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Trends in Spatial Statistics

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With many leading spatial analysts nearing retirement, reflection on the discipline becomes beneficial. To capture some of their collective perspective, fifty-eight researchers were surveyed on key spatial analysis developments, future challenges, and essential readings for newcomers. Geographic information systems (GIS), new data sources, improved understanding of spatial autocorrelation, spatially local methods, and the spread of spatial analysis beyond geography featured prominently among the twenty-four respondents. Future challenges included overcoming methodological limitations and retaining spatial analysis within geography. Twelve books highlighted by respondents are also summarized. Finally, a synthesis and some thoughts based on survey results are presented. **Key Words: GIS, local measures, quantitative revolution, spatial autocorrelation, trends in geography.**

因空间分析领域许多权威学者的即将退休，在此领域的反思从而变得有益。为了捕捉他们的一些集体的观点，本文对 58 个研究人员在空间分析领域的重点发展，未来的挑战，新学者的重要读物等方面进行了调查。地理信息系统（GIS），新的数据源，空间自相关上增进的理解，空间局域方法，和超越地理的空间分析的普及，在 24 个应答者之中被突出强调。未来的挑战包括克服方法的局限性和在地理中保留空间分析。也概述了受访者强调的 12 本书。最后提出基于调查结果的综合分析和一些想法。**关键词：GIS，局部措施，定量革命，空间自相关，地理的趋势。**

Con muchos de los principales analistas espaciales aproximándose al retiro, la reflexión sobre la disciplina se torna benéfica. Para captar algo de su perspectiva colectiva, se estudiaron cincuenta y ocho investigadores en relación con desarrollos claves en análisis espacial, retos futuros y lecturas esenciales para los recién llegados. Sistemas de información geográfica (SIG), nuevas fuentes de datos, mejor entendimiento de la autocorrelación espacial, métodos espacialmente locales y la dispersión del análisis espacial fuera de la geografía, figuraron de manera prominente entre los treinta y cuatro que respondieron. Los retos futuros incluyeron el remontar limitaciones metodológicas y retener el análisis espacial dentro de la geografía. Doce libros destacados por los entrevistados son también resumidos. Por último, se presentan una síntesis y algunos pensamientos basados en los resultados del estudio. **Palabras clave: SIG, mediciones locales, revolución cuantitativa, autocorrelación espacial, tendencias de la geografía.**

Although the story of spatial analysis might have begun earlier, the quantitative revolution is where many geographers begin reading the book. Much has been written about the quantitative revolution (e.g., Burton 1963; Curry 1967; Berry 1993; Casetti 1993; Getis 1993; Johnston 2000; Barnes 2001, 2003; Golledge 2008; Haggett 2008). We are fascinated by events that took place during this time and how a relatively small group of individuals shaped a discipline. More than fifty years later, many of the people who participated in the quantitative revolution have retired or are retiring. It therefore seems timely, if not necessary, to compile the thoughts about spatial analysis of those who have shaped our discipline during

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Table 1 *A list of survey respondents*

Last name	First name
Aldstadt	Jared
Armstrong	Marc
Boots	Barry
Casetti	Emilo
Fingleton	Bernard
Fotheringham	Stewart
Garrison	William
Getis	Art
Golledge	Reginald
Griffith	Daniel
Jacquez	Geoffrey
Miller	Harvey
Ord	Keith
O'Sullivan	David
Páez	Antonio
Yeates	Maurice

Note: There were eight additional respondents who did not respond to a request for permission to list their name.

the quantitative revolution and in the years that followed.

Whereas the established spatial analysts have shaped the past, it is those who are emerging now who will, most likely, guide future directions. It is those at the bench, along with their graduate students, who will shape the next decades. With one eye on the past and one on the future, the goals of this article are to (1) synthesize the opinions of spatial analysts in geography and (2) provide a new generation of spatial analysts with guidance as they prepare to address current challenges in our discipline. These goals are met by surveying leading researchers in the field of spatial analysis and synthesizing their responses within the context of academic literature.

From my review of the literature and advice from two well-known quantitative geographers, thirty-two still-active and established and twenty-six emerging researchers in geography were selected and surveyed. Responses were received from eighteen established and six newer spatial analysts (Table 1). Relative to established spatial analysts, a lower proportion of new scholars responded to the survey (23 percent vs. 56 percent); as such, results are biased toward the views of our more established colleagues. These scholars come from research universities in Canada, the United States, and the United Kingdom. They have published widely in the recognized and appropriate geography journal outlets for spatial analytical work. The perspectives represented in this article are not exhaustive but rather highlight trends in the thinking of a group of spatially minded and influential researchers. All thoughts of all respondents could not fit into this article; rather, I present and emphasize themes that were commonly highlighted.

Three questions were posed to respondent spatial analysts:

1. Since the quantitative revolution in the 1950s and 1960s, what have been the key developments in quantitative geography?
2. In your opinion, what are the key challenges in geographic information systems (GIS) and spatial analysis that need to be addressed in the short term? What are the longer term challenges?
3. Please list five papers or books that should be required reading for students interested in spatial analysis.

This article is organized into four sections. In the first section, I provide a summary of common responses on the developments in spatial analysis that have occurred since the quantitative revolution. In the second section, I outline research challenges and opportunities in spatial analysis identified by survey respondents. In the third section, I give an overview of fourteen books that are considered essential reading. The books outlined as essential reading for new spatial analysts were either listed by three respondents or listed by two respondents and highlighted by reviewers. I have taken the liberty of adding two new books, also suggested by reviewers, that were not published when the surveys were conducted. It is interesting that no journal articles were listed more than twice and the emphasis on books reflects survey results. The fourth section is my synthesis and perspectives on the survey results. All ideas presented in the first two sections are taken from the surveys, but I provide references for many of the ideas to present the thoughts of the survey respondents within the context of literature. In some cases, I have provided additional examples to illustrate ideas presented by those surveyed. Several of the survey respondents are referenced throughout this article. There was no attempt to link comments and references by individuals; in many cases references are associated with the perspective of a different spatial analyst. In this article I use the terms *spatial analysis* and *spatial statistics* synonymously, although I recognize that these two fields have distinctions. The emphasis of this article tends toward spatial statistics; however, there are topics covered that fall well into the spatial analysis realm and boundaries between the two fields are arguably fuzzy.

Past Trends

Commonly identified developments in spatial analysis since the quantitative revolution include the creation of geographic information systems, the availability of new data sources, progress in our understanding of spatial autocorrelation, the creation of spatially local methods, and the expansion of spatial science beyond geography.

Geographic Information Systems

There is little debate among survey respondents that since the quantitative revolution the development of GIS has had a large impact on quantitative geography. By all accounts, GIS has revolutionized how we handle spatial data and has become the vehicle for spatial analysis (Unwin 1996; Longley 2000). Concepts and methods developed during the quantitative revolution have become commonly used in GIS. For example, GIS has made network analysis functional (Haggett 1967), has enabled and extended the complexity of spatial modeling (Chorley 1968), and has allowed easy extraction of spatial metrics (i.e., distance) for statistical analysis (Bachi 1968).

Related to developments in GIS, survey respondents also touted the impact of computing on spatial analysis. Computing has advanced beyond the imagination of researchers who vied for mainframe computing time and were familiar with punch cards (O'Sullivan and Unwin 2003). Computers are fast, cheap, large, and ubiquitous and have enabled GIS and spatial analysis to permeate beyond the core group of researchers developing spatial quantitative methods (Unwin 1996). Computing has also led to new branches of spatial analysis such as geocomputation or spatial analysis methods developed to exploit computing power (Fotheringham 1998).

Several survey respondents noted that the popularity of GIS has increased as software and freeware have become more available and user friendly (Boots 2000). Evidence of the importance of easy-to-use software is the growing number of analysis methods that are published in combination with software packages (e.g., Rey and Janikas 2005; Robertson et al. 2007). Although commercial GIS software dominates the user market, freeware GIS (e.g., QGIS) and freeware spatial analysis packages (e.g., SpaceStat, GeoDa, and **sp** for R) with more advanced analysis functionality are important for distributing more advanced spatial analysis techniques.

Methodological developments are routinely coupled with GIS, and survey responses recognized this in highlighting the integration of rules of topology and geometry into a computing environment and visualization. The science of topology and geometry are the cornerstones of GIS functionality and enable basic GIS tasks, such as spatial querying and defining spatial neighborhoods. GIS has also transformed spatial data visualization (e.g., Fotheringham 1999). Textbooks on spatial analysis often indicate that exploratory analysis, which includes data visualization, is the first step in spatial analysis (Bailey and Gatrell 1995; Fotheringham, Brunsdon, and Charlton 2000). A forum for storing and retrieving data, GIS enables visualization of geographic data that is both interactive and dynamic (Andrienko and Andrienko 1999). The power of GIS as a tool for data visualization is being reexplored, as the GeoWeb, or integration of locational data with the Internet, extends our imagination (e.g., Butler 2006; Kamel Boulos and Burden 2007).

The introduction of GIS has also widened employment opportunities for geographers. Skills of spatial data handling and analysis are marketable in business and government, as well as academia. GIS, in combination with growing data sources (discussed later), has increased both the number of opportunities and motivations for analyzing spatial data. Geographers trained in applied spatial science and technologies have expertise transferable to many environments.

Data Sources

Several survey respondents agreed that changes to spatial data, becoming digital and much larger spatially, temporally, and in volume, are an important development since the quantitative revolution. Global Positioning System (GPS), remote sensing, and GIS have decreased the cost of data collection, enabled data to be collected over much larger areas and repeatedly through time, and improved data storage and organization. Particularly, as remote sensing capabilities expand to include sensors with high spectral, spatial (i.e., Light Detection and Ranging [LiDAR]), and temporal resolutions, data sets will continue to grow in number and size and support the exploration of new geographically explicit questions (Wulder, Niemann, and Goodenough 2000; Lim et al. 2003). Not only the existence but the accessibility to spatial data has changed. Data are increasingly being viewed as public properties, and the universal popularity of spatial data browsers, such as Google Maps, is transforming how society understands spatial data (i.e., C. Miller 2006).

Spatial Autocorrelation

Surveyed spatial analysts identified spatial autocorrelation as an area where substantive progress has been made. The history and development of the concept of spatial autocorrelation and the associated methods of quantification have recently been chronicled (Getis 2008), and I refer readers to this article for more detail. Two broad avenues of development include the generation of measures of spatial autocorrelation (Cliff and Ord 1981) and the development of a framework for spatial regression analysis (Anselin 1988; Casetti 1995). Our understanding of positive spatial autocorrelation is particularly well developed and provides broad support for spatial modeling (Getis 2008).

Local Methods

The development of spatially local methods was also highlighted by surveyed spatial analysts. As is common throughout statistics, many traditional spatial analysis methods assume stationarity. Although the assumption of stationarity might be appropriate when study areas are small, the availability of spatially extensive geographical data necessitates new methods. The response has been the development of spatially local methods, which can be defined in contrast to traditional spatially global methods, which produce one set of relationships and assume that the nature of this relationship does not vary within the study region (Fotheringham, Brunsdon, and Charlton 2000). Local methods define a relationship for each data site i in a data set (Boots 2003). In doing so, they enable characterization of relationships that change across space and produce results that are mappable.

Although there are earlier examples (i.e., Hudson 1969; Casetti 1972), it was in the 1990s that spatially local method development surged. Several spatially local methods have been developed: local measures of spatial association (Getis and Ord 1992; Anselin 1995; Boots 2006), which quantify the nature of spatial association for each site within a study area; spatially weighted regression (Brunsdon, Fotheringham, and Charlton 1996), which enables relationships in an exploratory regression model to be generated for locations throughout a study area; and spatially local point pattern analysis (Getis and Franklin 1987), a local version of the global K function that quantifies departures from patterns generated from random processes. The development of local measures has provided a new set of challenges for spatial analysts, and these are addressed in a later section of this article.

Spreading the Word Outside Geography

Participants in the quantitative revolution have highlighted that during the 1950s and 1960s geographers borrowed the work of physicists and mathematicians to generate a new kind of geography, quantitative geography (Burton 1968). Survey respondents indicated that, aided by the advancements already listed (GIS, software, new types of spatial data, and improved technology), spatial analysis has permeated other disciplines and gained popularity in ecology (Fortin and Dale 2005), economics (Anselin 1988), general social sciences (Goodchild et al. 2000), and epidemiology (Elliott et al. 2000). During the quantitative revolution, geographers were importers of techniques. Since then, geographers have advanced spatial analysis, becoming net exporters of methods (Longley 2000). Beyond geography, the spatial and quantitative perspective developed by geographers has achieved recognition inside and outside of academia, and other disciplines are becoming important sources of spatial analysis innovation.

Future Opportunities

In contrast to views of the past, there was less consistency among surveyed spatial analysts as to future research challenges. Interestingly, many trends that emerged from the surveys were opportunities that resulted from past successes. Research challenges and opportunities include better integration of GIS and spatial analysis, the development of methods for large spatial data sets, overcoming the limitations of local statistics, improving how spatial sciences are communicated, and retaining the home of spatial analysis within geography.

Integration of GIS and Spatial Analysis

Although gains in GIS continue to support current interest in quantitative geographic methods, the lack of integration between GIS and spatial analysis is seen by spatial analysts as a limit to growth in both areas (Goodchild, Haining, and Wise 1992). There are opportunities to more fully integrate GIS and spatial analysis, and transmission of ideas is required in both directions. Methods in spatial analysis do not fully exploit the geographic and topological information available from GIS (Boots 2000; Marble 2000). For instance, survey respondents suggested that a deeper union between computational geometry and GIS would be beneficial (Boots 2000). In contrast, some survey respondents commented on the inherent danger in blurring the distinction between GIS and spatial analysis. Although Google Maps has GIS functionality, it is not useful for spatial statistics and failure to distinguish the discipline could result in the misconception that spatial analysis is obvious and does not require specialized knowledge.

Methods for Large and Multitemporal Data Sets

Many of the spatial analysts indicated that methodological developments require attention, although which methodological developments were important varied from person to person. Broadly, methodological needs can be linked to the desire to analyze data sets that are large: spatially, temporally, or in sheer volume. Large data sets stretch the capacity of existing data management approaches (e.g., White and Wang 2003), invalidate assumptions of stationarity (Boots 2003), and present challenges for common data models (H. Miller 2000). In the past, data shortages limited the spatial analyst's ability to address research questions; however, currently methodological challenges are often the limiting factor. This is particularly true of space–time data sets, such as mobility and tracking data, where methods for representation and analysis are underexplored (Goodchild 2009). Method development priorities that were highlighted include dealing with data uncertainty and error propagation using Bayesian analysis, approaches to spatial-temporal analysis (Peuquet 2001), analysis and interpolation of mobile and tracking data (Derekenaris et al. 2001), increasing the flexibility of data models (including ability to handle time; H. Miller 2000), protecting privacy when employing fine spatial resolution data (i.e., relating to humans; Armstrong and Ruggles 2005), geocomputation (Openshaw 2000), and management of massive data volumes. Survey respondents most consistently listed spatial-temporal method development as an opportunity area.

Advancing Local Spatial Statistics

The development of local spatial statistics is another case where spatial analysts indicated that past success has generated new challenges. The utility and popularity of local measures is undeniable. Local measures are being used for research in fields such as ecology (Nelson and Boots 2008), health (Rushton 2003), and transportation (Flahaut et al. 2003), but there are a number of issues associated with local spatial measures that require further development. Specific to local spatial autocorrelation measures is the issue of detecting significant local spatial autocorrelation in the presence of significant global spatial autocorrelation (Ord and Getis 2001). Large-scale spatial processes impact smaller scale processes and their resultant patterns. When detecting local scale patterns, ignoring large-scale patterns increases the chance of Type 1 errors or false positives (i.e., the error of rejecting a null hypothesis when it is actually true).

Spatially local measures also require controls for multiple and correlated testing (Caldas de Castro and Singer 2006). Traditional global measures utilize one statistical test, whereas local measures implement several overlapping statistical tests and tend toward false positives. Current methods for dealing with multiple testing tend to be overly conservative (i.e., Bonferroni correction), and the typical response to current issues with local measures is to use them for exploratory, rather than confirmatory, analysis. Dealing with issues of global spatial autocorrelation and multiple and correlated testing will enable local measures to be applied for confirmatory hypothesis testing.

Communicating Spatial Analysis Results

Collectively, survey respondents have expressed the need to improve how spatial analysis results are communicated to researchers in domain-oriented sciences and planners in the private and public sectors. Spatial analysis is moving beyond one-number summaries (i.e., spatially global statistics) that provide a single solution. As the assumptions and results of spatial methods become more versatile (i.e., spatially local methods provide many results), we are challenged by how to clearly communicate complex findings. Methods that synthesize results cartographically and aid visualization (Armstrong and Densham 2008) are necessary if we aim for broader use of spatial analysis by decision makers and applied scientists.

Geography as the Home for Spatial Analysis

Several survey respondents expressed concern that spatial analysis is slowly finding more comfortable homes in fields outside geography. Letting go of discipline strengths is a trend that is not unusual for geography, which has given up leadership in areas such as climatology, environmental studies, and landscape ecology. From 2000 to 2008, 72 percent of citations to *Geographical Analysis* manuscripts and, from 2006 to 2008, 74 percent of citations to the *Journal of Geographical Systems* came from articles not in the "core" geographic journals: *Geographical Analysis*, the *Journal of Geographical Systems*, the *International Journal of Geographical Information Science*, the Regional Science journals (the *Papers*, *Journal*, *Annals*, and the *International Regional Science Review*), *Environment and Planning A* and *B*, and *Computers, Environment and Urban Systems* (personal communication, Antonio Paez, 3 December 2008).

Retaining geography as the home for spatial analysis is complicated given the disconnect between those trained to think spatially (geographers) and those trained to think mathematically, statistically, and computationally. The majority of geographers do not have the technical skills to develop the science of spatial analysis. Some spatial analysts, primarily geographers, have indicated that we must modify the geographic curriculum, linking it more closely with mathematics and computer science, and attract more students from outside geography, particularly at the graduate level. Others warn of further training issues developing if spatial sciences are adopted by many groups and lack a core rooted in geography.

Essential Readings for the New Spatial Analyst

Reading lists provided by spatial analysts varied. Not all respondents listed readings, and several indicated that such lists were nearly impossible to generate. Greater than forty readings were listed, with a few respondents providing more than five titles, indicating the breadth and variation within spatial analysis. The books outlined here have inspired, clarified, initiated new discussion, and organized current thought in spatial analysis. This list is far from exhaustive, however, and newcomers to the field should seek additional literature applicable to their interests. Most respondents did not comment on the readings; descriptions reflect reviews and my analysis.

Originally published in Swedish as *Innovationsflörloppet ur korologisk synpunkt* (1953), *Innovation Diffusion as a Spatial Process* was translated by Allan Pred in 1967. Using Monte Carlo techniques to characterize the processes associated with an observed pattern, Hägerstrand (1967) outlined approaches that continue to be at the core of spatial pattern analysis and developed a theory of spatial innovation diffusion. Over half a century later, even the topic of innovation diffusion is surprisingly modern. Today, we can see humor in a review by Morrill (1969) that mentions that lack of computing power during the 1950s limiting Hägerstrand's ability to deal with analytical issues.

Location and Space Economy by Walter Isard (1956) provided the first American view of spatial economic theory (McCarty 1958; Getis 1993). Evidence that the quantitative revolution was fueled by ideas from outside geography is a review by McCarty (1958) that suggested geographers were likely to find benefit from Isard (1956). The text for William Garrison's University of Washington courses (Getis 1993), *Location and Space Economy* contributed heavily to the events of the quantitative revolution.

Locational Analysis in Human Geography by Haggett (1967) remains a classic of visionary, integrative thinking about geographical phenomena and quantitative approaches. *Locational Analysis in Human Geography* was written after Haggett attended a workshop in quantitative methods funded by the National Defense Education Act and a regional science seminar at Berkeley and was influenced by the activities of the quantitative revolution in the United States (Getis 1993). Gould (1967) described students responding to *Locational Analysis in Human Geography* by doing "cartwheels down the hall." The strength of Haggett's book was the order and synthesis that it brought to the mixture of research that had emerged from the quantitative revolution (Jones 1966; Getis 1990). Another book that compiled ideas of the quantitative revolution was *Spatial Analysis: A Reader in Statistical Geography*. Edited by Berry and Marble (1968), *Spatial Analysis* contains thirty-seven articles, many written by Garrison's University of Washington students. In a review by Olsson (1968), *Spatial Analysis* was criticized for lacking longevity, but forty years later, it has stood the test of time. Divided into six parts, the book has chapters on methodology, spatial data and statistics, spatial distributions, spatial association, regionalization, and problems in the analysis of spatial series. *Spatial Analysis* has been described as a menu for students (Nordbeck 1970).

Originally titled *The Intelligent Student's Guide to Geography* (Pitts 1972), *Spatial Organization: The Geographer's View of the World* by Abler, Adams, and Gould (1971) was written to present approaches of geographic thought on spatial structure and processes in human behavior to students (Ray 1972). As with the previous two books, the authors of *Spatial Organization* brought order to the plethora of ideas circulating during the quantitative revolution. Chapters are organized into five parts: order, science, and geography; measurement, relationship, and classification; location and spatial interaction; spatial diffusion; and spatial organization and the decision process. One of the strengths of *Spatial Organization* is its emphasis on examples and figures (Pitts 1972; Ray 1972).

Spatial Autocorrelation and its child, *Spatial Processes*, by Cliff and Ord (1973, 1981, respectively) were the first comprehensive treatments of the statistical problem of spatial autocorrelation (Getis 1993). The result of collaboration between a geographer and a statistician, these books outline formal statistical tests for determining the strength of spatial autocorrelation and for identifying patterns that depart from those generated through random processes (Getis, Haining, and Cliff 1995). Remarkably ahead of their time, Cliff and Ord anticipated recent developments in the field of spatial analysis (i.e., local statistics) and generated some of the first spatial analytical tools necessary to support geography as a spatial science (Getis, Haining, and Cliff 1995).

The aims of Griffith (1988) in *Advanced Spatial Statistics* were to integrate advanced research on spatial data analysis and bridge dialogues between spatial statisticians and spatial econometricians. Griffith (1988) includes topics such as autoregressive models, areal unit configuration, missing data in two-dimensional surfaces, edge effects, simulation in spatial analysis, and eigenvalue structure of spatial configurations. As the title suggests, *Advanced Spatial Statistics* was written for a sophisticated audience and emphasizes matrix algebra.

The goals of Anselin's (1988) *Spatial Econometrics* were to identify a set of spatial econometric models and demonstrate how to estimate parameters and validate models (Getis 1990). The first section of *Spatial Econometrics* outlines economic analysis of spatial processes, which is differentiated from data- or pattern-driven approaches. Anselin emphasizes simultaneous autoregressive models with a linear regression context. Users of this book require a high level of econometric and statistical background, in particular, literacy in matrix notation. As is the case with many books outlined in this section, twenty years postpublication, the table of contents is relevant. For instance, Anselin (1988) considered spatial weights matrices, typology, spatial processes, Bayesian estimation of parameters, and spatial-temporal models.

In *Spatial Data Analysis in the Social and Environmental Sciences*, Haining (1990) synthesized many of the developments that occurred in spatial analysis during the 1980s (Gotway 1992). Haining (1990) provided readers with a discussion of spatial data that begins with data collection, proceeds to exploratory analysis, and ends with multivariate analysis. Haining provides a valuable framework for those new to spatial analysis and includes plenty for the advanced reader.

For a new student to spatial analysis, *Statistics for Spatial Data* by Cressie (1993) demonstrates the extensive scope of spatial statistics. Cressie organized the book into three sections based on geostatistical data, lattice data, and spatial patterns. The 900-page book requires a high level of mathematics and even the most numerically literate spatial analysts will find portions of it dense (de Veaux 1993). To aid in accessibility, the table of contents differentiates between sections of this book that are theoretical and applied.

Bailey and Gatrell's (1995) *Interactive Spatial Data Analysis* is intended for undergraduates and outlines a subset of spatial data analysis methods that the authors consider accessible and practical. Bailey and Gatrell (1995) begin with an overview of concepts and definitions in spatial analysis. The following sections are organized by the type of spatial data to which methods are applied and include points, lines, areas, and interaction data. Provided with this book are practical exercises complemented by a DOS-driven program for spatial analysis. Although the DOS software is now dated, it is also not as necessary given the increased availability of tools for conducting spatial analyses.

O'Sullivan and Unwin's (2003) *Geographic Information Analysis* provides a clear and up-to-date synthesis of concepts in spatial analysis that is particularly relevant for GIS users interested in more advanced quantitative analysis (Liu 2005). Complete with tutorials on statistics and matrix algebra, this book is ideal for the geography student who has discovered the power of spatial analysis and requires a technical tune-up. It is an accessible starting point for both undergraduate and graduate students and is a practical book that has excellent potential as geography textbook.

Subsequent to this survey, two edited books were published that reviewers suggested, and I agree, should be included in this reading list. The first is *The Sage Handbook of Spatial Analysis* by Fotheringham and Rogerson (2009). Designed for graduate students and researchers, this book covers both fundamentals and new frontiers in spatial analysis. Several of the chapters relate to topics raised by those surveyed for this article. For example, there are chapters on spatial autocorrelation and spatial regression, as well as chapters on Bayesian spatial analysis and geocompuation. Chapters emphasize state-of-the-art techniques, outline key debates, and highlight remaining problems in spatial analysis; in my view, many chapters would be excellent starting points for group discussions or specialized workshops.

The second new book is *Handbook of Applied Spatial Analysis: Software Tools, Methods, and Applications* by Fischer and Getis (2009). This book begins with practical reviews of recent GISoftware tools (i.e., ArcGIS, SAS, R, GeoDa, and six others). Given the growth in spatial analysis tools and the link between scientific innovation and tool development, the technology overview is valuable to both new and advanced spatial analysts. In the following section, general principles of spatial statistics and geostatistics are provided. A few examples of topics in this section include the nature of georeferenced data, exploratory spatial data analysis, and spatial autocorrelation. The editors' aim for this book was to enhance the interdisciplinary nature of the field of spatial analysis (Fischer and Getis 2009). As such, the final sections are thematic and include spatial econometrics, remote sensing, economics, environmental sciences, and health sciences. This book will be a valuable source for spatial analysts to "get their hands dirty."

Synthesis

Spatial analysts have much to gain from occasionally looking back at the lineage of our discipline. The results from the survey suggest that there is a strong link between where we have come from and where we are going to; past success creates new challenges and opportunities. It reminds me of a diagram that Peter Haggett presented in his plenary talk at the

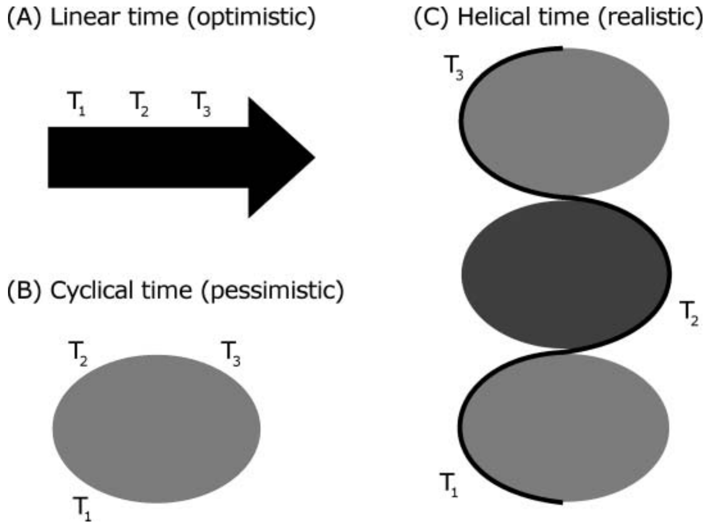

Figure 1 *The Haggett view of progress in geography.*

International Geographical Union at Glasgow in August 2004 (Figure 1). New knowledge is created after old truths are rediscovered. By visiting the past we will hopefully rediscover ideas more frequently and move the discipline forward.

Geographers are currently users, rather than producers, of GIS. This is limiting our ownership of spatial analysis and inhibiting integration of GIS and spatial analysis. Leaving the development of GIS software to others restricts the geographical component of commonly used analysis packages. As an example, the spatial weights matrices easily implemented in ESRI's Spatial Statistics Tools are all distance based. Other weights definitions commonly of interest to spatial analysts, such as contiguity or adjacency, are not considered. Putting geography into GIS development requires a new approach to spatial analysis training, which I discuss further next, and also obliges us to convince our academic departments that technical contributions are of institutional value. The quantitative revolution had many critics and, in my view, we continue to face opposition from inside. Whereas outside geography there is excitement for spatial sciences, from within there are dismissive voices that attempt to label us as too technique and technology oriented or, even worse, as "button pushers." We need to demonstrate the value of spatial analysis for answering geographical questions and, where possible, link the tools we build to applied research questions and theoretical foundations. A commitment to developing tools for conducting spatial analysis is required.

There is a disconnect between the skills required for advanced spatial analysis and those taught in most geography undergraduate programs. Geography students do not have the programming or mathematical skills often required at the graduate level. For many geography students, interest in advanced spatial analysis begins to peak during the latter half of their programs, usually once they become convinced that spatial statistics is important for addressing problems of interest to them. There might be benefit to offering mathematics, statistics, and computer programming at this later stage in a way that fits the flow of their program. Summer schools that provide intensive training in the fundamentals of computation and mathematics might be beneficial for the geography student who discovers spatial analysis late in the game. On the flip side, spatial analysis will benefit from attracting graduate students from outside the discipline, but this requires novel approaches to teaching geographical thought. Although technical skills are not learned quickly, the rich perspective that a geography undergraduate has on issues of sustainability, urban development, environmental change, and map literacy is also not rapidly learned.

With growing access to spatial data, spatial analysis software, and Internet- and Web-based mapping applications there are also challenges in public education. Nongeographers are engaging with maps in new ways (Sui and Goodchild 2001) and might not be interested in taking formal GIS courses to understand the details of scale, data management, and metadata. As the popularity of spatial data grows, there will be trade-offs between frequency and accuracy of use. Spatial analysts should identify which components of spatial knowledge are beneficial to the public and develop a compelling means for teaching these principles.

There is an exciting range of spatial analysis research opportunities. Technological developments have made us rich in geographical data and computational power. The current generation of spatial researchers has an opportunity to create new knowledge by improving and creating new methods for spatial analysis. There are many topics beyond those listed here that are developing and exciting. Each reviewer of this article has identified additional areas for future growth including visualization, cellular automata models, agent-based models, and spatial optimization analysis. I am confident that readers will add to this list, and I invite them to consider, as I do, this article a starting point for discussion rather than a definitive voice on trends in spatial statistics.

From my perspective, one of the greatest legacies that our discipline is endowed with is the frontier spirit that accompanied the quantitative revolution. We are provided with encouragement by those who were directly involved, such as Haggett (2005), who wrote, "An outstanding younger generation stands now ready to take up the baton and run with it. I hope they enjoy the race as much as my own cohort did." ■

Literature Cited

Abler, R., J. S. Adams, and P. Gould. 1971. *Spatial organization: The geographer's view of the world.* Englewood Cliffs, NJ: Prentice Hall.

Andrienko, G. L., and N. V. Andrienko. 1999. Interactive maps for visual data exploration. *International Journal of Geographical Information Science* 13:355–74.

Anselin, L. 1988. *Spatial econometrics: Methods and models.* Dordrecht, The Netherlands: Kluwer.

———. 1995. Local Indicators of Spatial Association—LISA. *Geographical Analysis* 27:93–115.

Armstrong, M., and P. Densham. 2008. Cartographic support for locational problem-solving by groups. *International Journal of Geographical Information Science* 22:721–49.

Armstrong, M., and A. Ruggles. 2005. Geographic information technologies and personal privacy. *Cartographica* 40:63–73.

Bachi, R. 1968. Statistical analysis of geographical series. In *Spatial analysis*, ed. B. Berry and D. Marble, 101–09. Englewood Cliffs, NJ: Prentice Hall.

Bailey, T., and A. Gatrell. 1995. *Interactive spatial data analysis.* Essex, UK: Longman.

Barnes, T. 2001. Lives lived and lives told: Biographies of geography's quantitative revolution. *Environment and Planning D: Society and Space* 19:409–29.

———. 2003. The place of locational analysis: A selective and interpretive history. *Progress in Human Geography* 27:69–95.

Berry, B. 1993. Geography's quantitative revolution: Initial conditions, 1954–1960. A personal memoir. *Urban Geography* 14:434–41.

Berry, B., and D. Marble. 1968. *Spatial analysis: A reader in statistical geography.* Englewood Cliffs, NJ: Prentice Hall.

Boots, B. 2000. Using GIS to promote spatial analysis. *Journal of Geographical Systems* 2:17–21.

———. 2003. Developing local measure of spatial association for categorical data. *Journal of Geographical Systems* 5:139–60.

———. 2006. Local configuration measures for categorical spatial data: Binary regular lattices. *Journal of Geographical Systems* 8:1–24.

Brunsdon, C., A. Fotheringham, and M. Charlton. 1996. Geographically weighted regression: A method for exploring spatial nonstationarity. *Geographical Analysis* 28:281–98.

Burton, I. 1963. The quantitative revolution and theoretical geography. *The Canadian Geographer* 7:151–62.

———. 1968. The quantitative revolution and theoretical geography. In *Spatial analysis*, ed. B. Berry and D. Marble, 13–23. Englewood Cliffs, NJ: Prentice Hall.

Butler, D. 2006. Virtual globes: The web-wide world. *Nature* 439:776–78.

Caldas de Castro, M., and B. H. Singer. 2006. Controlling the false discovery rate: A new application to account for multiple and dependent tests in local statistics of spatial association. *Geographical Analysis* 38:180–208.

Casetti, E. 1972. Generating models by the expansion method: Applications to geographical research. *Geographical Analysis* 4:81–91.

———. 1993. Spatial analysis: Perspectives and prospects. *Urban Geography* 14:526–37.

———. 1995. Spatial mathematics modeling and regional science. *Papers in Regional Science* 74:3–11.

Chorley, R. 1968. Geography and analog theory. In *Spatial analysis*, ed. B. Berry and D. Marble, 42–52. Englewood Cliffs, NJ: Prentice Hall.

Cliff, A. D., and J. K. Ord. 1973. *Spatial autocorrelation.* London: Pion Limited.

———. 1981. *Spatial processes: Models and applications.* London: Pion Limited.

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

Curry, L. 1967. Quantitative geography. *The Canadian Geographer* 2:265–74.

de Veaux, R. 1993. Book review of Statistics for Spatial Data by N. Cressie (1993). *Technometrics* 35:322–23.

Derekenaris, G., J. Garofalakis, C. Makris, J. Prentzas, S. Sioutas, and A. Tsakalidis. 2001. Integrating GIS, GPS and GSM technologies for the effective management of ambulances. *Computers, Environment and Urban Systems* 25:267–78.

Elliott, P., J. Wakefield, N. Best, and D. Briggs. 2000. *Spatial epidemiology: Methods and applications.* New York: Oxford University Press.

Fischer, M. M., and A. Getis. 2009. *Handbook of applied spatial analysis: Software tools, methods, and applications.* Berlin: Springer.

Flahaut, B., M. Mouchart, E. S. Martin, and I. Thomas. 2003. The local spatial autocorrelation and the kernal method for identifying black zones: A comparative approach. *Accident Analysis and Prevention* 35:991–1004.

Fortin, M. J., and M. Dale. 2005. *Spatial analysis: A guide for ecologists.* Cambridge, UK: Cambridge University Press.

Fotheringham, A. 1998. Trends in quantitative methods II: Stressing the computational. *Progress in Human Geography* 22:283–92.

———. 1999. Trends in quantitative methods III: Stressing the visual. *Progress in Human Geography* 21:88–96.

Fotheringham, A., C. Brunsdon, and M. Charlton. 2000. *Quantitative geography: Perspectives on spatial data analysis.* London: Sage.

Fotheringham, A., and P. A. Rogerson. 2009. *The Sage handbook of spatial analysis.* London: Sage.

Getis, A. 1990. Book review of *Spatial Econometrics: Methods and Models* by L. Anselin (1988). *Annals of the Association of American Geographers* 80:462–63.

———. 1993. Scholarship, leadership, and quantitative methods. *Urban Geography* 14:517–25.

———. 2008. A history of the concept of spatial autocorrelation: A geographer's perspective. *Geographical Analysis* 40:297–309.

Getis, A., and J. Franklin. 1987. Second-order neighbourhood analysis of mapped point patterns. *Ecology* 68:473–77.

Getis, A., R. Haining, and A. D. Cliff. 1995. Classics in human geography revisited. Commentaries by Getis, A., and R. Haining, and a response from Cliff, A. D. *Progress in Human Geography* 19:243–47.

Getis, A., and J. Ord. 1992. The analysis of spatial association by use of distance statistics. *Geographical Analysis* 24:189–206.

Golledge, R. 2008. Behavioral geography and the theoretical/quantitative revolution. *Geographical Analysis* 40:239–57.

Goodchild, M., R. Haining, and S. Wise. 1992. Integrating GIS and spatial data analysis: Problems and possibilities. *International Journal of Geographical Information Systems* 6:407–23.

Goodchild, M. F. 2009. Challenges in spatial analysis. In *The Sage handbook of spatial analysis* ed. S. A. Fotheringham and P. A. Rogerson, 470. London: Sage.

Goodchild, M. F., L. Anselin, R. Appelbaum, and B. Harthorn. 2000. Toward spatially integrated social science. *International Regional Science Review* 23(2):139–59.

Gotway, C. 1992. Book review of *Spatial Data Analysis in the Social and Environmental Sciences* by R. Haining (1990). *Technometrics* 34:499–500.

Gould, P. 1967. Book review of *Locational Analysis in Human Geography* by P. Haggett (1965). *Geographical Review* 57:292–94.

Griffith, D. A. 1988. *Advanced spatial statistics.* Boston: Kluwer Academic.

Hägerstrand, T. 1967. *Innovation diffusion as a spatial process.* Chicago: University of Chicago Press.

Haggett, P. 1967. *Locational analysis in human geography.* London: Edward Arnold.

———. 2005. Postscript: Continuity and change in spatial modelling. *Journal of Geographical Systems* 7:403–08.

———. 2008. The local shape of revolution: Reflections on quantitative geography at Cambridge in the 1950s and 1960s. *Geographical Analysis* 40:336–52.

Haining, R. 1990. *Spatial data analysis in the social and environmental sciences.* New York: Cambridge University Press.

Hudson, J. 1969. Diffusion in a central place system. *Geographical Analysis* 1:45–58.

Isard, W. 1956. *Location and space economy.* New York: Technology Press of Massachusetts Institute of Technology & Wiley.

Johnston, R. 2000. Intellectual respectability and disciplinary transformation? Radical geography and the institutionalisation of geography in the USA since 1945. *Environment and Planning A* 32:971–90.

Jones, E. 1966. Book review of *Locational Analysis in Human Geography* by P. Haggett (1965). *The Geographical Journal* 132:267–68.

Kamel Boulos, M. N., and D. Burden. 2007. Web GIS in practice V: 3-D interactive and real-time mapping in second life. *International Journal of Health Geographics* 6:51.

Lim, K., P. Treitz, M. Wulder, B. St-Onge, and M. Flood. 2003. LiDAR remote sensing of forest structure. *Progress in Physical Geography* 27:88–106.

Liu, Z. 2005. Book review of *Geographic Information Analysis* by D. O'Sullivan and D. Unwin (2003). *The Professional Geographer* 57:624–26.

Longley, P. 2000. The academic success of GIS in geography: Problems and prospects. *Journal of Geographical Systems* 2:37–42.

Marble, D. 2000. Some thoughts on the integration of spatial analysis and geographic information systems. *Journal of Geographical Systems* 2:31–35.

McCarty, H. 1958. Book review of *Location and Space-Economy* by W. Isard (1956). *Economic Geography* 34:90.

Miller, C. 2006. A beast in the field: The Google Maps mashup as GIS/2. *Cartographica* 41:187–99.

Miller, H. 2000. Geographic representation in spatial analysis. *Journal of Geographical Systems* 2:55–60.

Morrill, R.1969. Book review of *Innovation Diffusion as a Spatial Process* by T. Hägerstrand (1967). *Economic Geography* 45:277–78.

Nelson, T., and B. Boots. 2008. Detecting spatially explicit hot spots in landscape-scale ecology. *Ecography* 31:556–66.

Nordbeck, S. 1970. Book review of *Spatial Analysis* by B. J. L. Berry and D. F. Marble (1968). *Geographical Review* 60:297–98.

Olsson, G. 1968. Book review of *Spatial Analysis* by B. J. L. Berry and D. F. Marble (1968). *Journal of Regional Science* 8:253–54.

Openshaw, S. 2000. GeoComputation. In *GeoComputation*, ed. S. Openshaw and R. J. Abrahart, 1–31. London and New York: Taylor and Francis.

Ord, J. K., and A. Getis. 2001. Testing for local spatial autocorrelation in the presence of global autocorrelation. *Journal of Regional Science* 41:411–32.

O'Sullivan, D., and D. Unwin. 2003. *Geographic information analysis.* Hoboken, NJ: Wiley.

Peuquet, D. 2001. Making space for time: Issues in space–time data representation. *GeoInformatica* 5:11–32.

Pitts, F. R. 1972. Book review of *Spatial Organization: The Geographer's View of the World* by R. Abler, J. S. Adams, and P. Gould (1972). *Geographical Review* 62:431–32.

Ray, D. M. 1972. Book review of *Spatial Organization: The Geographer's View of the World* by R. Abler, J. S. Adams, and P. Gould (1972). *Economic Geography* 48:447–48.

Rey, S., and M. Janikas. 2005. STARS: Space-time analysis of regional systems. *Geographical Analysis* 38:67–86.

Robertson, C., T. A. Nelson, B. Boots, and M. A. Wulder. 2007. STAMP: Spatial temporal analysis of moving polygons. *Journal of Geographical Systems* 9:207–27.

Rushton, G. 2003. Public health, GIS and spatial analytic tools. *Annual Review of Public Health* 24:43–56.

Sui, D., and M. Goodchild. 2001. GIS as media? *International Journal of Geographical Information Science* 15 (5): 387–90.

Unwin, D. 1996. GIS, spatial analysis and spatial statistics. *Progress in Human Geography* 20:540–51.

White, S., and Y. Wang. 2003. Utilizing DEMs derived from LiDAR data to analyze morphologic change in the North Carolina coastline. *Remote Sensing of the Environment* 85:39–47.

Wulder, M., K. O. Niemann, and D. G. Goodenough. 2000. Local maximum filtering for the extraction of tree locations and basal area from high spatial resolution imagery. *Remote Sensing of the Environment* 73:103–14.

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