Journal of the
Royal Statistical Society

SERIES A
Statistics
in Society

J. R. Statist. Soc. A (2011)
174, *Part* 1, *pp.* 1–16

Exploring the implications of changing census output geographies for the measurement of residential segregation: the example of Northern Ireland 1991–2001

I. G. Shuttleworth and C. D. Lloyd

Queen's University Belfast, UK

and D. J. Martin

University of Southampton, UK

[Received October 2008. Final revision January 2010]

Summary. One problem in analysing social and demographic change through time by using census data arises from differences in the size and shape of the geographical units that are used to output data between different years. Failure to correct for changing output geographies may lead to unknown and possibly large biases when comparing results through time between different censuses. The paper addresses this issue by using the example of residential segregation in Northern Ireland. It has two main objectives. Firstly, by compiling 2001 Northern Ireland census data on 1991 census output geographies it assesses the sensitivity of indices of residential segregation to these changes in geographical units. Secondly, it suggests a method by which census analysts can assess how sensitive their results are to changing output geographies when they cannot correct for these changes and must work with the data 'as they are'. A subsidiary aim is to contribute to the evidence base on residential segregation in Northern Ireland. The paper finds that indices of residential segregation are insensitive to changes in output geographies between 1991 and 2001. The reason suggested for this is that the units in each zonal geography are smaller than the spatial scale over which population counts are positively auto-correlated. The use of spatially weighted segregation indices is advanced as a generalizable means of learning about the geographical patterning of population in different censuses. It is argued that these insights combined with knowledge of the size of geographical units used in each census can help researchers elsewhere to judge how sensitive their results might be to changing census output geographies through time.

Keywords: Census analysis; Modifiable areal unit problem; Output geographies; Residential segregation; Spatial statistics

1. Introduction

A common problem which is faced by census users who wish to examine population changes through time is the differences in the shapes and sizes of the spatial units that are used to present data in successive censuses (Wong, 1997; Martin *et al.*, 2002). This is an example of the well-known modifiable areal unit problem as discussed by Openshaw (1984). For census data providers (and users) there is a tension between the creation of new spatial units in response to current social and political needs and the use of consistent units that permit comparisons

Address for correspondence: I. G. Shuttleworth, School of Geography, Archaeology and Palaeoecology, Queen's University Belfast, Belfast, BT7 1NN, UK.
E-mail: i.shuttleworth@qub.ac.uk

 0964–1998/11/174001

through time. Usually, requests for consistent units come second to the need for new units and so it is often difficult to compare 'like spatial units with like' through time as census geographies are in flux. Responses to this problem range from the extraction and dissemination of census data by using spatial units that are consistent through time (Shuttleworth and Lloyd, 2009) to the use of methods such as areal interpolation or the construction of look-up tables (Gregory and Ell, 2005; Martin *et al.*, 2002; Martin, 2003). There are uncertainties that are inherent in these procedures which can lead to a lack of trust in findings. However, census users who have less expertise and fewer technical resources may simply use the data 'as they are' without attempting to compensate for changing output geographies which may also lead to unknown and possibly large biases in comparative results through time.

Residential segregation has been a particular research interest in Northern Ireland (NI) and elsewhere (see, for example, Poole and Doherty (1996) and Shuttleworth and Lloyd (2009)), but the well-known technical difficulties that were outlined above mean that it is problematic to measure changes in segregation through time by using census data despite the public and policy interest in so doing, and despite the fact that census data are uniquely suited in other ways for this purpose. On the one hand, adjusting for changed output geographies might introduce imprecision but, on the other, failing to do so could also lead to other unknown and potentially important errors in some, but not in all, circumstances. Wong (1997), for example, explored situations in which differing zonal units might, or might not, matter. He demonstrated that differences in the value of the index of dissimilarity, D, (which is defined below) for different aggregations of the population (what he termed 'scale sensitivity') were a function of the spatial auto-correlation of the population in relation to the zonal units that are used to output counts. Wong (1997) also argued that if population counts were negatively spatially auto-correlated the use of zones of different size would result in different values of D. Conversely, if the population counts were positively spatially auto-correlated then using zones of different sizes and shapes would make little difference for spatial units that are smaller than the area—or scale—over which population counts are positively spatially auto-correlated. Wong (2008) adopted a multi-dimensional approach to the study of changes in segregation, emphasizing the importance of local measures but not explicitly addressing issues of changes in geography. An assessment of the effect of different output geographies therefore hinges on

(a) the spatial structure of the population at each census and
(b) its relation to census zonal geography.

This paper aims to contribute to the literature on the measurement of population change through time by using census data. The case of residential segregation 1991–2001, as measured by the NI census, is used as an example. There are three main objectives. Firstly, the paper seeks to assess the effect of changing output geographies in 2001 in comparison with 1991 by examining the sensitivity of indices of residential segregation to these changes. Secondly, it attempts to add to the evidence base on changes in residential segregation in NI through time, building on the work of Shuttleworth and Lloyd (2009) and others such as Poole and Doherty (1996). Thirdly, it suggests a method through which census analysts more generally can make better judgements about the sensitivity of their results to changing output geographies when they cannot correct for these changes and must work with the data 'as they are'. The paper addresses these issues through the unique approach by which selected 2001 NI census data were recompiled, in their entirety, for analysis on 1991 census output geographies in a secure setting in the Northern Ireland Statistics and Research Agency (NISRA). This precedent will be of interest to researchers elsewhere who wish to make fuller use of census resources.

The paper has four main sections. The next section discusses the data that are used in the analysis and census output geographies. Its purpose is to outline more fully the background to the analysis, the data that were used and the rationale for the analytical choices that were made. After that, the method by which the analyses were undertaken will be presented. This is of importance in terms of the innovative modes of working that were developed to work with the NISRA as well as in presenting information on the indices that were calculated. Following this, results will be presented which assess the implications of changing census output geographies for the measurement of segregation 1991–2001 and outline ways, through exploring the spatial structure of the population, in which better judgements more generally can be made about the sensitivity of results to changing census output geographies. Finally, the findings are assessed in the concluding section.

2. Context of the data

The paper makes use of 2001 and 1991 religion and 2001 community background data from the NI census and we begin by discussing these variables. Since the analysis is based on the recompilation of these variables from the 2001 census on 1991 small areas it is also necessary to introduce the geographies of these censuses which are used later to characterize the geographical structure of the NI population.

2.1. Religion and community background data in the Northern Ireland census

Data on religion are very important in the NI context for the measurement of residential segregation. This is because religion is a marker of cultural, national and political allegiance (Macourt, 1995) with Catholics normally being associated with Irish nationalism and Protestants with British identity. Population numbers are therefore seen as having constitutional implications since NI was, at least in part, delimited on the basis of a head count of Catholics and Protestants (Anderson and Shuttleworth, 1998). It is therefore unsurprising that census analysis in NI has a strong focus on these questions (see, for example, Compton and Power (1986) and Poole and Doherty (1996)). Residential segregation is also often seen as a proxy for the state of community relations so its measurement is controversial but also difficult because of the problems that are inherent in measuring change through time by using the census.

The questions and responses selected for analysis were as follows:

(a) 2001 religion question—Roman Catholics, Protestants (including Presbyterian, Church of Ireland, Methodist and other Christians (including Christian related)); the other categories of ‘other religions’ and ‘no religion or religion not stated’ were excluded from this analysis;
(b) 2001 community background question—Roman Catholic, Protestant and other Christians (including Christian related); the categories of ‘other religions and philosophies’ and ‘none’ were excluded from this analysis;
(c) 1991 religion question—Roman Catholic, Protestant (including Presbyterian, Church of Ireland, Methodist and other denominations); other denominations included other Christians but also some other non-Christian religions; the effect of the inclusion of non-Christians was minimal because of their very small numbers. As above, those who had no religion or did not state a religion were excluded from this analysis.

There are differences between the 2001 religion and community background questions. The religion question is voluntary and seeks to discover respondents’ religious identity. It has been a feature of the NI census since its inception. However, since 1971 there have been varying degrees of non-response to this voluntary question. The new 2001 question on community background was developed as a way to overcome this problem—although some see it not as a problem but as an opportunity—as traditional cultural and religious identities are eroded by secularization. The question asks about the religious tradition that respondents currently profess, or were brought up in if they have no religion currently. Unlike the religion question, this question was not voluntary and data on community background were therefore imputed as part of the 2001 census process when people declined to give a response. This means that the 2001 census had two measures of religion or community affiliation. Given this context, it was therefore important to use both 2001 questions together with the 1991 religion question.

2.2. Census output geographies in Northern Ireland

Census output geographies in NI have the same structure as in the rest of the UK. In 1991, enumeration districts (EDs) and wards were used to present census data. EDs nest within wards. In 2001, EDs were replaced by output areas (OAs)—OAs also nest within wards—and wards (albeit with different boundaries from those in 1991) remained in use. These units are widely used for the measurement and description of local populations. The characteristics of the 1991 and 2001 NI census output geographies are summarized in Table 1. The differences between 1991 and 2001 wards in NI are less than the differences between the ED and OA geographies. There were 566 wards in 1991 and 582 in 2001. Many wards kept the same boundaries in 2001 as in 1991, but others represent a departure from the 1991 position with some 1991 wards, for instance, being subdivided in 2001.

In 1991 in NI there were 3729 EDs compared with 5022 OAs in 2001. As might be expected, 2001 OAs tended on average to have smaller populations when measured by both the mean and the median. The geographies and boundaries of 1991 EDs and 2001 OAs are fundamentally different, as they were created by using different methods and with different intentions. EDs were constructed before the census whereas OAs were generated by using data collected during the census. OAs in 2001 were designed by using an automated zone design methodology (Martin, 1997; Martin *et al.*, 2001). A social homogeneity constraint was applied, based on an intra-area correlation measure, but this was secondary to the constraint of obtaining total population and household numbers above threshold and close to the target size. The objective was to create OAs of similar population size that were internally socially homogeneous. The methodology minimized within-OA variability and maximized between-OA variability on the basis of the design variables housing tenure (e.g. owner occupied or rented) and housing type (e.g. semi-detached or terraced). The same variables were used in NI as in England and Wales. Religion and community background were not used as variables in the OA geography design

Table 1. Zones: summary statistics†

Zone	*Year*	*N*	*Minimum population*	*Maximum population*	*Mean population*	*Median population*	*Minimum size (km^2)*	*Maximum size (km^2)*	*Mean size (km^2)*	*Median size (km^2)*
EDs	1991	3729	70	2284	427	428	0.001	55.062	3.653	0.744
OAs	2001	5022	109	2582	336	333	0.001	101.317	2.712	0.147
Wards	1991	566	775	9752	2788	2443	0.183	191.682	24.068	5.577
Wards	2001	582	761	9572	2896	2600	0.189	205.112	23.401	4.746

†1991 ED and ward figures refer to the 1991 population (total 1 577 866); 2001 OA and ward figures refer to the 2001 population (total 1 685 297).

because of their social and political sensitivity. The housing variables were seen as being neutral and exogenous to the political issues that are associated with religion. The same computer programs were used to create OAs in NI as in England and Wales. In NI these were based on digitized postcode boundary maps whereas in England and Wales postcodes do not have formal boundaries and space filling polygons were generated automatically, resulting in more irregular shapes. Nevertheless, the two zonal systems remain strongly comparable. In contrast, EDs in 1991 were used both to collect and to output the census—they were not designed to be socially homogeneous for output purposes in the same ways as OAs and did not directly take account of religion or community background. However, their design, particularly in urban areas, did reflect the built environment and this might in part, and unintentionally, mirror religious geography in some places. Everything else being equal, then, it might be assumed that OAs would exaggerate the level of segregation in comparison with EDs because of their smaller size and their design which aimed at greater social homogeneity since housing structure, in some places, could be related, albeit indirectly, to the geography of religion. In NI, counts from the census are also provided on 1-km grid squares (for all NI from 1971) and 100-m grid squares (urban areas only for 1971–1991, and all areas in 2001). Shuttleworth and Lloyd (2009) utilized the NI grid square product in an analysis of changes in residential segregation between 1971 and 2001. These data are referred to later to support the argument.

3. Methodological context

This section will discuss how the data for the analysis were accessed and then the indices that were calculated to measure segregation and to characterize the geographical structure of the NI population.

3.1. Access to data

To assess how far changing output geographies influence the values of segregation indices it was necessary to place 2001 NI census data into 1991 output geographies. This permitted a direct assessment of the difference between measures of segregation that were calculated by using 2001 data on 2001 boundaries and on 1991 boundaries using the same 2001 data. It was considered better to place 2001 data on 1991 boundaries than vice versa because addresses in the 2001 census were georeferenced to 1-m spatial resolution, whereas the geographical referencing in the 1991 census was only to 100 m and so could not be linked accurately to 2001 OA boundaries.

The process was a radical new step in the UK context because it necessitated the recompilation of the religion and community background variables from the 2001 census on a different output geography. The prime difficulty was confidentiality owing to the potential danger of disclosure through differencing (see Duke-Williams and Rees (1998)). This refers to the unintended release of census data for populations that are smaller than a specified size of threshold, through the overlay and subtraction of data for two geographical areas which are themselves above threshold. Published census outputs are designed to avoid this possibility but the release of the same data aggregated to both 1991 and 2001 OAs would potentially create small overlaps for which subthreshold counts could be derived. This potential problem could only be avoided for sure by the non-release of census data to the research team and analysis in house by the NISRA. Hence, after 2001 religion and community background counts had been compiled by using 1991 census geographies by NISRA staff it was agreed that the research team would write programs in Fortran to produce the desired statistics. The accuracy of the Fortran programs was checked by running them on a dummy database in the NISRA, running them on the same dummy database externally, and then comparing the results. These programs were then sent to the NISRA where they were vetted. They were then compiled and run, by NISRA staff on NISRA machines, on the recompiled 2001 census database. The outputs that were generated were aggregate segregation indices but these were then carefully checked by NISRA staff to ensure that they were non-disclosive before they were returned to the research team. This is analogous to, but goes beyond, the 'safe setting' environment used to access confidential census information elsewhere in the UK and the USA (Marsh *et al.*, 1994).

3.2. Indices and measures of segregation—zone design and scale effects

The analyses of segregation were conducted by using concentration profiles and three indices of segregation that were calculated by the Fortran routines. Concentration profiles were introduced by Poulsen *et al.* (2002) and were used by Johnston *et al.* (2005) to examine racial segregation in Bradford. Shuttleworth and Lloyd (2009) used concentration profiles to explore residential segregation in NI in 1971, 1991 and 2001. Concentration profiles indicate the percentage of a group who live in areas with more than a given proportion of people of that same group. For example, the concentration profile for Protestants in NI can be used to ascertain the proportion of Protestants who live in areas which have a population which is 75% or more Protestant. Concentration profiles capture an additional dimension of residential segregation and complement the results that are obtained by using the segregation indices detailed below. The concentration profiles allow assessment of differences in the degree to which a population group is residentially segregated with change in the zonal system that is used to aggregate counts.

Four indices are used to measure the dimensions of evenness and exposure (Massey and Denton, 1988). These are two commonly used dimensions in segregation analysis. Evenness refers to the differential distribution of two (or more) groups across an area for a given set of zones. If a minority group is distributed unevenly across the areal units that are used to report population counts, it may be considered segregated (Massey and Denton, 1988). The index of dissimilarity, D, which is a widely used measure of evenness, is applied here. The segregation index S_m, which is another measure of unevenness (Gorard and Taylor, 2002), is also applied for reasons that are discussed below. Exposure, the second of the two dimensions of segregation that are considered in this analysis, refers to the degree of potential contact between members of minority and majority groups. The interaction index ${}_mP_n^*$ and the isolation index ${}_mP_m^*$ are used in this study to measure exposure. ${}_mP_n^*$ measures interaction between members of group m and group n, whereas ${}_mP_m^*$ measures the degree to which members of group m interact with other members of that group (Lieberson, 1981; Massey and Denton, 1988). In the analysis below, m indicates Catholics and n indicates Protestants. The indices are the same as those used by Shuttleworth and Lloyd (2009) and were considered, along with the concentration profiles, to represent the most important dimensions of residential segregation for the present purpose.

The index of dissimilarity, D, indicates the total differences between the spread of the two population groups over all of the areal units; it is given by

$$D = 0.5 \sum_{i=1}^{I} \left| \frac{N_{im}}{N_m} - \frac{N_{in}}{N_n} \right| \tag{1}$$

where N_{im} and N_{in} are counts of Catholics and Protestants respectively for areal unit i and there are I units. N_m and N_n are the total population counts for the two groups across the whole of the study area. D takes a value between 0 and 1, where a value of 0 indicates complete evenness (for example, all zones have 60% of one group and 40% of the other group) and 1 indicates complete segregation (i.e. all zones comprise members of only one group).

For a particular group the segregation index summarizes over subareas the differences between the proportion of the group in the subarea and the proportion of all the population in the subarea (Gorard and Taylor, 2002); for the Catholic group m it is given by

$$S_m = 0.5 \sum_{i=1}^{I} \left| \frac{N_{im}}{N_m} - \frac{N_i}{N} \right| \tag{2}$$

where N is the total population. In the following analysis the corresponding Protestants index S_n is also calculated. It can be noted that $D = S_m + S_n$. Gorard and Taylor (2002) argued that, since such a segregation index compares the proportion of one group with the total for one zone, it remains constant regardless of changes in the absolute levels of one group. In contrast, D compares the proportion of two groups in a zone and so that index does change if the absolute levels of one group change.

The interaction index ${}_mP_n^*$ is a measure of the degree to which members of the minority group m (i.e. Catholics) are exposed to members of the majority group n (i.e. Protestants) (Massey and Denton, 1988). The index takes a value between 0 and 1, where larger values indicate more interaction between members of the two groups; it is given by

$${}_mP_n^* = \sum_{i=1}^{I} \frac{N_{im}}{N_m} \frac{N_{in}}{N_i}. \tag{3}$$

The isolation index ${}_mP_m^*$ is the converse of the interaction index and it measures the degree to which members of the minority group m (Catholics, although the measure is also computed for Protestants) are exposed only to other members of that group. Like the interaction index, the isolation index takes a value between 0 and 1, where large values indicate greater interaction with members of the same group; it is given by

$${}_mP_m^* = \sum_{i=1}^{I} \frac{N_{im}}{N_m} \frac{N_{im}}{N_i}. \tag{4}$$

In this analysis, only the results for the isolation index are reported since, in the case of two groups such as Catholics and Protestants, ${}_mP_n^* + {}_mP_m^* = 1$. An alternative version of the isolation index has been proposed whereby the index is corrected to take account of the relative size of a given group (Noden, 2000; Johnston *et al.*, 2005):

$${}_mMP_m^* = {}_mP_m^* - \frac{N_{im}}{N}. \tag{5}$$

Noden (2000) defined N_{im}/N as the regionwide component whereas ${}_mMP_m^*$ is termed the within-region (here, NI) differences component. Such a measure is useful in an application that is concerned with change through time with changing proportions of members of each group and was included for that reason.

3.3. *Exploring the spatial structure of the population*

Assessments of the spatial structure of the population can be developed in a variety of ways. Firstly, they can be informed by mapping population distributions at different censuses and reviewing accounts of population change through time such as locality studies and media reports to gather qualitative insights. However, this type of evidence can sometimes be contradictory—qualitative accounts of local population change, as in NI, can sometimes run counter to the statistical evidence—and so at best this ‘softer’ evidence can only colour interpretation. It is better, then, to seek to characterize residential segregation quantitatively at a variety of spatial scales. This provides insights into the geographical distribution of the population and the different ways in which it is patterned. In this example, it is important to know more about the geography of the Catholic and Protestant populations and how they cluster at local, city and NI-wide spatial scales. This information can be obtained through an additional method—the use of spatially weighted indices of segregation. Geographically weighted indices reflect the likelihood that interactions will decrease as distances between neighbourhoods increase and so add something extra to indices (e.g. D(adj)) that deal only with neighbouring zones (Wong, 1993).

Geographically weighted indices can be used to explore the spatial structure of the population in relation to census output geographies. The spatially weighted indices have an analogous function to that of population variograms (functions which relate the difference between populations at particular locations to the distance and direction by which they are separated) in that they capture information about the geographical scales over which population varies but in a way (e.g. through segregation indices) that is likely to be more relevant to analysts of segregation. Wong (1993, 2003a) and others have developed global measures of segregation that account for spatial contiguity. However, in the present paper, spatial variants of D, ${}_mP_n^*$ and ${}_mP_m^*$ that were defined by Feitosa *et al.* (2007) are applied. With these measures, a spatially weighted population count is necessary:

$$\breve{N}_{im} = \sum_{j=1}^{I} w_{ij}(N_{jm}) \tag{6}$$

where N_{im} is the population of group m for zonal unit i. The distance decay function is given by w_{ij}. In other words, the weighted population of group m at location i is the weighted sum of the population of the group at neighbouring locations (indexed by j). The geographical weights that are employed are here determined by the Gaussian weighting scheme (Fotheringham *et al.*, 2002):

$$w_{ij} = \exp\{-0.5(d_{ij}/\tau)^2\} \tag{7}$$

where d_{ij} is the distance between locations i and j and τ is termed the bandwidth, which determines the size of the geographical kernel. A small bandwidth emphasizes local features whereas a large bandwidth captures information on variation over larger areas. The weighted proportion of group m at location i is given by

$$\breve{\rho}_{im} = \breve{N}_{im}/\breve{N}_i \tag{8}$$

where $\breve{N}_i$ is the weighted total population, which is derived following equation (6), but for all individuals. Feitosa *et al.* (2007) defined a spatial version of $D(m)$, which is a generalized version of D that allows for more than two population groups. The spatial version of the index is given by

$$\breve{D}(m) = \sum_{i=1}^{I} \sum_{m=1}^{M} \frac{N_i}{2NI} |\breve{\rho}_{im} - \rho_m| \tag{9}$$

with

$$I = \sum_{m=1}^{M} \rho_m(1-\rho_m) \tag{10}$$

where N is the total population, N_i is the population of zone i, ρ_m is the proportion of group m in the study area and $\breve{\rho}_{im}$ is the proportion of group m in the neighbourhood of zone i.

The spatial exposure index, which is defined as the average proportion of group n in the neighbourhood of each member of group m, is given by

$$ {}_{m}\breve{P}_{n}^{*}=\sum_{i=1}^{I}\frac{N_{im}}{N_{m}}\breve{\rho}_{in}. \tag{11} $$

The spatial isolation index is given by

$$ {}_{m}\breve{P}_{m}^{*}=\sum_{i=1}^{I}\frac{N_{im}}{N_{m}}\breve{\rho}_{im}. \tag{12} $$

The use of these indices is explored below and suggestions are made about how they can describe and measure the spatial scale over which population is structured. The approach is based on calculating indices of segregation for various bandwidths by using the smallest available standard census output geography. The rate of change in the segregation indices between different bandwidths is a function of the scale of spatial variation in segregation (and population) within the unit of analysis (e.g. city, region or country). If members of one community, for instance, live in well-defined spatial clusters that are on average about 10 km^2 in area then segregation indices that are calculated up to a bandwidth approximately corresponding to this size would have much larger values than their global values for the unit of analysis as a whole, reflecting the 'bumpy' and clustered nature of the population at this scale. However, as bandwidths increased beyond this point, the values of segregation indices that were calculated would change less quickly over space and converge with the spatial *D*-figure for a very large bandwidth. This would be because the population structure that is captured within the new, and larger, bandwidths would be similar to the population structure of the unit as a whole with clusters of both communities being included in the analysis in a way that is representative of the entire unit.

To try to generalize the approach for application outside NI, as well as to explain it more fully, the data and output geographies that are used are 1991 census data for 1991 EDs, and 2001 census data for OAs. Most analysts elsewhere will have access to standard UK census output geographies so only these are used. However, it is worthwhile noting that the conclusions that are drawn from the analysis below are replicated when using 100-m and 1-km grid square data and so are robust.

4. Results

4.1. Zone design and scale effects

The heart of the analysis of the effects of zone design and spatial scale is presented in Table 2. This compares the segregation indices that were calculated for 2001 census data (religion and community background) on

(a) 2001 census output geographies and
(b) 1991 census output geographies.

Looking at the ward level results first, it is apparent that the segregation indices are usually the same to two or three decimal places. There are only very minor differences if 2001 wards are used compared with 1991 wards and few effects seem to be associated with changes in zonal design. This is perhaps unsurprising—the changes in the numbers and shapes of wards between those used in 1991 and those used in 2001 were comparatively small. However, the change in the numbers, sizes and boundaries between 3729 EDs and 5022 OAs are more profound so it is far more surprising to see that the indices that were calculated remain constant to two or three decimal places especially since it might be assumed that OAs would be more homogeneous than EDs, both because they are on average smaller and because OAs were designed to be socially homogeneous. Possible reasons for this finding are explored below. Table 2 also demonstrates

Table 2. Segregation indices for 2001 population counts on 2001 and 1991 boundaries†

Zone	*Variable*	*D*	S_m	S_n	$_mP_m^*$	$_mMP_m^*$	$_nP_n^*$	$_nMP_n^*$
ED 1991	Religion	0.690	0.366	0.323	0.769	0.300	0.796	0.265
OA	Religion	0.692	0.368	0.325	0.772	0.303	0.798	0.267
Ward 1991	Religion	0.618	0.328	0.290	0.723	0.254	0.755	0.224
Ward 2001	Religion	0.617	0.328	0.290	0.723	0.254	0.755	0.224
ED 1991	Community background	0.669	0.367	0.302	0.745	0.293	0.790	0.242
OA	Community background	0.672	0.368	0.303	0.747	0.295	0.792	0.243
Ward 1991	Community background	0.601	0.330	0.272	0.700	0.248	0.753	0.205
Ward 2001	Community background	0.601	0.330	0.271	0.701	0.249	0.753	0.205

†*m* refers to Catholics; *n* to Protestants; 2001 data on 1991 and 2001 units.

that spatial scale is more important in this case than zone design effects. Normally, the values of indices are larger for OAs and EDs than for wards. The analysis of 2001 data by using 1991 geographies is extended through the information on concentration profiles in Tables 3 and 4 dealing respectively with Catholics and Protestants. They confirm the findings of Table 2. There are few differences between values that were calculated on 1991 and 2001 geographies when EDs, OAs and wards are compared. However, there are differences for different spatial scales. EDs and OAs have greater levels of population concentrated, for instance, in areas that are 90% or more either Catholic or Protestant than wards. Protestants were more likely to live in moderately polarized areas (greater than 75%) than were Catholics.

4.2. Changes in segregation through time

The results for OAs, EDs and wards confirm and add to the earlier grid-square-based analyses

Table 3. Percentage of Catholics in 2001 who lived in areas with more than the specified percentage of Catholics

Zone	*Variable*	*Results (%) for the following percentages of Catholics:*		
		>50%	*>75%*	*>90%*
ED	Religion	80.89	64.49	47.81
OA	Religion	81.75	64.33	48.30
Ward 1991	Religion	76.80	54.78	37.79
Ward 2001	Religion	76.93	54.48	37.67
ED	Community background	78.67	61.52	44.01
OA	Community background	79.06	61.51	44.06
Ward 1991	Community background	74.56	49.89	35.72
Ward 2001	Community background	74.70	50.76	34.15

Table 4. Percentage of Protestants in 2001 who lived in areas with more than the specified percentage of Protestants

Zone	*Variable*	*Results (%) for the following percentages of Protestants:*		
		>50%	*>75%*	*>90%*
ED	Religion	87.03	69.87	44.85
OA	Religion	86.40	69.54	45.87
Ward 1991	Religion	82.32	60.87	35.06
Ward 2001	Religion	83.34	61.39	34.84
ED	Community background	87.10	69.78	41.68
OA	Community background	86.65	69.65	43.12
Ward 1991	Community background	83.68	61.02	32.51
Ward 2001	Community background	84.03	61.30	32.46

Table 5. Segregation indices for 1991 population counts on 1991 census output geographies†

Zone	D	S_m	S_n	${}_mP^*_m$	${}_mMP^*_m$	${}_nP^*_n$	${}_nMP^*_n$
ED	0.695	0.395	0.300	0.759	0.327	0.817	0.248
Ward	0.620	0.353	0.268	0.705	0.274	0.776	0.208

†m refers to Catholics; n to Protestants.

that were presented by Shuttleworth and Lloyd (2009) which showed at the level of 1-km^2 cells that segregation in NI did not grow between 1991 and 2001. The basis for this finding is the comparison between Table 5—indices for 1991 data on 1991 geographies—with the indices that were calculated by using 2001 data on 1991 boundaries in Table 2. The similar comparison between the concentration profiles in Table 6 (based on 1991 data on 1991 boundaries) with the equivalent results in Tables 3 and 4 also supports this view. Comparisons should strictly be restricted to the religion variable as this was common to both the 1991 and the 2001 censuses. These demonstrate the value of using a range of segregation indices. The segregation indices indicate, however, that Catholics were more segregated than Protestants in 1991 and they continued to be so in 2001. Where the community background question is used instead as an alternative variable, the indication is of a decline in segregation based on all indices. A comparison of the data in Tables 3 (2001) and 6 (1991) for both Catholics and Protestants for equivalent zonal systems indicates that the proportions of both groups who lived in highly segregated areas (greater than 90% of a given group) has decreased slightly between 1991 and 2001, although there was a slight increase for Protestants in the greater than 90% category if wards are used.

4.3. Spatial structure of the population

It might have been expected that there would have been large differences between the values that were calculated for OAs and EDs given the different intentions and methods of construction

Table 6. Percentage of Catholics and Protestants in 1991 who lived in areas with more than the specified percentage of Catholics or Protestants

Zone	*Results (%) for the following percentages of the group:*		
	>50%	*>75%*	*>90%*
Catholics			
ED	81.28	65.65	50.42
Ward	77.83	54.70	38.65
Protestants			
ED	87.72	69.36	45.16
Ward	82.30	60.45	34.12

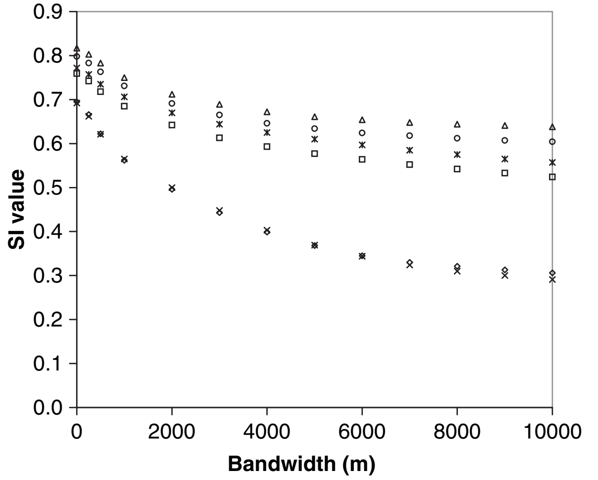

Fig. 1. Spatial segregation indices against bandwidth for 1991 and 2001 counts (by religion) over EDs (1991) and OAs (2001) (maximum bandwidth of 10 km): ◇, $\breve{D}(m)$, 1991 EDs; □, ${}_m\breve{P}^*_m$, 1991 EDs; △, ${}_n\breve{P}^*_n$, 1991 EDs; ×, $\breve{D}(m)$, 2001 OAs; ⋇, ${}_m\breve{P}^*_m$, 2001 OAs; ○, ${}_n\breve{P}^*_n$, 2001 OAs

that were used to create them. It was therefore surprising that any differences were discovered to be very small. This finding might be explained with reference to Wong's (1997) analysis of spatial population structure and zone design. The key issue is the relationship between the spatial structure of the population and the zonal design that is used at both time periods—if the phenomenon of interest is structured at a spatial scale that is larger than the areal units then the results are not sensitive to the changing scale. The spatially weighted indices of segregation that are discussed below were calculated by using the methods that were described earlier.

The results from the analysis are presented in Fig. 1, which shows values for segregation indices for 1991 data on 1991 EDs and 2001 data on 2001 OAs on the same graph. The values of the segregation indices on the y-axis are graphed against bandwidth (in metres) on the x-axis. As expected, values for all segregation indices are very large for small bandwidths. The values of the indices for different years and dimensions differ relative to each other as might be expected given the results that were tabulated earlier. However, it is noteworthy that, for both 1991 and 2001, the spatial indices share a common pattern of changes as the bandwidth increases. There are large decreases up to bandwidths of 5 km and then much smaller decreases from 5 km to 10 km. Our interpretation is that the spatial indices for 1991 EDs and 2001 OAs do not change much beyond 5 km and it makes little difference for the indices if the bandwidth is beyond this size. The key message, following Wong (1997), is that, as long as zonal units are used which are smaller than the dominant spatial scale of population for the variables of interest—in this case religion and community background—then the segregation indices in different censuses are unlikely to be sensitive to changes in zone design. This information can also be related to the information that is presented in Table 1 on zonal geographies in NI in 1991 and 2001. EDs and OAs are both much smaller than the 5-km scale that has been identified as the spatial scale of variation of segregation. It might therefore be expected that segregation indices for these units would be insensitive to these changes. This was observed earlier and is one element of the way in which the similarities between 2001 data on 2001 boundaries and the same data on 1991 boundaries can be understood.

The argument is less clear for wards in NI. These changed less markedly anyway between 1991 and 2001 but given their mean size (23 km^2 would correspond to unit sizes of 4.8 km $\times$ 4.8 km on average if the zone was square) they are very near the critical size that was identified. The relatively small size of ward boundary changes in 1991–2001 may explain the insensitivity of the value of the indices. However, there is also a possibility that wards in NI are just sufficiently small to fit within the spatial scale of religious segregation in NI, on average, and that intercensal comparisons of indices of residential segregation that are calculated by using wards would be insensitive to boundary changes as long as each set of wards in 1991 and 2001 was smaller than the dominant spatial scale of population variation. As a general rule, however, the smaller the zones the better, since smaller units will normally fit within the dominant spatial scale of population variation with greater certainty although one *caveat* is that some measures will lose meaning because for the highest spatial resolution individuals will be used in the analysis.

5. Conclusion

The analysis that was presented in the paper contributes to the evidence on changing segregation in NI, the effects of changing zonal units between censuses and the relationship between the spatial scale of population and zonal units. Furthermore, it reports the extension of the practice of accessing confidential UK census data in a safe setting by demonstrating a reworking of the entire census database rather than just a sample.

The results on levels of residential segregation in 1991–2001 supplement those derived by Shuttleworth and Lloyd (2009) by using the NI grid square product for 1-km^2 cells. The utility of the current results lies in their use of the more familiar geographies of OAs, EDs and wards and the finding that levels of segregation in 1991–2001 in NI did not increase when these units were used as the base for analysis. This is a further item of evidence that increases confidence in the robustness of the earlier conclusion.

The analysis also found that the values of indices were not sensitive to changes in zonal design between 1991 and 2001. The result at ward level is perhaps not unexpected since, although there were changes in the numbers of wards, and also changes in boundaries, these were not as extensive as those observed between 1991 EDs and 2001 OAs. The insensitivity of the values of indices at the ED or OA level was, however, surprising given that OAs were smaller than EDs and might therefore be expected to be more internally homogeneous (Wong *et al.*, 1999), especially as homogeneity was a consideration in the procedure that was used in their design

(Martin, 1997). The values of indices varied more according to the spatial scale of analysis (e.g. between wards and OAs or EDs) than between OAs and EDs. This suggests that, in this case, the values were more sensitive to scale than to zone design effects. This indicates that measuring segregation in NI through time by using census data 'as they are' might not be as fraught with difficulty as first imagined (Anderson and Shuttleworth, 1998; Shuttleworth and Lloyd, 2009) because of the problem of changing output geographies.

This result was explained in terms of the suggestions that were advanced by Wong (1997) that the use of zones of different sizes (e.g. EDs and OAs in this case) will make little difference as long as the units in each zonal geography are smaller than the spatial scale over which population counts are positively auto-correlated. There are some *caveats* to this observation. Firstly, it assumes spatial scale homogeneity throughout the unit of analysis. This might not be so—the spatial scale of population variability may vary between places. Nevertheless, global summaries are a useful place to begin to assess population structures in different time periods in general across a unit of analysis, and such global summaries are more easily understood. Further work could explore geographical variations in dominant spatial scales of variation in the population. If the unit of analysis, for example, was a city it would make sense to explore the spatial scale of variation in the population for this place. However, a global statistic is a reasonable summary measure, and in this case the unit of analysis was NI as a whole. Secondly, boundary effects can sometimes be important even if the spatial scale of the phenomenon for analysis is larger than the units. The importance of this limitation depends on the variables that are used for analysis and also the units that are used for analysis. The structure of UK census output geographies with OAs designed to maintain unit homogeneity, for instance, means that this will be less of a problem in this context. However, various studies in other contexts have concluded that scale effects are usually more important (Cockings and Martin, 2005; Morris and Munasinghe, 1993).

These comments lead on to the question of how far these findings are applicable to other places and census variables. Since the methods to define OAs in NI were also used in England and Wales, there are some grounds to expect that the experience for NI that was described above is transferable to other parts of the UK. The OA design variables are not directly related to ethnicity for instance—it was for this reason that housing variables were chosen—so OA boundaries are unlikely to be strongly related to ethnic boundaries. As long as OA and ED boundaries fulfil the conditions of being smaller than the spatial scale of population variation then it is probable that intercensal comparisons in segregation measures can be made with some security. The case for generalization to other census variables, e.g. unemployment or economic activity, is far less certain. These variables could vary at different—and perhaps smaller—spatial scales than religion in NI. This would mean that 1991–2001 comparisons using OA and ED data would be dangerous. These are, however, empirical questions which can be investigated and an approach to do so is outlined below.

The question of spatial scale can be approached through spatial statistics. In this paper spatially weighted segregation indices were reported. Where only irregular zones (e.g. EDs and OAs) are available to analyse change through time, the use of spatially weighted indices provides a solution to help to estimate the likely effect of zonal changes. Fotheringham *et al.* (2002) discussed further the use of spatial measures in the context of the modifiable areal unit problem. Their analysis, like that presented here, suggests that spatial measures, although not solving the modifiable areal unit problem, are a powerful means of overcoming its effects as knowledge of population spatial patterns, in combination with knowledge of the size of the zones in each census, can be used to help to make more meaningful comparisons through time. If applied elsewhere, analysts might

(a) calculate spatial indices for a variety of zonal units across several bandwidths for the variable of interest in one census and compare these with equivalent measures from another census,
(b) compare the way that the indices vary across different bandwidths for each census and
(c) assess the extent to which the units may be smaller than the areas over which population counts are positively auto-correlated in each census.

In cases where the units are smaller than the spatial scale of population in census A (say 1991) and in census B (say 2001), then it is highly likely that measures that are derived from the incompatible zonal systems can be compared. When spatial segregation indices are calculated for a variety of zonal systems, marked differences from the global indices will only be evident for

(a) bandwidths which are small relative to the average size of the zonal units and
(b) when there is variation within the zones that are used (that is to say when population is not positively auto-correlated within the zones—see Wong (1997)), and the assumptions that were made above cannot be supported. In this situation, intercensal comparisons are more problematic as results could be biased by the zonal system that is used. This conclusion is of significance to debates about future census output geographies, particularly the case for maintaining continuity of boundaries.

Further work arising from the analysis will seek to explore other ways to characterize the spatial structure of population by using irregular zonal systems. It will also try to examine the extent to which these findings in NI are generalizable elsewhere. There are major questions about whether the same effects could be observed in cities such as Birmingham, Bradford, Blackburn or London. The suggested use of spatial measures of segregation (and perhaps other methods to explore the spatial structure of population) can also be explored in other geographical contexts to examine their robustness. Analyses that extend the description of local variations in segregation (see Wong (2002, 2003b) for instance) are another avenue for development as is the exploration of scale and zonation effects separately in NI by using the grid square product. These developments should begin to answer some of the questions that are raised about segregation, zonal design and population structures by population geographers and those in cognate disciplines.

Acknowledgements

Richard Elliott and Robert Beatty of the Census Office (part of the NISRA) are thanked for making available the grid square data and the results for 2001 counts on 1991 zones. The support of the Economic and Social Research Council is acknowledged in funding, through awards RES-000-22-0271 and RES-000-23-0478, part of the work that made this research possible. We also thank the Joint Editor and referees who provided helpful comments on the paper. Any errors remain our responsibility.

References

Anderson, J. and Shuttleworth, I. (1998) Sectarian demography, territoriality and policy in Northern Ireland. *Polit. Geogr.*, **17**, 187–208.
Cockings, S. and Martin, D. (2005) Zone design for environment and health studies using pre-aggregated data. *Socl Sci. Med.*, **60**, 2729–2742.
Compton, P. and Power, J. (1986) Estimates of the religious composition of NI Local Government Districts between 1971 and 1981. *Econ. Socl Rev.*, **17**, 87–105.

Duke-Williams, O. and Rees, P. (1998) Can Census offices publish statistics for more than one small area geography?: an analysis of the differencing problem in statistical disclosure. *Int. J. Geogr. Inform. Sci.*, **12**, 579–605.
Feitosa, F. F., Câmara, G., Monteiro, A. M. V., Koschitzki, T. and Silva, M. P. S. (2007) Global and local spatial indices of urban segregation. *Int. J. Geogr. Inform. Sci.*, **21**, 299–323.
Fotheringham, A. S., Brunsdon, C. and Charlton, M. (2002) *Geographically Weighted Regression: the Analysis of Spatially Varying Relationships*. Chichester: Wiley.
Gorard, S. and Taylor, C. (2002) What is segregation?: a comparison of measures in terms of strong and weak compositional invariance. *Sociology*, **36**, 875–895.
Gregory, I. N. and Ell, P. S. (2005) Breaking the boundaries: geographical approaches to integrating 200 years of the census. *J. R. Statist. Soc.* A, **168**, 419–437.
Johnston, R., Poulsen, M. and Forrest, J. (2005) On the measurement and meaning of residential segregation: a response to Simpson. *Urb. Stud.*, **42**, 1221–1227.
Lieberson, S. (1981) An asymmetrical approach to segregation. In *Ethnic Segregation in Cities* (eds C. Peach, V. Robinson and S. Smith), pp. 61–82. London: Croom Helm.
Macourt, M. P. A. (1995) Using census data: religion as a key variable in studies of NI. *Environ. Planng* A, **27**, 593–614.
Marsh, C., Dale, A. and Skinner, C. J. (1994) Safe data versus safe setting: access to microdata from the British Census. *Int. Statist. Rev.*, **62**, 35–53.
Martin, D. (1997) From enumeration districts to output areas: experiments in the automated design of a census output geography. *Popln Trends*, **88**, 36–42.
Martin, D. (2003) Extending the automated zoning procedure to reconcile incompatible zoning systems. *Int. J. Geogr. Inform. Sci.*, **17**, 181–196.
Martin, D., Dorling, D. and Mitchell, R. (2002) Linking censuses through time: problems and solutions. *Area*, **34**, 82–91.
Martin, D., Nolan, A. and Tranmer, M. (2001) The application of zone design methodology to the 2001 UK Census. *Environ. Planng* A, **33**, 1949–1962.
Massey, D. S. and Denton, N. A. (1988) The dimensions of residential segregation. *Socl Forces*, **67**, 281–315.
Morris, R. and Munasinghe, R. (1993) Aggregation of existing geographic regions to diminish spurious variability of disease rates. *Statist. Med.*, **12**, 1915–1929.
Noden, P. (2000) Rediscovering the impact of marketisation: dimensions of social segregation in England's secondary schools, 1994–99. *Br. J. Sociol. Educ.*, **21**, 372–390.
Openshaw, S. (1984) *The Modifiable Areal Unit Problem*. Norwich: GeoBooks.
Poole, M. A. and Doherty, P. (1996) *Ethnic Residential Segregation in Northern Ireland*. Coleraine: University of Ulster.
Poulsen, M., Johnston, R. and Forrest, J. (2002) Plural cities and ethnic enclaves: introducing a measurement procedure for comparative study. *Int. J. Urb. Regnl Res.*, **26**, 229–243.
Shuttleworth, I. G. and Lloyd, C. D. (2009) Are Northern Ireland's communities dividing?: geographically consistent evidence from Census of Population data, 1971–2001. *Environ. Planng* A, **41**, 213–229.
Wong, D. W. S. (1993) Spatial indices of segregation. *Urb. Stud.*, **30**, 559–572.
Wong, D. W. S. (1997) Spatial dependency of segregation indices. *Can. Geogr.*, **41**, 128–136.
Wong, D. W. S. (2002) Modeling local segregation: a spatial interaction approach. *Geogr. Environ. Modllng*, **6**, 81–97.
Wong, D. W. S. (2003a) Implementing spatial segregation measures in GIS. *Comput. Environ. Urb. Syst.*, **27**, 53–70.
Wong, D. W. S. (2003b) Spatial decomposition of segregation indices: a framework toward measuring segregation at multiple levels. *Geogr. Anal.*, **35**, 179–194.
Wong, D. W. S. (2008) A local multidimensional approach to evaluate changes in segregation. *Urb. Geogr.*, **29**, 455–472.
Wong, D. W. S., Lasus, H. and Falk, R. F. (1999) Exploring the variability of segregation index D with scale and zonal systems: an analysis of thirty US cities. *Environ. Planng* A, **31**, 507–522.