Understanding the Extent, Demographic Causes, Consequences and Future of Population Decline in Europe

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by

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Abstract

European population dynamics are increasingly concerning population decline, with growth no longer operating at a continental scale. Across Europe, an abundance of sub-national areas and countries are currently enduring population loss, outweighing that of traditional population growth. Multilateral organisations expect for population decline to define European demographic change in the 21st century, with it continuing uninterrupted to reduce the continental population by as much as 20%. This represents an unprecedented demographic shift and is set to present a series of novel challenges to the regular functioning of societies.

Existing research that concerns European population decline has contributed to establish its occurrence and underlying causal mechanisms across the continent. Yet, evidence remains fragmented focusing on understanding place-specific incidences of population decline, with an overemphasis on case-study based research. However, the issue of population decline remains in the shadow of population ageing on the demographic research agenda, and is suffering from a lack of cross-country comparative analyses that consider depopulation holistically. Because of this, a series of research deficiencies persist despite its immediacy, and can relate to five distinct areas. First, the extent, pace, and geospatial distribution of population decline is largely unknown. Owing to a dominance of place-specific research, the severity of depopulation across Europe remains to be determined. This is compounded by a rural-urban dichotomy, in which depopulation processes are considered in isolation. Second, the temporal processes of population decline are frequently overlooked. Perhaps because of insufficient and inconsistent demographic data, the extent to which its trajectories differ between affected areas remains unknown. Third, a similar deficiency relates to the underlying demographic causes of population decline, and how these have manifested to produce differential depopulation experiences across different areas. Fourth, there exists a lack of a robust theoretical framework concerning contemporary depopulation, owing to the reliance of case-study based research. Fifth, a comprehensive forecast of future European population change outcomes is missing despite its necessity to implement effective policy responses.

This thesis aims to systematically address these research deficiencies, and significantly progressing our collective understanding of contemporary European population decline dynamics. To achieve this, a comprehensive methodological approach was developed that involved three distinct stages and implemented in three independent analyses. The first consisted of a novel application of sequence analysis within population studies to analyse the temporal processes of population decline. The second consisted of a detailed procedure to empirically evaluate the contributions from changing fertility, mortality, and net-migration trends to processes of population decline. The third stage sought to advance machine learning based population forecasts whilst simultaneously developing a prediction of future population decline outcomes in granular geographic units across Europe.

Collectively, the findings from three empirical analyses contribute to expanding our understanding of the extent, demographic causes, consequences, and future of population decline. They also make contributions to substantive knowledge, demographic theory, policy, methods, and data in the study of contemporary European population decline. This thesis provides detailed evidence of differential population decline trajectories and causal processes that coexist across different European sub-national areas. Two classifications are produced to represent these, whilst also acknowledging their geospatial distributions. Also, a unique insight into the likely future of population decline is provided in a machine learning derived forecast. These contributions are also evaluated with regards to the advancement of demographic theory. Specifically, they highlight the existence of heterogeneous temporal processes and underlying demographic cause, and their regularities. Regarding contributions to policy, the analyses bear implications for the management of population decline, highlighting the need for tailored initiatives that are sensitive to the unique pathway and cause. Finally, this thesis delivers a dataset that can be used to study the longitudinal population development of European sub-national regions.

Publications

This thesis consists of three journal articles. One (Chapter 2) of which has been published in a peer-reviewed journal, another (Chapter 3) is in the review process within the journal Population and Development Review. The final article (Chapter 4) is being prepared alongside this thesis, with a revised version to be submitted imminently. Alongside these articles, I have also contributed to additional projects beyond the scope of my PhD which have resulted in publications.

Academic publications included in this thesis

- **Chapter 2 –** Newsham, N., & Rowe, F. (2023). Understanding trajectories of population decline across rural and urban Europe: A sequence analysis. Population, Space and Place, 29(3), e2630.

- **Chapter 3 –** Newsham, N., & Rowe, F. (2023). The Demographic Causes of European Sub-National Population Decline. [Preprint]. Soc*ArXiv*

Other publications

- Darlington-Pollock, F., Arribas-Bel, D., Fleischmann, M., Newsham, N., & Rowe, F. (2021). Briefing: What do 'left behind' areas look like over time?.

- González-Leonardo, M., López-Gay, A., Newsham, N., Recaño, J., & Rowe, F. (2022). Understanding patterns of internal migration during the COVID-19 pandemic in Spain. Population, Space and Place, 28(6), e2578.

- González-Leonardo, M., Newsham, N., & Rowe, F. (2023). Understanding Population Decline Trajectories in Spain using Sequence Analysis. Geographical Analysis.

Open Data and Impact
Accessible here

- Demographic Time Series Database, NUTS3 Sub-national Regions of Europe.

- Area Attributes Database, NUTS3 Sub-national Regions of Europe.

- Population Decline Classifications (Trajectories, Causes)

- Population Forecast LSTM Model.

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Authors Declaration

The following is an attached declaration of my primary supervisor giving permission to use co-authored published material in this PhD thesis.

This PhD includes material published with co-authors.

I, Francisco Rowe, give permission for the following papers, co-authored with Niall Newsham, to appear in the PhD thesis:

Newsham, N., & Rowe, F. (2023). Understanding trajectories of population decline across rural and urban Europe: A sequence analysis. Population, Space and Place, 29(3), e2630.

Date: 20/12/2023 Signature:

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Introduction

1.1 Background

As the world population continues to soar towards unprecedented heights, Europe is faced with a very different set of demographic futures in population decline. The longstanding trajectory of continental population growth has recently reversed (UN 2022), as population decline has emerged as the dominant direction of population change, establishing an unfamiliar demographic pathway. Across Europe, neighbourhoods, regions, and countries are enduring a shrinking of their populations, outweighing the regular functioning of population growth and initiating a course of depopulation on an unprecedented scale. Though not entirely novel in demographic history, contemporary population decline is unique in demographic cause (Reher 2005), and geographic scale (Franklin 2020). Latest population projections expect for continental depopulation to persist unwaveringly until 2100, with expected reductions of 150 million, 20% of the European population (UN 2022). This trajectory of population change represents a stark contrast to demographic fortunes of the past 100 years, and its anticipation has generated concern within political and academic communities (Teitelbaum 2013, Bock & Haartsen 2021, European Parliament 2021).

Population decline will bring about novel challenges and will demand explicit consideration across a range of governance and policy issues. Such challenges are widespread over multiple domains, though fiscal concerns are most prominent (Clements et al., 2015). These range from concerns over economic growth and productivity (Coleman & Rowthorn 2011), the funding of public goods and services in the face of shrinking tax revenues (Van Dalen & Henkens 2011), reduced diversity (Franklin 2020) with subsequent increases in inequality (Bellman et al., 2018), and a diminished competitiveness and attractiveness of affected areas (Elshof et al., 2014) which can act to reinforce depopulation (Hoekveld 2012, Haase et al., 2016). Additionally, immigration will receive increasing consideration as a policy instrument to tackle decline and sustain local economic vitality, as has been considered in Japan and Germany (Dilley et al., 2022, Li et al., 2023). However, despite its immediacy and widespread implications, population decline remains overshadowed by ageing in demographic and political discourse. Though ageing arguably represents a more widespread and pressing issue, as reflected by current realities across the globe (UN 2022), demographic forerunners of Japan and countries in eastern Europe have illuminated the next stage of demographic change. Here, population decline is the principal feature, though it remains under-researched commensurate with its current reality and anticipated threat.

To understand contemporary population decline requires an understanding of its origins. Population change is determined entirely by fertility, mortality, and migration outcomes, with population decline resulting from a natural change deficit, whereby deaths outweigh births, and / or a negative migration balance, when out-migration is greater than in-migration. Contemporary demographic change is deeply rooted in historic developments and outcomes. Take, for example, the mass migration of foreign labour into Germany in the 20th century, which had both immediate and prolonged demographic implications (Mammey and Schwarz 2002) and continues to have a sizeable impact on population dynamics within Germany defining social and demographic outcomes in the west and east of the country (Aydin 2016). Historically, as European societies embraced industrialisation, they underwent unprecedented population growth. As described by the demographic transition model, successive transitions from high to low mortality and fertility resulted in a population explosion. As early adopters of industrialisation, European countries became the forerunners of this demographic change, which later spread across the world as other nations underwent respective economic transformations. Having now long completed this process, the demographic transition describes antiquated demographic change in Europe. However, its influence on contemporary dynamics is preserved through its establishment of an enduring low fertility trend, and its production of a young population structure (Bongaarts 2009) now aged, which collectively represent the requisite demographic conditions for a natural population decline.

Post-transition demographic developments have seen the realisation of population decline outcomes. They have concerned further reductions of fertility rates, which has been instrumental to population decline (Reher 2007, Lutz & Gailey 2020). Since its onset towards the end of the 20th century, low fertility below the replacement level of 2.1 births per woman has persisted in all European nations, and in some instances reached 'lowest lows' of under 1.3 (Kohler, Billari & Ortega 2002). The persistence of sub-replacement fertility has established a course of negative population momentum in which the size of successive reproductive cohorts are diminished, and, if not compensated by immigration, instigating an eventual course of population decline (Lutz, O'Neill, & Scherbov 2003, Reher 2007). Low fertility and its persistence are symptomatic of broad progressive societal change, best conceptualised within the second demographic transition framework (Lesthaeghe & van de Kaa 1986) and encompassing the development of contraceptive technologies, greater female economic autonomy (Kohler, Billari & Ortega 2006), increased domestic gender equity (McDonald 2000), delayed domestic independence (Reher 1998) and emphasis on individual autonomy (Beck & Beck-Gernsheim 2001). In this context, population decline can be considered the result of progress (Franklin 2020). Though forces of population decline have long been in play, population decline has only recently emerged as the dominant direction of change in most European countries. In northern and western Europe in particular, population growth has continued in the face of longstanding sub-replacement fertility. This is partly due to population momentum conditions, fuelled by continuing longevity improvements, but also sustained positive net-migration trends.

Mortality developments have manifested in the form of increased life expectancy and longevity, which has acted to reduce rates of mortality. This has resulted from continued epidemiological progress (Oeppen & Vauppel 2002), particularly in the form of cardiovascular related developments (Vallin & Meslé 2004). However, this has not been experienced uniformly across Europe, with less developed countries in eastern Europe initially lagging behind as innovation was slow to diffuse (Vallin & Meslé 2004, Hrzic et al., 2020), leading to mortality disparities and contributing to differential population change outcomes. Reduced mortality has acted to contribute towards a force of population growth, though also accelerating the rate of population ageing. Given that the force of mortality increases with age (Gompertz 1825), aged populations become associated with increased mortality rates (Cheng et al., 2020), later with depopulation symptomatic under certain low-fertility and high emigration scenarios.

Migration also plays a crucial role in the development of population decline. Unlike fertility and mortality, it is unique in that it simultaneously contributes to both growth and decline, in places of origin and destination respectively (Rowe et al., 2019). It therefore has a profound influence on population redistribution, and is a mechanism through which population decline can be either instigated or averted (Coleman & Rowthorn 2011, Newsham & Rowe 2019). This is demonstrated by current intra-European migration flows, with free movement in much of the continent facilitating mass migrations from less advantaged countries in the East, to more developed countries in the West (King & Okólski 2018). With regards to population change outcomes, these contemporary migration flows have contributed to population growth in a select few nations whilst initiating, or accelerating population decline in the remaining territory (Sobotka & Fürnkranz-Prskawetz 2020). Extra-European immigration trends, i.e. migration from outside of Europe to Europe, act to exacerbate this disparity, with the same developed countries in western Europe receiving a disproportionate population inflow (King & Okólski 2018, Eurostat 2022). Though intra-European and extra-European migration trends operate similarly in promoting population growth in select countries, they have differential impacts on population change processes at the continental scale. Despite the backdrop of continental population decline, extra-European net-migration remains positive (UN 2022) and therefore contributes a force of continental population growth. Intra-European migration, on the other hand, has no bearing on continental population size, though it is fundamental to population change disparities between origin and destination areas.

Thus far, population decline has been discussed from a continental and national perspective. However, depopulation is inherently a local issue, originating in households, neighbourhoods, and communities. As such, it is more pronounced at sub-national geographic levels and observable within wider contexts of regional and national population growth (Franklin 2019).

Reflecting this, an explicit focus is placed on sub-national population decline in this thesis and its analyses.

Sub-National Population Decline

In both historical and modern contexts, population declines have been observed in both rural and urban European areas, though they are underpinned by a different set of processes, as outlined below. Generally, rural areas are more prone to population decline than urban areas, as reflected by current population trends (Eurostat 2020) and historical developments (Martí-Henneberg 2005). However, the risk of depopulation is not equal for all areas, as it has been demonstrated that remote and disconnected rural areas are more prone to depopulation (Pužulis & Kūle 2016, Ubarevičienė et al., 2016, Wojewódzka-Wiewiórska 2019), primarily though out migration of young populations (Rodríguez-Vignoli, J. and Rowe, F., 2018), as well as less attractive urban areas with small population sizes (Kabisch & Haase 2011, González-Leonardo et al., 2023).

Studies into rural decline in developed nations are in general alignment in that political, economic, and social processes are largely responsible for depopulation (Kovats & Kovács 2012, Kuczabski & Michalski 2013, Viñas 2019, Wojewódzka-Wiewiórska 2019, Johnson & Lichter 2019, Batunova & Perucca 2019), though geographical factors, particularly proximity to urban areas and territorial factors have also been stressed (Ubarevičienė et al 2016, Viñas 2019, Reynaud et al., 2020). In both Europe and the US, rural areas have endured significant economic decline stemming from deagrarianization and the decline in primary sector productivity within local economies. The loss of traditional opportunities in these areas has thus been primarily responsible for exodus, resulting in a demographic stagnation of rural sending regions (Johnson & Lichter 2019). In this capacity, migrants are typically young and therefore the demographic potential of the rural areas is significantly impacted upon, accelerating aging processes and thus increasing the propensity for natural decline. Empirical studies have acknowledged a causal regularity in which economic migration precedes natural decline across Europe (Wojewódzka-Wiewiórska 2019) and in the US (Johnson & Lichter 2019). Other studies, whilst not explicitly recognising the order of such processes, have acknowledged the interplay of out-migration and natural decline (Kuczabski & Michalski 2013, Viñas 2019).

Relatively speaking, urban decline is a more modern phenomenon as, after all, it was urban areas that accumulated human capital as a result of historic rural out-migration (Martí-Henneberg 2005, Johnson & Lichter 2019). Explaining the causes of urban decline is not as straightforward, with studies asserting that urban decline is highly specific and context dependent (Haase et al., 2016, Wolf & Weichmann 2018). That being said, studies often include similar sets of macro-developments in explanatory models of urban shrinkage relating to demographic, economic and settlement system shifts (Oswalt and Rieniets 2006, Hoekveld 2012, Haase et al., 2016). Specifically, these include demographic changes akin to the second demographic transition, namely low fertility (Wolf & Weichmann 2018), economic decline

(Friedrichs 1993) and suburbanization (Couch et al., 2005). More recently, studies have moved beyond linear descriptions of urban decline, instead favouring concepts of feedback loops in which various processes interact in cause-and-effect relationships to promote a cycle of cumulative decline (Hoekveld 2012, Haase et al., 2014). Within this cycle, processes of industrial decline, unemployment, out-migration, and demographic change are responsible for urban depopulation. Recent empirical studies have confirmed the presence of this process but stress geographical specificities (Hoekveld 2012, Haase et al., 2016, Wolf & Weichmann 2018).

Is population decline a problem?

Population size is fundamental to all features of human-society, implicating culture, social institution, environment, government, and economy. Population change, then, has an implicit bearing on the functioning of societies and their change. For the past few centuries, these features have evolved alongside, and have been shaped by expansive population growth. Given that population decline represents such a contrasting and unfamiliar order of change, concerns over its threat to the regular functioning of societies are just and understandable. Prospects and realities of population decline, both historic and contemporary, typically command unfavourable perceptions and are often met with fear, particularly at institutional levels (Teitelbaum 2013, Van Dalen & Henkens 2011). This is reflected by extensive pro-natalist and pro-immigration policy (Prskawetz et al. 2006, Neyer & Andersson 2008), and often echoed by individual sentiment (Van Dalen & Henkens 2011). In academic discussion, perceptions of depopulation are more variable, with some optimistic for anticipated demographic change (Coleman & Rowthorn 2011, Götmark et al., 2018, Franklin 2020).

When evaluating the implications of population decline, commentators often jointly discuss issues relating to population ageing, which acts to compound pessimistic narratives. Though these demographic phenomena share a causal origin in low fertility and out-migration, it is important to recognise their distinctions. Population ageing is a demographic process whereby the average age of a population increases, creating a set of unique challenges relating to economic productivity and the provision of healthcare and social welfare. Ageing alone does not cause population decline, although it does establish demographic conditions that promote it, namely in low fertility and high mortality. Here, I attempt to evaluate the implications of population decline in isolation from that of population ageing.

Cons

Concerns for population decline chiefly relate to economy or finance domains and stem from a perceived incompatibility with economic growth. The relationship between population size and economy is non-trivial, or axiomatic (Coleman & Rowthorn 2011). The size of a labour force, or population, is essential for driving production and overall economic output. Population growth also symbolises a growing market and inspires confidence for investors and prospective businesses, promoting further growth. Finally, population growth inspires competition, and acts as a driver for technological progress and innovation (Boserup 1965), which acts to promote economic growth. Under regimes of population decline, these principals are fundamentally challenged. A shrinking population signals a diminishing workforce and therefore presents an obstacle for productivity, and a reduced capacity for innovation or technological advancement (Haga 2015). Furthermore, a smaller population represents a smaller market, with reduced demand and consumption. In this capacity, population decline de-incentivises prospective businesses and suppresses investment. Through these dynamics, population decline is said to be a self-propagating process as prospects for migration decrease (Hoekveld 2012).

Beyond concerns for continued economic growth, population decline also poses threats to the regular functioning of societies, primarily through the connection between population size and public finance (Van Dalen & Henkens 2011). Public goods and services are largely funded through tax revenues, with the budget dependent on the overall tax base, which itself is dependent on population size. Population decline signifies a diminishing tax base, and thus a reduced capacity for public spending. Though this poses obvious problems for local and national governments, it could also negatively impact communities and individuals through defunding vital services or, to combat this, increased tax rates. It is through these foreseeable issues that population decline commands an unfavourable opinion to individuals under threat of local depopulation (Van Dalen & Henkens 2011). On a less material level, population decline also infringes upon political power through representation, and may perhaps diminish the geopolitical stature of a region or country negatively impacting their political and financial position (Coleman & Rowthorn 2011).

Finally, as a demographic process, population decline not only concerns the size of populations but also their compositions and structure (Franklin 2020). This means that as populations endure a process of decline, they change in composition, diversity, attitude, and character. Bellman et al., (2018) discuss the implications of this itself, highlighting potential income inequalities and increased residential segregation. Closely related to this, Hospers & Reverda (2015) discuss the effects of population decline on civil society, describing a process of diminishing social capital in depopulating communities whereby formal and informal networks are eroded, leading to reduced community engagement, weakened civic institutions, and increased social isolation. Alongside this, population decline signals a loss of kinship of place, involving the decay of place-specific cultures and identities. Finally, population decline has political consequences. Recent studies have uncovered an empirical association between discontent, arising from the aforementioned contextual and compositional symptoms of population decline, and the rise of populism in political elections (Rodríguez-Pose & Lipp 2021, van Leeuwen et al., 2021). This has manifested in the form of an increased far-right representation in political office, with support concentrated in areas of stagnating economic growth, high immigration (Rodríguez-Pose et al., 2023) and population loss.

Pros

There are, on the other hand, good reasons to rejoice around population decline. Firstly, there exists no empirical evidence of population decline suppressing economic growth, individual wealth, or innovation (Coleman & Rowthorn 2011). It would appear that, when examining economic development of forerunning nations, that the economic concerns surrounding depopulation are baseless, at least in the immediate short term. Afterall, population decline does not necessitate diminished economic productivity in modern times. The loss of human capital can be offset by increases to productivity, either technological or through other means of social reform. Japan is a perfect example of this, having harnessed both technological advancement and efficient production methods to avoid GDP decline in face of depopulation (Clark et al., 2010). It remains to be seen though, if such growth in productivity can continue to offset demographic decline, economic projections in Japan would suggest otherwise (Honjo et al., 2021).

Advocates for the reversal of population growth are typically optimistic around its environmental benefits (Reher 2005, Hospers & Reverda 2015, Janicki 2017). Given finite natural resources, population growth rates are undoubtedly unsustainable in that they exceed the earth's carrying capacity. In this sense, depopulation is welcomed as a corrective process that will ensure the sustainability of future human societies (Abernethy 2001, McNeil 2006, Götmark et al., 2018). Other proponents for depopulation cite the benefits of living within places designed for more numerous populations. From an economic perspective, population decline is expected to increase individual wealth as the ratio of capital to population increases (Coleman & Rowthorn 2011), and as resources are allocated to improve standards of living as opposed to supporting population growth (Reddaway 1939). In a similar capacity, reduced populations are associated with prospects of reduced strain on transport and housing infrastructures (Franklin 2020). Smaller populations should, in theory, eradicate issues associated with overcrowding, including congestion, and high-density housing. In this regard, population decline can be viewed as promoting a somewhat idyllic society whereby some trials and tribulations of everyday life are eased.

Though the prospect of unfamiliar change can be daunting, it is important to remember that demographic change is often a slow-moving process, and the implications of population declines will not confront us abruptly, but rather unravel over time. This is empirically exemplified by Goldstein & Cassidy (2021) in a study of the lag between the realisation of replacement fertility and depopulation. It is also important to note that the specificities of resulting challenges will be shaped by the causal interactions between fertility, mortality, and migration, which will be specific to affected areas. Ultimately, though, population decline will inevitably command social and technological reform, and will also require an explicit consideration in policy and planning endeavours.

The next section identifies the main shortcomings of previous research into European population decline, drawing from a wide range of epistemological domains in which depopulation concerns. In doing this, I then establish the primary aims of the thesis.

1.2 Gaps in Research

Despite its novelty and significance, contemporary population decline remains under-researched and overshadowed by population ageing as an immediate demographic challenge. However, owing to its broad implications, research on modern population decline exists across a range of academic disciplines, including demography, geography, regional and urban studies. As a result, our understanding of depopulation as a contemporary phenomenon is broad, but also fragmented, and lacks cohesion with regards to scope. Particularly deficient, are the consideration of the spatio-temporal aspects of population decline. As emphasised by Franklin (2020), population decline has inherent spatial and temporal dimensions, most simply in that depopulation occurs between two points in time within a certain place. However, these facets are seldom considered elsewhere in existing research, at least explicitly. Next, the existing research deficiencies are discussed in more detail.

Geographic Scope / Spatial

The first, and perhaps most pressing research deficiency stems from the restricted and fragmented geographic scope of existing studies. Population decline is already widespread across Europe, occurring in abundance at sub-national geographies (Eurostat 2022). However, there exists a dominance of case-study (Galjaard et al., 2012, Hoekveld 2012, Hartt 2018, Viñas 2019) or country specific research regarding depopulation (Pužulis & Kūle 2016, Ubarevičienė et al., 2016, Čipin & Ilieva 2017, Reynaud et al., 2020, González-Leonardo et al., 2023) with our understanding of contemporary population decline processes then established via highly specific place evidence. This is problematic for a number of reasons, including the inability to understand contemporary decline holistically and leaving broad principles and patterns unidentified, an insufficient testbed for developing theory, and the generalisability of insights that contain relevance for policy development. Furthermore, the fragmented nature of population decline research has left a lack of systematic evidence of its extent, pace, and location across Europe. Though country-level studies have established that depopulation is more prevalent in eastern and southern countries (Pužulis & Kūle 2016, Ubarevičienė et al., 2016, Čipin & Ilieva 2017, Reynaud et al., 2020, González-Leonardo et al., 2023), in absence of a cross-country comparative study we do not know to what extent this holds true at sub-national levels. The fragmented nature of research into population decline is further compounded by a persistent rural-urban dichotomy, with studies often considering urban or rural decline exclusively. Synthesizing relevant studies, we understand that population decline is more prevalent across rural areas than urban counterparts, though it is unclear to what extent this represents an oversimplification.

Case study and country-specific research has, however, highlighted the contextual settings that are associated with population decline. From this, we establish how some areas are more prone to population loss than others, such as those in remote and disconnected places (Viñas 2019, González-Leonardo et al., 2023) or at high altitudes (Reynaud et al., 2020), though we do not know to what extent this remains consistent across Europe. We also understand that area specificities relating to demographic and economic configurations influence population decline outcomes in urban areas (Haase et al., 2014, 2016). The identification of broad and systematic patterns of this nature could help in formulating policy interventions with widespread applicability, and also expand demographic theory with added geographic resolution.

Temporal Dynamics

The temporal process through which population decline manifests has crucial implications for both its conceptualisation and management. Yet, it has scarcely been considered in existing research (Turok & Mykhnenko 2007, Wolff & Weichmann 2018, González-Leonardo et al., 2023). Depopulation is often considered as an outcome over two distant periods of time, for example decennial change in successive population censuses. Static analyses of population decline fail to acknowledge its dynamism, which is vital for understanding the accompanying compositional change and changing needs and challenges of areas as they endure population loss (Franklin 2020). As things stand, evidence of population decline as a dynamic process remains sparse, as research is fragmented. Research into the trajectories of urban areas enduring depopulation have demonstrated how it most often occurs in episodic or temporary periods with regular population growth resuming (Turok & Mykhnenko 2007, Wolff & Weichmann 2018). In rural areas, continuous and uninterrupted population declines appear to be more common, though evidence is particularly fragmented with just one study conducted in a singular European country (González-Leonardo et al., 2023). Limited evidence exists explicitly examining the temporal evolution of European depopulation across subnational areas within countries. Existing research focuses on urban or rural areas occurring in specific geographical settings. A holistic study of population decline inclusive of rural and urban areas is important for developing our understanding of contemporary population decline. Particularly, for uncovering disparities in population decline processes and causes that may require unique policy responses for its management. A key challenge exists in the availability of temporally consistent data for the entire European continent, though the harmonisation of annual population estimate national statistic data appears promising.

Demographic Process

Population decline is entirely a demographic process resulting from demographic outcomes, namely fertility, mortality, and migration. Yet, the demographic processes underpinning depopulation are seldom considered in existing research, leaving the demographic causes of the contemporary phenomenon largely unknown. Typically, the sub-replacement fertility endemic is cited as a blanket explanation of the causal origins of population decline (Reher

2007, Lutz & Gailey 2020), with little consideration for other factors. Though in theory, population decline would eventually result from persistent sub-replacement fertility in absence of increasingly greater and unsustainable in-migration. In actuality, population decline is the result of intricate interactions between fertility, mortality, and migration outcomes, with the timing and extent of those outcomes nuanced between countries and sub-national areas across the continent. At present, we lack empirical evidence of these different demographic interactions underpinning differential European population declines.

An understanding of the main demographic cause of depopulation is important because the main cause may dictate the overall experience of depopulation including its timing, pace, magnitude, and specific implications as well as the policy responses needed to address or reverse their negative impacts. To elaborate, a population decline driven by migration would represent an immediate population loss and potentially a hollowing out of age-structures, given migration schedules, bearing economic consequences in the form of labour shortages and diminished tax revenues. On the other hand, a population decline driven primarily by low fertility would be slow to manifest, owing to population momentum effects, and first resulting in a population ageing and placing a strain on healthcare services and pension systems. Under these two scenarios, a very different set of challenges would be confronted requiring unique policy considerations. Understanding the demographic causes of population decline is therefore crucial to developing appropriate responses and improving the targeting of these responses.

Theory

Demography is said to be rich in quantification, but short on theory (Kirk 1996), and no more is this true than for contemporary population decline. In short, no theory exists that explicitly concerns modern depopulation, though others, both demographic and non-demographic, relate to it. The demographic transition theory is widely referenced in studies of population dynamics, though its conception predates population decline and it is not explicitly concerned. It does, however, detail demographic processes from which depopulation has originated: low fertility and low mortality. The theory posits that, as countries industrialise and develop, they endure successive transitions from high to low mortality and fertility, resulting in rapid natural population growth. At completion of the demographic transition, natural population growth ceases as fertility rates stabilise at replacement level of 2.1 and the growth effect from population momentum wanes (Bongaarts 2009), establishing a potential for depopulation. The second demographic transition theory (Lesthaeghe and van de Kaa 1986, van de Kaa 1987) builds from the original demographic transition theory and comes close to theorising contemporary population decline. Instead, it details the further decline of fertility to below replacement levels, driven primarily by ideational change.

Both demographic transition theories are highly relevant to contemporary population decline, in that they detail its primary mechanism in low fertility. Population decline is inevitable to any society if the net-reproduction rate is below 1, which is attained through sub-replacement fertility. However, where these theories fall short, with regards to theorising contemporary population decline, is their failure to recognise the role of migration. In the face of neutral or near-neutral natural change, migration becomes the most crucial component of population change. In absence of its recognition in demographic change theory, migration-specific theories are essential for theorising contemporary population decline.

Future

Multilateral organisations and statistical offices expect for population decline to characterise future European population change outcomes throughout the 21st century (UN 2022, Eurostat 2023). Its occurrence at the continental level is then a near certainty, however, less is known about the future population change outcomes of sub-national regions. A final research deficiency relates to the anticipation of future population decline outcomes within Europe. Estimations of likely population decline outcomes are crucial to the development of effective management strategies, yet a deficiency persists in forecasting techniques for small sub-national areas (Wilson et al., 2022), where depopulation originates, and its consequences will be most pertinent. Most problematic is the insufficient demographic data for small areas, whereby incomplete time series from boundary changes and erratic demographic trends are characteristic. With this, established forecasting approaches are unsuited for small areas, neither are they designed for these applications. What is needed, then, is the development of a population forecasting approach that is sensitive to the data challenges of small areas, and particularly conscious of anticipated depopulation outcomes. Particularly promising in this regard are machine learning based time series forecasting models, such as XGboost and Long Short-Term Memory (LSTM) approaches. Thus far, their limited application into population forecasting have demonstrated a genuine potential to outperform traditional approaches, with respect to accuracy (Riiman et al., 2019).

1.3 Thesis Aims:

The primary aim of this thesis is to provide a more comprehensive understanding of European population decline, its extent within sub-national areas across the continent, its underlying demographic causes, and likely futures. To address the aforementioned research gaps, this thesis has the following aims:

1. Build a comprehensive database of European population change dynamics, including population count and its proximate determinants (fertility, mortality and migration) and a wide range of socio-economic and geospatial factors (e.g., population composition, unemployment rate, proximity to nearest urban agglomeration) at the national and sub-national levels.

This aim seeks to address a pressing obstacle for comparative population decline research in data availability. Specifically, it synthesises published data from Eurostat and national statistics offices and establishes a comprehensive spatial panel database on longitudinal population change outcomes and underlying demographic mechanisms in fertility, mortality, and migration, as well as relevant contextual information. In total, my database contains information for 2,035 sub-national areas across 40 European countries or territories. Regarding the spatial granularity, the majority of areas correspond to NUTS3 units from the Eurostat classification, representing small sub-national regions, however the size of areal units varies by country. A regular issue in spatial panel datasets is the changing of administrative boundaries over time which acts to disrupt time series. To overcome this, I harmonise the dataset by making use of information on historic boundary changes. Addressing this aim facilitates the completion of subsequent aims, and in this regard, it can be considered the foundation of the thesis.

2. Establish the extent, prevalence and timing of population decline within all European countries.

This aim seeks to develop a novel methodological framework for understanding the temporal evolution of population change outcomes in sub-national areas experiencing depopulation. This is achieved by applying a sequence analysis and clustering approach to compare the order of annual population changes between a total of 696 sub-national European areas, and group them according to shared longitudinal features of population decline. The primary outcome under this aim is a typology of European population decline trajectories, which capture variation in temporal population decline outcomes between sub-national areas over the period 2000-2018. Within this typology, a total of seven distinct trajectories are identified, representing pathways of accelerating, decelerating, stable and temporary population declines.

3. Identify the dominant demographic cause of population decline in European countries, and determine sub-national variations in the extent and causes of population decline.

This aim builds upon the previous aim by providing an understanding of the demographic mechanisms underpinning heterogeneous trajectories of depopulation. This is achieved through the development of a multi-stage methodology involving the decomposition of annual rates in population change to effects of changing fertility, mortality and migration outcomes, multi-functional principal component analysis to study the shapes of decomposition curves and compress this information into singular unit scores, used in subsequent K-medoid clustering. The results demonstrate nuances in contributions of fertility, mortality, and migration across the continent, but also highlight ubiquitous forces of natural decline initiated by fertility-mortality deficits.

4. Generate national and sub-national population projections for the most likely scenarios of population change.

This final aim seeks to produce sub-national population forecasts, and concludes a comprehensive study into contemporary population decline. To achieve this, I develop a state-of-the-art machine learning model utilising advanced recurrent neural networks. Specifically, I design multiple Long Short-Term Memory (LSTM) models with varying design specifications and implementation approaches in search of an optimal model design. To facilitate this, I make use of geographically consistent population estimate data from WorldPop, and account for spatial population dynamics by including the spatial lag of population change as an additional feature in LSTM models. To assess the accuracy of each LSTM model, I predict population size in 2020 for all areas and compare them with the actual values. The most accurate model is then developed to forecast population size in the year 2030. With a focus on forecasted population decline outcomes, the results reveal an increase in incidences of population decline, with 70.2% of all sub-national areas expected to be facing a depopulation by 2030. This spread is also reflected in national scale population change outcomes, with 30 of 40 European countries to be in decline by 2030. Furthermore, the results reveal the vulnerability of select remote and elevated areas to population decline, and the concentration of population growth in select urban centres and their peripheries.

1.4 Methodological Approach:

To address these research aims, this thesis develops a comprehensive methodology characterised by novel applications within studies of population change. Represented graphically below, the methodological approach aims to conceptualise different aspects of contemporary population decline in each analytical chapter, with a focus placed on understanding its temporal and geospatial dynamics. By design, it was intended for each chapter to build upon the previous study but also to present as stand-alone research papers. The first involves sequence analysis to study the trajectories of population decline and a subsequent clustering to group sub-national areas by shared longitudinal features. The second focuses on the demographic causes of depopulation, again grouping areas based on similarities. Specifically, a multi-stage approach inclusive of rate decomposition, multi-functional principal component analysis and k-medoid clustering is implemented to study and compare the contributions of demographic drivers to changing rates of population decline across European sub-national areas. The final chapter develops Long Short-Term Memory time series forecasting models, with varying specifications and implementation strategies, to predict future population change outcomes across European municipalities. Together, the studies provide a comprehensive picture of contemporary European population decline, producing an understanding of the trajectories, underlying demographic causes, and likely futures.

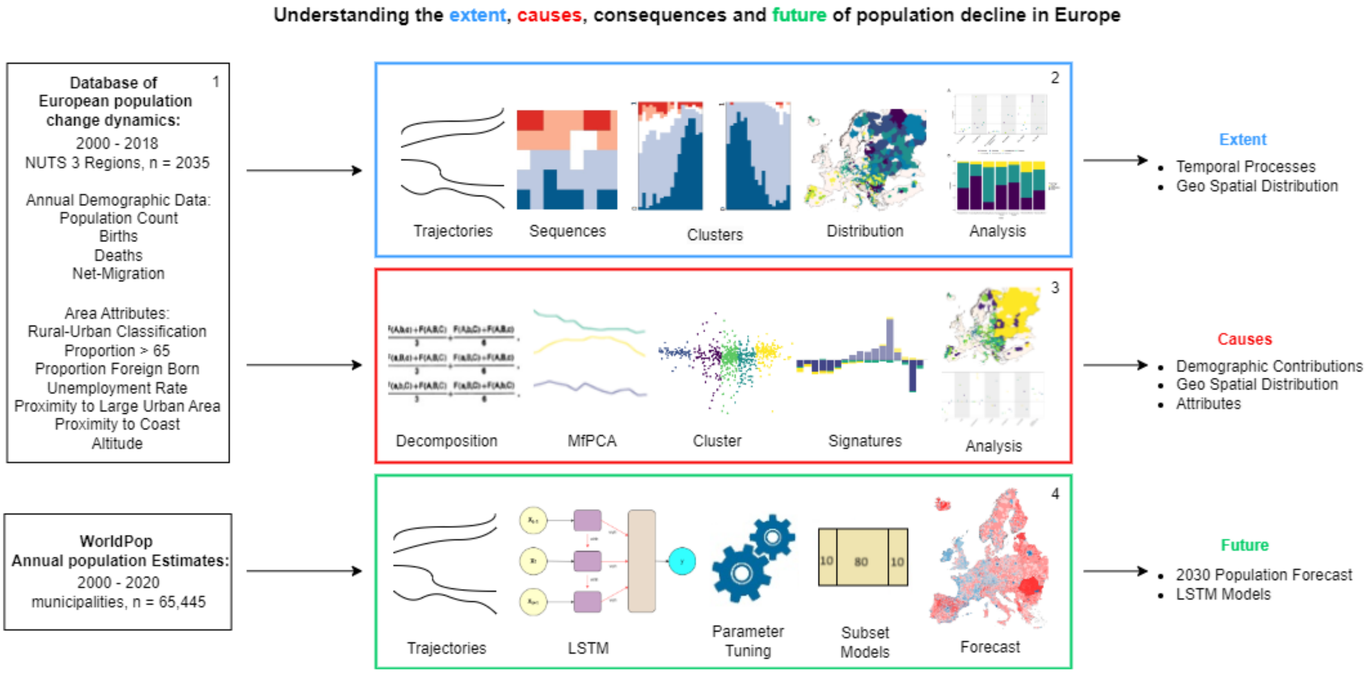

Figure 1.1 – Thesis Data and Methodological Procedure

1.5 Structure of Thesis:

The four research aims are addressed, in turn, in three analytical chapters and are presented in the format of a journal article. The first chapter has been published in a peer-reviewed journal (Population, Space and Place), with the second in review at the time of writing (Population and Development Review) and the third being prepared for submission. Each of these chapters are therefore standalone research papers and contain independent literature reviews outlining research gaps specific to the aim it addresses, the methodological procedure, and a description of empirical findings. The chapters are inherently connected by their contributions towards the over-arching aims of this thesis, and are linked here by an introductory statement preceding each chapter which explicitly acknowledges this contribution. A summary of these three analytical chapters is provided next.

Chapter 2 addresses the first two thesis aims. Specifically, it develops a novel methodological framework to analyse the temporal process of population changes across multiple areas from 2000 to 2018. It is the first study into population change to apply sequence analysis to study the longitudinal features of population change outcomes. It is used here, alongside cluster analysis, to identify the different trajectories of population decline across sub-national regions of Europe and group areas based on the timing and magnitude of depopulation. In doing this, a typology of European population decline is created, identifying the dominant trajectories of depopulation across the continent, and capturing processes of accelerating, decelerating, stable and temporary population decline. Furthermore, an exploratory analysis is performed on the clusters within the typology, consisting of a multinomial logistic regression model and using a rural-urban classification to classify areas by their positioning along the rural-urban spectrum. This facilitates an understanding of differences in the extent, prevalence and timing of population decline across different types of areas.

Chapter 3 addresses the third thesis aim. It builds upon the dataset that was established in chapter 2 by incorporating additional demographic, socio-economic, geospatial, and contextual information. This enables a more thorough study into contemporary population decline, and an understanding of its root demographic causes. Specifically, this chapter develops a comprehensive methodology, combining 3-factor rate decomposition (Gupta 1993), multi-functional principal component analysis and cluster analysis to study the different demographic causes of population decline across sub-national Europe. The results quantify the contribution of demographic factors (fertility, mortality, and migration) to changing rates of population decline from 2000 to 2018 in 732 areas. The findings establish the ubiquitous force of negative natural change, but also highlight the nuanced contributions of fertility, mortality, and migration in specific areas.

Chapter 4 addresses the fourth and final thesis aim. It develops an ambitious methodology involving state-of-the-art machine learning models to forecast population change outcomes to 2030 in 64,990 areas encompassing 40 European countries. This chapter makes use of an alternative dataset to previous chapters, using WorldPop data that is geographically consistent and highly granular. Specifically, a series of long short-term models (LSTM) are designed and implemented to produce population forecasts. These models represent advanced recurrent neural networks, and are capable of inferring temporal dependencies in time-series data and applying this to forecast future values. Here, I experiment with different model architectures and implementation approaches and compare their accuracy by comparing predicted values of population size in 2020 with known values using a median absolute percent error metric. The most accurate model is then extended to forecast population size in 2030, with a focus placed on population decline outcomes. Results reveal an increased spread of population decline, with 75% of all European areas experiencing depopulation in 2030, with 59.3% of Europe’s population directly affected.

Chapter 5 summarises the principal findings of the thesis, incorporating the findings of preceding chapters. It also outlines how the thesis has addressed each of its aims, and how the findings contribute to substantive knowledge and theoretical development concerning population decline. This chapter also discusses the main limitations and outlines potential avenues for future research to further study population decline.

2

Understanding the Trajectories of Population Decline Across Rural and Urban Europe: A Sequence Analysis

This chapter was published in Population, Space and Place

Reference: Newsham, N., & Rowe, F. (2023). Understanding trajectories of population decline across rural and urban Europe: A sequence analysis. Population, Space and Place, 29(3), e2630.

This first analytical chapter makes use of a new longitudinal spatial panel dataset containing population estimate data for 696 consistent European sub-national areas, enabling a novel spatio-temporal analysis of population decline trajectories from 2000 to 2018. The methodology combines sequence analysis, clustering, and multinomial logistic regression to develop a typology of the development of population declines. The analysis considers the ordering, timing, and magnitude of annual population losses in heterogeneous sub-national demographic contexts across 33 European countries. The key contribution of this Chapter is its identification of seven distinctive depopulation pathways that are driving the continental trajectory of population decline. These pathways are subjected to further analysis to document their geographic distribution and occurrence across rural and urban areas.

Abstract

Population decline is projected to become widespread in Europe, with the continental population set to reverse its longstanding trajectory of growth within the next five years. This represents unfamiliar demographic territory. Despite this, literature on decline remains sparse and our understanding porous. Particular epistemological deficiencies stem from a lack of both cross-national and temporal analyses of population decline. This study seeks to address these gaps through the novel application of sequence and cluster analysis techniques to examine variations in population decline trajectories since 2000 in 696 sub-national areas across 33 European territories. The methodology allows for a holistic understanding of decline trajectories capturing differences in the ordering, timing, magnitude and spatial structure of population decline. We identify a typology of population decline distinguishing seven distinct pathways to depopulation and chart their geographies. Results revealed differentiated pathways of depopulation in continental sub-regions, with consistent and rapid declines in the east, persistent but moderate declines in central Europe, accelerating declines in the south and decelerating population declines in the west. Results also revealed differentiated patterns of depopulation across the rural-urban continuum, with urban and populous areas experiencing a deceleration in population decline, while decline accelerates or stabilises in rural areas. Small and mid-sized areas displayed heterogeneous depopulation trajectories, highlighting the importance of local contextual factors in influencing trajectories of population decline.

2.1 Introduction

Europe is projected to become the first continent to undergo a unique demographic transition - population decline, or depopulation[1]. Most recent estimates from the United Nations predict the continental population to be in a state of decline by 2025 (UN 2019). This trajectory of depopulation is set to persist for the remainder of the 21st century, defining European demography. By 2100, Europe's population is forecast to shrink by around 120 million inhabitants, or by 15% (UN 2019 - medium variant). Population decline is not, however, expected to occur uniformly across the continent as significant differences in the rate and direction of population change are expected to continue, further exacerbating regional and country demographic imbalances (Eurostat 2020a, ONS 2020, UN 2019). At present, population decline is underway in 17 of 48 European countries, the majority of which confined to Eastern and Southern Europe. In the near future, decline is expected to spread to all regions of Europe with 33 countries set to undergo decline by 2050 (UN 2019). Depopulation at this scale is a previously unrecognised demographic phenomenon and will impose a wealth of novel challenges (Coleman & Rowthorn 2011, Clements et al., 2018, Franklin 2020).

Contemporary population decline is often portrayed in such a way that emphasises contrasting trajectories of population change between rural and urban areas (Coleman & Rowthorn 2011, Johnson & Lichter 2019, Franklin 2020). Though it is true that decline is more prevalent in rural areas (ESPON 2017), recent empirical evidence demonstrating population growth in certain rural areas (Pužulis & Kūle 2016, Salvati 2018, Wojewódzka-Wiewiórska 2019) and decline in urban areas (Turok & Mykhnenko 2007, Wolf & Weichmann 2018) would suggest that this notion is over-simplified. Rather, depopulation processes are sensitive to local contextual specificities (Haase et al., 2016, Doignon et al., 2016) and extend to all areas along the rural-urban continuum.

Though inherently a demographic process, population decline remains under researched. As a result, we lack a sufficient understanding of the spatial and temporal dynamics of the phenomenon. Population decline occurs within spatial-temporal containers, but research has typically focused on the occurrence of depopulation within a singular geographical setting or scale. However, population decline can co-occur with population growth. As demonstrated by Franklin (2019), depopulation can take place within a larger context of growth and vice versa. Indeed, examples of sub-national population decline occurring within countries of growth are abundant (see Wolff & Weichmann 2018). To capture these trends, it is vital to consider depopulation across small area units across a large geographical scale. Our current understanding of population decline stems from research that focuses on small scale case studies and provide only a highly specific account of localised population declines (Viñas 2019, Spórna et al., 2016, Szmytkie 2016).

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[1] *Population decline and depopulation are used interchangeably throughout this article.*

This issue is compounded by an intense rural-urban dichotomy that persists within relevant research, with studies exclusively concerned with either rural (Kuczabski & Michalski 2013, Wojewódzka-Wiewiórska 2019, Pužulis & Kūle 2016) or urban decline (Haase et al., 2016, Wolff & Weichmann 2018). A holistic understanding of European depopulation is needed but currently difficult to attain. Additionally, the temporal dynamics of decline are seldom considered in research. Too often studies focus only on the outcome of depopulation and fail to acknowledge the process in which decline unfolds. Population change is a path dependence process, and, as emphasised by Franklin (2020), population decline is both a process and an outcome. Also recognising this, Haase et al.,(2016), call for a move towards process-oriented research into population decline. Understanding past patterns of population change is key to build our knowledge about present and future population patterns (Patias et al. 2021a). To our knowledge, no study has empirically analysed population decline processes in a comparative cross-national spatial framework across the rural-urban continuum. We aim to address this by identifying distinctive trajectories of sub-national population decline; establish differences in the sequence, timing and degree in these trajectories; and determine the spatially differentiated extent of depopulation across Europe. To these ends, we apply a novel methodology in sequence analysis to a dataset of annual population change capturing trajectories of depopulation in 696 sub-national areas covering the period 2000-2018. Created for the study of DNA sequencing, sequence analysis has been applied in population studies to analyse individual-level trajectories over the life course (e.g., Rowe et al. 2017; Backman et al., 2021). But it has rarely been used to examine the temporal evolution of spatial population trajectories, except for applications to understanding changes in the socio-economic composition of neighbourhoods (Delmelle 2016, Patias et al., 2021a; 2021b). Sequence analysis has the potential to expand our understanding of population decline by embedding individual population changes within a wider framework of population trajectories; that is, a sequence of interlinked changes experienced by an area.

Next, we review existing literature on sub-national population decline in Europe and introduce the urban differentiation model (Geyer & Kontuly 1993) as a useful framework to contextualise and analyse trajectories of population decline across the rural-urban continuum. We then describe in detail the methodologic procedure, explaining the application of sequence analysis. Our results are then presented, followed by a discussion and a concluding section.

2.2 Literature Review

Europe is facing unprecedented population declines. Across the continent, in all countries, fertility rates no longer sustain population growth. Instead, fertility rates currently lie below the replacement level of 2.1 births per woman (UN 2019) and promote natural population declines. Though not yet occurring in all countries of Europe on a national scale, population decline is particularly pronounced in Eastern and Southern European countries. With population momentum waning in growing countries, population decline is averted through positive net migration streams (Sobotka & Fürnkranz-Prskawetz 2020). Migration, however, intrinsically promotes depopulation in the places of origin (Franklin 2020) and can accelerate population declines. Though it remains unclear how the effects of COVID-19 will shape the demographic future of Europe, early evidence of crude birth rate reductions (Aassve et al., 2021) combined with disrupted migration flows points to an immediate future with fewer people than present.

2.2.1 Consequences of Decline

Population decline is expected to bring about unprecedented challenges across society. Inherently a local issue, population decline poses considerable threats to communities. Particularly, areas in decline are faced with shrinking local tax revenues, impacting the provision of vital services (Carbonaro et al., 2018) including transport (Franklin et al., 2018). Areas in decline are also less attractive to prospective businesses and face a stagnation in regards to opportunity. Additionally, as a demographic process, population decline will alter the composition of areas. With this, changes to age structure, diversity, and attitudes will be likely observed (Franklin 2020). Such changes will bear social and economic implications of their own, namely income inequalities (Bellman et al. 2018) and the reduction in area competitiveness (Poot 2008), potentially fuelling further population losses. In short, decline will have a profound impact on the way local areas are experienced and perceived. On a national scale, depopulation poses challenges that are closely associated with aging populations. Particularly, increases in expenditure on pensions and health services accompany increasing public debts, severe cuts in other spending, and tax increases (Clements et al., 2018). Population aging, and decline, threaten future economic productivity and growth due to labour and skills shortages (see Bloom et al., 2010, Clements et al., 2018).

2.2.2 Sub-national Decline

The risk of population decline is not equal across sub-national regions. General patterns in the geographic distribution of depopulation show that rural areas are currently dominating the landscape of European population decline (Eurostat 2020a) with a growing number of rural regions experiencing depopulation in recent years (Dax & Fisher 2018). Rural population decline is more commonplace in central and eastern Europe than in western Europe (ESPON 2017), although it extends to all regions of the continent (Eurostat 2020a). It should be noted, however, that not all rural areas are prone to population decline. Rather there exists fragmented country specific evidence of population growth within rural areas situated in close proximity to large urban areas. This has been demonstrated in Lativa (Pužulis & Kūle 2016), Lithuania (Ubarevičienė et al., 2016) and Poland (Wojewódzka-Wiewiórska 2019). Rural decline is perhaps then more pronounced in remote and peripheral rural areas, though it remains unclear if this is a continental-wide pattern. In contrast, urban areas are continuing to record population growth (Eurostat 2020a) and are less likely to experience depopulation. Urban areas are not, however, exempt from depopulation. Rather, almost half of all European cities had experienced a period of decline between 1990-2010 (Wolf & Weichmann, 2018).

Certain cities, however, appear more likely to experience population decline than others. Geographically, incidences of urban population decline are three times more prevalent in the eastern EU-13 nations than in the western EU-15 (European Commission 2016). Recent research also suggests that position within the urban hierarchy is important in determining population decline outcomes. In an empirical test of the association between city size and population decline, Kabisch & Haase (2011) find that smaller sized city agglomerations were more likely to experience population decline than large and mid-sized agglomerations. The propensity for population growth in European capital cities reinforces this notion (Lutz et al., 2019, Karachurina & Mkrtchyan 2015). Despite this, anomalies to this trend are evident, for example recent population declines observed in Athens and Thessaloniki, the largest urban agglomerations in Greece (Salvati 2018).

2.2.3 Trajectories of Population Decline

Population decline is both an outcome and processes (Franklin 2020). Research concerning European depopulation too often considers only the measured outcome, i.e., the reduction in numbers of population, and ignores the process of decline over time (Turok & Mykhnenko 2007). This leaves many crucial questions unanswered; *How have areas experienced population decline over time? Are population declines sudden and rapid, or are they longstanding and gradual? Do trajectories of population decline differ between countries or between rural and urban regions? Are decline trajectories permanent or can they be reversed? What may influence trajectories of population decline?* Understanding the temporal evolution, pace and extent of decline is vital to developing appropriate policy responses, improving population projections and advancing demographic theory concerning decline.

From existing research, we understand the existence of divergent trajectories of population decline both within and between countries (Haase et al., 2016, Wolff & Weichmann 2018). However, such studies consider only urban regions and limit our understanding of continental wide depopulation processes, which chiefly concern rural regions. A comprehensive, cross-national, study into sub-national depopulation processes is desirable for numerous reasons. Firstly, the extent of population decline in individual countries and sub-national regions can be more effectively assessed when considered within a cross-national context. Secondly, cross-national comparative analyses have the potential to demonstrate new insights into population decline through uncovering nuanced patterns and processes. Finally, cross-national comparisons provide a more rigorous test-bed for theories concerning depopulation.

2.2.4 Urban Differentiation

In absence of a comprehensive understanding of temporal depopulation processes, the urban differentiation model (Geyer & Kontuly, 1993) provides a useful theoretical framework in which trajectories of population decline can be contextualised. Yet, we recognise that this model was not devised to study trajectories of population decline. The model assumes that national human settlement systems will follow a predefined sequence of cascading population changes driven mainly by net migration outcomes. The urban differentiation model postulates that groups of large, intermediate-sized and small cities undergo successive periods of fast and slow population growth or decline, resulting in stages of population concentration or deconcentration (Geyer & Kontuly 1996). In a first stage, fast population growth is assumed to occur in primate cities, with smaller cities and rural settlements losing population, resulting in urbanisation. This is followed by a second phase in which population growth is still concentrated in primate cities but occurs at a more modest pace, and intermediate cities start experiencing moderate population growth. In a third stage, population growth primarily occurs in intermediate cities, though small cities start recording population increases, while the rate of population change decreases in main urban centres. During a fourth phase, population deconcentration in the form of counter-urbanisation becomes the dominant pattern reflecting concentration of population growth in small cities, population decline in major cities and decreasing population growth in intermediate urban areas**.** The model assumes that the process restarts from the first stage with a new phase of population concentration occurring in primate cities, though subsequent cycles are expected to be less intense in magnitude than those during the initial phase.

Given that population dynamics are spatially varying, the urban differentiation model offers a useful framework to analyse changes in population over time. Particularly, the model recognises fluctuations in rates of population change and the divergence of trajectories across the urban-rural continuum. Should the model hold true, we would expect to find a structured set of population decline trajectories representing the individual stages of population concentration and deconcentration outlined in the model. For example, if a country is experiencing concentrated population growth in chief urban areas, we should observe trajectories of accelerating depopulation in rural and small cities. Similarly, if a country is experiencing urban population deconcentration or population decline, annual growth should be observed in rural or small cities. However, we postulate that trajectories of population decline are more complex and mediated by local contingencies, so we do not expect national settlement systems to follow these predetermined sets of transitions.

Furthermore, the model does not recognise population dynamics in post-growth settings, as the model was conceived and tested through the consideration of areas situated within nations of population growth only (Geyer & Kontuly, 1993). Considering that a sizeable proportion of European nations are currently experiencing national population losses, it can be expected that the model will not accurately depict contemporary population dynamics within these nations. However, distinct periods of population concentration and deconcentration, akin to that described by the urban differentiation model, have been identified within nations of population decline. Particularly, macro trends in European declining nations support the notion of rural depletion in favour of population growth in primate cities and subsequent sub-urbanisation. This is evidenced in Belarus (Antipova & Fakeyeva 2012), Bulgaria (Slaev & Kovachev 2015), Romania (Dumitrache et al., 2016) and Ukraine (Gnatiuk 2017).

2.3 Methodology

2.3.1 Data

We collected annual population data involving 2,035 areas in 43 European territories over an 18-year period between 2000 and 2018. A database was assembled using data from Eurostat and national statistics offices. Eurostat data were used as the base and supplemented with national statistics data for European territories excluded from Eurostat, or where data were incomplete. Appendix 1 provides a breakdown of data sources by territory. Data constraints do not allow to expand the period of analysis and build a longer time series. Given these constraints, we acknowledge that our data may not capture the start of the contemporary trajectory of population decline in some areas (e.g., Martí-Henneberg 2005).

We used NUTS (Nomenclature of Territorial Units for Statistics) 3 units, corresponding to the smallest regional unit in the Eurostat territorial classification system. NUTS 3 areas represent the smallest geographical unit for which consistent, longitudinal data were available for multiple European nations. Due to national variations in the classification of geographical units, NUTS 3 units are not consistently configured, creating differences in the total area and population size of the geographic units. This is compounded in our study by our use of multiple datasets in which the NUTS classification is not utilised. Our population data thus captures population processes at various spatial scales, and it is possible that small-scale instances of population decline are not recorded in large geographic units where multiple areas with heterogeneous population change trajectories are aggregated (see Franklin 2019). However, in an attempt to minimise the impact of this, we collected data on the smallest geographic areas for which consistent data was available. We also analyse population decline processes in similarly characterised areas, considering areas along the rural-urban continuum. In a study of this nature, it should be acknowledged the issues relating to the modifiable areal unit problem (MAUP) (Openshaw 1984). We recognise that alternative territorial boundaries or units may capture different population processes.

From our database, we identified a total of 736 sub-national areas that experienced an overall population decline from 2000 to 2018. These areas are characterised by their relative population losses and are the focus of this study. A significant challenge of building a spatial panel dataset is presented as geographic boundaries change over time (Rowe 2017). We were largely able to mitigate the impact of this through harmonising these changes based on Eurostat's correspondence files which provides a historical record of these changes. Yet, 40 areas were missing data for a significant portion of the time series and were removed from the analysis. These areas are exclusively located within Germany (25) and Poland (15) (see Appendix 1), within regional population decline hotspots. These areas have experienced substantial declines in the shortened time-period for which our data represents (Eurostat 2020b). Our analysis therefore concerns the trajectories of population decline in a total of 696 sub-national areas in 33 European territories. Of these areas, 131 have an incomplete time series on the basis of missing data for a single year (i.e., 2000 or 2001). We decided to include these areas in our analysis. Our results are robust to their inclusion. Additionally, we used data on the population distribution by settlement type to construct a rural-urban typology from NUTS-3 areas from Eurostat, and supplement with national statistics data for areas not included in the Eurostat dataset (Appendix 1).

2.3.2 Method

We developed a four-stage methodological strategy to define and analyse pathways of population decline, as shown in Figure 1. Our application of sequence analysis and clustering techniques enables the comparison of sub-national longitudinal trajectories of population change and identifies systematic pathways of depopulation. Our method yields a comprehensive overview of contemporary population decline processes across sub-national Europe. We first computed annual area-specific rates of population change and analysed their distribution across Europe to identify a set of thresholds that define differences in the direction and magnitude of population change. Second, we applied a sequence analysis technique, known as optimal matching, to measure differences in the temporal profile of population change across individual areas. Third, we used these measures to define a typology of population decline trajectories using a hierarchical clustering procedure. In a fourth stage, we examined the geographic distribution of these trajectories and analysed differences across the urban-rural continuum by applying a multinomial logistic regression model. Next, we describe the implementation of each of these stages.

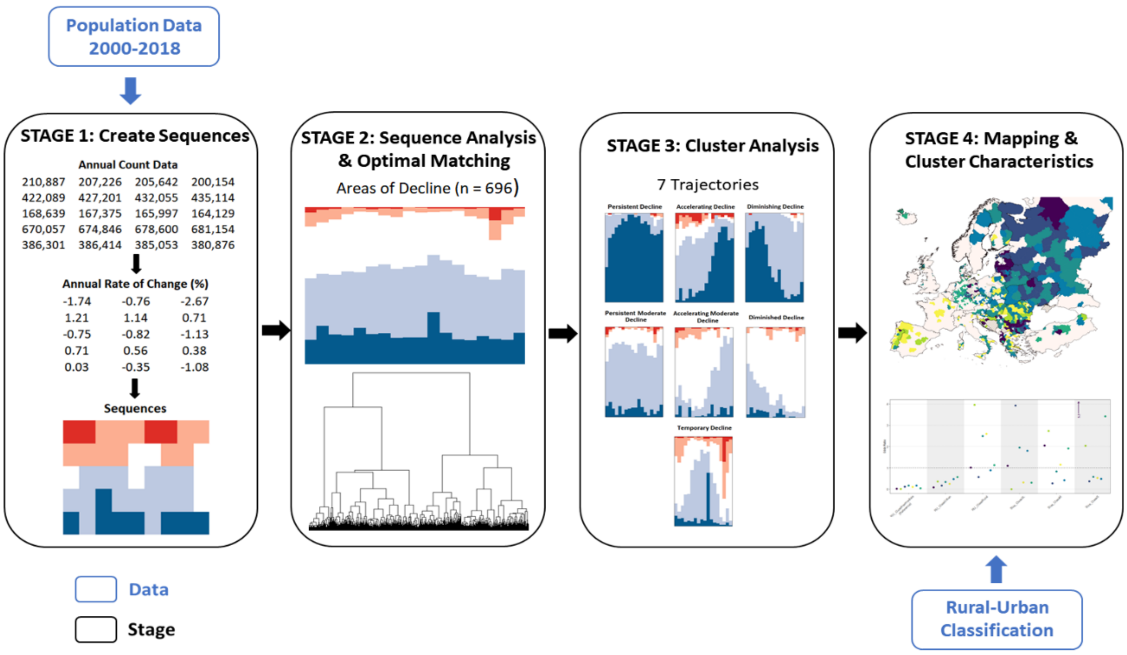


Figure 2.1 – Methodological Procedure

Stage 1

Sequence analysis requires longitudinal categorical data as an input, and is therefore incompatible with population count data. To enable the implementation of sequence analysis, we first classified population count data into distinct categorical classes, henceforth referred to as states of population change. We computed the annual percentage rate of population change for individual areas and used these rates to differentiate areas of high, moderate and stable population growth and decline. The annual rate of population change was calculated as follows:

$$\text{Rate of Population Change} = \frac{\boldsymbol{P(t2) - P(t1)}}{\boldsymbol{P(t1)}} \qquad \textbf{(1)}$$

Where P(t1) is the population at year t and P(t2) is the population at t+1.

We distinguished five categorical states of population change, capturing various magnitudes of population growth, decline and stability (Table 1), and representing the relative rate of annual population change. To determine appropriate thresholds for the definition of classes presented in Table 1, we analysed the distribution of the annual rate of population change, particularly its central tendency and dispersion over the 2017-18 period. The median (0.303) was used as the threshold to define the boundary between patterns of population *Stability* and *Moderate Growth*. The standard deviation (0.990) was used as the upper boundary to define trends of *Moderate Growth*. The additive inverse of these thresholds were used to define patterns of *Stability, Moderate Decline* and *Decline*. Symmetric thresholds for categories of population decline and growth were selected to ensure the simplicity of our sequence analysis and its interpretation. We recognise that the categorisation of rates of population change are subjective and dependent on regional context. However, our categorisation closely aligns with existing definitions of population decline (UN 2019, Wolff & Weichman 2018). We applied the classification to all area-year observations in our data set to identify how the pattern of population change evolves for individual areas. The resulting output of this stage is the transformation of count data to categorical format for subsequent sequence analysis, with each annual measure of population count transformed to a categorical state of population change (Table 1). The trajectories of population change are then represented by the chronological ordering of these states.

State	Definition (annual % change)	2000 - 2001	2008-2009	2017 - 2018
Decline	≤ -0.99	104	144	155
Moderate Decline	> -0.99 & ≤ -0.3	297	363	371
Stability	> -0.3 & < 0.3	488	627	679
Moderate Growth	≥ 0.3 & < 0.99	504	557	565
Growth	≥ 0.99	225	309	252

Table 2.1 – Defined States of Population Change for Sequence Analysis
Note: Count totals do not sum to total number of areas (n = 2035) due to year-specific missing data

Stage 2

The next stage concerns the application of sequence analysis to compare the longitudinal trajectories of population decline across sub-national Europe. Here, the units of analysis are individual sequences, consisting of the chronological ordering of individual sequence elements which are one of our five states of population change. Our sequences therefore represent the changing rate of population change over our time series, 2000-2018. For the application of sequence analysis, we used the TraMineR package in R (Gabadinho et al., 2011).

We measured the dissimilarity between individual sequences of population change, to identify similar types of trajectories in Stage 3. To this end, we used a sequence analysis technique, optimal matching (OM), which computes distances between sequences as a function of the number of transformations required to make sequences identical. A total of three transformation operations are used: insertion, deletion (indel) and substitution. Indel operations involve the addition or removal of an element within the sequence and substitution operations are the replacement of one element for another. Each of these operations are assigned a cost, and the distance between two sequences is defined as the minimum cost to transform one sequence to another (Abbott & Tsay 2000). The greater the cost to make two sequences identical, the greater the dissimilarity and *vice versa*. The costs of indel and substitution operations are not equally weighted. By default, indel costs are set to 1 and substitution costs are empirically derived from transition rates between states. The cost of substitution is inversely related to the frequency of observed transitions within the data. This means that infrequent transitions between states have a higher substitution cost. For example, transitions from the state of decline to stability are rarer than decline to moderate decline, and so this is represented by a higher cost (Table 2).

A total of 129 areas in our data set are missing observations for the year 2000, and 40 are also missing data for 2001. We considered missing observations as an additional class in our analysis and assigned a substitution cost of 2, the highest cost, to minimise the impact on our results. The intuition of this is that substitutions for missing data are costly so dissimilarity measures are rarely based on missing data, and if this happened, such observations are grouped into a single category (see below). Our weighting scheme, that is the cost of indel operations being less than substitutions, enables us to uncover differences in the sequencing of population changes according to our categories, rather than their timing. This is because the addition or removal of elements from indel operations produce a time shift between compared sequences in order to identify identical subsequences (Lesnard 2014). Indel operations favour the identical ordering of states irrespective of their position in the sequence (Lesnard 2010). The result of this stage is the production of a distant matrix, an empirical measure of the degree of closeness between areas according to their sequences.

	Decline	Moderate Decline	Stability	Moderate Growth	Growth	Missing
Decline	0	1.684	1.897	1.949	1.852	2
Moderate Decline	1.684	0	1.623	1.867	1.721	2
Stability	1.897	1.623	0	1.499	1.718	2
Moderate Growth	1.949	1.867	1.499	0	1.746	2
Growth	1.852	1.721	1.718	1.746	0	2
Missing	2	2	2	2	2	0

Table 2.2 – Substitution Cost Matrix Depicting the Costs Assigned to Each Transition.

Stage 3

The resulting distance matrix from Stage 2 was used as an input for a cluster analysis, to group areas by similar temporal processes of population decline and thereby producing a typology of population decline trajectories. To this end, Ward's hierarchical ascending clustering algorithm (Ward 1963) was used. We also tested alternative clustering methodologies, namely K-medoids, though Ward's method was favoured for its reduced heterogeneity between groups and its simplicity. To determine the optimal number of clusters, a range of cluster quality measures were empirically evaluated using the WeightedCluster package in R (Studer 2013). These include the Average Silhouette Width (ASW), a measure of distances between clusters and within group homogeneity (Kaufman & Rousseeuw 1990); Hubert's Somers' D (HGSD) which measures the clusters capacity to reproduce the distance matrix (Hubert and Arabie 1985); Point Biserial Correlation (PBC) which is similar to HGSD, but rather measures the capacity to reproduce the exact value of the distance matrix (see Hennig and Liao 2010). A graphical comparison of these metrics for a range of cluster solutions is provided (Appendix 2). From this, 7 clusters were determined to be the optimal solution.

Stage 4

In a final stage, we analysed the spatial distribution of the population decline trajectories. We measured the geographic spread and concentration of these trajectories by country in Europe and analysed differences in their incidence across the urban-rural continuum. For the latter, we estimated a multinomial logistic regression model with a multi-categorical variable representing the trajectories of decline as the dependent variable. Areas of population growth (n = 1,299) are included in this model, and used as the reference category. Our independent variables are a set of categorical variables representing population size and settlement type. We consider 2018 data to classify areas by population size and share of rural population based on four population size categories - derived from the OECD/EC urban centre size classification (Dijkstra & Poelman 2012) - and three settlement types - determined by the proportion of an area's rural population, in accordance with the Eurostat Urban-Rural typology (Eurostat 2013) – see Table 3. Cross-tabulating these categories produces a rural-urban typology that accounts for different population sizes, enabling a more rigorous analysis of population decline processes by considering both area classification and size. Our multinomial logistic regression model quantitatively assesses the probability of an area experiencing a particular trajectory of population decline according to population size and settlement type.

		Rurality (% share of rural population)		
		Urban (< 20%)	Intermediate (< 50%, ≥ 20%)	Rural (≥ 50%)
Population Size	XL (≥ 1,000,000)	86	86	6
	Large (≥ 500,000)	78	130	38
	Medium (≥ 250,000)	137	184	111
	Small (< 250,000)	217	445	518

Table 2.3 – Urban-Rural Typology

2.4 Results and Discussion

2.4.1 Overall Patterns of Decline

Population decline has taken place in Europe since 2000. Yet, less is known about the magnitude and spatial distribution of these changes. Figure 2 presents the extent of sub-national population declines from 2000-2018 and reveals an unequal distribution across the continent. We observe a critical disparity in the extent of such declines between the east and west of Europe. Generally, the prevalence and magnitude of population declines are greater within countries located east of Germany. Particularly, the greatest declines are observed within the Baltic and Balkan states where examples of sub-national areas exceeding 20% population decline are abundant.

Figure 2 also reveals the geographical spread and concentration of population decline within individual countries. Particularly, growth and decline contrasts are evident between northern and southern Italy (see Reynaud et al., 2020), western and eastern Germany, northern and southern Austria, eastern and western Portugal, northern-western and rest of Spain. Growth is typically observed in major urban areas, chiefly capital cities and its surrounding areas. In countries where depopulation is a prevailing feature, population growth is exclusively concentrated in these urban centres. This is true for Romania (Bucharest), Bulgaria (Sofia), Croatia (Zagreb), Latvia (Riga), Lithuania (Vilnius), Greece (Athens), Portugal (Lisbon and Porto) and Hungary (Budapest).

While our focus is on population decline, growth is acknowledged as the continuing dominant direction of population change in Europe, particularly within countries in the north and west of the continent. Of the 43 European territories investigated within this study, 5 do not observe sub-national depopulation: Belgium, Ireland, Malta, Norway, and Switzerland.

Another 5 have not recorded a population decline though they comprise small nations with no sub-national regions recognised at the NUTS 3 level: Cyprus, Liechtenstein, Luxembourg, Montenegro and San Marino.

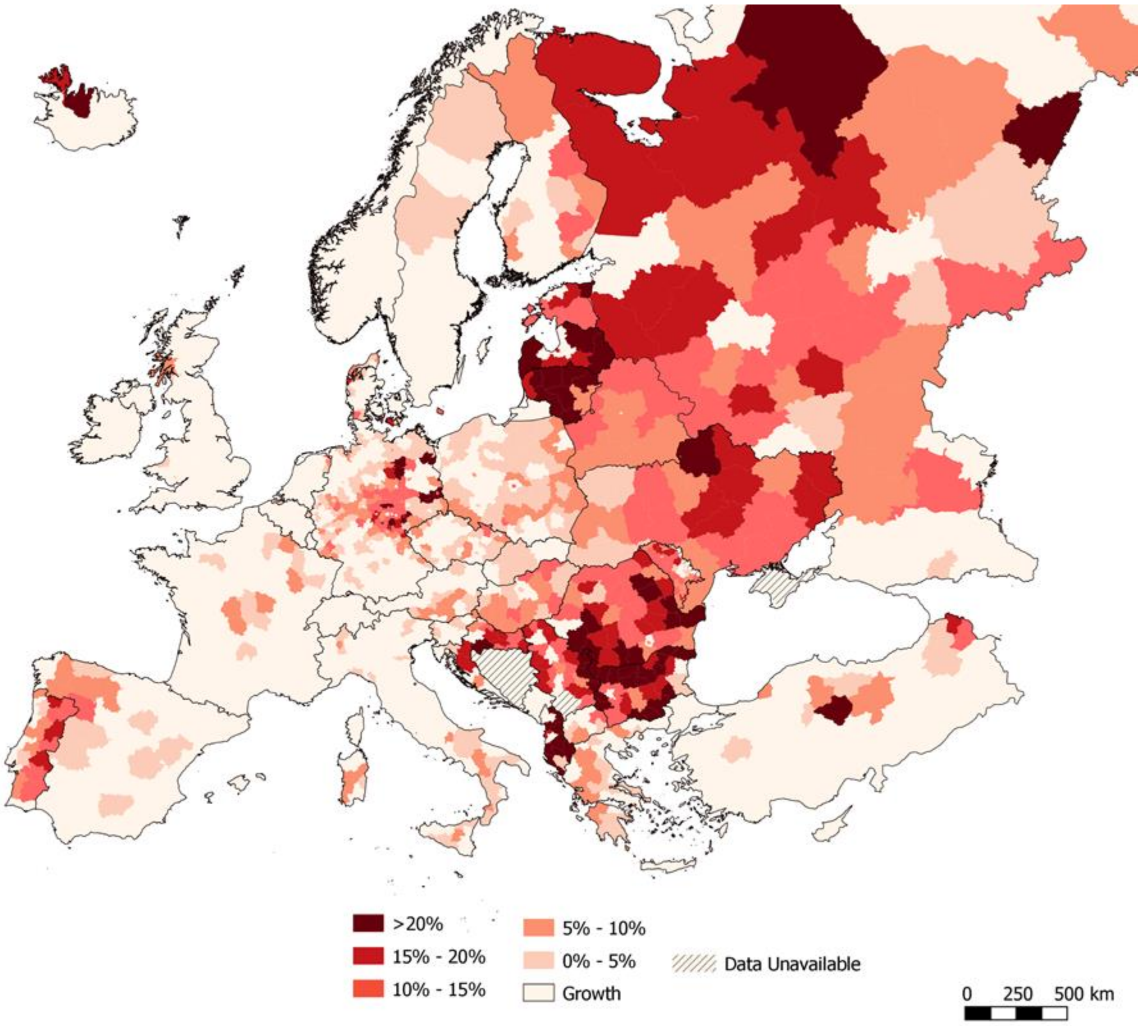


Figure 2.2 – Extent of Population Declines From 2000 - 2018

2.4.2 Trajectories of Population Decline

These differences in the extent of sub-national population declines are underpinned by systematic differences in the pace and timing of depopulation. Figure 3 presents seven distinct pathways of depopulation that were identified through the application of sequence and clustering analyses as described in Stages 2 and 3 of our methodology. These pathways represent distinctive ways in which population decline has unfolded across the continent.

Figure 3 presents three sets of plots: (1) state index plots, (2) state distribution plots, and (3) mean time plots for our seven trajectories of depopulation. Index plots display individual sequences, with each line representing an area and each colour denoting a class of population change from growth to decline. Reading horizontally, each line shows transitions between classes of population change over time, representing fluctuations in the rate and direction of population change. State distribution plots read vertically, showing the distribution of each class of population change for each year. Mean time plots indicate the average number of years that areas spend on each class. Table 4 complements these plots offering key summary statistics to describe each trajectory.

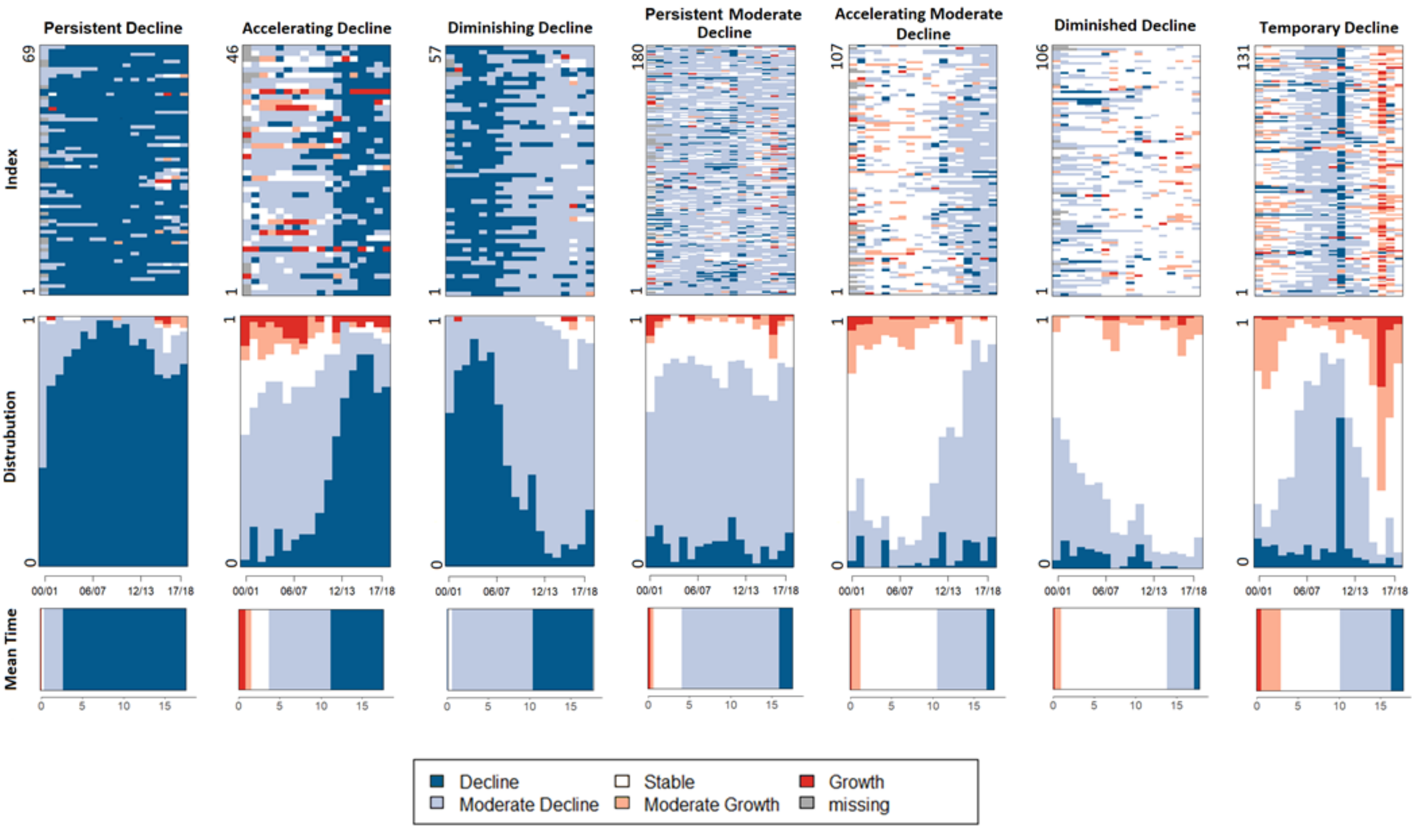


Figure 2.3 – Typology of European Population Decline

	Cluster						
	Persistent Decline	Accelerating Decline	Diminishing Decline	Persistent Moderate Decline	Accelerating Moderate Decline	Diminished Decline	Temporary Decline
n	69	46	57	180	107	106	131
n (%)	9.91	6.61	8.19	25.86	15.37	15.23	18.82
Population (2000)	16,204,176	10,533,267	52,011,267	84,589,205	33,390,791	76,373,660	24,265,912
Population (2018)	12,356,331	8,957,866	44,190,272	76,724,267	31,440,886	73,562,720	23,289,173
Decline	3,847,845	1,575,401	7,820,995	7,864,938	1,949,905	2,810,940	976,739
Decline (%)	23.75	14.96	15.04	9.30	5.84	3.68	4.03

Table 2.4 – Measurement of the Extent of Depopulation Within Each Trajectory Cluster

Persistent Decline (9.91%): This trajectory is composed of areas displaying an unwavering pattern of population decline of the highest magnitude (≤-0.99% per-annum, see Table 1). Areas tend to follow a consistent pattern of population decline. Very few transitions between classes are observed. Relative population loss in areas within this trajectory is the greatest of all seven trajectories, totalling 3.85 million from 2000 to 2018 - equating to a 23.75% reduction (Table 4). Geographically, areas within this trajectory are located exclusively in eastern and southern Europe - with the exception of areas in the former East Germany (Figure 4). Particularly concentrated in Balkan and Baltic countries and over-represented in Albania, Bulgaria, Latvia, and Lithuania. Considering the persistent and rapid nature of decline, areas in this trajectory are most likely already experiencing consequences of population decline.

Accelerating Decline (6.61%): Areas that have undergone this trajectory display a tendency of rising annual rate of population decline, denoted by the transition from classes of moderate decline to decline. They have declined by a total of 1.57 million since the year 2000, representing an overall decline of 14.96%. Predominantly located in Southern Europe, chiefly in the Balkan countries of Croatia and Romania. Instances of *Accelerating Decline* can also be found in western Europe, in non-coastal Portugal and Spain.

Diminishing Decline (8.19%): This trajectory describes a pattern of decelerating population decline, with a transition from our decline to moderate decline class, representing a decrease in rates of population decline. In total, areas experiencing this trajectory recorded a combined population loss of 7.82 million, or 15.04% (Table 4). These areas are largely located within eastern Europe, in former member countries of the Soviet Union - Belarus, Estonia, Russia and Ukraine - and parts of east Germany.

Persistent Moderate Decline (25.86%): This trajectory is defined by sustained moderate decline, with an annual rate of population change ranging between -0.3% to -0.99%, see Table 1. Very little movement between classes of population change are observed for this trajectory. This is the most common trajectory of population decline across Europe with a total of 180 sub-national areas, or 25.86%, experiencing this pathway. Since 2000, combined population losses in these areas have totalled 7.86 million equating to a reduction of 9.3%. This trajectory is distributed across Europe in a total of 25 European territories and is the predominant pathway of decline in Austria, Finland, Hungary, Moldova, Poland, Romania, and Serbia.

Accelerating Moderate Decline (15.37%): Areas in this trajectory tended to experience a trajectory of accelerating decline comprising of a transition from an extended period of stability to moderate population decline. These areas comprise a cluster of expansion of population decline in Europe in recent years. Population loss in these areas is moderate, totalling just 1.95 million or 5.84% (Table 4). Distributed across the continent in a total of 17 territories, this trajectory is over-represented in Southern Europe and is the most common trajectory of decline in the countries of France, Greece, Italy, Romania, Spain, Slovenia, and Portugal. These areas are set to experience further decreases in the rate of population growth and thus accelerating the process of depopulation, similar to the process experienced by *Accelerating Decline* areas.

Diminished Decline (15.23%): This trajectory describes a transitional pattern from the Moderate Decline to Stable classes. Here the annual rate of population decline is reduced to the point where areas are no longer considered in decline but rather in stability. This trajectory therefore represents the end of population decline, though a negative rate of annual population change is captured within the Stable state boundary (see Table 1). Areas in this trajectory have declined by a total of 2.81 million people, equating to a population reduction of 3.68% between 2000 and 2018. Geographically, these areas are predominantly found within central and eastern Europe and are most prevalent in Czechia, Slovakia, Sweden and the UK (Figure 4).

Temporary Decline (18.82%): This trajectory is characterised by a sequential trend of Stable to Moderate Decline, followed by a short spell of population growth, returning to within the bounds of the stability. Here, decline is a temporary phenomenon, though severe enough to reduce the combined populations by 0.97 million or 4.03% from 2000 (table 4). Areas experiencing this trajectory are heavily concentrated in Germany. Of the 131 areas, 101 are within Germany. Such abrupt reversal of population decline could be linked to the influx of migrants during the Syrian refugee crisis (see Newsham & Rowe 2019).

Taken together, the identified trajectories reveal distinctive patterns of accelerating and stable rates of population decline, as well as trends of population reversal and temporary decline.

2.4.3 Geographic Distribution of Decline Trajectories

In Figure 4, we plot the distribution of the seven population decline trajectory clusters. We also include areas that experienced population growth to present a complete picture of contemporary European population change. Analysing the geographic distribution of our population decline trajectories across the continent reveals marked differences between European sub-regions. Trajectories of *Accelerating Moderate Decline* and *Temporary Decline* are concentrated in the South-West and Central regions, particularly in Portugal, Spain, France, Germany, Italy and Slovenia. These patterns indicate that depopulation is either a recent or temporary phenomenon in these countries. In the North-East of Europe *Persistent Decline* and *Accelerating Decline* trajectories are dominant, reflecting a trend of fast paced population decline.

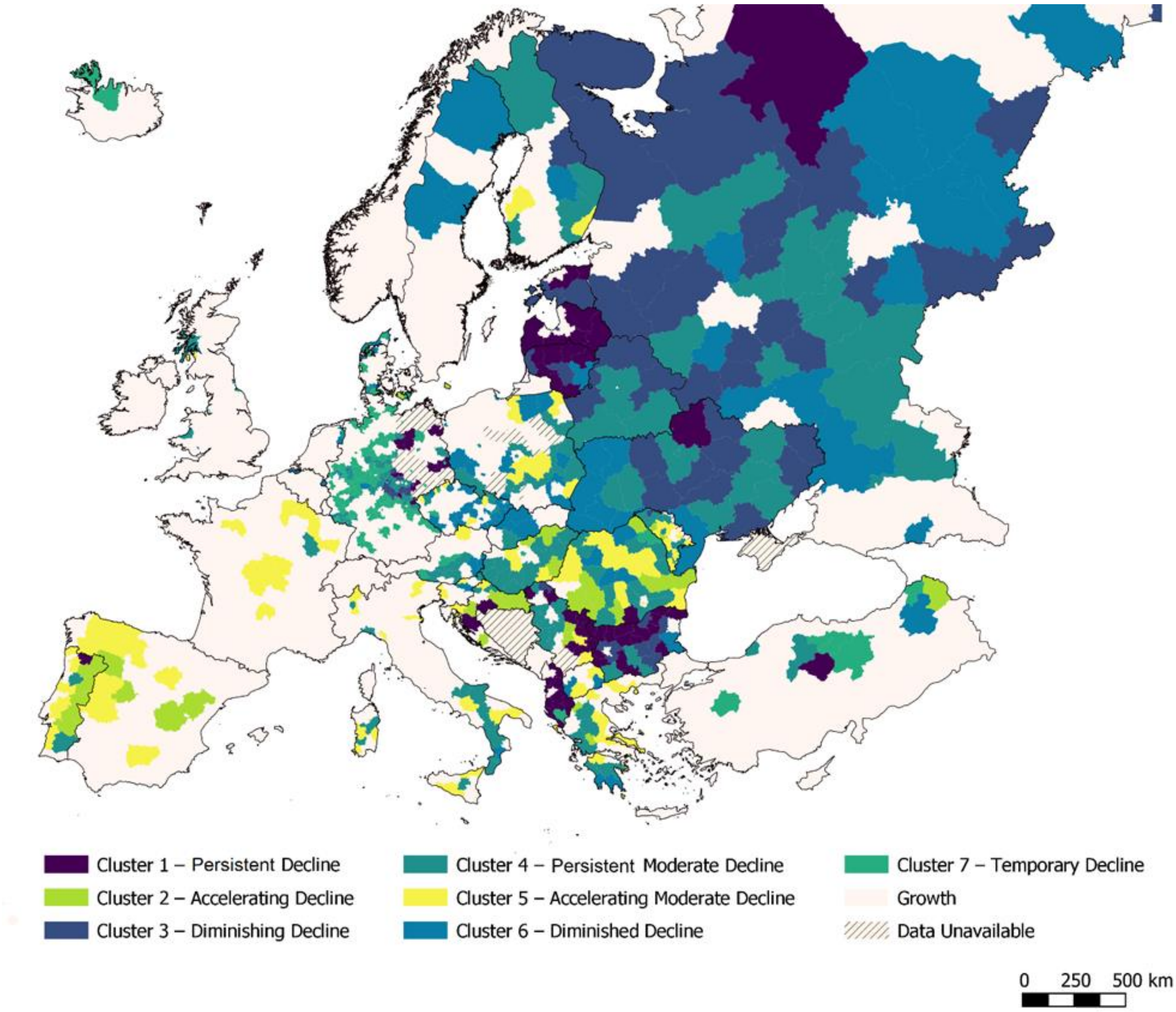


Figure 2.4 – Geographic Distribution of Population Decline Trajectory Clusters

Additionally, examining the distribution of trajectories by country reveals differences in the prevalence of the pace and evolution of sub-national population decline (Figure 5). These differences reveal the co-existence of sub-national patterns of population decline in individual countries. Baltic nations are dominated by the *Persistent Decline* trajectory, depicting a picture of consistent fast-paced population decline. Particularly, 80% of Latvian areas and 70% of Lithuanian areas are characterised by this decline trajectory. This is less evident in Estonia, where the trajectory *Diminishing Decline* is also well represented (50% of declining areas), indicating a slight divergence from the Baltic model of population change, characterised by a deceleration of depopulation in parts of the nation. The dominance of the *Persistent Decline* trajectory is echoed in Balkan nations of Albania, Bulgaria, and to a lesser degree, Serbia, with 90%, 61% and 36% of areas experiencing this trajectory of decline, respectively. The *Diminishing Decline* trajectory is the dominant decline pathway in Belarus (50%), Ukraine (37.5%) and Russia (35.5%), suggesting that these nations transitioned through a period of rapid depopulation, but this has started to decelerate from 2000. Elsewhere, in east and central Europe, *Persistent Moderate Decline* is widespread and is the prevailing trajectory of decline in Hungary (61.1%), Moldova (50%), Austria (45.5%), Poland (42.4%) and Romania (32.5%). Trajectories of accelerating population decline dominate the demographic landscape of Southern Europe. *Accelerating Moderate Decline* is the predominant pathway of decline in Spain (69.2%), Italy (53.3%), Slovenia (50%), Portugal (43.8%), and Greece (42.9%). Elsewhere in the South, within Croatia and Andorra, population decline has continued to accelerate with a rate of sub-national decline greater than in other nations in southern Europe. Here, 100% and 53.3% of declining areas have experienced this trajectory of decline, respectively. Generally, sub-national areas in western and northern Europe show a propensity for decelerating population declines. This is demonstrated by a dominance of the *Diminished Decline* trajectory in Sweden (100%), the Netherlands (60%) and the UK (50%), as well as *Temporary Decline* in Iceland (100%), Germany (61.8%) and Denmark (39.1%).

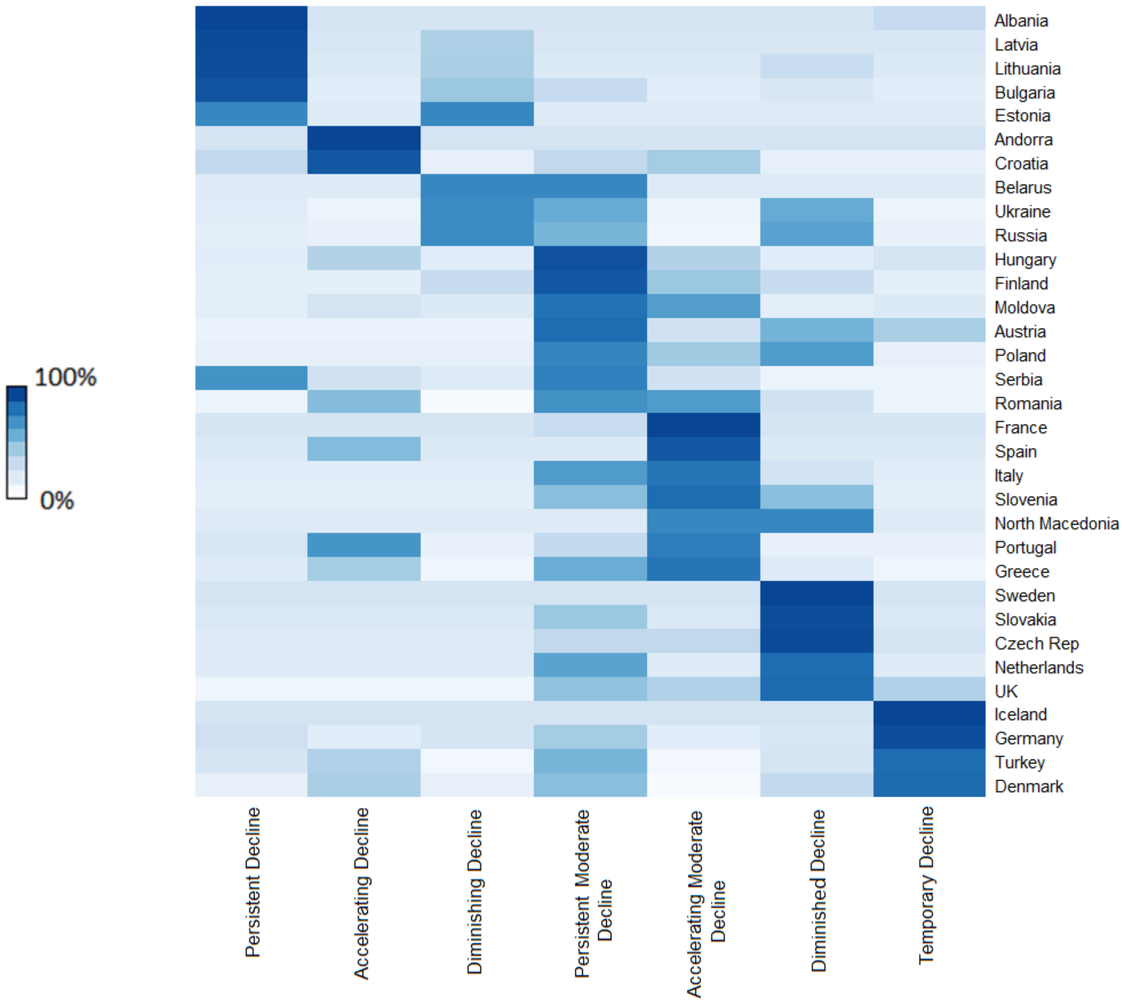


Figure 2.5 – Distribution of Trajectory Clusters in Each European Country

2.4.4 Urban and Rural Population Decline

While existing research suggests that countries follow a particular distribution of population decline spreading up across the urban hierarchy, our trajectories suggest that distinctive sets of patterns tend to coexist. To better understand differences in the temporal evolution of population decline across the rural-urban continuum, we classified sub-national areas by population size (X-large, Large, Medium, and Small) and rural population representation (Urban, Intermediate and Rural), as explained in the Method section. These classifications are used as categorical independent variables in a multinomial logistic regression model, enabling the assessment of the relationship between area characteristics and type of population decline trajectory. Figure 6 reports the results of this regression model, presented as odds ratios, and a series of stacked bar charts depicting the composition of each trajectory cluster.

We observe distinct differences in the occurrence and temporal pattern of population decline across rural, intermediate, and urban areas, and between areas of different population sizes. As expected, rural areas are more likely to experience a trajectory of population decline. However, Figure 6 reveals the unequal occurrence of depopulation across rural areas. Small and mid-sized rural areas are more likely to experience population decline than larger rural locales. Additionally, Figure 6 shows the distinctive pathways of population decline undergone by rural areas. Not all rural areas have experienced a continuing pattern of depopulation. Instead, some have observed accelerating or decelerating trends of decline. Results from our multinomial logistic regression show that rural areas are more likely to experience persistent and accelerating trajectories of population decline than urban and intermediate areas. Furthermore, we observe that small and medium sized rural areas are typically oriented towards the acceleration of population decline, whereas larger rural locales demonstrate a greater propensity for deceleration (see appendix 3). This evidence indicates that not all rural areas are the key driver of European population decline but predominantly those small in size.

Urban areas, on the other hand, are significantly less likely to experience population decline than rural and intermediate areas. Despite this, they are represented in all trajectories. Generally, urban areas are more likely to have experienced decelerating or temporary population declines than persistent or accelerating pathways. Depopulation in urban areas also seems to be associate with population size, with large urban areas more likely to undergo population decline than mid-sized and small urban locations (see appendix 3).

The likelihood of intermediate areas experiencing population decline rather aptly lies in-between that of rural and urban areas. Similar to these other areas, Figure 6 shows that the propensity for intermediate locales of different sizes to experience divergent pathways of depopulation. Particularly, we find that intermediate areas with small population sizes are more likely to experience accelerated population decline. Differently, larger intermediate areas show a tendency to experience trajectories of deceleration. On the whole, intermediate areas demonstrate the highest propensity for *Persistent Decline* and *Diminishing Decline*.

Intermediate areas are thus seen as having a similar propensity for rapid population declines as rural areas, but also are as oriented towards deceleration as urban areas.

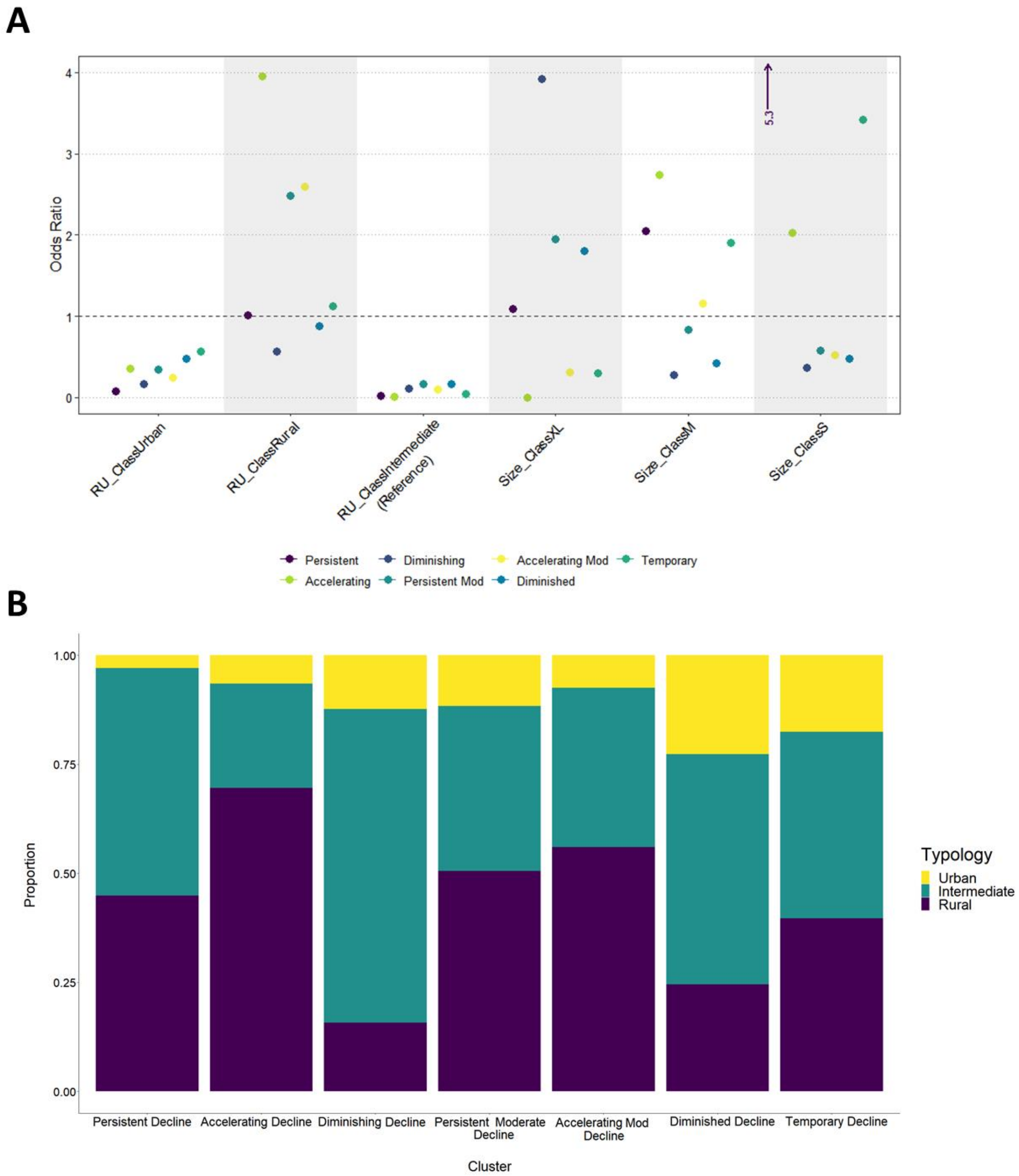


Figure 2.6 –Analysis of Population Decline Trajectory Clusters.
A. Multinomial logistic regression model characterising differences between trajectories of population decline.
B. Composition of Trajectory Clusters by Rural-Urban Typology.

2.5 Conclusion

Population decline is set to overtake population growth and become the main trend of population change in most countries across Europe, with wide-ranging societal and economic implications. Yet, we know very little about the spatial and temporal dynamics of population decline across the urban-rural continuum. This study sought to address this gap and developed a unique methodological approach to analyse the trajectories of depopulation in a total of 696 sub-national areas across 43 countries in Europe over an 18-year period (2000-2018). Our findings revealed that depopulation has occurred across the rural-urban continuum; in rural, urban and intermediate areas of Europe. A key contribution of our work is the identification of a typology of European population decline distinguishing seven distinct pathways to depopulation. These pathways represent the systematic ways in which population decline has unfolded since the year 2000. The pathways recognise persistent, temporary, accelerating and decelerating trajectories of depopulation and are distinguished by the extent, sequencing and timing of their transitions between various intensities of population decline. From our analysis we highlight three main findings.

Firstly, the most dominant pathway of population decline is *Persistent Moderate Decline*, though trajectories of accelerating and decelerating declines were well represented. Secondly, we identified the spatial concentration of the seven trajectories and noted patterns in individual countries and European sub-regions. Particularly, we observed persistent and rapid declines in the east, persistent but moderate declines in central Europe, accelerating declines in the south and decelerating population declines in the west. Population decline was demonstrated to be both a more widespread and longstanding feature of eastern Europe demography (Fihel & Okólski 2019, Coleman & Rowthorn 2011). Thirdly, we also revealed systematic differences in population decline across the rural-urban spectrum and between areas of different population size. We found that population declines in rural areas were oriented towards acceleration, signalling considerable challenges for these areas. Conversely in urban areas, the rate of population declines appears to be decelerating. We observed similar patterns between small and large populated areas, respectively, indicating that small and mid-sized rural areas are driving the process of population decline across Europe.

Our analysis also provided empirical evidence that can be used to enhance existing theories of population change across the urban-rural continuum. As proposed by the urban differentiation model, areas across this continuum are often assumed to follow a rigid progression through a set of predetermined stages (Geyer & Kontuly 1993). Yet, we showed that urban and rural areas of differing population size in individual countries do not transition through a single linear developmental pathway; that is, they do not follow a single pre-determined trajectory, in a similar fashion as suggested for the trends of fertility and mortality as anticipated by the demographic transition model. Local contingencies and past conditions act to create a set of distinct trajectories. We showed that a diverse number of depopulation trajectories can coexist, revealing simultaneous patterns of depopulation acceleration, stabilisation, and reversal. We also showed that the geographical distribution of these trajectories follows particular patterns, which capture the differentiated impact of national and local economic, social, and demographic forces.

Our typology of depopulation pathways has important policy implications. It can serve as a useful tool to identify at risk areas and areas of future concern in need of urgent policy intervention to mitigate or prevent the negative consequences associated with population decline. Our analysis revealed that population decline in the east of Europe has been more severe and sustained than elsewhere in the continent. At the same time, we identified areas that demonstrated the capacity to reverse trajectories of population decline in Germany, Sweden and the Netherlands, and now highlight the potential for further research into these areas to understand the processes underpinning this reversal in depopulation. We anticipate considerable value to such research in regard to developing policy measures that can be applied across the continent. Policy efforts to reverse population decline or mitigate the negative consequences of this trend on the economy and labour market should be concentrated, particularly on these geographic areas.

We anticipate multiple avenues for further research in relation to our typology of European population decline. Particularly, future work should focus on expanding this analysis into the future as new data become available, to assess the potential increase in severity of depopulation across Europe and geographical spread throughout the rural-urban continuum. Additionally, future research should also investigate the underlying demographic causes driving the observed spatio-temporal dynamics of depopulation. Understanding the relative importance of the ways fertility, mortality, internal and international migration contribute to shape local patterns of population decline would be of great importance to identify appropriate policy interventions.

3

The Demographic Causes of European Sub-National Population Decline

This Chapter, in its present form, was submitted to Population & Development Review

The second analytical chapter focuses on the demographic processes underpinning contemporary population decline across European sub-national areas. It involves a comprehensive methodological procedure inclusive of decomposition, multifunctional principal component analysis, clustering techniques and multinomial logistic regression modelling. A 3-factor rate decomposition empirically evaluates the contributions from changing fertility, mortality, and net-migration occurrences on population change outcomes, and forms the input into a comparative temporal analysis that considers differences in the functional shapes of these contribution curves. Multifunctional principal component analysis and k-medoid clustering are used to group areas by their shared demographic causes of population decline.

The main contribution of this chapter is the identification of five unique demographic processes that have operated differential population decline outcomes across a total of 732 sub-national areas in 33 European countries from 2000 to 2018. These processes describe unique contributions from fertility, mortality, and net-migration trajectories, and illuminate the dual-cause population decline implicating the majority of European areas undergoing population decline. These pathways are further analysed to understand their association with a broad range of areal characteristics that capture their socio-economic, demographic, and geo-spatial configurations.

Abstract

Population decline is projected to become widespread in Europe and will pose major challenges for the functioning of societies and economies. Existing literature is scattered and mostly comprises fragmented single country studies with limited comparative cross-national and temporal focus. We thus have a limited understanding of the current extent of sub-national population decline and the ways in which fertility, mortality and migration interact to shape these outcomes. This study analyses the demographic causes of sub-national population declines across 732 areas extending to 33 European countries. Drawing on data derived from national statistics, we employ a novel methodological approach consisting of decomposition, multivariate functional principal component analysis, and k-medoid clustering to analyse the longitudinal contributions from fertility, mortality and net-migration to population decline from 2000 to 2018. Our analysis reveals five unique signatures of population decline, encoding the different ways in which demographic trends have caused distinct depopulation processes. These signatures are distinguished by nuanced longitudinal contributions from fertility, mortality, and migration changes. Population decline is found to be a multi-causal process, with natural deficits and negative rates of net-migration both operating depopulations in most instances. We conclude that natural deficits are ubiquitous in causing sub-national population declines with net-migration patterns responsible for determining annual rates of population loss. We model the relationship between these signatures and wider demographic, socio-economic and geospatial attributes, finding that a distinct combination of contextual factors are associated with different demographic causes of population decline.

3.1 Introduction

The continental population of Europe is currently at the precipice of population decline, with the reversal of longstanding population growth imminent. Latest projections from the United Nations predict that, once initiated, population decline will persist and shrink the European population by 157 million, or 21%, by 2100 (UN 2022). Population decline will be a defining feature of European demography in the 21st century and is set to present a wealth of novel challenges to the functioning of societies (Coleman & Rowthorn 2011, Carbonaro et al., 2018, Clements et al., 2018, Franklin 2020). Yet, depopulation is by no means a new phenomenon within sub-national areas of Europe, as it has regularly occurred throughout demographic history (Martí-Henneberg 2005) More recently, it is becoming the dominant order of population change across broader regional units and is increasingly occurring at country levels (Newsham and Rowe 2021). Already, national population decline is observed in a total of 25 of 44 (57%) European territories, and is particularly prevalent across countries in eastern, south-eastern, and southern regions of the continent (UN 2022). By as soon as 2040, depopulation is projected to extend to all European regions (UN 2022), with its intensity and speed to be determined by fertility, mortality, and migration developments.

Much of academic and political discourse focuses on national scale population declines, yet it is inherently a localised occurrence. Across Europe, population declines are regularly measured in quantifications of regional, municipal and neighbourhood population size, even within countries experiencing population growth (Franklin 2020), and encompassing rural and urban areas alike (Raugze et al., 2017, Wolf & Weichmann 2018). Distinctive yet heterogeneous trajectories of European sub-national population decline have been identified, with depopulation occurring at differing rates and timings (Newsham & Rowe 2022). Underpinning the uneven development of depopulation are a set of demographic processes that govern the direction and magnitude of population changes, fertility, mortality, and migration outcomes. The occurrence of these demographic events are spatially variant, owing to differences in age-structure and influences exerted by the social, cultural, economic, political, environmental configurations of an area (Bongaarts 1978, Cutler et al., 2006, Campisi et al., 2020, Rowe et al., 2019).

At present, little is known about how contemporary fertility, mortality, and migration trends are driving differential population declines. An enhanced understanding of this is crucial to devising effective strategies to combat population declines through addressing the root demographic cause of population decline and not just its consequences (European Parliament 2021). Understanding the differential drivers of population decline is also important for the development of demographic theory and to inform the production of population forecasts, both of which will be crucial to the management of future population loss.

In this study, we aim to identify the demographic causes of sub-national population declines across the entire European continent comprising 33 countries. We devise a comprehensive and novel methodology to identify the ways in which fertility, mortality, and migration have interacted to produce differential population declines, referred to as depopulation signatures. Specifically, we decompose contributions from fertility, mortality, and net-migration to changing rates of population decline over the period 2000 – 2018. Applying a functional data approach (see Ramsay & Silverman 2002, Jung & Song 2022), we compare the shapes of demographic decomposition curves between 732 sub-national areas and cluster areas according to similarities in longitudinal causes of population decline. In doing so, we identify the dominant demographic causes of contemporary population decline across sub-national Europe, defining five unique signatures of population loss. We use multinomial logistic modelling to identify key demographic, socio-economic and geospatial features underpinning our identified depopulation signatures.

The remainder of this paper is structured as follows. We begin by establishing demographic trends across Europe, and outline their sensitivity to wider factors. This is accompanied by a review of the drivers of sub-national population decline. We continue with an explanation of the novel methodology used to study the different demographic contributions to European population declines. Next, we introduce the five depopulation signatures and describe their geographic distribution before analysing their demographic, socioeconomic and geo-spatial configurations. Finally, we summarise our main contributions to the understanding of contemporary population decline causes.

3.2 Literature Review

Population change is a function of fertility, mortality, and migration outcomes (Preston et al., 2000), and results in a decline when the net balance of these demographic processes is negative. Population decline can arise through two mediums; negative natural change, whereby the number of deaths outweigh that of births, or through a negative migratory balance, where emigration is greater than immigration. Historically, interactions between these demographic drivers have resulted in population growth, with exceptional events such as war, disease or famine triggering temporary declines in population (Reher 2005, Lutz & Gailey 2020). Rapid population growth was observed as countries underwent successive transitions from high to low mortality and fertility rates, as described by the demographic transition model (DTM) (see Kirk 1996). Though a cornerstone of demographic theory, the DTM is now considered antiquated, with limited relevance to modern-day population processes. Instead, contemporary European population dynamics are increasingly concerning population decline (Coleman & Rowthorn 2011, Newsham & Rowe 2021), owing to fertility, mortality, and migration developments. These demographic factors are themselves dependent on area-specific influences from social, cultural, economic, political, and environmental determinants (Bongaarts 1978, Cutler et al., 2006, Campisi et al., 2020), as well as age-structure dependencies. As a result, differential demographic drivers co-exist across space and time, operating to produce unequal developments in population change. Next, we summarise the dominant demographic trends across European sub-regions to contextualise the causes of sub-national population declines, to which the bulk of our paper pertains.

3.2.1 Fertility

European nations are united in their observance of sub-replacement period fertility rates, below 2.1 births per woman. Low fertility has persisted since its onset in all European nations (UN 2022), acting to diminish the size of successive birth cohorts and contributing to natural population decline. Low period fertility of late is explained by the postponement phenomenon (Kohler, Billari & Ortega 2006, Sobotka 2004), in which union formation and fertility are delayed to higher reproductive ages, and ultimately reducing the extent of completed fertility outcomes (Lesthaeghe and Willems., 1999).

Though all nations are implicated by similar societal changes, differential rates of low fertility are observed across the continent, both between and within countries. Nations experiencing population decline are distinguished by low fertility extremes, often below 1.5 births per woman and in some extreme cases reaching the "lowest-low" of 1.3 (Kohler, Billari & Ortega 2002). Lowest fertility rates are present across eastern and southern Europe, reflecting the prevalence of population decline in these regions. In contrast, higher fertility is observed within more economically affluent nations of Northern and Western Europe, where population declines are more sporadic (Newsham & Rowe 2022). Within-country fertility differentials are also prevalent across Europe, with most countries observing higher fertility rates in rural areas than in urban areas (Kulu 2013). Sub-national fertility differentials stem from timing and parity progression differences which are influenced by local contextual characteristics. In general, fertility tends to exhibit later timing and lower parity in urban areas (Kulu 2013, Buelens 2021). Timing differentials are closely related to a greater emphasis on economic pursuits in urban areas, and the greater competition for housing (Buelens 2021). Lower fertility parity in urban areas is closely linked to these timing effects, though housing characteristics and social exchanges are also important factors (Flori et al., 2014).

Explaining fertility differentials in Europe, studies have uncovered nuanced social, cultural, and economic regularities influencing fertility outcomes. Delayed domestic independence is cited as a cause of low fertility extremes in southern Europe (Reher 1998, Beaujouan 2020). Gender equality (see McDonald 2000), in which equal gender division of household labour reduces the burden of work-family conflicts and leads to positive fertility outcomes (Cooke 2009, Myrskylä et al. 2011, Thomas et al., 2022). Such equality is greatest in northern Europe (Fisher & Robinson 2011), where fertility is highest in the continent (UN 2022). Relative successes of service-oriented policy measures that reduce the opportunity cost of children, particularly in northern and western Europe (Neyer & Anderssen 2008), as opposed to relative failures of income-support policies (Sobotka et al., 2019). Finally, increases in fertility rates from migrant fertility (Newsham & Rowe 2021), disproportionately benefits select northern and western European countries, where immigration is greatest (King & Okólski 2018).

3.2.2 Mortality

Mortality represents the primary way in which populations shrink and is therefore fundamental to population decline. Contemporary mortality trends can present contrasting narratives, with regards to depopulation, depending on the chosen measure. For example, life expectancy has increased in every European territory from 2000 to 2018, signalling longevity improvements that are conducive to population growth. However, 29 of 45 countries (64%) have recorded increases in crude mortality rates during the same period (UN 2022), acting to promote natural population declines. Such increases are most prevalent across south, south-eastern, and central regions of the continent where mean ages are highest (UN 2022). Given the relationship between age and the force of mortality (Gompertz 1825), population ageing is strongly associated with observed increases in mortality, especially within European countries (Cheng et al., 2020).

As with fertility, differential trends in mortality are observed across Europe, owing to a range of wider determinants of health relating to environmental, cultural, social and economic conditions, as well as public health policies and strategies (Cutler et al., 2006, Karanikolos et al, 2017). Regarding both life expectancy and crude mortality rates, there exists a vast and persistent East-West European divide, with mortality considerably higher in eastern and central Europe than elsewhere. This mortality gap is symptomatic of asynchronous health developments in which decreases in cardiovascular mortality were key drivers of longevity improvements (Valin & Mesle 2004). As western European countries underwent cardiovascular revolutions and enjoyed improved longevity (Meslé, Vallin, & Obadia 2002) eastern countries experienced a stagnation of life expectancy due to increased cardiovascular (Grigoriev et al., 2010) and lifestyle attributable mortality (Jansen et al., 2021), namely high prevalence of smoking, obesity and alcohol related complications. Though a convergence has occurred since cardiovascular related mortality has decreased in the East (Hrzic et al., 2020), continued improvements in the west, albeit at a slower pace (Raleigh 2019), mean that extensive divisions persist. Differential mortality rates are also observed within countries, with rural populations typically experiencing higher mortality rates than their urban counterparts (Bremberg 2020). However, evidence for this across Europe is sparse and complex, with recent research showing that rural-urban mortality disparities exist only amongst aged populations (Ebeling et al., 2022).

3.2.3 Migration

Migration is regarded as the most crucial component of contemporary European population change dynamics (Sobotka & Fürnkranz-Prskawetz 2020), though it is also the most volatile and uncertain, with measurement difficulties hindering its accurate quantification (Bell et al., 2014, Zagheni et al., 2014). Migration represents a unique demographic process, as it simultaneously contributes to both population growth in receiving areas, and population decline in sending areas. Its multifaceted effects have a profound influence on population redistribution and exacerbates differential population change trajectories (Rowe et al. 2019). This significance is most pertinent within Europe, where free-movement agreements facilitate the movement and relocation across international borders between 26 countries. Since the expansion of the European Union in 2004, 95.9% of intra-European migrants settle in just 15 destination countries, all of which are located in western and northern Europe, with the UK, France, Germany, Switzerland, Italy and Spain receiving 75.4% alone (King & Okólski 2018). In contrast, intra-European migration flows have contributed to population declines in central and eastern nations, where significant outmigration has occurred, particularly within former-soviet states (Fihel & Okólski 2019). When combined with trends of extra-European migration, which also disproportionately benefits western, northern and a select few southern European nations (Eurostat 2022), contemporary migration flows serve to bolster the population of a select few countries whilst simultaneously contributing to depopulation in the rest. Similarly, contemporary internal-migration trends also serve to disproportionately benefit select sub-national regions. Most significant are rural to urban migration flows that have long persisted across Europe (Raugze et al., 2017), particularly amongst young and educated populations seeking greater economic opportunities in large cities (Rodríguez-Vignoli & Rowe, 2018). Processes of urban sprawl are also prevalent across Europe, with migration flows to peripheral metropolitan areas resulting in population growth, often at the expense of urban centres (Rowe et al. 2019). The significance of migration with regards to population change dynamics is extended due to its influence on fertility and mortality. Given that migration is most prevalent amongst young adults of peak reproductive ages, outmigration results in reduced fertility outcomes in origins as women migrants undergo childbirth in destinations (Johnson & Lichter 2019, Sobotka & Fürnkranz-Prskawetz 2020). Out-migration therefore represents a dual depopulating force in origin areas, as populations are immediately reduced and anticipated future fertility is lost. Regarding mortality, the young age profiles of migrants lead to a hollowing out of age structures in origin countries and accelerates population ageing (Fihel, Janicka, & Kloc-Nowak 2018). Given the positive association of ageing and increased mortality outcomes (Cheng et al., 2020), out-migration then represents an avenue in which crude mortality rates are exacerbated in places of origin.

3.2.4 Drivers of Sub-national population decline

Though most academic and public discourse surrounding population decline concerns national level scales, depopulation is inherently a local process. It occurs within households, neighbourhoods and communities but is detectable only at aggregated spatial units for which relevant data is collected. Such large-scale spatial units can mask localised instances of depopulation if they are situated within larger contexts of population growth (Franklin 2019), rendering it difficult to recognise and tackle. This is reflected by the sparsity of research into sub-national depopulation processes, with very few studies offering the geographic granularity required to fully understand contemporary population declines. Despite this, it is known that sub-national depopulation is a heterogeneous process, occurring at different intensities and timings across Europe (Wolf & Weichman 2018, Newsham & Rowe 2022) and with various demographic, geographic and socio-economic characteristics mediating distinct demographic processes (González-Leonardo et al., 2023). Next, we briefly describe a range of demographic, geographic and socio-economic characteristics associated with sub-national population decline.

Firstly, as a demographic process, population decline is dependent on the demographic composition of populations. Empirical analyses have determined that the size and structure of populations are the most important factors associated with trajectories of population decline (Johnson et al., 2015, Newsham & Rowe 2022, González-Leonardo et al., 2023). Demographic events occur at various stages of the life course but follow rigid age-patterns. As such, younger populations are at a greater risk of experiencing fertility and migration outcomes, and elderly populations a greater risk of mortality. With regards to population decline, smaller and older populations are linked to trajectories of persistent and intense depopulation (*ibid*). The loss of young populations, most prominently through migration, accelerates ageing which in turn contributes to depopulation (Reynaud & Miccoli 2018, Rodríguez-Vignoli & Rowe 2018). Additionally, the share of migrant populations is also a key determinant of population change, with established migrant settlements reinforcing positive migration flows by attracting new immigrant populations (Patias et al., 2023). Across Europe, migrant populations and their descendants also tend to experience higher fertility outcomes than native populations (Kulu 2017), contributing to higher fertility rates (Sobotka 2008, Newsham & Rowe 2021).

Secondly, the function of sub-national areas, with regards to positioning within the urban hierarchy, also tend to dictate demographic trends. Rural and urban areas fundamentally differ in population size, composition, density, and economic function and thus command differing demographic outcomes. Rural areas are more prone to population decline than urban areas and are more likely to experience persistent and fast-paced trajectories of population decline (Newsham & Rowe 2022). Economic restructuring and technological advancements have diminished economic opportunity in rural areas, resulting in mass out-migrations of young populations which facilitates population declines (Viñas 2019, Wojewódzka-Wiewiórska 2019, Johnson & Lichter 2019). Though urban depopulation is less prominent (Newsham & Rowe 2022), examples across Europe are abundant (Wolf & Weichmann 2018). Causal explanations refer to self-propagating mechanisms involving place-specific processes of economic decline driving out-migration, demographic change facilitating natural population loss and trends of sub-urbanisation (Hoekveld 2012, Haase et al., 2016, Hartt 2018). Certain urban areas are, however, better aligned to resist depopulation, particularly those with more dynamic and vibrant economies (Rodríguez-Pose & Ketter 2012), larger in population (Wolf & Weichmann 2018) and younger age structures (Haase et al., 2016).

Finally, a range of geographic factors are associated with population decline. Numerous studies have identified the role of location in determining the direction of population changes. Peripheral rural areas with poor physical and economic accessibility are most implicated by population decline (Li et al., 2019) whereas those in close proximity to urban areas are better connected and benefit from population growth via sub-urbanisation and counter-urbanisation migration flows (Pužulis & Kūle 2016). Territorial characteristics are also influential to population decline, with geographically isolated areas of high altitude prone to intense rates of depopulation (Viñas 2019, Reynaud et al., 2020) and coastal regions more conducive to population growth (González-Leonardo et al., 2023). Economic performance of neighbouring areas can also influence migration trends, with economic growth in adjacent cities leading to urban decline in some European cities (Wolf & Weichmann 2018).

3.3 Data & Method

3.3.1 Data

To study the demographic causes of contemporary European population decline, we collect annual demographic data for 2,035 sub-national areas in 43 European territories between the years 2000 and 2018. Our data captures changes in population size and annual fertility, mortality, and migration outcomes over an 18-year period. We build a spatial panel database consisting of Eurostat and national statistics data, see Appendix 1 for data sources by territory. We make use of the NUTS (Nomenclature of Territorial Units for Statistics) regional classification system, collecting data for NUTS 3 units which represent small sub-national regions. Given the large spatial scale of our study and the extent of demographic data required for analysis, we are constrained to a limited time series because of the lack of systematic long-time series capturing population at small geographical scales. In some areas of Europe, population decline is an historic process (Martí-Henneberg 2005), and we recognise that our data does not capture the onset of population decline in all areas. We also utilise national statistics data to study the contextual factors associated with distinct cause-of-decline processes. Unlike our demographic data, these are time-invariant due to their infrequent collection, though we recognise that they may shape or be shaped by changes in local population structures. The demographic features considered include the proportion of elderly population, proportion of foreign-born population and unemployment rate. In addition to these contextual variables, we also calculate the proximity of each area to the nearest large city (with population greater than 1 million), the proximity to the coast, and average altitude using elevation data from the European Environment Agency.

From our dataset, we identify a total of 732 sub-national areas that have experienced an overall reduction in population size between 2000 and 2018, or from the first to last data record in instances of missing data. These areas are characterised by their relative population declines and are the focus of our study. We recognise that we omit some European areas that have experienced episodic population declines but overall population growth between 2000 and 2018. We focus our analysis on areas recording overall population decline during this period as our purpose is to better understand the demographic causes of population decline.

Our database contains some areas that are affected by a boundary change, presenting a significant challenge in obtaining a complete time series. We are able to mitigate the disruptive impact of this through harmonisation, enabled through Eurostat and National Statistic correspondence files which maintain historical records of these changes. Areas in our database therefore correspond to the latest boundaries at the time of data collection. A greater challenge is the acquisition of complete data for all demographic components. Though complete data are available for the majority of areas, a total of 276 (37.7%) were missing data for a single demographic component in a specific year and were thus incomplete. Most instances of missing data relate to migration, reflecting the insufficient quality of migration data (Bell et al., 2014). We are able to limit the impact of this by computing a total of 1,395 net-migration estimates across 199 areas using the demographic balancing equation (Preston et al., 2000), given complete population, fertility, and mortality estimates - see Appendix 2. Despite this, data scarcity does not allow for a complete time-series for areas in certain countries as often data is only collected from a certain period beyond the year 2000. As a result, we are unable to analyse the demographic causes of population decline consistently throughout our time-series for all areas, though our results are robust to their inclusion.

3.3.2 Method

We employ a novel five-stage methodology to analyse longitudinal patterns of demographic causes of population decline, outlined in Figure 1. We first decompose changes in the annual rate of population decline to quantify contributions from fertility, mortality, and net-migration over an 18-year period from 2000 to 2018. Next, we z-standardise each demographic variable independently to ensure a consistent scale for comparison of longitudinal trends between areas. We then apply a functional data approach to measure the shapes of temporal trajectory curves representing varying influences on population decline by demographic drivers – fertility, mortality, and migration. Fluctuations in crude rates of fertility, mortality and migration are captured empirically through Multivariate Functional Principal Component Analysis (MFPCA), reducing the complexity/variable dimensions of functional data curves. Next, we apply a k-medoid clustering algorithm to group sub-national areas by similar temporal demographic causes of population decline, referred to as depopulation signatures. Finally, we analyse the demographic, economic, social, and geo-spatial attributes of areas to construct profiles of sub-national population decline across Europe. Finally, we plot the geographic distribution of these signatures.

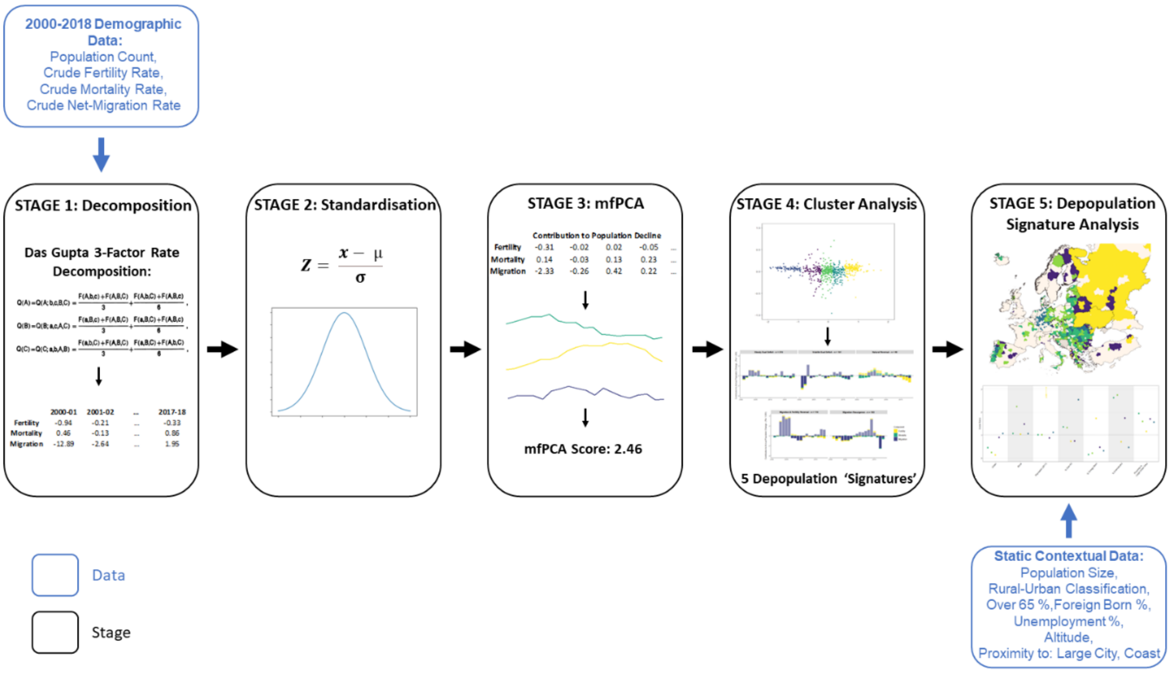


Figure 3.1 – 5-Stage Methodological Strategy

3.3.3 Stage 1 – Decomposition

In the first stage, we quantify the contributions, or effects, of crude fertility, mortality, and net-migration rates to the difference in annual rates of population change over an 18-year period during 2000-2018. To this end, we apply a decomposition technique to our longitudinal dataset enabling the identification of time-specific demographic causes of population decline. Previous studies have applied decomposition techniques to disentangle the effects of demographic factors on changing rates of population growth (Horiuchi 1992; 1995, Vaupel & Canudas-Romo 2002, Pullum & Jadhav 2021). We apply a three-factor rate decomposition (Gupta 1993), to study population decline.

We use the demographic balancing Equation (1); where population change is a function of fertility, mortality, and migration, with the rate of population change equal to the crude birth (CBR) rate minus the crude death (CDR) rate plus the crude rate of net-migration (CNM).

$$P = CBR - CDR + CNM$$

The resulting output is a metric quantifying the effect size of each demographic component on the difference in the rate of population change between two consecutive years. Over a period of 18 years, we generate a total of 17 data points per component for each sub-national area representing the longitudinal contributions of fertility, mortality, and migration to changing rates of population decline.

3.3.4 Stage 2 – Standardisation

Next, we rescale the decomposition rate data by z-standardisation to ensure a consistent scale for area-year observations and between demographic components. Areas in our sample differ widely in size and population numbers and therefore demographic rates. Standardising the data ensures we can focus on the longitudinal trends and more easily compare population trajectories across areas. We later account for population size and additional contextual attributes.

$$Z = \frac{x - \mu\_st}{\sigma\_st}$$

where x is the original value, μ_st space-time mean population value, i.e. the average population value across all areas and time points, and σ_st is the space-time standard deviation of the population distribution. We perform Z-standardisation for each demographic component separately, pooling together all areas of decline (n = 732) and years (n = 19).

3.3.5 Stage 3 – Multifunctional Principal Component Analysis

In a third stage, we adopt a functional data analysis (FDA) framework to analyse the longitudinal effects of each demographic component on changing rates of population decline. FDA has been scarcely applied within the field of demography, and typically for forecasting (Hyndman & Booth 2008, Shang et al., 2016). To our knowledge, FDA has not been used to identify groupings of areas with similar retrospective population change curves until now.

FDA contends with data presented as functions, defined as a series of observations occurring over a continuum. FDA considers the shape of a function, or curve, as its unit of analysis, as opposed to conventional multivariate data analysis which concern separate data points (Ramsay & Dalzell 1991, Jung & Song 2022). We use FDA here to analyse the shapes of demographic component curves and quantify differences and similarities in time-specific demographic causes of population decline between European sub-national areas. This allows us to capture key differences in the time-dynamics of the demographic components of population change underpinning population decline. For each area of decline (n = 732), we convert our standardised decomposition time-series data, derived from stages 1 and 2, into three functional data elements which represent the changing influence of fertility, mortality, and migration to rates of population decline. These functional data units are combined to create a multi-functional data unit for each area of decline (see Happ & Greven 2018). This process facilitates the application of multivariate functional principal component analysis (mfPCA). mfPCA reduces the dimensionality of our multi-functional fertility, mortality, and migration time-series data by extracting the key features that capture their variability over time. The variation in fertility, mortality, and migration curves are represented by functional principal component scores, and are used in subsequent trajectory clustering. Our application of mfPCA follows that of Happ & Greven (2018) and we use the R package 'MFPCA' for its implementation (see Happ-Kurz 2020). The procedure of MFPCA in our study is described in four key steps and outlined below.

First, we calculate univariate functional principal components for each of the three functional data elements, resulting in estimated eigenfunctions and principal component scores for suitably chosen truncation lags, or principal components. We examine the estimated eigenvalues and select the minimum number of principal components that explain 90% of variance (see Ramsay & Silverman 2005, chap 8.2). We calculate a multivariate functional principal component analysis with two principal components, explaining 100% of total variance, using univariate FPCA with one principal component for the fertility and migration curves, and four principal components for the mortality curve. Second, all coefficients are combined into one matrix and a joint covariance matrix is calculated. This considers the covariation between each element by using the joint covariance of the principal component scores of all three elements. Next, eigenfunctions of the covariance matrix are found, with the first eigenfunction representing the greatest variation within the functional data and the last representing the smallest amount (Jung & Song 2022). Finally, estimated mfPC functions and scores are calculated, based on results from the first and third steps, serving as the primary outputs from this stage. The final output is a set of mfPC scores which capture the functional characteristics of the demographic decomposition curves for fertility, mortality and migration, with similar scores demonstrating comparable characteristics in temporal cause of decline patterns.

3.3.6 Stage 4 – Cluster Analysis

In the fourth stage of our methodology, we apply k-medoid clustering to the mfPC scores. Here, k-medoid clustering enables our sample to group areas based on their shared longitudinal patterns of demographic cause of population decline. We also explored the application of the k-means algorithm, though groupings were imbalanced in size due to its sensitivity to outliers. In our case, the k-medoid method results in a more accurate categorisation of areas by their demographic cause of depopulation. We judge the optimal number of clusters (k) both empirically and contextually, determining that five clusters are the most appropriate solution to strike a balance between detail and the identification of broad systematic patterns. A total of thirty empirical indices are tested, in accordance with the NbClust package (Charrad et al., 2014), with the majority confirming a five-cluster solution as optimal. Additionally, to further validate our decision, we conduct a sensitivity analysis to test the suitability of alternative k solutions. We find that a greater number of clusters ($k > 5$) presented recurrent cause of decline patterns and lower values ($k < 5$) masked nuanced causes, see Appendix 3.

3.3.7 Stage 5 – Depopulation Signature Analysis

We analyse the composition of depopulation signatures, implementing a multinomial logistic regression model to understand the extent to which contextual attributes are associated with specific demographic causes of population decline. We model a multicategorical outcome variable, representing our five cause-of-decline signatures, as a function of a series of demographic, socio-economic, and geographic independent variables. These include population size, rural-urban classification, proportion of elderly population, proportion of foreign-born population, unemployment rate, proximity to large city, proximity to the coast, and altitude. We standardise continuous variables, by z-standardisation, to allow for a robust comparison of coefficients. Our regression results are presented as odd ratios, enabling the assessment of the likelihood of an area experiencing a particular demographic cause of population decline, given the status of each contextual attribute. We consider areas of population growth as a reference category, and therefore our results are interpreted as the likelihood of experiencing a specific demographic cause of decline relative to population growth. In this final stage, we also explore the geographic distribution of demographic causes of decline across Europe, discerning geographic regularities, and anomalies. We consider this, alongside results of our logistic regression to construct descriptive profiles of areas bound to a specific demographic cause of population decline.

3.4 Results and discussion

We evaluate the extent to which differential demographic drivers have shaped contemporary population declines in two critical stages. Resulting from the initial four stages of our methodology, we first introduce five depopulation signatures which capture different demographic causes of sub-national population decline, before analysing the contextual characteristics of each signature. Specifically, we quantify differences in the demographic, socio-economic and geo-spatial configurations of areas to construct profiles of areas that experience a particular demographic cause of population decline.

3.4.1 Depopulation Signatures

European sub-national areas have been demonstrated to follow differential trajectories of population decline, distinguished by differences in the rate and timing of population loss (Newsham & Rowe 2022). This suggests that differential demographic processes co-exist across the continent, and underpin such trajectories. In Figure 2 below, we present five unique depopulation signatures that empirically represent the longitudinal contributions of fertility, mortality, and migration to population decline processes within European sub-national areas. These demographic signatures are the main focus of our analysis, and are named according to the temporal trends they depict in Figure 2. Positive values represent an annual increase to the contribution of population change relative to the previous year and reflect an annual increase in crude rates. Neutral scores indicate no annual change and therefore no contribution to changing rates of population change for that period [1]. Negative values indicate a contribution to population decline, and are emphasised in Figure 2 to highlight the focus of this study.

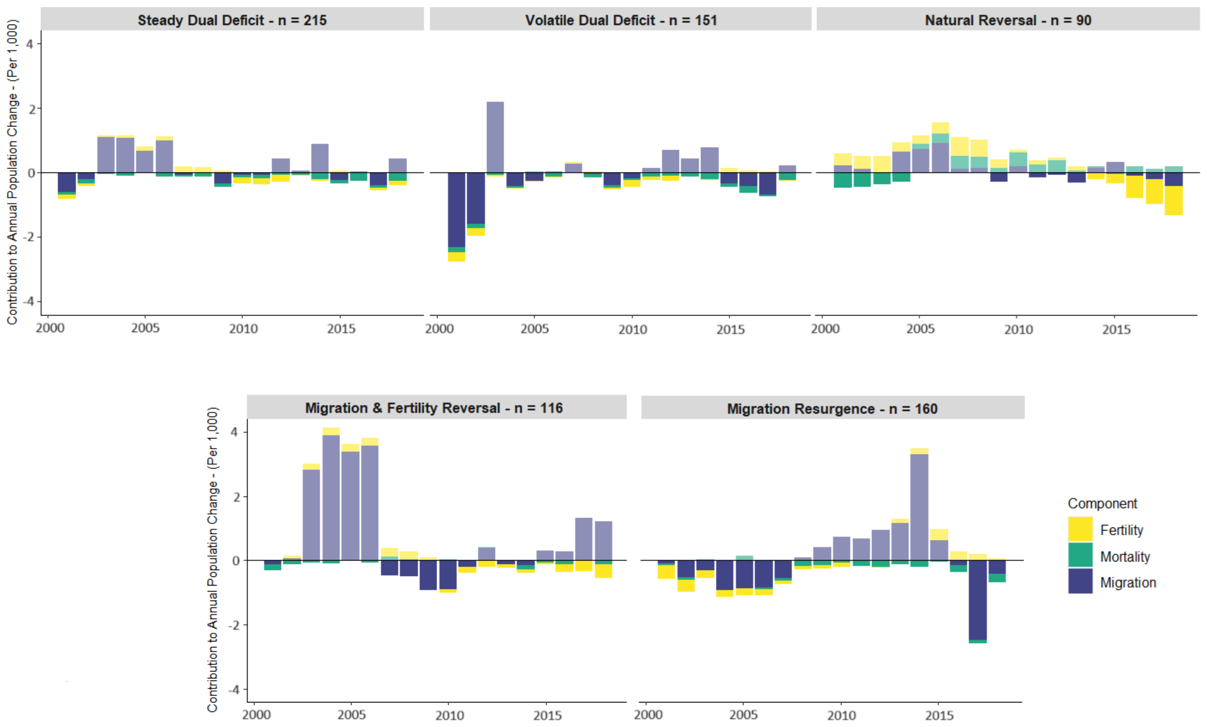


Figure 3.2 - Depopulation Signatures, Depicting Demographic Contributions to Annual Rates of Population Change

Footnote [1]: This does not mean that this component has no contribution to population decline; for that specific period conditions are the same and so there is no change to that specific year.

Signature	N	Decline	Decline (%)	Births	Deaths	Natural Change	Natural Change (%)	Net-Migration	Net-Migration(%)
Steady Dual Deficit	215	5,230,908	8.72	6,806,319	9,188,776	-2,382,457	45.55	-2,167,351	41.43
Volatile Dual Deficit	151	4,301,564	11.10	5,422,804	7,503,172	-2,080,368	48.36	-1,528,576	35.54
Natural Reversal	90	13,869,153	9.99	26,427,584	37,792,185	-11,364,600	81.94	-1,961,923	14.15
Migration & Fertility Reversal	116	3,049,773	8.45	5,565,269	7,126,080	-1,560,811	51.18	-859,236	28.17
Migration Resurgence	160	2,500,480	7.30	5,534,911	7,214,921	-1,680,010	67.19	-515	0.02

Table 3.1 – Descriptive Statistics of Depopulation Signatures

Steady Dual Deficit: This signature depicts moderate contributions from all demographic drivers, highlighting how population change is often a slow process. Here, mortality contributions are consistent towards population decline, with fertility also becoming a factor from 2010. Net-migration fluctuates, making contributions to both decline and growth in different years. Its contributions towards decline are relatively small; yet total population decline is substantial amongst areas in this signature at 11.1% from 2000 to 2018 (Table 1). This suggests that pre-existing demographic conditions, which are not captured within our time series, are significant in establishing a rate of considerable annual population loss.

Volatile Dual Deficit: This signature depicts comparable contributions from fertility and mortality, though is distinguished from *Steady Dual Deficit* by more intense and regular contributions from net-migration. This signature is bookended by significant contributions from migration, though natural change has the greatest contribution overall (Table 1).

Natural Reversal: This signature captures a reversal in the direction of contribution from fertility and mortality. Fertility initially contributes to population growth, though it gradually diminishes and eventually contributes to population decline. Conversely, mortality promoted depopulation until 2005, when it then abruptly reverses to foster population growth. The significance of contribution from natural drivers is emphasised in Table 1, where 81.94% of population declines are accounted for by fertility and mortality changes.

Migration & Fertility Reversal: This signature is also characterised by a reversal in contribution, though instead concerning migration and fertility. Initial contributions to population growth from migration are reversed in 2006, whereby net-migration declines drive depopulations until 2015. This pattern is mirrored by fertility, shifting to a contribution to depopulation from 2007 until 2018. A relatively low overall contribution from net-migration (Table 1) suggests that the fertility reversal is most significant in causing population declines.

Migration Resurgence: This signature is characterised by a resurgence in positive net-migration contribution. Initial conditions depict a contribution towards population decline, though later reversing to promote population growth until 2015. A sudden and considerable depopulation contribution is recorded in 2015, with negative net-migration resuming a trend to fuel depopulation. A similar shift in contribution from decline to growth is observed for fertility, though a resurgence in depopulation contribution is not observed. Meanwhile, mortality displays a gradually increasing contribution to depopulation. Natural demographic drivers are the main apparent demographic cause of population decline (Table 1), given the significant positive net-migration upswing.

Taken together, our signatures represent the different demographic causes of European sub-national population decline. Despite their nuances, they also depict some regularities. Most crucially, we observe similar contribution patterns from mortality and fertility between most of our signatures. All signatures, except *Migration Resurgence,* depict an increasing contribution to depopulation from fertility declines over time. The timing of such change is consistent, tending to occur from 2010 and perhaps reflecting a lagged impact of the Global Financial Crisis (Sobotka et al., 2011). This regularity supports the notion of a near-ubiquitous fertility decline in Europe resulting from rising unemployment and uncertainty (Vignoli et a., 2020, Matysiak et al., 2021), and demonstrates its effect on promoting population declines. A similar temporal regularity is observed for mortality, with a consistent but moderate contribution to depopulation in all but one signature, *Natural Reversal.* The patterns observed demonstrate a commonality in demographic cause of decline processes amongst European sub-national regions, with natural change conditions near-ubiquitously driving contemporary population declines. Furthermore, our depopulation signatures illuminate the critical role of migration in depopulation processes. Unlike the contributions from fertility and mortality, net-migration contributions are less regular across signatures in both timing and magnitude. However, except for in *Migration Resurgence* all signatures demonstrate a notable contribution from migration (Table 2), indicating that population decline is a multi-causal process resulting from the cumulative or often counterbalancing impacts of fertility, mortality, and migration.

Given that our signatures depict the evolution of contributions to population change from demographic drivers, they are representative of changing trends. Next, we present the crude rate trajectories of fertility, mortality, net-migration, and overall population change for each signature (Figure 3). These trajectories are crafted from the annual changes presented above, in figure 2, and provide a contextualisation of our depopulation signatures by highlighting their demographic trends.

Figure 3.3 - Demographic Trends of Depopulation Signatures

As expected, given differences between depopulation signatures, we observe distinct temporal trends of demographic drivers and population change. In signatures *Steady Dual Deficit, Volatile Dual Deficit*, and *Migration Resurgence,* fertility and mortality trends signify a natural divergence which acts to accelerate population declines and counteract contributions to growth from net-migration increases. Conversely in signatures *Natural Reversal* and *Migration & Fertility Reversal*, we observe a trend of natural convergence as a result of early fertility increases (and also rapid mortality declines in the case of *Natural Reversal*). In both cases, this promotes the deceleration of population decline, though later divergences are instigated from falling fertility.

Although trends ultimately differ in direction and timing across our signatures, we observe significant similarities in cause of decline patterns. In all signatures, fertility rates are consistently outweighed by that of mortality, emphasising the ubiquitous role of natural deficits in causing contemporary sub-national population declines. Furthermore, except *Migration Resurgence*, all signatures depict both a consistent fertility-mortality discrepancy and negative net-migration trend. These patterns indicate that contemporary population declines are most often driven by dual deficits, with depopulation caused by natural change and migration processes.

Additionally, Figure 3 displays mirroring functional shapes between population change and net-migration curves for all signatures. The consistency of this pattern encodes the regularity of the role of net-migration balances in shaping population decline trajectories with net-migration balances working to counterbalance, mitigate or exacerbate population declines (that are chiefly driven by natural change deficits). In this context, migration represents the principle differentiating demographic factor of population decline trajectories across sub-national European areas.

3.4.2 Characteristics of Depopulation Signatures

Next, we seek to understand the underpinning contextual features of our five depopulation signatures. To this end, we estimate a multinomial logistic regression model (Figure 4) using our depopulation signatures as outcome variables and population growth as a reference category, with estimated coefficients presented as odds ratios. We interpret the results as the likelihood of an area experiencing a particular signature of population decline relative to population growth. Specifically, we examine the socio-economic, demographic, and geospatial characteristics of areas in 2011, that are associated with our demographic signatures. Whilst we recognise that these attributes may change over time as areas undergo depopulation (Franklin 2020), data limitations prevent our ability to capture such temporal processes. Our analysis also does not allow for an investigation into the direction of causality between demographic trends and contextual attributes i.e., whether population decline instigates a hollowing out of migrant populations, or whether decline is caused by a lack of such populations, for example.

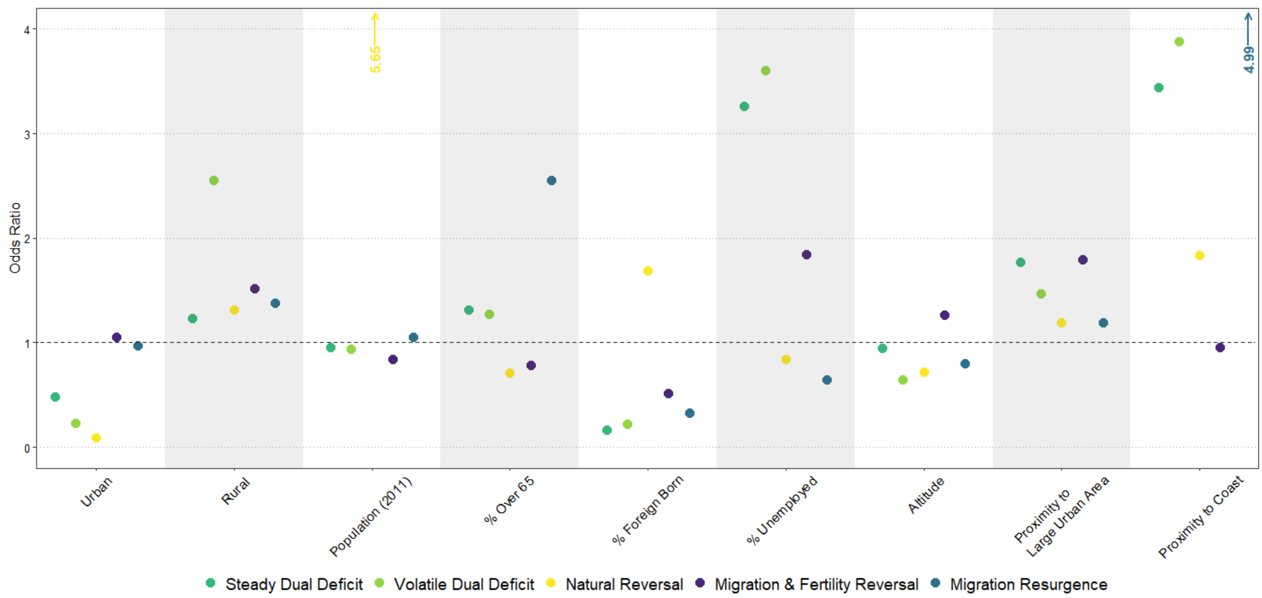


Figure 3.4 – Multinomial Logistic Regression Model

The results reveal key differences in the demographic, socio-economic and geo-spatial configurations of depopulation signatures. Firstly, the results indicate that rural areas are more likely to experience all cause-of-decline processes than intermediate areas (our reference category), particularly the *Volatile Dual Deficit* depopulation signature. Given that this signature depicts a contribution to depopulation from mortality rate increases (Figure 2), this finding likely reflects the elder age profiles of rural areas (UNECE 2017) with a greater mortality risk (Cheng et al., 2020). Urban areas, on the other hand, show a lower odds ratio to experience population decline. In this context, if urban areas should experience decline, the results indicate that they are most likely to undergo *Migration & Fertility Reversal* and *Migration Resurgence* signatures. This signifies the propensity for urban revival, whereby decline-to-growth trajectories are enabled by positive net-migration flows (Figure 2). Urban areas act as centres for economic opportunity and therefore possess an ability to attract migrants (Zelinsky, 1971, Rodríguez-Vignoli & Rowe, 2018). Indeed, contemporary migration dynamics typically concern movements to urban areas, either from underperforming rural regions, or other urban areas (Rowe et al. 2019).

Our regression model also evidences how demographic attributes can influence causes of population decline. Here, we consider the proportion of elderly and non-native populations. The results show positive odds ratios for the percentage of population aged 65 and over for the signatures *Steady Dual Deficit, Volatile Dual Deficit and Migration Resurgence*. Given that these signatures are characterised by increasing mortality rates (Figure 3) and thus contributions to population decline (Figure 2), this positive association likely captures the relationship between ageing and increased mortality risk (Cheng et al., 2020). Interestingly, we observe the strongest positive association between aged populations and the depopulation signature *Migration Resurgence*. Though this may be surprising, given relative low migration outcomes amongst the elderly (Rogers et al., 1978), positive migration inflows to these areas may be symptomatic of the high mortality outcomes that also characterise this signature. High mortality rates would act to increase the number of vacant properties, creating housing opportunities for migrants to replenish populations (Lycan & Ryerson 2013). Regarding the extent of foreign-born populations, we find that all signatures display a negative association, except for *Natural Reversal.* With higher proportions of non-native populations then more associated with population growth, this result highlights the significance of positive international migration flows in reinforcing population growth (Patias 2023). Furthermore, given the reversal of natural demographic conditions depicted in the signature *Natural Reversal* (See Figures 2 & 3), the sole positive association here evidences a population growth effect outside of net-migration gains, namely in the form of fertility increases (see Sobotka 2008, Newsham & Rowe 2021) and mortality decreases (Domnich et al., 2012, Aldridge et al., 2018).

Examining the effects of unemployment, we also assess the role of economic opportunity in determining cause-of-decline processes. We find that unemployment is positively associated with some depopulation signatures, namely *Steady Dual Deficit, Volatile Dual Deficit, and Migration & Fertility Reversal.* These signatures depict either consistent negative or decreasing net-migration trends (Figure 3) and a rural orientation (Figure 6). This positive association then likely evidences the significance of poor economic opportunity in shaping negative migration outcomes of rural areas (Johnson & Lichter 2019). Our results extend this, showing a positive association between unemployment and population decline.

Finally, our multinomial regression model illuminates the role of geo-spatial characteristics in determining population decline outcomes. Our results show a near-consistent negative effect between population decline outcomes and altitude, indicating that areas situated in higher altitudes are more likely to observe population growth than decline. Though this may differ in specific contexts as there is evidence from Italy and Spain pointing to a positive relationship between depopulation and altitude (Reynaud et al., 2020, González-Leonardo et al., 2023). We also explore the propensity for distinct depopulation processes in disconnected and less-desirable areas, represented by proximity to large urban areas and the coast. Our results show consistent positive odds ratios for both spatial variables, indicating that increased remoteness to large urban areas and coastal areas are associated with population decline processes. The effect of proximity to large urban areas is consistent for all depopulation signatures, though is volatile for coastal proximity. Depopulation signatures of *Steady Dual Deficit, Volatile Dual Deficit* and *Migration Resurgence* display particularly high odds ratio coefficients, whereby there is no association for the signature *Migration and Fertility Reversal*.

3.4.3 Geographic Distribution of Depopulation Signatures

Next, we explore the geographic distribution of demographic cause-of-decline signatures and observe distinct within-country and cross-country spatial patterns. Figure 3 displays the geographic location of each cause-of-decline signature; areas that have observed a population growth are included to provide a holistic view of contemporary population change. First, we observe a considerable heterogeneity in the geographic distribution of cause-of-decline signatures across the continent. Particularly, we note how most demographic causes of depopulation are represented in all European sub-regions, highlighting the complexity of demographic regimes across Europe. We also acknowledge this heterogeneity within countries, which is prevalent across south-eastern European nations but also considerably within Germany, Portugal, Belarus, and Hungary. With regards to the management of population decline, this observation demonstrates the need for tailored responses that are sensitive to its demographic cause to be implemented at local levels.

We also observe some general geographic consistencies. Notably, regions in Eastern Europe are overrepresented by *Natural Reversal* processes, particularly within Russia, Ukraine, and Belarus. This signature of depopulation captures the influence of mortality rate decreases (Hrzic et al., 2020) and fertility rate increases (Romaniuk & Gladun 2015, Shcherbakova 2022), observed within these countries from 2005-2015, on decreasing the rate of population decline. Additionally, we observe how depopulation signatures that depict natural divergences, *Steady Dual Deficit* and *Volatile Dual Deficit,* are predominant in central and south-eastern European regions. The prevalence of these signatures here reflect the stalling of fertility and mortality rates that has plagued most of central and south-eastern Europe since the turn of the millennium (Sobotka & Fürnkranz-Prskawetz 2020). We also detect the presence of the signature *Migration & Fertility Reversal* in peripheral areas throughout Europe, but particularly in the south-east (in Albania and Bulgaria) and east (in Belarus and Moldova) where out-migration processes are well documented (Denisenko et al., 2020). Finally, we observe the occurrence of *Migration Resurgence* processes in selective sub-national region, in western Germany and northern Hungary, Portugal and Romania. These trends are consistent with known regional migration disparities (see King & Okólski 2018).

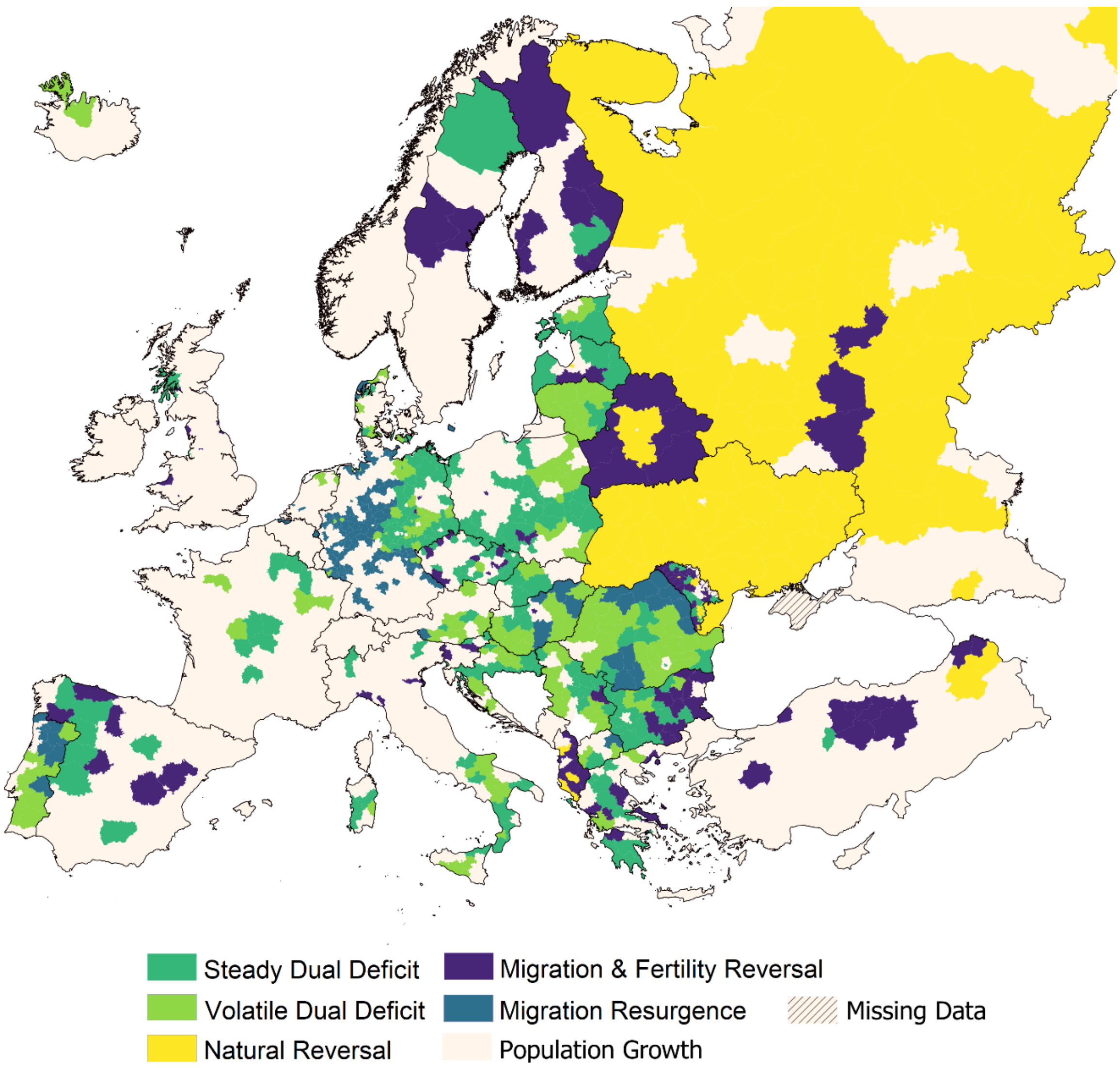


Figure 3.5 – Geographic Distribution of Depopulation Signatures

3.4.4 Profiles of Depopulation Signatures

Synthesising the results of our analysis, we finally construct profiles of each depopulation signature to summarise their defining attributes (Figure 6). Firstly, the signature *Steady Dual Deficit* consists of rural and intermediate areas with relatively small population sizes. Situated predominantly in in-land central and western Europe in high altitude regions, this signature is characterised by high unemployment rates, elderly and native populations. Similarly, the signature *Volatile Dual Deficit* also describes small population areas with high unemployment, elderly and native populations. Distinguishable characteristics are found within its greater rural orientation and low altitudes. This signature is well-distributed across Europe, and prevalent across the south-east, central, and western sub-regions. *Natural Reversal* predominantly consists of intermediate areas, but also is a relatively common urban depopulation signature. These areas are generally more populous, have the highest proportion of non-native populations and the lowest proportion of elderly. This signature is concentrated nearly exclusively within eastern European nations. The signature *Migration & Fertility Reversal* characterises high altitude areas isolated from large cities. This signature is well-represented across the rural-urban hierarchy and is prevalent in all European sub-regions. Finally, the signature *Migration Resurgence* is distinguished by its very high proportion of elderly, very low unemployment, and small average population size. This signature typically concerns in-land areas of western Europe.

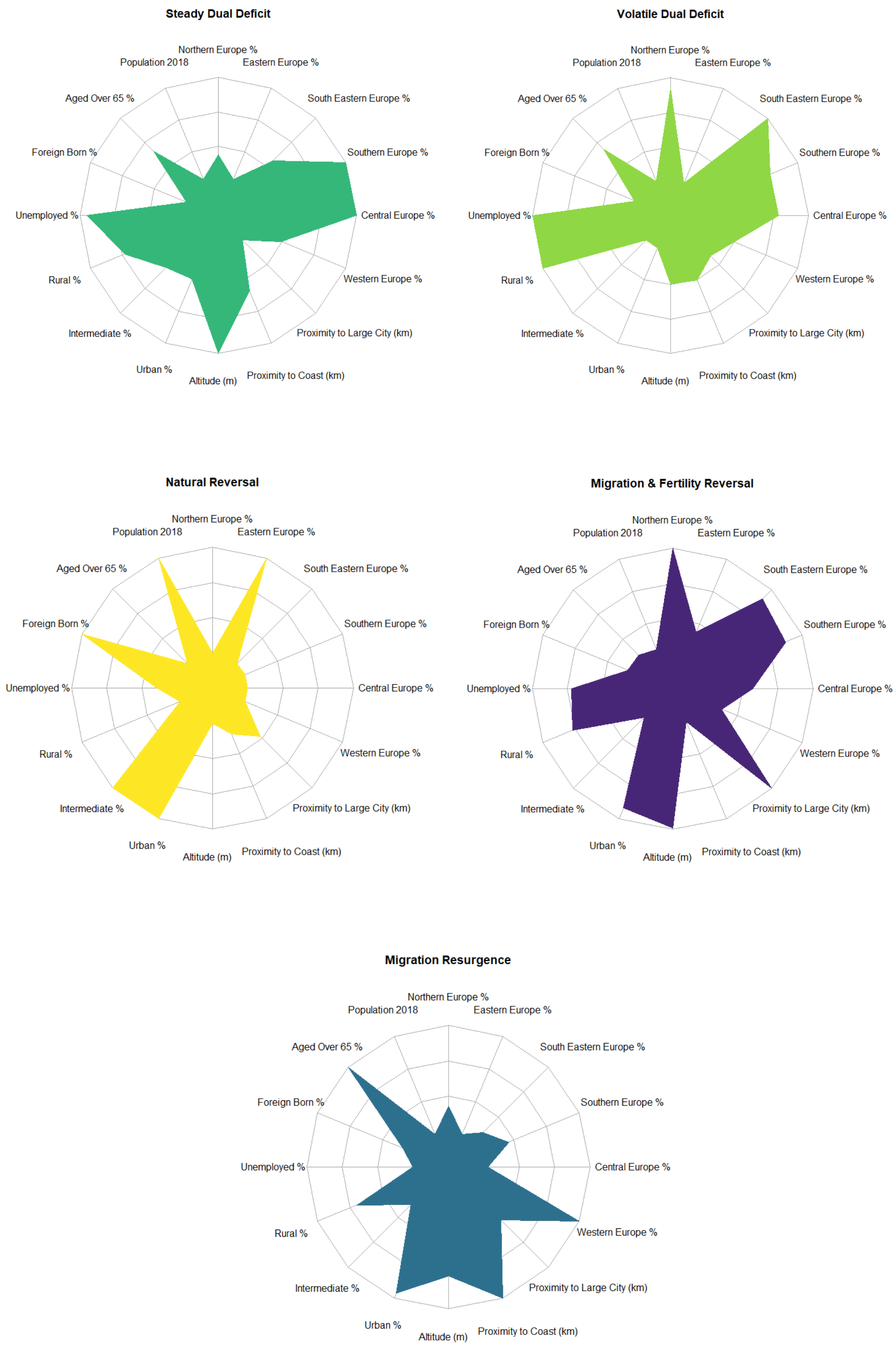


Figure 3.6 – Contextual Profiles of Depopulation Signatures

3.5 Conclusion

Population decline is becoming the dominant order of population change across Europe. This represents a significant shift in the demographic landscape of the continent and, in absence of social and technological reform, will pose unique threats to the functioning of societies. Such challenges will be determined by the severity of population loss, but also by its underlying demographic cause. Yet, we know little about how differential demographic drivers are producing population declines across the continent, rendering us largely unprepared. Understanding how changing fertility, mortality and migration outcomes are shaping trajectories of population decline is central to developing multiple avenues of research; for developing appropriate policy responses, population forecasting, and demographic theory. We present a methodological approach that adheres to the fundamental principles of demographic change to quantify the extent to which differential demographic processes have caused distinctive population declines. This is accomplished by applying novel functional data analysis, in which the shapes of demographic trajectory curves are compared to group areas undergoing population declines based on similar longitudinal demographic causes.

Using publicly available data from Eurostat and national statistics institutions, we present evidence of the coexistence of distinct demographic causes of population decline. In total, we identify five unique depopulation signatures that are distinguished by nuanced longitudinal contributions from fertility, mortality, and migration. To summarise, these signatures capture processes of diverging and converging natural change, accelerating out-migration and negative-to-positive net-migration. Overall, we find that negative natural rates of natural change, which is rates of mortality outweighing fertility, is the most prevalent demographic cause of contemporary European population decline. These natural deficits are ubiquitous across all five signatures, but they do not act in isolation. In addition to natural deficits, most areas facing population losses also record population loss through migration. This depopulation is better characterised as a dual-cause outcome. Our evidence indicates that natural change is the most significant driver of population decline across Europe, though migration is most crucial in determining the pace of population decline within sub-national areas.

Our analysis also reveals how certain areas undergoing depopulation are predisposed to a particular demographic cause. We analyse a range of areal characteristics that are associated with each depopulation signature, capturing their demographic, socio-economic and geo-spatial configurations. We evidence how rural areas with particularly poor employment prospects and aged populations are predisposed to natural divergences, in which increasing mortality and falling fertility are exacerbating rates of population decline. We also find that urban areas, typically those smaller in size and isolated from chief cities and coastal areas, are associated with processes of migration resurgence and decelerating population decline. Additionally, we note that areas with a high proportion of non-native populations have observed a deceleration of population decline, owing to the simultaneous increase in fertility and decrease in mortality rates. Complementing this, we also present evidence of a well-defined geographic landscape of the way cause-of-decline processes are taking place in Europe. Population declines in eastern Europe are predominantly a consequence of natural deficits but are undergoing a deceleration reflecting a convergence process of increasing fertility and decreasing mortality. Depopulation is less prevalent in Western Europe, and negative net-migration balances have recently reversed to establish a force of population growth. In contrast, depopulation in central, southern, and particularly south-eastern European regions are a function of the combined effects of both natural deficits and negative net-migration outcomes. Coupled with sudden and large negative migration balances, increasing mortality and decreased fertility have created a natural population deficit rapidly accelerating depopulation in these regions.

Our research is not without limitations. Firstly, our analyses are constrained by the scarcity of demographic data within countries of east and south-eastern Europe, the epicentres of European population decline. Particularly problematic are missing demographic data from initial years of our investigation and periodic migration estimates. Though we attempt to mitigate the impact through restructuring the demographic balancing equation and imputing net-migration estimates, we are unable to ensure a complete time series for all demographic rates in all 732 areas of interest. Our data also does not allow for the distinction between immigration and internal migration, instead reporting only net-migration figures. We recognise the differential effects on population redistribution and overall population change of these two different migration types, and stress the need for migration statistics to be disentangled in similar research. Similarly, our data does not enable an investigation into the effects of changing age structures in producing population declines. Though we acknowledge the role of age structure in regular demographic decomposition (see Canudas-Romo 2003), we are unable to obtain relevant annual data for all European sub-national areas. Secondly, data limitations restrict our analysis to the years 2000 – 2018, meaning that we do not capture the onset of population decline in some places. We are also unaware of their historical demographic trajectories, and whether they have concerned an acceleration or deceleration of population decline. Furthermore, our data predates the COVID-19 pandemic, in which considerable disruption to demographic occurrences have occurred (see Sobotka et al., 2022, Wang et al., 2022, González-Leonardo et al., 2022). From limited research, we understand that the direction of population change trajectories have reversed as a result, and acting to overturn depopulation processes in some instances (Ramani & Bloom 2021, González-Leonardo et al., 2022), however we are not able to assess its effects on depopulation here. Future research should strive to uncover the impact of COVID-19 on European population trajectories. Finally, our research here has identified associations between a range of demographic, socioeconomic and geospatial characteristics, and differential causes of population decline. However, it remains unclear whether such characteristics are responsible for instigating distinctive depopulation processes, or whether they are shaped as places undergo population decline. Future research should aim to disentangle these relationships, which would serve to illustrate a series of consequences that are seldom considered in research concerning depopulation (see Franklin 2020).

Despite these limitations, our findings yield important advancements to knowledge of population decline processes and are particularly relevant in two key domains. Firstly, concerning policy formulation, given that demographic drivers of population decline fundamentally differ across different sub-national regions, we argue that mitigation initiatives must be tailored to individual areas and be devised with a focussed consideration of the specific underlying demographic cause. We argue that specificities of demographic causes will initiate unique challenges and thus require different solutions. Secondly, with regards to advancing population decline forecasts, the recognition of differential depopulation processes is crucial to devising accurate depictions of future population declines. Particularly, forecasts should explicitly consider the specific fertility, mortality, and migration contexts of areas, and perhaps include contextual information that has here been demonstrated to dictate depopulation processes.

4

High-Resolution Forecasting of European Population Decline: A Long Short-Term Memory Approach

The final analytical chapter incorporates WorldPop data that captures temporal population processes at a granular geographic scale from 2000 to 2020. The data is consistent for a total of 65,445 municipalities in 40 European countries, enabling a time series forecast that predicts the future of European population change to the year 2030. The forecast is the product of a Long Short-Term Memory (LSTM) model that is designed within this thesis and subjected to a rigorous tuning process to maximise its predictive capacity. This process is described thoroughly within this chapter, with its evaluation contributing to the development of machine learning based population forecasting methods. The contribution of this chapter is therefore both the model and the population forecast itself. The forecast offers an insight into the likely futures of population decline developments across Europe, with a focus placed on describing its geospatial distribution. The forecast depicts the spread of population decline to a substantial majority of European municipalities by 2030 and its disproportionate concentration and intensity in specific European sub-regions and otherwise geographically disadvantaged areas.

Abstract

Population decline is becoming widespread across Europe, though is disproportionately affecting certain sub-national areas. Understanding where future population declines will be concentrated remains a considerable challenge, though is essential in preparing for such unprecedented population change. Population forecasts are often only produced at large spatial scales, owing to the requirement of highly detailed demographic data, which are typically lacking for small areas. However, recent advancements in remote sensing have yielded spatially granular demographic estimates, enabling the production of high-resolution population forecasts. Further developments in machine-learning based forecasting methodologies present an exciting opportunity to predict demographic futures. Making use of WorldPop gridded population count data, we develop a Long Short-Term Memory (LSTM) recurrent neural network to forecast municipal level population change across the entire European continent. In search of optimal parameters for population forecasting, a series of models are developed that differ by data specification, architecture, and implementation approach. Their evaluation highlights the advantages of models with a singular LSTM layer, longer input sequences, subset implementation and explicit consideration of spatial population dynamics resulting in improved forecast accuracy. Our best performing model, with a median absolute percentage error of 1.29, is further developed to predict future population change outcomes to 2030. The forecast reveals that population decline will take place in 70.2% of European municipalities by 2030, and a majority of countries (75%), directly implicating over half (59.3%) of the European population.

4.1 Introduction

An unprecedented demographic shift has emerged in Europe, with population decline overtaking growth as the new dominant order of population change. Since 2000, *incidences* of sub-national population decline have increased within Europe (Newsham & Rowe 2022), occurring across the rural-urban spectrum and instigating courses of national and continental population loss. According to the latest UN projections, population decline is expected to persist for the remainder of this century and reduce the total population of Europe by 150 million, or 20% (UN 2022). Population decline will concern a majority of the continent and promises to present novel challenges to the functioning of European societies, demanding explicit consideration in planning and policy developments. In this context, population forecasts represent a foundational resource for co-ordinating responses to changing and unfamiliar demographic regimes, informing of the likely occurrence and extent of sub-national population declines. However, approaches to population forecasting remain problematic when applied to small areas, with relatively high rates of error compared with regional or country level applications (Wilson & Rowe 2011). Traditional approaches, such as the cohort component method, are also unsuited for application to small areas, given their copious data demands. Indeed, requite demographic information on population structure and age-specific fertility, mortality, and migration schedules are sparsely available at the small area level. These data are also frequently subject to interruption stemming from boundary changes and are noisy by nature, leading to high error in forecasts amongst areas with small populations, typically of a few thousand (Wilson et al., 2018).

Recent advancements in demographic data and time-series forecasting methods are promising for the generation of accurate small-scale population projections. With regards to population data, developments in remote sensing have facilitated alternative estimates of population size. These data are derived from remotely sensed geospatial data, whereby settlements are mapped and used to redistribute census population counts to gridded 100m population distribution estimates (Stevens et al., 2015). The WorldPop group have produced high-resolution population count, enabling a consistent annual time-series that can facilitate population forecasts. Alongside data developments, the emergence of machine learning based approaches to time-series forecasting appear promising for forecasting small area populations (Grossman et al., 2022, Wilson et al., 2023). Most prominent are recurrent neural networks (RNN) which possess the ability to capture longitudinal dependencies in sequential data. Recent applications of Long-Short Term Memory (LSTM) models, an enhanced RNN, represent the forefront of methodological advancement in population forecasting (Riiman 2019, Wang & Lee 2021, Grossman et al., 2023), with previous efforts demonstrating a genuine potential for outperforming conventional approaches (Riiman 2019). However, LSTM population forecasts suffer from numerous drawbacks that hinder their ability to rival traditional methods in practical settings, owing to their early development to the application of population change. Particularly, they are difficult to understand and to design, requiring ornate knowledge of complex machine learning concepts, and currently lack a proven model specification that optimises forecast accuracy on a consistent and reproducible basis.

Motivated by the prospect of widespread population loss across Europe, we develop a series of LSTM models to produce geographically granular forecasts of population change outcomes across Europe. Specifically, we make use of consistent longitudinal demographic estimate data from WorldPop to forecast population in 65,445 sub-national areas across 40 countries. Building upon existing efforts from Rijman 2019, Wang & Lee 2021, and Grossman et al., 2023, we design and implement a series of LSTM models with varying specifications in search of an optimal LSTM approach to population forecasting. As such, this paper primarily focuses on advancing LSTM models for this specific purpose, and its contributions relate to the design and implementation approaches that result in improved population forecast accuracy. Our models are distinguished by unique combinations of varying architectural design, input data, sequence lengths or window sizes, and implementation approach. These are compared with each other and to a baseline Autoregressive Integrated Moving Average (ARIMA) extrapolative forecast, with the most accurate LSTM model developed to explore population change outcomes in 2030 across European municipalities. An explicit focus is placed on population decline outcomes in the results section, given its anticipated spread across the continent (UN 2022). Next, we review existing work on LSTM population forecasting and establish the context of sub-national population decline.

4.2 Literature Review

Population forecasts are integral for effective planning around population changes. For governments and other decision makers, they are used to inform decisions and are fundamental to social and economic planning. Though such policies and schemes are often developed at granular geographic scales, existing population forecasting methods remain insufficient when applied to small areas (Wilson et al., 2022). Forecasts are most erroneous for areas with population size of a few thousand (Wilson et al., 2018), owing to particularly erratic demographic trends (Wilson & Rowe 2011) as well as infrequent collection, MAUP sensitivity, and boundary changes. These geo-demographic challenges impact the consistency of requisite demographic data and introduce considerable uncertainty to small area population forecasts. However, promising advancements in time-series forecasting may alleviate these issues.

At the forefront of methodological developments are a range of machine learning approaches that are capable of out-performing traditional population forecasts, with less input data (Folorunso et al., 2010, Otoom et al., 2019, Rijman et al., 2019). Particularly suited for time series forecasting are Recurrent Neural Networks (RNN), which, as an advanced machine learning model, possess the ability to retain sequential information. Already, RNN time series models have been applied to a wide range of domains whereby temporal dependencies are important, including epidemiology (Wu et al., 2018), finance (see Zhang et al., 1998), business analytics (Salehinejad & Rahnamayan 2016, Tello-Leal et al., 2018), weather prediction (Zaytar

& Amrani 2016), and mobility analysis (Feng et al., 2018), among others. Recent applications have demonstrated the potential of RNNs to generate accurate demographic time series forecasts, including population size (Rijman et al., 2019, Wang & Lee 2021, Grossman et al., 2023). The most promising approaches are Long-Short Term Memory (LSTM) models (Hochreiter & Schmidhuber, 1997).

LSTM models represent an advanced RNN that addresses their early shortcomings. Previously, RNNs suffered from the vanishing gradient problem which dictated the diminishing effect of past inputs in model optimisation, resulting in an inability to leverage long-term dependencies in forecasts. In other words, these models struggled to capture distant relationships in input data, instead over-emphasising more recent trends. LSTM models overcome this by regulating the flow of relevant information through the model, achieved via a series of input, output, and forget gates which enable LSTMs to retain or forget information from previous time steps, and capture relevant temporal dependencies within the input data. As an RNN, LSTM models work by processing sequential information from an input sequence in incremental time steps. At each time step, the model receives input cells from the preceding time step and sends an output to the following time step, continually updating model parameters, or weights, to reduce the discrepancy between predicted and actual values. This process is facilitated by a backpropagation algorithm, which computes gradients of the prediction errors with respect to the weights. Essentially, the learned knowledge of the network is stored through these weights, and as an iterative process, the model learns from historic patterns and considers these in its predictions.

Unlike other approaches to population forecasting, LSTM models require the specification of various parameters and configurations that influence the overall accuracy of outputs. As a result, the quality of forecasts are largely dependent on the ability of the user/designer, with intricate knowledge of LSTM processes required to positively influence the performance of the model. One crucial design aspect is the number and type of LSTM layers included in the model, with this parameter influencing the ability to capture intricate temporal patterns in input data. A greater number of layers increases the complexity of the model but also may lead to overfitting, where the model becomes excessively tailored to the training data and struggles to generalize new, and unseen data. Another important parameter is the length of input and output sequences, which determines the extent of sequential information the model considers and predicts in forecasts. Other specifications include the batch size, which indicates how many sequences are processed by the LSTM model at a time, the number of epochs, which specifies the number of times the data is processed in training, and the learning rate, which influences the rate of parameter updates during optimisation. Beyond this, a range of data considerations must be addressed, including the number of variables included in the model and the number of areas to be forecasted. Essentially, these decisions relate to the extent of information that is studied and considered in LSTM predictions, relevant to population change contexts. Thus far, no comprehensive model specification has been identified as optimal for accurate population forecasting, with this arguably the most crucial obstacle preventing LSTM approaches from being utilised in practical applications.

4.2.1 LSTM Population Forecasts

Though limited in application to population forecasting, existing research has demonstrated the potential for LSTM models to generate more accurate estimates of future population size than traditional approaches, including cohort component models and extrapolative approaches (Rijman et al., 2019, Grossman et al., 2023). Accurate small-area forecasts have been produced under a range of LSTM model specifications. Rijman et al., (2019) compare a range of LSTM models, with differing demographic input data and training regimes, to cohort component forecasts of Alabama counties. When using decennial census data and training LSTM models for each county individually, forecasts were improved over those produced by a CCM, with 5.0% MAPE compared with 6.1%. However, this out-performance was not consistent in models using annual population data or when training a singular model to generate forecasts for all counties. In another effort, Wang & Lee (2021) implement a series of LSTM models with varying sequence lengths, with these determining the number of consecutive data points in input sequences, from which temporal patterns are learnt during the training procedure. Though they find no improvement over a baseline linear regression forecast, the experiment highlights the importance of sequence length in determining the accuracies of LSTM models, with shorter sequence lengths performing best. Collectively, these efforts emphasise the sensitivity of forecast accuracy to model specification and highlight a need to discover optimal model parameters. In an initial step towards this, Grossman et al., (2023) found that best-performing LSTM model did not improve forecast accuracy consistently across Australian small area units, when compared to baseline extrapolative approaches. Particularly, forecast accuracy decreased amongst areas with small populations (<5,000) and remote areas, defined as a function of proximity to functional population centres.

Though pioneering works have demonstrated the potential of LSTM models for population forecasting and highlighted some optimal design specifications, there are many avenues yet to be explored with regards to model design, specification, and implementation. Namely, application of demographic data in multivariate models, capturing spatial dependencies, and multi-country models. It is non-trivial that the inclusion of information on known factors that influence population change in a predictive model should improve accuracies of forecasts. Particularly valuable in this context, are information on demographic processes, fertility, mortality and migration that are fundamental to population change outcomes (Preston et al., 2000). With these outcomes following well defined life-course patterns, the inclusion of age-structure information would also be beneficial to predictive models of population change. Furthermore, population change outcomes are known to exhibit spatial relationships (Han et al., 2016), as supported by the First Law of Geography (Tobler 1970) and the spatial diffusion theory (Hudson 1972). This holds true for population decline dynamics (Franklin 2020), with evidence of both positive (González-Leonardo et al., 2023a) and negative (Wolff & Wiechmann 2018) spatial autocorrelation. Therefore, we anticipate that the consideration of spatial dependencies would improve the predictive capacities of LSTM population forecasting models, though this is yet to be tested.

4.2.2 A (Very) Brief history of Population Decline in Europe

Over the past half century, Europe has experienced an unprecedented demographic shift that has signalled the end of population growth and the onset of population decline. In the early and mid-20th century, as countries underwent respective demographic transitions characterised by successive declines in mortality and fertility, rapid population growth was observed (Kirk 1996). Following wartime population losses, population growth was rejuvenated by post-war population dynamics, in which rapid fertility increases and life expectancy improvements were characteristic (Hall 1993). Towards the end of the century, demographic conditions began to favour population decline, with fertility reaching historic lows (Kohler, Billari & Ortega 2002) and longevity improvements waning (Raleigh 2019). However, most European countries continued to experience population growth, despite these stagnating demographic conditions, due to population momentum. Countries in eastern Europe represented an exception, however, with population decline beginning in the 1990's following the dissolution of the Soviet Union. Population decline, here, was attributed to the collapse of fertility and mortality (Haub 1994, Kucera et al., 2012), and the liberation of migration which served to benefit Russia at the expense of other eastern European states (Bara et al., 2013). Following the millennium, demographic conditions remained insufficient to support population growth, with population momentum waning and an increasing number of countries implicated in population decline (Coleman & Rowthorn 2011). This period is also characterised by the expansion of the European Union, with countries in central and south-eastern Europe accessing the European single market. This is crucial in the population development of these countries, with free movement resulting in significant out-migrations (King & Okólski 2018) and subsequent population declines (Sobotka & Fürnkranz-Prskawetz 2020). Contemporary European population dynamics portray a largely divided continent, with population growth concentrated in a select few countries in northern and western Europe, primarily supported by positive net-migration, and population decline prevailing across most of southern and eastern Europe (UN 2022).

4.2.3 Sub-national population decline

Though country-level population decline receives most attention within political and academic discourse, it is inherently a localised issue – occurring first within households, neighbourhoods, and communities. Population decline is only measured, and observed, at aggregate geographic/spatial units once localised decline prevails as the dominant order of population change, outweighing the aggregate sum of population growth elsewhere occurring. Population decline can also occur within the wider context of population growth (Franklin 2020). For it to be recognised at the aggregate area and country level means that depopulation is occurring at mass across most of the territory. Sub-national population decline is symptomatic of localised demographic conditions, with fertility, mortality and migration outcomes occurring differentially across space, producing place-specific population change trajectories (Newsham & Rowe 2022). Unlike national depopulation, sub-national population decline is a more regular process occurring in historic abundance (Martí-Henneberg 2005), traditionally tied to local economic decline instigating extensive out-migration (Haase et al., 2016, Johnson & Lichter 2019, Viñas 2019). Contemporary population change dynamics have resulted in an increasing number of sub-national areas observing population declines across Europe, with various demographic causes (Newsham & Rowe 2023) found to be driving heterogeneous population decline trajectories (Newsham & Rowe 2022, González-Leonardo et al., 2022).

However, there exists some consistencies, most notably the difference in occurrence amongst urban and rural areas, with an absolute population loss occurring in 44.8% (301/673) of European rural areas and 17% of 88/518 of urban areas from 2000-2018 (Newsham & Rowe 2022). Incidences of episodic and temporary population decline are also common, though only recognised amongst urban areas (Wolf & Weichman 2018). This disparity is partly explained by contemporary migration flows, whereby extensive rural to urban economic migration is a ubiquitous phenomenon (Johnson & Lichter 2019), serving to simultaneously contribute to depopulation, in rural sending areas, and growth, in receiving urban agglomerations (Rowe et al., 2019). Population decline trends also display spatial regularities, with decline more prevalent amongst remote and economically isolated areas (González-Leonardo et al., 2023a), particularly within areas of high altitude (Reynaud & Miccoli 2018). Population decline is also strongly linked to areas with elder age profiles (González-Leonardo et al., 2023a, Newsham & Rowe 2023), reflecting the risk of demographic outcomes at certain age schedules. Given the age limits to fertility and higher relative risk of mortality at greater ages, populations with aged profiles are prone to population decline.

4.2.4 The Future of European Population Decline

Though accurately predicting future population size remains a challenging task, the trajectory of European population change points towards a future with less people than present. According to the latest United Nations median population projection scenario (UN 2022), the population of Europe is expected to decline by 150 million, or 20%, by 2100. Given that the direction and magnitude of population declines are largely heterogeneous across national and sub-national Europe (Newsham & Rowe 2022), the greatest challenge is understanding where such population declines will occur. Population change is a path-dependent process, with past demographic conditions a strong indicator of future outcomes. This is particularly true for areas experiencing population decline, as self-propagating mechanisms dictate that depopulation occurring in one year is a strong predictor of decline occurring in the next (Newsham & Rowe 2022). Such mechanisms are consequential of the changing population size under regimes of population decline, with diminishing human capital restricting the provision of local services and disincentivising business (Hoekveld 2012), promoting out-migration (Elshof et al., 2014). Furthermore, as a demographic process, population decline alters the age-structures of affected areas, which can reinforce population loss. In instances where out-migration is the key driver of decline, the resultant outcome is both population loss and population ageing. This reinforces future population decline outcomes, since anticipated fertility is not realised (Sobotka & Fürnkranz-Prskawetz 2020).

Given path-dependencies of population change and the self-propagation of population decline, we can perhaps expect for contemporary depopulation trends to persist. This would signal the continued depopulation of peripheral areas, particularly amongst rural and small urban areas (Newsham & Rowe 2022), with population growth concentrated in select urban areas, typically regional or national capitals. Evidence of population distribution trends from within countries with an established and continued national population decline would suggest that this is a reasonable prospect. Indeed, in countries of eastern Europe, the epicentre of European depopulation, population growth has been recorded in only primate cities and surrounding areas (Pužulis & Kūle 2016, Ubarevičienė et al., 2016). Though perhaps not directly comparable, trends in Japan also support this, with population decline widespread except in primary urban areas and other regional capitals (Morikawa 2017, Inoue et al., 2021).

Though it is plausible that such population decline trends will persist, in actuality this has seldom been realised (Newsham & Rowe 2022). Population change processes are highly variant over time and across space. From previous research, we understand that trajectories of sub-national population decline are largely heterogeneous in that they follow divergent pathways of population change. This is true for both cities and rural areas, with rates of population decline having accelerated, decelerated, and reversed to that of growth over time (Turok & Mykhnenko, 2007, Haase et al., 2016, Wolf & Weichman 2018, Newsham & Rowe 2022; 2023, González-Leonardo et al., 2023a). In a comprehensive study of urban and rural population decline trajectories, Newsham & Rowe (2022) find that 50.57% of depopulating areas have endured a continuous trajectory of population loss, with the remainder experiencing temporary, reversal or onset pathways. Within these trajectories, significant variation in the rate of annual population decline were observed. Existing research therefore evidences how consistent rates of population declines seldom exist within the European context. Fertility, mortality, and migration outcomes are non-stationarity, with variable endogenous and exogenous influences dictating fluctuations. In the past decade alone, Europe has experienced unpredictable and stochastic events that have directly impacted these demographic outcomes, and thus altered the trajectories of population change. These include the Syrian migration crisis, COVID-19 pandemic, and the Ukraine-Russia war. The extent of influence from these events to demographic processes are yet to be fully understood, though early evidence suggests significant disruption (Newsham & Rowe 2021, González-Leonardo et al., 2022, González-Leonardo et al., 2023b). With regards to population decline, evidence has shown a reversal of depopulation processes in some rural regions during the COVID-19 pandemic (Ramani & Bloom 2021, González-Leonardo et al., 2022, Gutiérrez et al., 2022), though it remains to be seen if these trends will endure.

4.3 Data & Method

4.3.1 Data

Population forecasting requires detailed and consistent demographic data. This is difficult to obtain at small area levels, with administrative boundary changes and infrequent data collection restricting availability (Wilson et al., 2022). To overcome this, we make use of temporally consistent population data published by the WorldPop group. These data are derived from the dasymetric redistribution of census data, with remotely sensed geospatial datasets used to map settlements and estimate population counts for gridded 100m cells (Stevens et al., 2015). The data represents annual population count estimates from 2000 to 2020 at high spatial resolution. With our focus on small area population change, we aggregate WorldPop gridded population estimates to municipal boundaries. We collect population data for 40 European nations, resulting in annual estimates for a total of 65,445 subnational areas and therefore capture extensive heterogeneous population processes. The size and scale of these units vary between countries, though we utilise the smallest boundaries in cases where municipal units are not available.

This data serves as one of the inputs into our LSTM time-series forecast models. Previous efforts to forecast population size with similar LSTM approaches have made use of univariate data (Grossman et al., 2023), with population count the singular input, and output. In such cases, the predictive capacity of the model is entirely dependent on its ability to learn temporal patterns of population change. In reality, we understand how population changes are dependent on fertility, mortality, and migration outcomes, and their respective influence from age-structure and indirect determinants (Bongaarts 1978) and spatial processes (Franklin 2020). Univariate LSTM models fail to account for these relationships and in theory, should underperform when compared with multivariate models. In an attempt to improve the predictive capacity of our LSTM models, we input an additional variable capturing spatial effects. Specifically, we compute the spatial lag of population size, following a queen contiguity criterion. The output represents the sum of population size for all neighbouring areas and captures spatial diffusion processes (Hudson 1972) and the influence of interaction networks between neighbouring areas (Franklin 2020). From existing research, we understand that the development of adjacent areas can influence both population growth via spatial spillover effects (Hoekveld 2012) and population decline through competition dynamics, given a mobile workforce (Wolff & Weichmann 2018).

4.3.2 Method

In brief, our methodological procedure is designed to compare the predictive capabilities of multiple Long-Short Term Memory population forecasts. These LSTM models are nuanced in specification and implementation (described in detail below), and are compared to a baseline extrapolative ARIMA forecast, designed as a naïve benchmark model. We design and implement all LSTM models in R, making use of Keras and TensorFlow binding packages to facilitate the implementation of our models. For all models, we forecast population size to the year 2020, and evaluate the distribution of percentage errors following a median absolute percentage error (MedAPE) metric, a measure of the difference between predicted and actual values. We extend the best performing LSTM model to forecast population size in the year 2030, and discuss the geographic and spatial patterns of future population decline. Next, we focus our attention to the specificities of our LSTM models, describing their shared and distinguishable features.

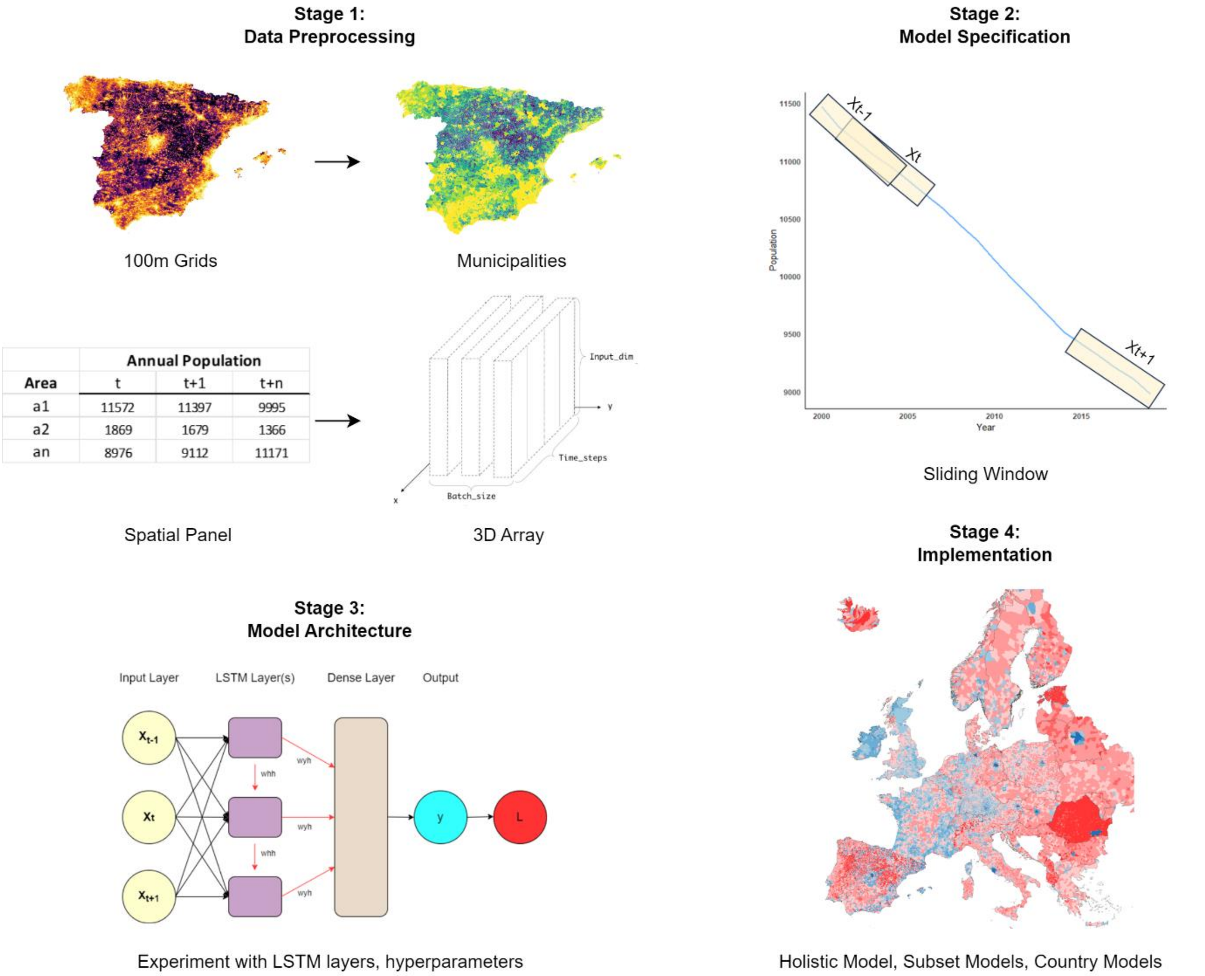


Figure 4.1 - Methodological Procedure

We design and compare multiple time-series forecast models to predict population change outcomes at municipal level across Europe. Models are long-short term memory (LSTM) models that consider temporal dependencies in demographic input data and are thus advantageous over other ML approaches. We also design an extrapolative forecast model

(ARIMA), which serves as a baseline for which we compare our various LSTM models. Our models are distinguished by varying duration of input sequences, and implementation across different subsets of areas. We extend the best performing model, measured in MedAPE, to forecast population change outcomes to 2030 for a total of 64,624 European municipalities across 40 countries. Our results and discussion constitute an analysis of our different models and their performance, and also the likely futures of European population decline. Next, we outline our methodological process in detail, and describe the stepwise LSTM procedure (Figure 1).

4.3.3 Stage 1 – Data Preprocessing

The first step involves preparing and structuring the input data in a format that is readable by the LSTM model. It is imperative that data is formatted as a 3-dimensional array, with dimensions corresponding to samples (number of areas), time-steps (time series values), and features (input variables). Next, data is normalised independently for each variable, ensuring the input data are represented on similar scales. This acts to promote efficient gradient descent during backpropagation, facilitating a stable and faster convergence. Here, we scale the data using the z-score normalisation method:

$$\boldsymbol{Z} = \frac{x - \mu}{\sigma}$$

Whereby x is the original value, μ is the mean value and σ is the standard deviation.

Input data is normalised using the scale of training data, ensuring non-exposure of test data to model training process (Chollet & Allaire 2018). To partition the input data into train and test subsets, we follow the conventional approach of reserving the first 80% of the data range for training, and the remainder allocated for test. For each area, the train subset represents historic annual population data in which patterns of population change are learned, and applied to unseen test data, representing the latest sequence of annual population values, to forecast future population size.

4.3.4 Stage 2 – Model specification

Following the conventional pre-processing steps, the design of LSTM specifications is less rigid and structured. From this stage, we are faced with numerous design choices that influence the accuracy of predictions generated from the LSTM model. The first design specification relates to the length of subsequences that are fed to the model. The input sequence for each area is broken down into subsequences that consist of sequential population values (t, t+1, t+n), or windows. We design a sliding window approach to facilitate this segmentation (Figure 2), and experiment with differing window lengths (n) representing a main variable of model specification. Greater window lengths reduce the total number of input subsequences from which patterns are learned and applied, though they also capture longer temporal patterns of population change. Here, we are constrained by a short input sequence (2000 to 2020, 21 total values of annual population size), meaning that we cannot experiment with larger windows as train/test split would not accommodate. With regards to our forecast horizon, we predict population size one year ahead, considering longitudinal data from 2000-2019 to forecast 2020.

Another aspect of our model specification is the number of variables included in the model. A promising advantage of machine learning time series forecasting models is its ability to produce accurate predictions with minimal variables. To explore this potential for applications of population forecasting, we design a simple univariable model capturing population size only, and compare this to a bivariate model in which population size and the spatial lag of population size are considered to predict future population size. The bivariate model captures spatial dependency relationships of population change (Hoekveld 2012, Franklin 2020).

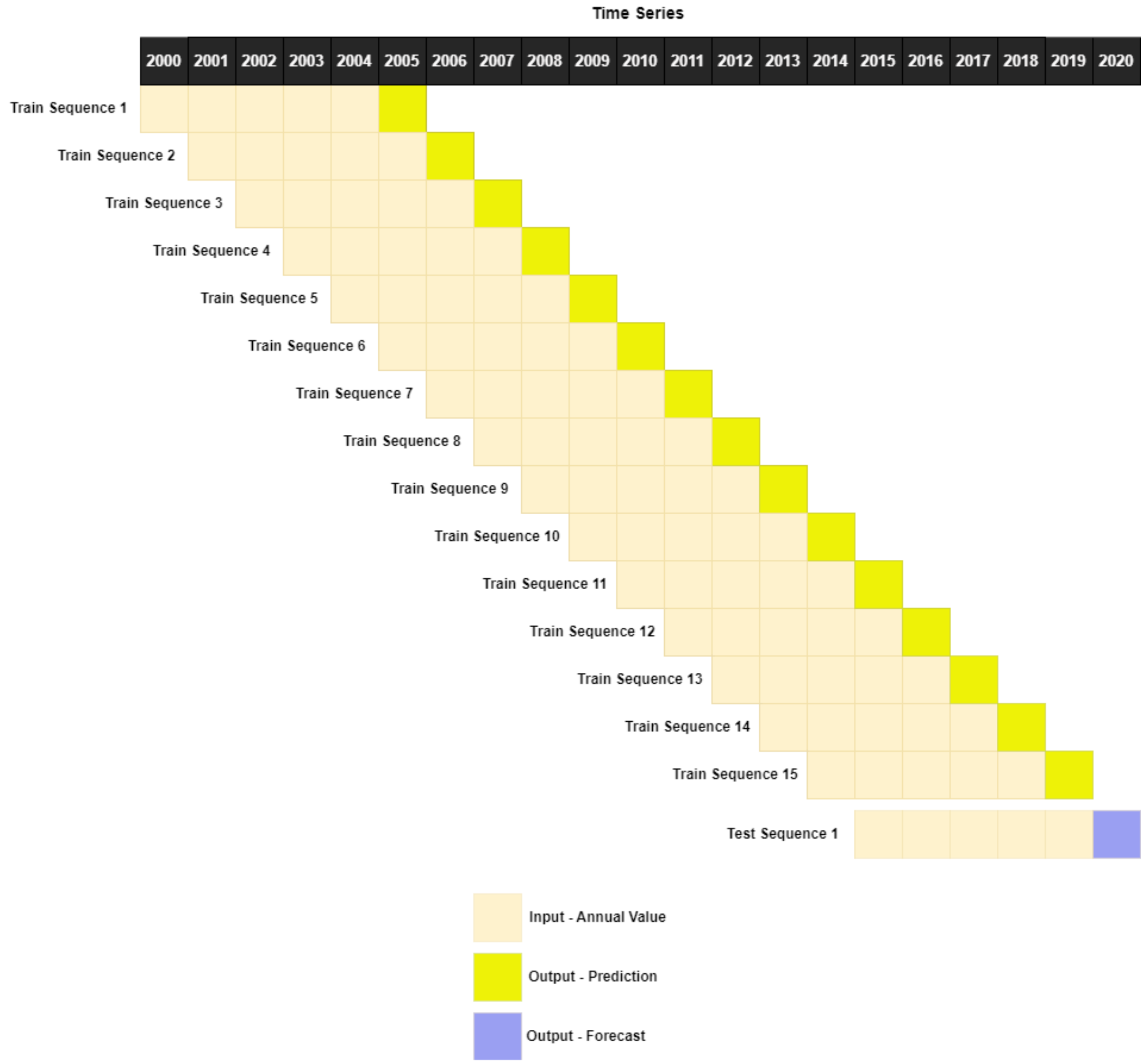


Figure 4.2 – Sliding Window Approach, Sequence Length = 5.

4.3.5 Stage 3 - Model Architecture:

The next stage involves the design of the model architecture, referring to parameters that relate to the inner workings of the model (Figure 3). The first architectural decision relates to the number of layers included in the model, with more layers representing a complex model with an enhanced learning capacity. We experiment with three distinct layer architectures; a simple model with a singular LSTM layer with 48 cells combined with a dense layer, a more advanced bidirectional model with an additional LSTM layer that processes the input sequence in reverse order, and a complex model consisting of two stacked LSTM layers, each with 48 units, and three dense layers (Figure 3). Next, we define various model hyperparameters that impact the behaviour of the model and the accuracy of its forecasts. To determine the optimal combination of hyperparameters, we make use of the KerasTuner package (O'Malley et al., 2019). After an extensive tuning process, we selected the following hyperparameters based on consistencies in model performance: Rectified Linear Unit activation function (Agarap 2018), Adam optimisation algorithm (Kingma & Ba 2014), Mean Squared Error loss function, 8 epochs. These hyperparameters remain consistent throughout all LSTM models and iterations.

	Model								
	Simple			**Bidirectional**			**Deep**		
Layer 1		Input Data			Input Data			Input Data	
Layer 2	LSTM	48 Units	ReLU	LSTM	48 Units	ReLU	LSTM	48 Units	ReLU
Layer 3	Dense	1 Unit	Linear	LSTM	48 Units	ReLU	LSTM	48 Units	ReLU
Layer 4				Dense	1 Unit	Linear	Dense	64 Unit	Linear
Layer 5							Dense	32 Unit	Linear
Layer 6							Dense	1 Unit	Linear

All Models	
Loss Function	Mean Squared Error
Optimizer	Adam
Learning Rate	0.001
Epochs	8
Batch Size	No. Training Sequences

Figure 4.3 – Summary of LSTM Model Architectures

4.3.6 Stage 4 - Implementation

The performance of LSTM population forecasts are also influenced by the extent of input data used for training. As demonstrated by Riiman et al., (2019), individual area models, in which training and forecasting is performed by separate LSTM models for each area, tend to outperform holistic models which train on data for all areas, despite the risk of overfitting in non-generalised training. Though this approach is not feasible for our specific application, given the large number of areas (n = 65,445), we instead experiment with segmenting our data by training and predicting for unique subsets (Figure 1). The total input data is segmented into three subsets, with each LSTM model implemented for each subset. First, a holistic model is implemented in which all areas are included in training and forecasting. Here, the LSTM model is exposed to extensive heterogeneous population processes in training, captured by the 65,445 unique population trajectories. The subsequent subset models are informed by area population size, with our data representing areas with vastly different population sizes. We identify outlier areas with extreme large and small populations as those with the 10% highest and lowest population values for the year 2020, respectively. The resulting partitions therefore produce three decile subsets; 10% of areas with the largest populations (n =), 10% of areas with the smallest populations (n =), the remaining 80% of areas that are considered as non-outliers (n =). By explicitly considering areas with extreme population contexts, subset models are, in theory, better equipped to understand specific nuances, which reduces the likelihood of biases that are present in holistic models due to underrepresentation. To facilitate a comparison between the holistic and subset models, a weighted average of model accuracy is calculated, accounting for the proportion of input data included in each subset.

Similarly, we conduct a further implementation experiment by segmenting our input data by country, maintaining the decile subset approach as described above (Figure 1). Here, we homogenise population contexts, with individual country LSTM models exposed only to country-specific demographic data in training. Given the national specificities in administrative boundary designation, it is possible that areas from certain countries are overrepresented in all country holistic and subset models, introducing sampling biases. For each European country included in our data (n = 40), we therefore implement a country-specific holistic model, containing all corresponding sub-national areas, decile outlier subset models, capturing the 10% high and low population outliers, and the remaining areas in an 80% non-outlier model.

4.3.7 Stage 5 – Validation

To gauge the forecasting capability of our various LSTM models, we assess the prediction accuracy of our models in a comparative framework. Here, we design a simple ARIMA extrapolative forecast as a baseline model for the purpose of evaluating the performance and effectiveness of the more advanced LSTM approach. The inclusion of the ARIMA baseline allows us to compare the experimental LSTM models against a more traditional time-series forecasting approach. As we place an explicit focus on developing LSTM approaches for population forecasting, we do not experiment with subset ARIMA models. Essentially, then, our baseline ARIMA model is comparable to our holistic LSTM models. For all LSTM and ARIMA models, we make use of 20 annual population values, from 2000 to 2019, to train models, and generate a population count prediction for the year 2020. We determine the accuracy of both ARIMA and LSTM models by comparing predicted values at year 2020 with actual values following a median absolute percentage error (MedAPE) metric, calculated by:

$$\textbf{MedianAPE = median} \left| \frac{At-Ft}{At} \right| \times 100$$

where At is the actual value and Ft is the forecast value. To facilitate a direct comparison between our subset LSTM models, holistic LSTM, and ARIMA models, we compute a composite MedAPE metric. This metric is a weighted average of the individual MedAPE scores from subset models, with weights proportional to their share of the total number of areas.

All ARIMA and variable LSTM implementations, each characterised by unique model specification, architecture and implementation nuances as described above, are subjected to a repeated cross-validation procedure. This involves a complete repetition of model training and forecasting operations a total of 10 times, and accounts for random weight initialisation during training, which can produce differences in the forecast. Through this repetition, we obtain a more robust assessment of the model performance. The reported results are therefore averaged across these iterations.

4.4 Results

4.4.1 Best model selection

Currently there are few applications of Long-Short Term Memory networks (LSTM) for population forecasting (Riiman 2019, Wang & Lee 2021, Grossman et al., 2023). These studies have demonstrated the potential of these models to outperform traditional population forecasting approaches, under certain LSTM architecture, specification, and implementation configurations. However, we currently lack a proven model configuration that consistently optimises population forecast accuracy. In an effort to address this, we focus our analysis on the discovery of optimal LSTM design parameters for population forecasting, evaluating model performance through comparing MedAPE values, a measure of average accuracy. We first introduce the results of our holistic population forecasting models that include data from 65,445 sub-national areas across 40 European countries. The holistic models are therefore exposed to extensive population change processes, inclusive of both population growth and decline trajectories. Here, we experiment with different input sequence window lengths (see Figure 2) and model architectures (see Figure 3). Results are presented below.

Table 1 shows that LSTM models are less accurate than baseline ARIMA forecasts of population size one year ahead if they are trained on the entire range of European sub-national population change trajectories (n = 65,445), showing consistently larger MedAPE measures. This underperformance implies that the inclusion of extensive heterogeneous population contexts in model training does not translate to improved forecast accuracy, and that a cross-country approach is perhaps not a viable population forecasting strategy. Irrespective of this, our results here highlight interesting model performance patterns between different model specifications, and are useful in pursuit of optimal LSTM configurations for population forecasting.

		Simple			Bidrectional			Deep			ARIMA		
Model	Variables	W3	W4	W5	W3	W4	W5	W3	W4	W5	W3	W4	W5
Univariate	Population Count	3.84	4.70	3.09	5.15	6.94	4.88	8.05	9.73	8.56	1.34	1.36	0.28
Bivariate	Population Count Lag Population Count	3.60	3.27	3.01	5.02	4.91	4.39	6.94	12.85	9.71			

Table 4.1 - Average MedAPE Accuracy from Holistic Models. Values Averaged Over 10 Model Iterations.

Firstly, we find that the inclusion of a spatial lag variable, capturing spatial dependencies of population change, consistently improves the accuracy of population forecasts. Table 1 shows an improved MedAPE value in bivariate LSTM models compared with univariate models within simple and bidirectional model architectures, and holds true for all variations of window length. This finding is consistent with other studies that compare univariate and multivariate LSTM model performance, though in a variety of non-population applications (Widiputra et al., 2021). This suggests that incorporating additional data that captures dependencies of population dynamics could further improve the predictive capacity of LSTM models for population forecasting. However, the consistency and availability of relevant data remains a challenge for this exercise. Secondly, we observe less accurate population forecasts within more complex LSTM model architectures. Though in theory a model's capacity to learn of complex patterns from data is increased when adding layers, this does not seem to occur for predicting population in our application, as indicated by lower MedAPE accuracy amongst bidirectional and deep models and consistent across both univariate and bivariate data specifications. Our results therefore evidence that reduced model complexity is associated with greater forecast accuracy of LSTM population forecasts. Thirdly, we find a less clear relationship between sequence length and population forecast accuracy. In univariate models, our results are inconsistent, with the longest length of 5-year sequences producing more accurate forecasts for most architectural configurations. This relationship is clearer in our bivariate models, with a low-to-high gradient observable as input sequences increase in length. This is echoed in our baseline ARIMA forecasts, with the 5-window approach significantly outperforming models with smaller sequence windows.

From considering this evidence collectively, we conclude that the best holistic LSTM model configuration for population forecasting is a bivariate, simple model with longer input sequence windows. Bivariate models display a clear improvement in population forecast accuracy over univariate models and are the sole data specification in subsequent analyses of LSTM configuration experimentation. Given the inconsistencies in accuracy under varying input sequence length, we maintain each of these as a specification variant in subsequent testing. As our deep holistic models display a consistent and significant underperformance, we do not include these models as architectural variants in the following experimentation, instead considering simple and bidirectional models.

4.4.2 Subset Models

Next, we experiment with running individual LSTM models for subsets of our population data, determined by population size (see Table 1). Given vast differences in population size contexts in our holistic models, it is possible that these models may not generalise to outlier areas that are characterised by either extreme large or small populations. Producing individual LSTM models for these outlier areas may eradicate these biases and improve population forecast accuracy. The results of this approach demonstrate a significant improvement over holistic models, with reduced composite MedAPE errors rivalling that of our ARIMA forecasts. We observe the lowest forecast errors for non-outlier areas, i.e., the remaining 80% of our data, demonstrating the effect of reduced heterogeneity in producing improved forecasts. As expected, the model forecasting the smallest outlier areas generated the highest errors, reflecting the erratic nature of small-area population trajectories whereby small absolute population changes are represented by large percentage changes. This relatively high MedAPE error is not mirrored within our other outlier model, which forecasts population change in areas with large populations. Instead, we note considerably reduced errors when compared with the holistic model. In comparing forecast errors between different LSTM architectures, specifically a simple, singular LSTM layer and a more complex bidirectional model, we observe a consistent improvement amongst the simple models. Table 2 shows that, under all window length specifications, and within each individual subset, the simple LSTM architecture produces more accurate population forecasts with lower MedAPE errors.

		Simple			**Bidirectional**		
Model	Subset	W3	W4	W5	W3	W4	W5
Holistic	All Areas	3.23	3.27	3.01	5.02	4.91	4.39
Subset	80% Range	0.94	0.85	0.87	1.15	1.07	0.95
	10% Lowest	4.04	4.10	3.77	4.63	5.16	4.18
	10% Highest	1.83	1.91	1.99	2.43	2.75	3.08
	Composite	**1.36**	**1.30**	**1.29**	**1.64**	**1.67**	**1.51**

Table 4.2 - Average MedAPE Accuracy - Subset Models. Values Averaged Over 10 Model Iterations.

In examining the distribution of our decile subset model forecasting errors by population size (Figure 4), we further evidence the relatively poor performance of LSTM population forecast accuracy for areas with small population sizes. Particularly, we note that MedAPE errors are considerably larger for areas with populations below 1,000. We attribute this to the combined effects of multiple factors including the erratic trajectories of small areas which are notoriously hard to predict, limited data in training which restricts the predictive capacity of the model, and the magnified percentage error metric of small values. Though these factors may explain the high forecast error for the smallest population size category, these are not entirely applicable to other population size categories with relatively high errors.

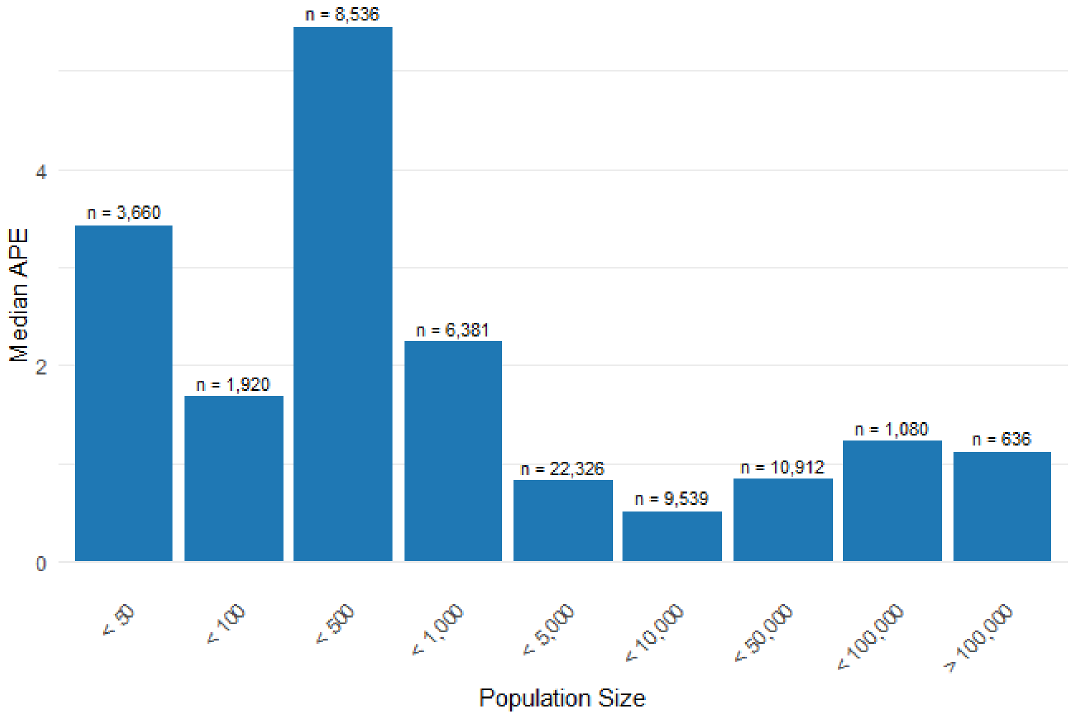


Figure 4.4 - Median APE Accuracy by Population Size – Decile Subset Model

4.4.3 Country Specific Models

In our third implementation, we design and implement LSTM models for each European country and repeat our segmentation approach as above, forecasting population size of outlier areas in separate models. In doing this, we homogenise population contexts, with LSTM models exposed only to country-specific demographic data, with consistent geographic scale, in training. The results of this exercise reveal inconsistent effects on overall forecast accuracy across European countries, compared with previous subset models that are trained on European-wide data. To demonstrate this inconsistency, Figure 5 depicts how individual country models produce improved population forecasts in half of the European countries, with the remaining half better forecasted in all-country models. The extent of the difference between the two approaches varies considerably, with composite MedAPE worsening by as much as 460% in Cyprus, but improving by 60.65% in Portugal. The performance of country-specific models appear largely dependent on the extent of input data, with poor forecast accuracies observed in countries with a small number of sub-national areas. Conversely, we observe significant increased forecast accuracy within countries with extensive data across numerous sub-national areas. These results reflect the ability, and inability of LSTM models to learn of generalisable temporal dependencies from input data. LSTM approaches are simply not feasible when lacking sufficient data, which is the case for many countries included within this study.

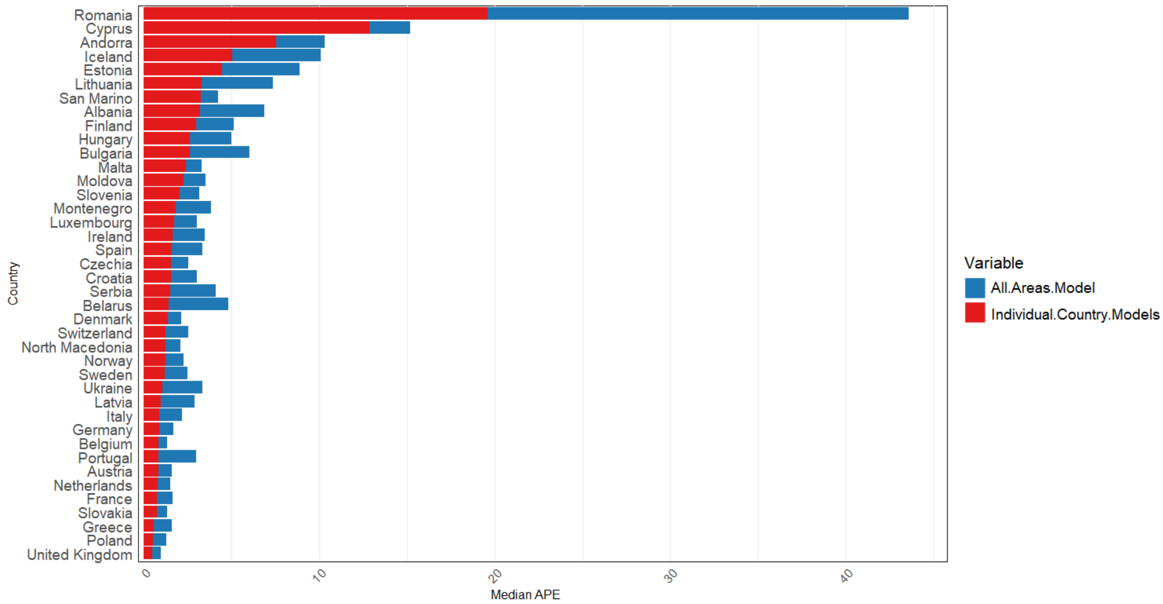


Figure 4.5 – Median APE Accuracy by Country – Country Specific Models and Holistic Model

4.4.4 Forecast of European Population Decline

Observing the MedAPE forecast accuracies of all LSTM implementations, above, we consider the decile subset approach to be optimal in an application to forecast 2030 population size across the European continent at small area level. To achieve this, we designed a recursive LSTM approach, whereby initial predictions of population size are used as inputs for subsequent predictions (see Figure 2) Our forecast enables an investigation into likely futures of population decline, a contemporary phenomenon encroaching the landscape of European demography (Newsham & Rowe 2022). Specifically, we forecast population change outcomes in a total of 65,445 sub-national areas, encompassing 40 European countries.

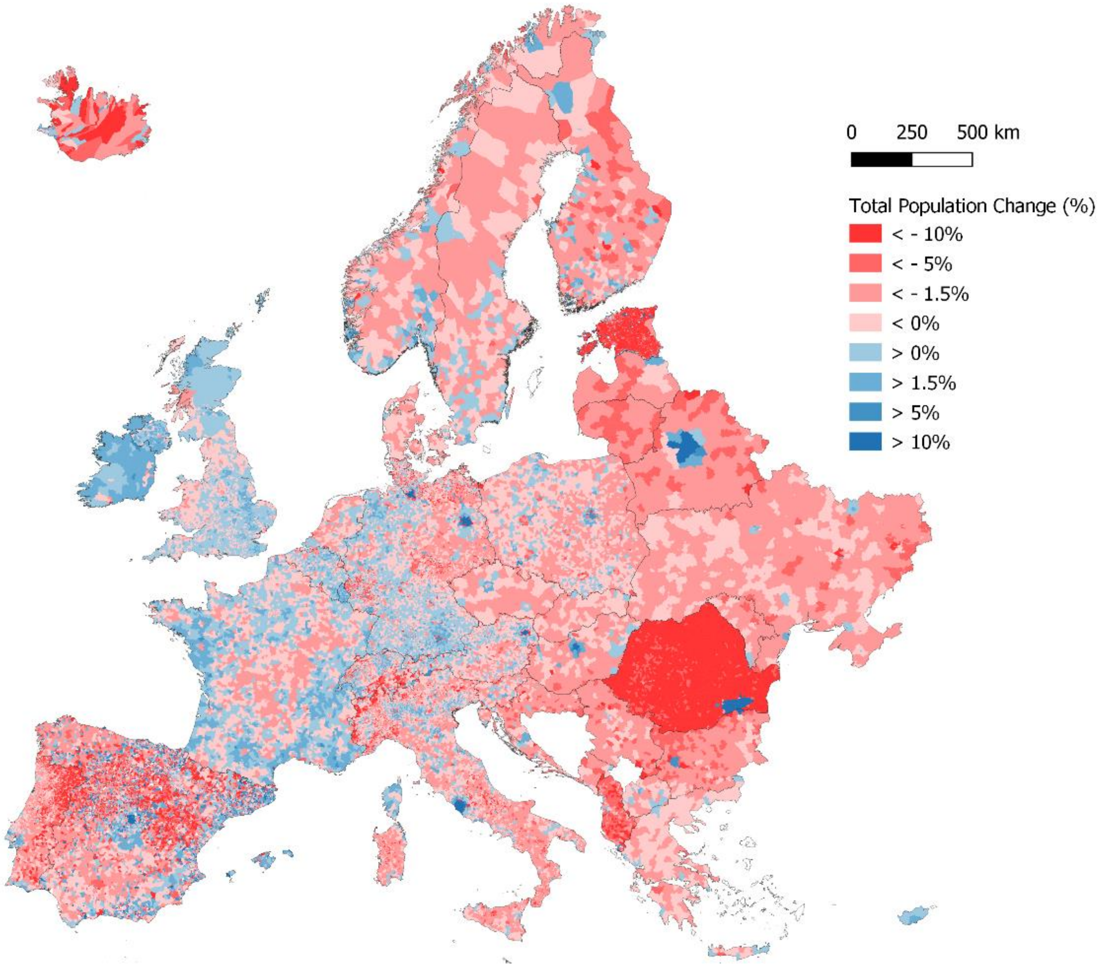


Figure 4.6 – 2030 Forecast of European Population Change

In broad terms, our forecast reveals a significant spread of population decline across the continent. Overall, total population is expected to decline by 3.6 million, or 0.62% by 2030. Though moderate on a continental scale, population decline will disproportionately affect certain nations. In total, 30 of 40 (75%) of European countries will be implicated in national scale depopulation by 2030. At sub-national level, 70.2% of all areas will observe a population decline, directly affecting over half (59.26%) of Europe's population.

Our forecast of 2030 small area population size reveals a mosaic of varying demographic trends across the continent. We observe geospatial patterns in the concentration of population growth and decline across all hierarchies. At the continental level, we observe broad differences in population change outcomes between sub-regions, with a refined east-west distribution of decline and growth, respectively. Highest population losses are observed in southern and eastern Europe, representing a continuation of recent trends (Newsham & Rowe 2022), and growth widespread in select few western territories. However, an increasing number of countries in central, northern, and western Europe are expected to experience depopulation by 2030.

At country levels, the distribution of growth and decline is also uneven (Figure 7). Population growth and decline will co-exist within all countries. All countries will contain vulnerable sub-national areas, with population decline disproportionately affecting remote regions, most typically those located away from cities and coastal regions or in high altitude. Our forecast expects for population growth to occur in isolated sub-national areas within countries of prevalent depopulation. It appears that select urban centres and their peripheries will emerge as the focal points of population growth in an increasing number of countries. This reflects trends observed within forerunning countries of population decline, including Japan (Morikawa 2017, Inoue et al., 2021) and those in eastern-Europe (Karachurina & Mkrtchyan 2015, Pužulis & Kūle 2016, Ubarevičienė et al., 2016).

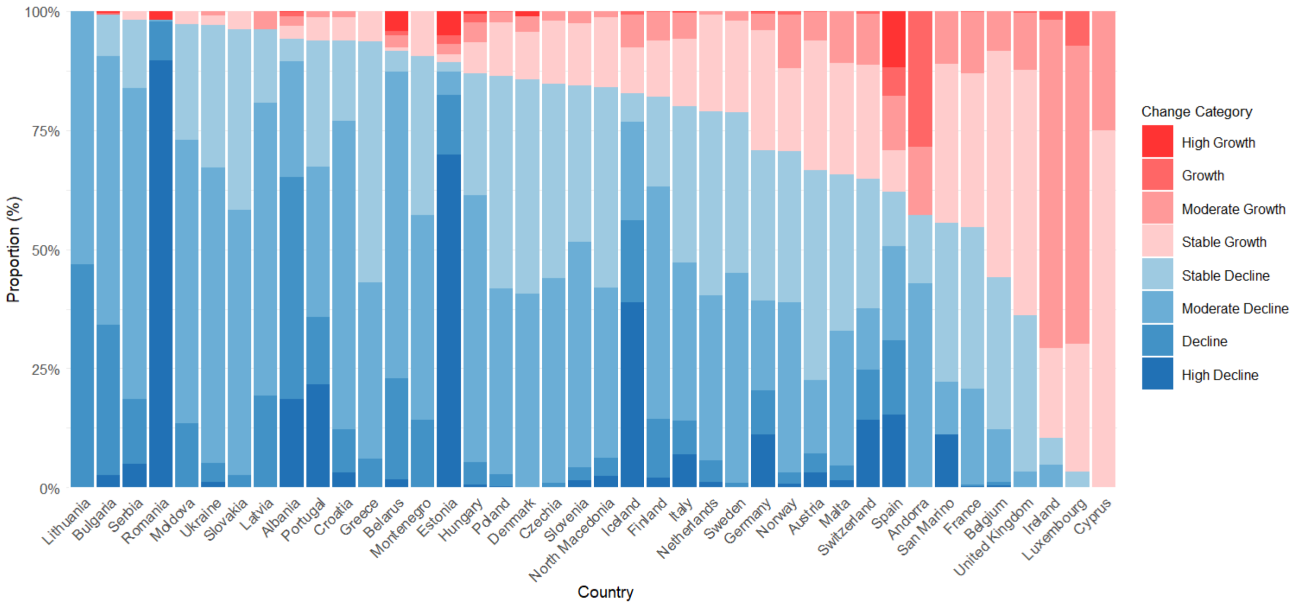


Figure 4.7 –Forecasted 2030 Population Change Categories by Country

4.5 Discussion & Conclusion

Motivated by the prospect of widespread population decline across Europe, we have developed a Long Short Term Memory approach to forecast population change outcomes and applied it to small area level, encompassing the continent of Europe. Thus far, there are very few examples of these models being utilised within the field of demography or population studies, perhaps owing to their insurmountable data demands. Previous efforts have concentrated on singular countries (Grossman et al., 2023), or sub-national regions (Riiman et al., 2019), and demonstrated a potential for out-performing traditional population forecasting approaches. We extended these efforts to forecast population decline for the entirety of Europe, training an LSTM with more comprehensive capabilities. The application of LSTM models for population forecasting remains in its infancy, with considerable development required to rival traditional approaches in practical applications. With LSTM models highly flexible in terms of their architecture and implementation, a significant hurdle persists in discovering the optimal configurations for this exercise. Our research provides a foundation for this effort, by comparing various LSTM models with varying architectural design, data specification, and implication approaches.

We present consistent evidence for the enhanced population forecast accuracy of LSTM models, with models consisting of a singular LSTM layer combined with a dense layer outperforming more complex bidirectional and deep models with multiple LSTM layers. We also conduct rigorous testing into the effect of sequence duration, or window length, on forecast accuracy, finding that a longer window incorporating population counts for a sequence of five consecutive years consistently outperforms shorter sequences. We therefore confer with Rijman et al., (2019) in this regard, though we do not extend our sequence duration values to enable a direct comparison with Grossman et al., (2023). Though we employ an extensive LSTM hyperparameter tuning search to select the optimal components, we did not experiment with varying activation and optimiser functions, learning rates, batch sizes and epochs. Future research should explore the effect of varying hyperparameter components on LSTM population forecast accuracy. It is possible that further optimisation could be achieved, particularly for models tailored towards areas with small populations, which remain more erroneous than larger areas here in this paper. We instead place a greater focus on developing LSTM population forecast models for an application to an expansive geographic scope, addressing previous shortcomings of existing efforts. This involved the experimentation of various segmentation approaches, whereby we partitioned our input data according to population size thresholds and country, and developed separate LSTM models. In doing this, we significantly improved upon average forecast accuracy, reducing error whilst maintaining a feasible approach to forecasting across vast territory with geospatial granularity. Overall, our best performing model produced a median absolute percentage error (MedAPE) of 1.29%, though considerable variation was observed between areas of differing population size and within different European countries.

To demonstrate the potential of our approach, we adapted our best performing model to produce a forecast of population size to 2030 across 65,445 sub-national areas in 40 European countries. In doing this, we observe granular geospatial patterns in population change outcomes, with implications for understanding likely futures of population decline. Our forecast expects depopulation to concern an increasing number of areas, spreading to the majority of European territory and directly affecting over half of the continental population by 2030. These results highlight the pressing need for depopulation to be considered explicitly within governmental, planning, and academic endeavours. Particularly, research within the fields of demography, population geography and regional studies remain insufficient commensurate to its immediacy.

Though our LSTM approach represents an expansion of existing works, there remain a number of limitations that should be addressed in future research. Firstly, we have demonstrated the effectiveness of LSTM models, for generating population forecasts with small margins of error, with very little input data. Our models therefore reflect the capabilities of LSTM models to produce predictions of future outcomes when contained in historical trends. However, past population change trends are not always an indicator of future trajectories. To account for this, LSTM models should be expanded, with regards to input data, which would enable predictions outside of historical observations. Particularly, future efforts should incorporate additional variables, particularly those with known influence on population dynamics, such as age-sex population structures and fertility, mortality, and migration outcomes to further improve upon the predictive capacity of LSTM models for population forecasting. A second limitation is that our input data does not capture the disruptive effects observed during the COVID-19 pandemic. Though the magnitude of its impact is yet to be fully understood, evidence suggests considerable shifts in demographic outcomes and thus population change dynamics. Our data, for example, does not capture the reversal of depopulation trajectories in rural areas, observed during COVID-19 period.

5

Conclusion

5.1 Introduction

Population decline has become well-established across Europe, increasingly affecting sub-national areas, and setting an unfamiliar course of continental population decline. Already, it has acted to overturn longstanding continental population growth, and threatens to diminish the European population by over 20% during the present century (UN 2022). The expected population decline is anticipated to pose novel challenges that will bear explicit consideration to numerous political and societal structures. Despite its advent as an unprecedented demographic phenomenon and its anticipated threat of disruption, it remains overlooked and understudied in political and academic settings. Research deficiencies are pressing, given the immediacy of continental population decline, and wide-ranging. Particularly, the temporal development of population decline, as a demographic process, and its spatial dimensions are largely overlooked. A spatio-temporal analysis of contemporary population decline is essential for devising informed strategic responses, improving forecasts, and advancing demographic theory.

Firstly, population decline is often considered statically, as an outcome between two points in time. However, population decline is a dynamic process, and understanding how it unfolds and changes over time is crucial not only for its conceptualisation, but also for its management. Secondly, existing works are lacking in a cross-national and comparative research scope. Perhaps due to inconsistencies in data collection and availability between different European countries, existing research lacks a comprehensive and cross-national understanding of contemporary population decline outcomes and processes. This is highlighted by an over-reliance on case study research, and heightened by a strong rural-urban dichotomy within comparative research. Thirdly, the demographic processes underpinning depopulation are seldom considered in existing research, with low fertility often used as a blanket explanation of its origins. In actuality, population decline is the result of intricate interactions between fertility, mortality, and migration outcomes, with the timing and extent of these outcomes unique to individual areas. Finally, despite multilateral organisations unanimously expect for population decline to characterise European population change throughout the 21st century, few works have attempted to forecast population decline in sub-national areas. Population decline first occurs within small geographic units, and an understanding of likely future outcomes are essential for its effective management.

Addressing these four major shortcomings, this thesis sought to provide an enhanced understanding of contemporary population decline commensurate to its threat, including its current extent, temporal development, underpinning demographic processes, and its likely future within Europe. To achieve this, a comprehensive methodological approach was developed, consisting of three broad stages. The first stage developed an analytical framework to study the temporal evolution of population decline processes across sub-national European areas. The second stage aimed to empirically evaluate the contributions of demographic factors of fertility, mortality and net-migration to population decline trajectories. Finally, the third stage involved the construction and deployment of multiple long short-term memory (LSTM) time series forecasting models to produce an estimation of future population decline outcomes within geographically granular sub-national areas. This chapter summarises the main research findings of the thesis before evaluating its contributions towards data products, quantitative methods, substantive knowledge, theory, and policy. It then discusses some limitations and highlights avenues for potential future research that would build upon and enhance the knowledge gained from this thesis.

5.2 Summary of key research findings

This thesis identified and addressed four key aims. Here in this section, I re-state each aim and outline the relevant research findings.

1. **Build a comprehensive database of European population change dynamics, including population count and its proximate determinants (fertility, mortality and migration) and a wide range of socio-economic and geospatial factors (e.g., population composition, unemployment rate, proximity to nearest urban agglomeration) at the national and sub-national levels.**

The first aim acted as a foundation for addressing subsequent aims. It identified the importance of using a consistent spatial panel dataset to capture longitudinal changes in population development and its associated covariates. In achieving this, it addressed a significant obstacle preventing a spatio-temporal analysis of contemporary sub-national population decline within the entirety of Europe, as no such database previously existed. The database contains information for a total of 2,035 sub-national areas spanning 43 European countries. With the exception of Kosovo and Bosnia & Herzegovina, the data captures the entire wider European region, according to United Nations definitions. The areas represent small regions, and mostly correspond to NUTS3 units (nomenclature of territorial units for statistics) in the Eurostat regional classification system. However, these vary between countries, ranging from 401 in Germany to a singular, national-level area in smaller countries of Cyprus, Liechtenstein, Luxembourg, Montenegro, and San Marino. Though the geographic scope then varies between European countries, the dataset still captures significant sub-national variation in population decline processes and permits novel continental-wide analyses of depopulation. The bulk of longitudinal population count data was sourced from Eurostat, who receive data from national statistics institutions from countries within the

European Union (EU), on an annual basis in accordance with the Regulation (EU) No 1260/2013. In total, data for 28 of 44 countries, and 1,246 of 2,035 sub-national areas were sourced from Eurostat. Data for the remaining areas were sourced from national statistics institutions directly, and for covariate data from some EU countries.

The database consists of annual year-end population count and proximate determinant (birth, death and net-migration) event count data for the period 2000 to 2018. Due to differences in national statistical institution practices, these population data are either derived from register data, administrative data, or are estimates. The availability of population data is also not consistent across all European countries throughout the duration of the timeseries. Owing to this, the database is incomplete and contains some missing values; 2.67%, 11.21%, 11.06%, 11.70%, for population count, births, deaths, net-migration, respectively. In some cases, it was possible to estimate and impute values by restructuring the demographic balancing equation (Preston et al., 2000), which reduced the impact of missing values in subsequent analyses. A common issue with spatial panel data is the changing of geographic boundaries over time, however the impact of this was mitigated by harmonising changes based on correspondence files from Eurostat and national statistics institutions that contain a historical record of changes.

The database also contains information on a range of contextual variables that captures the demographic, economic and geo-spatial characteristics of each area. Specifically, these include the proportion of the population above the age of 65, the proportion of the population who are foreign born, the population density, the proportion of working age population who are unemployed, average altitude, distance to the coast, and distance to the nearest principal urban area with a population greater than 1 million. These variables have known relationships to population decline outcomes, according to previous empirical research (Reynaud et al., 2020, González-Leonardo et al., 2023). Unlike the population count and demographic event times series variables, these contextual variables are cross sectional, and measured at one time point. For most variables and countries, the contextual data is from the year 2011, a census year, and the near mid-point of the time series. Finally, the dataset includes a rural-urban classification which categorises each area by their level of urbanisation. The criteria is consistent with Eurostat's definition and based solely on the share of the population within the area living in urban grid cells of $1km^2$ with a population of at least 5,000 and a density of 300 inhabitants per km^2. An area is considered to be rural if less than 50% of inhabitants reside in urban grids, intermediate if this value falls between 50% and 80%, and urban if more than 80% of the population resides in these urban grids. This variable is also cross-sectional, with 2011 data informing the categorisation. The rural-urban classification facilitated an analysis of population decline across different area types, and was particularly valuable in overcoming the rural-urban dichotomy of previous research.

2. **Establish the extent, prevalence and timing of population decline within all European countries.**

The second thesis aim sought to recognise the absence of a basic understanding of the current status of population decline outcomes and processes across Europe. Owing to the constrained geographic scope of existing research, our collective understanding of contemporary depopulation, as a demographic process, is fragmented. Particularly, the incidence, timing, magnitude, and sequencing of population decline across different European areas are largely unknown. In response to this research gap, this thesis presented an analytical framework that studies the spatio-temporal dynamics of population decline. A novel application of sequence analysis techniques enabled a holistic analysis of multiple temporal population decline processes occurring across sub-national areas of Europe. Specifically, the method captured differences in the ordering, timing, magnitude, and spatial structure in chronological sequences of population change in areas that have declined in population size from 2000 to 2018. With the application of the dataset constructed in the first aim of this thesis, this aim explored the extent to which different types of areas, with regards to their geographic location, urban-rural status, and population size, have undergone distinct temporal depopulation processes.

Two significant substantive findings resulted from the analysis. First, insights into the existence of unique depopulation pathways were provided, with the identification of seven distinct population trajectories capturing different temporal processes of population decline. Collectively, these represent processes of the emergence of population decline from growth, its acceleration, deceleration, persistence in various annual intensities, and reversal. In more detail, of a total of 696 areas, 107 areas experienced the onset of depopulation from previous population growth, representing an increase in incidence across Europe. A further 46 areas experienced an increase in the annual rate of population decline, capturing a process of acceleration. Counteracting this, 57 areas observed a decrease in their annual rate of decline, showing a coexistence of deceleration. Most areas (n = 249) observed a relative stability in annual population decline, though a majority (n = 180) at less than 1% per year, and others (n = 69) at a faster pace, with more than 1% annual population loss. A further 106 areas ceased to decline in population size, instead experiencing stability or population growth towards the end of the period 2000 to 2018. Finally, a considerable number of areas (n = 131) observed a period of temporary population decline, beginning and ending the period in a state of stability or growth. Here, depopulation was fleeting, though significant enough in intensity to register an overall negative aggregate population change from 2000 to 2018.

Second, this thesis analysed the extent to which these seven distinct depopulation trajectories are experienced across different types of areas, between rural, intermediate, and urban areas of small to large size. To this end, a multinomial logistic regression model was developed and revealed systematic patterns of population decline across rural and urban Europe. Typically, rural areas displayed an orientation towards accelerating trajectories of population decline, particularly those within eastern and southern Europe where depopulation is long established, and those small in population size. Conversely, urban areas displayed a tendency for decelerating population declines, though this is less consistent within smaller and mid-sized urban areas. Furthermore, results revealed broad differences in depopulation processes in continental subregions, with more longstanding and fast paced annual loss in the east, persistent but relatively slow declines in central Europe, a widespread acceleration in the south and south-east, and finally a temporary or decreasing trajectory in the west. Considering the results collectively, the findings revealed heterogeneous decline trajectories across the continent, with a degree of regularity within geographic sub-regions and rural-urban characteristics.

3. **Identify the dominant demographic cause of population decline in European countries, and determine sub-national variations in the extent and causes of population decline.**

The third thesis aim built upon the findings of the second aim, and sought to understand the different demographic processes underpinning contemporary population decline in European sub-national areas. Within existing research, persistent sub-replacement fertility is frequently cited as the demographic driver of decline at broad country levels (Lutz & Gailey 2020, Reher 2007). However, less is known about how the three demographic factors, fertility, mortality, and migration, have interacted to produce depopulation at sub-national levels, and to what extent these processes are differential across the continent. To address this research deficiency, this thesis developed a comprehensive analytical framework that empirically analyses the contributions of each demographic factor to annual population changes in European areas in decline. Specifically, a decomposition technique was applied to facilitate this, coupled with a multifunctional principal component analysis and cluster analysis to compare and group areas based on their shared longitudinal demographic causes of depopulation. Making use of the full dataset from aim one, a multinomial logistic regression model was developed to identify key contextual demographic, economic, and geo-spatial attributes characterising the different demographic causes of depopulation.

Two main findings emerged from this analysis. First, the analysis revealed the different demographic causes of population decline across Europe. In total, five unique signatures of depopulation were identified, highlighting unique interactions between fertility, mortality, and migration. These signatures displayed some commonalities, but also nuances in contributions to population decline. Most apparent was the ubiquitous depopulating effect of a natural deficit, with crude rates of mortality outweighing that of fertility in all signatures consistently from 2000 to 2018, acting to diminish the size of European populations. Another widespread commonality existed in the presence of a dual-deficit, characterised by a natural and net-migration deficit, and present in four of five signatures. The presence of such a dual-deficit contributes to improve our understanding of the demographic causes of population decline, and highlights the crucial role of migration that is often overlooked as explanations tend to focus on low fertility. Furthermore, as characterised by four signatures, most areas experienced an increasing contribution to population decline from fertility reductions over the period, but particularly after 2010, further highlighting the widespread impact of low-fertility rates across Europe.

However, the signatures we identified differed in the extent and temporal trend of these dual-deficit causes, and in extent of net-migration balances. Of the 732 sub-national areas included in the study on the basis of their absolute decline in population size from 2000 to 2018, 215 areas experienced a dual-deficit with relative constant annual rates of fertility and mortality. This demographic cause of population decline is widespread across Europe, though is particularly prevalent in central and south-eastern Europe. A further 151 areas exhibited similar trends in fertility, mortality and net-migration, but with more volatile net-migration patterns, fluctuating between a contribution to population growth and decline over time. The geographic distribution of this demographic cause of decline is also widespread, but particularly prominent in central Europe, in Austria, Hungary, Romania and Serbia. A total of 90 areas displayed rather unique contributions, with a minimal influence of migration but instead a reversal of fertility and mortality trends towards a convergence, ultimately resulting in the deceleration of population decline. This cause of depopulation is nearly exclusive to eastern Europe, in Russia and Ukraine. A further 116 areas are characterised by reversing fertility and migration trends, both contributing to decline by the end of the period. These areas are concentrated in south-eastern Europe, and chiefly in Albania and Bulgaria but also Belarus and Spain. Finally, 160 areas displayed unique demographic trends characterised by a resurgence in positive migration that acted to contribute to population growth, though this is offset by increasing natural declines owing to a widening fertility-mortality disparity. This signature is predominantly located in western Germany, but also Portugal and Romania.

Secondly, this thesis explored the extent to which different areas experienced different demographic causes of population decline. The findings revealed some unique perspectives with implications for the development of policy surrounding the management of population decline. Findings revealed that rural areas are prone to dual-deficit causes and associated with processes of increasing negative net-migration. Conversely, urban areas are found to be associated with signatures depicting a deceleration of population decline, particularly those with migration resurgence processes and demonstrating the propensity for urban revival. With regards to demographic characteristics, this thesis revealed how aged populations are associated with signatures characterised by increasing rates of mortality, capturing the relationship between ageing and increased mortality risk (Cheng et al., 2020). Areas with high proportions of non-native populations are most associated with converging trends of fertility and mortality, and therefore lend support to studies that detail a significance of international migration flows in reinforcing population growth (Patias 2021b, Newsham & Rowe 2021). Perhaps unsurprisingly, high unemployment is associated with processes of increasing negative net-migration, reflecting the importance of economic opportunity in migration processes. Finally, all depopulation signatures displayed a similar association with distance to primary city, indicating that population decline is more prevalent in remote and disconnected areas.

4. **Generate national and sub-national population projections for the most likely scenarios of population change.**

The final thesis aim sought to assess the likely immediate future of population decline outcomes across Europe. To facilitate this, a machine learning approach was developed, involving the design and implementation of multiple long short-term memory (LSTM) time series forecasting models. Thus far, very few works have been published that make use of LSTM models for population forecasting (Riiman et al., 2019, Wang & Lee 2021, Grossman et al., 2023). All of which are narrow in the geographic scope of their application, either to a singular sub-national region or country. This thesis develops a forecasting approach that is applied to the entire continent of Europe, in a total of 65,445 sub-national areas. Yielding a median absolute percentage error (MedAPE) of 1.29, the population forecasts produced in this thesis outperformed previous LSTM efforts whilst extending the geographic scope significantly. The approach consisted of the implementation of multiple different LSTM models, unique in model specification and implementation strategy. Each model produces a forecast of population size in the year 2020, and validated in a comparison with actual values. The accuracy of each model's forecast was compared using a MedAPE indicator, with the best performing model extended in a recursive multi-step approach to produce a forecast of population size in the year 2030. An explicit focus was placed on population decline outcomes in the analysis, though population growth outcomes were also forecasted. For this particular aim, a new dataset was utilised, consisting of 1km gridded population estimates from 2000 to 2020 and published by the WorldPop organisation. These gridded data were aggregated to municipalities to overcome existing inaccuracies in the original gridded data but still contribute to produce a granular analysis of population decline. The WorldPop data enables the production of a complete time series for all areas within Europe.

The findings revealed novel insights into the future of sub-national population decline across Europe. Firstly, the LSTM forecast expects depopulation to become widespread within Europe by 2030, spreading to 70.2% of municipalities and directly implicating over half (59.26%) of the European population. This represents a significant spread, as 51.33% of European municipalities are currently experiencing depopulation. At the national level, it is expected that 75% of countries will observe a population decline by 2030, with depopulation then firmly overtaking population growth as the dominant order of population change. Regarding the expected severity of population decline, LSTM models forecasted the total European population to decline by 3.6 million, or 0.62% by 2030. Though this represents a moderate population loss and a slow annual decline, certain areas are expected to experience disproportionate extensive losses. These areas are disadvantaged in their locations, either remote from urban agglomerations, at high altitudes, or are confined to a country that has a long-term history of population decline. Within these countries, which are typically soviet-occupied states, population decline was forecast to become increasingly widespread, occurring in all areas except a select few chief urban areas. These patterns reflect those observed in Japan, a forerunner of population decline, with population growth highly concentrated in national and regional capitals.

5.3 Contribution and implications

Through addressing the four research aims, this thesis contributed to data, methods, applied substantive knowledge, theory, and policy regarding the demographic phenomenon of population decline. Firstly, relating to data and methods, this thesis produced a total of six outputs that aim to progress our understanding of contemporary European population decline, and these outputs can be used in a wider set of applications extending beyond the study of population decline. A comprehensive database was produced that accounts for annual population size and demographic event information for temporally consistent sub-national geographic units inclusive of the wider European continental region. The database contains contextual information relating to a number of known determinants of population change and demographic events, including socio-economic and geo-spatial variables. This database is utilised in Chapters 2 and 3 to study the trajectories and underlying demographic causes of sub-national population decline. The database could also facilitate future research into European population dynamics.

This thesis also produced two population decline classifications for European sub-national areas: 1) one that groups areas based on their longitudinal trajectories of population change; and 2) another that classifies the demographic causes of depopulation over the period 2000 to 2018. Next, a forecast of 2030 population size was produced for the entirety of Europe at granular municipal level geographies. LSTM machine learning models used to produce population forecasts also form a data product of this project, and are capable of being adapted to wider time series prediction applications. The last outputs are a set of interactive maps that summarise the primary outputs from Chapters to 2 to 4; the classification of population decline trajectories, the classification of demographic causes of population decline, and the 2030 forecast of population size. These maps are beneficial to a range of stakeholders interested in understanding the geographic and spatial dimensions of population decline dynamics.

Secondly, this thesis made four contributions to the development of substantive knowledge regarding contemporary population decline processes and dynamics within Europe. The first substantive contribution was presented in Chapter 2, and identified seven distinct trajectories of population change within sub-national regions that are driving the continental trend of population decline. These trajectories captured the temporal processes of population decline by considering the sequential development of annual states of population change, as opposed to periodic changes over distant points in time. The trajectories highlight the different longitudinal pathways of depopulation, and represent the unique ways in which sub-national European areas have experienced population declines since the turn of the century. Collectively, the trajectories illuminated both moderate and rapid processes of depopulation acceleration, deceleration, stability, and transience. These trajectories were subject to further analysis, which yielded an additional contribution to substantive knowledge, namely in uncovering which types of areas have experienced distinctive population decline trajectories. The trajectories follow relatively consistent distributions with regards to rural-urban characteristics, population size, and geographic location. Trajectories of accelerating population decline were found to be characteristic of rural areas, with small populations and over-represented in southern and south-eastern Europe. Conversely, decelerating rates of depopulation, and those temporary in nature were found to be strongly associated with urban and populous areas, particularly those located within western Europe.

The second contribution of this thesis to substantive knowledge stems from an analysis of the demographic causes of contemporary population declines, provided in Chapter 3. Inspired by the functional cluster analysis in Jung & Song (2021), a comprehensive methodological strategy was developed to study the longitudinal demographic causes of depopulation across sub-national areas of Europe. This addressed a significant research gap, with no clear understanding of the demographic processes underpinning current population declines, or how they vary between different European areas. A total of five unique demographic causes of population decline were identified, named depopulation signatures, and distinguished by nuanced trends in crude rates of fertility, mortality, and net-migration. Of these five depopulation signatures, two depicted relatively stable demographic trends characterised by consistent dual fertility-mortality and net-migration deficits. Here, a gradual widening fertility-mortality disparity contributed to accelerated population declines, and exaggerated by a persistent negative net-migration trend. The other three depopulation signatures are characterised by distinct reversals in demographic trends. The first depicted an abrupt decline in mortality and a gradual increase in fertility, resulting in a convergence in natural change drivers and a deceleration of population decline. The second described a concurrent fertility and mortality decline, which acted to accelerate depopulation. The final signature depicted a negative to positive migration reversal, resulting in a decline to growth trajectory despite decreasing fertility widening the natural disparity. Collectively these depopulation signatures provide evidence that European population decline has been driven primarily by negative natural change, but with highly specific net-migration trends contributing to shape temporal changes in the overall trajectory of depopulation.

A further analysis of the depopulation signatures yielded a third substantive knowledge contribution. Namely an understanding of the areas which are prone to experience specific demographic causes of depopulation. The analysis found that across Europe, rural areas with small population sizes consisting of elderly and native people were undergoing constant dual-deficit depopulations. In contrast, the signature depicting a natural reversal and decelerating population decline predominantly takes place within eastern Europe, in populous urban and intermediate areas with a larger share of young and non-native populations. Population declines driven by the simultaneous reversal of fertility and mortality were found to be distributed across the continent in rural, intermediate, and urban areas alike, but typically characterise high altitude areas that are distantly located from large cities. Finally, the depopulation signature depicting a decline to growth trajectory owing to resurgences in positive net-migration was found to be a western European phenomenon, occurring in non-coastal areas with high elderly populations and low unemployment.

A fourth and final substantive knowledge contribution is provided in Chapter 4, whereby insights into the likely future of population decline are gleaned at a geographically granular scale, specifically for 65,445 European municipalities. The forecast expects for past trends to largely persist to 2030, and highlights the severity of the population decline phenomenon in Europe. Specifically, results indicate that population decline will continue to spread throughout the continent, and occur in a majority of European municipalities (70.2%) and countries (75%) by 2030. Population decline is also likely to occur at disproportionately high rates in select areas, particularly those at disadvantaged locations such as at high altitude, distant from either large cities or coastal regions. Though an explicit focus is placed on population decline, the forecast also has implications for the future of European population growth and contributes to substantive knowledge in this regard. In countries experiencing national depopulations, population growth is expected to become increasingly confined to select large cities, either capital or principal cities within a large region, and their peripheries. It is therefore likely that, under country level regimes of depopulation, patterns of population distribution will conform to that of the forerunners of population decline, namely Japan. Though policy interventions could help shape the spatial pattern of population distribution attenuating the impacts of population decline.

This thesis also made contributions to the development of *theory* relating to contemporary population decline, namely the provision of novel empirical evidence and an enhanced conceptual understanding of its spatiotemporal dimensions. Thus far, theoretical work has been restricted geographically to specific countries and regions (Van Dalen & Henkens 2011, Sobotka & Fürnkranz-Prskawetz 2020) with a limited focus towards the temporal dynamics of decline (Coleman & Rowthorn 2011, Janicki 2017). In this thesis, an emphasis is placed on studying European depopulation holistically, considering all sub-national areas affected by population decline in empirical analyses in order to provide a comprehensive and robust evidence pool. In doing this, this thesis evidenced the heterogeneous nature of sub-national depopulation trajectories and underlying demographic cause, as well as quantifying their relationship to various area characteristics. These findings contributed to the conceptual understanding of population decline as a highly area-specific and dynamic process. This thesis demonstrated that population decline does not occur uniformly, in timing, pace, or magnitude, between sub-national areas. The underlying demographic mechanisms and subsequent trajectories of population decline are unique to individual areas, and are evidenced to be sensitive to a range of contextual area-level attributes, including population composition, economic opportunity, geographic location, and the broader region in which they are situated. Yet, this thesis showed that areas can be grouped based on their broad longitudinal similarities of depopulation trajectory and demographic cause to identify distinctive empirical historical patterns. These patterns can help in conceptualising the specific historic, geographic, demographic, political and social forces that have shaped the distinctive trajectories of depopulation identified and may help inform future trajectories of decline.

Demographic theory often gains traction through the identification of homogeneous processes, whereby regularities in trends are observed between different places. In contrast, the cumulative evidence from this thesis suggests that European population decline is heterogeneous in both cause and outcome. This thesis presented evidence of differential population decline processes and the existence of nuanced demographic causes. There is no singular trajectory or demographic cause of depopulation across all European sub-national areas, but rather a set of well-defined pathways and underpinning processes. However, this thesis does acknowledge a regularity in the demographic cause of population decline that may lend support to the development of an overarching theory. The prevalence of a depopulating effect from natural change, i.e., mortality outweighing fertility, is evidenced to be ubiquitous across all causes of decline clusters. In the same analysis, the significance of net-migration in determining the shapes of population change trajectories is also demonstrated. This is due to the marginal disparity between fertility and mortality creating a moderate negative natural change effect. Taken together, these findings highlight the importance of all demographic drivers in contributing to population decline. Low fertility is too often cited as the sole driver of depopulation, though the conclusions of this thesis should help to refine this oversimplified narrative.

The final contribution of this thesis relates to the development of public policy surrounding the management of population decline in two key areas. Population decline is already being considered at European governance level and its importance will soon be elevated as it affects a greater proportion of European territory and its consequences become apparent. Firstly, the granular forecast of 2030 population size provided in Chapter 4 has highlighted the areas that will be most impacted by population decline and should be considered as priority areas for policy intervention. The forecast shows that many municipalities will begin to experience population loss in the next few years, but also others that will observe a depopulation at a greater rate than previously. Important distinctions can be made between areas, such as this, which can assist the development of targeted policy.

Secondly, the analyses in Chapters 2 and 3, which evidence distinctive signatures of depopulation in terms of demographic cause and trajectory, could be beneficial for the development of tailored policy initiatives. In the development of responses to population decline, the specific pathway and underpinning demographic drivers should be explicitly considered, as they dictate the way in which depopulation is experienced and its consequences. At the very least, the conclusions of this thesis suggest that a blanket solution to population decline should not be desired as its inability to account for the nuanced experiences of each affected area would likely render it ineffective. However, while all European areas may benefit from increased birth rates, at least with regards to avoiding or mitigating population decline, persistently high levels of fertility have proven very difficult to accomplish in the past and will most likely be difficult to maintain if achieved. A more feasible solution likely lies with the promotion of in-migration outcomes and the retention of current populations. Particularly promising, in this regard, is the shift towards remote and hybrid employment which has enabled people to live further away from their workplace as physical commuting is replaced by virtual connections. In part, this has been facilitated by the transition to remote and hybrid working during the COVID-19 outbreak. This shift should be leveraged to steam the ongoing trend of hybrid working. To facilitate potential migration gains from this, places should prioritise the development of technological infrastructures, particularly internet connectivity as well as transport accessibility and infrastructure to access major employment areas.

With regards to contributions to policy, this thesis primarily focuses on avenues for the mitigation of population decline through promoting certain demographic outcomes, owing to the analysis of demographic causes of depopulation. Here, successful policy would result in increased fertility rates, the retention of populations that are susceptible to migrating, and the attraction of migrants. To achieve this is no easy feat, however, and relies on complementary policy initiatives from both national and local governments. Regarding the promotion of fertility outcomes, governments should develop initiatives that address the underlying barriers of family formation inherent in modern day societies. These exist largely in the form of economic opportunity costs and individual aspirations (McDonald 2006). Successful policies across Europe have established a confidence that family formation will not infringe on these principals, often through adopting a service-oriented approach that facilitates a reconciliation between work and family life through emphasising the provision of childcare (Neyer & Anderssen 2008, Sobotka 2019). Regarding the retention and attraction of migrants, successful policy likely lies with the development of dynamic economic opportunity. This too is no easy feat, given the competition amongst areas to attract businesses and industry. Certain areas are further disadvantaged by geographical constraints such as remoteness. An initial step in fostering economic opportunity then lies improving physical and technological connectivity by developing relevant infrastructures. For example, in the face of the remote-working movement, internet connectivity is essential and initiatives similar to the Digital Spain 2025 Agenda should be developed.

Another policy focus exists in the management of ongoing population loss, and is applicable to countries and areas where population decline is deep-rooted, and its consequences are presenting challenges. Here, attempts to increase fertility or attract migrants are futile, and so an alternative policy avenue should be developed. A critical economic challenge that is likely to be at the forefront of such areas is the diminishing size of the workforce and taxbase. Such a challenge will necessitate a social or technological reform to ensure continued productivity and economic growth, and the Japanese case can serve as an inspiration for appropriate policy initiatives (see Clark et al., 2010). Such policy developments should aim to galvanise the available workforce and reduce the size of economically inactive populations, as well as fostering technological solutions that increase economic efficiency and productivity.

5.4 Limitations

This study would be incomplete without a recognition of the various limitations that influenced the overall scope of this study. Though these have already been acknowledged within analytical chapters above, they should be summarised here. First, the production of area classifications is subjective by nature. They involve numerous decisions pertaining to the clustering algorithm of choice, the number of variables considered, and the optimal number of clusters that best captures homogeneity within groups and heterogeneity between them, all of which are critical to the resulting output. In this thesis, in Chapters 2 and 3, I present area classifications of population decline trajectories and their underlying demographic causes. To ensure a thorough assessment of their robustness, I aimed to describe the decision-making process with transparency and outlined the relevant literature and statistical tests that reinforced my decisions. Another source of subjectivity within the area classification process stems from the naming of individual clusters. In both instances, in population decline trajectory and cause of decline classifications, the groups are named after the temporal processes they depict. These names were decided upon in a collaborative effort with my primary supervisor, so as to ensure they are appropriately titled, but it would be difficult to defend other names that would be as equally appropriate.

Secondly, the analyses presented in this thesis were restricted by the availability of demographic data. This research placed a dual focus on the temporal processes of contemporary population declines and their spatial regularities across expansive geographic territory, and thus required extensive data. Specifically, annual counts of population size and demographic events were needed, alongside relevant covariate data. The availability of such data restricted multiple aspects of this thesis, including its temporal and spatial scope. Demographic data prior to the year 2000 were not consistently available for all countries, and so the onset of population decline was not captured for many areas, particularly forerunning regions in eastern Europe. Owing to the lag between data collection and publication, this thesis does not consider population change outcomes beyond the year 2020. Since this period, a series of unforeseen global, and European, developments have occurred that have had a profound impact on European population dynamics, namely the COVID-19 pandemic and the Russo-Ukrainian war.

Requisite demographic data was also not available at coarser geographic scales, meaning that small-scale instances of depopulation were not captured if nested within a wider context of population growth (Franklin 2019). Despite this, the analyses produced in this thesis remain novel, and respond to a pressing need to understand the temporal and spatial dimensions of European population decline. Furthermore, the expansive geographic scope of this thesis required data to be sourced from individual national statistics institutions. Owing to country specificities in designating administrative divisions, the sub-national units studied in Chapters 2 and 3 are inconsistent in size between countries. This follows a relatively consistent geographic pattern, with areas in western Europe typically comprising a singular urban agglomeration, whereas in the east these boundaries are larger and may consist of multiple cities in a broader regional unit.

The final data limitation relates only to Chapter 3, where area characteristics are considered as covariates to population decline processes. Here, data for a range of variables are collated, though they are cross sectional, due to the infrequent manner in which they are collected. The characteristics of areas are understood to change as areas endure population decline (Franklin 2020). While these changes were not considered, I would also argue that these types of structure changes in places take a long time to realise. This however does not mean that they did not occur in localised areas of Europe.

A final limitation exists in the machine learning population forecasting model developed in Chapter 4. The model represents an improvement over existing LSTM approaches, in terms of average forecast accuracy, and further developments could help increase its predictive capabilities. In theory, additional data incorporated into the LSTM model would allow capturing more complex and multidimensional relationships. Population change outcomes are influenced by a range of direct and indirect factors, though these are not explicitly considered within the existing model. Particularly beneficial would be the inclusion of demographic events, namely fertility, mortality, and migration, as well as data that capture the structure of populations. Beyond increasing the amount of data, other improvements could exist in the form of architectural design and further hyperparameter optimisation. In Chapter 4, I design and compare the performance of multiple LSTM models distinguished by architectural differences, namely the number of layers, though the existing approach is not exhaustive. This is largely due to the novelty of the forecasting approach, with the optimal model yet to be definitely realised. Further research is needed to uncover the best architecture and implementation approach for population forecasting, as described below.

5.5 Future research

The findings of this thesis can aid in the development of numerous future research efforts relating to the spatio-temporal analysis of population dynamics, contemporary population decline, and population forecasting. Firstly, the methodological framework presented in Chapter 2 demonstrates the potential of sequence analysis as a comparative analytical tool for conceptualising longitudinal demographic change. Though population decline was the explicit focus in this thesis, the method could be applied to understand differential population growth pathways, or other aspects of demographic change.

Similarly, the analysis presented in Chapter 2 should also be extended to consider the development of population change outcomes initiated by the COVID-19 pandemic. Given its profound disruption to regular fertility (Sobotka et al., 2022), mortality (Wang et al., 2022), and migration (González-Leonardo et al., 2022) occurrences, COVID-19 represents a profound alteration to population change dynamics. However, this is yet to be fully understood, particularly within the context of European population decline.

Another way in which the analysis of Chapter 2 could be extended is to explicitly consider the changing demographic characteristics of areas as they undergo population decline. As a demographic process, depopulation is about more than the reduction of population size. It also concerns the changing compositions of populations which bears implications in itself (Franklin 2020, Bock & Haartsen 2021). Chapter 2 focused on identifying trajectories of population decline and the characteristics of areas associated with these trajectories. However, data limitations prevented an investigation into how these characteristics change alongside depopulation. Building upon this analysis, and that of Franklin (2019), future work should consider how the demographic characteristics of areas have evolved as places endure a process of population loss. Such research would provide an insight into the demographic consequences of depopulation, with changing age structures and population compositions capturing the changing needs of populations.

Secondly, future work should consider the empirical analyses presented in this thesis in an effort to develop policy initiatives for the management of population decline. This thesis has provided a unique contribution to existing knowledge regarding depopulation processes, including how different kinds of areas experience differential population decline trajectories and demographic causes. From this, it is clear that responses should be tailored to the specific experiences of individual areas. A starting point ought to consider the wide-ranging implications of future population decline, and how specific trajectories and demographic causes will impact the rate and dimensionality of its realisation. For example, a population decline driven mainly by low fertility will command a different set of challenges than depopulations fuelled by out-migration. Explicit considerations of these dynamics are imperative to developing an effective strategy to manage future population loss.

Finally, further efforts are required to improve the LSTM population forecasting models developed in chapter 4 of this thesis. Long Short-Term Models represent the forefront of machine learning based time series forecasting models. Though their predictive capabilities with regards to population forecasting are documented, and improved upon in this thesis, further research is required to fully harness their potential. From the few relevant applications thus far, it remains unclear of the optimal model architecture, specification, data inputs, and implementation approach that produces the most accurate population forecasts on a consistent and reproducible basis. No specific model may produce optimal forecasts for each area, or groups of areas, and rather individual models need to be finely tuned for the specific application, further complicating this process. It therefore should be considered a priority for researchers to conduct an exhaustive study that tests different combinations of LSTM parameters in search of an optimal model design for population forecasting.

Similarly, another area of future development relates to the varied application of LSTM models for population forecasting. It could be beneficial to implement LSTM forecasts of population, or individual demographic components, in an integrated approach that combines traditional methods, such as the cohort component model. In particular, LSTM models could generate forecasts of net-migration or directional migration rates, which are typically assumed to remain constant or converge to zero, however unrealistic that may be. This would address a considerable limitation of existing approaches, and represent an enhanced estimation of future population outcomes through leveraging the strengths of both approaches. The potential of LSTM models within demographic forecasting is clear but yet to be fully realised, and these approaches could represent a considerable breakthrough to forecast demographic changes and thus the future of global population at high spatial resolutions than what has been possible so far.

Appendices

A

Chapter 2 Appendix

A.1 – Data Breakdown

Country	Data Source	Areas	Areas in Decline	Incomplete Time Series	Removed from Analysis
Albania	National Statistics	12	10	10	
Andorra	National Statistics	7	1		
Austria	Eurostat	35	11	11	
Belgium	Eurostat	44	0		
Bulgaria	Eurostat	28	26		
Belarus	National Statistics	7	6	6	
Switzerland	Eurostat	26	0		
Cyprus	National Statistics	1	0		
Czech Rep	National Statistics	76	37		
Germany	Eurostat	401	192	27	25
Denmark	National Statistics	99	23		
Estonia	Eurostat	5	4		
Greece	Eurostat	52	21		
Spain	Eurostat	59	13		
Finland	Eurostat	19	9		
France	Eurostat	99	13		
Croatia	Eurostat	21	15	15	
Hungary	Eurostat	20	18		
Ireland	Eurostat	8	0		
Iceland	National Statistics	8	2		
Italy	Eurostat	110	30	30	
Liechtenstein	Eurostat	1	0		
Lithuania	Eurostat	10	10		
Luxembourg	Eurostat	1	0		
Latvia	Eurostat	6	5	5	
Montenegro	Eurostat	1	0		
North Macedonia	Eurostat	8	4		
Moldova	National Statistics	35	32	31	
Malta	Eurostat	2	0		
Netherlands	Eurostat	40	5	5	
Norway	National Statistics	19	0		
Poland	Eurostat	73	48	15	15
Portugal	Eurostat	25	16		
Romania	Eurostat	42	40		
Serbia	National Statistics	25	22		
Russia	National Statistics	83	58		
Sweden	Eurostat	21	3		
Slovenia	National Statistics	12	4		
Slovakia	Eurostat	8	4	4	
San Marino	UN	1	0		
Turkey	Eurostat	81	12	12	
UK	National Statistics	379	18		
Ukraine	National Statistics	25	24		
		2035	736	171	40

Table A.1 – Data Source, Count of Areas, Count of Areas in Decline, Areas with Incomplete Time Series and Areas Removed From Analysis for Each European Country

Our spatial panel dataset comprises annual population estimates for a total of 2,035 areas across 43 European territories, of which 736 areas that experienced a population decline was the focus. The data was primarily sourced from Eurostat, however for non-EU countries data was collected from the national statistics agency of that country. A significant proportion of the 736 decline areas had an incomplete time series on the basis of our period of enquiry preceding data collection. In total 171 of the 736 areas of decline were affected by this. However, just 40 of these areas were missing data for a period greater than two years and were removed from our analysis as a result. These areas are located exclusively in Germany and Poland. Our analysis therefore concerns the population decline trajectories of 696 European sub-national areas.

A.2. Empirical cluster solutions test

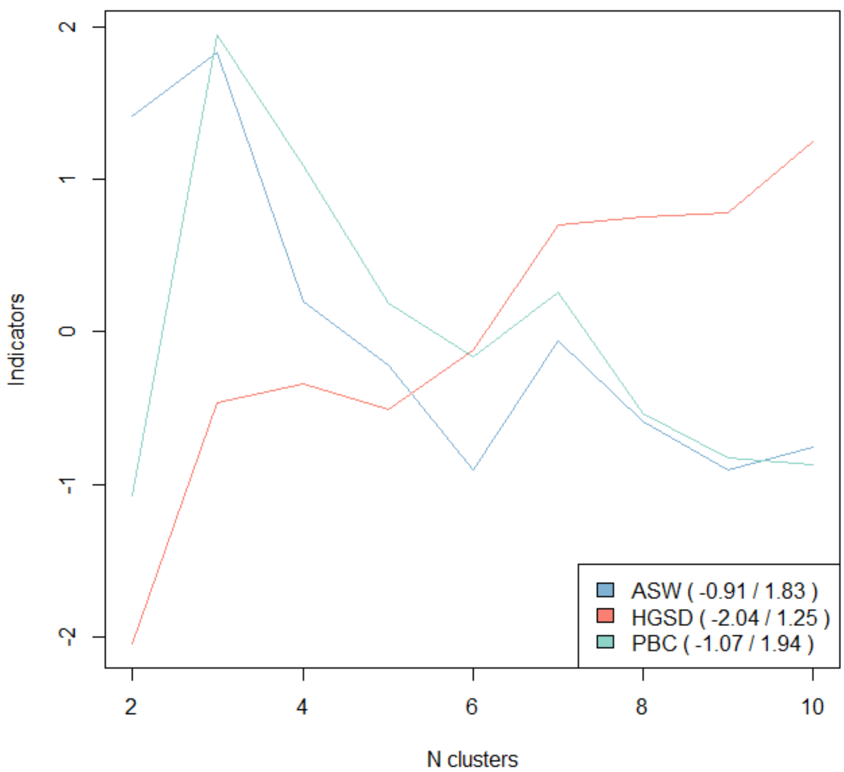


Figure A.1 – Empirical Tests of Cluster Solutions Using the WeightedCluster Package in R

To assess the most appropriate cluster solution for our typology of European population decline, we ran a range of empirical tests using the WeightedCluster package in R. Tests include the Average Silhouette Width (ASW), Hubert's Somers' D (HGSD) and Point Biserial Correlation (PBC). The figure reveals that a two-cluster solution is most appropriate, however for the purpose of producing a typology, this would not suffice since population decline trajectories of interest are not acknowledged. Considering this, a seven-cluster solution was selected in which the empirical tests are satisfied and a range of trajectories are represented

A.3 Cluster distributions by area classification and population size category

	Urban					Intermediate					Rural				
Trajectory Cluster	**X-Large**	**Large**	**Mid-Sized**	**Small**	**Total**	**X-Large**	**Large**	**Mid-Sized**	**Small**	**Total**	**X-Large**	**Large**	**Mid-Sized**	**Small**	**Total**
Persistent Decline	-	1	-	1	**2 (2.27%)**	1	1	4	30	**36 (11.73%)**	-	-	3	28	**31 (10.30%)**
Accelerating Decline	-	1	1	1	**3 (3.41%)**	-	1	5	5	**11 (3.58%)**	-	-	5	27	**32 (10.63%)**
Diminishing Decline	3	3	1	-	**7 (7.95%)**	19	8	3	11	**41 (13.36%)**	-	-	1	8	**9 (2.99%)**
Persistent Mod Decline	3	6	7	5	**21 (23.86%)**	17	15	10	26	**68 (22.15%)**	1	3	21	66	**91 (30.23%)**
Accelerating Mod Decline	1	2	2	3	**8 (9.09%)**	1	7	16	15	**39 (12.70%)**	-	6	15	39	**60 (19.93%)**
Diminishing Mod Decline	5	6	4	9	**24 (27.27%)**	13	11	7	25	**56 (18.24%)**	3	4	4	15	**26 (8.64%)**
Temporary Decline	1	2	8	12	**23 (26.14%)**	-	4	12	40	**56 (18.24%)**	-	-	-	52	**52 (17.28%)**
In Decline	13	21	23	31	**88**	51	47	57	152	**307**	4	13	49	235	**301**
All Areas	86	78	137	217	**518**	86	130	184	445	**845**	6	38	111	518	**673**
In Decline (%)	16.46	26.92	16.79	14.29	**16.99**	60.00	36.15	30.98	34.16	**36.33**	66.67	34.21	44.14	45.37	**44.73**

Table A.2 – Distribution of Trajectory Clusters by Area Classification and Size

We classify our sub-national areas according to population size and settlement type in a rural-urban typology. This is used to understand the composition of our trajectory clusters and to explore the relationship between area characteristics and trajectories of population decline. This table depicts the composition of each trajectory cluster by area size

B

Chapter 3 Appendix

B.1 – Data source by country

Country	Variable				
	Demographic Counts	**Population Over 65**	**Foreign Born Population**	**Unemployment Rate**	**Rural-Urban Typology**
Albania	National Statistics	National Statistics	National Statistics	National Statistics	Eurostat
Andorra	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
Austria	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Belarus	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
Belgium	Eurostat	National Statistics	National Statistics	Eurostat	Eurostat
Bulgaria	National Statistics	Eurostat	National Statistics	Eurostat	Eurostat
Croatia	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Cyprus	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Czechia	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
Denmark	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
Estonia	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Finland	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
France	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Germany	National Statistics	Eurostat	National Statistics	Eurostat	Eurostat
Greece	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Hungary	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Iceland	National Statistics	Eurostat	National Statistics	National Statistics	National Statistics
Ireland	Eurostat	National Statistics	National Statistics	Eurostat	Eurostat
Italy	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Latvia	National Statistics	Eurostat	National Statistics	Eurostat	Eurostat
Liechtenstein	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Lithuania	Eurostat	Eurostat	National Statistics	National Statistics	Eurostat
Luxembourg	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Malta	Eurostat	Eurostat	-	Eurostat	Eurostat
Moldova	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
Montenegro	Eurostat	Eurostat	-	Eurostat	Eurostat
Netherlands	National Statistics	Eurostat	National Statistics	Eurostat	Eurostat
North Macedonia	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Norway	National Statistics	Eurostat	National Statistics	National Statistics	Eurostat
Poland	National Statistics	National Statistics	National Statistics	Eurostat	Eurostat
Portugal	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Romania	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
Russia	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
San Marino	National Statistics	Eurostat	-	-	National Statistics
Serbia	National Statistics	National Statistics	National Statistics	National Statistics	Eurostat
Slovakia	National Statistics	Eurostat	National Statistics	National Statistics	Eurostat
Slovenia	National Statistics	Eurostat	National Statistics	Eurostat	Eurostat
Spain	Eurostat	Eurostat	National Statistics	National Statistics	Eurostat
Sweden	Eurostat	Eurostat	National Statistics	National Statistics	Eurostat
Switzerland	Eurostat	Eurostat	National Statistics	National Statistics	Eurostat
Türkiye	Eurostat	Eurostat	National Statistics	Eurostat	Eurostat
UK	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics
Ukraine	National Statistics	National Statistics	National Statistics	National Statistics	National Statistics

Table B.1. Data Source by Country and Variable. Demographic Counts Include Annual Population Estimates, Births, Deaths, and Net-Migrations.

Our spatial panel dataset consists of annual population estimates and cross-sectional covariate data for a total of 2,035 areas across 43 European territories. However, as we place an explicit interest on studying population decline, we include in our analysis a total of 732 areas that are characterised by their absolute population loss from 2000 to 2018 (see Appendix 2 for included data by country). These data were sourced from Eurostat, and national statistics institutes. Eurostat data comprises of European Union member states only, though national statistics data is used in some instances where Eurostat data was incomplete.

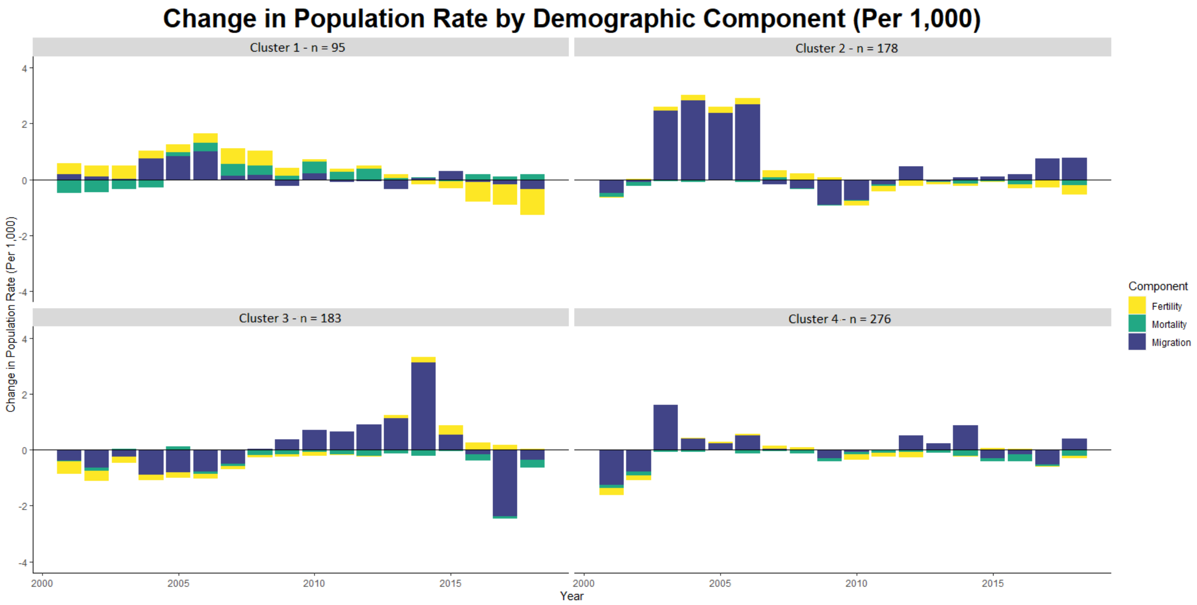
B.2 – Assessment of data completeness by country

Country	Country	n	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
AL	Albania	10	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100
AN	Andorra	1	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
AT	Austria	11	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
BG	Bulgaria	26	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
BR	Belarus	6	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
CZ	Czechia	37	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
DE	Germany	193	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
DK	Denmark	23	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
EE	Estonia	4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
EL	Greece	21	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
ES	Spain	14	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
FI	Finland	9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
FR	France	13	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
HR	Croatia	15	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
HU	Hungary	18	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
IS	Iceland	2	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
IT	Italy	30	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
LT	Lithuania	10	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
LV	Latvia	5	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
MK	North Macedonia	4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
ML	Moldova	32	3.13	3.13	6.25	6.25	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
NL	Netherlands	8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
PL	Poland	39	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
PT	Portugal	16	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
RO	Romania	40	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
RS	Serbia	22	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100
RU	Russia	58	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
SE	Sweden	3	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
SI	Slovenia	4	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
SK	Slovakia	4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
TR	Türkiye	12	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100
UK	United Kingdom	18	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
UN	Ukraine	24	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table B.2 – Proportion of Complete Annual Demographic Data by Country. Completeness of data is represented by a percentage scale, with 0 indicating missing data for all sub-national areas and 100 indicating complete data.

Despite making use of Eurostat and National Statistics data, we are still affected by missing data for certain European countries. Of the 732 areas included in our analysis, 63.3% are represented by complete demographic time series data. However, 37.7% are missing data for a demographic component, either fertility, mortality, or migration. Appendix 2 details the proportion of complete data by country. Imputation was performed by restructuring the demographic balancing equation, and has reduced the impact of missing data somewhat.

B.3 – Cluster sensitivity analysis



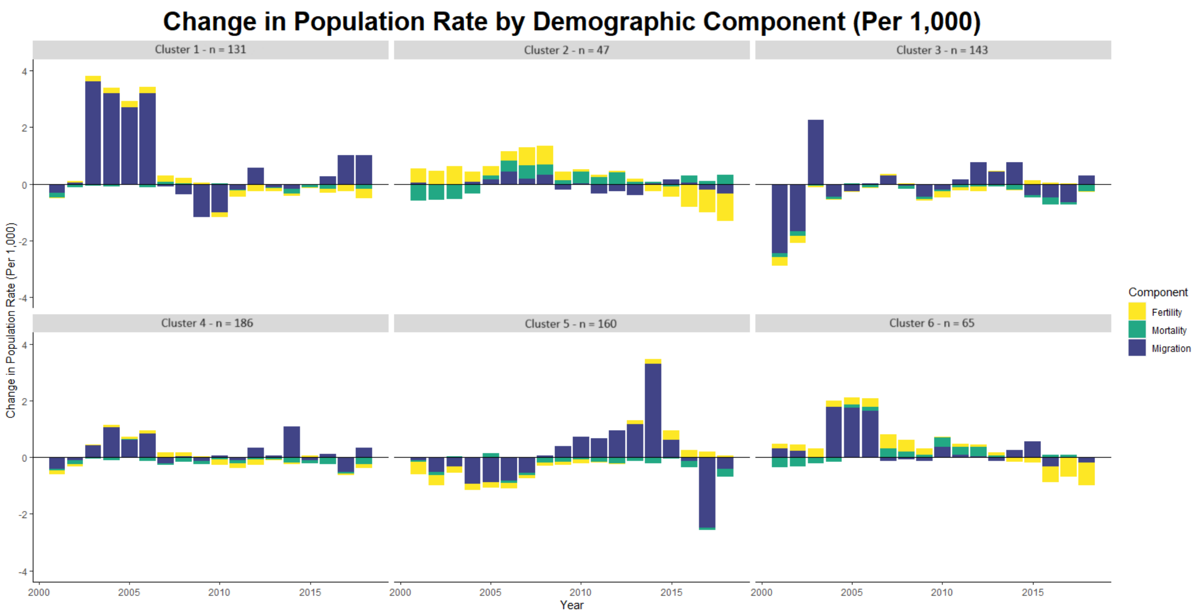


Figure B.1 – Sensitivity Analysis. Results of k-medoid Clustering Given k = 4 and k = 6

To verify our k=5 cluster solution, we explore the results of a k-medoid clustering algorithm under differing values of k. Here we present the results from a k = 4 and a k = 6 solutions. We observe the grouping of two distinct processes under a k = 4 solution, and the splitting of a homogeneous process under a k = 6 solution. The latter results in two very similar population decline processes, distinguished only by a greater contribution to population growth by positive net-migration from the period 2005-2008 (clusters 2 and 6 above). These alternative cluster solutions provide credence to our k = 5 solution, as each cluster depicts a distinct set of demographic processes underpinning population decline.

Bibliography

Aassve, A., Cavalli, N., Mencarini, L., Plach, S., & Sanders, S. (2021). Early assessment of the relationship between the COVID-19 pandemic and births in high-income countries. Proceedings of the National Academy of Sciences, 118(36), e2105709118.

Abbott, A., & Tsay, A. (2000). Sequence analysis and optimal matching methods in sociology: Review and prospect. Sociological methods & research, 29(1), 3-33.

Abernethy, V. D. (2001). Comment on Bermingham's summary of the UN's year 2000 Replacement Migration, is it a solution to declining population and aging?. *Population and Environment*, *22*, 365-375.

Agarap, A. F. (2019). *Deep Learning using Rectified Linear Units (ReLU)* (arXiv:1803.08375). arXiv. http://arxiv.org/abs/1803.08375

Aldridge, R. W., Nellums, L. B., Bartlett, S., Barr, A. L., Patel, P., Burns, R., ... & Abubakar, I. (2018). Global patterns of mortality in international migrants: a systematic review and meta-analysis. *The Lancet*, 392(10164), 2553-2566. https://doi.org/10.1016/S0140-6736(18)32781-8

Antipova, E., & Fakeyeva, L. (2012). Demographic processes in rural areas of Belarus: geographical structure and spatial dynamics. Bulletin of Geography. Socio-economic series, (17), 5-12.

Aydın, Y. (2016). The Germany-Turkey Migration Corridor. *Refitting Policies for a transnational age,[online]*.

Backman, M., Lopez, E., & Rowe, F. (2021). The occupational trajectories and outcomes of forced migrants in Sweden. Entrepreneurship, employment or persistent inactivity? Small Business Economics, 56(3), 963-983.

Bara, A., Di Bartolomeo, A., Brunarska, Z., Makaryan, S., Mananashvili, S., & Weinar, A. (Eds.). (2013). Regional migration report: Eastern Europe. Publications Office.

Batunova, E., & Perucca, G. (2020). Population shrinkage and economic growth in Russian regions 1998–2012. *Regional Science Policy & Practice*, *12*(4), 595-609.

Beaujouan, E. (2020). Latest-Late Fertility? Decline and Resurgence of Late Parenthood Across the Low-Fertility Countries. *Population and Development Review*, *46*(2), 219–247. https://doi.org/10.1111/padr.12334

Beck-Gernsheim, E., & Beck, U. (2001). Individualization: Institutionalized individualism and its social and political consequences. *Individualization*, 1-222.

Bell, M., Charles-Edwards, E., Kupiszewska, D., Kupiszewski, M., Stillwell, J., & Zhu, Y. (2014). Internal Migration Data Around the World: Assessing Contemporary Practice. *Population, Space and Place*, *21*(1), 1–17. https://doi.org/10.1002/psp.1848

Bellman, B., Spielman, S. E., & Franklin, R. S. (2018). Local population change and variations in racial integration in the United States, 2000–2010. International regional science review, 41(2), 233-255.

Bloom, D. E., Canning, D., & Fink, G. (2010). Implications of population ageing for economic growth. Oxford review of economic policy, 26(4), 583-612.

Block, B. A., & Haartsen, T. (2021). Who is afraid of population decline? The struggle of keeping rural depopulation on the Dutch agenda. *Journal of depopulation and rural development studies*, (33), 35-56.

Bongaarts, J. (1978). A framework for analyzing the proximate determinants of fertility. *Population and development review*, 105-132.

Bongaarts, J. (2009). Human population growth and the demographic transition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1532), 2985-2990.

Boserup, E. (1965). *The conditions of agricultural growth: The economics of agrarian change under population pressure*. Routledge.

Bremberg, S. (2020). Rural-urban mortality inequalities in four Nordic welfare states. *Scandinavian Journal of Public Health*, *48*(8), 791–793. https://doi.org/10.1177/1403494820921684

Buelens, M. (2021). Subnational spatial variations of fertility timing in Europe since 1990. Cybergeo: *European Journal of Geograpy.*

Campisi, N., Kulu, H., Mikolai, J., Klüsener, S., & Myrskylä, M. (2020). Spatial variation in fertility across Europe: Patterns and determinants. *Population, Space and Place*, *26*(4), e2308. https://doi.org/10.1002/psp.2308

Canudas-Romo, V. 2003. Decomposition Methods in Demography. Amsterdam: Rozenberg Publishers

Carbonaro, G., Leanza, E., McCann, P., & Medda, F. (2018). Demographic Decline, Population Aging, and Modern Financial Approaches to Urban Policy. *International Regional Science Review*, *41*(2), 210–232. https://doi.org/10.1177/0160017616675916

Charrad, M., Ghazzali, N., Boiteau, V., & Niknafs, A. (2014). NbClust: An *R* Package for Determining the Relevant Number of Clusters in a Data Set. *Journal of Statistical Software*, *61*(6). https://doi.org/10.18637/jss.v061.i06

Cheng, X., Yang, Y., Schwebel, D. C., Liu, Z., Li, L., Cheng, P., Ning, P., & Hu, G. (2020). Population ageing and mortality during 1990–2017: A global decomposition analysis. *PLOS Medicine*, *17*(6), e1003138. https://doi.org/10.1371/journal.pmed.1003138

Chollet, F., & Allaire, J. J. (2018). Deep Learning with R Manning Publications Co. Shelter Island, NY.

Čipin, I., & Ilieva, N. (2017). Coping with demographic decline in Croatia and Bulgaria. *Friedrich Ebert Stiftung-Croatia*.

Clark, R. L., Ogawa, N., Kondo, M., & Matsukura, R. (2010). Population decline, labor force stability, and the future of the Japanese economy. *European Journal of Population/Revue européenne de Démographie*, *26*, 207-227.

Clements, M. B. J., Dybczak, M. K., Gaspar, V., Gupta, M. S., & Soto, M. (2015). *The fiscal consequences of shrinking populations.* International Monetary Fund.

Coleman, D., & Rowthorn, R. (2011). Who's afraid of population decline? A critical examination of its consequences. *Population and Development Review*, 37(s1):217-248. https://doi.org/10.1111/j.1728-4457.2011.00385.x

Cooke, L. P. (2009). Gender equity and fertility in Italy and Spain. *Journal of social policy*, 38(1), 123-140. https://doi.org/10.1017/S0047279408002584

Couch, C., Karecha, J., Nuissl, H., & Rink, D. (2005). Decline and sprawl: an evolving type of urban development–observed in Liverpool and Leipzig. *European planning studies,* 13(1), 117-136.

Cutler, D., Deaton, A., & Lleras-Muney, A. (2006). The determinants of mortality. *Journal of economic perspectives*, 20(3), 97-120. https://doi.org/10.1257/jep.20.3.97

Dax, T., & Fischer, M. (2018). An alternative policy approach to rural development in regions facing population decline. European Planning Studies, 26(2), 297-315.

Delmelle, E. C. (2016). Mapping the DNA of urban neighborhoods: Clustering longitudinal sequences of neighborhood socioeconomic change. Annals of the American Association of Geographers, 106(1), 36-56.

Denisenko, M., Mkrtchyan, N., Chudinovskikh, O. (2020). Permanent Migration in the Post-Soviet Countries. In: Denisenko, M., Strozza, S., Light, M. (eds) Migration from the Newly Independent States. Societies and Political Orders in Transition. Springer, Cham. https://doi.org/10.1007/978-3-030-36075-7_3

Dijkstra, L. and Poelman, H. (2012). Cities in Europe: the new OECD-EC definition. Regional focus, 1(2012), pp.1-13.

Dilley, L., Gkartzios, M. and Odagiri, T., 2022. Developing counterurbanisation: Making sense of rural mobility and governance in Japan. *Habitat International,* 125, p.102595. https://doi.org/10.1016/j.habitatint.2022.102595

Doignon, Y., Oliveau, S., & Blöss-Widmer, I. (2016). L'Europe méridionale depuis 20 ans: dépeuplement, dépopulation et renouveau démographique. Espace populations sociétés. Space populations societies, (2015/3-2016/1).

Domnich, A., Panatto, D., Gasparini, R., & Amicizia, D. (2012). The "healthy immigrant" effect: does it exist in Europe today?. *Italian Journal of Public Health*, 9(3). https://doi.org/10.2427/7532

Dumitrache, L., Zamfir, D., Nae, M., Simion, G., & Stoica, I. V. (2016). The Urban Nexus: Contradictions and Dilemmas of (Post) Communist (Sub) Urbanization in Romania. Human Geographies--Journal of Studies & Research in Human Geography, 10(1).

Ebeling, M., Rau, R., Sander, N., Kibele, E., & Klüsener, S. (2022). Urban–rural disparities in old-age mortality vary systematically with age: Evidence from Germany and England & Wales. *Public Health*, *205*, 102–109. https://doi.org/10.1016/j.puhe.2022.01.023

Elshof, H., Van Wissen, L., & Mulder, C. H. (2014). The self-reinforcing effects of population decline: An analysis of differences in moving behaviour between rural neighbourhoods with declining and stable populations. *Journal of Rural Studies*, *36*, 285–299. https://doi.org/10.1016/j.jrurstud.2014.09.006

ESPON., (2017). Shrinking rural regions in Europe Towards smart and innovative approaches to regional development challenges in depopulating rural regions. Policiy brief, Espon Egtc, Bruxelles.

European Parliament, Committee on Regional Development. (2021). Report on Reversing Demographic Trends in EU Regions Using Cohesion Policy Instruments (2020/2039(INI)). https://www.europarl.europa.eu/doceo/document/A-9-2021-0061_EN.html#:~:text=Urges%20Member%20States%20and%20regional,35.

Eurostat. (2013). Urban-Rural typology, http://ec.europa.eu/ eurostat/web/rural-development/methodology.

Eurostat. (2020a). Population statistics at regional level. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_statistics_at_regional_level#Population_change

Eurostat. (2020b). Population change - Demographic balance and crude rates at regional level (NUTS 3)(demo_r_gind3). Available: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_r_gind3&lang=en

Eurostat. (2022). Migration and migrant population statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Migration_and_migrant_population_statistics#Migrant_population:_23.8_million_non-EU_citizens_living_in_the_EU_on_1_January_2022

Eurostat. (2023). Population on 1st January by age, sex and type of projection, proj_23np. [Dataset]. https://ec.europa.eu/eurostat/databrowser/view/proj_23np/default/table?lang=en

Feng, J., Li, Y., Zhang, C., Sun, F., Meng, F., Guo, A., & Jin, D. (2018). DeepMove: Predicting Human Mobility with Attentional Recurrent Networks. *Proceedings of the 2018 World Wide Web Conference on World Wide Web - WWW '18*, 1459–1468. https://doi.org/10.1145/3178876.3186058

Fihel, A., Janicka, A., & Kloc-Nowak, W. (2018). The direct and indirect impact of international migration on the population ageing process: A formal analysis and its application to Poland. *Demographic Research*, *38*, 1303–1338. https://doi.org/10.4054/DemRes.2018.38.43

Fihel, A., & Okólski, M. (2019). Population decline in formerly communist countries of the European Union. *Population & Societies* , (6), 1-4. https://doi.org/10.3917/popsoc.567.0001

Fisher, K., & Robinson, J. (2011). Daily Life in 23 Countries. *Social Indicators Research,* 101(2), 295–304. https://doi.org/10.1007/s11205-010-9650-3

Fiori, F., Graham, E., & Feng, Z. (2014). Geographical variations in fertility and transition to second and third birth in Britain. *Advances in life course research*, 21, 149-167.

Folorunso, O., Akinwale, A. T., Asiribo, O. E., & Adeyemo, T. A. (2010). Population prediction using artificial neural network. *African Journal of Mathematics and Computer Science Research*, 3(8), 155-162.

Franklin, R. S., van Leeuwen, E. S., & Paez, A. (2018). Transportation where people leave: An introduction. In R. S. Franklin, E. S. van Leeuwen, & A. Paez (Eds.), Population loss: The role of transportation and other issues (Vol. 2, pp. 1–14). Academic Press. https://doi.org/10.1016/bs.atpp.2018.09.008

Franklin, R. S. (2019). The demographic burden of population loss in US cities, 2000–2010. *Journal of Geographical Systems*, 23(2), 209–230. https://doi.org/10.1007/s10109-019-00303-4

Franklin, R. S. (2020). I come to bury (population) growth, not to praise it. *Spatial Economic Analysis*, *15*(4), 359–373. https://doi.org/10.1080/17421772.2020.1802056

Friedrichs, J. (1993). A theory of urban decline: economy, demography and political elites. *Urban Studies*, *30*(6), 907-917.

Gabadinho, A., G. Ritschard, N.S. Muller and M. Studer (2011). “Analyzing and Visualizing State Sequences in R with TraMineR.” Journal of Statistical Software, 40(4), 1–37. DOI 10.18637/jss.v040.i04.

Galjaard, R., Van Wissen, L., & Van Dam, K. (2012). European regional population decline and policy responses: Three case studies. *Built Environment*, *38*(2), 293-302.

Geyer, H. S., & Kontuly, T. (1993). A theoretical foundation for the concept of differential urbanization. International Regional Science Review, 15(2), 157-177.

Geyer, H. S., & Kontuly, T. (Eds.). (1996). Differential urbanization: integrating spatial models. John Wiley & Sons Incorporated.

Gnatiuk, O. (2017). Demographic dimension of suburbanization in Ukraine in the light of urban development theories. AUC Geographical, 52(2), 151-163.

Goldstein, J. R., & Cassidy, T. (2021, September). The formal demography of peak population. In *Ext. Abstract PAA. Available online at: https://www. oeaw. ac. at/fileadmin/subsites/Institute/VID/PDF/Conferences/2021/Slides/Keynote_ Goldstein_extended_abstract. pdf*

Gompertz, B. (1825). XXIV. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. In a letter to Francis Baily, Esq. FRS &c. *Philosophical transactions of the Royal Society of London*, (115), 513-583. http://www.jstor.org/stable/107756

González-Leonardo, M., López-Gay, A., Newsham, N., Recaño, J., & Rowe, F. (2022). Understanding patterns of internal migration during the COVID-19 pandemic in Spain. *Population, Space and Place*, 28(6), e2578. https://doi.org/10.1002/psp.2578

González-Leonardo, M., Newsham, N., & Rowe, F. (2023a). Understanding Population Decline Trajectories in Spain using Sequence Analysis. *Geographical Analysis.* https://doi.org/10.1111/gean.12357

González-Leonardo, M., Neville, R., Gil-Clavel, S., & Rowe, F. (2023b). Sensing population displacement from Ukraine using Facebook data: Identifying potential settlement areas within host countries.

Götmark, F., Cafaro, P., & O’Sullivan, J. (2018). Aging human populations: good for us, good for the earth. *Trends in ecology & evolution*, 33(11), 851-862.

Grigoriev, P., Shkolnikov, V., Andreev, E., Jasilionis, D., Jdanov, D., Meslé, F., & Vallin, J. (2010). Mortality in Belarus, Lithuania, and Russia: Divergence in Recent Trends and Possible Explanations. *European Journal of Population / Revue Européenne de Démographie*, *26*(3), 245–274. https://doi.org/10.1007/s10680-010-9210-1

Grossman, I., Bandara, K., Wilson, T., & Kirley, M. (2022). Can machine learning improve small area population forecasts? A forecast combination approach. *Computers, Environment and Urban Systems*, *95*, 101806. https://doi.org/10.1016/j.compenvurbsys.2022.101806

Grossman, I., Wilson, T., & Temple, J. (2023). Forecasting small area populations with long short-term memory networks. *Socio-Economic Planning Sciences*, *88*, 101658. https://doi.org/10.1016/j.seps.2023.101658

Gupta, P. D. (1993). Standardization and decomposition of rates: A user's manual (No. 186). US Department of Commerce, Economics and Statistics Administration, Bureau of the Census. C

Gutiérrez, E., Moral Benito, E., & Ramos, R. (2022). Population dynamics during the COVID-19 pandemic. *Documentos Ocasionales/Banco de España,* 2206.

Haase, Annegret, Dieter Rink, Katrin Grossmann, Matthias Bernt, and Vlad Mykhnenko. "Conceptualizing urban shrinkage." *Environment and Planning A* 46, no. 7 (2014): 1519-1534.

Haase, A., Bernt, M., Großmann, K., Mykhnenko, V., & Rink, D. (2016). Varieties of shrinkage in European cities. *European Urban and Regional Studies*, 23(1), 86–102. https://doi.org/10.1177/0969776413481985

Haga 1, K. (2015). Innovation and entrepreneurship in aging societies: theorical reflection and a case study from kamikatsu, Japan. *Journal of Innovation Economics & Management*, (3), 119-141.

Hall, R. (1993). Europe's changing population. *Geography*, 78, 3-15.

Han, M., Håkansson, J., & Rönnegård, L. (2016). To What Extent do Neighbouring Populations Affect Local Population Growth Over Time?. *Population, Space and Place*, 22(1), 68-83. https://doi.org/10.1002/psp.1864

Happ, C., & Greven, S. (2018). Multivariate functional principal component analysis for data observed on different (dimensional) domains. *Journal of the American Statistical Association*, 113(522), 649-659. https://doi.org/10.1080/01621459.2016.1273115

Happ-Kurz, C. (2020). Object-Oriented Software for Functional Data. *Journal of Statistical Software*, *93*(5). https://doi.org/10.18637/jss.v093.i05

Hartt, M. D. (2018). How cities shrink: Complex pathways to population decline. *Cities*, *75*, 38–49. https://doi.org/10.1016/j.cities.2016.12.005

Haub, C. (1994). Population change in the former Soviet Republics. *Population Bulletin*, 49(4), 1-52.

Hennig, C., & Liao, T. F. (2010). Comparing latent class and dissimilarity based clustering for mixed type variables with application to social stratification. Technical report. Hubert, L., Arabie, P., (1985). “Comparing Partitions.” Journal of Classification, 2, 193–218.

Hochreiter, S., & Schmidhuber, J. (1997). Long short-term memory. *Neural computation*, 9(8), 1735-1780.

Hoekveld, J. J. (2012). Time-space relations and the differences between shrinking regions. *Built Environment*, 38(2), 179-195. https://doi.org/10.2148/benv.38.2.179

Honjo, K., Gomi, K., Kanamori, Y., Takahashi, K., & Matsuhashi, K. (2021). Long-term projections of economic growth in the 47 prefectures of Japan: An application of Japan shared socioeconomic pathways. *Heliyon*, *7*(3).

Horiuchi, S. (1992). Stagnation in the Decline of the World Population Growth Rate During the 1980s. *Science*, *257*(5071), 761–765. https://doi.org/10.1126/science.1496396

Horiuchi, S. (1995). The Cohort Approach to Population Growth: A Retrospective Decomposition of Growth Rates for Sweden. *Population Studies*, *49*(1), 147–163.

Hospers, G. J., & Reverda, N. (2014). *Managing population decline in Europe's urban and rural areas*. Springer. https://doi.org/10.1080/00324720310001482906

Hrzic, R., Vogt, T., Janssen, F., & Brand, H. (2020). Mortality convergence in the enlarged European Union: A systematic literature review. *European Journal of Public Health*, *30*(6), 1108–1115. https://doi.org/10.1093/eurpub/ckaa038

Hudson, J. (1972). Geographical diffusion theory. Studies in Geography. Evanston, IL: Northwestern University, Deptartment of Geography.

Hyndman, R. J., & Booth, H. (2008). Stochastic population forecasts using functional data models for mortality, fertility and migration. *International Journal of Forecasting*, *24*(3), 323–342. https://doi.org/10.1016/j.ijforecast.2008.02.009

Inoue, T., Koike, S., Yamauchi, M., & Ishikawa, Y. (2022). Exploring the impact of depopulation on a country’s population geography: Lessons learned from Japan. *Population, Space and Place*, *28*(5), e2543. https://doi.org/10.1002/psp.2543

Janicki, W. (2017). Depopulation as an opportunity, not a threat to cities and regions: a paradigm change. *Europa XXI*, *32*, 89-96.

Janssen, F., Trias-Llimós, S., & Kunst, A. E. (2021). The combined impact of smoking, obesity and alcohol on life-expectancy trends in Europe. *International Journal of Epidemiology*, *50*(3), 931–941. https://doi.org/10.1093/ije/dyaa273

Johnson, K. M., Field, L. M., & Poston Jr, D. L. (2015). More deaths than births: Subnational natural decrease in Europe and the United States. Population and development review, 41(4), 651-680. https://doi.org/10.1111/j.1728-4457.2015.00089.x

Johnson, K. M., & Lichter, D. T. (2019). Rural Depopulation: Growth and Decline Processes over the Past Century. *Rural Sociology*, 84(1), 3–27. https://doi.org/10.1111/ruso.12266

Jung, P. H., & Song, J. (2022). Multivariate Neighborhood Trajectory Analysis: An Exploration of the Functional Data Analysis Approach. *Geographical Analysis*, *54*(4), 789–819. https://doi.org/10.1111/gean.12298

Kabisch, N., & Haase, D. (2011). Diversifying European agglomerations: Evidence of urban population trends for the 21st century. Population, space and place, 17(3), 236-253.

Karachurina, L., & Mkrtchyan, N. (2015). Population change in the regional centres and internal periphery of the regions in Russia, Ukraine and Belarus over the period of 1990-2000s. Bulletin of Geography. Socio-economic Series, (28), 91-111.

Karanikolos, M., Adany, R., & McKee, M. (2017). The epidemiological transition in Eastern and Western Europe: A historic natural experiment. *European Journal of Public Health*, *27*(suppl_4), 4–8. https://doi.org/10.1093/eurpub/ckx158

Kaufman, L., & Rousseeuw, P.J., (1990). Finding groups in data. an introduction to cluster analysis. Wiley, New York.

King, R., & Okólski, M. (2018). Diverse, Fragile and Fragmented: The New Map of European Migration. *Central and Eastern European Migration Review*, *online first*, 1–24. https://doi.org/10.17467/ceemr.2018.18

Kingma, D. P., & Ba, J. (2014). Adam: A method for stochastic optimization. *arXiv preprint arXiv*:1412.6980.

Kirk, D. (1996). Demographic transition theory. *Population studies*, 50(3), 361-387.

Kohler, H. P., Billari, F. C., & Ortega, J. A. (2002). The emergence of lowest-low fertility in Europe during the 1990s. *Population and development review*, 28(4), 641-680. https://doi.org/10.1111/j.1728-4457.2002.00641.x

Kohler, H. P., Billari, F. C., & Ortega, J. A. (2006). Low fertility in Europe: Causes, implications and policy options. *In F. R. Harris (Ed.), The Baby Bust: Who will do the Work? Who Will Pay the Taxes?* Lanham, MD: Rowman & Littlefield Publishers, 48-109.

Karcagi-Kovats, A., & Katonane-Kovacs, J. (2012). Factors of Population Decline in Rural Areas and Answers Given in EU Member States' Strategies. *Studies in Agricultural Economics*, 114, 49-56.
https://doi.org/10.7896/j.1105

Kucera, T., Kucerova, O. V., Opara, O. B., & Schaich, E. (Eds.). (2012). *New demographic faces of Europe: the changing population dynamics in countries of Central and Eastern Europe.* Springer Science & Business Media.

Kuczabski, A., & Michalski, T. (2013). The process of depopulation in the rural areas of Ukraine.

Kulu, H. (2013). Why Do Fertility Levels Vary between Urban and Rural Areas? *Regional Studies*, *47*(6), 895–912. https://doi.org/10.1080/00343404.2011.581276

Kulu, H., Hannemann, T., Pailhé, A., Neels, K., Krapf, S., González-Ferrer, A., & Andersson, G. (2017). Fertility by birth order among the descendants of immigrants in selected European countries. *Population and Development Review*, 31-60. https://doi.org/10.1111/padr.12037

Lesnard, L. (2010). Setting cost in optimal matching to uncover contemporaneous socio-temporal patterns. Sociological methods & research, 38(3), 389-419.

Lesnard, L. (2014). Using optimal matching analysis in sociology: Cost setting and sociology of time. In Advances in sequence analysis: Theory, method, applications (pp. 39-50). Springer, Cham.

Lesthaeghe, R., & Van de Kaa, D. J. (1986). Two demographic transitions. *Population: Growth and decline*, 1, 9-24.

Lesthaeghe, R., & Willems, P. (1999). Is low fertility a temporary phenomenon in the European Union?. *Population and development review,* 25(2), 211-228. https://doi.org/10.1111/j.1728-4457.1999.00211.x

Li, W., Zhang, L., Lee, I., & Gkartzios, M. (2023). Overview of Social Policies for Town and Village Development in Response to Rural Shrinkage in East Asia: The Cases of Japan, South Korea and China. *Sustainability*, *15*(14), 10781. **https://doi.org/10.3390/su151410781**

Li, Y., Westlund, H., & Liu, Y. (2019). Why some rural areas decline while some others not: An overview of rural evolution in the world. Journal of Rural Studies, 68, 135-143. https://doi.org/10.1016/j.jrurstud.2019.03.003

Lutz, W., O'Neill, B. C., & Scherbov, S. (2003). Europe's population at a turning point. *Science*, 299(5615), 1991-1992.

Lutz, W., Amran, G., Bélanger, A., Conte, A., Gailey, N., Ghio, D., & Stonawski, M. (2019). Demographic scenarios for the EU: migration, population and education. Publications Office of the European Union.

Lutz, W., & Gailey, N. (2020). Depopulation as a policy challenge in the context of global demographic trends.

Lycan, R., Rynerson, C. (2013). Senior Shedding: Mortality and Migration of Seniors Create Vacancies for Gentrifying Neighborhoods. Presentation to American Association of Geographers, Los Angeles, CA, April 2013.

Mammey, U., & Schwarz, K. (2002). The demographic characteristics of the immigrant population in Germany. *Haug, Werner; Compton, Paul; Courbage, Youssef*, 193-244.

Martí-Henneberg, J. (2005). Empirical evidence of regional population concentration in Europe, 1870–2000. *Population, Space and Place*, 11(4), 269-281. https://doi.org/10.1002/psp.373

Matysiak, A., Sobotka, T., & Vignoli, D. (2021). The Great Recession and Fertility in Europe: A Sub-national Analysis. *European Journal of Population*, 37(1), 29–64. https://doi.org/10.1007/s10680-020-09556-y

McDonald, P. (2000). Gender equity in theories of fertility transition. *Population and development review*, 26(3), 427-439. https://doi.org/10.1111/j.1728-4457.2000.00427.x

McDonald, P. (2006). Low fertility and the state: The efficacy of policy. *Population and development review,* 485-510.

McNeill, J. R. (2006). Population and the natural environment: Trends and challenges. *Population and Development Review*, *32*, 183-201.

Meslé, F., Vallin, J., & Obadia, Y. (2002). Mortality in Europe: the divergence between east and west. *Population*, 57(1), 157-197. https://doi.org/10.2307/3246630

Morikawa, H. (2017). Urban systems and regional policies in population declining Japan. *Kokon Shoin*. (J)

Myrskylä, M., Kohler, H. P., & Billari, F. (2011). High development and fertility: fertility at older reproductive ages and gender equality explain the positive link. Max Planck Institute for Demographic Research, Rostock, Germany

Newsham, N., & Rowe, F. (2021). Projecting the demographic impact of Syrian migration in a rapidly ageing society, Germany. *Journal of Geographical Systems*, *23*(2), 231–261. https://doi.org/10.1007/s10109-018-00290-y

Newsham, N., & Rowe, F. (2022). Understanding trajectories of population decline across rural and urban Europe: A sequence analysis. *Population, Space and Place*, *29*(3), e2630. https://doi.org/10.1002/psp.2630

Neyer, G., & Andersson, G. (2008). Consequences of family policies on childbearing behavior: Effects or artifacts? *Population and development review*, 34(4), 699-724. https://doi.org/10.1111/j.1728-4457.2008.00246.x

Oeppen, J., & Vaupel, J. W. (2002). Broken limits to life expectancy. *Science*, 296(5570), 1029-1031.

O'Malley, T., Bursztein, E., Long, J., Chollet, F., Jin, H., & Invernizzi, L. (2019). Keras tuner.

ONS. (2020). Subnational population projections for England: 2018-based. Available: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/subnationalpopulationprojectionsforengland/2018based

Openshaw, S. (1984). Ecological fallacies and the analysis of areal census data. *Environment and Planning A,* 16(1), 17-31.

Otoom, M. M., Jemmali, M., & Qawqzeh, Y. (2019). *Comparative Analysis of Different Machine Learning Models for Estimating the Population Growth Rate in Data-Limited Area.*

Patias, N., Rowe, F., & Arribas-Bel, D. (2021a). Trajectories of neighbourhood inequality in Britain: Unpacking inter-regional socioeconomic imbalances, 1971− 2011. The Geographical Journal.

Patias, N., Rowe, F., Cavazzi, S., & Arribas-Bel, D. (2021b). Sustainable urban development indicators in Great Britain from 2001 to 2016. Landscape and Urban Planning, 214, 104148.

Patias, N., Rowe, F., & Arribas-Bel, D. (2023). Local urban attributes defining ethnically segregated areas across English cities: A multilevel approach. *Cities*, 132, 103967. https://doi.org/10.1016/j.cities.2022.103967

Poot, J. (2008). Demographic change and regional competitiveness: the effects of immigration and ageing. University of Waikato, Population Studies Centre.

Preston, S. H., Heuveline, P., & Guillot, M. (2000). Demography: Measuring and modeling population processes. Oxford: Blackwell Publishers Ltd.

Prskawetz A, Buber I, Sobotka T, Engelhardt H (2006) Recent changes in family policies in Austria and Germany: a response to very low fertility. Entre Nous 63:27–29

Pullum, T.W., & Jadhav, A. (2021). A Decomposition of Sources of Change in Population Size and Median Age, 1970–2020. DHS Working Papers No. 178. Rockville, Maryland, USA: ICF.

Pužulis, A., & Kūle, L. (2016). Shrinking of rural territories in Latvia. *European Integration Studies*, (10), 90-105. https://doi.org/10.5755/j01.eis.0.10.14988

Raleigh, V. S. (2019). Trends in life expectancy in EU and other OECD countries: Why are improvements slowing?. https://doi.org/10.1787/18152015

Ramani, A., & Bloom, N. (2021). The Donut effect of COVID-19 on cities. *National Bureau of Economic Research*. https://doi.org/10.3386/w28876

Ramsay, J. O., & Dalzell, C. (1991). Some tools for functional data analysis. *Journal of the Royal Statistical Society Series B: Statistical Methodology,* 53(3), 539-561. https://doi.org/10.1111/j.2517-6161.1991.tb01844.x

Ramsay, J. O., & Silverman, B. W. (Eds.). (2002). Applied functional data analysis: methods and case studies. New York, NY: Springer New York.

Ramsay, J. O., & Silverman, B. W. (2005). Principal components analysis for functional data. Functional data analysis, 147-172.

Raugze, I., Daly, G., & van Herwijnen, M. (2017). Shrinking Rural Regions in Europe. Towards Smart and Innovative Approaches to Regional Development Challenges in Depopulating Rural Regions. ESPON EGTC Policy Brief: 15pp. Luxembourg: ESPON EGTC

Reddaway, William B. 1939. The Economics of a Declining Population. London: Allen and Unwin.

Reher, D. S. (1998). Family Ties in Western Europe: Persistent Contrasts. *Population and Development Review*, 24(2), 203–234. https://doi.org/10.2307/2807972

Reher, D. (2005). Long-term population decline, past and future. *In International Union for the Scientific Study of Population. XXV International Population Conference*. Session (Vol. 94).

Reher, D. S. (2007). Towards long-term population decline: A discussion of relevant issues. *European Journal of Population*, *23*, 189- 207.

Reynaud, C., & Miccoli, S. (2018). Depopulation and the aging population: The relationship in Italian municipalities. *Sustainability*, 10(4), 1004. https://doi.org/10.3390/su10041004

Reynaud, C., Miccoli, S., Benassi, F., Naccarato, A., & Salvati, L. (2020). Unravelling a demographic 'Mosaic': Spatial patterns and contextual factors of depopulation in Italian Municipalities, 1981–2011. Ecological Indicators, 115, 106356. https://doi.org/10.1016/j.ecolind.2020.106356

Riiman, V., Wilson, A., Milewicz, R., & Pirkelbauer, P. (2019). Comparing Artificial Neural Network and Cohort-Component Models for Population Forecasts. *Population Review*, 58(2). https://doi.org/10.1353/prv.2019.0008

Rodríguez-Pose, A., & Ketterer, T. D. (2012). Do local amenities affect the appeal of regions in Europe for migrants? *Journal of Regional Science*, 52(4), 535-561. https://doi.org/10.1111/j.1467-9787.2012.00779.x

Rodríguez-Pose, A., Lee, N., & Lipp, C. (2021). Golfing with Trump. Social capital, decline, inequality, and the rise of populism in the US. *Cambridge Journal of Regions, Economy and Society, 14(3), 457-481.*

Rodríguez-Pose, A., Terrero-Dávila, J., & Lee, N. (2023). Left-behind vs. unequal places: interpersonal inequality, economic decline, and the rise of populism in the US and Europe. *Journal of Economic Geography.*

Rodríguez-Vignoli, J., & Rowe, F. (2018). How is internal migration reshaping metropolitan populations in Latin America? A new method and new evidence. *Population Studies*, *72*(2), 253–273. https://doi.org/10.1080/00324728.2017.1416155

Rogers, A., Raquillet, R., & Castro, L. J. (1978). Model Migration Schedules and Their Applications. *Environment and Planning A: Economy and Space*, *10*(5), 475–502. https://doi.org/10.1068/a100475

Romaniuk, A., & Gladun, O. (2015). Demographic trends in Ukraine: Past, present, and future. *Population and Development Review*, 41(2), 315-337. https://doi.org/10.1111/j.1728-4457.2015.00049.x

Rowe, F. (2017). The Chilean Internal Migration (CHIM) database: temporally consistent spatial data for the analysis of human mobility. Region, 4(3), R1-R6.

Rowe, F., Corcoran, J., & Bell, M. (2017). The returns to migration and human capital accumulation pathways: non-metropolitan youth in the school-to-work transition. The Annals of Regional Science, 59(3), 819-845.

Rowe, F., Bell, M., Bernard, A., Charles-Edwards, E., & Ueffing, P. (2019). Impact of Internal Migration on Population Redistribution in Europe: Urbanisation, Counterurbanisation or Spatial Equilibrium*? Comparative Population Studies*, 44. https://doi.org/10.12765/CPoS-2019-18

Salehinejad, H., & Rahnamayan, S. (2016, December). Customer shopping pattern prediction: A recurrent neural network approach. *IEEE symposium series on computational intelligence (SSCI)* (pp. 1-6). IEEE.

Salvati, L. (2018). Population growth and the economic crisis: understanding latent patterns of change in Greece, 2002–2016. Letters in Spatial and Resource Sciences, 11(2), 105-126.

Shang, H. L., Smith, P. W., Bijak, J., & Wiśniowski, A. (2016). A multilevel functional data method for forecasting population, with an application to the United Kingdom. *International Journal of Forecasting*, 32(3), 629-649. https://doi.org/10.1016/j.ijforecast.2015.10.002

Shcherbakova, E. M. (2022). Population Dynamics in Russia in the Context of Global Trends. *Studies on Russian Economic Development*, *33*(4), 409–421. https://doi.org/10.1134/S1075700722040098

Slaev, A. D., & Kovachev, A. (2015). Specific issues of urban sprawl in Bulgaria. European Spatial Research and Policy, 21(2), 155-169.

Sobotka, T. (2004). Postponement of childbearing and low fertility in Europe. Dutch University Press, Amsterdam, The Netherlands, Population Studies Series

Sobotka, T. (2008). Overview Chapter 7: The rising importance of migrants for childbearing in Europe. *Demographic Research*, *19*, 225–248. https://doi.org/10.4054/DemRes.2008.19.9

Sobotka, T., Skirbekk, V., & Philipov, D. (2011). Economic recession and fertility in the developed world. *Population and development review*, 37(2), 267-306. https://doi.org/10.1111/j.1728-4457.2011.00411.x

Sobotka, T., Matysiak, A., & Brzozowska, Z. (2019). Policy responses to low fertility: How effective are they*? United Nations Population Fund.*

Sobotka, T., & Fürnkranz-Prskawetz, A. (2020). Demographic change in Central, Eastern and Southeastern Europe: Trends, determinants and challenges. In R. Holzmann, D. Ritzberger-Grünwald, & H. Schuberth (Eds.), *30 Years of Transition in Europe*. Edward Elgar Publishing. https://doi.org/10.4337/9781839109508.00027

Sobotka, T., Jasilioniene, A., Zeman, K., Winkler-Dworak, M., Brzozowska, Z., Galarza, A. A., ... & Jdanov, D. (2022). From bust to boom? Birth and fertility responses to the COVID-19 pandemic. SocArXiv. https://doi.org/10. 31235/osf.io/87acb.

Spórna, T., Kantor-Pietraga, I., & Krzysztofik, R. (2016). Trajectories of depopulation and urban shrinkage in the Katowice Conurbation, Poland. Espace populations sociétés. Space populations societies, (2015/3-2016/1).

Stevens, F. R., Gaughan, A. E., Linard, C., & Tatem, A. J. (2015). Disaggregating Census Data for Population Mapping Using Random Forests with Remotely-Sensed and Ancillary Data. *PLOS ONE*, *10*(2), e0107042. https://doi.org/10.1371/journal.pone.0107042

Studer, M. (2013). WeightedCluster library manual: A practical guide to creating typologies of trajectories in the social sciences with R.

Szmytkie, R. (2016). Depopulacja zespołów miejskich w sudeckiej części Dolnego Śląska. Konwersatorium Wiedzy o Mieście, 29(1), 75-83.

Teitelbaum, M. S. (2013). *The fear of population decline*. Academic Press.

Tello-Leal, E., Roa, J., Rubiolo, M., & Ramirez-Alcocer, U. M. (2018, November). Predicting activities in business processes with LSTM recurrent neural networks. *Kaleidoscope: Machine Learning for a 5G Future* (ITU K) (pp. 1-7). IEEE.

Thomas, J., Rowe, F., & Lin, E. S. (2022). Declining fertility in Taiwan: The deterring impact of housework imbalance. *Asian Population Studies*, *19*(3), 270–288. https://doi.org/10.1080/17441730.2022.2035555

Tobler, W. R. 1970. A computer movie simulating urban growth in the Detroit region. *Economic Geography*, 46: 234-40.

Turok, I., & Mykhnenko, V. (2007). The trajectories of European cities, 1960–2005. *Cities*, 24(3), 165–182.

Ubarevičienė, R., Van Ham, M. & Burneika, D., (2016). Shrinking regions in a shrinking country: The geography of population decline in Lithuania 2001–2011. Urban Studies Research, 2016.

United Nations Economic Commission for Europe. (2017). Older persons in rural and remote areas. UNECE Policy Brief on Ageing No. 18. *Available: https://unece.org/policy-briefs*

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019, Volume I: Comprehensive Tables (ST/ESA/SER.A/426).

United Nations, Department of Economic and Social Affairs, Population Division. (2022). World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3.

Vallin, J., & Meslé, F. (2004). Convergences and divergences in mortality: a new approach of health transition. *Demographic research*, 2, 11-44. https://doi.org/10.4054/DemRes.2004.S2.2

Van Dalen, H. P., & Henkens, K. (2011). Who fears and who welcomes population decline? *Demographic Research*, *25*, 437–464. https://doi.org/10.4054/DemRes.2011.25.13

van de Kaa DJ. Europe's second demographic transition. Washington, D.C: *Population Reference Bureau;* 1987.

van Leeuwen, E. S., Vega, S. H., & Hogenboom, V. (2021). Does population decline lead to a "populist voting mark-up"? A case study of the Netherlands. *Regional Science Policy & Practice, 13(2), 279-302.*

Vaupel, J. W., & Canudas-Romo, V. (2002). Decomposing demographic change into direct vs. Compositional components. *Demographic Research*, *7*, 1–14. https://doi.org/10.4054/DemRes.2002.7.1

Viñas, C. D. (2019). Depopulation processes in European rural areas: A case study of Cantabria (Spain). European Countryside, 11(3), 341-369. https://doi.org/10.2478/euco-2019-0021

Wang, C.-Y., & Lee, S.-J. (2021). Regional Population Forecast and Analysis Based on Machine Learning Strategy. *Entropy*, *23*(6), 656. https://doi.org/10.3390/e23060656

Wang, H., Paulson, K. R., Pease, S. A., Watson, S., Comfort, H., Zheng, P., ... & Murray, C. J. (2022). Estimating excess mortality due to the COVID-19 pandemic: a systematic analysis of

COVID-19-related mortality, 2020–21. *The Lancet*, 399(10334), 1513-1536. https://doi.org/10.1016/S0140-6736(21)02796-3

Ward Jr, J.H., (1963). Hierarchical grouping to optimize an objective function. Journal of the American statistical association, 58(301), pp.236-244.

Widiputra, H., Mailangkay, A., & Gautama, E. (2021). Multivariate CNN-LSTM Model for Multiple Parallel Financial Time-Series Prediction. *Complexity*, *2021*, 1–14. https://doi.org/10.1155/2021/9903518

Wilson, T., & Rowe, F. (2011). The forecast accuracy of local government area population projections: a case study of Queensland. *Australasian Journal of Regional Studies*, The, 17(2), 204-243.

Wilson, T., Brokensha, H., Rowe, F., & Simpson, L. (2018). Insights from the evaluation of past local area population forecasts. *Population Research and Policy Review*, 37, 137-155. https://doi. org/10.1007/s11113-017-9450-4

Wilson, T., Grossman, I., Alexander, M., Rees, P., & Temple, J. (2022). Methods for Small Area Population Forecasts: State-of-the-Art and Research Needs. *Population Research and Policy Review*, *41*(3), 865–898. https://doi.org/10.1007/s11113-021-09671-6

Wilson, T., Grossman, I., & Temple, J. (2023). Evaluation of the best M4 competition methods for small area population forecasting. *International Journal of Forecasting*, *39*(1), 110–122. https://doi.org/10.1016/j.ijforecast.2021.09.005

Wojewódzka-Wiewiórska, A. (2019). Depopulation in rural areas in Poland–Socio-economic local perspective. *Research for Rural Development*, 2, 126-132. https://doi.org/10.22616/rrd.25.2019.059

Wolff, M., & Wiechmann, T. (2018). Urban growth and decline: Europe's shrinking cities in a comparative perspective 1990–2010. *European Urban and Regional Studies*, *25*(2), 122–139. https://doi.org/10.1177/0969776417694680

Wu, Y., Yang, Y., Nishiura, H., & Saitoh, M. (2018). Deep Learning for Epidemiological Predictions. *The 41st International ACM SIGIR Conference on Research & Development in Information Retrieval*, 1085–1088. https://doi.org/10.1145/3209978.3210077

Zagheni, E., Garimella, V. R. K., Weber, I., & State, B. (2014). Inferring international and internal migration patterns from Twitter data. *Proceedings of the 23rd International Conference on World Wide Web*, 439–444. https://doi.org/10.1145/2567948.2576930

Zaytar, M. A., & El Amrani, C. (2016). Sequence to sequence weather forecasting with long short-term memory recurrent neural networks. *International Journal of Computer Applications*, 143(11), 7-11.

Zelinsky, W. (1971). The Hypothesis of the Mobility Transition. *Geographical Review*, *61*(2), 219. https://doi.org/10.2307/213996

Zhang, G., Eddy Patuwo, B., & Y. Hu, M. (1998). Forecasting with artificial neural networks: *International Journal of Forecasting*, *14*(1), 35–62. https://doi.org/10.1016/S0169-2070(97)00044-7