2011; Suárez-Vega *et al.*, 2012; Roig-Tierno *et al.*, 2013; Ahmad and Hiyasat, 2017). Global evidence sharply points to increasing retail sprawl and car dependency in the developed world, something which increases travel-related emissions and degrades regional environments, underscoring the need for this type of research. Most surveyed literature recognises private cars to be the preferred transport mode for shoppers, rendering many studies effectively unimodal in scope (Määttä-Juntunen *et al.*, 2011; Mohamad *et al.*, 2015; Ahmad and Hiyasat, 2017). However, evidence suggests that transit or active modes can serve as primary modes when shopping depending on built environment considerations (Susilo *et al.*, 2013; National Transport Authority, 2014), justifying a multi-modal approach when investigating the environmental impact attributable to travelling for leisure. Mapping optimal routes has been employed in studies concerned with city accessibility (Vandenbulcke *et al.*,

2009), consumer behaviour (Kristoffersson *et al.*, 2018), commute lengths (Giorgi *et al.*, 2017), and travel-related emissions (Määttä-Juntunen *et al.*, 2011). This research expounds these models by incorporating a multi-modal transport system and a proxy for retail attractiveness (retail centre size) into the emissions minimising retail location literature.

8.3 Data and Methods

8.3.1 Study Area

This analysis focuses on Ireland's five administrative city regions: Dublin, Cork, Limerick, Galway, and Waterford. Retail centres are selected according to administrative county boundaries, meaning any retail centre which lies outside these boundaries are excluded from this analysis. In a global context, this approach aligns with that adopted in existing literature (Määttä-Juntunen *et al.*, 2011; Dolega, Pavlis and Singleton, 2016; Ahmad and Hiyasat, 2017; Dolega *et al.*, 2021), but it is worth noting how in an Irish context, one major retail centre (The Kildare Village Outlet Centre) lay outside these boundaries. While this may alter trip distributions at national level, this research contends that city-level shopping distributions will remain largely unaffected by this omitted destination, with the biggest potential effects stemming from the Dublin city-region. As a result, although this omission may constitute a research limitation, this approach does facilitate a comprehensive contextualisation of each administrative city-region's retail environment using a replicable selection process. Retail centre catchment areas are based on travel times along a modal-specific network (i.e., roads or active transport networks). This regulates the population cohorts available to travel to each retail centre while also accounting for the fact that although the retail landscape itself is a concern for administrative areas, the populations which utilise these environments are independent of these boundaries.

Existing literature cites anywhere between 10km and 100km as an appropriate travel boundary for this type of study when travelling by car/transit (Hay, 2005; Cheng *et al.*, 2007; Määttä-Juntunen *et al.*, 2011). The National Travel Survey (2016) refines this by demonstrating one-hour trips to capture 73% of all one-way shopping related journeys, with 45.7% of these being completed in thirty-minutes, further suggesting that trips typically diminish in quantity and frequency as travel time increases, indicating one-hour is a suitable threshold for denoting the maximum travel time accountable for 'regular' shopping- and leisure-related journeys (Central Statistics Office [CSO], 2016). These figures are independent of good/service hierarchies, indicative that these travel thresholds are consistent regardless of whether individuals are

travelling to purchase lower- or higher-order goods⁵¹. Evidence within active travel literature is remarkably consistent in its conclusion that, when travelling for shopping, 10-minutes is an appropriate one-way travel threshold for walkers/cyclists and that strong distance decay effects emerge thereafter (Millward, Spinney and Scott, 2013; Spinney and Millward, 2013; Gunn *et al.*, 2017).

8.3.2 Retail Centres and City Cores

The definition of retail centres employed in this chapter builds on the work of Pitt and Musa, (2009) and Dolega *et al.*, (2021), who attempt to distinguish between increasingly convergent supermarket and retail centre characteristics. They illustrate how there is no one-size-catch-all definition, and that a robust approach to classification is to ensure replicability and transparency in the criteria for retail centre selection. Considering this, I define retail centres as any planned developments which consist of either a single, or agglomeration of, building(s) with no size constraints (Dennis, Marsland and Cockett, 2002; Pitt and Musa, 2009; Rice, 2020). Furthermore, these establishments must be surrounded by a car park, the establishment as a whole must serve multiple consumer purposes, and there should be some accommodation of social activities through the provision of leisure amenities (i.e., open seating areas) (Guy, 1998; Dennis, Marsland and Cockett, 2002; Dolega *et al.*, 2021). Finally, if an overarching centre shares a title with its anchor store, and/or this anchor store constitutes >50% of the centre's total square footage, these centres are generally excluded from the analysis based on the wide body of evidence which shows that retail centres of this description are primarily dedicated to local supermarkets (Pitt and Musa, 2009). These characteristics combine to ensure that establishments which *exclusively* provide lower-order goods and services (i.e., everyday groceries) are excluded from the analysis on the basis that retail centres, in a broad sense, should provide a mix of lower-, intermediary-, and higher-order goods⁵² (Dolega *et al.*, 2021).

With this framework in place, OpenStreetMap's (OSM) QuickOSM plugin is used to identify commercial/business units within these regions. QuickOSM is a plugin dedicated to

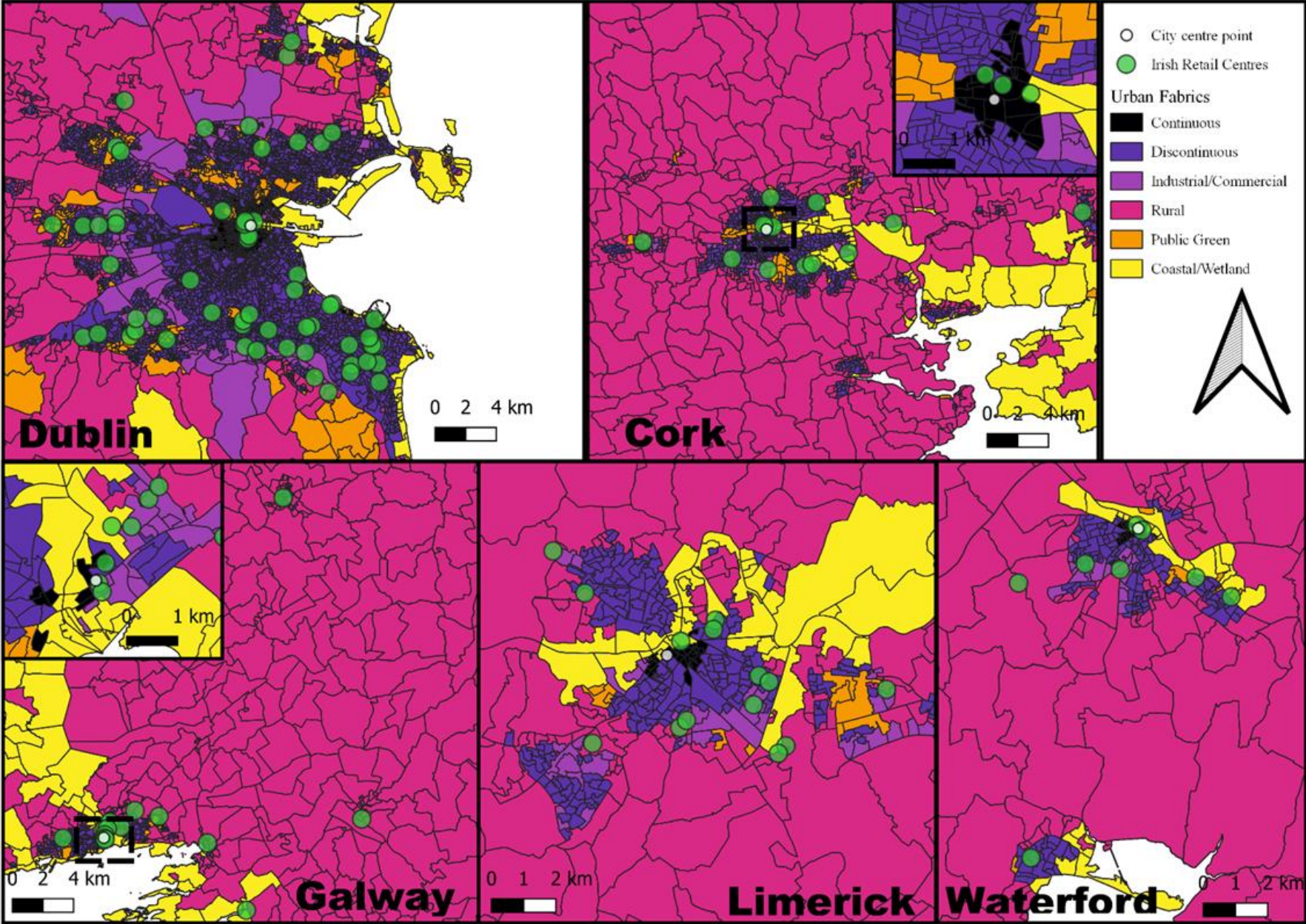
⁵¹ Future research may seek to further develop this by probing how these trip distance/duration distributions differ depending on the context of the good/service hierarchy offered at different destinations. However, there is currently no data in the Irish context which allows further extraction of this at the traveller-level or retail centre level. In other words, no data exists tracking individuals travel behaviours when pertaining to different types of retail environments, and no data exists which explicitly categorises retail centres according to the hierarchy of goods/services provided.

⁵² Future research could develop this further by explicitly developing a tenant-mix index. Indices of this nature provide opportunities to develop more nuanced classifications of retail environments which go beyond the spatial extent of the physical environment. However, detailed tenant data is unavailable for many of the retail centres analysed here (particularly the smaller centres), rendering this infeasible.

classifying OpenStreetMap landscape data and subsequently provides a replicable source for classifying morphological entities across space. In this context, if OpenStreetMap's algorithm (as employed in QuickOSM) fails to classify land-use polygons as commercial or business entities, they are not considered, ensuring consistency and replicability in the selection process of retail centres in this analysis. One concern with data sources like OpenStreetMap is that the underlying data is volunteered, implying that it may not be as accurate and reliable as alternative sources. Two things are worth considering in this context. Firstly, a global body of evidence has emerged in the last decade indicating that this data is highly accurate and that, in urban areas especially, this data is equivalent to traditional datasets (i.e., centrally administered) data in its quality and accuracy in describing landscape characteristics (Haklay and Weber, 2008; Cipeluch *et al.*, 2010; Haklay, 2010; Mooney, Corcoran and Winstanley, 2010; Fan *et al.*, 2014; Arsanjani *et al.*, 2015; Mobasheri, Zipf and Francis, 2018; Biljecki, Shin and Lee, 2023). Secondly, to mitigate any outstanding concerns of this nature, the retail centres selected by the OpenStreetMap algorithm are manually checked through Google Maps satellite imagery, and through a survey of any official documentation which exists about said centre (something usually corresponding to an official website). All retail centres retained in this research satisfy *all* criteria for the above definition of retail centres.

This research refers to a retail centre's location in the context of a core-suburban-periphery continuum. Here, city cores refer to historical city centres prior to the emergence of car technologies, something which existing literature equates to a (singular) Central Business District (CBD) (Knowles *et al.*, 2020). This historical centre is approximated as the main shopping street within a city. However, I supplement this delineation by plotting areas within cities classified by continuous urban fabrics (classifications stemming from the CORINE Land Cover dataset (Copernicus Land Monitoring Service, 2021)), and selecting a precise CBD point according to the centroid of this area – a point which usually lay within close proximity to the main shopping street of a city. Using this same data, departures from cores (and the arrival of suburban areas) is gauged according to the emergence of discontinuous urban fabrics, while the arrival or peripheral areas is gauged according to the relative dissipation of urban fabrics and the emergence of rural landscapes Figure 8.1 below maps existing retail centres according to their regional urban fabric, with cores represented by the darkest coloured cluster in each region.

Figure 8.1: Retail Centres in Irish Cities and Their Surrounding Built Environment



8.3.3 Data

This research employs commuting data from the 2016 Irish Census to proxy the travel behaviours of shoppers when travelling to major retail centres. This provides travel mode choice data across Small Areas in the Republic of Ireland. Complementing this, is the transport network data stemming from OpenStreetMap. OpenStreetMap transport network data is imported via Transport Infrastructure Ireland (TII), so the network data itself is identical to that from traditional sources. Furthermore, transport network data stemming from OpenStreetMap is more up to date than that stemming from TII, as TII's most up-to-date shapefile captures road networks up to 2013, while the OpenStreetMap road network employed in this study captures Irish road networks up to 2021, hence its use here.

Using this data within the Quantum Geographical Information Systems (QGIS) Q-Neat3 Network Analysis plugin, I construct an origin-destination matrix. Origin-Destination matrices describe the movement of individuals from a trip origin to a trip destination whilst travelling along a pre-defined network. In this case, origins correspond to residential locations (which are proxied here as the centroid of all Small Areas within the catchment zone of retail centres) while destinations correspond to retail locations (points describing the precise location of retail centres). The overarching matrix calculates the travel times associated with travelling from *each* origin to *every* destination, but each traveller is assumed to use the minimum-cost route (i.e., the route with the shortest (weighted) travel time), meaning only the O-D pair with the minimum cost route is retained⁵³. While residential locations (i.e., Small Area centroids) are used to proxy for residential locations in this research generally, when buses are the mode under study, bus stops proxy as trip origins to mitigate the risk of overestimating network accessibility.

Small Areas (SA), the smallest spatial units within the Irish Census, are the spatial unit of analysis used in this study. The centroids of each Small Area are used as departure points (origins) for all trips (except for the bus analysis), a commonality in existing literature (Määttä-Juntunen *et al.*, 2011). The network layer used is the national road network with speed limits manually inputted as per Road Safety Authority standards and road types (Road Safety

⁵³ In this case, minimum-cost route refers to both the shortest travel time as well as the shortest travel time weighted according to the size of the specific retail centre. More information on this weight can be found in Section 8.3.4.

Authority [RSA], 2021). This network consists of every publicly accessible road⁵⁴ and is filtered to incorporate bus routes when analysing bus-use, while a new combination of footpaths, cycle lanes, and any walkable surfaces, make up the network for walkers and cyclists. The overarching scenario is that when travelling by motorised transport, people will go to their largest, nearest retail centre, but when travelling by active modes, they will go to their nearest centre, scenarios implicit in existing evidence (Song and Sohn, 2007; Wilson *et al.*, 2013). This weight explicitly divides the size of the retail centre by the travel time required to reach said retail centre by car/bus along the road/bus network. When analysing active travel, travel time is the only consideration used to determine the retail centre people will travel to.

8.3.4 Model Specifications

This research adopts three assumptions to balance the constraints present within the datasets employed in the model. Firstly, it assumes that the travel mode used when commuting is also the mode used when shopping. This stems from global mode-choice literature which highlights substantial amounts of study populations to be unimodal in nature (Susilo *et al.*, 2013; Ton *et al.*, 2020). That is, people will generally exhibit habitual behaviour whereby they travel for work and leisure using the same mode (Heinen and Chatterjee, 2015; Ton *et al.*, 2019; Jeong, Lee and Gim, 2022). While specific statistics on retail centre visits by mode at national level are unavailable, the National Travel Survey (2016) documents mode choice by broad journey purpose and by journey duration separately for unweighted samples (Central Statistics Office [CSO], 2016). Table 8.1 below details these statistics and shows that across the modes investigated here, the relative share used for commuting and shopping varies by <10.1% throughout, showing reasonable consistency and robustness in this assumption. Secondly, I assume people's shopping trips start and end at the home, a similar approach to that of Gim, (2018). Finally, I assume that any catchment pulls beyond the chosen travel threshold for any mode will have a negligible effect in attracting regular customers, something supported by existing evidence (Mohamad *et al.*, 2015; Central Statistics Office [CSO], 2016b).

⁵⁴ The specific classifications employed include Motorways, Primary Roads, Secondary Roads, Tertiary Roads, and Unclassified Roads. The only network entities excluded are those which capture alleys, trails, and similar routes.

Table 8.1: Transport Mode Share by Journey Purpose and Duration

Journey Purpose	Private Car	Public Transport	Walk/Bike
Commute (to Work)	28.6%	28%	15.5%
Shopping	22.5%	19.1%	25.6%
Journey Duration			
15 minutes or less	77.4%	1.6%	17.8%
16-30 minutes	71.3%	7.5%	16.7%
31-45 minutes	70.8%	13.8%	10.9%
46-60 minutes	67.2%	16.4%	12.9%

This study is broken into four separate analyses examining hypothetical patterns of car-use, bus-use, cycling, and walking to retail centres. For motorised transport, catchment zones are capped at 60-minute one-way trips. To prevent overestimating accessibility, only populations living within a 10-minute walk from bus stops are used when travelling by bus (Millward *et al.*, 2013). Similarly, the walking and cycling travel time to any existing retail centre is capped at 10-minutes per one-way trip, in line with active travel literature (Millward, Spinney and Scott, 2013; Roig-Tierno *et al.*, 2013; Spinney and Millward, 2013; Gunn *et al.*, 2017; Ton *et al.*, 2019). The insights provided here prove robust with travel-time changes to 15- and 20-minute active travel trip lengths. The results of which are available in **Appendix 8**.

Travel-related emission figures are based on indicators produced by Walsh *et al.*, (2008)⁵⁵ (and replicated in Crowley *et al.*, (2021)), who calculate emission factors for multiple modes based on kilograms of CO₂ released per kilometre travelled. For this study, I convert these factors to kilograms of CO₂ released per minute travelled, a figure generated using speed limit data. From there, calculating the travel-related emissions attributable to these journeys is a multi-step process. First, mode-specific travel-related emission estimates are created by multiplying the kgCO₂ released per minute factor by the travel time associated with each O-D pair. Second, this value is multiplied by the proportion of the population residing in each Origin (Small Area) who commute via each mode under study – thereby capturing the different distribution of mode-use across every Small Area. Table 8.2 illustrates this process further by documenting mode-specific speed and kgCO₂ emission estimates.

⁵⁵ Alternative emission variables can vary considerably. The consequence of inaccurate emissions variables in-and-of-itself is non-consequential in this analysis due to the variables only changing the absolute values of the hypothetical estimates, not their relative value.

Table 8.2: Travel Mode Information And Emission Estimates As Per Walsh *et al.*, (2008)

Mode	Average Speed (km/h)	Travel Time per-km	Kg CO ₂ per-km	Kg CO ₂ per-minute	Kg CO ₂ per-minute, per-occupant
Private Car (Max Occupancy [4])	66	0.9167mins	0.17	0.155839	0.03896
City bus [50 / 90]	20	3.0mins	1.26	0.42/ 0.42003	0.0084 / 0.004667
Regional bus [57]	70	0.8571mins	0.84	0.719964	0.012631
Cycling [1]⁵⁶	16	3.75mins	0.005	0.001333	0.001333
Walking [1]⁴	6	10mins	0.005	0.0005	0.0005

This explicitly links every possible trip Origin with a single destination (retail centre), and subsequently quantifies the travel-related emissions attributable to travelling from each Origin to the retail centre with the shortest (weighted) travel time. So, while the primary goal of this research is to quantify hypothetical emission outputs, I can also gauge the hypothetical accessibility of each retail centre for each mode as greater emission outputs is indicative of a greater number of trips. Initially, the destination of these hypothetical trips is based on travel time alone. Thereafter, this destination is chosen by weighting retail centre size with travel time (i.e., dividing retail centre size by travel time), proxying retail attractiveness. The size variable used in this analysis is collected by manually measuring the relevant building areas in Google Maps ($size_m$). This method is chosen because not every retail centre under study has official and publicly available data on building footprints. However, when official data does exist, it is shown to be consistent with the estimates produced by measuring building footprints on Google Maps.

When a weight proxying attractiveness is not included, the implicit assumption is that people only consider travel time when travelling for shopping. Arguably, when $size_m$ is included, the study's theoretical underpinning is strengthened because choosing shopping destination is more nuanced than travel time alone, especially when travelling by car and when travelling to retail environments which provide a blend of lower- and higher-order goods/services (Öner, 2017). Retail centre attractiveness, at its foundation, tends to be a function of service diversity,

⁵⁶ While walking and cycling do produce positive emission estimates, and I acknowledge the literature dedicated to quantifying such measures, these values are relatively negligible in absolute size due to their source stemming from dietary and metabolic activity. Given this analysis' focus on transport policy, I provide a greater contribution by focusing on using these modes to measure travel behaviour in-and-around retail centres.

site investment, and consumer perspectives, variables generally correlated with size (Mohamad *et al.*, 2015; Öner, 2017; Kristoffersson *et al.*, 2018), meaning in this analysis, a region's largest retail centre is usually its most attractive, subject to travel-times from each trip origin.

Analysing the use of active modes (walking and cycling) when shopping focuses on incorporating active, low-carbon transport modes into a typically motorised modelling framework. Specifically, I pivot from estimating travel-related emissions in this context to quantifying mode use, complementing the previous analyses by highlighting the infrastructural characteristics surrounding retail centres. This analysis excludes retail centre size as a determining variable for active modes, concluding that travel time alone provided adequate estimates for the destination of active shoppers given the diminishing effect each additional minute has on the likelihood of regularly travelling actively (Gunn *et al.*, 2017; Rao and Pafka, 2021), an effect whose strength increases once travel-times go beyond 10 and 15-minute one-way thresholds (Spinney and Millward, 2013; Gunn *et al.*, 2017).

8.4 Results and Discussion

In the subsequent series of Figures⁵⁷, retail centres are presented as circular points within the context of their regional urban fabric. The size of each circular point increases/decreases in size in unison with travel-related emission outputs as estimated by the model (or mode-use in the case of active travel). The Figures presented in this section are comparable because they present travel-related emission estimates using proportional symbol mapping. This allows comparisons between maps, and objects within maps, because the size of symbols is directly tied to a particular quantitative variable – in this case travel-related emissions or mode-use. Similarly, in these Figures, consistent legend scaling is used, rendering the distribution of symbol sizes directly comparable across Figures. **Appendix 8 (A8)** replicates this analysis utilising 15- and 20-minute travel thresholds when analysing walking and cycling.

8.4.1 Shopping By Car

Initially, this research assumes that people only consider travel time when shopping by car. These results generally proved inconclusive, as some regions showed peripheral retail centres to generate the most hypothetical travel-related emissions, while some showed central retail centres to generate the most hypothetical emissions, and some showed no distinguishable

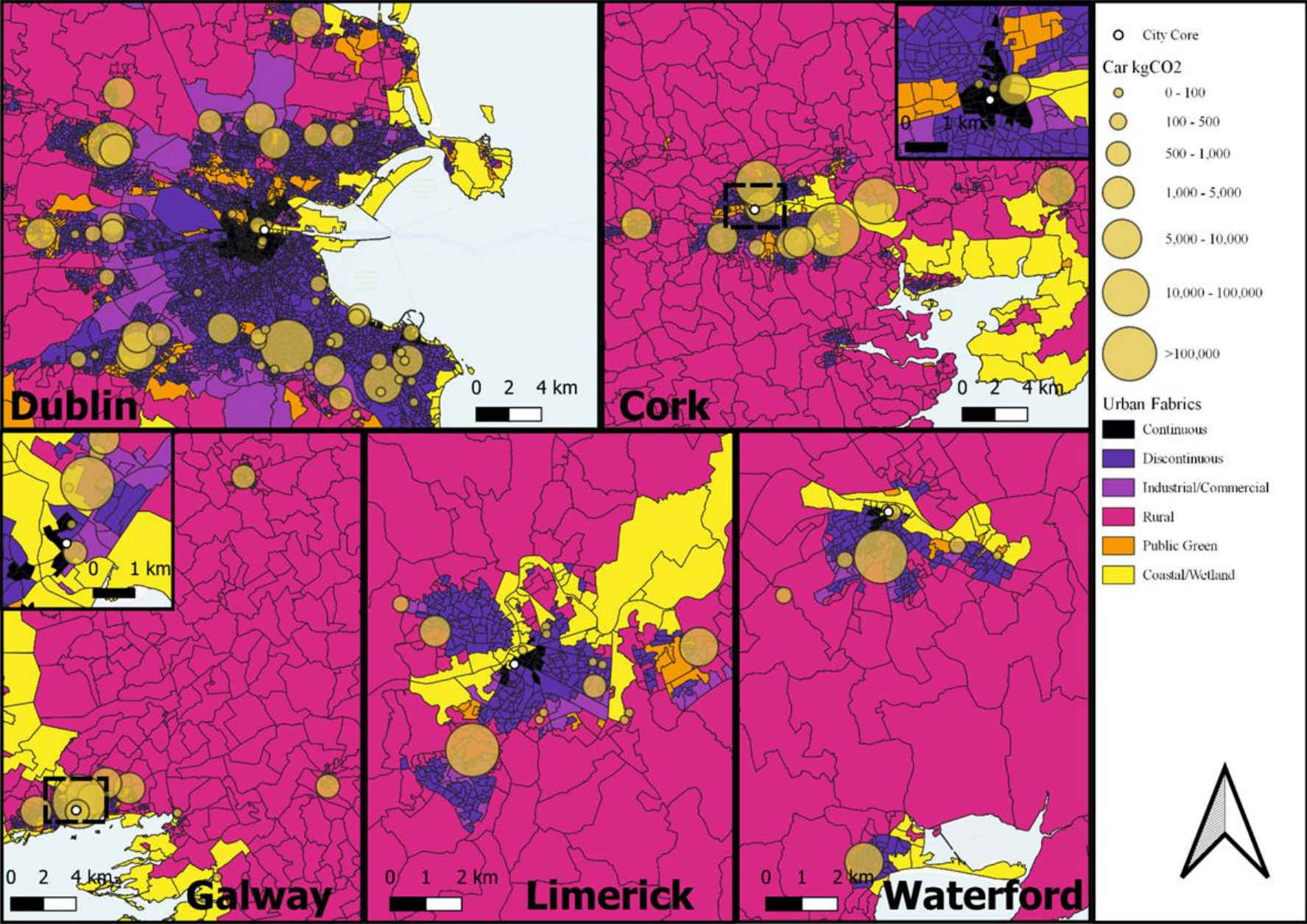
⁵⁷ Many colour schemes can be used to represent urban fabrics. These gradients could affect colour-blind readers, potentially hampering the interpretation of colour encoded information (Geissbuehler and Lasser, 2013). O'Driscoll *et al.*, (2022), implement a pastille, magma colour hue in the Irish case to ensure maps are accessible to colour blind readers. I implement a similar colour scheme as O'Driscoll *et al.*, (2022) in this paper.

pattern. Thereafter, $size_m$ was introduced. In Cork, Dublin, and Limerick, peripheral retail centres generate the most hypothetical emissions, whereas those generating the least emissions cluster in-and-around city cores⁵⁸, supporting existing evidence (Määttä-Juntunen *et al.*, 2011; Dolega *et al.*, 2016). Galway and Waterford offer exceptions to this, highlighting central locations as generating the most emissions. But because most of the retail centres in these city regions are located in-and-around city cores to begin with, this result is unsurprising.

Nationwide, the specific retail centres generating the least and most hypothetical emissions generally change upon introducing $size_m$. Specifically, upon introducing $size_m$, I find that high-profile retail centres account for >85% of all hypothetical travel-related emissions generated by cars. These retail centres are generally found outside city cores, as existing literature predicts (Hay, 2005; Dolega *et al.*, 2016). Because $size_m$ acts as an attractiveness weight, and because the final estimates indicate relative accessibility levels for each mode, these emissions further illustrate regional transport hierarchies by indicating the amount of people utilizing specific modes to travel to major retail centres. Figure 8.2 below illustrates these results by presenting every retail centre weighted by the hypothetical kgCO₂ output produced by cars.

⁵⁸ Nuances arise whereby some retail centres generating minimal emissions are in suburban areas. This appears to happen because of competition-effects whereby bigger (i.e., more attractive) retail centres are within proximity, and absorb other centres' theoretical customer bases.

Figure 8.2: The Hypothetical Travel-Related Emissions Attributable To Travelling To Retail Centres By Car

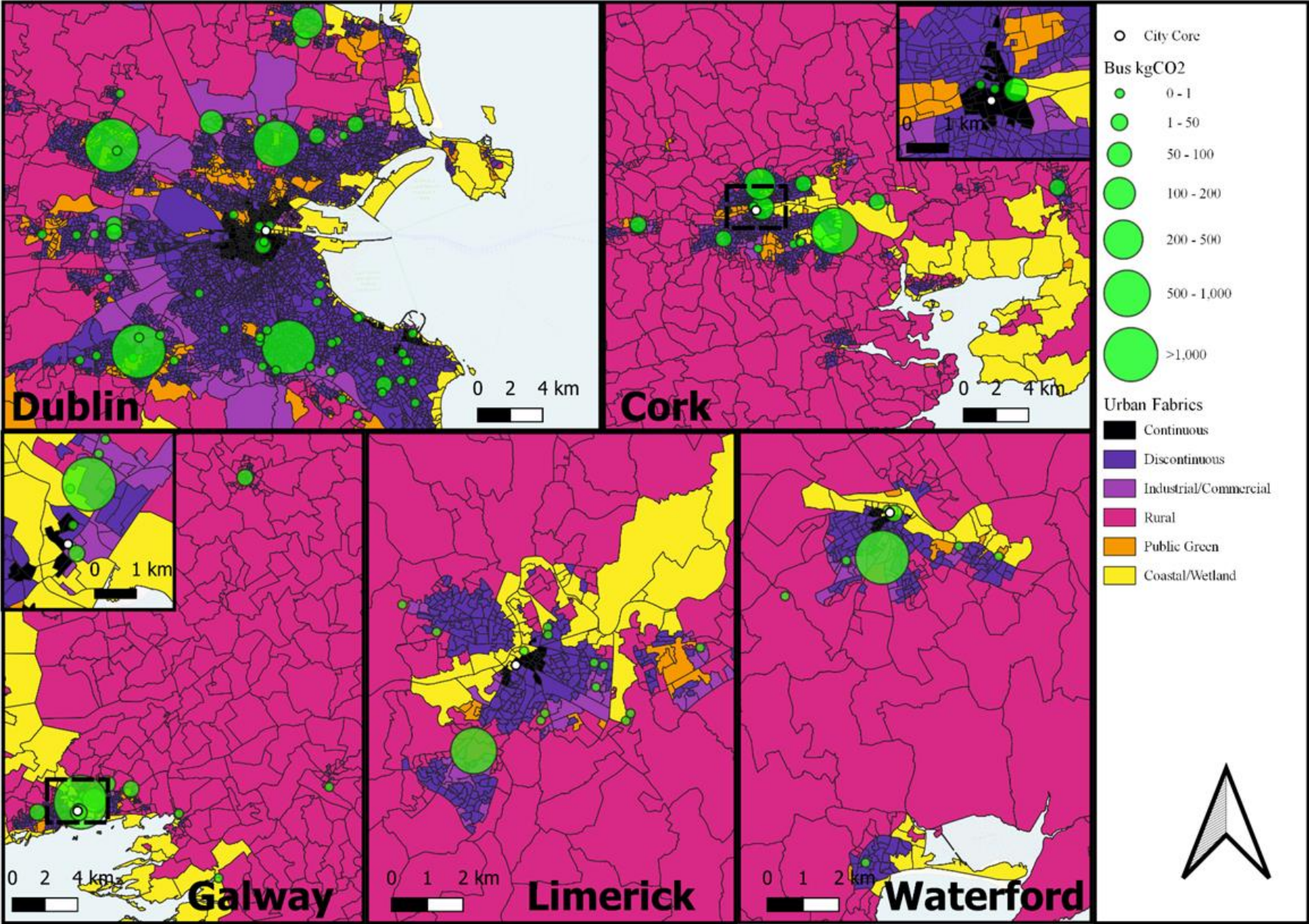


8.4.2 Shopping By Bus

Like above, this research initially assumes that people only consider travel time when shopping by bus. Again, consistent patterns fail to emerge in these results. Some regions have random spatial distributions of travel-related emissions, while others display patterns showing these emissions are most prevalent outside city cores.

Size_m provides clarity. Like before, in Cork, Dublin, and Limerick, travel-related emissions are more prevalent in fringe areas than inside city cores. Again, Galway and Waterford offer unsurprising exceptions to this because most of these retail centres are centrally located. Unlike before, the specific retail centres generating the most hypothetical emissions generally stayed the same. However, a more pronounced skewing of the results is observed, resulting in one-or-two retail centres contributing >95% of regional hypothetical travel-related emissions for buses. This illustrates discrepancies in retail attractiveness because of mode changes. Most of these discrepancies occur outside city cores, perhaps exposing how fringe retail centres tend to offer poor public transport links and subsequently experience relatively low visits from bus users, as gauged by minimal hypothetical emissions (Wilson *et al.*, 2013; Cats and Birch, 2021). Figure 8.3 below illustrates these results by presenting every retail centre according to the hypothetical kgCO₂ output produced by buses.

Figure 8.3: The Hypothetical Travel-Related Emissions Attributable To Travelling To Retail Centres By Bus

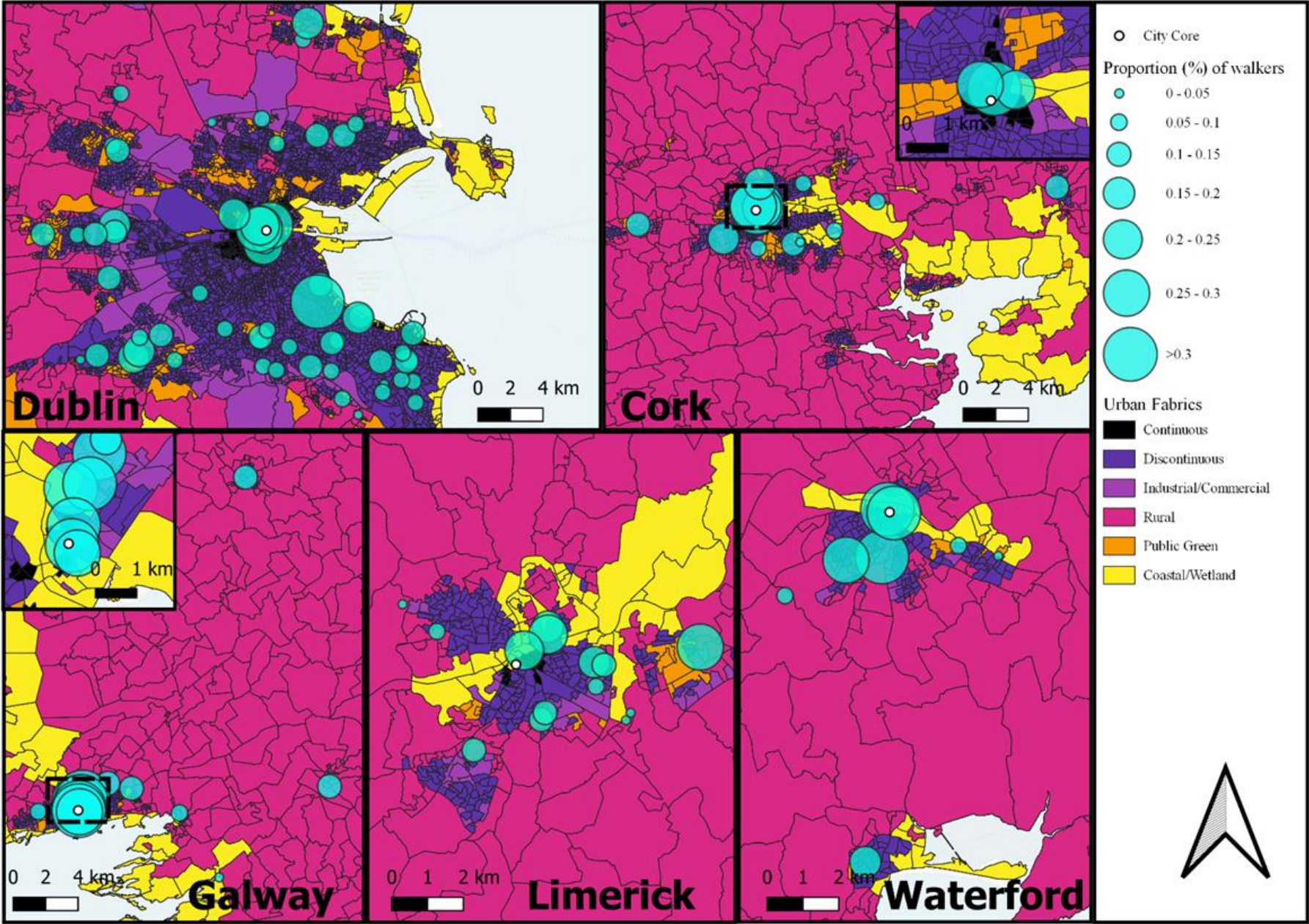


8.4.3 Shopping Actively

As noted in *Section 8.3.4*, $size_m$ was excluded when analysing active travel, meaning people only consider travel time when visiting retail centres using these modes. These analyses investigate the car dependency implied in Figure 8.2, while also gauging which retail centres have the infrastructural capabilities to reduce travel-related emissions by accommodating active modes.

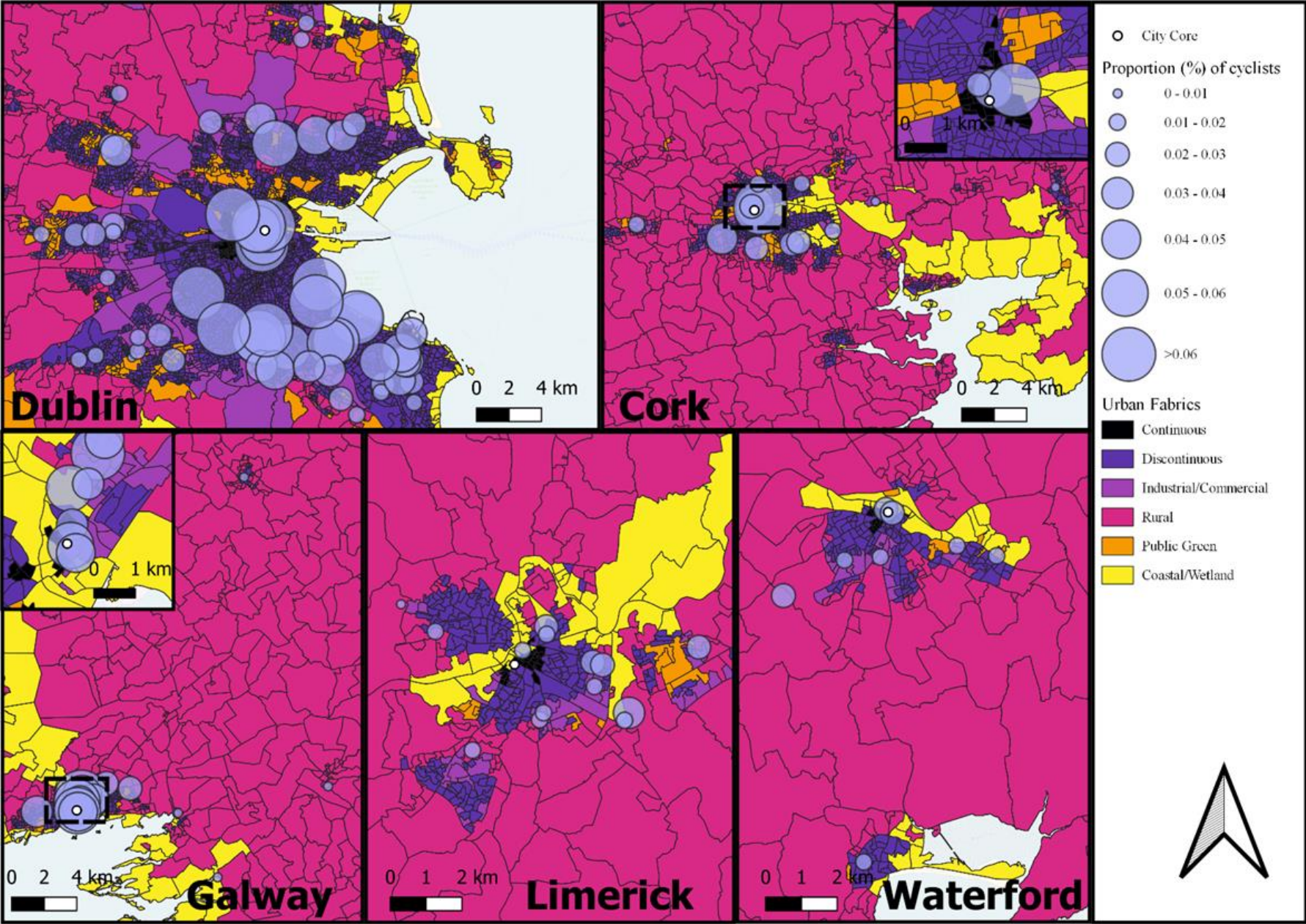
When analysing walking to retail centres, a nationwide pattern emerges whereby centrally located retail environments generally facilitate active modes more frequently than peripheral environments. This indicates that central locations offer better quality and more comprehensive active transport infrastructure than suburban and peripheral locations, something gauged by higher amounts of walking commuters in the vicinity. Figure 8.4 below illustrates these results by presenting every retail centre according to the proportion of its surrounding population that commute by walking.

Figure 8.4: The Proportion of People Within A 10-Minute Walk From Nearest Retail Centre Who Commute By Walking



Cycling behaviour is more nuanced. In Galway, these results imply that cyclists do not typically travel to centrally located retail centres, but a substantial number of walkers do. In Limerick, there is no discernible pattern with cyclists, but central locations are relatively more accommodating to walkers than peripheral locations. In Dublin, there is a clear North-South divide in cycling uptake, potentially highlighting investment inequalities in infrastructure, something which is linked to the implicit costs of travel and subsequent behaviours (Button, 2010). In Waterford and Cork however, walking and cycling illustrate that city cores accommodate greater active travel relative to fringe areas. Where patterns do emerge, it is apparent that locations typically characterised by multi-modal transport infrastructure experience more active and public transport use (Wilson *et al.*, 2013; Gunn *et al.*, 2017; Eldeeb *et al.*, 2021). Figure 8.5 below illustrates these results by presenting every retail centre according to the proportion of the surrounding population who commute by bike.

Figure 8.5: The Proportion of People Within A 10-Minute Walk From Nearest Retail Centre Who Commute By Cycling

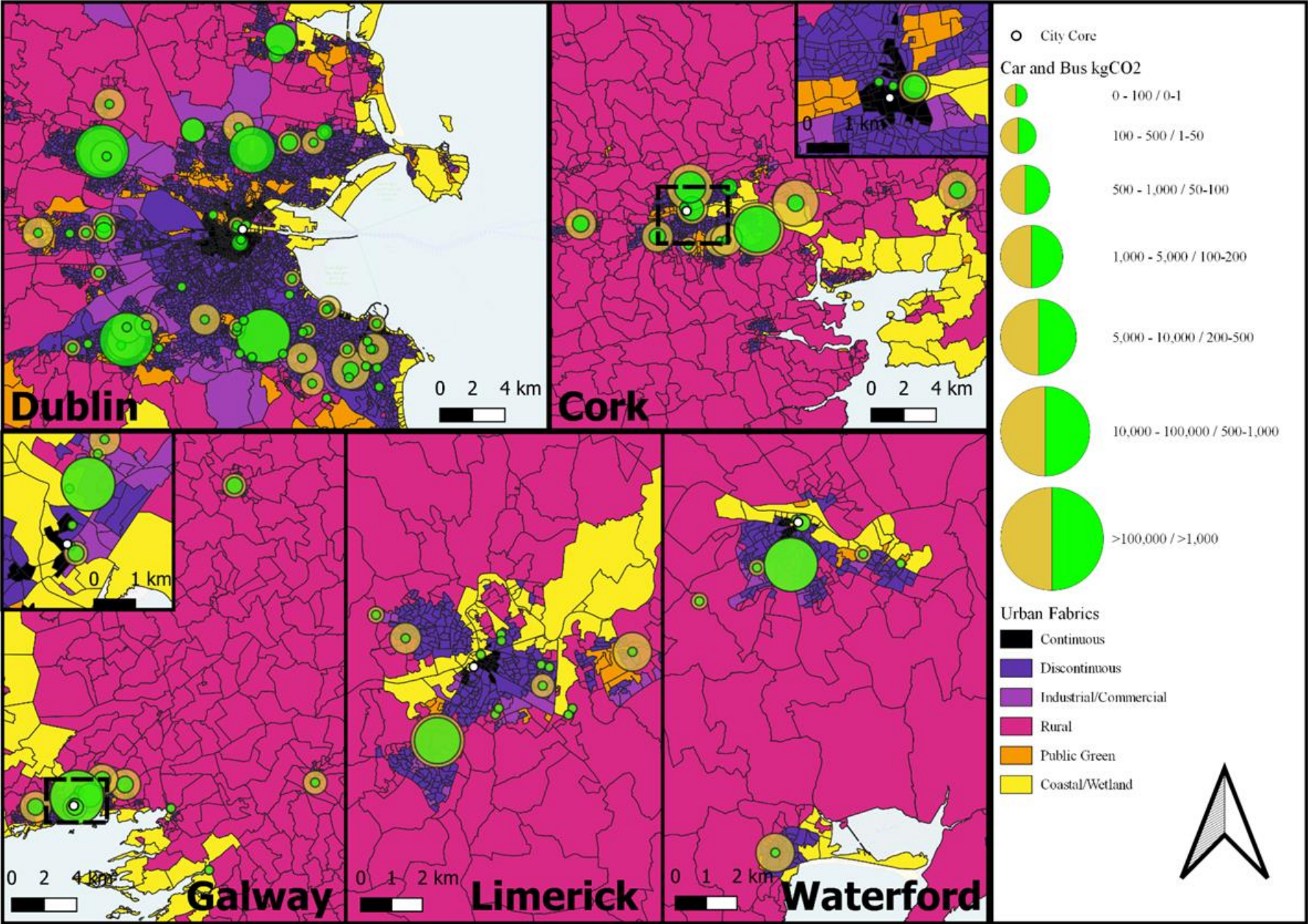


8.4.4 Cross-Modal Comparisons

When comparing motorised modes, there are clear spatial disparities in their use. Specifically, retail centres moderately accessible to car users, become inaccessible to bus users. Because this analysis holds everything constant, except the mode used, these discrepancies are unjustified at their scale, assuming a truly multi-modal transport network. In other words, changes in the relative attractiveness of destinations by mode are theoretically minor in a transport network which is multi-modal, whereby any fluctuations may reflect the changing tastes and preferences of individuals, but significant fluctuations in trip visits (something proxied by travel-related emissions) is associated with significant changes in the quality and accessibility of mode-specific network infrastructure (Button, 2010). This observation is supported given the tendency of these disparities to be greatest in areas typically served sub-optimally by transit – peripheral areas (Wilson *et al.*, 2013; Mohamad *et al.*, 2015; Cats and Birch, 2021), exposing a unimodal nature to Ireland’s transport infrastructure.

Additionally, these results imply that for car users, the most attractive retail centres are in fringe areas, *potentially* pulling people out of cities to avail of larger suburban retail environments, or *potentially* disincentivizing people from shopping in cities when travelling by car, a finding implicit in Mohamad *et al.*, (2015). Figure 8.6 below illustrates these results by presenting every retail centre according to the hypothetical kgCO₂ output produced by buses and cars.

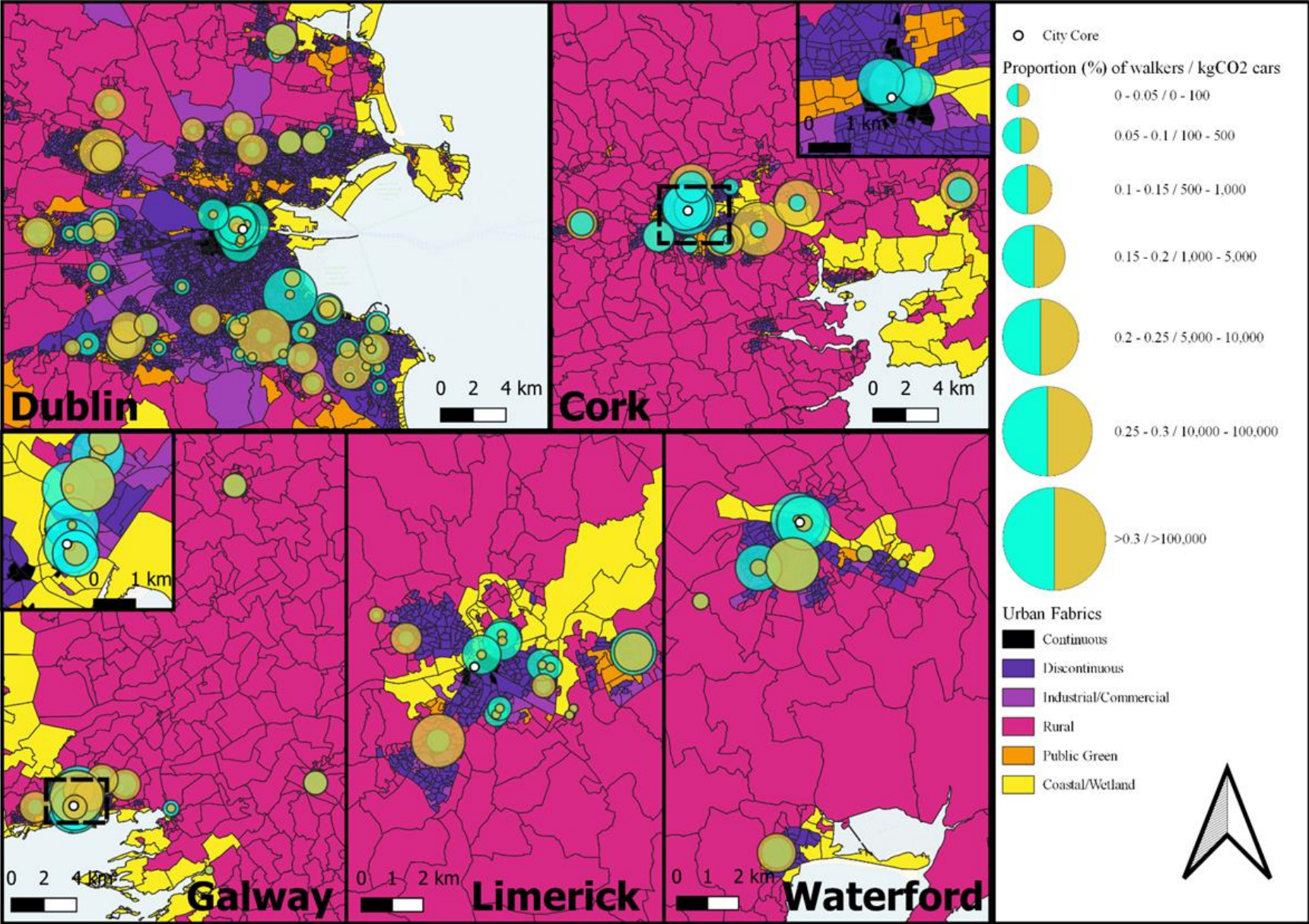
Figure 8.6: The Hypothetical Travel-Related Emissions Attributable To Car-Use Relative To Bus-Use



In the case of active modes, cross-modal discrepancies in the attractiveness (i.e., choice) of destination (i.e., retail centre) are not as drastic as they are between motorised modes. This is perhaps attributable to the fact that leisure cyclists and walkers usually share the same infrastructure and have similar accessibility requirements (Gan *et al.*, 2021). Thus, this research does not explicitly compare active mode use differences as the results are close to identical. However, another viable alternative to cars is active travel, particularly when travelling for shorter distances; something which the National Travel Survey suggests is becoming a growing problem in Irish cities (Central Statistics Office [CSO], 2016).

Subsequently, this final Figure compares the travel-related emissions attributable to travelling by car to these retail centres and the proportion of people in the surrounding area who walk regularly. This allows inferences to be made into the quality of active transport infrastructure in these areas, possibly providing solutions to curb growing car dependency in Ireland. Figure 8.7 shows that car-use increases (something gauged by rising emissions) with distances from city cores. This is further supported by the observation that the retail centres which generate the most travel-related emissions by car, tend to exhibit the least active mode use, implying that car-use tends to dominate in these areas. These findings suggest that peripheral retail centres may offer inadequate infrastructure to facilitate shifts away from excessive car-use, underlining car dependency as a contributing factor to excessive travel-related emissions. Figure 8.7 below illustrates these results by presenting every retail centre according to the proportion of the surrounding population who commute by walking and according to the hypothetical kgCO₂ output produced by car.

Figure 8.7: The Hypothetical Travel-Related Emissions Attributable To Car-Use Compared With The Proportion of People Within A 10-Minute Walk From Nearest Retail Centre Who Commute By Walking



These results generally provide evidence surrounding the environmental impact associated with current retail centre locations. Specifically, it is evidenced that peripherally located retail centres produce excessive levels of travel-related emissions and this is principally attributed to a lack of multi-modal transport infrastructure in these areas. Conversely, it is apparent that centrally located retail environments are relatively less damaging because they see increased levels of multi-modal travel, which reduces the overall levels of travel-related environmental damage (Määttä-Juntunen *et al.*, 2011; Wilson *et al.*, 2013).

However, the accessibility of specific retail centres (something gauged by mode use in the local area) is also found to significantly alter the environmental damage associated with travelling to-and-from these environments. Specifically, the gravity theories employed here show that retail location *alone* will not necessarily determine travel-related emissions attributable to retail centre locations because the surrounding transport infrastructure also plays a role by influencing the implicit costs of travel (Button, 2010; O'Driscoll *et al.*, 2023). But these locations can provide general indications, particularly in city-regions characterised by monocentric expansion, urban sprawl, and car dependency – like the city regions of Ireland.

Therefore, while in principle travel-related emissions can be expected to increase as distances from city cores increase, in practice, it is apparent that a retail centre's design plays an important role in determining emission levels once retail centres leave central areas. Figures 8.2-8.7 indicate that retail centres situated outside city cores which are designed for cars will attract cars, inflating travel-related emissions, while those designed for sustainable transport will generally attract sustainable transport users, reducing emissions, no matter their relative peripherality.

Table 8.3 illustrates this further by linking the environmental damage attributable to travelling to different retail environments based on their distance from city cores. Table 8.3 groups each retail centre under study into its respective city-region and also contextualises their location by grouping them according to the distance from their respective city core. Numbers in brackets represent the number of retail centres within each city region that lay inside the respective distance band. This allows readers to spatially contextualise the regional retail environment, and also contextualises the emission patterns therein. Importantly, because this study analyses 110 retail centres in total, it is impractical to have them presented individually and any subsequent modal-specific frequency distributions.

Table 8.3: Travel-Related Emissions Per Retail Centre And Their Distance from City Centres

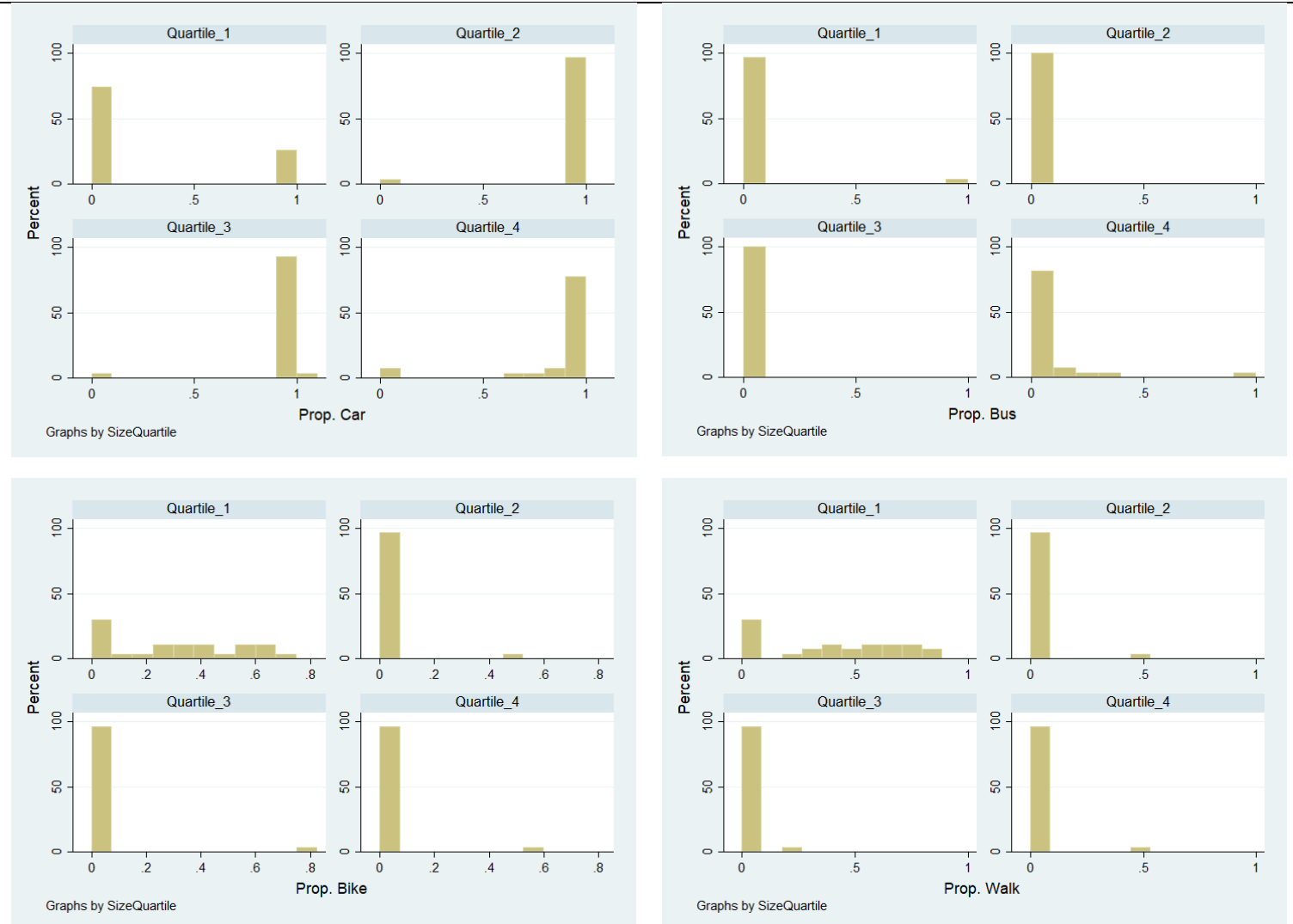
Retail Centre Information		KgCO ₂ released per retail centre by mode of travel	
County	Retail Centre Distance from City Centre (Km)	Cars	Buses
Dublin	0-1km [5]	180	10
	1.01-5km [2]	435	0.00
	5.01-10km [29]	17,934	856
	>10.01km [22]	2,115,384	61,017
Cork	0-1km [3]	1,305	71
	1.01-5km [6]	17,707	193
	5.01-10km [2]	732,424	1,009
	>10.01km [1]	8,610	13
Galway	0-1km [5]	1,749,153	6,310
	1.01-5km [6]	8,373	88
	5.01-10km [1]	27	0.36
	>10.01km [3]	1,593	8
Limerick	0-1km [1]	16	0.06
	1.01-5km [12]	1,743,052	638
	5.01-10km [1]	6,001	0.05
	>10.01km [0]	0.00	0.00
Waterford	0-1km [2]	243	11
	1.01-5km [5]	1,835,454	1,634
	5.01-10km [0]	8,187	0.36
	>10.01km [1]	0.00	0.00

Supplementing this is Figure 8.8, which provides frequency distributions of shopping trips generated by centre when scaling for size. Here, retail centre sizes are delineated according to quartiles (each with a sample of 27 retail centres). Quartile One represents retail centres smaller than 51,491 square feet, Quartile Two represents retail centres sized between 51,491 and 112,137 square feet, Quartile Three represents retail centres sized between 112,137 and 199,038 square feet, and Quartile Four represents retail centres larger than 199,038 square feet (with one retail centre reaching a maximum size of 2,450,000 square feet). Larger retail centres generally attract more car-users than retail centres in Quartile One (i.e., the smallest retail centres). Considering the results presented across *Section 8.4*, this may be attributable to the fact that larger retail centres tend to concentrate in suburban areas and are thus less likely to accommodate regular public and active transport use due to the sprawling nature of the developments these centres are situated in. The trip distributions of bus-users display no apparent pattern when scaling these retail centres according to size, suggesting that perhaps more explicit consideration for place-based variables (i.e., land-use configurations and

transport infrastructure/network provision) is needed. This aligns with research suggesting that the propensity to use public transport is highly sensitive to local time-space geographies and the accessibility of infrastructure, networks, and access nodes (Reynolds-Feighan, 2003).

A greater proportion of walkers and cyclists typically frequent smaller retail centres than larger ones. This may be related to regional development patterns, and the subsequent land-use configurations and infrastructure distribution it creates, but it could also relate to the type of retail environment being visited, or intangible characteristics related to individual perceptions. From a regional development perspective, evidence suggests that larger retail centres are generally located in suburban peripheries, areas typically characterised by limited multi-modal transport infrastructure and larger required travel distances, offering one possible explanation for low trip frequencies for these modes in these environments (Millward, Spinney and Scott, 2013). Similarly, smaller retail environments may be associated with greater perceptions of safety for bike storage, but also greater perceptions of convenience should these environments be located near residential areas, providing more opportunities for active travel (Wilson *et al.*, 2013). Finally, these trip distributions could be explained by the fact that larger retail centres may constitute higher-order retail environments. In this context, Central Place Theory predicts that larger retail centres will have larger catchment areas than smaller ones on the basis that the former will provide a wider variety of luxury goods and services (Mohamad *et al.*, 2015). From this perspective, smaller retail environments may capture centres which primarily serve local populations (i.e., people who live relatively nearby), hence explaining the greater frequency of travelling to these centres via active transport. Importantly however, formal retail centre classifications could not be sourced for this analysis, meaning these inferences should be validated in future research.

Figure 8.8: Frequency Distributions of Shopping Trips Generated By Centre When Scaling For Size



8.5 Conclusions

This research highlights the environmental issues associated with peripheral retail developments, an issue often treated as an afterthought to wider regional development problems (European Environmental Agency [EEA], 2006; Department of Housing Planning Community and Local Government, 2012; OECD, 2018). My objectives revolve around modelling retail development in terms of travel-related emissions and investigating how retail centre locations relate to travel mode choices when travelling for leisure and the environmental damage associated with these behaviours. Thereafter, specific comparisons are made between the environmental damage attributable to retail centres located in central and peripheral locations, thereby testing the environmental merits of central place and gravity theories.

The principal finding of this work is that travel-related emission problems occur when retail centres are in fringe areas. These retail environments generally witness reduced levels of public and active transport use as distances from city cores increase, something attributable to excessive car-use and inadequate public and active transport infrastructure, something proxied by current commuting behaviour. I argue that retail centres that are most accessible by car, tend to be inaccessible to alternative transport modes, exposing a transport hierarchy in these fringe areas dominated by cars. In city cores travel-related emission problems are arguably not as prevalent because the proportion of trips is shared more evenly across multiple transport modes – something clearly linked to the provision of infrastructure, and subsequently, land-use and transport policies.

Considering this problem, ensuring retail developments provide adequate public and active transport accessibility could be a first step in alleviating the troublesome emission figures produced by global transport sectors by facilitating shifts away from car-use. Taking Ireland as an example, the combined (monthly) hypothetical emissions generated by cars in this analysis accounts for ~9% of the 2016, 2019, and projected 2020 monthly CO₂ output of the transport sector, whereas the same figure for buses accounts for ~0.008%, underlining the scale of these potential savings (Environmental Protection Agency [EPA], 2021, p. 6). This research highlights the unsustainable character of retail developments in peripheral areas, corroborating the environmental merits of central place theories by arguing that centrally located retail centres offer optimal conditions to minimise carbon impacts because of their infrastructural tendency to incentivise public and active transport usage by reducing local time-space geographies, something conceptually analogous to required travel distances, and as a consequence, the implicit costs associated with travel.

This evidence supports policymaking which advocates for mixed use, accessibility-driven development to alleviate urban sprawl, adding an otherwise absent clarity to the role retail sprawl plays in exacerbating sprawl-induced environmental degradation. The results presented in this analysis support calls that advocate for developments which accommodate multi-modal travel. This is because these initiatives offer a tangible mechanism to pursue long-term emission reductions by incentivizing shifts away from excessive car-use and increasing the efficiency associated with regional development. In this context, international evidence demonstrates a propensity for people to utilise sustainable transport if given the opportunity (Millward *et al.*, 2013; Eldeeb *et al.*, 2021), meaning governments should aim to optimize current infrastructure by developing compactly and efficiently before expanding peripheral

boundaries, something known to encourage greater public and active transport use due to reduced required travel distances. Complimenting this, policymakers should aspire to make future suburban retail environments less attractive than central locations to car users. This could be done by restricting parking supply or restricting development possibilities (Feitelson and Rotem, 2004), disincentivizing locating far from urban cores, and encouraging developments to explicitly incorporate multi-modal transport infrastructure into their proposals.

The robustness tests undertaken in this analysis adjust network speeds, retail centre sizes, and travel times. While generally, these changes saw minor changes in the results, the overarching narrative remained unchanged across modes and regions. However, this analysis did not contain real shopping trip data, meaning the results rely on the assumptions presented in *Section 8.3.4* holding. Future research could incorporate congestion effects into this methodology or use principal-agent based modelling and microsimulation techniques to generate shopping trip data, thereby broadening our understanding of travel behaviours in a leisure/shopping context. Additionally, researchers could adapt this methodology when analysing commuting patterns, when focusing on the relationship between residential locations and other places of interest, or the relationships between infrastructure provision, land-use configurations, and the location decisions of economic agents. Finally, future research may build upon this analysis by providing a more refined classification of retail centres; perhaps linking these centres to the hierarchy of goods/services provided in these environments. This could be achieved through the creation of indices which capture tenant mixes, thereby providing opportunities to classify retail centres in line with central place theory frameworks. This will facilitate more nuanced investigations into the relationship between travel behaviours and different *types* of leisure activities, like everyday grocery shopping, shopping mall attendance, and amenity visits. Adequate data for this purpose could not be sourced for this research as much of the retail centres assessed here do not have granular tenant information. Furthermore, the national scope of this research renders site visits or some alternative infeasible.

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Chapter 9: Conclusions

9.1 Introduction

This research investigates the consequences of regional development patterns across Ireland and Europe with a particular focus on land-use configurations, travel behaviours, and the relationships therein. In an Irish context, I focus on the economic, social, and environmental dimensions of regional development, how land-use configurations influence travel behaviours, and the environmental degradation attributable to such behaviours. In a European context, I enhance the empirical instruments used to assess land-use configurations and patterns, thereby providing more nuanced insights into issues related to the sustainability and efficiency of land-use developments in city-regions. Using fine-grain built/social environment data, nationally comprehensive Census data, and highly disaggregated spatial scales, this research employs Geographic Information Systems (GIS), advanced econometric techniques, and network analysis methods to investigate four principal research questions across six empirical chapters (**Chapters 3-8**).

These preceding chapters provide insights into the sustainability and efficiency of land-use configurations across Irish (**Chapters 3 and 4**) and European regions (**Chapter 5**); illustrate how opensource data can improve our understanding of developmental patterns and how these configurations can positively contribute to sustainability efforts within regional development (**Chapters 3, 4, and 5**); investigate the interrelationships between socio-demographics, built and social environments, and travel behaviours for commuters (**Chapter 6**) as well as students (**Chapter 7**); and finally assess the hypothetical travel-related emissions attributable to travelling when shopping across Ireland's retail landscape (**Chapter 8**).

This chapter illustrates the major research problems addressed within each empirical chapter and outlines the principal findings of this work. Thereafter, I construct policymaking recommendations based on these findings. Finally, I discuss the limitations of this work and provide directions for future research.

9.2 The Research Problem

In 2022 it took society 7 months and 28 days to expend all the natural resources Earth could sustainably replenish within one year (Global Footprint Network, 2022). The passing of this “overshoot day” so early in the calendar year in the context of the wider climate crisis means that researchers and policymakers must reflect upon the instruments which can reduce the environmental degradation attributable to human activities. This research contributes to this

discussion when pertaining to human settlements, and in particular land-use configurations and travel behaviours.

Land and space are finite natural resources which determine the spatial distribution and intensities of human activities (Gao *et al.*, 2020). Therefore, land-use configurations can influence regional economic and environmental outcomes by determining the efficiency of land and infrastructure use while also dictating the levels of habitat destruction attributable to regional development because these configurations define regional time-space geographies (Ewing, 1997; Reynolds-Feighan, 2003; Nechyba and Walsh, 2004; Gao *et al.*, 2020). Considering this problem, **Chapters 3** and **4** analyse land-use configurations across the Republic of Ireland and assess how these configurations contribute to efforts to achieve sustainability in regional development.

Another key issue in regional development is that when resources like land, space, and infrastructure are used inefficiently, wasteful development patterns can emerge which negatively contribute to sustainability efforts (Nechyba and Walsh, 2004). One way to address this issue involves minimising regional time-space geographies and prioritising developments which accommodate the maximum number of people in the smallest space, thereby increasing the efficiencies of resource usage (Reynolds-Feighan, 2003; Zhang and Zhao, 2017; O’Riordan *et al.*, 2022). But up until recently, investigating these trends was difficult as spatial data was inconsistent, imprecise, and unavailable in many spatial contexts, a problem remedied by the development of open data repositories. Considering this, **Chapter 5** (but also **Chapters 3** and **4** to a lesser extent) investigates whether the incorporation of opensource data can enhance the datasets typically used when analysing land-use configurations and their subsequent contribution to regional sustainability efforts.

Land-use configurations directly influence the spatial distribution and intensities of human activities, meaning issues related to the configuration of human settlements can spill-over into other realms, such as travel behaviours (O’Riordan *et al.*, 2022). Generally, travel behaviours can be influenced by individual tastes and preferences, built and social environments, and trip-specific concerns (i.e., journey durations), but the relative influence of each, and how they interact, is difficult to assess (Handy, Cao and Mokhtarian, 2005; Mokhtarian and Cao, 2008; Ding, Cao and Wang, 2018; Guan, Wang and Cao, 2020). Trips which are habitual in nature (i.e., trips which have consistent origins, destinations, and travel routes) and frequent in their occurrence are characterised by derived demand, rendering them highly sensitive to the implicit

costs of travel, like those associated with land-use and transport policies, making an analysis of these interrelationships possible. Two staple trips across global households which fit these characteristics relate to commuting and school-runs. Considering this, **Chapters 6 and 7** build structural models which assess how individual socio-demographics, travel considerations, and residential built and social environments are related, while also investigating how these interrelationships influence travel mode choices for commuters (on workplace commutes) and students (on school-runs) across the Republic of Ireland.

Regular, habitual journeys provide unique insights into how individual travel behaviours are shaped because they assume fixed environmental circumstances, tastes and preferences, and trip-specific concerns (i.e., by using fixed origins, destinations, and travel routes). But journeys designated for shopping constitute another substantial element of household travel and are fundamentally linked to land-use configurations because they concern travelling to places of economic and social interest, like retail centres. Therefore, it is important that researchers understand how land-use configurations and the spatial distribution of economic and social amenities can influence travel behaviours, something explicitly linked to the economic and environmental outcomes of regional development (Cao, Mokhtarian and Handy, 2009; Määttä-Juntunen *et al.*, 2011). Considering this, **Chapter 8** investigates the relationship between travel behaviours, environmental degradation, and the spatial distribution of major retail outlets.

9.3 Contributions To The Thesis

9.3.1 Novel Data Classification and Analysis of Land-Use Configurations

An overarching theme within this thesis involves analysing land-use configurations and how these configurations (and broader developmental patterns) may contribute to regional economic, environmental, and social objectives. Subsequently, I develop novel land-use classification catalogues which combine comprehensive institutionally sourced data and fine-grain opensource data to acquire more nuanced insights into land-use configurations and patterns across the urban-rural continuum of Irish and European regions.

Chapter 3 is a cartographic study of land-use configurations and patterns across the Republic of Ireland. These configurations are assessed in the context of how they may contribute to regional environmental objectives. **Chapter 3's** principal contribution to existing literature is that it presents visualisations of land-use patterns and configurations through high-quality cartography. But it also provides a replicable methodology for merging traditional land-use data sources (The CORINE Land Cover) and more refined opensource data, like that from

OpenStreetMap. The maps presented in this chapter illustrate how both datasets classify land-use and their subsequent strengths and weaknesses, but they also present estimates of land-use mixing and compare cross-dataset differences in these estimates. The principal finding from this research is that OpenStreetMap data can provide more nuanced insights into land-use developments by focusing on function over form, and that estimates for key land-use characteristics, like land-use mixing, are more robust when these data are included (Haklay, 2010; Fan *et al.*, 2014; Patias *et al.*, 2021; Biljecki, Shin and Lee, 2023).

Chapter 4 analyses land-use configurations and developmental patterns across Irish metropolitan areas. **Chapter 4's** principal contribution to existing literature lay in its assessment of land-use patterns and configurations in the context of theories embedded in urban economics alongside the historical context of land-use planning in Ireland. This assessment employs a blend of CORINE Land Cover data and OpenStreetMap at highly disaggregated spatial scales, providing novel insights into these configurations at sub-neighbourhood levels. The principal finding of this research is that Ireland's developmental history of uncontrolled urban sprawl, a lack of strategic local and regional policymaking, and restrictive zoning laws have created a developmental landscape characterised by inefficient and unsustainable land-use developments in Irish city-regions (European Environmental Agency [EEA], 2006; Winston, 2007; OECD, 2018b).

Chapter 5 investigates the broader implications of using opensource data to analyse land-use configurations through a case-study which merges the most prominent traditional land-use dataset (The CORINE Land Cover) and the most prominent Volunteered Geographical Information dataset (OpenStreetMap). **Chapter 5's** principal contribution to existing literature is its development of a data-driven framework for analysing regional development structures across European city-regions at highly disaggregated spatial scales. The main finding of this work is that the incorporation of opensource data can enhance our understanding of built environments because of their ability to distinguish unique land-uses within otherwise homogenous urban fabrics, findings which are consistent across European city-regions – thereby justifying its use in future regional research (Haklay, 2010; Mobasheri, Zipf and Francis, 2018; Patias *et al.*, 2021; Biljecki, Shin and Lee, 2023).

9.3.2 Transport Infrastructure and Travel Behaviours

Another important theme throughout this research concerns the mechanisms which influence travel behaviours, specifically those pertaining to land-use configurations, tastes and

preferences, and trip-specific considerations (i.e., distance). Subsequently, I analyse travel behaviours across the Republic of Ireland using structural models which analyse the interrelationships between individual socio-demographics, built and social environments, trip-specific considerations, and travel mode choices while also investigating how existing behaviours contribute to the environmental degradation attributable to travel.

Chapter 6 investigates the interrelationships between individual socio-demographics, residential built and social environments, and trip-specific considerations while also analysing how these factors influence the travel mode choices of workers when commuting. **Chapter 6's** principal contribution to existing literature is the development of a structural model to assess these relationships using individual-level Census data and highly refined spatial data inclusive of transport infrastructure, land-use metrics, and area quality indicators. The principal finding of this work is that areas characterised by reduced time-space geographies are associated with significant increases in local connectivity, a characteristic which can reduce individual sensitivities to social exclusion and transport poverty, but also increase the likelihood of using public and active transport instead of cars.

Chapter 7 assesses the interrelationships between individual socio-demographics, built/social environments, trip-specific concerns, as well as how these interrelationships influence the travel mode choices of students during school-runs. **Chapter 7's** principal contribution to existing literature is the development of a structural model which assesses these interrelationships using individual-level Census data and highly refined spatial data inclusive of transport networks, land-use metrics, and area quality indicators. The principal finding of this work is that the availability of travel-related resources in households is significantly associated with residential and school locations and that shifts away from excessive car-use are most likely when areas are characterised by reduced time-space geographies, high degrees of land-use mixing, and multi-modal transport infrastructure provision.

Chapter 8 assesses the environmental costs associated with current travel behaviours and analyses under what circumstances these behaviours may change. **Chapter 8's** principal contribution to existing literature is its quantification of the travel-related emissions associated with travelling from residential areas to major retail centres using travel data from the 2016 Irish Census alongside OpenStreetMap transport network data. **Chapter 8** shows how peripherally located retail centres are associated with significant increases in car-use relative to alternative modes, something which increases travel-related emissions. Conversely, retail

centres in areas characterised by high-degrees of multi-modal transport infrastructure exhibit less car-use and subsequently produce lower levels of travel-related emissions.

9.4 Policymaking Recommendations

An underlying theme in **Chapters 3-8** concerns the relationship between land-use configurations, travel behaviours, and environmental degradation. I analyse these relationships in the wider context of regional development within the Republic of Ireland and Europe and probe how land-use and transport policies can mitigate the environmental and economic costs associated with current developmental patterns.

From a land-use perspective, **Chapters 3, 4, and 5** demonstrate how urban sprawl has created a developmental landscape characterised by high degrees of land-use segregation, low settlement densities, and large regional time-space geographies; characteristics linked to negative environmental, economic, and social consequences for individuals, households, and regions. To mitigate these problems, this research recommends maximizing the use of existing infrastructure and man-made settlements prior to initiating outward expansion. This will reduce the spatial demands attributable to human settlements, reduce time-space geographies, and create greater efficiency in land and infrastructure use. This objective can be achieved by easing zoning restrictions surrounding the mixing of unique land-uses and the intensity (i.e., verticality) of developments, thereby reducing the pressure to expand outwardly (Cho and Rodriguez, 2015; Zhang and Zhao, 2017; O’Riordan *et al.*, 2022). Or it could be achieved by better coordinating local-, regional-, and national-level objectives for regional development, something that may improve the efficiency of developmental resource allocation (Moore-Cherry and Tomaney, 2019). Finally, area-based policies which restrict the isolation of, and distance between, residential areas and places of economic and social interest can limit the spatial expanse of regions and facilitate increased levels of regional self-sufficiency⁵⁹ (Ouweland, van Oort and Cortinovis, 2022).

Land-use configurations characterised by increased spatial demands create regions characterised by larger required travel distances, something which influences behaviours. In this context, **Chapters 6 and 7** demonstrate how commuters and students residing in areas characterised by low required travel distances and high levels of land-use mixing are more

⁵⁹ From a policymaking perspective, these recommendations reinforce evidence arguing for policies that promote the development of “X-minute cities”. A more detailed discussion on this can be found in Knap *et al.*, (2023).

likely to travel by public and active transport relative to cars. While **Chapter 8** highlights how retail centres located in areas characterised by high levels of multi-modal transport infrastructure provision exhibit increased public and active transport use, a shift which reduces the environmental degradation attributable to travelling for leisure. Policymakers can act upon these findings in numerous ways. Firstly, coordinating land-use and transport policies around the principals of land-use mixing, developmental compactness, and low required travel distances offer tangible mechanisms to reduce the implicit costs of active travel, thereby encouraging shifts away from excessive car-use (Button, 2010; Millward, Spinney and Scott, 2013). Secondly, initiatives which explicitly segregate transport infrastructure (i.e., through the creation of dedicated bus/cycle lanes and footpaths) reduce the amount of road space dedicated to car-use, thereby altering regional transport hierarchies and further reducing the implicit costs associated with moving away from regular car-use (Eichler and Daganzo, 2006; Millward, Spinney and Scott, 2013; Tirachini, 2015; Wolday, 2023).

These recommendations align with global and national policymaking initiatives, particularly The United Nations *Sustainable Development Goals (SDG)* and *Project Ireland 2040*. At an international level *SDG 11: Sustainable Cities and Communities* strives to transform the way human settlements are built and managed, and the subsequent economic, environmental, and social costs of these settlements. Key targets include ensuring the accessibility of public and active transport for all, but especially vulnerable populations. In **Chapter 6** (and **Chapter 7** to a lesser extent), I show that improvements in this realm will positively contribute to reducing the environmental burden attributable to transport but may also positively impact social mobility by increasing the accessibility of employment (OECD, 2013, 2018a, 2018b; The United Nations, 2022). *SDG 11* also aspires to enhance the efficiency and sustainability of land and infrastructure use, particularly in urban areas. One priority is to mitigate the destruction of natural landscapes and to reduce the costs of development, initiatives which **Chapters 3, 4, and 5** show can positively contribute to sustainability efforts from a land-use perspective.

Project Ireland 2040 seeks to align Ireland's regional planning frameworks with these Goals. Here, major emphasis is placed on reducing the spatial expanse of regions and enhancing the efficiencies of land and infrastructure use through increased land-use mixing, developmental compactness, and an easing of zoning restrictions surrounding development verticality. Significant initiatives which can help achieve these objectives include the Living City Initiative and The Vacant Upper Floor Refurbishment Scheme. These are tax-incentives for refurbishing buildings in urban centres to create greater vitality, urban regeneration, and efficiency in the

use of existing infrastructure and developments, something further discussed in **Chapter 4** (Dublin City Council, 2022; Department of Housing Local Government and Heritage, 2023). Also prioritised throughout *Project Ireland 2040* is greater coordination between land-use and transport policies so that shifts away from car-use can be facilitated, something discussed across **Chapters 6-8** (Government of Ireland, 2018; OECD, 2022). Aiding the pursuit of these objectives are initiatives which aim to transform public and active transport networks through increased network segregation, connectivity, and investment, something embodied by the *Bus Connects* schemes being introduced across Irish cities (National Transport Authority, 2023).

9.5 Research Limitations and Directions for Future Research

9.5.1 Research Limitations

While the specific limitations of each empirical analysis are outlined across **Chapters 3-8**, in general, the quality of empirical investigations concerning the economic, social, and environmental dimensions of regional development can be improved by employing a greater variety of opensource data, like remote sensing technologies or data repositories like OpenStreetMap and Google Maps⁶⁰ (Arribas-Bel, Garcia-López and Viladecans-Marsal, 2021; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021). The accumulation of this data will allow researchers to gain highly refined insights into the composition of urban/regional environments and the various factors which influence their evolution (Arribas-Bel, 2014; Guerra *et al.*, 2018; Ahrens and Lyons, 2019). Particularly pertinent is the departure from using administrative spatial boundaries when conducting spatial analysis. Emerging machine learning methods can potentially provide researchers with opportunities to utilise spatial units comprised of natural breaks within landscapes, be they natural or man-made, enabling sophisticated investigations into urban and regional dynamics at sub-neighbourhood levels (Arribas-Bel, 2022).

Network analysis allows researchers to acquire greater knowledge on the efficacy of local and regional transport infrastructure and related policies. This research frontier lays in the incorporation of opensource Application Programme Interface (API) data which tracks travellers in real time and facilitates the computation of congestion, wait-time, and network

⁶⁰ Also relevant here in the Irish context is the National Land Cover Map currently being developed by *Tailte Ireland*. This dataset will offer a spatial resolution 250 times greater than that provided by the CORINE Land Cover and will provide Ireland with a uniquely disaggregated dataset containing 36 land-use classification categories across the urban-rural continuum. However, it is unclear whether its ability to classify unique urban land-uses will surpass that of OpenStreetMap. More information can be found at: Tailte Éireann, (2023).

efficiency effects, while also enabling research into how these may relate to travel behaviours (Bagchi and White, 2005; Toole *et al.*, 2015; Milne and Watling, 2019; Harding *et al.*, 2021). This research could not acquire such data at the required scale, but the insights provided by future investigations will allow researchers to analyse the impacts of pricing mechanisms, like congestion charges and fare subsidisation, in facilitating changes in travel behaviours (Christiansen *et al.*, 2017; Holz-Rau and Scheiner, 2019). Furthermore, temporal analyses into the efficacy of transport routes along given networks at different times of the day can be analysed (Toole *et al.*, 2015; Harding *et al.*, 2021; Credit and Arnao, 2022). For example, in a public transport context, the accessibility of the network to regional populations can be gauged by mapping the dispersion of nodes and the configuration of routes, whereas the accessibility and reliability of the service can be gauged by comparing scheduled departure times with actual departure times at key periods throughout the day, such as the hours associated with commuting (Bagchi and White, 2005; Tu *et al.*, 2018; Credit and Arnao, 2022).

Finally, the incorporation of data which facilitates time-series investigations into the dynamic relationships between land-use configurations, transport infrastructure investment (and subsequent travel behaviours), and economic growth will improve our knowledge of the mechanisms which drive urban and regional expansion, enabling investigations into how particular developmental patterns emerge. This will allow researchers to explicitly link dynamic developmental patterns, like urban sprawl, to phenomena like economic growth, social cohesion, and environmental stewardship.

9.5.2 Towards A New Research Agenda

There are still major uncertainties surrounding the precise definition of sustainability in regional development, something partly attributable to the imprecise interpretation of key concepts like urban sprawl and sustainable land-use. Future research should focus on exploring how such concepts have evolved and attempt to develop frameworks which synergise regional economic, social, and environmental objectives (Jaeger, Bertiller, Schwick and Kienast, 2010; Jaeger, Bertiller, Schwick, Cavens, *et al.*, 2010; Jaeger and Schwick, 2014; O'Driscoll *et al.*, 2023). This will allow for greater interdisciplinary research into pressing societal issues like spatial inequalities, climate change, and perhaps even the geographies of discontent.

More specifically, research that investigates the spatiotemporal interrelationships between landscape characteristics and a multitude of social, economic, and environmental variables is needed – something possible through the use of Difference-in-Difference methodologies (He

et al., 2022; Tan *et al.*, 2022). For instance, researchers could investigate how population dynamics influence land-use configurations while also analysing how policymakers can address subsequent issues relating to legacy effects, thereby providing instruments to shape future development in more balanced and perhaps equitable ways (Button, 2010; Neatt, Millward and Spinney, 2017; Heumann *et al.*, 2020; Pan, Jin and Liu, 2020). This research may also investigate how property markets and phenomena like residential and job sprawl respond to changes in regional development patterns, spatial mismatches in infrastructure distribution, and the changing geographies of work. Alternatively, research may prioritise the development of Decision Support Tools, simulation interfaces that can quantify (and compare) the economic, environmental, and social costs of multiple development initiatives/proposals (Timmermans, 2011; Cantillon, 2022).

Tobler's first law of geography highlights the importance of spatial dependence and autocorrelation in spatial analysis (Tobler, 1970). However, when analysing the sustainability and efficiency of land-use configurations (a key consideration in regional economic and environmental policy), many empirical indicators (i.e., relative entropy) fail to capture this. Similarly, little is known about the economic and social mechanisms influencing regional development patterns and how different settlement arrangements (i.e., polycentricity and urban sprawl) impact economic growth, social mobility, and phenomena like innovation, competition, and labour mobility. Considering this, future research should seek to improve our understanding of the potentially heterogeneous economic, environmental, and social outcomes associated with different types of land-use configurations across diverse spatial contexts (Zhang and Zhao, 2017; Druga and Minár, 2018; Chen and Song, 2020). This may require the development of new metrics to characterise land-use configurations/patterns, but it may also involve using methodologies that allow researchers to investigate multiple interrelated hypotheses simultaneously (i.e., Structural Equation Modelling). Either way, greater efforts to understand these spatially heterogeneous interrelationships will elevate our understanding of how these phenomena interact, and what policymakers can do to mitigate their consequences.

A key element to achieving sustainability in regional development is a reduction in car-use in favour of public and active transport use, something explicitly highlighted by the *United Nations Sustainable Development Goals*. Future research should seek to further assess how travel behaviours are shaped. Here, research may incorporate network and landscape analyses which link environmental characteristics to travel behaviours (Neatt, Millward and Spinney, 2017; Pan, Jin and Liu, 2020; Carpio-Pinedo, Benito-Moreno and Lamíquiz-Daudén, 2021;

Liu, Wang and Duan, 2023; Wolday, 2023). This will shine some light on the environmental costs of regional development while also showing how policymakers can use land-use and transport policies to reduce these costs (McCormack, Giles-Corti and Bulsara, 2008; Crane and Guo, 2012; O'Driscoll *et al.*, 2022a, 2022b).

Contemporary wisdom in transportation science states that there is a positive relationship between mode-specific infrastructure provision (i.e., roads) and mode-specific use (i.e., cars). But practical issues, like morphological considerations (i.e., terrain, weather, and absolute distance) also play a role. While for conventional active travel (cycling and walking), these considerations are sometimes insurmountable, the commercialisation of e-bikes appears to be circumventing issues pertaining to terrain and distance due to reduced physical exertion demands (Neatt, Millward and Spinney, 2017; Sun *et al.*, 2020). While e-bikes show promise in this regard, electric cars falter because car dependency and congestion occur regardless of whether cars are electric. Therefore, future research should investigate the economic, social, and environmental trade-offs associated with adopting novel technologies and how these technologies may impact regional transport hierarchies.

Future research into travel behaviours could also analyse the economic mechanisms behind sustaining shifts away from excessive car-use. For instance, investigating the relationships between significant events (i.e., fare changes and infrastructure development) and travel behaviours can help researchers gauge the effectiveness of instruments (i.e., subsidies, congestion charges, and transport infrastructure provision) in influencing travel behaviours, but they can also provide insights into how policymakers can effectively price travel and subsequent externalities (Button, 2010). Interesting research avenues in this regard may address concerns that congestion may be under-priced and that remedying this inefficiency could regulate unsustainable travel behaviours and catalyse increased public and active transport use (Button, 2010; Friedrich and Quinet, 2011; Anas, 2012; Department of Transport, 2022). The theoretical implications of this are particularly interesting because if car-use is underpriced then cities may become more spread out than is optimal, something compounded by the fact that this mis-pricing may induce a disproportionate amount of land to be allocated to this (unjustifiably) cheap use (Anas, Arnott and Small, 1998).

Additional avenues for future research include analysing the relationships between transport infrastructure/service provision, economic growth, and labour market outcomes. Specific investigations could analyse how public transport infrastructure improvements influence

regional economies, social fabrics, and environments over time. Coupled with cross-country investigations into government spending on such infrastructure, this will allow researchers to gauge the relative effectiveness of different policymaking instruments in instigating positive economic (and social and environmental) outcomes across regions. This will provide greater clarity surrounding the hierarchy of trade-offs policymakers face when trying to implement regional planning initiatives.

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Appendix 1 (A1): Land-Use Mixing Across The Republic of Ireland

A concern when using a metric like relative entropy as an indicator of land-use sustainability and efficiency is that the results may be subject to the spatial unit of analysis, or in other words the Modifiable Area Unit Problem. As discussed in **Chapters 3, 4** and **5**, this can artificially bias estimates and therefore create inaccurate results. This Appendix examines the robustness of our analysis in **Chapter 3** by replicating our analysis of visualising land-use mixing (i.e., relative entropy) across the Republic of Ireland using an alternative spatial scale.

We analyse land-use developments from the perspective of efficiency in space and infrastructure usage. We argue that developments which are mixed-use and compact in nature utilise these resources more efficiently, mitigate the levels of habitat destruction attributable to regional development, and subsequently positively contribute to achieving greater developmental sustainability. We measure the relative levels of land-use mixing within localities across Ireland using the relative entropy metric. Relative entropy quantifies the mixing of distinct land-use types within pre-defined geographical spaces (Song, Merlin and Rodriguez, 2013). The logic for using this metric is that increases in relative entropy increase the mixed-use and compactness of developments, thereby inferring that natural resources, like space, are used more efficiently (Jain and Tiwari, 2019; Eldeeb, Mohamed and Páez, 2021).

The spatial scale we use here are Ireland's Small Areas (SAs). Small Areas contain between 80-120 dwellings and provide us with 18,641 localities to analyse (Central Statistics Office [CSO], 2016). Small Areas are the most disaggregated spatial units in Ireland which provide area boundaries at sub-neighbourhood levels. Due to their highly disaggregated nature, they align with *Project Ireland 2040's* objectives to ensure the economic, environmental, and social development of small towns through numerous mechanisms, one of which being land-use policies (Government of Ireland, 2018). However, Small Areas may compromise the ability of researchers to provide coherent policymaking recommendations due to conflicting results and insights within administrative areas, hence their use as a robustness check. The next largest spatial unit in Ireland beyond the Electoral Division level (which are used in **Chapter 3**) are Local Electoral Areas, of which there are 166. Because of their highly aggregated nature, they cannot provide meaningful insights into the sub-regional nuances of land-use configurations and developmental patterns and are therefore not utilised throughout this analysis.

Figure A1 below illustrates the results of this analysis. Lighter colours indicate lower levels of relative entropy and by implication, lower levels of efficiency in land and infrastructure use

alongside lower levels of developmental sustainability, whereas darker colours indicate higher levels of relative entropy. When comparing differences in relative entropy estimates across our CORINE and CORINE-OSM datasets, darker colours indicate severe differences (i.e., Severe Overestimation or Severe Underestimation), while lighter colours indicate relatively consistent cross-dataset estimates.

Figure A1: Measuring Land-Use Mixing Across The Republic of Ireland

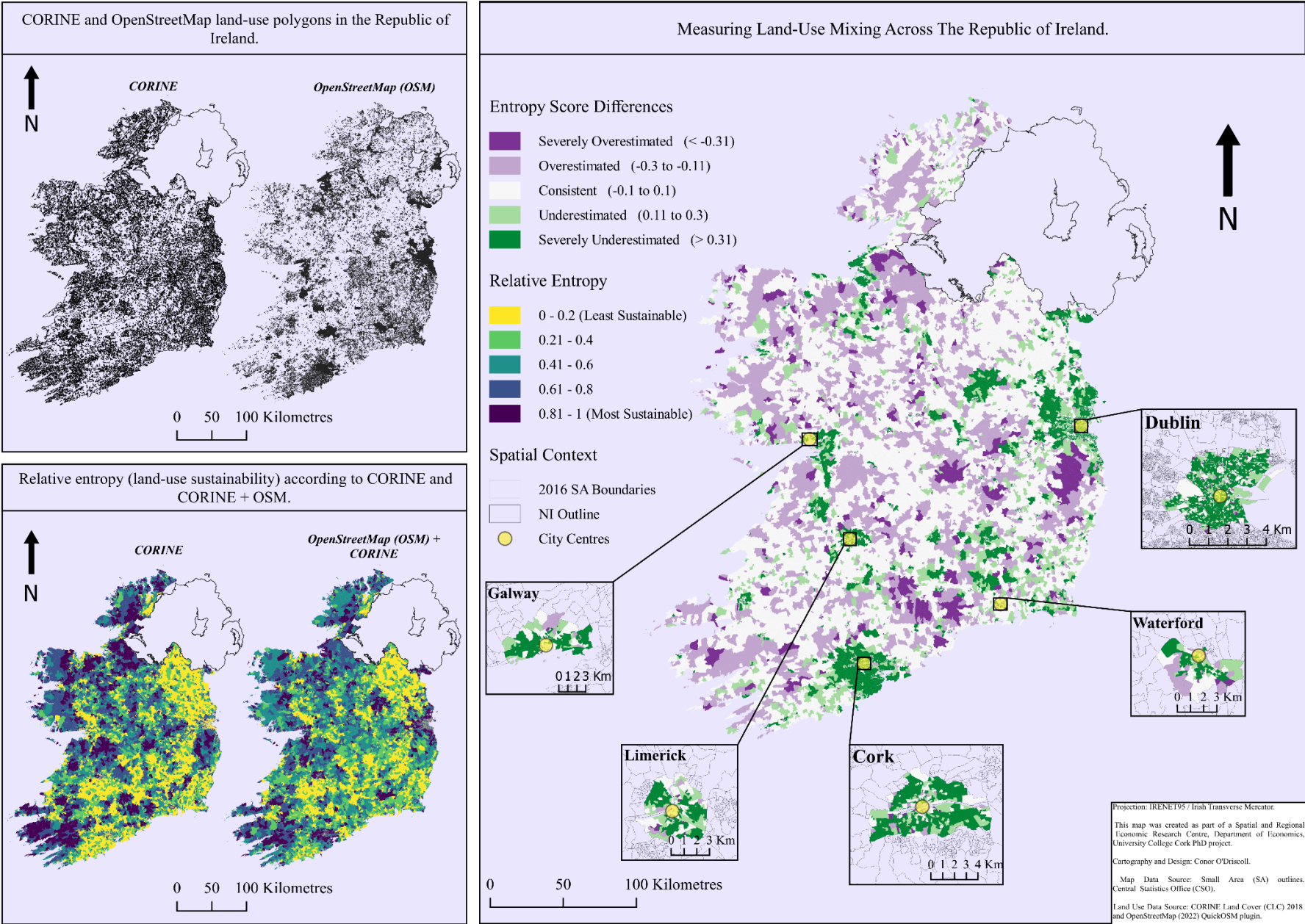


Figure A1 supports the results reported in **Chapter 3**. We find that when using the CORINE dataset alone, relative entropy estimates are typically lower than those computed using our CORINE-OSM dataset in urban areas. We argue that this is attributable to OpenStreetMap's superior ability to classify land-uses at highly refined spatial scales in these environments, thereby producing more robust results. Furthermore, this allows us to clearly distinguish between urban centres, regional peripheries, and rural land-uses at highly refined spatial scales.

Here, we see that across urban centres, relative entropy scores are typically low when using the CORINE Land Cover dataset, but quite high when using the CORINE-OSM dataset. This may suggest that discipline-standard datasets like the CORINE cannot adequately distinguish urban land-uses and therefore may underestimate the level of land-use mixing in these environments, something which may significantly impact policies surrounding developmental sustainability. Somewhat surprisingly, the Main Map indicates that the CORINE Land Cover dataset produces higher relative entropy estimates in rural areas relative to the CORINE-OSM dataset. This finding may be principally linked to the fact that the CORINE dataset is more heavily weighted towards documenting rural land-use categories, thereby creating a bias in land-type counts.

Considering this, we argue that in urban areas, relative entropy may be higher than typically accounted for in urban areas whereas it may be lower than typically accounted for in peripheral and rural areas. In-and-around cities, this may create problems as local heterogeneities in the efficiency of land and infrastructure use are hidden due to an inability to differentiate unique urban land-uses. Similarly, in regional peripheries (i.e., suburbs), this may create problems by understating how inefficient these developmental patterns are in land and infrastructure use.

Overall, these results indicate that our principal analysis in **Chapter 3** is robust by showing how the results not change significantly when spatial units are adjusted. This is significant because the principal concern when utilising relative entropy as an indicator for land-use sustainability is its susceptibility to the Modifiable Area Unit Problem. Whilst there are alternative mechanisms to address this, such as those methods employed in **Chapter 4**, the use of multiple administrative spatial scales is one typically employed measure (Song, Merlin and Rodriguez, 2013).

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Appendix 2 (A2): Land-Use Mixing in Irish Cities: Implications for Sustainable Development

The Modifiable Area Unit Problem (MAUP) implies that the results produced by spatial analysis are inherently subject to the scale of spatial units. When analysing land-use configurations, evidence suggests that smaller spatial scales can produce more meaningful results than larger spatial scales on account of their ability to capture sub-regional heterogeneities in development patterns (Song, Merlin and Rodriguez, 2013). When using administrative spatial scales, this can produce problems as different administrative units may produce different results in otherwise identical analyses (Chen and Song, 2020). When mitigating this effect, best-practice involves either conducting analyses at multiple administrative scales or using standardised/natural spatial units (Song, Merlin and Rodriguez, 2013; Chen and Song, 2020; Fleischmann and Arribas-Bel, 2021; Patias *et al.*, 2021). We incorporate the former as a sensitivity analysis in this Appendix, while the latter is addressed in *Section 4.5* of **Chapter 4** as a directive for future research.

This analysis uses relative entropy (i.e., land-use mixing) as an indicator of the sustainability and efficiency of land and infrastructure use across Irish metropolitan areas. Our spatial scale here consists of 3,409 Irish Electoral Divisions (ED) which constitute the smallest administrative unit within the state, while we maintain our regional boundaries defined by the OECD Functional Urban Areas (Dijkstra, Poelman and Veneri, 2019). This adds further international transferability to our results as Electoral Divisions are analogous to the European commune. The results of this robustness check are presented through cartographic visualisation whereby darker colours represent higher levels of relative entropy.

Figure A2.1 below visualises the relative entropy of each Electoral Division within Irish metropolitan areas. Core areas typically produce the highest relative entropy scores meaning they exhibit higher levels of land-use mixing and consequently higher levels of efficiency in infrastructure and land use. Conversely, peripheries generally produce lower relative entropy scores, suggestive of lower levels of land-use mixing and efficiency in development. We observe a consistent pattern whereby relative entropy scores typically decrease with distances from urban centres, confirming expectations that urban sprawl, as experienced in Ireland, inefficiently utilises land and infrastructure and has excessive spatial demands (Ahrens and Lyons, 2019). Accordingly, we argue that urban sprawl in Ireland has thwarted efforts to achieve sustainable land-use developments as infrastructure and land-use are inefficiently utilised.

Figure A2.1: The Relative Entropy of Electoral Divisions within Irish Metropolitan Areas

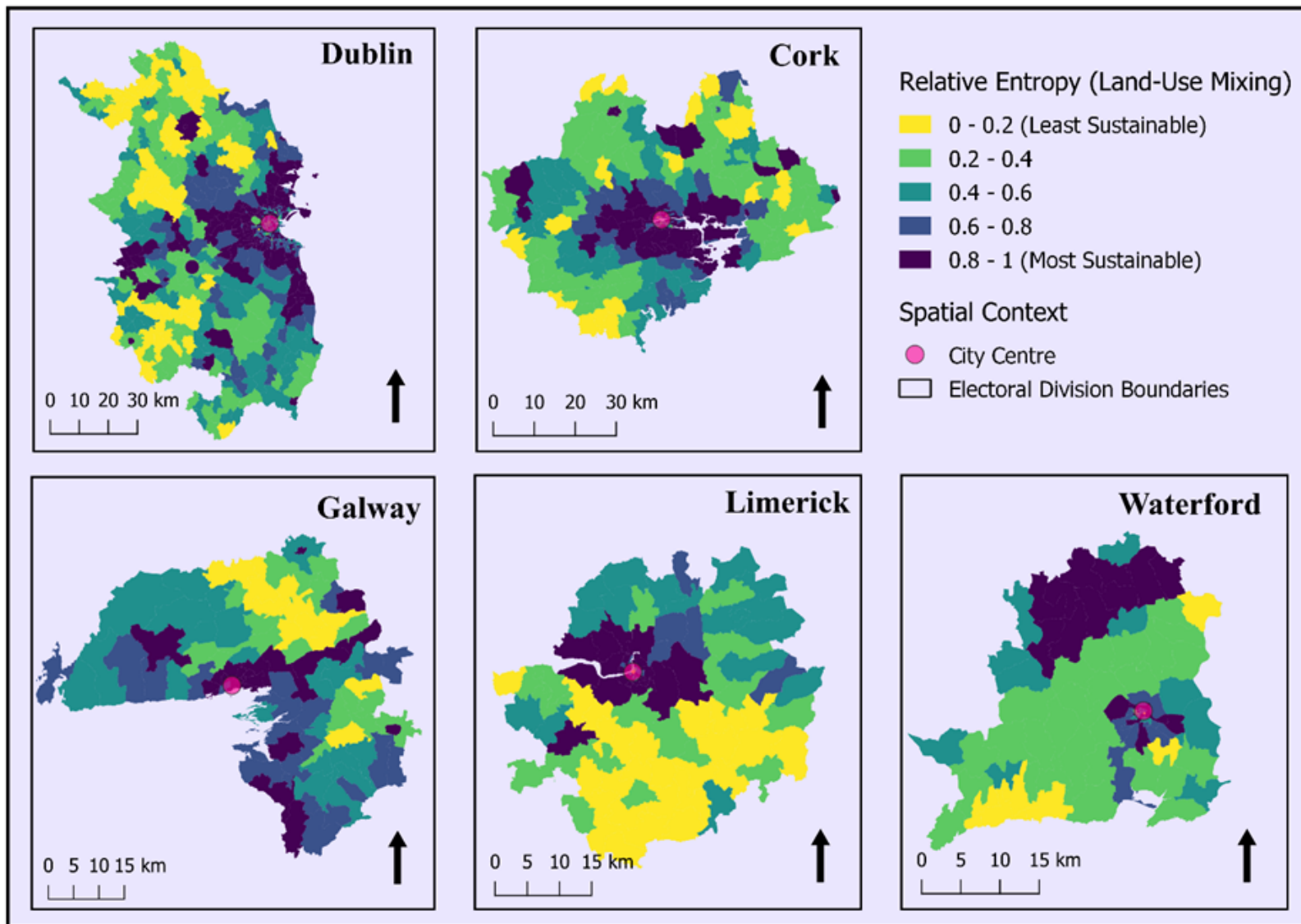
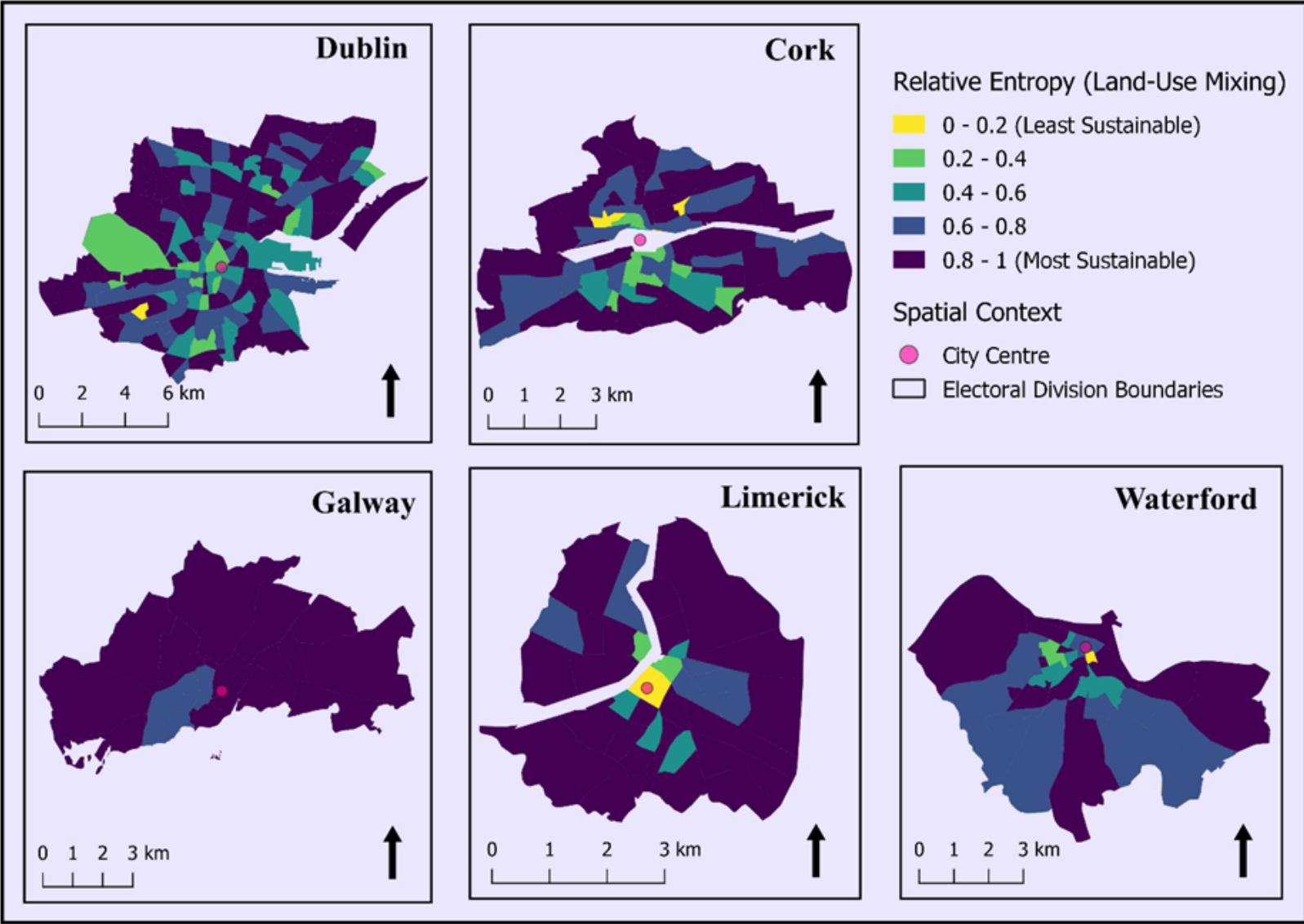


Figure A2.2 visualises the relative entropy of each Electoral Division within Irish city cores. Here, we observe that EDs within city cores produce consistently high levels of relative entropy. Low relative entropy scores in these areas appear best explained by the presence of natural parks (as in Dublin), or the clustering of commercial, industrial, and retail land-uses (as in Dublin and Limerick). Unlike in the main manuscript, we see little volatility in relative entropy estimates within and across city cores. Because Electoral Divisions serve as the smallest administrative unit of the state, these results may suggest that regional planning frameworks within cities are positively contributing to sustainability efforts by utilising land and infrastructure to a high degree of efficiency. However, the scale of our spatial units may also be masking important local heterogeneities in land-use configurations, like those highlighted in our main manuscript, and may therefore inadequately gauge the effectiveness of local land-use policies in contributing to achieving sustainability in development.

Figure A2.2: The Relative Entropy of Electoral Divisions within Irish City Cores



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Appendix 3 (A3): Comparing Relative Entropy Scores in Alternative European City Functional Urban Areas

Chapter 5 uses land-use mixing as an instrument to gauge the relative sustainability and efficiency of land-use developments across 28 European capital cities. However, only a sample were retained for the final chapter. Here, we present the results of identical analyses into the relative entropy of developments within the remaining European cities' Functional Urban Areas at a spatial scale consisting of 1km x 1km grids. Specifically, the cities presented here include Belfast, Lisbon, Rome, Athens, Warsaw, Ljubljana, Vilnius, Riga, Tallinn, Helsinki, Stockholm, Oslo, Copenhagen, and Reykjavik.

Figure A3.1 below illustrates our capital cities and their Functional Urban Areas. It contextualises the scale of our spatial units and their boundaries through the input of a city centre point, represented by the centroid of urban cores, whereby urban core is defined according to OECD standards (see (Dijkstra, Poelman and Veneri, 2019)).

Figure A3.1: Inset Maps Detailing The Functional Urban Areas of Our Capital Cities

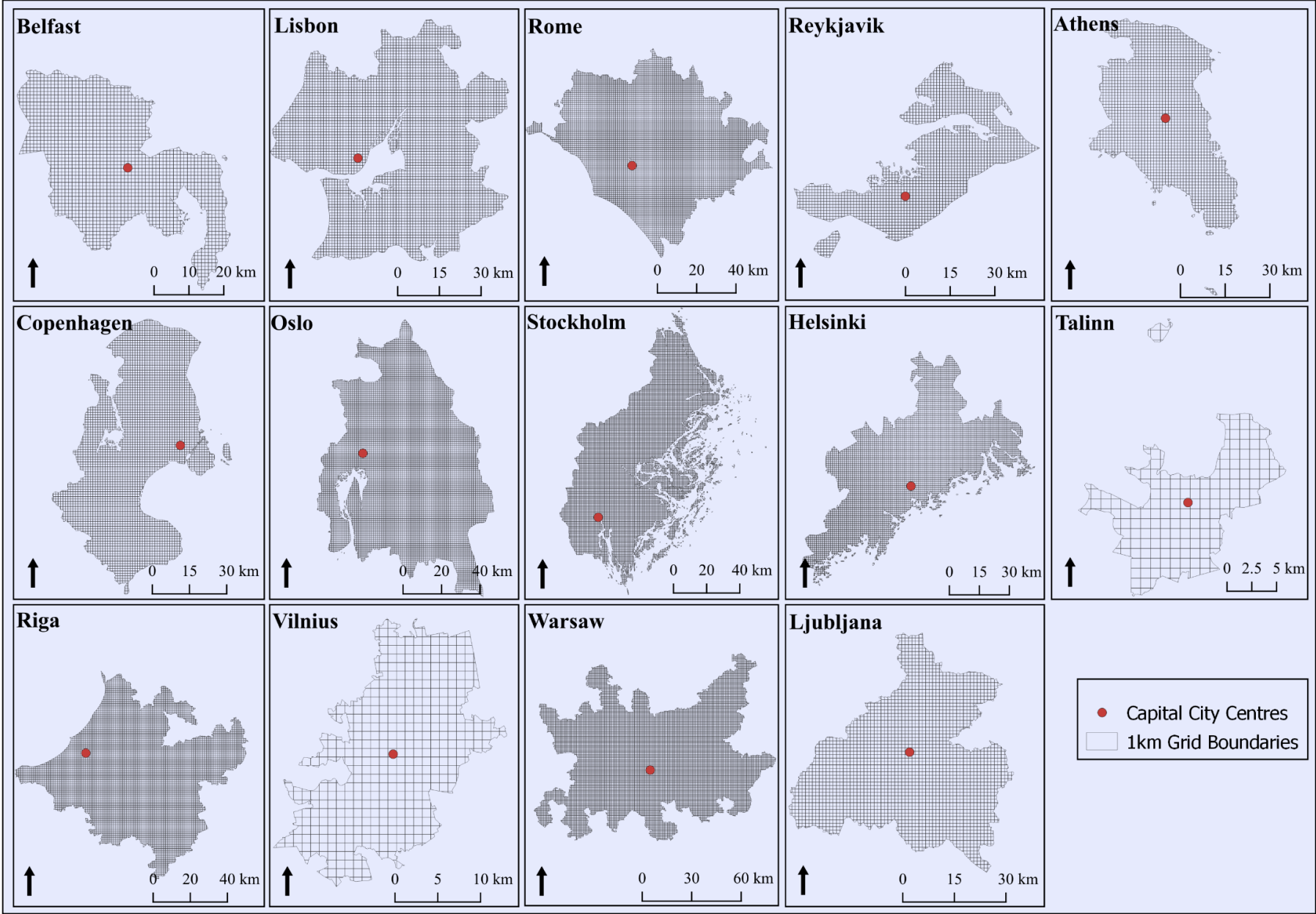


Figure A3.2 below displays the relative entropy scores obtained using just CORINE Land Cover data. Darker colours represent higher levels of relative entropy, and therefore, higher levels of efficiency and sustainability in land and infrastructure use. Across our sample of metropolitan areas, relatively high entropy scores generally concentrate in-and-around urban cores. As in **Chapter 5**, the theoretically expected inverse relationship between relative entropy and distances from urban cores is not apparent in most cities, except for parts of Belfast and Rome.

Therefore, we produce results which run contrary to a substantial body of literature (Lemoy & Caruso, 2020, 2021). In this context, we argue that this may stem from data inadequacies, hence our focus on improving discipline-standard datasets. Related to this concern is the considerable volatility in relative entropy scores both inside and outside urban cores. Volatility in this context may result from land-use segregation within city regions stemming from clustering phenomena which produce areas like Central Business Districts, national parks, or commuter belts. However, it could also suggest a lack of coordination between local developmental strategies accumulating to form uncontrolled and inefficient urban expansion patterns, something which aligns with historical manifestations of urban sprawl in monocentric regions across Europe (European Environmental Agency [EEA], 2006; OECD, 2018). But it could also be indicative of inadequate and restrictive zoning laws which may morph the developmental landscape. Collectively, these cities conform to the results and trends presented in **Chapter 5**.

Figure A3.2: Relative Entropy Estimates in European City Regions Using The CORINE Land Cover Dataset

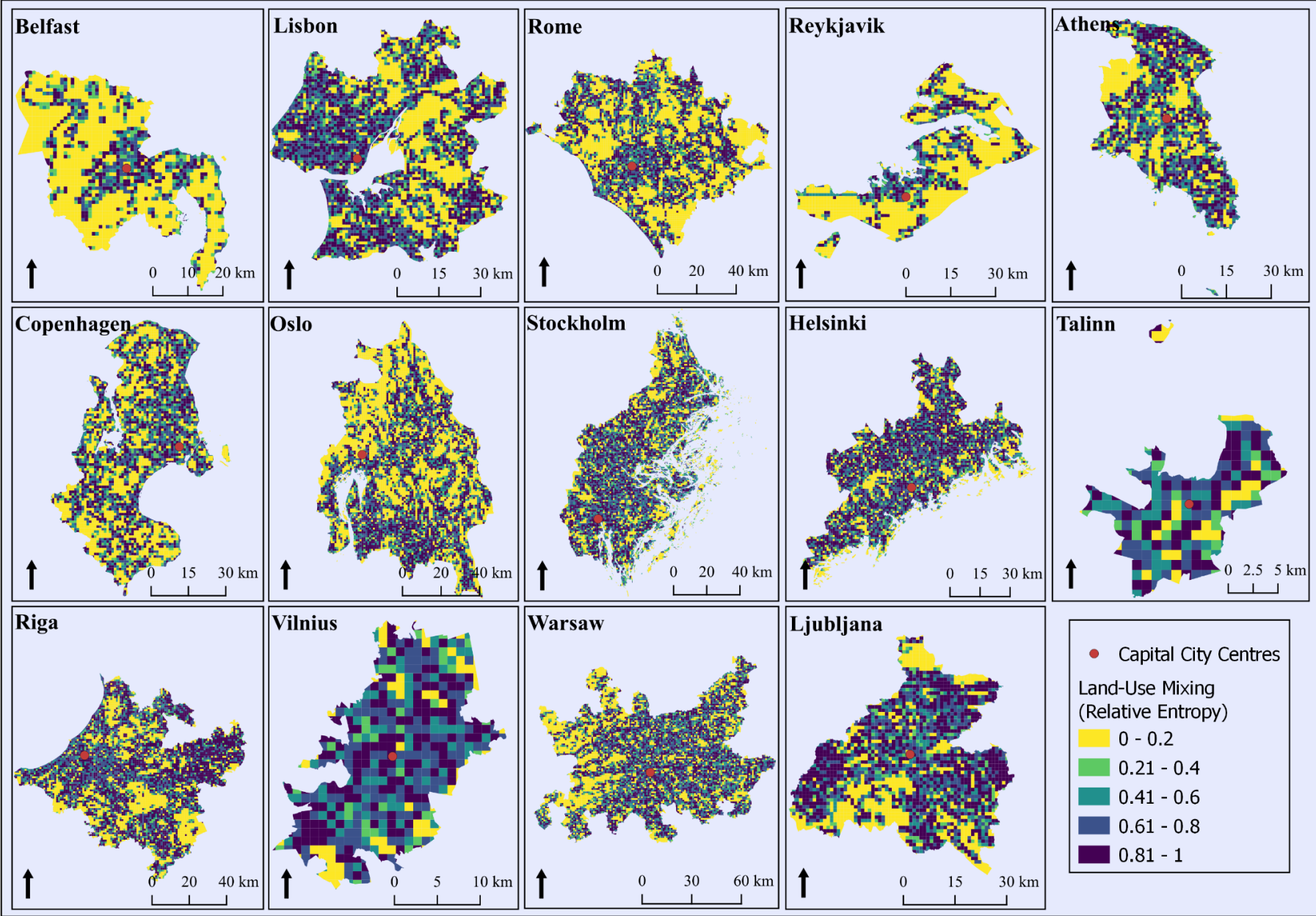


Figure A3.3 below displays relative entropy scores using our combined CORINE-OSM land-use dataset. Like before, we see that higher relative entropy scores generally concentrate in-and-around urban cores (i.e., the immediate surrounding area of city centre points), suggesting that urban centres across Europe are generally characterised by mixed-use and compact developments and these areas exhibit relatively higher densities. But they also cluster in peripheral areas. Here, the theoretically expected inverse relationship between distances from urban cores and relative entropy scores is more apparent across cities, particularly in Belfast, Rome, Reykjavik, and Oslo.

Also apparent here is the high relative entropy scores across regional peripheries, particularly in parts of Lisbon, Copenhagen, Stockholm, Helsinki, Riga, and Warsaw. While it is apparent that as you leave core areas, land-use segregation typically increases and land-use mixing generally decreases, it is not clear-cut, something possibly suggesting the emergence of polycentricity (Lemoy & Caruso, 2020, 2021). Despite this, within core areas, we see more consistent relative entropy scores and scores which are generally higher. This is indicative of land-use developments characterised by efficient land and infrastructure use, a finding generally harder to identify when using the CORINE Land Cover data alone, something we attribute to the lack of refined land-use classes within urban centres.

Figure A3.3: Relative Entropy Estimates in European City Regions using The Combined CORINE and OSM Dataset

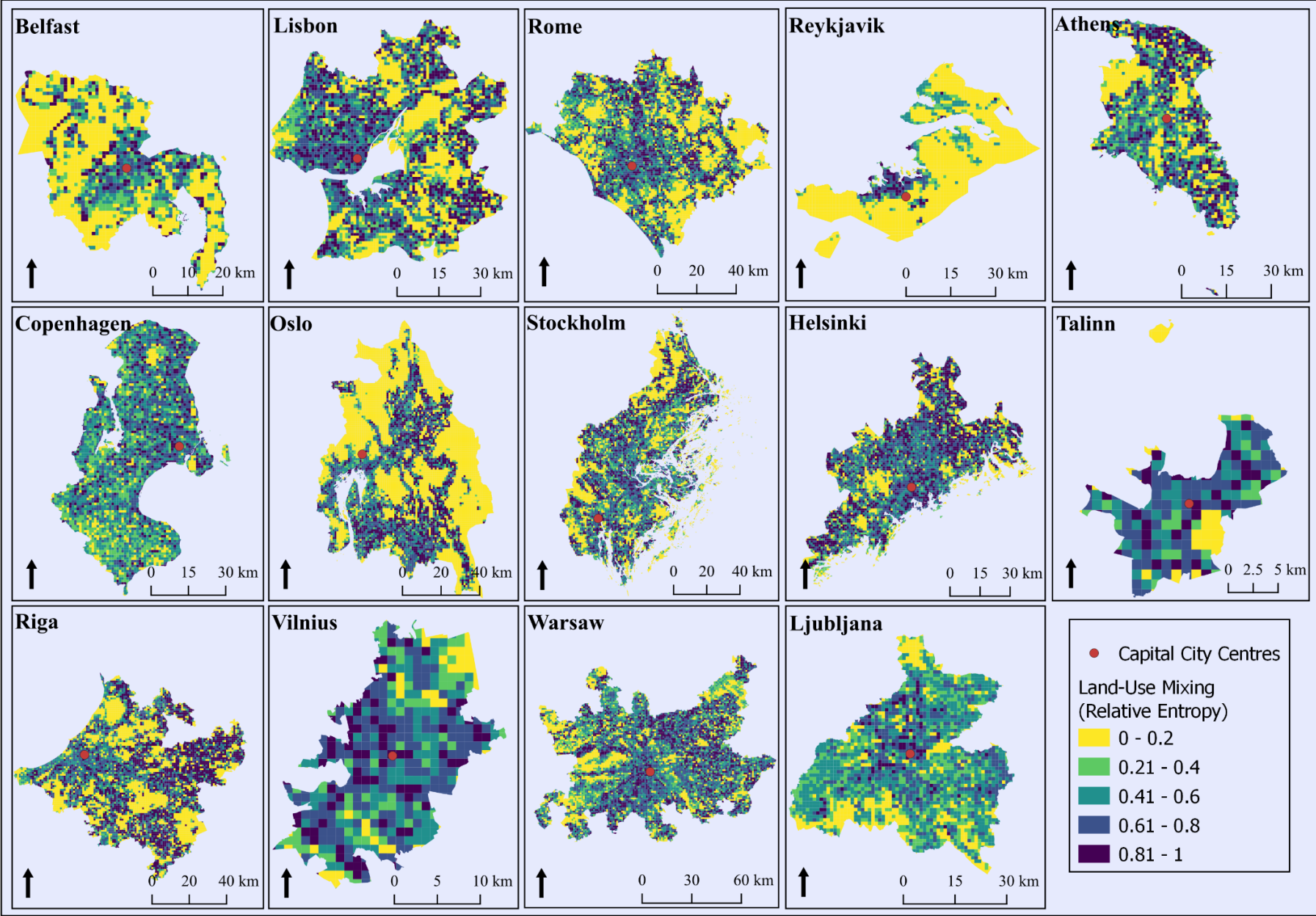


Figure A3.4 below displays the absolute cross-dataset differences in relative entropy scores. Dark colours reflect extreme disparities in the estimates, suggesting imprecision through either overestimation or underestimation, while lighter colours suggest relative consistency. We find that in most cities, both datasets produce significantly different estimates in many spatial units.

We argue that because the combined CORINE-OSM land-use catalogue produce more theoretically robust results which align with empirical literature, the combined land-use catalogue produces more accurate estimates. This argument is complimented by the fact that the land-use catalogues themselves contain a similar number of unique land-use classes, meaning if the underlying data are equally as insightful, they should produce similar relative entropy estimates. Considering this, our results suggest that in certain contexts, the CORINE Land Cover data underperforms as an empirical instrument but so too does OpenStreetMap.

As before, we find no discernible pattern between disparities in relative entropy scores and distances to urban cores (something reflected by low correlation scores) and observe that many spatial units report consistent relative entropy scores, indicators of both data sets' strength. Subsequently, we argue that underestimations in relative entropy (i.e., when relative entropy for the combined dataset exceeds that of the CORINE dataset) occur due to the CORINE's coarseness in land-use classification, particularly land relating to human activities like residential, commercial, retail, and industrial land. This is particularly evidenced in Rome, Copenhagen, and Tallinn. On the other hand, overestimations in relative entropy (i.e., when relative entropy for the combined dataset is lower than that of the CORINE dataset) occur because of CORINE's disproportionate weighting of land-use classes for rural/natural landscapes. This is particularly apparent in the natural landscapes surrounding Oslo, Stockholm, Lisbon, and Ljubljana.

Figure A3.4: Cross-Dataset Differences in Relative Entropy Estimates In European City Regions



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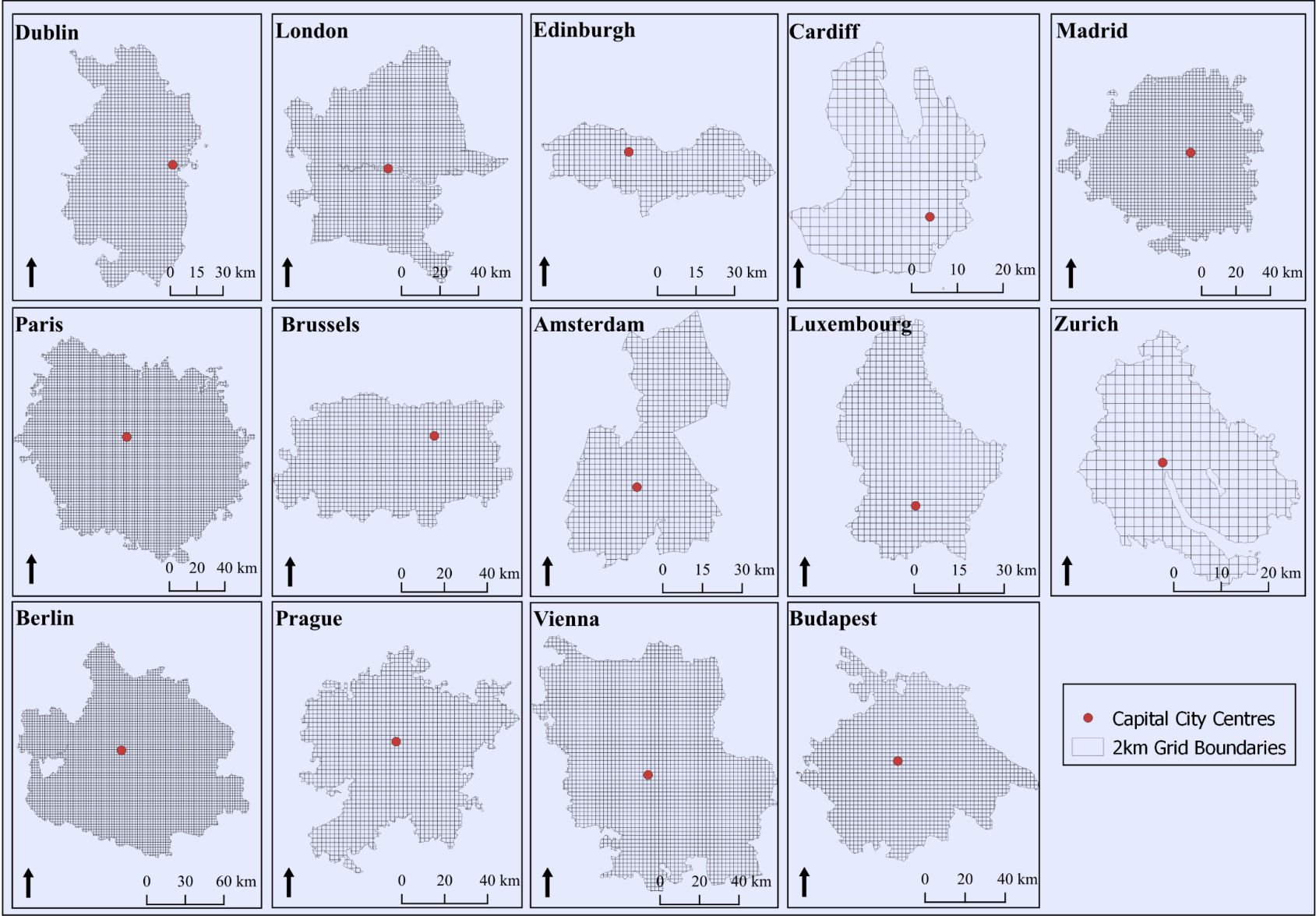
Appendix 4 (A4): Comparing Relative Entropy Scores in European City Functional Urban Areas at Alternative Spatial Scales

Chapter 5 uses land-use mixing as an instrument to gauge the relative sustainability and efficiency of land-use developments across 28 European capital cities. However, metrics of this nature can be highly sensitive to the Modifiable Area Unit Problem (MAUP), whereby the size of spatial units is typically determined by distances to urban centres, as with administrative data (i.e., NUTS Regions), and that the size of these units can significantly influence results (Song, Merlin and Rodriguez, 2013; Lemoy and Caruso, 2020, 2021).

There are two considerations to this issue. The first of which involves accounting for the role of spatial unit size on results. To address this, best practice involves employing multiple spatial scales and compare the results, as done in **Chapters 3** and **4** (Song, Merlin and Rodriguez, 2013). The second issue concerns the influence of distance from urban centres on relative entropy scores. To address this, researchers are advised to employ spatial weights into relative entropy calculations, a task for future research as laid out in **Chapter 5** (Chen and Song, 2020; Lemoy and Caruso, 2020, 2021).

The role of this Appendix is to investigate the role of spatial unit size in influencing the relative entropy scores produced in **Chapter 5**. **Chapter 5** used a standardised spatial scale consisting of 1km x 1km grids. Here, we replicate that analysis using a standardised spatial scale consisting of 2km x 2km grids. Figure A3.1 illustrates our capital cities and their Functional Urban Areas. It contextualises the scale of our spatial units and their boundaries through the input of a city centre point, represented by the centroid of urban cores, whereby urban core is defined according to OECD standards (see (Dijkstra, Poelman and Veneri, 2019)).

Figure A4.1: Inset Maps Detailing The Functional Urban Areas of The European Capital Cities Presented In Chapter 5 and Appendix 3



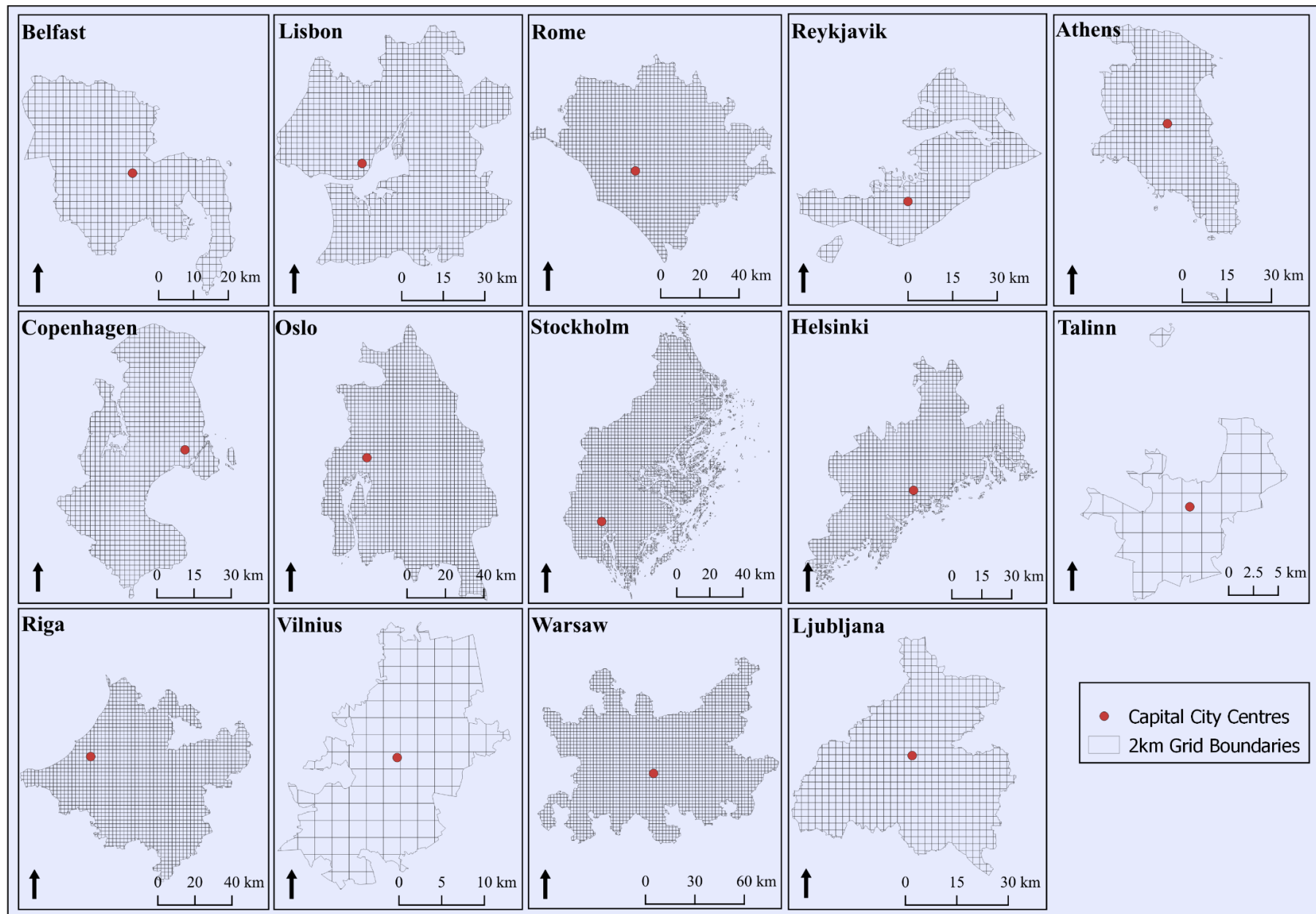
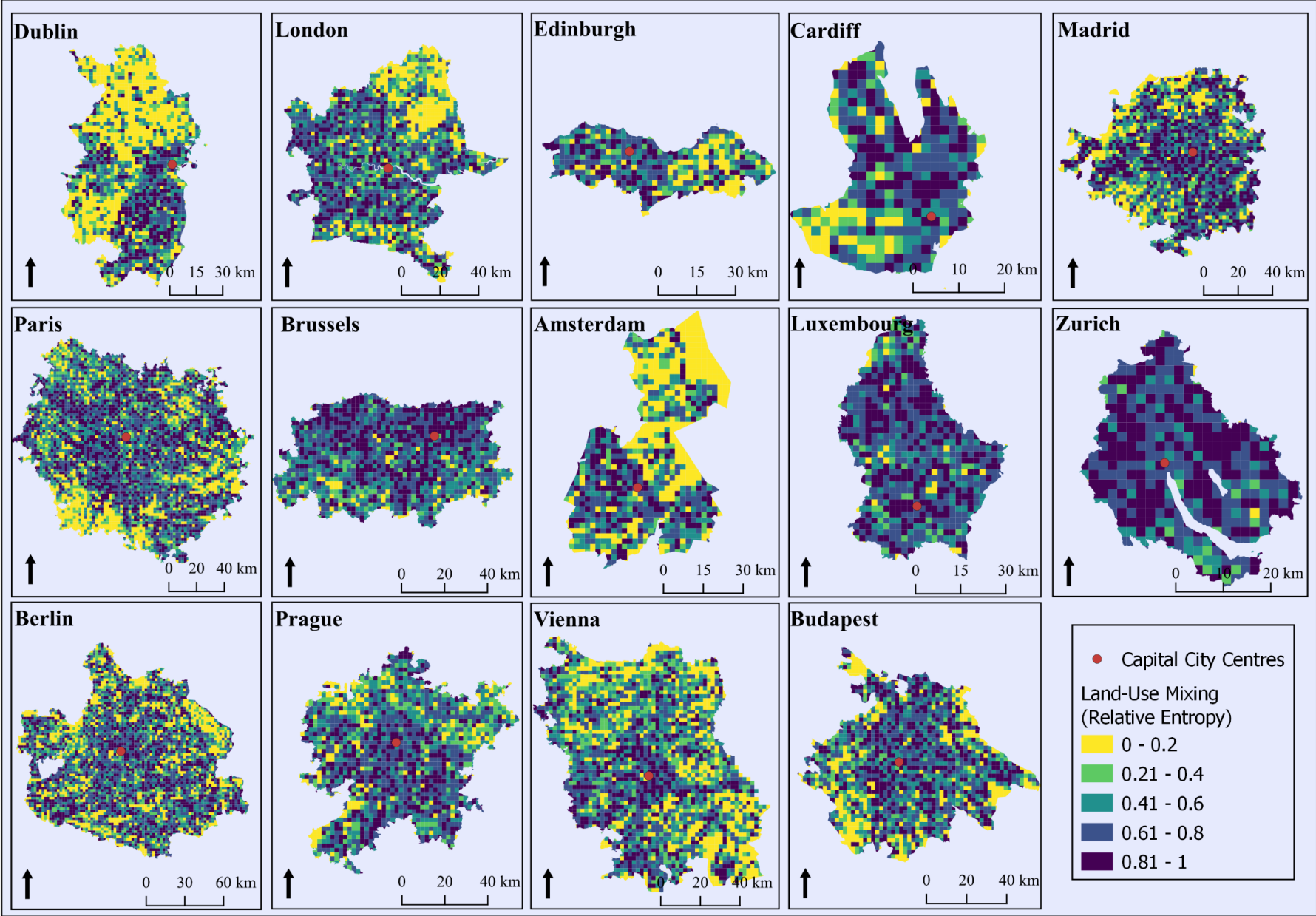


Figure A4.2 below displays the relative entropy scores obtained using just CORINE Land Cover data. Darker colours represent higher levels of relative entropy, and therefore, higher levels of efficiency and sustainability in land and infrastructure usage. Here, we see results consistent with those in **Chapter 5** and **Appendix 3 (A3)** in that the theoretically expected inverse relationship between relative entropy and distances from urban cores is not apparent in most cities, except for parts of Dublin, Vienna, Belfast, and Rome.

As before, we generally produce results which run contrary to existing literature, and results which produce highly volatile relative entropy scores. In this context, we argue volatility may be indicative of natural land-use segregation (i.e., the creation of natural parks, Central Business Districts, or commuter belts), a lack of coordination between local land-use developments/policies, and possibly restrictive zoning laws (European Environmental Agency [EEA], 2006; OECD, 2018; Moore-Cherry and Tomaney, 2019; Lemoy and Caruso, 2020, 2021). However, we also find that relative entropy is generally higher across all spatial units, something particularly evidenced in peripheries as the prominence of low-entropy areas has significantly decreased compared to when using the 1km x 1km spatial grid, as in **Chapter 5**.

Figure A4.2: Relative Entropy Estimates From The European Capital Cities Presented In Chapter 5 and Appendix 3 (CORINE)



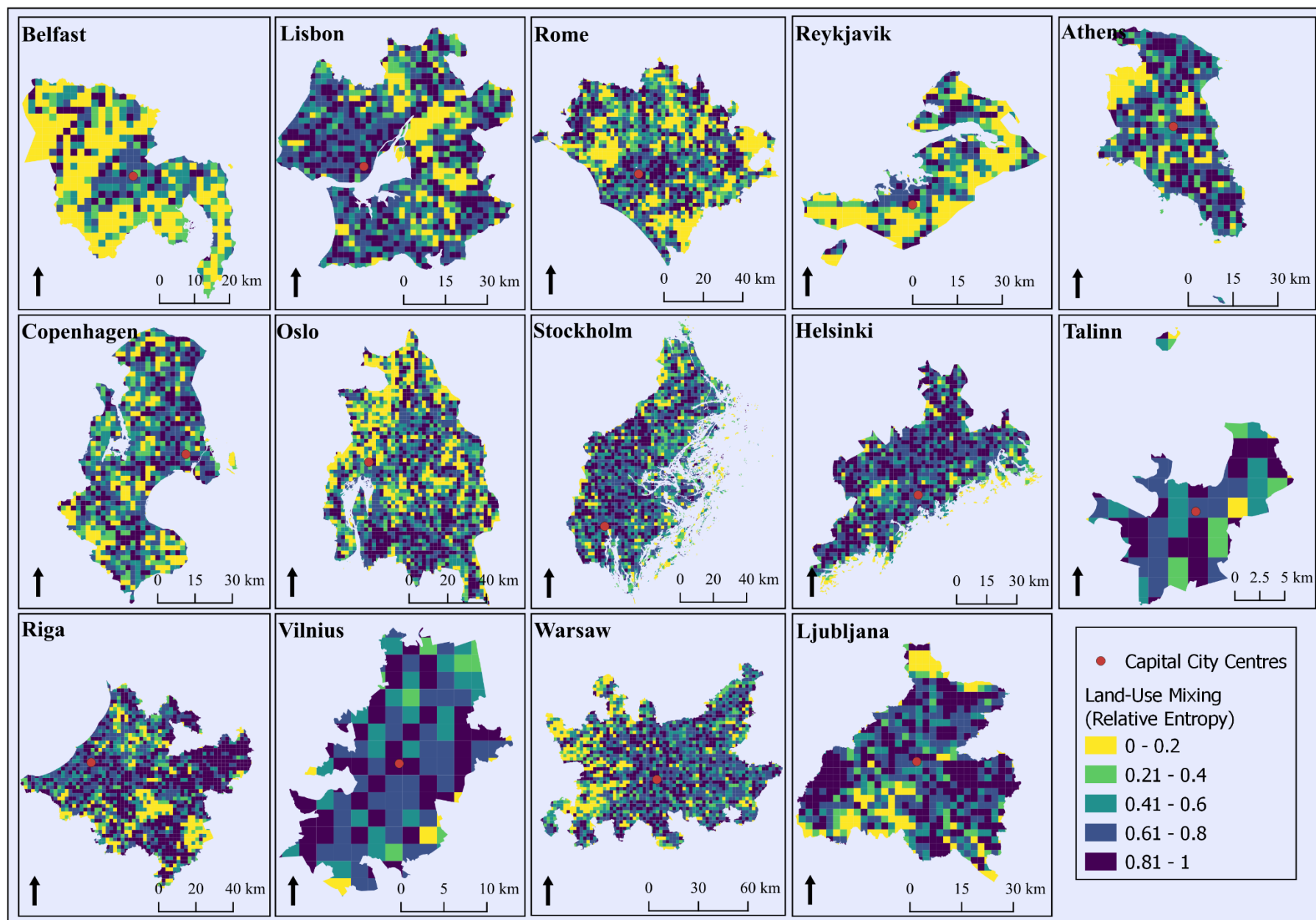
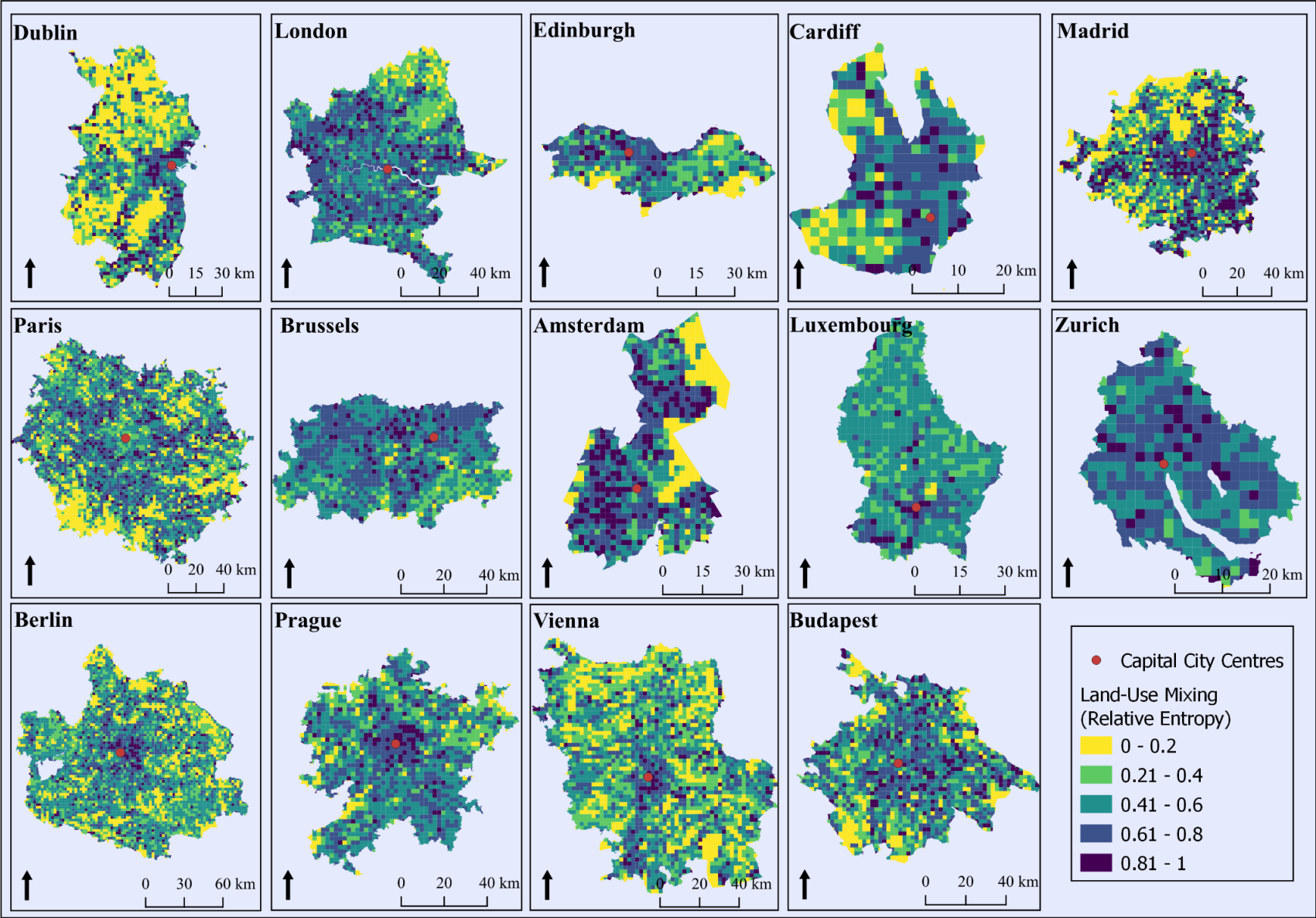


Figure A4.3 below displays the relative entropy scores obtained using our combined CORINE-OSM land-use dataset. We see that higher relative entropy scores generally concentrate in-and-around urban cores (i.e., the immediate surrounding area of city centre points), suggesting that urban centres across Europe are generally characterised by mixed-use and compact developments. But in some cities, like London, Brussels, Luxembourg, Zurich, and Copenhagen, relative entropy is consistently high throughout the entire Functional Urban Area, a finding not prevalent when using the 1km x 1km spatial boundaries. Here, we interpret these results to suggest that larger spatial units naturally facilitate higher levels of relative entropy due to their capturing of greater volumes of land, something which, if at an aggregated enough level, may always produce higher levels of land-use mixing (Song, Merlin and Rodriguez, 2013).

Figure A4.3: Relative Entropy Estimates From The European Capital Cities Presented In Chapter 5 and Appendix 3 (CORINE and OSM)



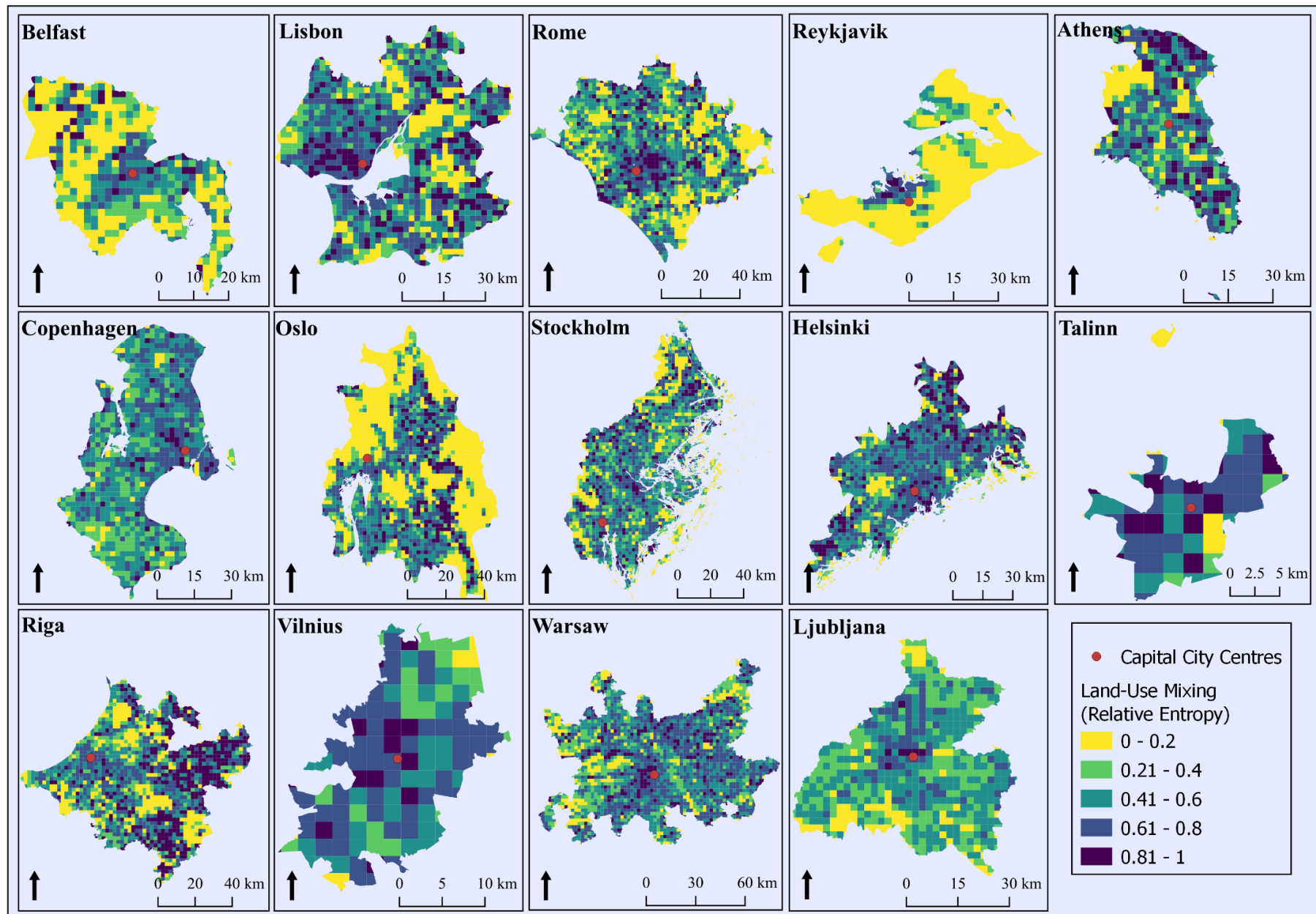
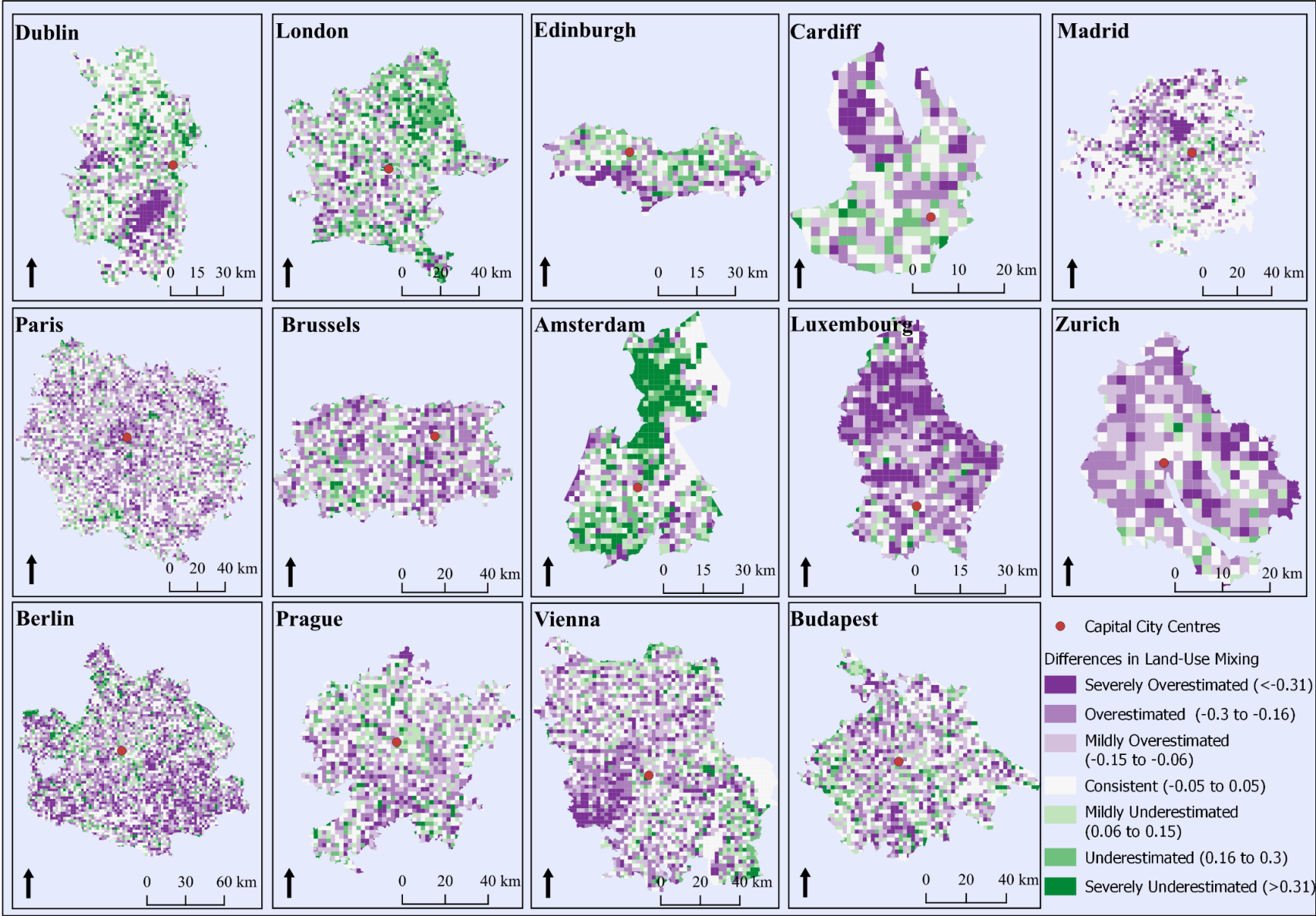


Figure A4.4 below displays the absolute cross-dataset differences in relative entropy scores. Here, dark colours reflect extreme disparities in the estimates, suggesting imprecision through either overestimation or underestimation, while lighter colours suggest relative consistency. We find that in most cities, both datasets produce significantly different estimates in many spatial units. Considering this, our results suggest that in certain contexts, the CORINE Land Cover data underperforms as an empirical instrument but so too does OpenStreetMap.

We find no discernible pattern between disparities in relative entropy scores and distances to urban cores (something reflected by low correlation scores) and report that many spatial units report consistent relative entropy scores, indicators of the strength of both datasets. However, we do observe that relative entropy estimates obtained from the CORINE dataset are much higher than those obtained from the combined catalogue in general, but particularly outside urban cores. This is not apparent in **Chapter 5** or **Appendix 3** and may therefore be directly related to the size of our spatial units. Considering this, we argue that because the CORINE Land Cover disproportionately weighs land-use classes in rural/natural landscapes, it facilitates higher degrees of land-use mixing in these areas easier. As in **Chapter 5** and **Appendix 3**, this is particularly evidenced in parts of Dublin, Luxembourg, Berlin, Oslo, Stockholm, Reykjavik, and Ljubljana.

Figure A4.4: Cross-Dataset Differences In Relative Entropy Estimates From The Capital Cities Presented In Chapter 5 and Appendix 3





List of References

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Appendix 5 (A5): Spatial Distribution of Relative Deprivation and Travel Mode Choices

The following paragraphs entail a supplementary investigation conducted to strengthen the robustness of our principal analysis in **Chapter 6: The relationship between built environments, transport infrastructure, and commute mode choices in Ireland**. Here, we visualise mode-use across Ireland and compare how the spatial distribution of mode use relates to the relative deprivation of residential areas. This allows us to spatially analyse the distribution of travel mode usage.

When analysing the spatial distribution of mode use across Ireland, we present a series of maps visualising the proportion of people per residential Electoral Division which travel using each mode under study, as shown in Figure A5.1. Complimenting this, is Figure A5.2, which visualises the relative deprivation of residential Electoral Divisions across Ireland. This analysis seeks to compare the spatial distributions of individual travel mode use and the socio-demographic deprivation of residential areas.

When analysing travel mode use (Figure A5.1), our results align with theoretical expectations. Car-use is the most popular mode used in most areas outside of major urban centres, a topic further addressed in **Chapters 6 and 7** (Vega and Reynolds-Feighan, 2008; O'Driscoll *et al.*, 2022; O'Riordan *et al.*, 2022). Mass public transport use concentrates in-and-around the five major administrative cities and is virtually absent elsewhere. Cycling is a mode generally not used by many people, regardless of residential locations. Finally, walking is a mode not frequently used by many people either, but people walk most frequently for commuting when residing in urban centres as well as in areas characterised by high levels of relative deprivation. This is evidenced through increases in variable correlation between the relative deprivation of areas and the frequency with which walking is chosen as the preferred commute mode. Collectively, the insights provided by Figure A5.1 complement the figures produced within Table 6.1 in **Chapter 6**.

Figure A5.2 maps the relative deprivation of residential Electoral Divisions. Comparing locations in which walking to work is most frequent with areas which suffer from the highest relative deprivation illustrates a pattern that suggests greater numbers of relatively deprived persons walk to work and subsequently must live and work in the same locality, indicating that these populations follow the expectations of Tiebout Sorting mechanisms (Nechyba and Walsh, 2004), results indicated throughout **Chapter 6**.

Figure A5.1: Mode Use Across Irish Electoral Divisions Expressed As A Percentage of ED Populations

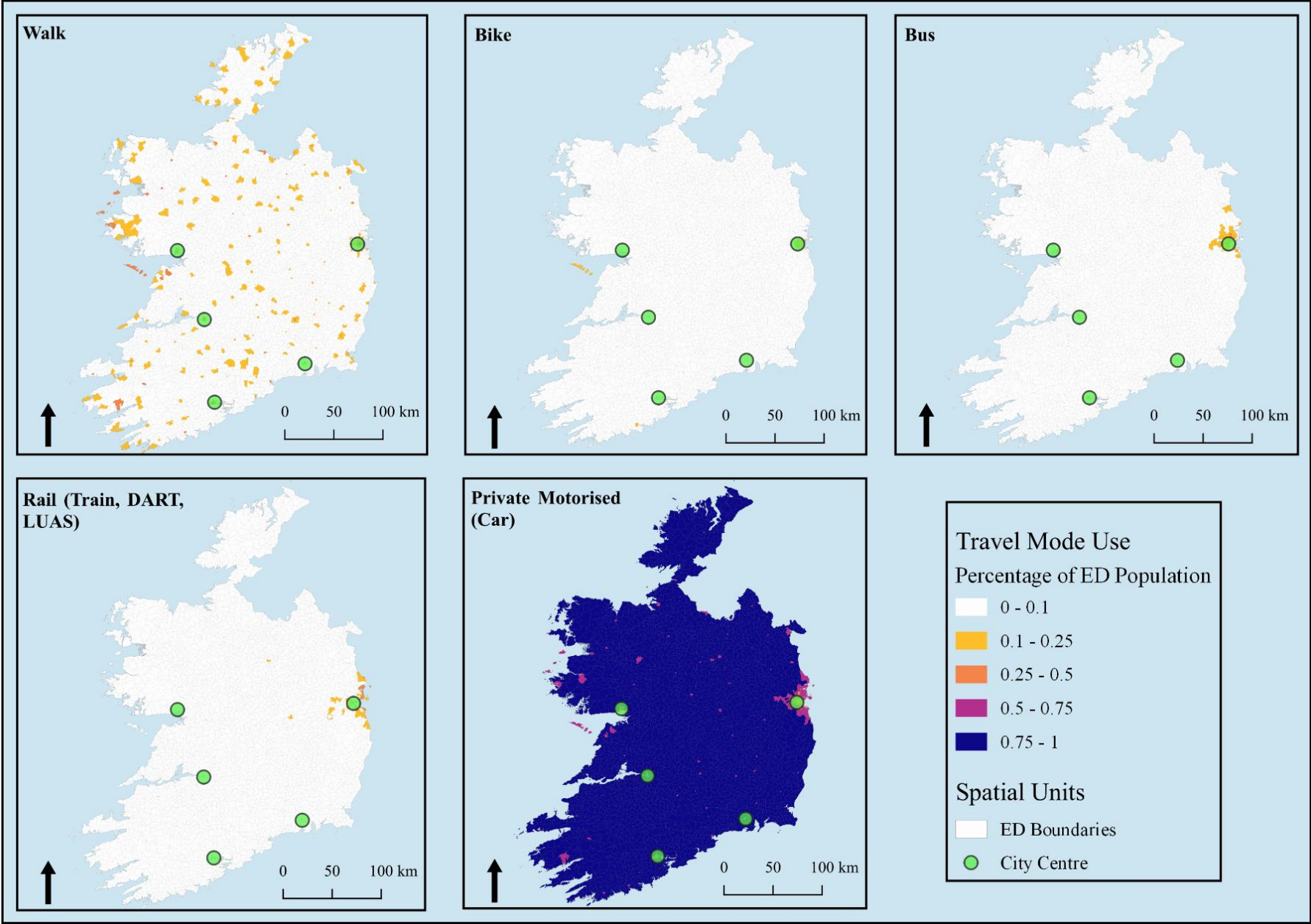
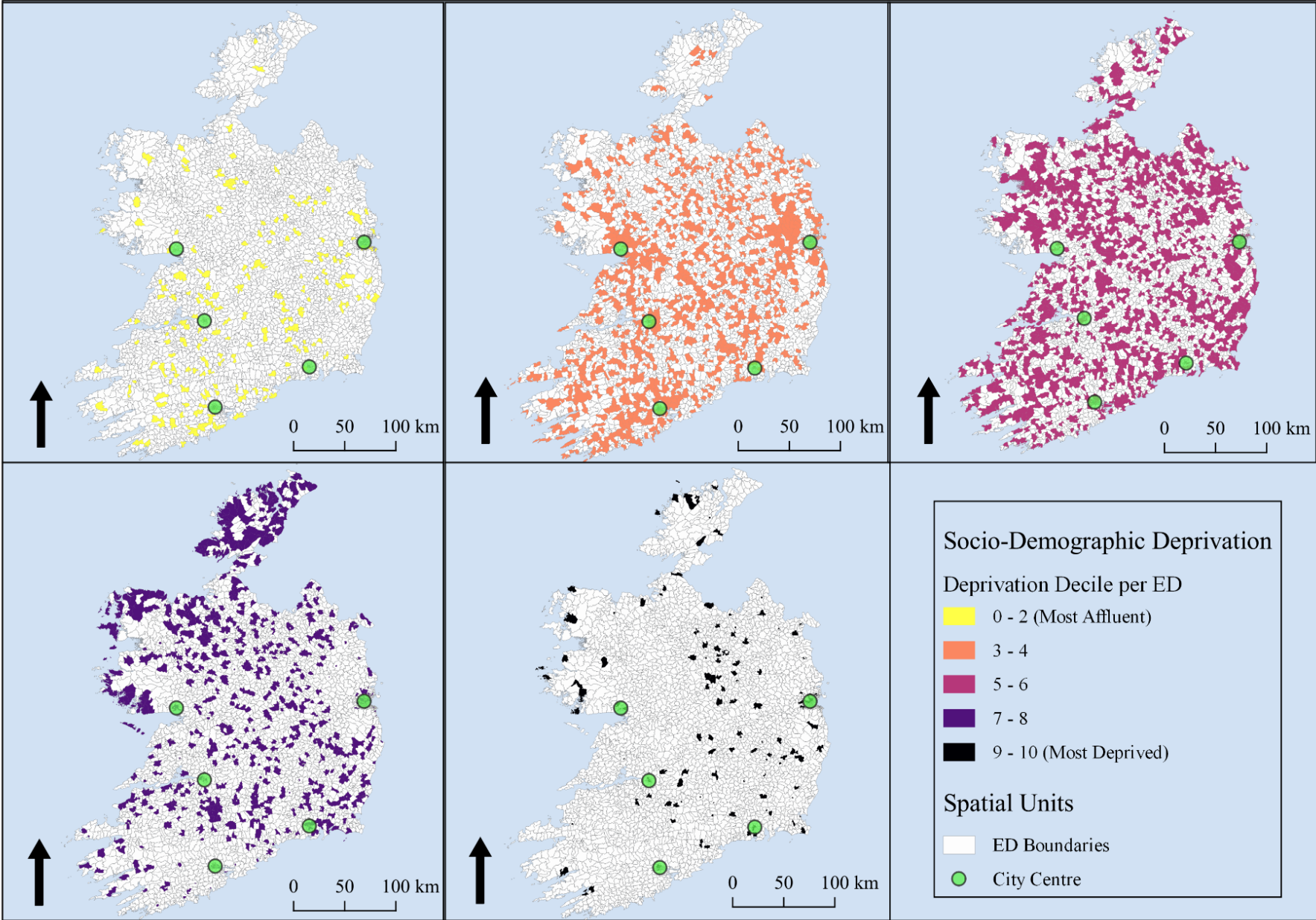


Figure A5.2: The Relative Socio-Demographic Deprivation of Residential Electoral Divisions



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Appendix 6 (A6): Variable and Model Robustness Checks For Chapter 6

The following paragraphs detail supplementary analyses conducted to strengthen the robustness of our principal investigations in **Chapter 6: The relationship between built environments, transport infrastructure, and commute mode choices in Ireland**. We conduct a correlation matrix on our key variables to test for multicollinearity and present the results here. We also provide a robustness test for our results by replicating the analysis in **Chapter 6** using an alternative modelling framework (spatially disaggregated Multinomial Logit Regression). Complementing this, is a robustness check surrounding the efficacy of our proposed model by comparing goodness-of-fit scores with alternative model configurations.

When testing for multicollinearity through a correlation matrix, all correlations lay between -0.48 and 0.57, as illustrated in Table A6.1 below. This supports the use of these variables in this analysis as low correlation (<0.65), suggests that these variables uniquely relate to one another. The pairs of variables with the highest correlation in this study relate to House Prices and Residential Area Types (correlation = 0.57), Roads and Active (correlation = 0.54), and Bus Stops ED and Residential Area Types (correlation = 0.51). All reported correlation coefficients are unchanged and are significant at the 1% level. In this case, we argue that this does not present problems related to multicollinearity due to our large sample size (235,936 unique observations) and because the nature of our methodological approach captures these correlations. Considering that most correlation coefficients are also relatively weak, we argue that statistical significance is unsurprising given the size of our sample.

Collectively, these relationships suggest that property market values and relative deprivation are negatively correlated, something theoretically expected, (Yang *et al.*, 2020; Zhang, van Duijn and van der Vlist, 2020), while urbanisation is also positively associated with the provision of public transport nodes, something also theoretically expected (Nechyba and Walsh, 2004; Millward, Spinney and Scott, 2013; Neatt, Millward and Spinney, 2017). In this case, a positive correlation between road networks and active travel networks is mostly due to the overlap of these data points. Specifically, to get a comprehensive network of footpaths, we were required to use roads with low speed limits as proxies. For more information of these transport networks, see **Chapter 8**.

Table A6.1: Correlation Matrix for Key Variables

	Means of Travel	Sex	Age	Seg	Journey Minutes	House hold Comp.	Residence Area Type ED	CORINE ED	Same Res- Work ED	Same Res- Work SA	Roads ED	Active ED	Bus Stops ED	Rail Stops ED	Deprivation ED	House Prices ED
Means of Travel	1															
Sex	0.001***	1														
Age	0.13***	0.01***	1													
Seg	-0.01***	0.15***	0.01***	1												
Journey Minutes	0.05***	0.05***	-0.03***	-0.11***	1											
Household Composition	-0.03***	0.09***	-0.15***	0.02***	0***	1										
Residence Area Type ED	-0.31***	0.03***	-0.1***	-0.08***	0.01***	0.01***	1									
CORINE ED	0.28***	-0.02***	0.1***	0.01***	0.02***	0***	-0.48***	1								
Same Res- Work ED	-0.2***	-0.01***	0.02***	0.1***	-0.29***	-0.02***	-0.08***	-0.04***	1							
Same Res- Work SA	-0.12***	0.02***	0.03***	0.06***	-0.11***	0***	-0.08***	0.03***	0.39***	1						
Roads ED	0.28***	0***	0.06***	0.07***	0***	-0.04***	-0.4***	0.27***	0.15***	0.02***	1					
Active ED	0.03***	0.01***	0***	0***	0.01***	-0.03***	0.26***	-0.15***	10***	-0.02***	0.54***	1				
Bus Stops ED	-0.09***	0.02***	-0.04***	-0.05***	0.06***	0.02***	0.51***	-0.18***	-0.03***	-0.05***	0.2***	0.5***	1			
Rail Stops ED	-0.1***	0.01***	-0.05***	-0.03***	0.01***	0.02***	0.23***	-0.05***	0***	-0.01***	-0.03***	0.11***	0.42***	1		
Deprivation ED	-0.16***	0***	-0.09***	0.15***	-0.1***	-0.03***	0.03***	-0.29***	0.13***	0.01***	-0.16***	-0.12***	-0.18***	0***	1	
House Prices ED	-0.16***	0.03***	-0.02***	-0.16***	0.08***	0.04***	0.57***	-0.25***	-0.12***	-0.06***	-0.2***	0.26***	0.43***	0.18***	-0.44***	1

*** denotes 1% Significance ** denotes 5% Significance * denotes 10% Significance.

Complementing this robustness check of our variable selection, is an analysis into the robustness of our results. Table A6.2 below illustrates the results of the marginal effects derived from changes in Socio-Demographics, Built and Social Environments, and Travel Considerations on Commute Mode Choices using a spatially disaggregated Multinomial Logit regression, a standard methodological framework within existing literature (Wilson *et al.*, 2010; Ermagun and Samimi, 2015; Arbués *et al.*, 2016; Guerra *et al.*, 2018; Eldeeb, Mohamed and Páez, 2021). Here, we utilise the entire 1,299,821 valid POWSCAR sample detailed in **Chapter 6**. This modelling approach produces results which are consistent with those obtained from our Generalised Structural Equation Modelling (GSEM) framework and subsequently support our results theoretical robustness.

When analysing this research question through a single-equation Multinomial Logit, we find that from a demographic perspective, increases in age the complexity of household structures are associated with increased likelihoods of car-use, while improvements in socioeconomic status are also associated with increased likelihoods of car-use. From a travel consideration perspective, we find that increases in commute duration negatively impacts the likelihood of active travel while living and working in the same localities positively influences the likelihood of active travel. From a built environment perspective, we observe how increases in land-use mixing and the continuity of urban fabrics are positively associated with the likelihood of active travel whilst the provision of transport infrastructure is only significant in influencing the likelihood of car-use. As in **Chapter 6**, we find that the quality of infrastructure shares a stronger association with the likelihood of public and active transport use than the provision of infrastructure on its own. Similarly, from a social environment perspective, we see that increases in deprivation are negatively associated with the likelihood of car-use.

Table A6.2: Marginal Effects of Built Environment, Socio-Demographic, Social Environment, and Travel Consideration Changes on Commute Mode Choices

Variables	dy/dx Walk	dy/dx Bike	dy/dx Bus	dy/dx TT	dy/dx Private Motor
Socio-Demographics					
Sex (1 = Male)	-0.0064*** (0.0005)	0.0168*** (0.0005)	-0.0051*** (0.0003)	0.0006*** (0.0001)	-0.0059*** (0.0008)
Age	-0.0076*** (0.0004)	-0.0022*** (0.0001)	-0.0076*** (0.0003)	-0.0029*** (0.0002)	0.0204*** (0.0006)
Household Composition					
Single Person			Base		
Single Parent	-0.0227***	-0.0072***	-0.0031***	-0.0021***	0.0353***

	(0.0017)	(0.0005)	(0.0009)	(0.0005)	(0.0023)
Two Parent Households	-0.0326***	-0.0037***	-0.0120***	-0.0018***	0.0502***
	(0.0015)	(0.0004)	(0.0008)	(0.0003)	(0.0019)
Other	0.0184***	0.0057***	0.0080***	0.0011**	-0.0333***
	(0.0017)	(0.0005)	(0.0009)	(0.0004)	(0.0024)
Socioeconomic Group					
Employers/Managers			Base		
Non-Manual	0.0264***	0.0004	0.0209***	0.0022***	-0.0500***
	(0.0014)	(0.0003)	(0.0008)	(0.0003)	(0.0018)
Manual (Semi) Skilled	0.0016	-0.0014***	0.0013**	-0.0074***	0.0059***
	(0.0012)	(0.0004)	(0.0006)	(0.0005)	(0.0017)
Unskilled and Agriculture	0.0419***	0.0065***	0.0279***	-0.0046***	-0.0717***
	(0.0023)	(0.0008)	(0.0015)	(0.0005)	(0.0031)
Other (Incl. Farmers)	0.0130***	-0.0037***	0.0039***	-0.0046***	-0.0086***
	(0.0013)	(0.0005)	(0.0008)	(0.0005)	(0.0020)
Travel Considerations					
Journey Minutes	-0.0011***	-0.0002***	0.0011***	0.0005***	-0.0003***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Same Res-Work ED	0.0886***	0.0108***	-0.0167***	-0.0174***	-0.0652***
	(0.0026)	(0.0009)	(0.0026)	(0.0030)	(0.0048)
Same Res-Work SA	0.0580***	0.0018	0.0158***	0.0102***	-0.0859***
	(0.0026)	(0.0012)	(0.0031)	(0.0035)	(0.0059)
Built Environment					
Relative Entropy	0.0002	-0.0005	0.0153***	0.0063**	-0.0213**
	(0.0054)	(0.0024)	(0.0038)	(0.0025)	(0.0090)
Land-Use (CORINE)	-0.0246***	-0.0056***	-0.0083***	-0.0083***	0.0470***
	(0.0025)	(0.0009)	(0.0015)	(0.0010)	(0.0039)
Bus Stops ED	0.0002	0.0000	0.0006***	0.0001***	-0.0007***
	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0002)
Rail Stops ED	0.0030**	-0.0001	-0.0029***	0.0016***	-0.0015
	(0.0013)	(0.0005)	(0.0006)	(0.0002)	(0.0021)
Bus Routes ED	0.0009***	0.0002***	0.0004***	-0.0000	-0.0015***
	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0002)
Rail Routes ED	0.0007	0.0003	0.0003	0.0015***	-0.0029**
	(0.0008)	(0.0003)	(0.0002)	(0.0002)	(0.0011)
Log Road ED	-0.0195***	-0.0083***	-0.0133***	-0.0026**	0.0439***
	(0.0020)	(0.0008)	(0.0018)	(0.0011)	(0.0036)
Log Active ED	-0.0027**	0.0010	0.0022**	0.0005	-0.0011
	(0.0012)	(0.0007)	(0.0009)	(0.0007)	(0.0023)
Log House Price ED	0.0245***	0.0091***	0.0071***	0.0102***	-0.0512***
	(0.0038)	(0.0012)	(0.0014)	(0.0013)	(0.0052)
Social Environment					
Deprivation ED	0.0084***	0.0009***	0.0016***	-0.0002	-0.0107***
	(0.0008)	(0.0003)	(0.0003)	(0.0003)	(0.0012)

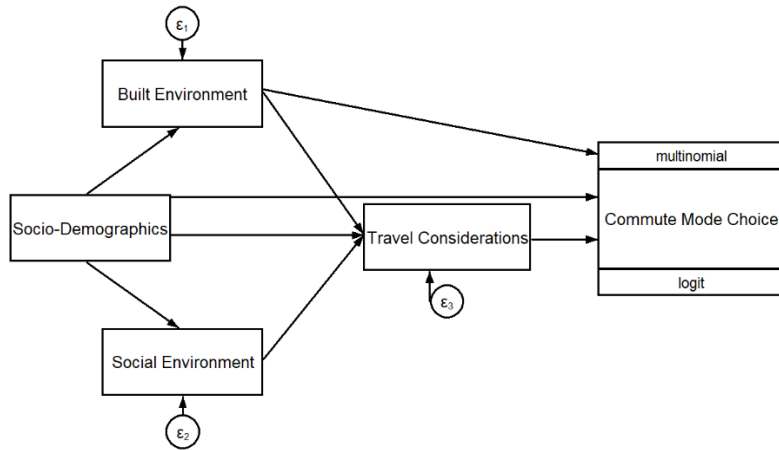
*** denotes 1% Significance ** denotes 5% Significance * denotes 10% Significance. Standard Errors are clustered around residential EDs in the Multinomial Logit prior and are presented here in brackets.

When employing (Generalised) Structural Equation Modelling, an important robustness check involves analysing whether the proposed model is the best model to describe the relationships of interest. In this regard, we construct four alternative modelling frameworks and evaluate

whether they produce superior Goodness of Fit, whereby goodness of fit is gauged according to Akaike Information Criterion (AIC) and Schwartz Bayesian Information Criterion (SBIC) scores. This primarily involves the construction of new path diagrams using the same key variable groups (i.e., Socio-Demographics, Built Environments, Social Environments, Trip Considerations). We refrain from removing any key variable group from the model entirely because there is substantial evidence justifying their inclusion across theoretical and empirical literature (Button, 2010; Ewing and Cervero, 2010; Millward, Spinney and Scott, 2013; Gim, 2018). Therefore, we argue that excluding one key group constitutes the omission of a key variable within this multi-stage decision. AIC and SBIC scores allow us to evaluate the efficacy of our modelling specification by measuring how effectively the proposed model fits the underlying data, something also considered by (Ding *et al.*, 2017). In this regard, lower scores are typically perceived as better.

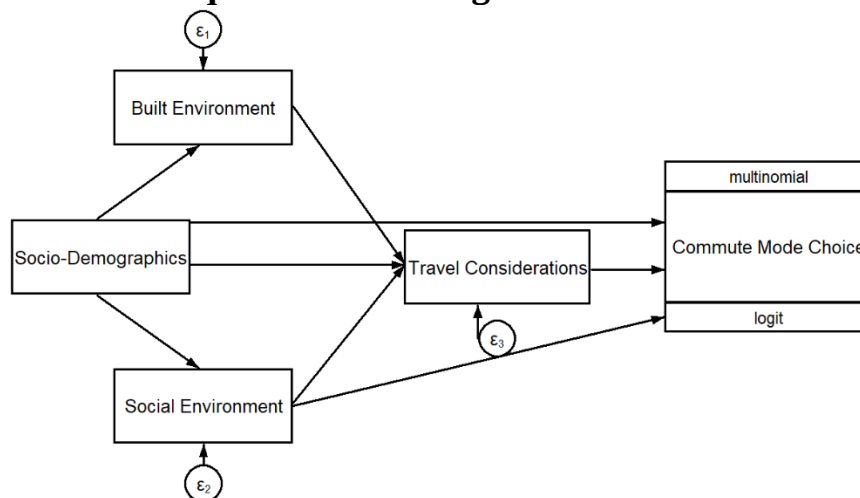
Our first alternative specification (Figure A6.1 below) posits that the underlying social characteristics of residential environments (i.e., socio-demographic deprivation) do not directly influence commute mode choices. Instead, they only directly influence travel considerations, meaning they indirectly influence these choices. Specifically, in this path diagram there is no arrow directly linking Social Environments and Commute Mode Choices. As indicated previously, removing this consideration from the modelling framework entirely is inappropriate due to the theoretical and empirical evidence base suggesting that spatial mismatches in the provision of (high-quality) infrastructure can occur along socio-demographic lines (Zenou and Boccoard, 2000; Tyndall, 2017; Picard and Zenou, 2018; Bastiaanssen, Johnson and Lucas, 2022). We find that the model presented in **Chapter 6** produces lower (superior) AIC and SBIC scores than the model presented in Figure A6.1, justifying its use as our principal model.

Figure A6.1: Alternative Theoretical Model Describing A Generalised Structural Equation Modelling Framework



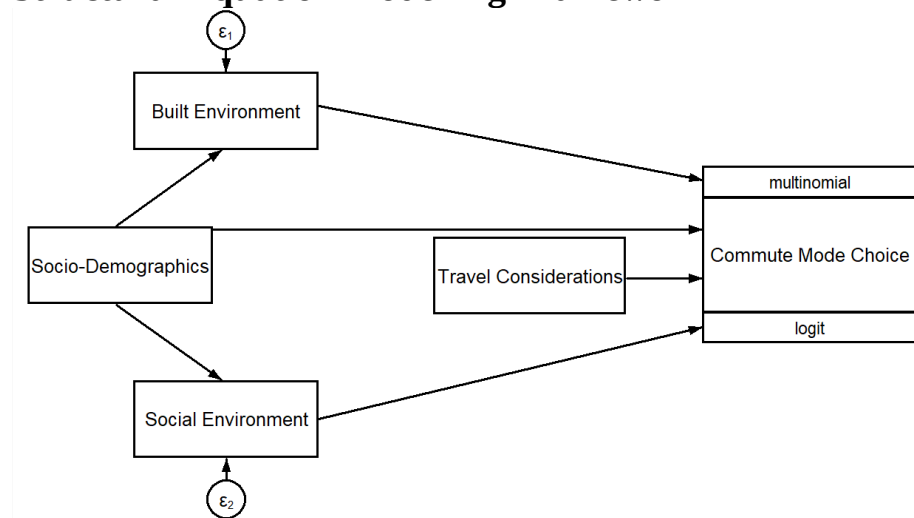
Our second alternative specification (Figure A6.2 below) posits that the physical characteristics of residential environments do not directly influence commute mode choices. Instead, they only directly influence travel considerations, meaning they indirectly influence these choices. Specifically, in this path diagram there is no arrow directly linking Built Environments and Commute Mode Choices. Removing this consideration from the modelling framework entirely is inappropriate due to the theoretical and empirical evidence base suggesting that the physical configuration of built environments (i.e., land-use configurations and infrastructure provision) exert a distinct influence on commute mode choices by defining regional time-space geographies (and by extension required travel distances) while also defining the mode choice set available to individuals (Ewing and Cervero, 2010; Gim, 2013). We find that the model presented in **Chapter 6** produces lower (superior) AIC and SBIC scores than the model presented in Figure A6.2 below.

Figure A6.2: Alternative Theoretical Model Describing a Generalised Structural Equation Modelling Framework



Our third alternative specification (Figure A6.3 below) argues that travel considerations are independent of socio-demographics and built/social environments, but directly influence commute mode choices. Specifically, in this path diagram there are no arrows directly linking Socio-Demographics, Built Environments, and Social Environments to Travel Considerations. Removing travel considerations from the modelling framework is inappropriate because considerations like travel distances clearly influence the mode choices available to individuals. We find that the model presented in **Chapter 6** produces lower (superior) AIC and SBIC scores than the model presented in Figure A6.3 below.

Figure A6.3: Alternative Theoretical Model Describing a Generalised Structural Equation Modelling Framework



Our final alternative specification (Figure A6.4 below) argues that socio-demographic considerations do not directly influence commute mode choices. Instead, they indirectly influence these choices by defining the types of environments people reside alongside trip-specific concerns. Specifically, in this path diagram there is no arrow directly linking Socio-Demographics and Commute Mode Choices. Omitting this direct link between socio-demographics and commute mode choices implies that these variables do not appropriately proxy for tastes/preferences and that these variables do not define the travel-related resources available to households (resources which directly influence the travel mode options available to individuals for everyday travel), implications which go against a large body of theoretical and empirical evidence (Tiebout, 1956; Nechyba and Walsh, 2004; Button, 2010). We find that the model presented in **Chapter 6** produces lower (superior) AIC and SBIC scores than the model presented in Figure A6.4 below.

Figure A6.4: Alternative Theoretical Model Describing a Generalised Structural Equation Modelling Framework

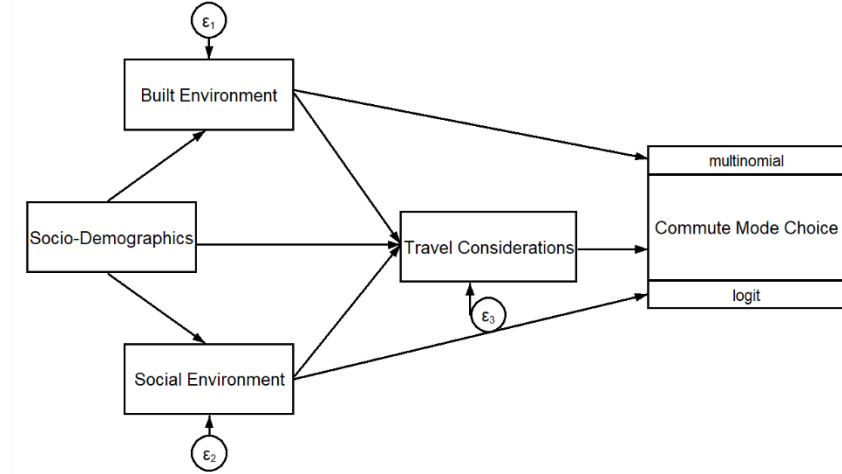


Table A6.3 below extrapolates these robustness tests and presents the specific AIC and SBIC scores associated with each modelling structure relative to the model proposed in the main manuscript (Figure 6.1). We can clearly see that the model proposed in our main manuscript produces lower (better) AIC and SBIC scores relative to alternative specifications, justifying its retention in **Chapter 6**.

Table A6.3: AIC and BIC Scores For Each Modelling Structure

Model Specification Described According To Differences From Figure 6.1	AIC	SBIC
Figure 6.1: Modelling specification proposed in main manuscript.	4871696	4873776
Figure A6.1: No direct relationship (arrow) between Social Environments and Commute Mode Choice.	4872602	4874642
Figure A6.2: No direct relationship (arrow) between Built Environments and Commute Mode Choice.	4896619	4898425
Figure A6.3: Travel Considerations are independent (no arrows) of Socio-Demographics, Built and Social Environments.	4872547	4874548
Figure A6.4: No direct relationship (arrow) between Socio-Demographics and Commute Mode Choice.	4878450	4880178

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Appendix 7 (A7): Variable and Model Robustness Checks For Chapter 6

The following paragraphs detail supplementary analyses conducted to strengthen the robustness of our principal investigations in **Chapter 7: Travel Behaviours and Built Environments On The School-Run**. We conduct a correlation matrix on our key variables to test for multicollinearity and present the results here. We also provide a robustness test for our modelling framework in the form of a single-equation spatially disaggregated Multinomial Logit Regression which analyses the relationship between the built and social characteristics of residential and school environments, travel considerations, and travel mode choice using the same variable structure as presented in our Generalised Structural Equation Model in the main manuscript.

We find no issues relating to multicollinearity within our dataset as all variable correlations lay between -0.36 and 0.62, as illustrated in Table A7.1 below. This supports the use of these variables in this analysis as low correlation (<0.65), suggests that these variables relate uniquely to one another. The pairs of variables with the highest correlation in this study relate to Road Network Provision and the CORINE Land Cover (0.62) whereby the provision of roads is positively associated with the segregation of land-use; Deprivation and Bus Stop Provision (0.44), whereby bus stop provision is positively associated with the relative deprivation of Small Areas; and House Prices and CORINE Land Cover (-0.36), whereby property market values are positively associated urbanisation. All reported correlation coefficients are significant at the 1% level. In this case, we argue that this does not present problems related to multicollinearity due to our large sample size and because the nature of our methodological approach captures these correlations. Considering that most correlation coefficients are also relatively weak, we argue that statistical significance is unsurprising given the size of our sample.

Table A7.1: Correlation Matrix for Key Variables

	Means of Travel	Sex	Seg	Journey Minutes	House Comp.	Relative Entropy	CORINE SA	Same Res- Work ED	Same Res- Work SA	Roads SA	Active SA	Bus Stops SA	Rail Stops SA	Bus Routes SA	Rail Routes SA	Depriva tion SA	House Prices SA
Means of Travel	1																
Sex	-0.02***	1															
Seg	-0.11***	-0.01**	1														
Journey Minutes	-0.07***	-0.01**	0.01***	1													
House Comp.	0.12***	0.01***	-0.31***	-0.01***	1												
Relative Entropy	-0.08***	-0.01	0.00	-0.03***	-0.05***	1											
CORINE SA	0.26***	0.00	0.00	0.02***	0.11***	-0.16***	1										
Same Res-School ED	-0.24***	0.01***	0.03***	-0.33***	-0.03***	0.12***	-0.07***	1									
Same Res-School SA	-0.10***	0.01**	0.00***	-0.12***	0.00***	0.02***	0.02***	0.24***	1								
Roads SA	0.29***	0.00**	-0.01***	0.06***	0.15***	-0.22***	0.62***	-0.19***	0.01***	1							
Active SA	0.05***	0.00	-0.01***	0.01***	0.03***	0.18***	0.10***	-0.01***	0.01***	0.21***	1						
Bus Stops SA	-0.05***	0.00	-0.02***	0.02***	-0.01***	0.15***	-0.19***	-0.01***	0.03***	-0.07***	0.08***	1					
Rail Stops SA	-0.01***	0.00	0.00	0.00***	-0.01***	0.04***	-0.05***	0.00***	0.00***	-0.01***	0.02***	0.17***	1				
Bus Routes SA	-0.08***	0.00	-0.01***	0.00	-0.04***	0.13***	-0.25***	-0.01***	0.01***	-0.13***	0.01***	0.07***	0.09***	1			
Rail Routes SA	-0.01*	0.00	-0.01***	0.00***	0.00	0.04***	-0.01***	0.00***	0.00***	0.00***	0.03***	0.20***	0.11***	0.09***	1		
Deprivation SA	-0.09***	0.00***	0.16***	-0.06***	-0.10***	0.02***	-0.06***	0.09***	0.04***	-0.11***	-0.06***	0.44***	0.00***	0.00***	-0.03***	1	
House Prices SA	-0.04***	0.00	-0.14***	0.03***	0.04***	0.11***	-0.36***	-0.01***	-0.03***	-0.34***	0.06***	-0.03***	0.03***	0.19***	0.07***	-0.27***	1

Complementing this robustness check of our variable selection, is an analysis into the robustness of our modelling framework and subsequent results. Table A7.2 below illustrates the relative risk ratios (whereby coefficients > 1 indicate positive values and coefficients < 1 indicate negative values) derived from changes in Socio-Demographics, Built and Social Environments, and Travel Considerations on Travel Mode Choices using a spatially disaggregated Multinomial Logit regression, a standard methodological framework within existing literature (Wilson *et al.*, 2010; Ermagun and Samimi, 2015; Arbués *et al.*, 2016; Guerra *et al.*, 2018; Eldeeb, Mohamed and Páez, 2021). Here, we use the same POWSCAR sample detailed in **Chapter 7**. This modelling approach produces results which are consistent with our Generalised Structural Equation Modelling (GSEM) framework used in the main manuscript and subsequently support our model's theoretical robustness.

When analysing this research question through a single-equation Multinomial Logit, we find that from a demographic perspective, we find that boys are have greater odds of travelling actively and via transit relative to cars than girls. Additionally, increases in the complexity of household structures is associated with increased odds of car-use relative to all other modes, while improvements in socioeconomic status are also associated with greater odds of car-use relative to all other modes. From a travel consideration perspective, we find the same inconsistencies with our travel time variable whereby it produces counterintuitive results. However, as in **Chapter 7**, we find that other variables clearly related to trip durations, such as living and going to school in the same locality, are consistently associated with increased odds of active travel.

From an environmental perspective, we see that land-use configurations and transport infrastructure provision exert similar influences over travel mode choices at both residential and school locations, departing slightly from the insights provided in **Chapter 7**. However, the effects these variables have on travel mode choices remains consistent. For instance, increases in land-use mixing and developmental compactness is consistently associated with increased odds of public and active transport use, while increases in mode-specific infrastructure (i.e., roads) provision is consistently associated with increased odds of mode use (i.e., cars). Again, this relationship is strongest between cars and roads. When focusing on the social characteristics of residential and school environments, we find that increases in the deprivation of Small Areas is consistently associated with increased odds of walking relative to cars.

Table A7.2: The Relationships Between Socio-Demographics, Residential/School Environment Characteristics, Travel Considerations, and Travel Mode Choice

	Walk	Bike	Bus	Rail	Car
Socio-Demographics					
Sex (Male =1)	1.1297*** (0.0153)	11.884*** (0.6017)	1.0375*** (0.0112)	1.3784*** (0.0561)	Base
Household Composition					
Other	Base				
Single Parent	0.8728*** (0.0412)	0.7690** (0.0787)	0.9260 (0.0438)	1.0871 (0.1447)	Base
Two Parent Homes	0.6280*** (0.0291)	0.6165*** (0.0621)	0.7759*** (0.0359)	0.8821 (0.1161)	Base
Socioeconomic Group					
Other (Incl. Farmers)	Base				
Employers/Professionals	0.6574*** (0.0147)	0.8292*** (0.0403)	0.6681*** (0.0125)	0.9365 (0.0622)	Base
Non-Manual	0.8427*** (0.0184)	0.8876** (0.0459)	0.8847*** (0.0171)	0.9635 (0.0657)	Base
Manual (Semi) Skilled	1.1162*** (0.0282)	1.0645 (0.0625)	1.0957*** (0.0243)	1.1526* (0.0977)	Base
Unskilled/Agri	1.4274*** (0.0603)	1.2957*** (0.1349)	1.3846*** (0.0545)	0.9343 (0.1598)	Base
Residential Social Environment					
Deprivation	1.0241*** (0.0051)	1.0228*** (0.0071)	1.0052 (0.0038)	0.9750** (0.0112)	Base
Residential Built Environment					
CORINE SA	0.6107*** (0.0228)	0.5974*** (0.0327)	0.9284** (0.0317)	0.6267*** (0.0559)	Base
Relative Entropy SA	1.2046*** (0.0536)	1.0381 (0.0673)	0.7597*** (0.0265)	1.0084 (0.1031)	Base
Roads	0.4304*** (0.0085)	0.4806*** (0.0137)	1.0112 (0.0127)	0.7466*** (0.0293)	Base
Active	1.1033*** (0.0124)	1.1060*** (0.0240)	0.9977 (0.0055)	0.9452*** (0.0178)	Base
Bus Stops	1.0708*** (0.0168)	1.0756*** (0.0204)	1.0272** (0.0122)	1.0514** (0.0242)	Base
Rail Stops	1.0219 (0.1029)	0.9116 (0.1103)	1.0965 (0.0658)	1.8143*** (0.1846)	Base
Bus Routes	1.0330*** (0.0031)	1.0217*** (0.0038)	1.0275*** (0.0030)	0.9869* (0.0067)	Base
Rail Routes	1.0477*** (0.0145)	1.0442** (0.0202)	0.9947 (0.0113)	1.2678*** (0.0256)	Base
House Prices	0.9665 (0.0234)	1.2089*** (0.0442)	0.8673*** (0.0147)	1.8081*** (0.0945)	Base
Destination Social Environment					
Deprivation	1.0161*** (0.0045)	0.9549*** (0.0064)	0.9771*** (0.0031)	0.9287*** (0.0078)	Base
Destination Built Environment					
CORINE SA	0.9942 (0.0301)	1.0964* (0.0568)	1.3957*** (0.0316)	0.7139*** (0.0417)	Base

Relative Entropy SA	1.0543 (0.0519)	1.7883*** (0.1493)	0.8323*** (0.0307)	0.6798*** (0.0659)	Base
Roads	0.8524*** (0.0141)	0.7325*** (0.0196)	1.2002*** (0.0158)	0.7572*** (0.0184)	Base
Active	1.0576*** (0.0124)	1.1045*** (0.0230)	0.9752*** (0.0073)	0.9085*** (0.0199)	Base
Bus Stops	1.0218*** (0.0063)	1.0915*** (0.0087)	0.9809*** (0.0051)	0.9614*** (0.0086)	Base
Rail Stops	1.1330*** (0.0386)	0.5551*** (0.0615)	1.0004 (0.0236)	1.7298*** (0.0617)	Base
Bus Routes	0.9970** (0.0012)	1.0114*** (0.0016)	1.0090*** (0.0010)	1.0031** (0.0014)	Base
Rail Routes	0.9772** (0.0106)	1.0630*** (0.0127)	1.0174** (0.0076)	1.1643*** (0.0130)	Base
House Prices	0.8673*** (0.0178)	1.5178*** (0.0465)	0.8365*** (0.0183)	1.4939*** (0.0580)	Base
Travel Considerations					
Journey Minutes	1.0227*** (0.0012)	0.9834*** (0.0022)	1.1066*** (0.0009)	1.1265*** (0.0018)	Base
Same Res-School ED	5.1531*** (0.1518)	1.5436*** (0.0762)	0.2757*** (0.0119)	0.0762*** (0.0207)	Base
Same Res-School SA	5.3009*** (0.3607)	1.8855*** (0.3527)	0.8142 (0.1122)	3.1196 (3.2959)	Base

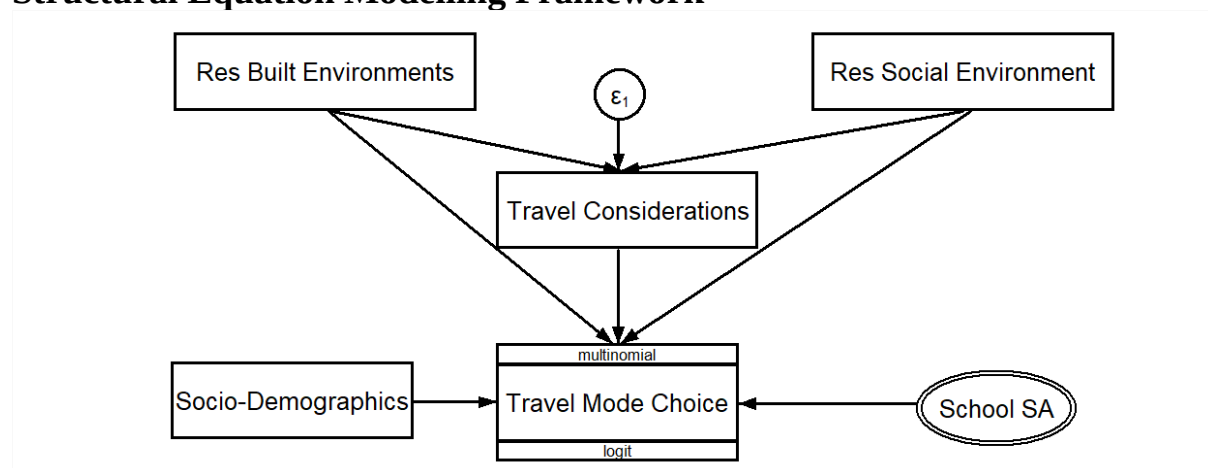
*** denotes 1% Significance ** denotes 5% Significance * denotes 10% Significance. Standard Errors are clustered around residential EDs in the Multinomial Logit prior and are presented here in brackets.

When employing (Generalised) Structural Equation Modelling, an important robustness check involves analysing whether the proposed model is the best model to describe the relationships of interest. In this regard, we construct alternative modelling frameworks and evaluate whether they produce superior Goodness of Fit, whereby goodness of fit is gauged according to Akaike Information Criterion (AIC) and Schwartz Bayesian Information Criterion (SBIC) scores. This primarily involves the construction of new path diagrams using the same key variable groups (i.e., Socio-Demographics, Built Environments, Social Environments, Trip Considerations). We refrain from removing any key variable group from the model entirely because there is a significant evidence base justifying their inclusion across theoretical and empirical literature (Button, 2010; Ewing and Cervero, 2010; Millward, Spinney and Scott, 2013; Gim, 2018). Therefore, we argue that excluding one key group constitutes the omission of a key variable within this multi-stage decision. AIC and SBIC scores allow us to evaluate the efficacy of our modelling specification by measuring how effectively the proposed model fits the underlying data, something also considered by (Ding *et al.*, 2017). In this regard, lower scores are typically perceived as better.

Our first alternative specification (Figure A7.1 below) posits that the built and social characteristics of destination (school) environments do not directly influence travel mode choices. Instead, our Latent Variable capturing school locations may sufficiently capture

destination-specific variation in travel behaviours. In this path diagram, although the arrows remain the same, we remove all destination-specific variables pertaining to land-use configurations and transport infrastructure. The rationale for this change is that the model configuration presented in Chapter 7 (Figure 7.1) may be overfitted and that our Latent variable capturing school locations can sufficiently capture school-location environmental effects on travel behaviours. However, as indicated previously, removing this consideration from the modelling framework entirely may be inappropriate due to the theoretical and empirical evidence base suggesting that destination environments do exert a distinct influence on travel behaviours by defining travel routes, hence our retention of the latent variable (Ding, Cao and Wang, 2018; Ton *et al.*, 2019; Wang *et al.*, 2021; Jeong, Lee and Gim, 2022). We find that the model presented in Figure 7.1 produces lower (superior) AIC and SBIC scores than the model presented in Figure A7.1, justifying its use as our principal model.

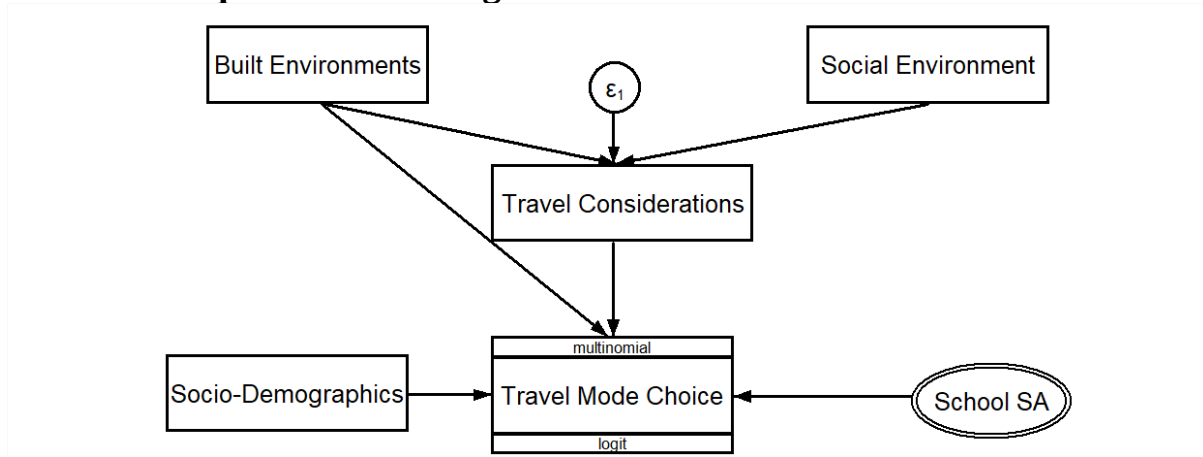
Figure A7.1: Alternative Theoretical Model Visualising A Generalised Structural Equation Modelling Framework



Our second alternative specification (Figure A7.2 below) argues that the underlying social characteristics of residential environments (i.e., socio-demographic deprivation) do not directly influence travel mode choices. Instead, they only directly influence travel considerations, meaning they indirectly influence these choices. Specifically, in this path diagram there is no arrow directly linking Social Environments and Travel Mode Choice. As indicated previously, removing this consideration from the modelling framework entirely is inappropriate due to the theoretical and empirical evidence base suggesting that spatial mismatches in the provision of (high-quality) infrastructure can occur along socio-demographic lines, mismatches which can define the efficiency, reliability, and safety associated with transport modes (Zenou and Boccard, 2000; Tyndall, 2017; Picard and Zenou, 2018; Bastiaanssen, Johnson and Lucas,

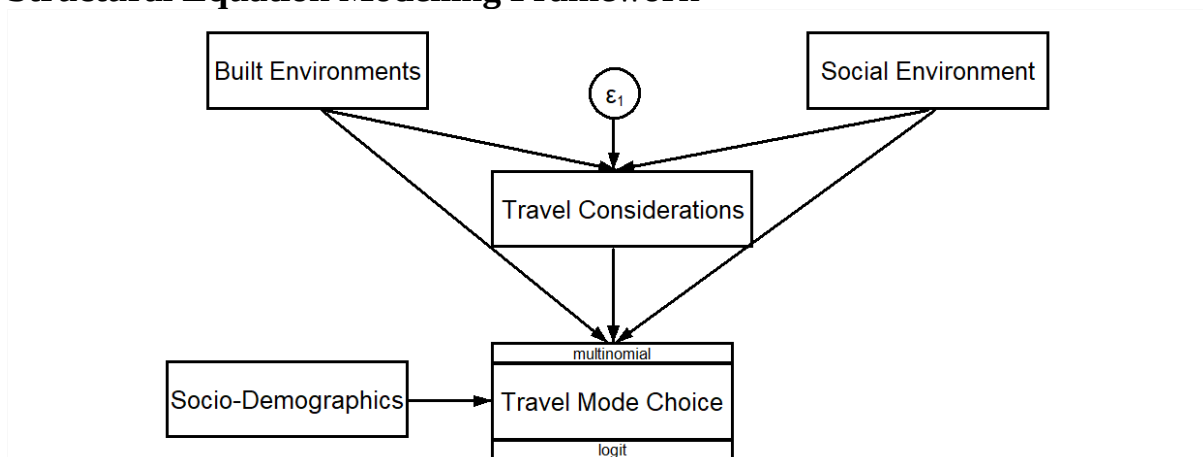
2022). We find that the model presented in Figure 7.1 produces lower (superior) AIC and SBIC scores than the model presented in Figure A7.2, justifying its use as our principal model.

Figure A7.2: Alternative Theoretical Model Visualising A Generalised Structural Equation Modelling Framework



Our third alternative specification (Figure A7.3 below) suggests that school-specific concerns (our Latent Variable) do not directly influence travel mode choices. Specifically, in the path diagram there is no latent variable used. This specification argues that factors outside of the built and social environment of school locations, like those pertaining to parental perceptions of travel route safety, do not influence mode choices. Instead, the built and social characteristics of these environments capture these perceptions, an argument which goes against existing evidence (Ermagun and Samimi, 2015; Mitra and Buliung, 2015; Christiansen *et al.*, 2017; Sun, Ermagun and Dan, 2017). We find that the model presented in Figure 7.1 produces lower (superior) AIC and SBIC scores than the model presented in Figure A7.3, justifying its use as our principal model.

Figure A7.3: Alternative Theoretical Model Visualising A Generalised Structural Equation Modelling Framework



Importantly, additional changes to our modelling framework produce models which cannot be created and computed. In instances where: 1) our model argues that built environments do not directly influence travel mode choices, only indirectly through travel considerations and 2) our model argues that travel considerations are independent of built and social environments; issues arise because starting values cannot be defined and the model is perpetually not concave. Despite this, the three specifications offered here describe reasonable alternative modelling specifications which may describe the relationships within our dataset.

Table A7.3 below extrapolates these robustness tests and presents the specific AIC and SBIC scores associated with each modelling structure relative to the model proposed in the main manuscript (Figure 7.1). We can clearly see that the model proposed in our main manuscript produces lower (better) AIC and SBIC scores relative to alternative specifications, justifying its retention in our manuscript.

Table A7.3: AIC and BIC Scores For Each Modelling Structure

Model Specification Described According To Differences From Figure 7.1	AIC	SBIC
Figure 7.1: Modelling Specification Proposed in Main Manuscript	2729712	2731769
Figure A7.1: Destination Environments (Built and Social) Do Not Directly Influence Travel Mode Choice	2734090	2735723
Figure A7.2: Social Environments (Residential and School Locations) Do Not Directly Influence Travel Mode Choice	2730091	2732063
Figure A7.3: Destination-Specific Considerations (Latent Variable) Do Not Directly Influence Travel Mode Choice	2756137	2758152

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Appendix 8 (A8): Adjusting Active Travel Thresholds Used In Chapter 8

In the series of Figures below, we present the results of multiple sensitivity analyses conducted on the active mode travel threshold adopted in **Chapter 8: Retail Sprawl and CO2 Emissions: Retail Centres in Irish Cities**.

Within the active travel literature, 10-minutes is commonly used as the maximum distance people will regularly travel actively when shopping/for leisure (in a one-way trip). However, to investigate the robustness of our analysis in **Chapter 8**, we extend these thresholds to 15- and 20-minutes. The travel speeds assumed in our analysis do not change, meaning people are assumed to walk/cycle at a normal, leisurely pace (6km/h for walking; 16km/h for cycling). These speed metrics, like our travel-time measures are taken from a wide evidence base within the active travel literature (Millward *et al.*, 2013; Spinney and Millward, 2013; Susilo *et al.*, 2013; Heinen and Chatterjee, 2015; Central Statistics Office [CSO], 2016; Gunn *et al.*, 2017; Ton *et al.*, 2019; Ton *et al.*, 2020; Jeong *et al.*, 2022).

The Figures below present results which are consistent with those presented in **Chapter 8**. Specifically, bigger circles demonstrate greater numbers of active travellers, whilst smaller circles illustrate smaller numbers. They represent the sum of the surrounding population who are assumed to travel for shopping/leisure via walking and cycling to their nearest retail centre. This indicates probable destinations for shopping, and the locations in which active travel is arguably best facilitated, something known to abate travel-related environmental degradation by encouraging shifts in travel mode use away from car-use (Millward *et al.*, 2013; Gunn *et al.*, 2017; Ton *et al.*, 2019; Ton *et al.*, 2020).

These Figures demonstrate that our findings using a 10-minute travel threshold are robust. While retail-centre specific results change slightly once travel thresholds are adjusted, our overall results remain unchanged. That is, centrally located retail centres are hypothetically more accessible to greater numbers of active travellers. Despite natural increases in the absolute numbers of active travellers theoretically visiting these retail centres as thresholds are extended, evidence indicates that the likelihood of people visiting these centres decreases with every additional minute travelled, an effect especially pronounced after 15-minutes.

Figure A8.1: 10-Minute Thresholds For Walking And Cycling

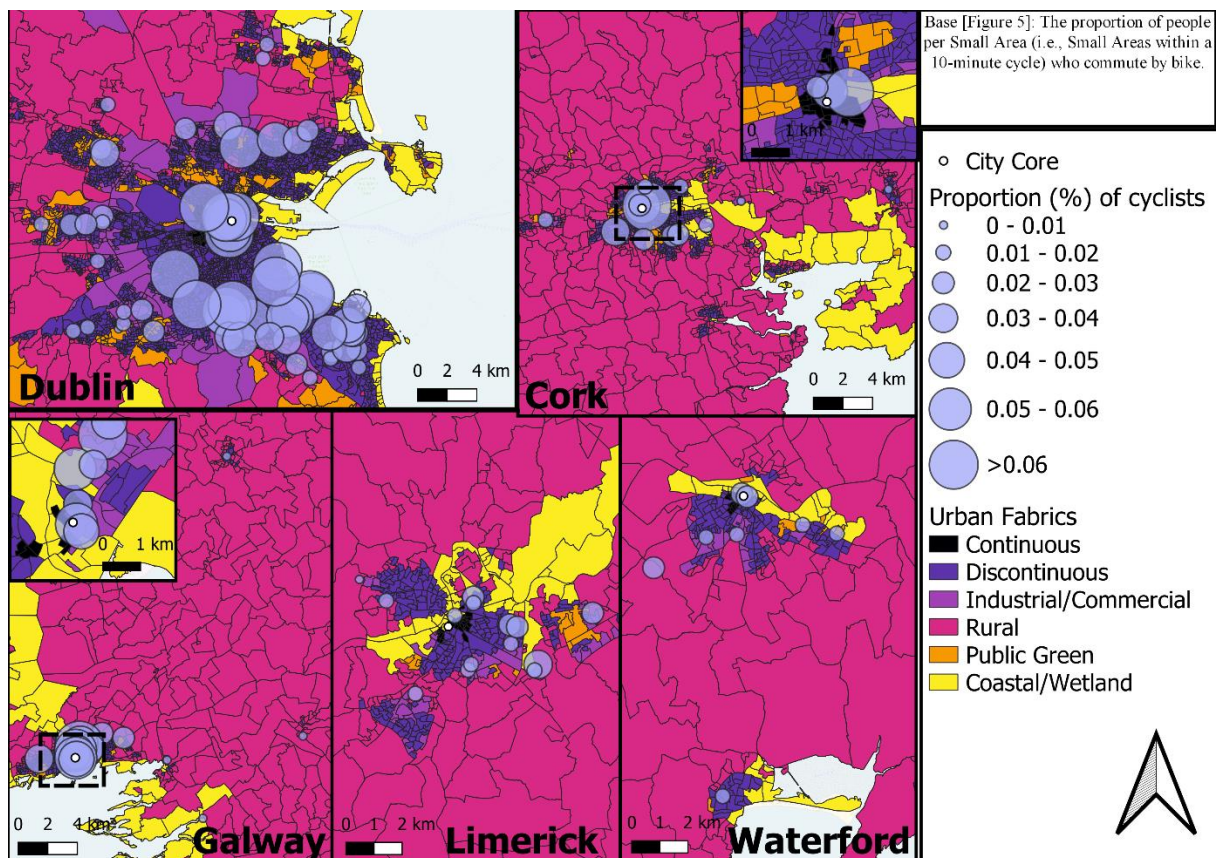
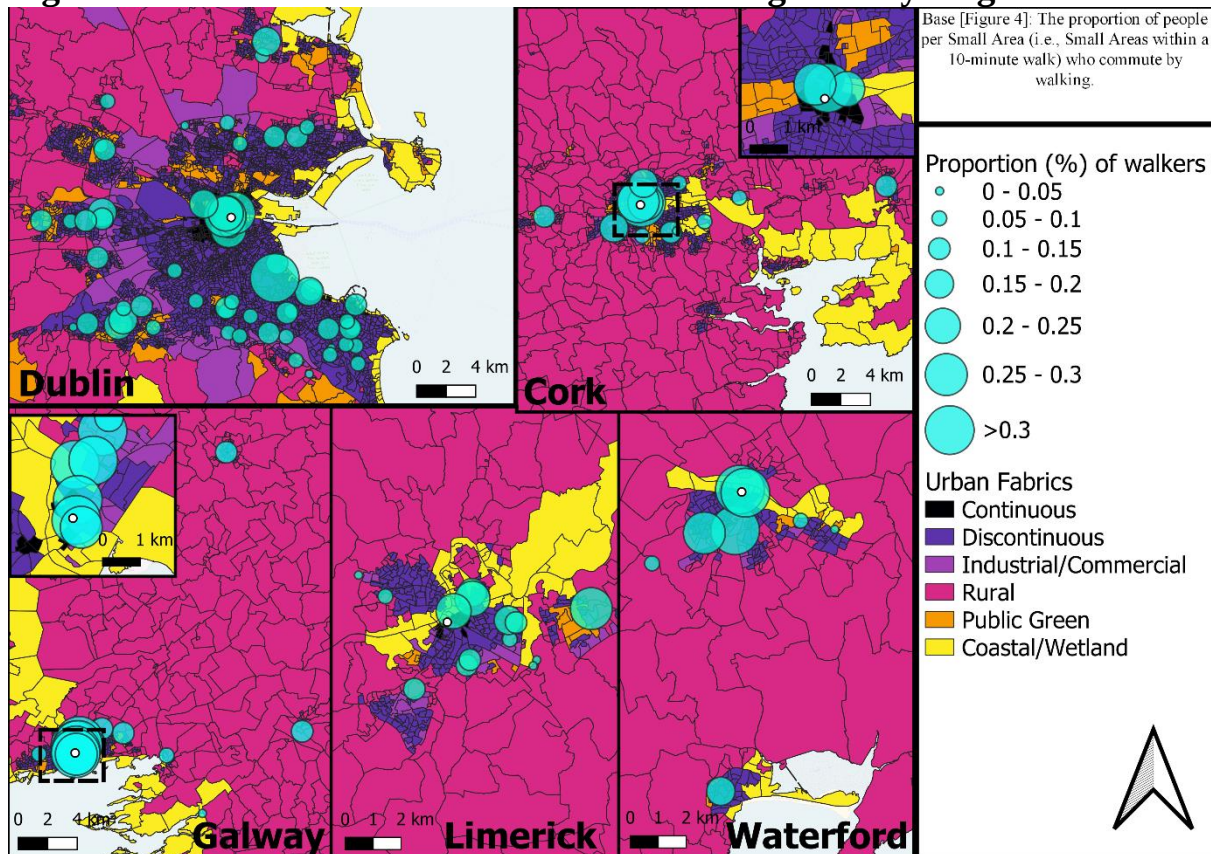


Figure A8.2: 15-Minute Thresholds For Walking And Cycling

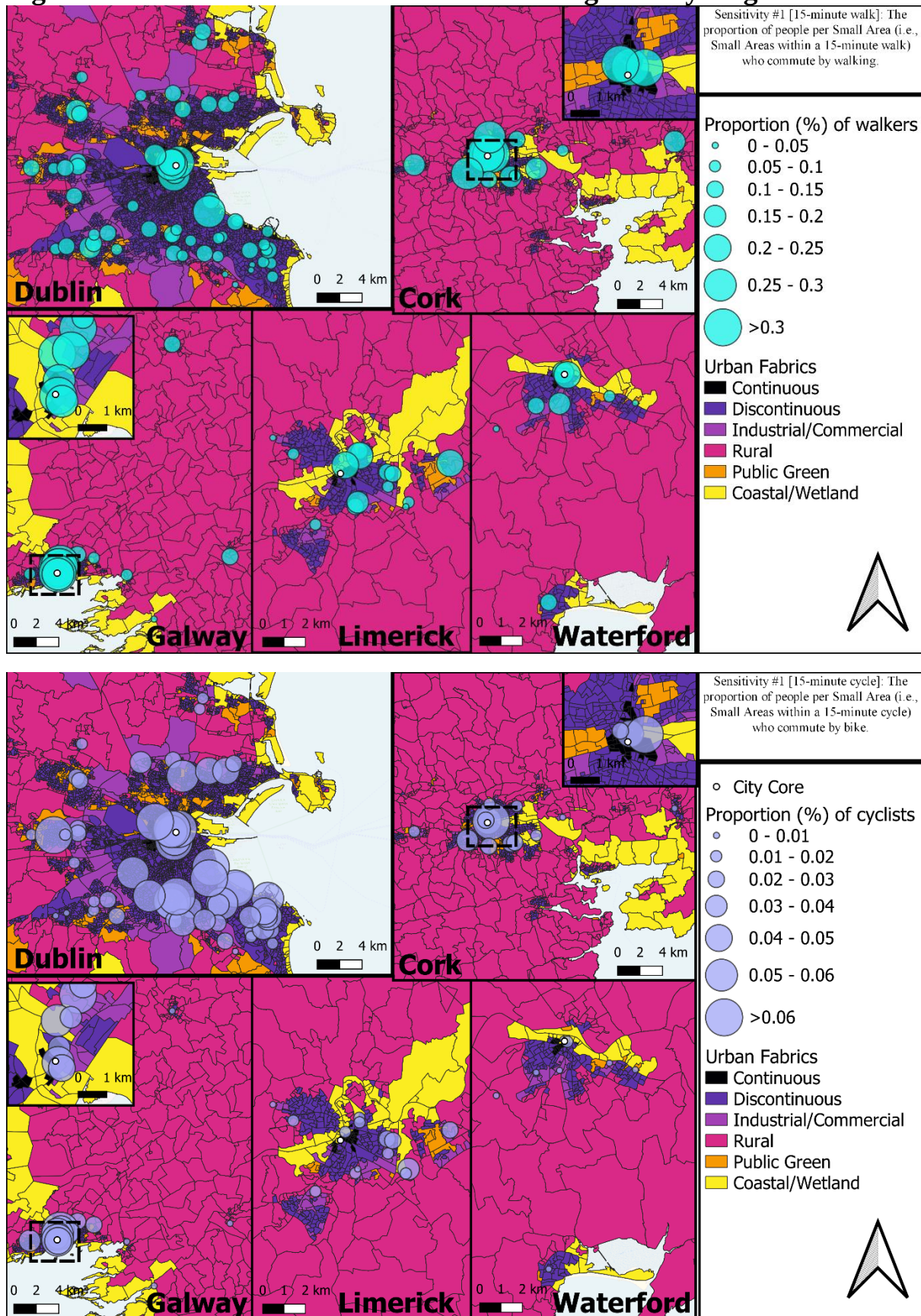
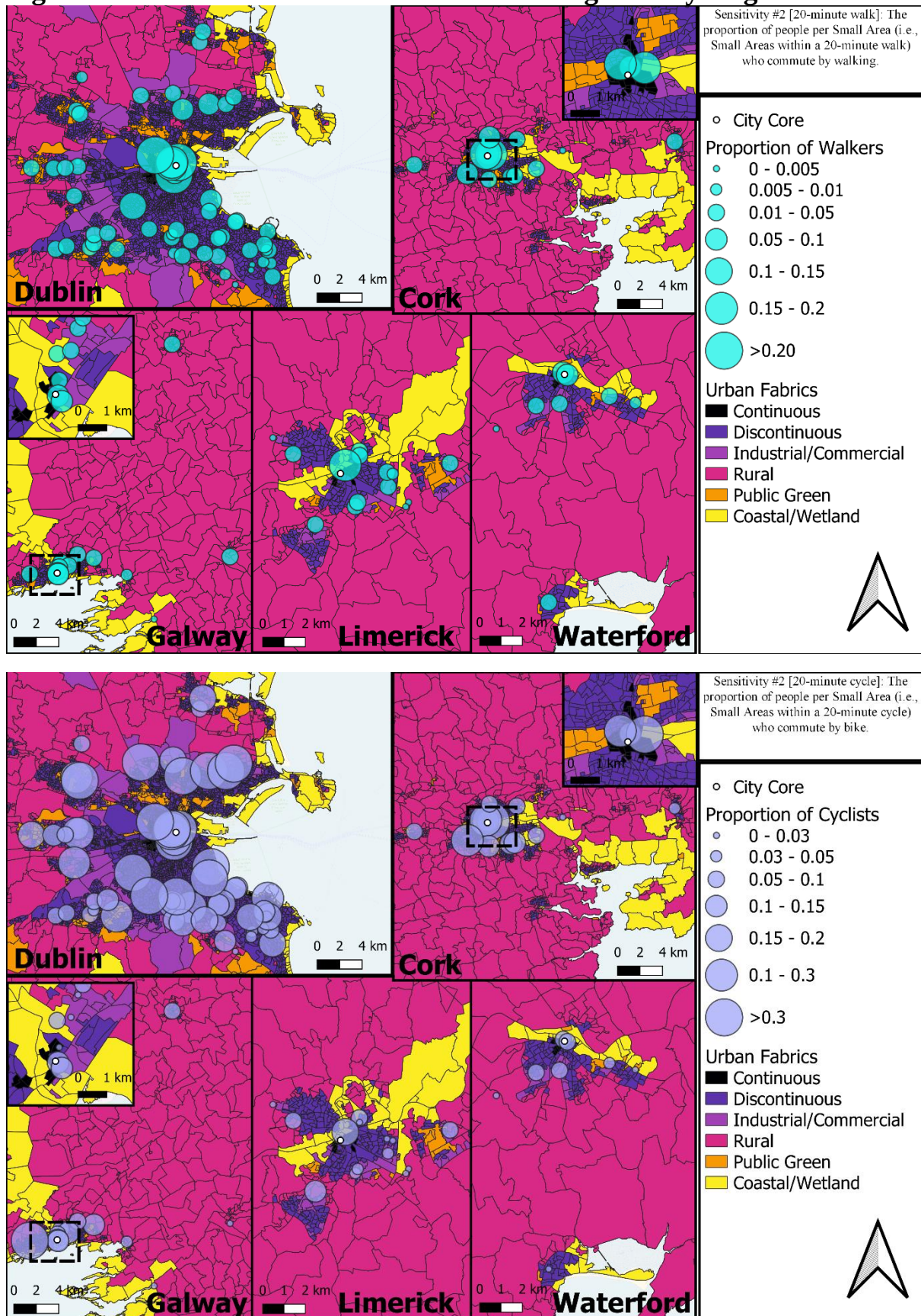


Figure A8.3: 20-Minute Thresholds For Walking And Cycling



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