Spatial Demography: an opportunity to improve policy making at diverse decision levels

Marcia Caldas de Castro
Department of Geography, University of South Carolina
mcaldas@sc.edu

"…although basic science is directed at the discovery of general principles, the ultimate value of such knowledge, apart from simple curiosity, lies in our ability to apply it to local conditions and, thus, determine specific outcomes. Although such science may itself be placeless, the application of scientific knowledge in policy inevitably requires explicit attention to spatial variation, particularly when the basis of policy is local." (Goodchild, Anselin, Appelbaum and Harthorn 2000: 142)

Introduction

One hundred and fifty two years ago, John Snow created a map that showed the location of pumps and cholera deaths in a London neighborhood (Snow 1855). A careful examination of the map led him to conclude that the source of cholera deaths was one specific pump, and this finding facilitated the discovery of the disease aetiology. Forty four years ago, Andrei Rogers proposed a multiregional approach for population modeling and estimation (Rogers 1966). This approach facilitates the understanding of regional differences on population growth and distribution. What did Snow and Rogers have in common? An ability to think spatially.

Space is a crucial element for demographic studies. Migratory movements only exist because people perceive some places to be more attractive than others. One of the explanations for fertility declines is the diffusion of ideas, in other words, ideas move from one or more locations to others. Mortality levels are far from being spatially homogenous, since the presence or absence of certain risk factors varies by location. Nevertheless, population studies that include a spatial component have not occupied a significant space in major demography journals, and spatial demography is virtually ignored as part of the regular training of future professionals in the field (Weeks 2004).

Even so, the number of applications in spatial demography has been growing recently. Different reasons account for that. First, there is a large availability of spatial data, including all the information released by the US Census Bureau (Wachter 2005). Second, several computer programs have been developed to facilitate the use of spatial analysis (Rey and Anselin 2006). Third, computer capabilities to store and analyze large datasets have improved dramatically. Fourth, there have been major initiatives to develop a spatial thinking among the social sciences (Goodchild, Anselin, Appelbaum and Harthorn 2000). Fifth, the importance of spatially targeted policies has been recognized in different areas (Fuchs 1984; Carter, Mendis and Roberts 2000; Bradshaw and Muller 2004). Finally, Wachter (2005) argues that another reason for the increase in spatial demography applications (specifically related to the U.S.) is "*adversarial legalism*", or resolving legal disputes that involve the equitable distribution of resources across administrative units.

The growing number of applications address space in several ways, ranging from a simple visualization of one or more variables in a map, to sophisticated spatial statistical models that seek to explain why a particular spatial pattern is observed. This article reviews spatial demography applications on population growth, mathematical models of population, fertility, mortality, and migration. Only applications that apply spatial statistical techniques are considered, and therefore visualization applications, although important, are not included in the review. A strong case is made that the findings of these studies offer a significant contribution to monitoring, evaluation, and implementation of population policies. Different types of spatial data are described and current sources of freely distributed spatial data are listed. Mostly important, this article outlines major challenges that still exist for the development of spatial demography applications. These challenges range from technical issues to lack of adequate training. Finally, potential areas of future applications of spatial demography are suggested.

1. Spatial demography: a review

From a multidisciplinary point of view one could consider as spatial demography a myriad of population studies that ultimately aim to investigate one or more issues related to population size, change, composition, and distribution at a particular scale. Consequently, a review of previous work would result in a long list of studies, covering a wide range of topics, and applying a variety of spatial techniques. Among these techniques are simple visualization methods, regression models that include variables describing location as covariates (but not necessarily checking for the presence of spatial autocorrelation in the residuals), multilevel models, and applications of geostatistics and spatial statistical analysis.

In order to focus the discussion, two criteria were used to narrow down the scope of the review presented in this article. First, spatial demography includes only research on the core of demographic analysis. The core is defined by population growth, mathematical models of population, and the three demographic components – fertility, mortality, and migration. Second, spatial demography implies the use of techniques in spatial statistical analysis and geostatistics, as well as the formulation of population models in three dimensions – age, time and space. Therefore, studies that rely solely on the visualization of mapped variables without performing any statistical test to validate visual patterns are not considered in this review. Also, applications that incorporate binary variables as indicators of a particular location or that perform independent analysis for each location were not considered either, since these models do not explicitly account for the effects of space on the outcome variable. Finally, applications of multilevel models were not included in this review, since the spatial units used at each level of hierarchy are chosen a priori, and do not necessarily reflect the underlying spatial process. Spatial effects are expected to operate in a continuous way, so there is no reason to expect that once the border between different hierarchical units is crossed the underlying process should change (Fotheringham, Brunsdon and Charlton 2000). Not considering these applications does not, in any way, minimize their contributions to the field. They are extremely important, had and still have a crucial contribution to demographic studies, and answer different questions than those being addressed by spatial approaches.

Therefore, the goal of the review present next is to highlight the extent to which the spatial dimension has been introduced in the core of demographic analysis (as defined above), and the additional contribution that these studies have brought to the field and to the studied areas.

1.1. Fertility

A significant number of studies have been done addressing fertility changes at different spatial scales. While some address mainly the diffusion theory of fertility decline, others explicitly relate the findings with policy implications for the implementation of family planning programs. Specifically, issues addressed by these studies in a spatial context include: (i) the impact that the distance to a birth control clinic has on the use of contraception (Fuller 1974), (ii) the relationship between population density and fertility (Loftin and Ward 1983), (iii) the pace and pattern of fertility decline over time (Pandit and Bagchi-Sen 1993; Guilmoto and Rajan 2001), (iv) testing the diffusionist theory of fertility (Tolnay 1995), (v) investigating patterns of spatial diffusion of fertility, their points of origin, and the location of zones of abrupt changes (Bocquet-Appel and Jakobi 1996; 1998; Balabdaoui, Bocquet-Appel, Lajaunie and Rajan 2001; Bocquet-Appel, Rajan, Bacro and Lajaunie 2002), (vi) assessing the spatial variability in the enforcement of family planning policies (Skinner, Henderson and Jianhua 2000), (vii) identifying variables associated with fertility transition (Balabdaoui, Bocquet-Appel, Lajaunie and Rajan 2001; Weeks, Getis, Hill, Gadalla and Rashed 2004), and (viii) examining the occurrence of different diffusion patterns over time (Bocquet-Appel, Rajan, Bacro and Lajaunie 2002).

A wide-range of methods was applied to address these questions. Some studies used only one technique while others used a combination of methods. Kriging (Cressie 1993), a geostatistical model of spatial estimation, was widely used in studies aimed at investigating the types and patterns of spatial diffusion (Bocquet-Appel and Jakobi 1998; Balabdaoui, Bocquet-Appel, Lajaunie and Rajan 2001; Guilmoto and Rajan 2001; Bocquet-Appel, Rajan, Bacro and Lajaunie 2002). Wombling (Womble 1951; Bocquet-Appel and Bacro 1994), a technique that allows the identification of zones of discontinuity, was applied individually (Bocquet-Appel and Jakobi 1996) and in combination with kriging (Balabdaoui, Bocquet-Appel, Lajaunie and Rajan 2001; Bocquet-Appel, Rajan, Bacro and Lajaunie 2002). A spatial autocorrelation model, analogous to an autoregressive time-series model, was applied to show that previous aspatial work overestimated the effect of population density in fertility Loftin and Ward (1983). A space-time analysis of fertility decline was performed with the Dual Expansion Method (Casetti 1972; 1986), which assumes that the parameters of an initial model (where only time is considered) can be expressed as functions of other attributes such as location (Pandit and Bagchi-Sen 1993). A two-stage least square model (Land and Deane 1992) showed evidence for a diffusion model of variation in fertility levels, although no inference could be made regarding the changes in fertility and the likely causes for a diffusion pattern (Tolnay 1995). A Hierarchical Regional Space (HRS) model, which included two spatial dimensions accounting for core-periphery and urban-rural zones, linked with longitudinal census data, was adopted to facilitate a space-time analysis of fertility decline (Skinner, Henderson and Jianhua 2000). Combined with kriging, the Knox's statistics (Knox 1964), a test to detect the presence of space-time clustering, facilitated the identification of the point of origin for the contraceptive diffusion (Bocquet-Appel and Jakobi 1998). Regression trees (Hastie, Tibshirani and Friedman 2001) were used to identify thresholds in female literacy rate that facilitate the classification of areas of abrupt fertility change (Balabdaoui, Bocquet-Appel, Lajaunie and Rajan 2001). An indicator of spatial autocorrelation, Moran's I (Anselin 1995) was used to assess the neighborhood effect on fertility levels (Guilmoto and Rajan 2001). Finally, in order to identify the predictors of fertility variation, a spatial filtered regression (Getis 1995), based in the $G_i^*(d)$ statistic of local spatial autocorrelation (Ord and Getis 1995; Getis and Ord 1996) was applied (Weeks, Getis, Hill, Gadalla and Rashed 2004). This method allows the assessment of spatial and non-spatial effects that each of the covariates has on the dependent variable.

The results of these studies bring new perspectives to the discussion of fertility transition. The data collected by the Princeton European Fertility Project (Coale and Watkins 1986) were revisited, and new support and explanations for the diffusion theory was set forth with a spatial and temporal perspective. Furthermore, they highlight the diversity in patterns of fertility decline, both between and within countries, and make a clear point that there is still a lot to learn about the paths that lead to the demographic transition.

Specifically related to policy, Fuller (1974) argues that political decisions regarding the location of clinics is decided on the basis of aspatial analysis, and therefore family planning programs may not have the expected impact on fertility levels. The results of his study could be used as a guidance to optimize the number and location of clinics in communities.

Finally, on a more theoretical perspective, the Easterlin theory (Easterlin 1987), which suggests a link between cohort sizes and fertility, was tested in a multiregional context using Italy as a case study (Waldorf and Franklin 2002). An elaborated spatial autoregressive model (Anselin 1988) was formulated, showing that: (i) the space-time components are highly significant and therefore cannot be neglected in studies to assess Easterlin's theory, (ii) diffusion does play a major role and cannot be neglected either, and (iii) the link between cohort sizes and fertility varies across regions and time (some southern regions, for example, do not substantiate Easterlin's theory).

1.2. Mortality

There is a vast literature on the use of spatial analysis on mortality studies. Specifically, the scope of the studies is concentrated on causes of death, and the goal is to model prevalence or incidence rates, characterize the spatial patterns of transmission, find focal points of transmission and model the spread of diseases, identify clusters, and scrutinize potential risk factors. These applications are found mostly under the field of spatial epidemiology, which has produced a large number of articles, special editions of journals (e.g. Social Science and Medicine), and textbooks. Good reviews are found in Lawson (1999) and Elliott, Wakefield, Best and Briggs (2000).

The spatial methods used in those studies is highly sophisticated, including kriging (Cressie 1993), measures of spatial autocorrelation that capture the spread and the clustering pattern of diseases, spatial econometrics (Anselin 1988), spatial autoregressive models (Griffith, Layne, Ord and Sone 1999), and Bayesian analysis (Lawson and Kleinman 2005), among others. The findings of these studies are crucial for public health (Gobalet and Thomas 1996). They provide guidance for the introduction of new policies regarding the provision of health services, adoption of spatially targeted interventions for disease control, and resource allocation. However, it is beyond the scope of this article to review these studies. In particular, the objective is to find applications in mortality in a much broader sense, so that the spatial distribution and variation of mortality (overall, child, neonatal) levels in a population can be understood at a space-time approach.

Using the above criteria, aside from important contributions to modeling (multiregional demographic models, as detailed later in this article), there are few applied studies linking mortality data and spatial analysis. Santos and Noronha (2001) investigate the relationships between mortality and socioeconomic profiles of neighborhoods. The neighborhoods were defined based on the multivariate K-means cluster method. The results provide important evidence for the evaluation of current health policies, for the implementation of alternative policies aiming to improve the availability of health care, and for redirecting the use of financial resources, which ultimately will minimize social inequalities (Santos and Noronha 2001).

Leal and Szwarcwald (1997) present a spatio-temporal analysis of neonatal mortality. A statistics of spatial autocorrelation, Geary *c*, combined with multivariate analysis led to findings that served as the basis for a comprehensive discussion of state policies targeted to reduce infant mortality.

An innovative model, formulated within a Bayesian context, was proposed to generate spatially varying regression coefficients in a multivariate and longitudinal framework (Congdon 2003). The model is applied to suicide mortality in London and highlights the variability that social indicators can have on health outcomes when assessed at a spatial dimension. The results are crucial for accurately identifying risk factors and for proper allocation of resources (Congdon 2003).

Childhood mortality in West Africa was analyzed using data collected by the Demographic Health Surveys (DHS) (Balk, Pullum, Storeygard, Greenwell and Neuman 2003). This study used spatial variables that characterize an urban-rural continuum and the climatic patterns in each location. These variables were simply introduced as covariates in generalized linear models. Therefore, this application does not fit the definition of spatial demography used in this article (as described earlier). However, its inclusion in this review serves the purpose of highlighting the unique opportunity that DHS now offers to demographers: introduce a spatial component in analysis of child and maternal mortality, family planning efforts, and fertility decline, among other topics, in developing countries. These studies not only have the potential to unravel local disparities that facilitate the understanding of demographic processes, but also to offer crucial information for public policy monitoring, evaluation, and implementation.

1.3. Migration

Migration is naturally a spatial process. It implies the movement of an individual from one region to another. Therefore, some of the earlier applications of spatial demography are expected to be found in this area. In fact, much of the applications have its roots on multiregional demographic models first introduced by Rogers (1966). Several of those are presented in an edited volume published in 1986 (Woods and Rees 1986), which is a must-read for those interested in following how spatial demography has been addressed over time.

The impacts of heterogeneity and selection in migration indices were assessed through a multiregional perspective (Rogers 1992). Results indicate that three indices should be avoided whenever other data is available: net migration rates, lifetime migration rates, and return migration proportions (Rogers 1992). A multiregional perspective was also applied to address the impact that past international and interregional migration had on the growth and distribution of the elderly population in the U.S. (Rogers and Raymer 2001). Results show that immigration led to a decline in the elderly dependency ratios during 1950-1990, however a decomposition of elderly regional growth rates revealed that the most important factor related to changes in the growth and distribution of the elderly population was net aging-in-place (Rogers and Raymer 2001). These findings have relevant policy implications. As the authors highlight, the United Nations (2000) released a report in 2000 that suggested the ideal number of migrants that would be necessary to compensate for the aging of the population in eight countries (France, Germany, Italy, Japan, Republic of Korea, Russian Federation, United Kingdom and United States) and two regions (Europe and the European Union), considering five different scenarios. In light of the results presented by Rogers and Raymer (2001), the potential adoption of an immigration policy to offset the impacts of the ageing of the population needs careful evaluation.

Linear models formulated in a spatial approach were proposed to assess migration patterns. Using a time series of place-to-place migration flows observed in the Netherlands during 1958-1982, Willekens and Baydar (1986) proposed a migration forecasting model that accounts for spatial and temporal effects. Rogers, Willekens, Little and Raymer (2002) suggested a log-linear model that describes the spatial structure of migration, capturing the effects of population size at areas of origin and destination, as well as a combined effect between each pair of origins and destinations.

The shift in the U.S. interregional migration during the 1970s (significant increase in the net outflow from the Northeast and Midwest to the South and West) was evaluated considering the age structure of the population (Plane and Rogerson 1991; Plane 1992). Specifically, the studies assess the impact that the baby boom generation might have had in the patterns of interregional migration. The evaluation was made by adopting an analogy to Easterlin's theory (Plane and Rogerson 1991) and through the proposal of a method to decompose age-specific interregional migration flows into three components – population base, mobility, and geographic distribution – (Plane 1992). Results not only shed light on the most important forces driving the shift in the interregional migration pattern, but also facilitate the conjecture of future migratory patterns for adults and elderly in the U.S.

The concept of step migration, initially introduced by E. G. Ravenstein in 1885, and that dominated the rural-to-urban movements in the U.S. during late 1800s-1950s was tested for recent data (Plane, Henrie and Perry 2005). Seven hierarchical levels of metropolitan areas were defined on the basis of population size. The findings suggest that instead of an overall set of determinants of migration, the decisions vary over the life course; the way that internal migrants perceive the quality of life vary by age (Plane, Henrie and Perry 2005). Besides an important academic contribution, pointing that studies that aim to model the migration decision will not capture the dynamics of the current population movement (Plane, Henrie and Perry 2005), the study also raises some policy considerations. One can speculate that eventual policies to attract or retain population need to consider the age structure, and to account for the diversity in the relocations throughout the life course.

The spatial focus of regional migratory flows has been assessed through different indicators. Previous attempts include the Gini index and the coefficient of variation (Plane and Mulligan 1997; Rogers and Sweeney 1998) formulated in a multiregional approach, which provide an assessment of the migration patterns spatially (e.g. locations that are major sources for out-migration or in-migration).

Finally, explicit spatial approaches in migration studies have a crucial policy component. Monitoring and evaluating current population redistribution programs, and better designing future ones are both conditioned on the availability of clear and detailed spatial analyses of migratory flows (Fuchs and Demko 1983; Fuchs 1984). These programs are no novelty. They reflect the dissatisfaction that governments from developing and developed countries have regarding the spatial distribution of the population (United Nations 1980). Evaluation and implementation of such programs without an understanding of the regional patterns of population distribution and mobility would be misleading, to say the least.

1.4. Population models, population size and population growth

Stable population theory (Ledent and Rogers 1987) and the Lotka-Volterra model of population interaction (Hudson 1970; El Ghordaf, Hbid and Arino 2004) were addressed under a spatial perspective. In the first, Preston and Coale's (Preston and Coale 1982) generalization of the age distribution function for any population in a single region is extended to a multiregional approach in discrete form (Ledent and Rogers 1987). In the second, the Lotka-Volterra model, which was developed independently by Lotka in 1925 and Volterra in 1926, is extended to a two-region system: a metropolitan area and a non-metropolitan hinterland (Hudson 1970). Two modifications are introduced to the model to make it more realistic: (i) the migratory flow between two regions depends on the networks established between them, and (ii) population growth is not necessarily an explosive process. The implications of the model are analyzed in the context of growth and population stability in the two regions (Hudson 1970). A more recent application evaluates the asymptotic behavior of a two-regional Lotka-Volterra model, and provides an interpretation of its results in an urban context (El Ghordaf, Hbid and Arino 2004).

In addition to the mathematical models that generalized the Lotka-Volterra model, as described above, population growth and distribution in space was addressed by fractal analysis. The study the spatial organization of urban areas with the aid of fractal geometry allows the characterization of the morphology of cities (Frankhauser 1998). Although the results are mainly descriptive, they provide guidance on ways to construct models and theories that might explain the observed urban structure.

Regarding population size and estimation, two important contributions have been made: (i) multiregional models, and (ii) use of remote sensing. Multiregional models were first proposed by Rogers (1966) to allow interregional population estimates. His contributions in this area are imperative, which includes several articles and two textbooks, which were published in 1975 (Rogers 1975) and 1995 (Rogers 1995). The method was applied to U.S. Census data, and the results compared with the Census population projection by state issued in 1988 (Rogers and Woodward 1991). Forty years ago, Rogers stated that "… *in demography the need for theories and methods which simultaneously consider the spatial as well as the temporal character of interrelated population processes is increasingly apparent.*" (Rogers 1966: 538). The need is still apparent, the current technology and data availability facilitate the task, but regional population estimates still lack popularity among scholars and governmental institutions, despite all the advantages that the model has (Rees and Woods 1986; Rogers 1990).

Multiregional models represent a contribution not only for population estimates, but for population modeling in general (Woods and Rees 1986). It is curious to note that another textbook on multiregional demographic models was published in 1977 by Rees and Wilson (1977). The book was written as an attempt to integrate spatial analysis and demography in the study of population and population change. Some of the formulations presented in the book overlap with Roger's models described above. However, it was a main reference for population geographers, remaining mostly ignored by demographers.

Additionally, multiregional models facilitate the formulation of multistate mathematical demography, in which transitions between different states are modeled. The journal Environmental and Planning A dedicated a whole edition to multistate mathematical demography (Volume 12, number 5, published in 1980). The papers address issues regarding population estimation and multistate life tables (in which location may be one of the dimensions under study).

A different model was proposed to assess population change in small areas (Akkerman 1992), based on fuzzy models and fractal analysis. A cohort component model or a multiregional approach would not be suitable for studying small areas due to the data requirement and the fact that vital rates are likely to be unstable (Akkerman 1992). Demographic change is characterized by a degree of fuzziness, and similarities between each small area are identified through fractal analysis.

The use of remote sensing to estimate population is not a substitute to census data collection, but an alternative approach that can provide information during intercensal years, especially for areas experiencing rapid expansion. Different imagery was used for that purpose, including aerial photographs (Pollé 1984), satellite data (Webster 1996), and night-time satellite image (Sutton, Roberts, Elvidge and Baugh 2001). Different methods can be applied to obtain population estimates from remotely sensed data, as detailed by Webster (1996). Regardless of the chosen method, the results obtained through imagery analysis constitute an important planning tool – e.g. urban expansion and renewal (Pollé 1984). The most unique imagery used so far to obtain population estimates is the night-time satellite image (Elvidge, Baugh, Kihn, Kroehl and Davis 1997; Imhoff, Lawrence, Stutzer and Elvidge 1997; Elvidge et al. 2001). The availability of energy and patterns of consumption directly impact how lit an area is. Parameters to account for this fact are introduced in the model. They vary between and within countries (Sutton, Roberts, Elvidge and Baugh 2001). In addition to the policy relevance of the application, as highlighted above, the night-time satellite image can also be used as proxy for levels of energy consumption worldwide (Sutton, Roberts, Elvidge and Baugh 2001).

Finally, the assessment of conventional borders has also been the focus of analysis. First, an important contribution lies in the use of spatial data to redefine conventional borders (administrative units within a country, and frontier between countries) into social borders that better illustrate the population with respect to specific characteristics (ethnicity, religion, language, etc.). Using spatial data collected by DHS in West Africa, Hill (1998) created maps that delineate the borders of major ethnic enclaves. This social map can then be used as the spatial reference for the evaluation of a potential association between ethnic enclaves and variables such as median age at first birth, women's ideal number of children, and total fertility rate, among others (Hill 1998).

Second, the individual perception of neighborhoods was assessed using data from the Los Angeles Family and Neighborhood Survey – L.A.FANS (http://www.lasurvey.rand.org/index.htm), examining the extent to which individual or neighborhood characteristics may play a role (Sastry, Pebley and Zonta 2002). The results can be combined with health data (Pebley and Sastry 2003), revealing inequalities that can be addressed in public health programs promoted by local governments.

2. Types and sources of spatial data

Spatial demography, as defined in this article, is only viable due to the availability of data that contain geographical information (location). Different strategies can be applied to obtain such data. First, geographic coordinates (e.g. latitude and longitude) can be obtained for each record in the dataset (a person, a house, a health facility, etc) through GPS (Global Positioning Systems) readings or with the aid of remotely sensed imagery, so each record is a point in the map. Second, data can be aggregated at a certain administrative level unit (e.g. counties). In this case, each record refers to an area, or is represented as a point in the center of the area. Third, available data can be interpolated generating an estimated surface of observations. While the first and second strategies are straightforward, depending only on field work and visualization efforts, the third relies on data generation modeling.

Bracken and Martin (1989) proposed an approach to generate an estimated surface based on census centroid data. Once the size of the cells (spatial resolution) was selected, the estimated surface was generated considering a model of distance-decay. One of the important uses of this approach is to capture localized variations in certain population characteristics that would be imperceptible at the centroid level (Bracken and Martin 1989).

A more comprehensive discussion is provided by Openshaw and Rao (1995). They highlight one of the most important problems in spatial analysis: the modifiable areal unit problem – MAUP

(Fotheringham, Brunsdon and Charlton 2000). This problem will be discussed in detail in the next session, but briefly, it is analogous to the ecological fallacy problem largely recognized in social sciences (Robinson 1950). Therefore, administrative units used by the Census, such as enumeration districts, are not necessarily comparable, and aggregations to higher levels (ward, district, counties, etc) are expected to avoid some of the MAUP problems (Openshaw and Rao 1995). A better strategy, however, is to pursue aggregation procedures that are less arbitrary, and the authors propose three algorithms that facilitate this task.

Another important contribution is the result of a major project that converted subnational population data to a gridded population data with 1548 rows by 4320 columns (Tobler, Deichmann, Gottsegen and Maloy 1997). The challenges on producing the gridded population data are clearly detailed in the article, such as the fact that some countries lacked detailed national data. At the time of publication, the authors were seeking for the dissemination of the data, so that its usefulness could be assessed. Their efforts resulted in the development of the Gridded Population of the World (GPW), a worldwide dataset freely distributed by the Center for International Earth Science Information Network (CIESIN), as detailed next.

Several population data are publicly available for any researcher willing to combine demographic analysis and spatial methodology. The spatial coverage and spatial resolution varies. Also, anyone willing to use the data needs to be aware of the challenges of spatial analysis, as described in the following session of this article. The main sources are (all freely distributed):

- World Demographic Data (http://rockyweb.cr.usgs.gov/outreach/worlddemography.html) – Includes data on fertility, mortality, economic indicators, and health, among others. The data is stored at the Rocky Mountain Mapping Center (US Geological Survey – USGS) and has a variety of sources.
- Gridded Population of the World – GPW (http://sedac.ciesin.columbia.edu/plue/gpw/) – The conceptual formulation of a gridded population data has its roots on the work of Tobler, Deichmann, Gottsegen and Maloy (1997). The first version was released in 1995. Currently in its third version, users can have access to GPWv3, with data for 1995, 1995, and 2000, and GPWfe, with population estimates for 2005, 2010, and 2015. Distributed by the Center for International Earth Science Information Network (CIESIN).
- Global Rural-Urban Mapping Project – GRUMP (http://sedac.ciesin.columbia.edu/gpw/index.jsp) – A gridded population dataset, similar to GPW, which includes a rural-urban specification. Distributed by the Center for International Earth Science Information Network (CIESIN).

- LandScan™ (http://www.ornl.gov/sci/landscan/index.html) – Distributed by the Oak Ridge National Laboratory. Contains worldwide population data compiled on a 30" x 30" latitude/longitude grid. The current version is LandScan™ 2004 (released in 2005).
- Geographically Based Economic Data – G-Econ (http://gecon.yale.edu/) – A dataset that has information on total population and gross domestic product measured at a 1-degree longitude by 1-degree latitude resolution at a global scale (Nordhaus 2006).
- Integrated Public Use Microdata Series – IPUMS (http://www.ipums.umn.edu/) – Hosted by the Minnesota Population Center, University of Minnesota. Collects and distributes worldwide census data.
- US Census Bureau (http://www.census.gov/) – Distributes geographic data that facilitates the use and analysis of census information on a spatial dimension, as well as census summary files, and public use microdata sample (PUMS) files.
- National Historical Geographic Information System – NHGIS (http://www.nhgis.org/) – Hosted by the Minnesota Population Center, University of Minnesota. Collects and distributes U.S. Census data between 1790 and 2000, incorporated into a GIS (Geographic Information Systems) framework.
- Demographic and Health Survey – DHS (http://www.measuredhs.com/) – Nationally-representative household surveys conducted in developing countries, typically every 5 years, collecting information on population, health, and nutrition. Since 1996, DHS surveys have been collecting locational data (Rutstein 2000) that not only allows the use of spatial analytic techniques, but also facilitates linking DHS data with other spatial datasets.

It is important to mention that some of these datasets can be linked with each other, or with other survey data. For example, information on rainfall, temperature, humidity, and vegetation extracted from remotely sensed data can be combined with other data (e.g. GPW, hospital records, etc) in order to identify the population under the risk of transmission of diseases such as malaria (Thomson et al. 2006). The use and analysis of any spatial data, however, may raise specific concerns, which are detailed in the next session.

3. Major challenges

The additional contribution that the use of spatial analysis can bring to demography is enormous. However, it comes at a price. While issues related to data storage, assembly, and availability, computer software, and development of spatial statistical methods have witnessed spectacular advancements and improvements lately, there are still major challenges to be addressed. First, any analysis that uses spatial data faces two concerns: (i) modifiable areal unit problem (MAUP), and (ii) confidentiality. Second, in the vast majority of institutions that provide formal training in demography "spatial thinking" is yet to be established. Next, each of those aspects in discussed in detail.

The modifiable areal unit problem (MAUP) is a potential source of error in studies that analyze aggregated spatial data. Results found at one level of aggregation (e.g. census tract) are not necessarily the same when a different aggregation is used (e.g. county) (Pryor 1984). In a loose concept, MAUP is a spatial ecological fallacy. As Openshaw (1984) stated: "*the areal units (zonal objects) used in many geographical studies are arbitrary, modifiable, and subject to the whims and fancies of whoever is doing, or did, the aggregating.*"

MAUP has two components: (i) a scale effect – spatial data analysis at different scales may produce different results, and (ii) a zoning effect – regrouping zones at a given scale may produce different results (Fotheringham, Brunsdon and Charlton 2000). Although several strategies have been proposed to deal with the MAUP problem, the question is if current analyses of aggregated spatial data actually address the problem at all. The work of Openshaw and Rao (1995), described earlier, explicitly address this problem, and proposes algorithms to generate alternative zoning schemes. Among the studies reviewed in this article, Skinner, Henderson and Jianhua (2000) overcome the MAUP problems by disaggregating the Chinese county level data to obtain more compatible areal units.

In summary, disaggregated data should be used in order to avoid MAUP problems, although that is not always possible. MAUP can be carefully addressed through a sensitivity analysis of the results at different scales and zoning schemes, or through the use of strategies to optimize the aggregation of the areal units (Fotheringham, Brunsdon and Charlton 2000; Ali et al. 2005).

Protecting the identity of interviewees when collecting, analyzing, and disseminating survey data is imperative (Fox, Suryanata and Hershock 2005; VanWey, Rindfuss, Gutmann, Entwisle and Balk 2005). Census data is publicly released only at a certain level of aggregation, and data collected in any survey are released without identifiers (e.g. name and address). This guarantees that no single individual can be identified. The advantage of a spatial data (and what makes it so unique and useful for spatial analysis) is a measure of the location of each observation. Depending on the scale of the observation, releasing the location violates the confidentiality of the respondents. On the one hand, if the location refers to a person or a house, the identification is straightforward. On the other hand, if the location describes a central point in a larger area, such as a village, neighborhood, census tract, or county, the possible identification of the informant is conditioned on the additional variables available in the data (e.g. sex, age, education, professional activity, marital status, race, and living arrangements) and the number of people living in the area.

Major funding institutions, such as the National Institutes of Health (NIH) and the National Science Foundation (NSF) request that data collected under their grants should be made publicly available (Rindfuss, Walsh, Mishra, Fox and Dolcemascolo 2003), therefore spatial data needs to be released in such a way that confidentially is guaranteed. Confidentiality can be broken when data is released in tabular (the data set) or visual (maps) form (VanWey, Rindfuss, Gutmann, Entwisle and Balk 2005). Different strategies can be pursued in order to address this problem (check the review in VanWey, Rindfuss, Gutmann, Entwisle and Balk 2005), although there is no clear-cut answer or recommendation that fits all kinds of spatial data. Geographic methods to mask data are largely studied, and have the potential to preserve data confidentiality and accuracy (Armstrong, Rushton and Zimmerman 1999; Kwan, Casas and Schmitz 2003).

Finally, it is necessary to address the challenge of developing a "spatial thinking" in the social science community, particularly among demographers. Unfortunately, the lack of a spatial thinking happens before one gets college education, and therefore is not an exclusive concern to social scientists. But what we miss by not having a spatial thinking? The best way to answer this question is to describe the purposes of spatial thinking: "*It has (1) a descriptive function, capturing, preserving, and conveying the appearances of and relations among objects; (2) an analytic function, enabling an understanding of the structure of objects; and (3) an inferential function, generating answers to questions about the evolution and function of objects.*" (National Academies Press (U.S.) 2006:33). In this definition, *objects* can be interpreted as variables, and the first purpose describes visualization efforts. Additionally, *understanding the structure* refers to describing how a variable is distributed in space (spatial patterns), and is associated to the use of exploratory spatial data analysis (spatial autocorrelation, clusters, etc). Finally, *inferential function* deals with how and why a spatial pattern is observed, and requires the use of multivariate spatial analysis. Therefore, without a spatial thinking we miss the visual power, the spatial exploratory investigation, and the understanding of the impacts that space can have in life outcomes (health, behavior, inequalities, etc). Above all, we miss the chance to properly address these "unknown" effects, and therefore fail to provide adequate guidance for policy making.

Not surprisingly, the majority of spatial demography studies reviewed in this article was not produced by demographers, and was not published in population journals. This is not to claim that only demographers should do them, but to call attention to the fact that they are not making as many contributions to the field as they could. A quick check on the list of 25 training population centers that are members of the Association of Population Centers (APC) (http://www.popcenters.org/) may offer some clues on why. Out of the 25 population centers, only two have a geographic information analysis unit, and only one has a spatial analysis unit directly linked with the center. Those three institutions offer regular classes on GIS and spatial analysis. Eight out of the 25 universities hosting population centers do not have a Geography Department, which may add an additional difficulty to the development of a spatial thinking, and the offering of spatially oriented courses. These facts highlight that a change in curriculum is on demand. But could this happen immediately? There is not one single answer to this question; it depends on the institution.

There are two key references for anyone interested in pursuing a spatially oriented research in demography: (i) the Center for Spatially Integrated Social Science – CSISS (http://www.csiss.org/), and (ii) the Spatial Perspectives on Analysis for Curriculum Enhancement – SPACE (http://www.csiss.org/SPACE/) program. Funded by the NSF, CSISS was established in 1999 and focuses on promoting a spatial approach in the social sciences through different programs. Among the resources provided by CSISS are: description of spatial methods and literature, syllabi and lecture outlines, clearinghouse of spatial data (under development), clearinghouse of spatial analysis software, and promotion of workshops. Regarding the latter, more than 350 people (including myself) from a myriad of disciplines in the social sciences have participated in workshops promoted by CSISS. Also funded by NSF, the SPACE program was created in 2003 and aims to strengthen academic programs and student capabilities to apply spatial techniques across a wide range of disciplines. SPACE promotes national workshops, and web-based teaching and learning resources. Specific material for demography is available at http://www.csiss.org/SPACE/directory/?cat=7.

While initiatives such as CSISS and SPACE are very likely to continue in the future (Goodchild, Anselin, Appelbaum and Harthorn 2000), a commitment from demographers and from training population centers is required to increase the use and dissemination of spatial methods in the field.

4. Potential contributions

The review presented in this article highlights two issues. On the one hand, the use of spatial techniques to address fertility, mortality, migration, and population models has helped to answers a wide range of questions, and offered important evidence with the potential to help the monitoring, evaluation, and implementation of population policies. On the other hand, the review shows that the potential of spatial techniques has not been fully realized yet. Some of the areas/questions that could be addressed in the future are highlighted next.

A myriad of studies have addressed specific diseases/causes of death. Their importance is unquestionable: without them the implementation of spatially targeted interventions for disease control would not be feasible (Carter, Mendis and Roberts 2000). However, there is still a lack of studies that approach a spatial analysis of mortality at a broader level. While there is a major effort to understand the patterns of fertility decline, both with historical and current data, the same is not true for mortality. Although fertility is the most important component determining the age structure of a population (and not surprisingly demographic transitions theories tend to search for explanations for its decline), one might wonder the role that mortality played. Has mortality decline been spatially homogenous within countries? How did public health policies influence the observed gains in mortality across different localities? Does the spatial pattern of mortality variation have any links with the spatial pattern of fertility? Is the spatial pattern of mortality related to levels of spatial inequality? Is there any relationship between the spatial pattern of mortality and the spatial distribution of migrants? Can the use of a spatial approach shed further light on the links between socio-economic status and health? Does the continuous exposure to natural disasters (e.g. hurricanes and earthquakes) impact the health status of the population?

Additionally, there is still a lot to be learned about the onset and pace of fertility decline in developing countries. How does the spatial pattern of fertility declines relate to the spatial pattern of poverty (if a link exists at all)? Does the spatial distribution of contraceptive methods result in different spatial patterns of fertility decline? What impact, if any, does international migration have on local levels of fertility? Does the spatial pattern of the onset of the 2nd demographic transition in Europe resemble the spatial pattern of the 1st demographic transition?

Regarding formal population models, it is expected that applications using a multiregional approach are likely to increase. Topics of future development include the potential contribution of demographers for the discussion of appropriate levels of scale/neighborhood size in population analysis, and to what extend fractal analysis is one of the methodological approaches to pursue for that matter. In addition, to what extend satellite images will become a powerful tool to monitor urban expansion during intercensal years, and therefore guide policies related to provision of infrastructure and health care? Finally, should the window of opportunity be discussed at the local level, considering the spatial variability in fertility decline?

All these questions could render excellent dissertations and publications, but above all, they would reveal local specificities that, at the moment, are yet to be found. But would this make a difference? Yes, and to see why, let us look at one example: the Millennium Development Goals (http://www.un.org/milleniumgoals/). All United Nations members have pledged to achieve eight goals (addressing poverty, education, health, gender equality, and environmental sustainability) by 2015. Countries implement their own strategies to achieve the goals. How can national strategies mitigate problems that vary at the local level? In other words, can aspatial strategies address spatial-related issues? Clearly the answer is no (although, unfortunately, aspatial policies are largely used). Therefore, if population issues are to be addressed properly by policy measures, they require a prior spatial assessment.

5. Conclusion

While addressing environmental research in the field of demography, Pebley (1998) pointed out that demographers should pay special attention to the impacts that the spatial distribution of the population could have on the environment, since in an era of globalization changes to the local environment ignore boundaries and are likely to be a result of demands originated from national and international markets. This is just one example of why a spatial approach should be considered in population studies.

This article presented a review of spatial demography applications in the study of population growth, population models, fertility, migration, and mortality. The review indicates that indeed several important issues in demographic analysis gained a whole new perspective when analyzed spatially (e.g. the Easterlin theory and the diffusionist model of demographic transition). Above all, the findings of those studies provide important information for proper decision making. Monitoring, evaluation, and proposal of new population policies at the local level do need studies that account for the effect that location has on the outcome of particular variables. The optimization of the distribution of local services (e.g. hospitals and family planning agencies) can benefit from these studies as well.

Yet, many questions remain unanswered, and demographers have a wide range of topics to choose from. Some of the potential areas of application are presented in this article. Also, a list of sources providing free spatial datasets of interest to demographers is provided. However, any future analysis of spatial population data needs to account for scale and confidentiality problems. Although there is no specific solution for those issues, ignoring them is definitely not a good strategy.

Finally, here is a quote from Woods and Rees (1986: ix): "*This is a book with a message. It argues the case for viewing demographic patterns, structures and systems from a spatial perspective. For by so doing new insights will be gained on the complex forms of human populations and more effective methods will be advanced to monitor and forecast – even change – the growth and distribution of future populations. Spatial demography […] represents an aspect of population studies in which recent developments have been considerable and new advances promise to be spectacular in this and the next century.*"

During the 20-year period since the above quote has been written new advances were, indeed, spectacular. The availability of spatial data increased dramatically, numerous software facilitate the application of spatial techniques (for an updated review check Rey and Anselin, (2006), new spatial analytic methods have been proposed, and new remotely sensed imagery brought up innovative ways to estimate population. Yet, further advances are likely to emerge in the coming years.

To conclude, such as Woods and Rees' textbook, this article has a message. It is a wake-up call to the importance of a spatial approach in demographic analysis. If those performing population studies do want to have a say in policy making (even better, policy making done in the right way), then we need to move in a "spatial direction".

6. References

Akkerman, A. (1992). "Fuzzy targeting of population niches in urban planning and the fractal dimension of demographic change." *Urban Studies* 29(7), 1093-1114.

Ali, M., et al. (2005). "Neighborhood size and local geographic variation of health and social determinants." *International Journal of Health Geographics* 4(12).

Anselin, L. (1988). *Spatial econometrics: methods and models*: Dordrecht; Boston, Kluwer Academic Publishers.

Anselin, L. (1995). "Local Indicators of Spatial Association - LISA." *Geographical Analysis* 27(2), 93-115.

Armstrong, M. P., G. Rushton and D. L. Zimmerman (1999). "Geographically masking health data to preserve confidentiality." *Statistics in Medicine* 18, 497-525.

Balabdaoui, F., J.-P. Bocquet-Appel, C. Lajaunie and S. I. Rajan (2001). "Space-time evolution of the fertility transition in India, 1961-1991." *International Journal of Population Geography* 7, 129-148.

Balk, D., T. Pullum, A. Storeygard, F. Greenwell and M. Neuman (2003). *Spatial Analysis of Childhood Mortality in West Africa*: Calverton, Maryland, ORC Macro and Center for International Earth Science Information Network (CIESIN), Columbia University.

Bocquet-Appel, J.-P. and J. N. Bacro (1994). "Generalized Wombling." *Systematic Biology* 3, 316-329.

Bocquet-Appel, J.-P. and L. Jakobi (1996). "Barriers to the spatial diffusion for the demographic transition in Western Europe." *in* Bocquet-Appel, J.-P., Courgeau, D. and Pumain, D., eds., *Spatial Analysis of Biodemographic Data*: Paris, John Liberty Eurotext/INED: 117-129.

Bocquet-Appel, J.-P. and L. Jakobi (1998). "Evidence for a spatial diffusion of contraception at the onset of the fertility transition in Victorian Britain." *Population, English selection: New methodological approaches in the social sciences* 10(1), 181-204.

Bocquet-Appel, J.-P., S. I. Rajan, J. N. Bacro and C. Lajaunie (2002). "The onset of India's fertility transition." *European Journal of Population-Revue Europeenne de Demographie* 18(3), 211-232.

Bracken, I. and D. Martin (1989). "The generation of spatial population distributions from census centroid data." *Environment and Planning A* 21, 537-543.

Bradshaw, T. K. and B. Muller (2004). "Shaping policy decisions with spatial analysis." *in* Goodchild, M. F. and Janelle, D. G., eds., *Spatially Integrated Social Science: examples in best practice*: New York, Oxford University Press.

Carter, R., K. N. Mendis and D. Roberts (2000). "Spatial targeting of interventions against malaria." *Bulletin of the World Health Organization* 78(12), 1401-1411.

Casetti, E. (1972). "Generating models by the expansion method: application to geographic research." *Geographical Analysis* 4, 81-91.

Casetti, E. (1986). "The dual expansion method: an application for evaluating the effects of population growth on development." *IEEE Transactions on Systems, Man and Cybernetics* 16(1), 29-39.

Coale, A. J. and S. C. Watkins (1986). *The decline of fertility in Europe: the revised proceedings of a Conference on the Princeton European Fertility Project*: Princeton, N.J., Princeton University Press.

Congdon, P. (2003). "Modelling spatially varying impacts of socioeconomic predictors on mortality outcomes." *Journal of Geographical Systems* 5, 161-184.

Cressie, N. (1993). *Statistics for spatial data*: New York, J. Wiley.

Easterlin, R. A. (1987). *Birth and fortune: the impact of numbers on personal welfare*: Chicago, University of Chicago Press.

El Ghordaf, J., M. L. Hbid and O. Arino (2004). "A mathematical study of a two-regional population growth model." *Comptes Rendus Biologies* 327(11), 977-982.

Elliott, P., J. C. Wakefield, N. G. Best and D. J. Briggs (2000). *Spatial epidemiology: methods and applications*: Oxford; New York, Oxford University Press.

Elvidge, C. D., K. E. Baugh, E. A. Kihn, H. W. Kroehl and E. R. Davis (1997). "Mapping city lights with nighttime data from the DMSP operational linescan system." *Photogrammetric Engineering and Remote Sensing* 63(6), 727-734.

Elvidge, C. D., et al. (2001). "Nighttime lights of the world: 1994-95." *ISPRS Journal of Photogrammetry and Remote Sensing* 56, 81-99.

Fotheringham, A. S., C. Brunsdon and M. Charlton (2000). *Quantitative geography: perspectives on spatial data analysis*: London; Thousand Oaks, Calif., Sage Publications.

Fox, J., K. Suryanata and P. Hershock (2005). *Mapping Communities: Ethics, Values, Practices*: Honolulu, HI, East-West Center.

Frankhauser, P. (1998). "The fractal approach. A new tool for the spatial analysis of urban agglomerations." *Population, English selection: New methodological approaches in the social sciences* 10(1), 205-240.

Fuchs, R. J. (1984). "Government policy and population distribution." *in* Clarke, J. I., eds., *Geography and population: approaches and applications*: Oxford [Oxfordshire]; New York, Pergamon Press: 127-137.

Fuchs, R. J. and G. J. Demko (1983). "Rethinking population distribution policies." *Population Research and Policy Review* 2(2), 161-187.

Fuller, G. (1974). "On the spatial diffusion of fertility decline: the distance-to-clinic variable in a Chilean community." *Economic Geography* 50(4), 324-332.

Getis, A. (1995). "Spatial filtering in a regression framework: examples using data on urban crime, regional inequality, and government expenditures." *in* Anselin, L. and Florax, R. J. G. M., eds., *New directions in spatial econometrics*: Berlin, Springer: 191-203.

Getis, A. and K. J. Ord (1996). "Local spatial statistics: an overview." *in* Longley, P. and Batty, M., eds., *Spatial analysis: modelling in a GIS environment*: Cambridge, New York: 261-277.

Gobalet, J. G. and R. K. Thomas (1996). "Demographic data and geographic information systems for decision making: the case of public health." *Population Research and Policy Review* 15(5-6), 537-548.

Goodchild, M. F., L. Anselin, R. P. Appelbaum and B. H. Harthorn (2000). "Toward spatially integrated social science." *International Regional Science Review* 23(2), 139-159.

Griffith, D. A., L. J. Layne, J. K. Ord and A. Sone (1999). *A casebook for spatial statistical data analysis: a compilation of analyses of different thematic data sets*: New York, Oxford University Press.

Guilmoto, C. Z. and S. I. Rajan (2001). "Spatial patterns of fertility transition in Indian districts." *Population And Development Review* 27(4), 713-738.

Hastie, T., R. Tibshirani and J. H. Friedman (2001). *The elements of statistical learning: data mining, inference, and prediction*: New York, Springer.

Hill, N. D. (1998). Creating Social Borders from the WASAP Data Sets. *West Africa Spatial Analysis Prototype Exploratory Analysis (WASAP)*. Calverton, Maryland, Macro International, Inc.

Hudson, J. C. (1970). "Elementary models for population growth and distribution analysis." *Demography* 7(3), 361-368.

Imhoff, M. L., W. T. Lawrence, D. C. Stutzer and C. D. Elvidge (1997). "A technique for using composite DMSP/OLS "city lights" satellite data to map urban area." *Remote Sensing of Environment* 61, 361-370.

Knox, G. (1964). "The detection of space-time interactions." *Applied Statistics* 13, 25-29.

Kwan, M. P., I. Casas and B. C. Schmitz (2003). "Protection of geoprivacy and accuracy of spatial information: how effective are geographic masks?" *Cartographica*.

Land, K. C. and G. Deane (1992). "On the large-sample estimation of regression models with spatial- or network-effects terms: a two-stage least squares approach." *in* Marsden, P. V., eds., *Sociological Methodology*: Washington, DC, American Sociological Association: 221-248.

Lawson, A. (1999). *Disease mapping and risk assessment for public health*: Chichester; New York, Wiley.

Lawson, A. and K. Kleinman (2005). *Spatial and syndromatic surveillance for public health*: Chichester; Hoboken, NJ, Wiley.

Leal, M. d. C. and C. L. Szwarcwald (1997). "Characteristics of neonatal mortality in the State of Rio de Janeiro, Brazil, in the 1980's: a spatio-temporal analysis." *Revista de Saúde Pública* 31(5), 457-65.

Ledent, J. and A. Rogers (1987). "Spatial dynamics of populations with changing birth, death, and migration rates: a generalization of multiregional stable population theory." *Environment and Planning A* 19, 819-828.

Loftin, C. and S. K. Ward (1983). "A spatial autoccorelation model of the effects of population density on fertilty." *American Sociological Review* 48, 121-128.

National Academies Press (U.S.) (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum*: Washington, D.C., National Academies Press.

Nordhaus, W. D. (2006). "Geography and macroeconomics: new data and new findings." *Proceedings of the National Academy of Sciences of the United States of America* Pinted online, February 10, 2006(10.1073/pnas.0509842103).

Openshaw, S. (1984). *The modifiable areal unit problem*: Norwick, UK, GeoBooks.

Openshaw, S. and L. Rao (1995). "Algorithms for reengineering 1991 Census geography." *Environment and Planning A* 27, 425-446.

Ord, J. K. and A. Getis (1995). "Local spatial autocorrelation statistics: distributional issues and an application." *Geographical Analysis* 27(4), 286-306.

Pandit, K. and S. Bagchi-Sen (1993). "The spatial dynamics of U.S. fertility, 1970-1990." *Growth and Change* 24, 229-246.

Pebley, A. R. (1998). "Demography and the environment." *Demography* 35(4), 377-389.

Pebley, A. R. and N. Sastry (2003). Neighborhoods, Poverty and Children's Well-being: a review. *Labor and Population Program, Working Paper Series 03-04*. Los Angeles, RAND.

Plane, D. A. (1992). "Age-composition change and the geographical dynamics of interregional migration in the U.S." *Annals of the Association of American Geographers* 82(1), 64-85.

Plane, D. A., C. J. Henrie and M. J. Perry (2005). "Migration up and down the urban hierarchy and across the life course." *Proceedings of the National Academy of Sciences of the United States of America* 102(43), 15313-15318.

Plane, D. A. and G. F. Mulligan (1997). "Measuring spatial focusing in a migration system." *Demography* 34(2), 251-262.

Plane, D. A. and P. A. Rogerson (1991). "Tracking the baby boom, the baby bust, and the echo generations: how the age composition regulates US migration." *Professional Geographer* 43(4), 416-430.

Pollé, V. F. L. (1984). "Population estimation from aerial photos for non-homogeneous urban residential areas." *ITC Journal*.

Preston, S. H. and A. J. Coale (1982). "Age structure, growth, attrition, and accession: a new synthesis." *Population Index* 48(2), 217-259.

Pryor, R. J. (1984). "Methodological problems in Population Geography." *in* Clarke, J. I., eds., *Geography and population: approaches and applications*: Oxford [Oxfordshire]; New York, Pergamon Press: 25-34.

Rees, P. H. and A. G. Wilson (1977). *Spatial population analysis*: London, E. Arnold.

Rees, P. H. and R. Woods (1986). "Demographic estimation: problems, methods and examples." *in* Woods, R. and Rees, P. H., eds., *Population structures and models: developments in spatial demography*: London; Boston, G. Allen and Unwin: 301-343.

Rey, S. J. and L. Anselin (2006). "Recent advances in software for spatial analysis in the social sciences." *Geographical Analysis* 38, 1-4.

Rindfuss, R. R., S. J. Walsh, V. Mishra, J. Fox and G. P. Dolcemascolo (2003). "Linking household and remotely sensed data." *in* Fox, J., Rindfuss, R. R., Walsh, S. J. and Mishra, V., eds., *People* *and the environment: approaches for linking household and community surveys to remote sensing and GIS*: Boston, Kluwer Academic Publishers: 1-29.

Robinson, W. S. (1950). "Ecological Correlations and the Behavior of Individuals." *American Sociological Review* 15, 351-357.

Rogers, A. (1966). "The multiregional matrix growth operator and the stable interregional age structure." *Demography* 3(2), 537-544.

Rogers, A. (1975). *Introduction to multiregional mathematical demography*: New York, Wiley.

Rogers, A. (1990). "Requiem for the net migrant." *Geographical Analysis* 22(4), 283-300.

Rogers, A. (1992). "Heterogeneity, spatial population dynamics, and the migration rate." *Environment and Planning A* 24, 775-791.

Rogers, A. (1995). *Multiregional demography: principles, methods and extensions*: Chichester; New York, Wiley.

Rogers, A. and J. Raymer (2001). "Immigration and the Regional Demographics of the Elderly Population in the United States." *Journal of Gerontology: Social Sciences* 56B(1), S44-S55.

Rogers, A. and S. Sweeney (1998). "Measuring the spatial focus of migration patterns." *Professional Geographer* 50(2), 232-242.

Rogers, A., F. Willekens, J. Little and J. Raymer (2002). "Describing migration spatial structure." *Papers in Regional Science* 81, 29-48.

Rogers, A. and J. A. Woodward (1991). "Assessing state population projections with transparent multiregional demographic models." *Population Research and Policy Review* 10, 1-26.

Rutstein, S. O. (2000). Cluster Typing Procedures. *West Africa Spatial Analysis Prototype Exploratory Analysis (WASAP)*. Calverton, Maryland, Macro International, Inc.

Santos, S. M. and C. P. Noronha (2001). "Mortality spatial patterns and socioeconomic differences in the city of Rio de Janeiro." *Cadernos de Saúde Pública* 17(5), 1099-1110.

Sastry, N., A. R. Pebley and M. Zonta (2002). Neighborhood Definitions and the Spatial Dimension of Daily Life in Los Angeles. *Labor and Population Program, Working Paper Series 03-02*. Los Angeles, RAND.

Skinner, G. W., M. Henderson and Y. Jianhua (2000). "China's fertility transition through regional space." *Social Science History* 24(3), 613-652.

Snow, J. (1855). *On the mode of communication of cholera*: London, John Churchill.

Sutton, P. C., D. Roberts, C. D. Elvidge and K. E. Baugh (2001). "Census from Heaven: an estimate of the global human population using night-time satellite imagery." *International Journal of Remote Sensing* 22(16), 3061-3076.

Thomson, M. C., et al. (2006). "Malaria early warnings based on seasonal climate forecasts from multi-model ensembles." *Nature* 439, 576-579.

Tobler, W., U. Deichmann, J. Gottsegen and K. Maloy (1997). "World Population in a grid of spherical quadrilaterals." *International Journal of Population Geography* 3, 203-225.

Tolnay, S. E. (1995). "The spatial diffusion of fertility: a cross-sectional analysis of counties in the American South, 1940." *American Sociological Review* 60, 299-308.

United Nations (1980). World Population Trends and Monitoring Report, Vol II, Population Policies. New York, United Nations, Population Division.

United Nations (2000). Replacement Migration: Is it A Solution to Declining and Ageing Populations? New York, Population Division, Department of Economic and Social Affairs, United Nations Secretariat.

VanWey, L. K., R. R. Rindfuss, M. P. Gutmann, B. Entwisle and D. L. Balk (2005). "Confidentiality ans spatially explicit data: concerns and challenges." *Proceedings of the National Academy of Sciences of the United States of America* 102(43), 15337-15342.

Wachter, K. W. (2005). "Spatial demography." *Proceedings of The National Academy of Sciences of The United States of America* 102(43), 15299-15300.

Waldorf, B. and R. Franklin (2002). "Spatial dimensions of the Easterlin hypothesis: fertility variation in Italy." *Journal of Regional Science* 42(2), 549-578.

Webster, C. J. (1996). "Population and dwelling unit estimates from space." *Third World Planning Review* 18(2), 155-176.

Weeks, J. R. (2004). "The role of spatial analysis in demographic research." *in* Goodchild, M. F. and Janelle, D. G., eds., *Spatially Integrated Social Science: examples in best practice*: New York, Oxford University Press.

Weeks, J. R., A. Getis, A. G. Hill, M. S. Gadalla and T. Rashed (2004). "The fertility transition in Egypt: intraurban patterns in Cairo." *Annals of the Association of American Geographers* 94(1), 74-93.

Willekens, F. and N. Baydar (1986). "Forecasting place-to-place migration with generalized linear models." *in* Woods, R. and Rees, P. H., eds., *Population structures and models: developments in spatial demography*: London; Boston, G. Allen and Unwin: 203-244.

Womble, W. G. (1951). "Differential systematics." *Science* 114, 315-322.

Woods, R. and P. H. Rees (1986). *Population structures and models: developments in spatial demography*: London; Boston, G. Allen and Unwin.