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Urban Morphology and Residential Differentiation across Great Britain, 1881–1901

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The nineteenth century saw rapid urbanization and dramatic social change in Great Britain, some of which can now be viewed at national scales for the first time through linkage of georeferenced digital historical data to contemporary and historical framework data. Here, we attempt to georeference every individual address record from the 1881, 1891, and 1901 censuses for Great Britain and to define the fast-growing historical street networks and residential geographies of every urban settlement. We next devise a scale-free historical geodemographic classification using variables common to these three censuses and assign cluster group characteristics to every urban street segment. We also link the evolution of the urban street morphology with changes in residential differentiation and the geodemographic assignments over the twenty-year study period. The results of this intensive data processing make it possible to chart the development of urban residential areas across Great Britain and bring focus to the changing social structures of the cities. We examine these changes with examples drawn from the entire British urban settlement system. Our conclusions discuss the implications of this extensive analysis for improved understanding of the evolution of Great Britain's urban system. *Key Words: geodemographics, georeferencing, Great Britain, historical censuses, urban dynamics.*

Study of the residential differentiation that accompanies urban growth and morphology change follows a long and illustrious tradition in urban geography and sociology, dating back nearly 100 years to the analysis of the dynamics of change in Chicago during the 1920s (Park, Burgess, and McKenzie 1925). First attempts to systematize such work using computers developed in the 1950s (Shevky and Bell 1955) and led to a plethora of factorial ecologies of cities during the 1970s and early 1980s: Robson (1975) provided an early review and interpretation. A substantial research field subsequently evolved into the study of geodemographics, described simply by Harris, Sleight, and Webber (2005) as "the analysis of people by where they live." Despite periodic ontological and epistemological critique (e.g., Goss 1995; Burrows and Gane 2006), geodemographics has spawned many developments of the basic underpinning methodology (e.g., Lloyd et al. 2017) and substantive applications that have been reported worldwide (e.g., Ingwe et al. 2008; Spielman and Singleton 2015; Uesugi and Yano 2018).

Although the history of intraurban geography can be thought of as intertwined with the development of geodemographics, the field has never itself taken a historical perspective on the evolution of settlement systems or individual settlements within them. Rather few studies have galvanized digital sources to disinter and compare historical urban structures (but see Schürer and Penkova 2015; Smith, Bennett, and Radicic 2018), and past physical and social structures of settlement systems have yet to be systematically linked to contemporary outcomes. Here we rise to the very significant empirical challenges it raises. This is vitally important because cities are economic and social engines for development and change, yet intraurban quantitative geography has not addressed how they shape social and spatial mobility at disaggregate scales of measurement (but see Swinney and Thomas [2015] for more aggregate analysis).

Our response to this challenge develops a highly innovative geodemographic analysis of the forms and residential functioning of the Great Britain settlement system built using 100 million individual records from the 1881, 1891, and 1901 Censuses of Victorian Britain, available through the Integrated Census Microdata (I-CeM) Project[1] (Higgs and Schürer 2019). This period was chosen because of the availability of individual census records through

the I-CeM project for the whole of Great Britain, avoiding the nonavailability of individual-level data through I-CeM for England and Wales in 1871 and Scotland in 1911. Innovative handling of individual records frees geodemographic analysis from potential analytical issues of ecological fallacy. We also address the challenge of georeferencing residential addresses at more granular levels than those typically used by local historians, thereby addressing concerns that enumeration districts might not adequately represent important neighborhood morphological or ownership divides (Dennis 1984).

The geographic and temporal extent of our analysis is ambitious: We use individual census records from the three censuses for all of Great Britain made available under special license by the UK Data Service. We attempt, for the first time, to georeference all individual historical census records for 1881 through 1901 at street or individual property level, using contemporary Ordnance Survey (OS) AddressBase Premium[2] and the historical GB1900 Gazetteer[3] (Aucott and Southall 2019). Overall success in this endeavor makes possible fulfillment of two further important objectives: charting the evolution of urban morphology and the growth of residential areas across Great Britain and unraveling the geodemographic neighborhood changes that accompany urban growth and the evolution of urban morphology. We reconstruct historical street networks by geocoding census addresses in different years to demarcate urban settlement footprints and to chart their physical change throughout the 1881 to 1901 period. Linkage of these to the locally differentiated neighborhood characteristics makes it possible to relate local build form to residential function and to chart the evolution of various neighborhoods. The underpinning data processing methods are summarized in Figure 1 and are each elaborated in the following sections.

Creating Georeferenced Street Infrastructure for the Period 1881 to 1901

Previous research using the I-CeM data has established the value of classifying parishes or towns in England and Wales (Schürer and Penkova 2015; Smith, Bennett, and Radicic 2018). Table S.1 (see the online supplementary file) summarizes the parish population statistics for Great Britain, which are at the most granular unit of analysis recorded in the three I-CeM data sets. The recorded population sizes of each of the 16,000 or so parishes are highly variable, ranging from a single resident to hundreds of thousands. The population size distributions of parishes have a strong positive skew, with about 75 percent having fewer than 1,000 residents. As such, these units are less than ideal for recording population characteristics and dynamics.

Accordingly, we instead propose residential street segments, defined by their intersections with adjoining streets, as elemental units for defining the extent and characteristics of Great Britain's residential areas. Similar formulations have been used in space syntax studies (Vaughan 2018) and street-based segregation research (Grannis 1998; Logan et al. 2011). Contemporary UK Census Output Areas are designed to preserve within-zone homogeneity of built form and population characteristics such as housing tenure in systems that are changing only incrementally between censuses. Given the rapid urban change dynamics of late Victorian cities, we advocate street segment geographies that normally preserve some degree of homogeneity of built form and resident characteristics. This unit of measurement and analysis is not without drawbacks. For example, Charles Booth's London maps depict homogeneous street segments despite survey evidence from the underpinning diaries that every street contained a mixture of his eight poverty classes (Dennis forthcoming). More generally, many nineteenth-century street segments took twenty to thirty years to complete and develop as a patchwork of small-scale developments and vernacular developments (see, e.g., Dyos [1961] on Camberwell, Reeder [1968] on West London, and Whitehand and Morton [2003] on Birmingham). This resonates with Booth's contemporaneous poverty maps, which align street segments with resident characteristics. Street segments also enable robust and transparent definition of the changing extents of settlements in late Victorian Great Britain's expanding urban and regional system.

Creating Framework Data Sets of Residential Street Addresses, 1881 to 1901

Georeferencing Historical Residential Addresses

We begin by attempting the hugely ambitious task of georeferencing every residential address
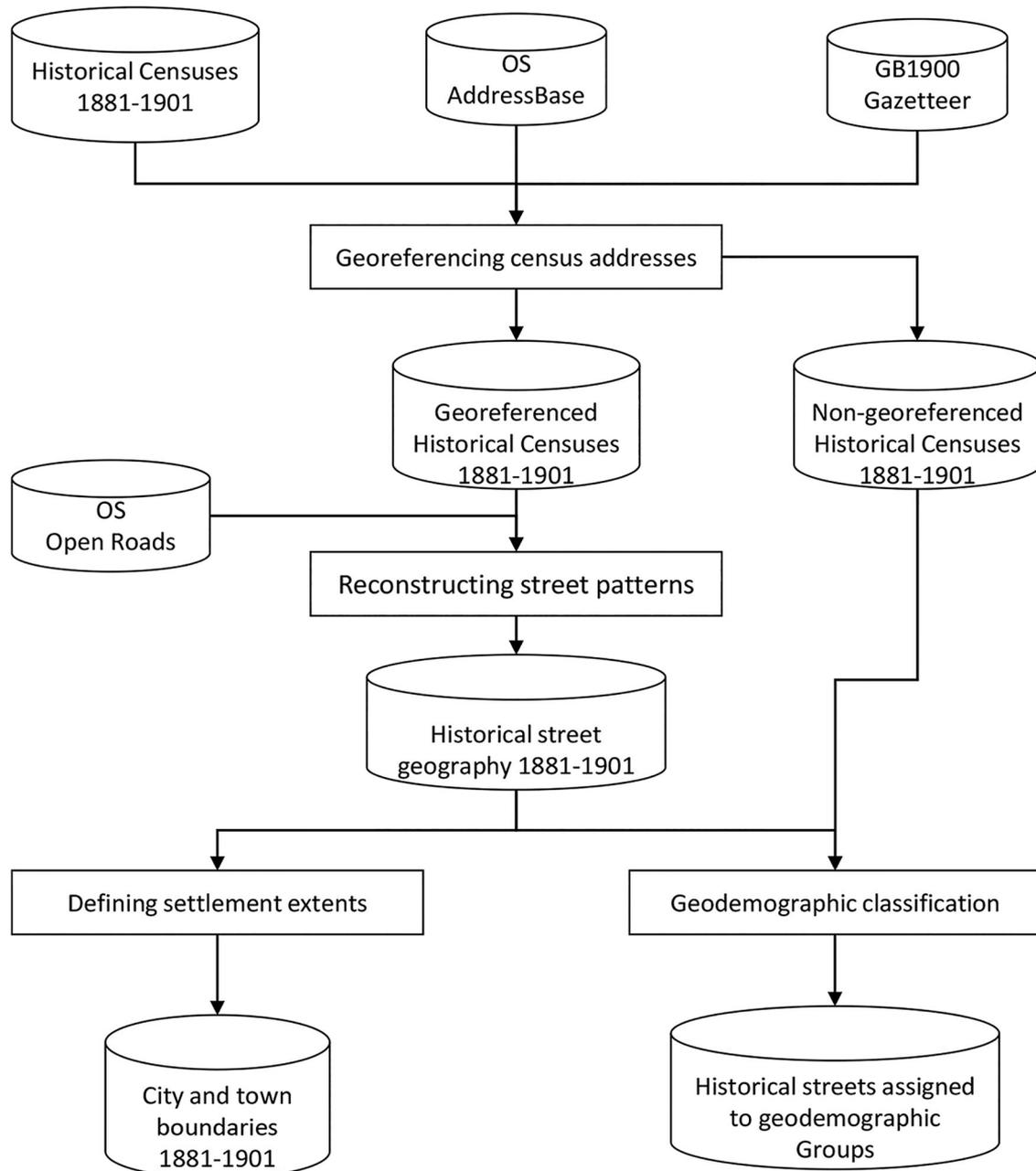
Figure 1. Workflow of the data processing.

contained in the 1881, 1891, and 1901 censuses, using contemporary OS AddressBase and the historical GB1900 Gazetteer. The task is made difficult by the extent of street name changes, especially in big cities where local government reorganization (e.g., in 1890s London) led to renaming of many streets within reorganized jurisdictions that bore the same name. In other instances, individual streets that historically bore different names were frequently rationalized. Successive waves of subsequent slum clearance selectively removed the poorest streets in inner areas, and other street names associated with poverty or notorious crimes or buildings were also changed for marketing purposes. The Gazetteer is an index of place names extracted from the OS six-inch maps of the time and is known to omit the names of short or very narrow streets, alleys, and courts. The digital reference frames thus likely bias the pattern of successful matching, particularly in inner cities—and especially the streets in which the poorest lived. Other technical causes of matching failures include vague address strings, transcription

Table 1. Geocoding matches at building or street level, and resident population georeferenced

	1881	1891	1901
Total number of unique addresses	3,504,903 (100%)	1,281,442 (100%)	5,253,912 (100%)
Addresses matched using AddressBase at building level	762,696 (22%)	80,485 (6%)	2,054,451 (39%)
Addresses matched using AddressBase at street level	1,151,978 (33%)	535,937 (42%)	1,683,920 (32%)
Addresses matched using the GB1900 Gazetteer	427,234 (12%)	240,441 (19%)	489,930 (9%)
Geocoded unique addresses	2,341,908 (67%)	856,863 (67%)	4,228,301 (80%)
Geocoded British population	19,791,935 (66%)	24,428,674 (73%)	28,325,057 (77%)

errors, and nonpermanent accommodation (Lan and Longley 2019; Walford 2019).

Although significant and widespread, these shortcomings have limited impact on our analysis of physical growth of settlements and the geodemographic composition of residential neighborhoods. The extents of major settlements use the concave hulls of the street segment clusters, where the street network is less dense (and hence fully documented) and unlikely to be affected by subsequent redevelopment. Our geodemographic classification includes almost the entire population, irrespective of success in georeferencing, and although our maps are incomplete, georeferencing of adjacent georeferenced street segments should preserve the sense of visual balance in map interpretation. The underpinning georeferencing algorithm and its efficacy are described in Lan and Longley (2019). In essence, each historical address is assigned to its exact or most probable location within the known parish using fuzzy string matching. Overall, 67 percent, 67 percent, and 80 percent of unique addresses are geocoded for the 1881, 1891, and 1901 censuses, respectively, accounting for approximately 66 percent, 73 percent, and 77 percent of the respective corresponding populations (Table 1). Fewer unique addresses have been digitally encoded in the 1891 Census I-CeM records and building numbers are recorded for only 8 percent in that year—compared to 56 percent and 69 percent, respectively, in 1881 and 1901. Street segment georeferencing rates are thus high, although the lower rates of building-level matches might provide only spurious precision in instances in which street addresses have been resequenced following incremental local construction.

The two address corpora complement each other by georeferencing both well-formatted addresses in urban areas and nonstandard addresses such as place names or building names (e.g., farms or cottages) in rural areas. Although some entire streets might subsequently have been demolished in slum clearances (especially after the 1930 Housing Act) or have been renamed (especially in post–World War II reconstruction), the matching process is otherwise generally successful and thus provides an elemental framework for the investigation of urban morphological and demographic change.

Reconstructing Historical Residential Street Patterns

We extract the geometries of the historical street networks from the contemporary OS Open Roads database. We first match the geocoded address points to their closest street segments, irrespective of side of street. A street segment is defined by intersections with adjoining streets at both ends. We throw a maximum 500-m buffer around each georeferenced address point and prioritize assignments to streets for which thoroughfare names match.

Figure 2 shows the population size frequency distributions of the geocoded street segments for each census. In our subsequent analysis of residential characteristics and built form, we consider only segments that housed twenty or more individuals. This operation excludes about 14 percent, 10 percent, and 11 percent of the 1881, 1891, and 1901 Great Britain populations, respectively. Of these percentages, approximately 62 percent, 65 percent, and 60 percent, respectively, were identified as belonging to parishes inhabited by less than one person per acre and defined on this basis as "rural" by Lan and Longley (2019). These operations create framework data sets of residential streets for 1881, 1891, and 1901, making it possible to discern the changing physical extents of residential streets across the entirety of Great Britain. The historical parish geographies, by contrast, are both less granular and highly variable in size and extent, thereby bearing less detailed testimony to the processes of industrialization and associated changes. In what follows, we analyze street segment geodemography to bring focus
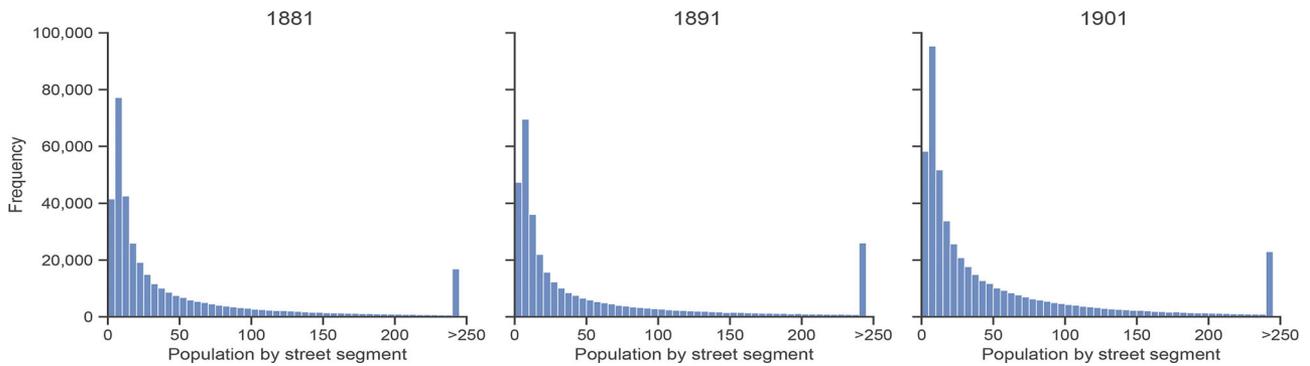
Figure 2. Frequency distributions of the geocoded population sizes by street segments for 1881, 1891, and 1901, including streets housing institutions and similar with more than 250 residents.

to growth and reorganization of urban social areas within the wider British economy. The connectedness of these units in physical and social space forms the basis of a geotemporal classification to residential areas in Great Britain's changing urban and regional system.

Identifying the Extents of Residential Areas

New residential development occurs along existing streets or following the construction of new ones. The identification and designation of new street segments as residential thus charts a key component of urban growth and changes the extent, connectivity, and morphology of urban land use. The transition to residential land use is typically irreversible, although georeferencing might be frustrated by urban redevelopment or local issues of street renaming or resequencing of street addresses, whereas changes in the morphology of different urban land use categories might be a cause or effect of changes in urban function (Masucci, Stanilov, and Batty 2013; Barrington-Leigh and Millard-Ball 2015; Arcaute et al. 2016). Here we use georeferencing of residential streets to define the extents of urban settlements and explore temporal changes in the rank order of settlements (Batty 2006) within the national settlement system.

Defining the Extents of Major Settlements

We define the extents of the major resident population concentrations by examining the contiguity of historical residential street segments for 1881, 1891, and 1901. Our objective is to establish a consistent basis to charting the growth and change of residential areas across Great Britain at high spatial

granularity and independent of administrative divisions such as parishes. We also assume that unmatched addresses are predominantly rural or pertain to redeveloped inner urban areas that do not shape the outer boundaries of established urban areas.

Choice of contiguity threshold is inherently subjective, although we are guided by notions of walkability as the dominant travel to work requirement of the time, notwithstanding the observation that availability and routing of public transport become increasingly relevant to the functional definition of large urban areas over this period. Accordingly, we experiment with 100 m, 200 m, 300 m, 500 m, 700 m, 900 m, 1,200 m, and 1,500 m contiguity thresholds using the 1881 data, defining urban extents as housing at least 10,000 residents. Figure 3 presents three illustrative sets of results. An appropriate contiguity threshold should be neither too small, to amalgamate the integral parts of urban areas that span railways or rivers, nor too large, to maintain the integrity of freestanding settlements set within adjoining rural areas. We also compare the spatial extents of our street networks in London in 1881 and 1901 with the streets manually digitized from the historical maps of London (Masucci, Stanilov, and Batty 2013). Full consideration leads us to adopt the 200 m contiguity threshold as sufficient to span physical structures such as rivers and to represent both the historical cores of both major and minor settlements. The appropriateness of this chosen threshold is reinforced in the subsequent analysis of the power law distribution of the city sizes (see also Figure S.1 in the online supplementary file), which has also been observed in many other empirical pieces of evidence. The 700 m threshold coalesces many urban centers into conurbations, whereas the 1,500 m threshold depicts expansive regional structures.
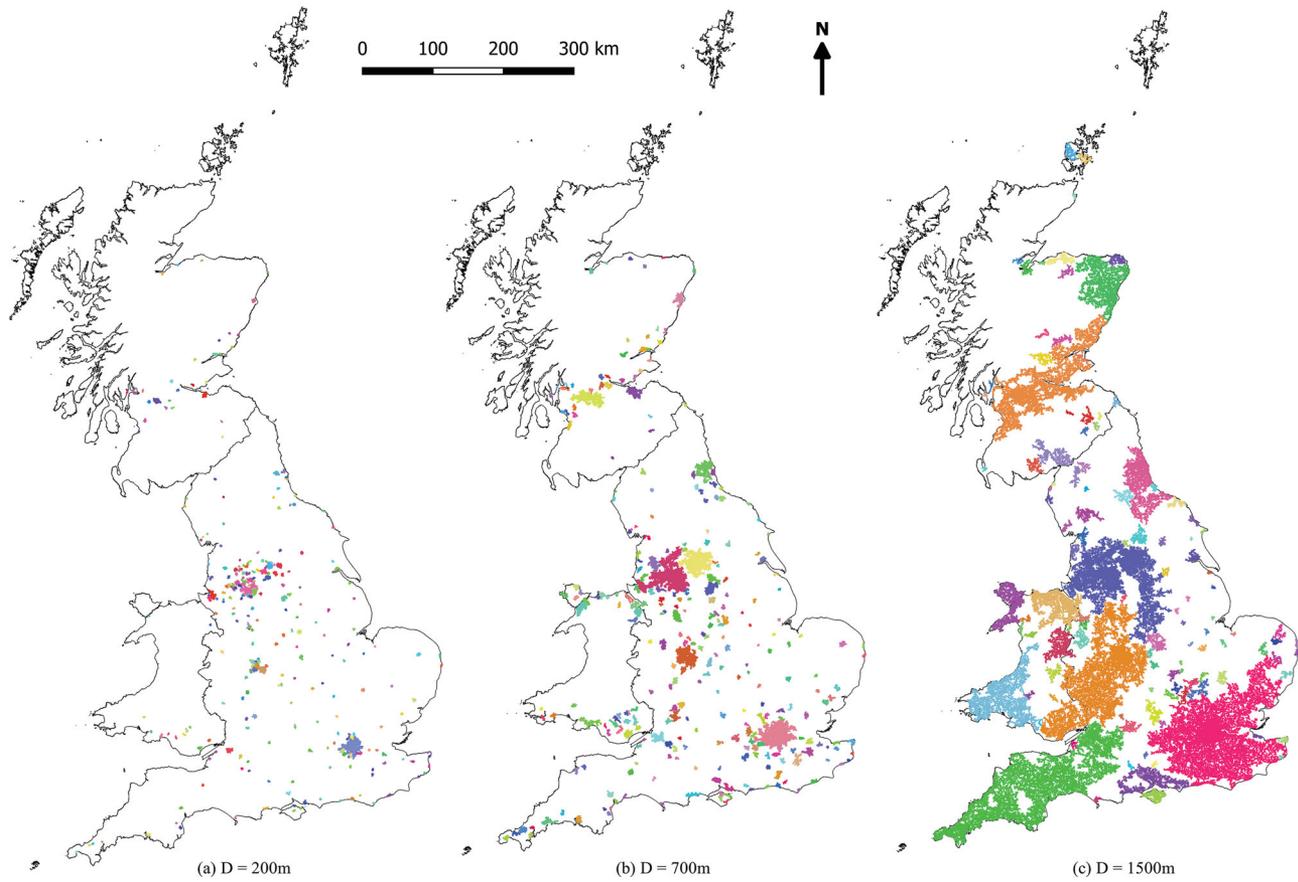
Figure 3. Contiguous residential settlements in 1881 using distance thresholds. (A) D = 200 m; (B) D = 700 m; and (C) D = 1,500 m. Color coding is used to identify different freestanding settlements.

In what follows, we use the 200 m threshold to define urban extents. Figure 4 shows the street segments that bound London in 1901 along with the urban envelope defining the city in 1881 using the same distance thresholds. Figure 4 illustrates some of both the strengths and weaknesses of our approach. It appears to clearly define the outer extent of the city, particularly the extent of ribbon development long before this term was widely invoked—notably in the tentacles following the major roads out of London, such as the Brighton Road south of Croydon and the Great West Road beyond Hammersmith. Places such as Haringey, Enfield, Richmond, and Kingston are accommodated within the 1901 extent but are seen as freestanding settlements in 1881; other settlements such as Harrow and Sutton remain freestanding. The map, however, provides uneven data coverage of internal parts of the city—Tower Hamlets, the East End, and inner southeast London appear to have no more dense a pattern of streets than West London and Mayfair, where mostly all streets have survived and retained

the same names. There are also holes in the pattern where residential development has been replaced by new developments or land uses, notably Burgess Park in Southwark.

Great Britain–Wide Urban Development between 1881 and 1901

Adopting the 200 m contiguity threshold to define the 1,000 largest settlements in 1881, 1891, and 1901 defines a slightly curvilinear power law distribution consistent with Zipf (1949) and Batty (2006), a settlement's population size is inversely proportional to its rank, as shown in the online supplementary file (Figure S.1). We calculate the power law exponents of the curves presented in Figure S.1 using the open-source 'powerlaw' Python package (Alstott, Bullmore, and Plenz 2014), which reports values of 2.01, 1.92, and 1.90 for the 1881, 1891, and 1901 distributions, respectively. The results resonate with many empirical observations (e.g., Jiang and Jia 2011) about city size distributions wherein
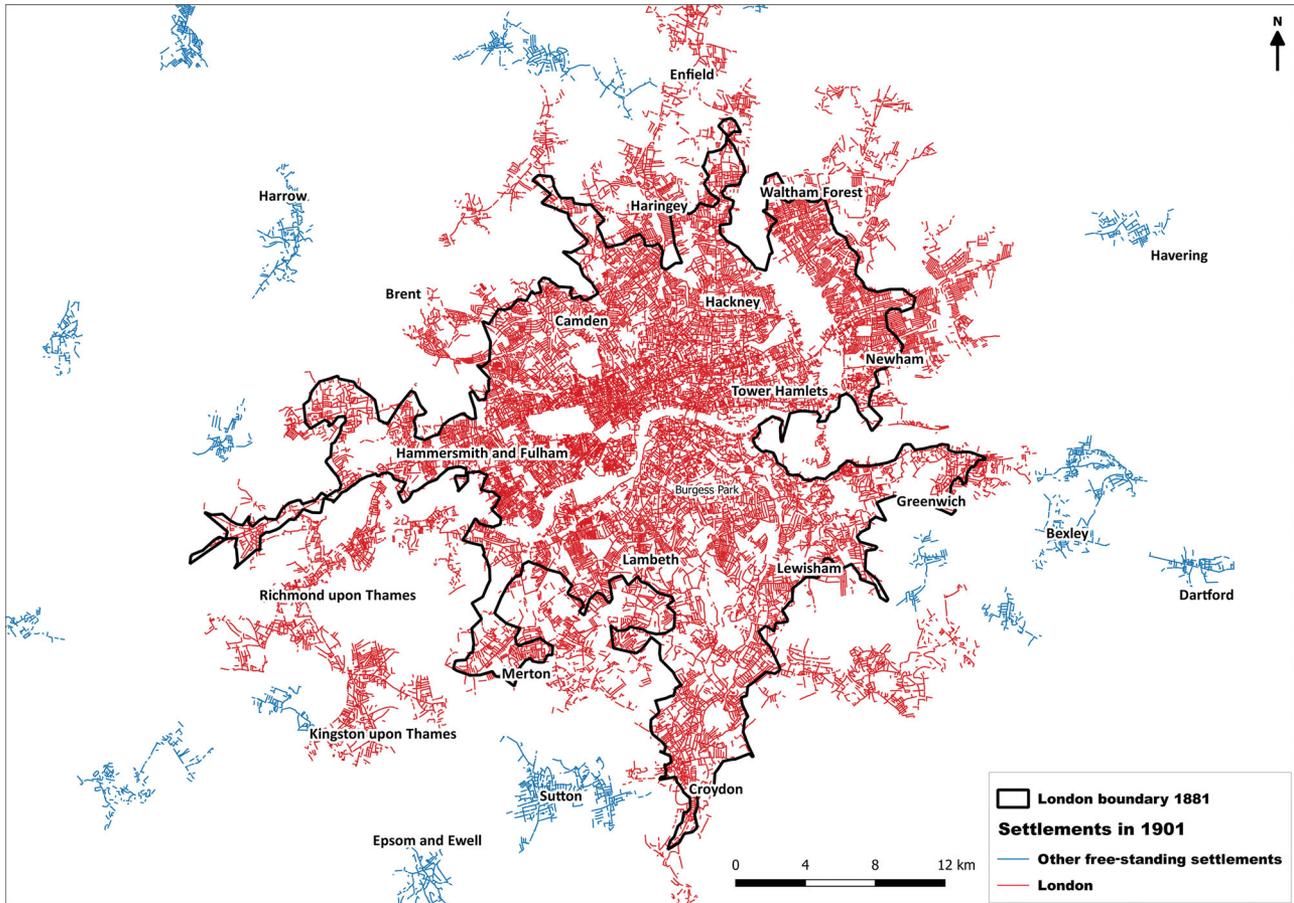
Figure 4. Street segment cluster (shown in red) defining the 1901 residential extent of London and its bounding envelope in 1881 (shown in black).

the exponent of Zipf's law (usually around 1) is taken as the power law exponent minus one. The population sizes of settlements within this distribution increase over this period, although this size effect is attenuated among the smallest settlements: The population size of London was about 2.9 million, 4.0 million, and 5.1 million in the three time slices, and the population of the one thousandth settlements grew only from 1,595 through 1,915 to 2,013, respectively. There are many changes in the rank of settlements within this distribution, including among the largest settlements (Figure S.2).

Great Britain's Evolving Occupational and Geodemographic Structure

Occupational Classification and Change over Time

Occupational classification provides one street segment–scale measure of the change in the residential structure (whether successfully georeferenced or not). Several occupational classification schemes have been developed for use with historical data, notably HISCAM (Lambert et al. 2013) and the HISCO classification (Van Leeuwen, Maas, and Miles 2002). Using the built-in coding scheme HISCO in the I-CeM data (Schürer, Penkova, and Shi 2015), we calculate counts and percentages of modal street segment occupational category in 1881, 1891, and 1901 and the transitions occurring over this period (see the online supplementary file, Table S.2). We identify high apparent rates of transition between modal occupational categories of street segments—only 58 percent of streets retain the same category between 1881 and 1891, 59 percent retain this between 1891 and 1901, and 55 percent retain it over the 1881 to 1901 study period.

Set against the overall pattern of relatively modest changes in total numbers of streets assigned to each occupational category, it is thus likely that the

Table 2. Initial input variables and their descriptions

Domains	ID	Variables	Definition (by road segments)
Demographics and household structure	1	infant	% of people age 0–4
	2	y_child	% of people age 5–10
	3	o_child	% of people, age 11–14
	4	adult	% of people, age 15 or over
	5	single	% of single people (age ≥12 for females or age ≥14 for males)
	6	married	% of married people (age ≥12 for females or age ≥14 for males)
	7	widowed & divorced	% of widowed or divorced people (age ≥12 for females or age ≥14 for males)
	8	overseas	% of people born outside the (then) United Kingdom
	9	longevity	% of people age >41 (male) or >43 (female)
	10	hhs	Average household size
	11	hh_kid6	% of households that had six or more children
	12	hh_kins	% of households that lived with relatives
	13	hh_sers	% of households that had live-in domestic servants
	14	hh_inmates	% of households that had live-in lodgers or boarders
Employment	15	work_kids	% of children age 11–14 who had jobs
	16	work_f15	% of female adults age 11 and over who had jobs
Occupation	17	g123	% of people (age >14) who were professional, managerial, or clerical workers (e.g., scientists, doctors, government administrators, religious workers)
	18	g123_head	% of household heads (age >14) who were professional, managerial, or clerical workers
	19	g4	% of people (age >14) who were sales workers in wholesale or retail trade and business services (e.g., shop owners, insurance salesmen, estate agents)
	20	g5	% of people (age >14) who were service workers (e.g., housekeepers, cooks, servants, waiters)
	21	g6	% of people (age >14) who were agricultural, animal husbandry, and forestry workers or fishermen (e.g., farmers)
	22	g7	% of people (age >14) who were factory production and raw material processing-related workers (e.g., miners, weavers, dyers)
	23	g8	% of people (age >14) who were artisanal workers (e.g., shoemakers, blacksmiths, toolmakers, jewelers)
	24	g9	% of people (age >14) who were general laborers and physical workers conducting routine jobs (e.g., bricklayers, construction workers, engine operators, dockers)
Residential mobility	25	local_birth	% of people resident in their parish of birth
	26	local_head	% of household heads resident in their parish of birth

modal measure is rendered volatile by within-street heterogeneity of occupational classes and inevitable ambiguities in precise occupational classification. For these reasons, we extend our analysis beyond the occupational dimension of social structure to develop a multivariate classification that enables robust comparison of any elements within the national settlement system over time.

Geodemographic Classification and Change over Time

Our response to the limitations of occupational classification is to classify street segments using a wider range of census variables originally collected to assess the broader condition of the general population (Dewdney 1981). We adapt the standard geodemographic cluster analysis approach used to summarize neighborhood conditions using the output areas of the 2011 Census (Gale et al. 2016), using our consistent 1881 to 1901 street segment geography. This approach develops and extends data reduction approaches used in historical geography in terms of factorial ecology (Lawton and Pooley 1974; Dennis 1984; Smith, Bennett, and Radicic 2018) to enable multivariate comparisons of neighborhood areas using a shorthand typology of classes that

facilitates ease of comparison between areas. Cluster analysis is useful for building national typologies of the composition of urban areas that enable researchers to question "What place is like this place?" across the entire settlement system, based on data representing a mélange of lifestyle-related data. Although different areas of the country might have distinctive characteristics, the objective of this analysis is to establish a basis of comparison, founded on a comprehensive range of variables of interest.

We initially select twenty-six candidate variables to represent geodemographic domains of demography and household structure, employment, occupation, and residential mobility, set out in Table 2. The choice of age thresholds is made cognizant of social conditions of the time, such as the usual age of school leaving age (ten in the 1880s), minimum age of marriage (twelve for females and fourteen for males), life expectancy (forty-one years for males, forty-three years for females); the prevalence of domestic service; occupational structure as classified by Schürer, Penkova, and Shi (2015); and the historical tendency of most people not to move far from their birthplaces. The three highest status occupations are aggregated because of their low frequency throughout Great Britain, and an additional variable is created to identify locations where domestic servants resided with their employers.

Average household size is retained as an interval measure and the other twenty-five input variables are converted into percentages. The population size and number of households in each street segment are also calculated. Following data exploration, three variables are removed because they are relevant to less than 10 percent of the national population: percentage of children between eleven and fourteen years old (o_child), percentage of widowed or divorced individuals (widowed & divorced), and percentage of individuals born overseas (overseas). Logarithmic transformation and Z score standardization are applied to the remaining input variables to ensure normality and a common scale. Pearson correlation coefficients are calculated between each pair of input variables to identify possible data redundancy, resulting in the removal of six highly correlated (>0.6; see Figure S.3) variables: married (married); younger children (y_child); infants (infant); individual residents in parish of birth (local_birth); individuals (as opposed to heads of household) in professional, managerial, or clerical occupations (g123); and individuals in service

occupations (g5). Seventeen variables were thus retained in the geodemographic classification.

Following Singleton, Pavlis, and Longley (2016), we seek to devise a temporally consistent geodemographic classification spanning 1881 to 1901. We pool data from a set of street segments identified in 1881, 1891, or 1901 together with nongeocoded streets identified by thoroughfare names and use k-means clustering (Vickers and Rees 2007) to derive a common classification. This makes it possible to examine transitions of streets extant throughout the period, as well as to compare the composition of new streets present in 1891 and 1901 with preexisting ones. We use the elbow method and silhouette analysis to settle on a six-cluster typology as the most parsimonious (see the online supplementary file, Figures S.4 and S.5), again consistent with the approach of Gale et al. (2016), which uses the greater number of available variables to represent the greater complexity of contemporary social structures. Radial plots detailing the distinctive profiles of the six clusters are shown in Figure 5, and these are used to develop the following "pen portraits" (Batey and Brown 1995) of the six groups.

1. High social status households and service workers. Principally headed by professionals, managers, or clerical workers, many of these households retain resident (single, and predominantly female) housekeepers, maids, governesses, or other domestic service workers. Partly as a result, but also because of live-in relatives and extended family, average family sizes are the largest of all groups. Household heads are the least likely to reside in their parish of birth. Overall, longevity is just above average, perhaps reflecting the different circumstances of household heads and those in domestic service. Within London, this group is found around Hyde Park and Regent's Park, as well as outlying areas south of the Thames (Figure 6). Beyond London, this group is particularly evident in established towns and cities such as those Edinburgh (Figure S.6), Birmingham (Figure S.7), Cardiff (Figure S.8), and Liverpool (Figure S.9).

2. Sales and service families. This group hosts the highest concentrations of sales workers (e.g., shop assistants, insurance salesmen, and estate agents), although professionals, managers, and clerical workers are also present in significant numbers. Households are small in size, households with more than six children are rare, and many adults (including service workers) are present. The group's life span is the longest of all groups. Women are quite active in the
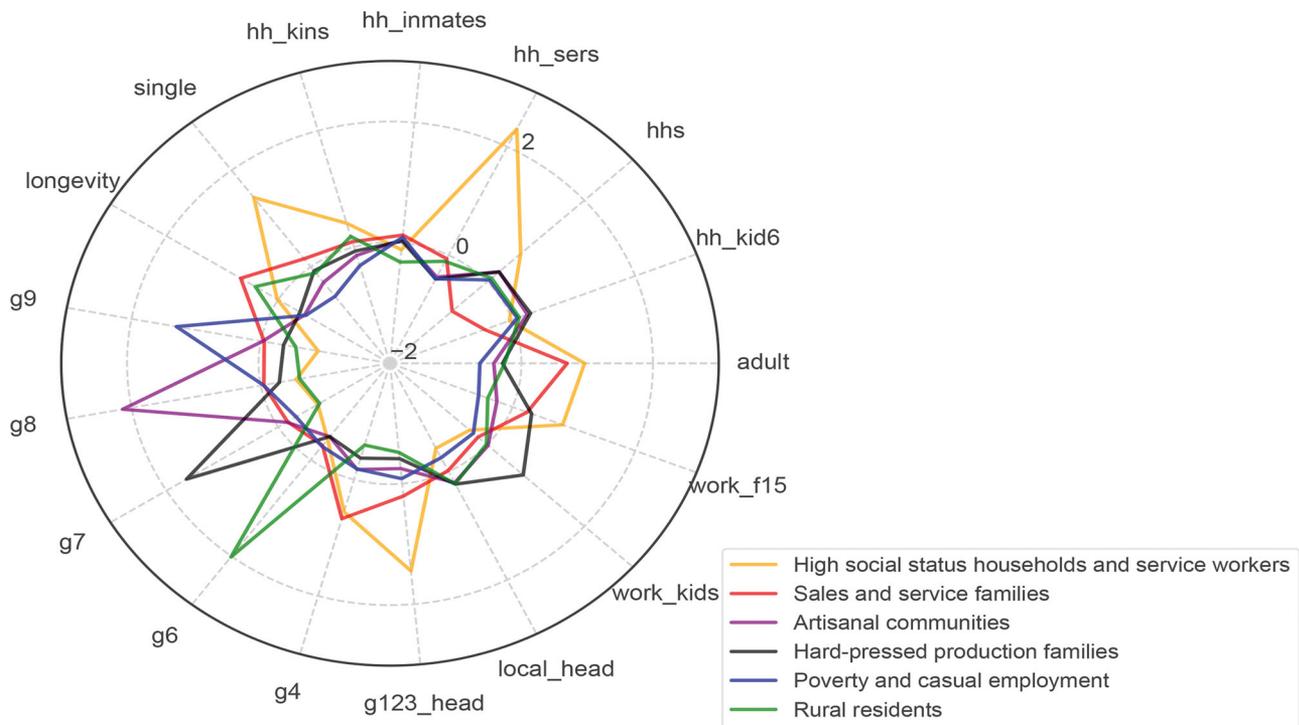
Figure 5. Radial plot showing the group variations from the mean values of the input variables across the pooled 1881–1901 census data.

labor market. Enclaves of this group are found throughout London's inner suburbs as well as other cities such as Edinburgh (Figure S.6).

3. Artisanal communities. This group has a very distinctive occupational structure, with high male employment rates in production and related work including shoemakers, blacksmiths, toolmakers, and jewelers. Female employment rates are quite low, and marriage rates are high. Households tend to be large and include many young children. Longevity is below average and household heads are unlikely to have remained resident in their parishes of birth. This group occurs widely throughout the country, reflecting the universal demand for many artisanal products, but concentrations also occur in and around Birmingham (Figure S.7) and in parts of other major urban areas, such as South Hackney in London.

4. Hard-pressed production families. Employment is predominantly in factory production, raw material processing, or related occupations such as mining, weaving, or tailoring. Households are large and include many children. Female employment is common and child employment rates are particularly high. Individuals are likely to have remained resident in their parish of birth. Incidence of individuals aged beyond average life expectancy is the third lowest of all groups. Vast communities of this group are found in the coal mining areas of South Wales

(see Figure S.8), Durham, and Yorkshire and the mill towns in and around Manchester and in Yorkshire. In London, the main occurrence of the group is the dye works and foundries in present-day Tower Hamlets.

5. Poverty and casual employment. Physical labor is predominantly in engine or other equipment operation, bricklaying, construction work, or dock labor, and the casual nature of such employment might account for the low recorded incidence of child and female employment. Marriage rates are very high and families include above-average numbers of children. Longevity is the lowest of all groups and families are likely to take in lodgers. Migration, transience, or movement between close-packed urban parishes means that many household heads are no longer resident in their parishes of birth. This group occurs throughout urban Great Britain, with particular concentrations in Merseyside (see Figure S.9), whereas in London the group is found near the docks that line the Thames.

6. Rural residents. Workers are employed in agriculture, animal husbandry, forestry, or fishing and are resident throughout the countryside. Household heads tend to remain in their parishes of birth. Residence with relatives and extended families is common. Household size tends to be large and includes many children. Longevity is above average.
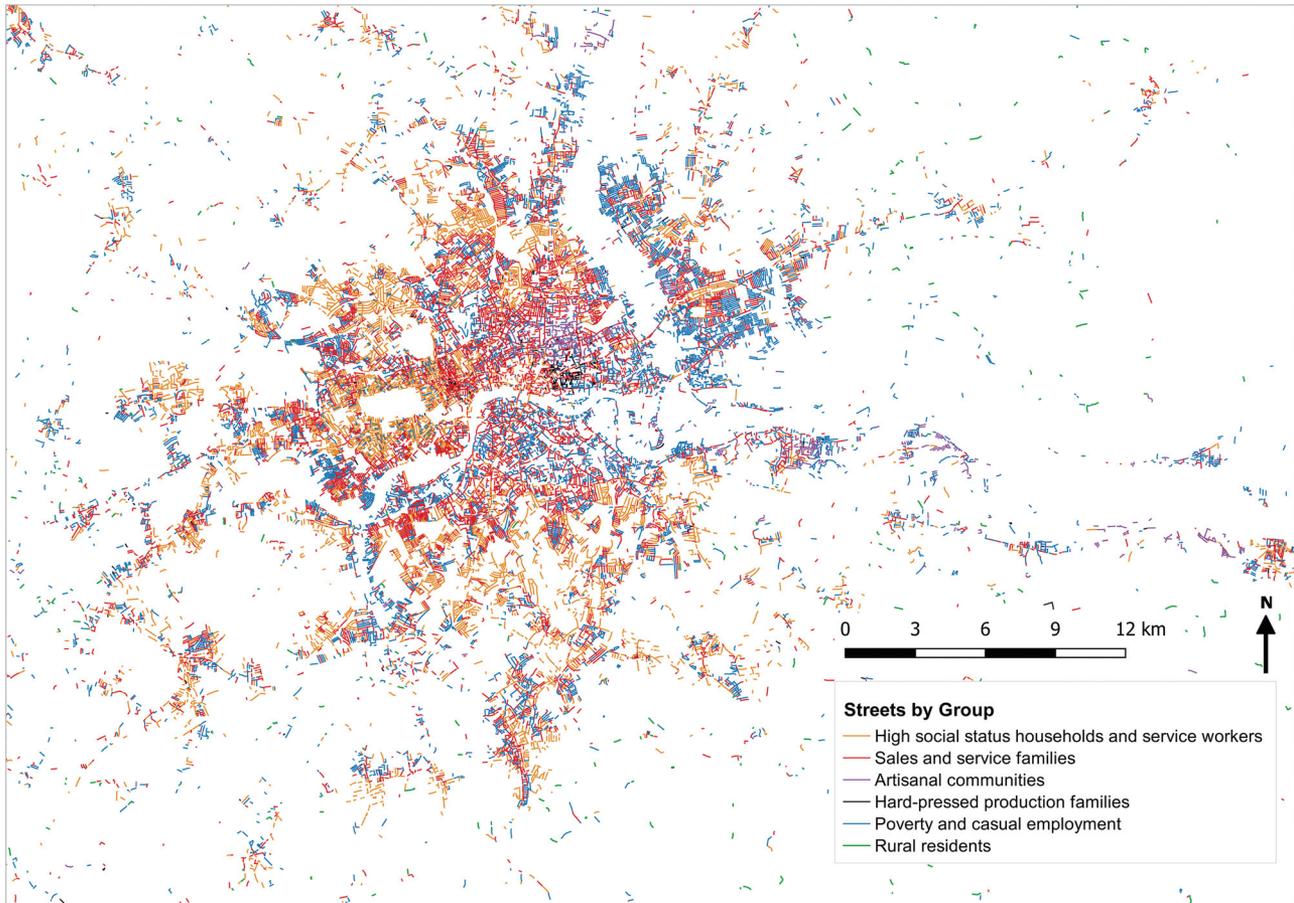
Figure 6. Geodemographic group assignments of historical residential street segments in and around London in 1901.

Figure 6 presents an illustration of the 1901 distribution of the geodemographic groups in London. We note that this map presents a broadly contemporaneous snapshot to that assembled over seventeen years by social reformer Charles Booth and that the broad brush of social groupings is essentially similar to the London Poverty Maps[4] disseminated in digital form by the London School of Economics and by Orford et al. (2002). The Booth maps offer much greater differentiation of the lower socioeconomic echelons than we have been able to derive using census data, although the Great Britain–wide coverage of our classification enables some benchmarking of conditions in London with those prevailing elsewhere across the island.

The relative sizes of our groups are set out in Table 3, which also reports the Great Britain–wide changes in geodemographic groups over the periods 1881 to 1891, 1891 to 1901, and 1881 to 1901. The respective percentages of all streets remaining in the same group over these periods are 64 percent, 64 percent, and 59 percent, respectively. Even allowing for the lower number of groups than occupational categories reported in Table S.2, we contend that the geodemographic classification provides a clearer basis than occupation alone for comparing residential geography over space and time.

Table 4 presents the breakdown of numbers and percentages of the total streets in 1881, 1891, and 1901 and the new streets in 1891 and 1901 ascribed to the geodemographic groups. New streets are attributed to every group, with the increases in sales and service families over the study period consistent with the rise of the lower middle class identified in previous historical geography research. Despite additions to streets attributed to rural residents in 1891, which might reflect densification of rural settlement such that more street segments pass the "residential street" threshold, there is a marked decrease in the share of total street segments attributed to rural residents.

Table 3. Geodemographic groups of all continuously occupied residential street segments in 1881, 1891, and 1901, and changes between geodemographic groups over this period (1881–1891, 1891–1901 and 1881–1901)

		High social status households and service workers		Sales and service families		Artisanal communities		Hard-pressed production families		Poverty and casual employment		Rural residents		Total 1881 and 1891
		1891	1901	1891	1901	1891	1901	1891	1901	1891	1901	1891	1901	
High social status households and service workers	1881	**58.8** / 5,588	**54.0** / 5,131	**32.8** / 3,114	**38.6** / 3,664	**1.8** / 168	**1.8** / 169	**1.2** / 116	**1.1** / 100	**3.7** / 353	**3.1** / 293	**1.7** / 161	**1.5** / 143	**11.3** / 9,500
	1891		**61.6** / 4,477		**30.5** / 2,220		**1.8** / 129		**1.5** / 108		**3.1** / 223		**1.5** / 112	**8.7** / 7,269
Sales and service families	1881	**5.2** / 922	**4.3** / 757	**64.8** / 11,403	**67.7** / 11,911	**5.6** / 982	**5.7** / 1,005	**7.2** / 1,267	**6.4** / 1,134	**14.1** / 2,479	**13.2** / 2,326	**3.0** / 532	**2.6** / 452	**21.0** / 17,585
	1891		**6.3** / 1,454		**67.6** / 15,564		**5.1** / 1,185		**5.7** / 1,312		**12.8** / 2,946		**2.5** / 565	**27.5** / 23,026
Artisanal communities	1881	**1.4** / 141	**0.8** / 83	**14.2** / 1,447	**20.9** / 2,129	**59.7** / 6,086	**56.6** / 5,776	**7.5** / 764	**7.1** / 726	**16.2** / 1,656	**13.7** / 1,402	**1.1** / 108	**0.8** / 86	**12.2** / 10,202
	1891		**0.9** / 98		**17.3** / 1,825		**62.2** / 6,563		**7.2** / 756		**11.8** / 1,249		**0.6** / 65	**12.6** / 10,556
Hard-pressed production families	1881	**0.8** / 152	**0.6** / 106	**11.5** / 2,170	**18.8** / 3,560	**6.3** / 1,192	**7.8** / 1,478	**72.0** / 13,603	**64.0** / 12,096	**8.2** / 1,550	**7.6** / 1,438	**1.2** / 229	**1.2** / 218	**22.6** / 18,896
	1891		**0.6** / 110		**16.6** / 2,881		**5.9** / 1,021		**69.9** / 12,150		**6.2** / 1,086		**0.8** / 141	**20.8** / 17,389
Poverty and casual employment	1881	**1.6** / 319	**1.2** / 241	**20.3** / 4,042	**27.8** / 5,539	**10.2** / 2,037	**12.2** / 2,428	**7.4** / 1,466	**7.4** / 1,473	**57.1** / 11,371	**48.8** / 9,718	**3.4** / 669	**2.5** / 505	**23.8** / 19,904
	1891		**1.1** / 206		**24.8** / 4,484		**10.9** / 1,981		**6.6** / 1,200		**54.0** / 9,781		**2.5** / 451	**21.6** / 18,103
Rural residents	1881	**1.9** / 147	**1.9** / 148	**11.1** / 850	**16.1** / 1,235	**1.2** / 91	**1.6** / 122	**2.3** / 173	**2.0** / 151	**9.0** / 694	**9.1** / 695	**74.5** / 5,719	**69.4** / 5,323	**9.2** / 7,674
	1891		**1.6** / 121		**14.3** / 1,064		**1.3** / 99		**2.1** / 154		**7.9** / 587		**72.7** / 5,393	**8.9** / 7,418
Total 1901			**7.7** / 6,466		**33.5** / 28,038		**13.1** / 10,978		**18.7** / 15,680		**18.9** / 15,872		**8.0** / 6,727	**100** / 83,761

Table 4. Numbers and percentages of all street assignments in 1881, 1891, and 1901, and corresponding figures for new residential streets

Geodemographic groups		1881	1891		1901	
		All streets	All streets	New streets	All streets	New streets
High social status households and service workers	Counts (%)	30,153 (12%)	22,683 (10%)	12,854 (11%)	32,328 (11%)	20,000 (11%)
Sales and service families	Counts (%)	45,586 (18%)	53,523 (23%)	23,289 (19%)	87,975 (29%)	44,237 (25%)
Artisanal communities	Counts (%)	25,492 (10%)	23,037 (10%)	10,268 (9%)	35,830 (12%)	19,947 (11%)
Hard-pressed production families	Counts (%)	52,067 (21%)	43,620 (19%)	20,491 (17%)	55,079 (18%)	31,318 (18%)
Poverty and casual employment	Counts (%)	54,024 (22%)	47,706 (20%)	24,387 (20%)	58,281 (19%)	36,237 (20%)
Rural residents	Counts (%)	43,711 (17%)	42,771 (18%)	28,314 (24%)	37,446 (12%)	26,355 (15%)
Total		251,033 (100%)	233,340 (100%)	119,603 (100%)	306,939 (100%)	178,094 (100%)

Note: Values in bold indicate the largest proportions in the columns separately.

Case Study Analyses of Geodemographic Change

Our geodemographic and street segment infrastructure makes it possible to develop comparative historical analyses over space and time, at granular intra- and interurban scales. We observe that the internal residential structures of contiguous urban areas across nineteenth-century Great Britain take a number of very different forms, reflecting town or city function and social organization within the wider settlement system. We can develop a system-wide perspective, representative elements of which are shown in Figure 7, in which the radial distances on the plots identify the percentages of the populations of the selected urban areas (defined by the 200 m threshold) that fall into each geodemographic group in each period. The selected areas point to a tentative typology arising from inspection of the plots from the wider settlement system, namely, (1) service and administrative centers, such as Bristol, Edinburgh, and London that host distinctive blends of casual, professional, and service employment; (2) urban structures that are underpinned foremost by artisanal occupations, such as Birmingham and nearby Midlands towns such as Sheffield; (3) industrial towns such as Manchester and Nottingham with blends principally of production and service workers; (4) ports such as Liverpool and Hull that primarily function through casual and service employment; and (5) factory towns such as Bradford and Dundee in which production workers predominate but service workers are also present.

A sizable number of freestanding urban areas clearly developed strong functional specialization in manufacturing or mining industries, and the study period charts the rise of emergent middle-class roles in retail and other service occupations. The relative size and residential concentrations of households that fulfilled these roles vary between settlements, which is key to understanding the development trajectories followed by these settlements. The Great Britain–wide temporal trends identified in Table 4 are manifest across all of these towns and cities: The share of production, casual, and professional workers declines over time, whereas the proportions of sales and service workers increase. This overall pattern conceals settlement-specific variation in the level of change in street segment assignments, which, for the twenty largest settlements, ranges from a high of 53 percent in Bristol to just 25 percent in Birmingham (see Figure S.10). Comparative analysis of both the
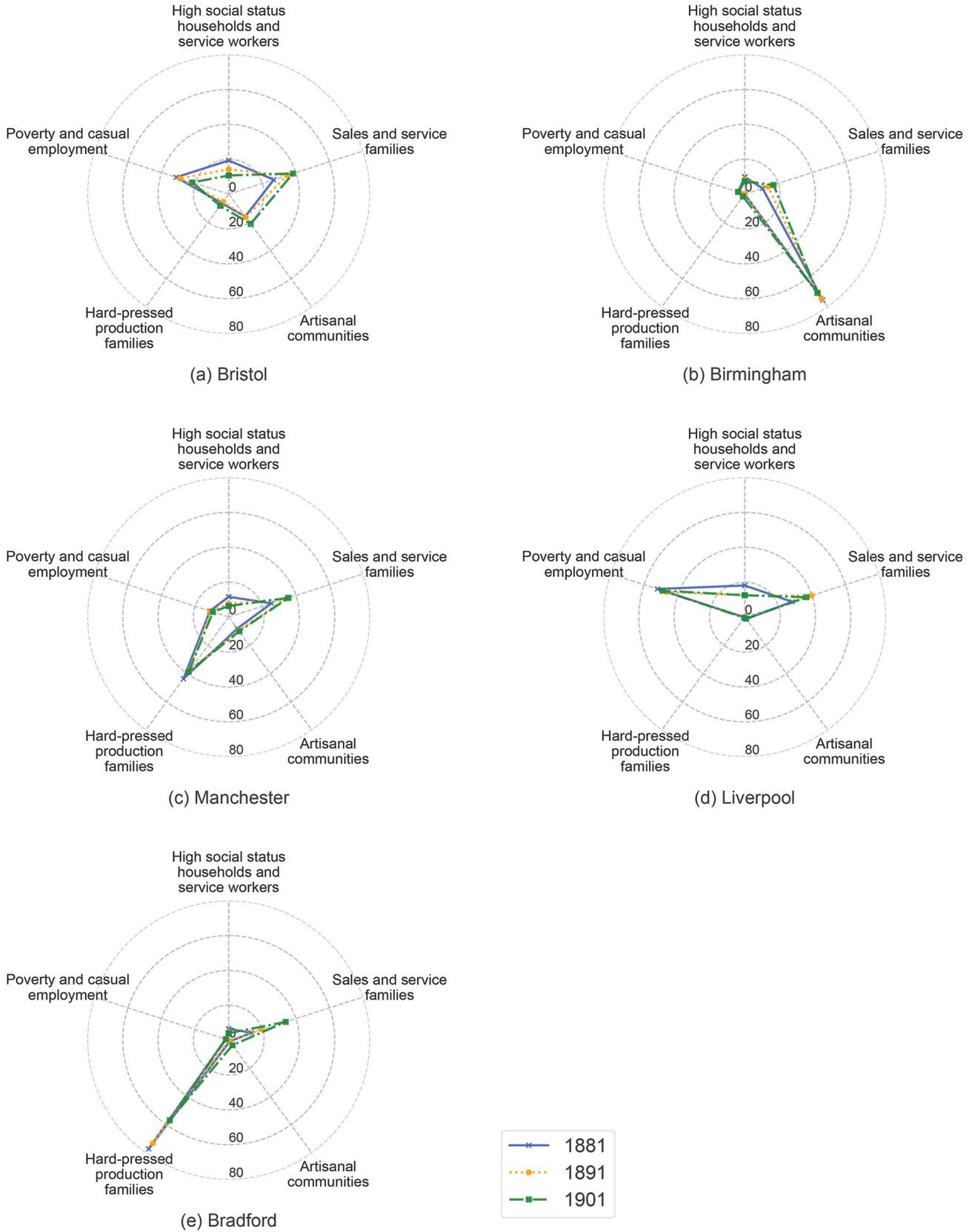
Figure 7. Radial plots of changes in population composition of (A) Bristol, (B) Birmingham, (C) Manchester, (D) Liverpool, and (E) Bradford over the period 1881 to 1901.
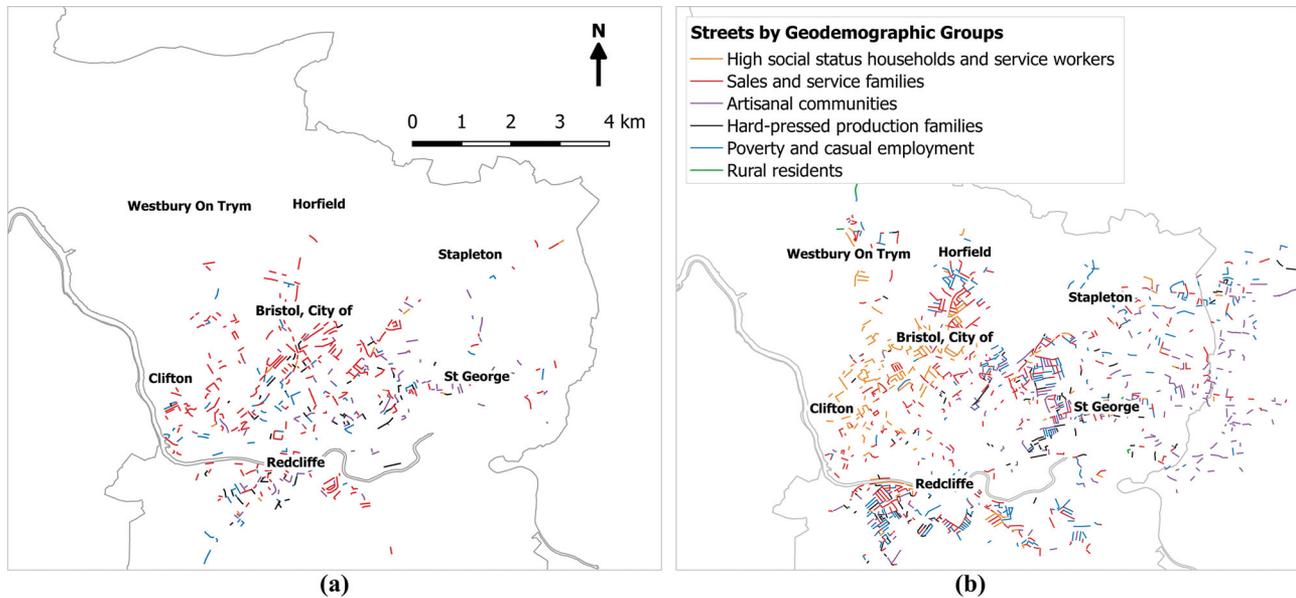
Figure 8. (A) Changes in the residential structure of 1881 streets in Bristol by 1901 and (B) 1901 group geodemographic assignments of new streets added, 1881 to 1901.

magnitude and detail of change is a fertile area for future research.

As an interim, the patterns of change for Bristol are shown in Figure 8 and for London in Figure 9. Figure 8A shows only the street segments present in 1881 that had changed geodemographic group by 1901—specifically those in the northwest to the sales and service families, contrasting with transitions to hard-pressed groups and casual employment in the city's industrial areas south of the Avon. These transitions are complemented by the group assignments of new streets, such as the new high-status neighborhoods in the north of Clifton and development in Southville neighborhoods newly dominated by factory and casual employment.

Figure 9A shows the 1901 transitions in the London streets introduced in Figure 6, and Figure 9B shows how these changes complement new street additions to the residential structure. This general pattern manifests the then-prevailing transitions toward sales and service families and poverty and casual employment. Here, the assignment of new streets in central city areas is more variegated, and identical group assignments are usually made to proximal streets. New high social status households and sales and service families are located along the 1881 bounding envelope while new enclaves of poverty and casual employment streets develop in the new eastern extents of present-day Newham and Waltham Forest.

Discussion

Over the last ninety years, intraurban geography has developed fundamental concerns with the ways in which variegated residential structures both manifest and enable social and economic change. What has become known as geodemographics, however, has remained focused on contemporary snapshots of the present and has foregone systematic attempts to generalize about the kaleidoscope of changes that characterizes Robson's urban social areas (Robson 1975) across settlement systems. The painstaking geographical analysis reported here has established a framework for understanding the geotemporal dynamics of changes in morphology and residential structure in all towns and cities in Great Britain over the last twenty years of the Victorian period, viewed in the context of their changed relative sizes and the functions performed by their residents. These are important contributions to the long-established geographical pieces of literature on the physical development of the Great Britain–wide settlement system and the evolving socioeconomic milieux that characterize the mosaics of urban land use in any time period. Highly granular data infrastructure is integral to charting these changes, and as quantitative geographers we are unapologetic that the foundations of the analytically rigorous measurement task have necessarily filled most of the available space in this article.
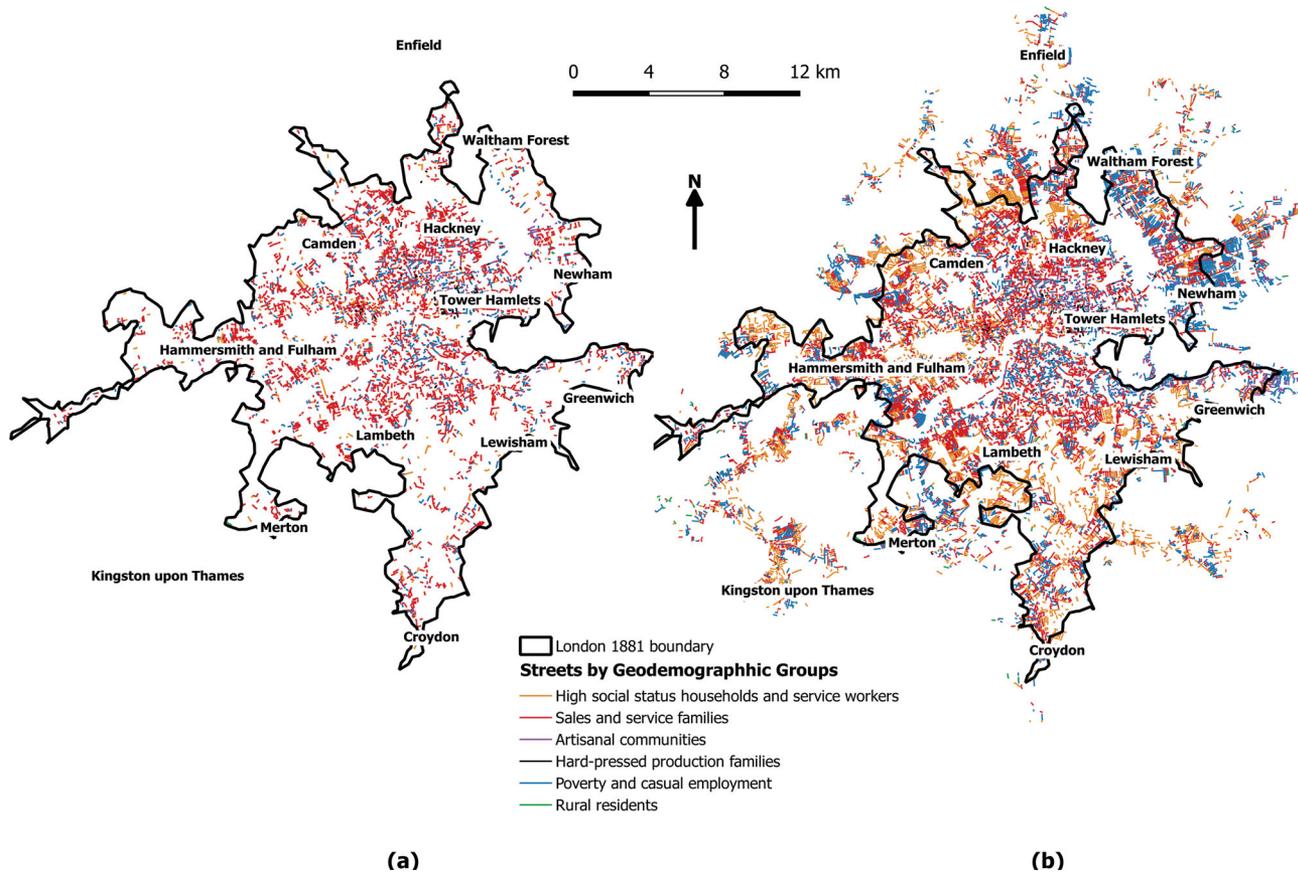
Figure 9. (A) Changes in the residential structure of 1881 streets in London by 1901 and (B) 1901 group geodemographic assignments of new streets added, 1881 to 1901 (1881 bounding envelope of the city shown for comparison).

We have proposed a granular street segment geography and associated distance thresholds that we believe are appropriate for generalized analysis of urban evolution and social change. In enabling historical geodemographic analysis, we establish baselines against which it becomes possible to characterize the detailed composition of residential areas within today's towns and cities and to visualize the degree to which settlements deviate from our Great Britain–wide mix of neighborhood types. The same granularity makes it possible to understand the residential trajectories on which different Victorian cities embarked and to characterize the residential structures of newly established neighborhoods with those of established residential areas.

As a first step in developing geotemporal demographics, we have investigated the mix of 2011 Output Area Classification geodemographic supergroups (Gale et al. 2016) that have today occupied the fabric of the core areas of the five cities represented in Figure S.11. Direct comparison of the elements of Figure 7 and Figure S.11 is not appropriate,

given the different range of variables and geodemographic domains investigated in the Output Area Classification. It is apparent, though, that the 1881 core areas today share greater similarities in urban lifestyle, population structure, and educational attainment. This said, two of the cities, Liverpool and Bradford, also include significant enclaves of high relative deprivation. If cities like these are indeed engines of economic and social change, it behooves future geotemporal demographics research to investigate the extent to which different outcomes manifest less diverse nineteenth-century economic and social structures and the degrees to which a broad-based social or artisanal structure laid the foundations to greater success elsewhere—as argued, for example, by Swinney and Thomas (2015) and echoing the classic work of Jacobs (1961) and Briggs (1993) on diversity and economic creativity. The kind of data infrastructure created here provides one approach to understanding how different cities are adaptable to economic transitions and the skill levels that underpin them.

Conclusion

The work reported here matters because it offers the prospect of greater empirically grounded understanding not only of how neighborhood change affects individual cities but also of how more and less successful city economies within city systems evolve. Grounding of this analysis at the level of the individual and household makes it possible to chart the changing social inequalities that characterize this evolution (Dorling 2015). Here we have built a consistent geodemographic and physical infrastructure for a twenty-year period that makes it possible to demonstrate the patterns of change in the built environment and the population that resides within it. As such, this contribution creates a Great Britain–wide framework within which the richness of individual census records can be viewed and comparative analysis of town and city evolution can be developed. This also facilitates detailed change analysis of individual urban forms alongside comparative analysis of developments across an entire settlement system. We thus establish a basis to the investigation of city and regional specialization and diversification that can be related to changes in morphology and migration patterns.

This analysis is at the same time comprehensive and formative, most obviously in that we are unable to georeference about 30 percent of addresses. Nongeocoded street segments (but not isolated, overwhelmingly rural addresses) are included in our cluster analysis of geodemographic structure, but there is bias in their omission from our historical maps that can only be corrected through detailed historical studies using archival maps and records (e.g., see Daunton 2001) or using other digital solutions (e.g., Digitising Scotland: Daras, Feng, and Dibben 2015). Yet with these caveats, we believe that our geodemographic classification can be considered to be population-wide, and the limits to success in georeferencing do not compromise our representations of urban extent because most omissions pertain to streets and courts that were well embedded in central urban areas by the start of our study period. Geodemographic classification uses many variables to summarize social structures of the time, although not, unfortunately, overcrowding, measures of which were only first included halfway through our study period, in the 1891 Census.

One of our important contributions is the definition of the spatial extents of urban residential settlements, because it frees our analysis from reliance on administrative jurisdictions—some of which, such as parishes, might not be fit for purpose following urbanization and industrialization. To the best of our knowledge, the city envelopes defined in our research are the first digital boundaries across Great Britain of the extents of residential areas in all significant towns and cities in late Victorian Great Britain, although it remains for future research to extensively explore other possible ways of fine-tuning the street clustering parameters and methods. In this context, fractal approaches to define urban boundaries (e.g., Tannier et al. 2011; Tannier and Thomas 2013) and regionalization algorithms for neighborhood delineation (Wei, Rey, and Knaap 2020), each present interesting paths to explore in further systematic studies.

Our classification and maps also provide a resource relevant to other recurring themes in geography, most obviously analysis of the dynamics of residential segregation (Lan, Kandt, and Longley 2020b) and neighborhood change attendant on changing positive and negative externality effects (e.g., Harris 2017). This would address two key issues in the study of urban historical geography: the interdependence between the highest and lowest social echelons, resident in proximal front and back streets and how the scale of residential segregation (Lan, Kandt, and Longley 2020) changed over time, partly as this interdependence became less important and as the rising homeowner class sought distancing of their investments from negative externalities such as factories or poor neighborhoods. Our ability to detect incremental changes in the dominance of the modal group at the street segment level is valuable in this context. The urban analytics tradition also has much to offer through quantitative metrics such as fractal dimensions (Batty and Longley 1994) to characterize urban space-filling in this regard.

In all of these respects, this research offers a fresh and data-intensive approach to the strands of literature on intraurban geography and residential structure and provides a novel and generalizable approach to relate the dynamics of change in the physical forms and demographic functions of cities. This development toward comprehensive geotemporal demographics offers the prospect of understanding how legacies of regional development shape today's successful and sustainable city systems.

Supplemental Material

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Notes

1. See https://www1.essex.ac.uk/history/research/icem/.
2. See https://www.ordnancesurvey.co.uk/business-government/products/addressbase-premium.
3. See http://www.visionofbritain.org.uk/data/.
4. See https://booth.lse.ac.uk/map.

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