Report on SPARC Workshop: Scale and Spatial Analytics

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Background

A small and focused workshop on the topic of scale and spatial analytics was held at Arizona State University (ASU) on February 10 and 11, 2020. It was organized under the auspices of the ASU Spatial Analysis Research Center (SPARC), with funding from Esri, SPARC, and the ASU School of Geographic Sciences and Urban Planning (SGSUP). The workshop was organized by myself and ASU faculty members Stewart Fotheringham (Director of SPARC), Wenwen Li, Peter Kedron, Amy Frazier, and Daoqin Tong, with the assistance of Nick Ray and Aryn Musgrave.

The workshop

In early October 2019 the organizers distributed the following invitation, using the mailing lists of the AAG's relevant specialty groups:

> Spatial Scale is one of a small number of quintessential geographic topics that define geography as a discipline. We talk about the scale of a map with phrases such as a small-scale or large-scale study. We refer to the scale of a study area, implying its spatial extent. We talk about some descriptors being scale-invariant (fractal dimension) while others are seriously affected by the extent to which data are spatially aggregated (modifiable areal unit problem). When focusing on the processes underlying spatial patterns, we frequently describe some processes as operating on a local, regional, or global scale. Although we frequently refer to scale, what exactly do we mean by this term and how can we measure the spatial scale at which different processes operate? We have long recognized that the phenomena we observe are often the product of multiple processes operating at multiple scales, which raises a number of additional questions:

- What methodological developments are needed to accurately translate information across scales?
- How do decisions surrounding the scale of data and analyses (and the uncertainties that accompany those scales) impact our inferences about the world?
- In terms of processes, what exactly do we mean by scale and how do we measure it?
- Why is it useful to know the spatial scale at which different processes operate?

Although scale and geography have been virtually synonymous for centuries, it would seem timely to hold a brain-storming workshop on Scale and Spatial Analytics for several reasons:

- Spatial data are increasingly available at a very fine spatial (and temporal) scale;

- Multi-scale analysis is now possible under various learning frameworks opening up the possibility of directly measuring the spatial scale at which different processes operate;
- The three-dimensionality of the world we live on and in is increasingly recognized so that scale on the globe is of growing importance."

A total of 38 participants attended the workshop: the six organizers, an additional 12 faculty members and graduate students from ASU, two Esri staff (Charlie Frye and Kevin Butler), six special invitees (Michael Batty from University College London, David Folch from Northern Arizona University, Phaedon Kyriakidis from Cyprus University of Technology, Nina Lam from Louisiana State University, David Manley from the University of Bristol, and Jianguo Wu from ASU), and 12 selected from the responses to the open call. The full list of participants is included below and will be accessible on the meeting website https://sgsup.asu.edu/SPARC.

The workshop opened with an introduction based on the earlier announcement, with words of welcome from Dean Libby Wentz, and with brief introductions from each of the participants. The following sections outline the seven keynote presentations, the Esri presentation, and the lightning talks given by other participants. This is followed by a section of general discussion and plans for follow-up activities. All of the presentations and powerpoints will be available on the workshop website.

Presentations

The Wu presentation

Jianguo (Jingle) Wu gave an overview of the importance of scale in landscape ecology, stressing the similarities between landscape ecology and geography, and indeed all social and environmental sciences. He identified three causes for the rapid growth in interest in landscape ecology in the past few decades: advances in technology, the development of theory, and the need to examine landscapes at multiple scales. Landscapes are heterogeneous and dynamic, requiring an approach that addresses time as well as space. The importance of scale is demonstrated by the fact that it has been the most commonly addressed topic in the landscape ecology literature in the past 25 years.

Scale has many meanings and many components. He reviewed the various definitions of scale, and the confusing tendency to use the term to refer both to the geographic and temporal extent of a study, and also to its level of spatial and temporal detail. Further confusion results from the use of large and small to qualify scale: to a cartographer large-scale means that the representative fraction of the map is large and the map therefore has a fine level of detail, but to everyone else large-scale most often means that the project covers a large area with a correspondingly coarse level of detail. Jianguo also introduced the concept of space-time correspondence: fine spatial detail often corresponds to fine temporal detail, a tendency first noted by Stommel (for a historical perspective on the Stommel diagram see Vance and Doel 2010).

Jianguo presented a list of ten rules for addressing scale. Among the most intriguing and novel of these is "say no to single-scale studies." Today we have several ways of addressing scale as a hierarchy, and linking coarse-scale information and processes to fine-scale. He also drew attention to the modifiable areal unit problem, an issue first identified by geographers and now widely understood in landsape ecology: that the results of any analysis of spatial data depend on the configuration of spatial units used as the basis of the analysis.

The Batty presentation

Mike began with examples of cities and the transformations that occur as the scale of a city changes, from megalopoli to the smallest villages. But despite these dramatic changes, many aspects of cities remain invariant under changes of scale. His early work with Paul Longley (1994) focused on modeling cities as fractals, a model of phenomena that are in a sense invariant under changes of scale. More recent work has applied concepts of multifractals, to deal for example with the heterogeneity that results when 19^{th} Century street plans are compared to late-20^{th}.

His presentation then focused on recent work on the hierarchy of cities in Britain. Research on urban agglomeration economies has found that cities grow disproportionately more wealthy as their population expands, but this simple picture becomes much more complex when populations are partitioned into rich and poor. A novel method based in percolation theory has allowed Mike and his colleagues to analyze the structure of urban Britain in unprecedented detail, building clusters from the network of street segments in both a top-down and bottom-up fashion. This work on breaking up Britain echoes recent political developments, including the Brexit vote and the recent General Election.

The Fotheringham presentation

Stewart began his presentation by contrasting four definitions of scale: the cartographic (ratio of distance on the map to distance on the ground, and problematic therefore for born-digital and born-photographic data that can be displayed at any scale); the geographic, as the spatial extent of the study area; measurement scale, defined by the spatial units used to capture data, for example by the size of pixels in a raster; and operational or process scale, the scale of processes operating on the landscape. The presentation focused mostly on the last, but with links to both geographic and measurement scales. But how to measure process scale? How, for example, to rigorously define the differences between macro-scale, meso-scale, and micro-scale climate processes? From the perspective of the spatial analyst, how is it possible to infer process scale from cross-sectional data? This problem has long been recognized, and until now no effective solutions have been devised.

Geographically weighted regression (GWR) was introduced by Stewart and his colleagues two decades ago. It allows the analyst to explore the degree to which the parameters of a model vary spatially; at any point the model is estimated by borrowing data locally, using weights that decline with distance from the point. In GWR the decay of weight with distance is determined by a single parameter, the bandwidth of the decay function, which is optimized using an appropriate goodness-of-fit criterion and interpreted as the scale of the process. Recent work by Stewart and his colleagues has generalized GWR to multi-scale GWR, or MGWR. In this approach each independent variable is given a distinct and separately optimized bandwidth, allowing the model to incorporate different process scales.

Stewart demonstrated MGWR using county-level voting data from the 2016 presidential election and 14 independent variables. Some variables, such as income, were found to have very large bandwidths, indicating a global process, while others such as % African-American were evidently responsible for much more local impacts on voting. MGWR has clearly achieved a very significant breakthrough in a longstanding problem in spatial analysis.

The Lam presentation

Nina began by asking how one should determine the right scale for a project. She drew on work on land loss and fragmentation in the Mississippi delta region of Louisiana, and showed that scale, in the form of pixel size, was a critical choice in understanding the relationship between these two variables. A broader context was provided by the ten topics identified in a chapter on scale in a book describing the research agenda for the University Consortium for Geographic Information Science (McMaster and Usery 2004). Variation in terminology, especially between disciplines and across the four meanings of scale, is clearly a major issue as science becomes more multidisciplinary. The role of scale in metadata is also a critical issue: how can metadata help a researcher to understand the impact of scale in an analysis using a specific data set, and how can measurement scale be defined for vector data? The impact of scale on classification is also critical in many areas of geographic research, where definitions of classes tend to be valid only over certain ranges of scale: what, for example, is the effective scale range for classes of land use or land cover?

The Kyriakidis presentation

Phaedon introduced geostatistics as the branch of spatial statistics that focuses on continuous fields, and addresses issues of scale in a rigorous way. Its applications include spatial prediction, spatial interpolation, and downscaling, all of which are built on the representation of variability in a variogram or correlogram; that is, on how variation between two points in the field changes with the distance between them. Geostatistics can deal with both 2D and 3D data, and with variation that is anisotropic, that is, depends on direction. Scale appears in geostatistics in many forms, most obviously in the parameter of a variogram known as the range: the distance beyond which difference stops increasing. The range is clearly related to similar concepts in other disciplines, including grain and granularity. The variogram is sometimes the result of analysis of data, and sometimes driven by theory, especially by physics.

While many applications of geostatistics deal with fields of interval or ratio variables, it is also possible to address fields of categorical variables, and thus what are often known in GIScience as area-class maps: maps of land cover, land use, or soils. In this case it is transition probabilities that are of interest, rather than numerical differences. Multivariate geostatistics allows for predictions from multiple inputs; often one variable is represented by a few high-quality measurements (the hard data) and other variables that are potential predictors are represented by dense but low-quality measurements (the soft data). Phaedon also showed how geostatistics can be used for interpolation and for downscaling of coarse data. His final comments concerned the use of artificial intelligence and a new form of geostatistics in which it is an image rather than a variogram that controls the processing.

The Folch presentation

David offered a person-centric perspective on scale, using the context of demography. He identified three types of spatial unit that are often used for spatial data: administrative areas including states and counties; demographic areas used for reporting statistical data; and hybrid areas such as ZIP codes and voting districts. Space can be divided in many ways, some of which focus on divisions of equal area (e.g., raster cells) and some on divisions of equal population (e.g., House voting districts, census tracts). From the demographic perspective there are three relevant types of scale: spatial scale, temporal scale, and attribute scale. The American Community Survey combines a 100% sample every ten years with a minimal number of questions, and a smaller continuous sampling of detailed questions. This allows for accurate estimates through time, especially for areas of high population density, but less accurate estimates across space than those that were achieved in the past using the decennial long form. In all demographic sampling there is always a need to balance the cost of survey with the accuracy of results.

David offered several examples of the importance of scale and the balance between spatial, temporal, and attribute scales. Various strategies can be used to address the scale issue, including direct access to microdata (subject to privacy constraints). In general diversity decreases with coarser scales, a principle that applies generally across many areas of geographic research. Also the Census finds it easier to deal with change in time: changes in spatial scale are problematic, notably in dealing with census tracts and the impossibility of maintaining tract boundaries in areas of rapid demographic change.

The Manley presentation

Ed's presentation focused again on the question of getting scale right in spatial analysis, using segregation as the theme. It has long been believed that segregation is greater at finer scales, but it is not clear whether this effect is an accurate representation of real social geography or an artifact of the methods used. He constructed a simple example to demonstrate the issues. He then moved to two case studies, one of Leicester and one of Amsterdam. In the Leicester case, which is one of the most ethnically diverse of British cities, it seems that segregation is highest when the perspective is either micro or macro, but lower at intermediate scales. In the Amsterdam case the question was a little different: how big should a neighborhood be? In the literature there are examples of studies of neighborhoods of 500 citizens, all the way up to neighborhoods of hundreds of thousands.

In summary, scale is clearly important in studies of the demographic mix of cities, and researchers should be cautious about ascribing the results of research to real patterns, since the choice of methods can have what in some cases is an even greater impact.

The Esri presentation

Kevin Butler opened with some comments on the relationship between Esri and the academic community represented at the workshop. Esri sees its role as implementing the results of research, bringing the content of academic papers that might reach tens or perhaps hundreds of readers to the attention of tens or hundreds of thousands of Esri users, and making GIScience understandable and usable by the general public. Charlie Frye followed with some comments on dealing with the curved surface of the globe, and the impossibility of laying a regular raster over a curved surface. If a raster is laid on a projected Earth it follows that the cells must vary in either shape, area, or both depending on the projection. This is the problem addressed by the field of discrete global grid systems (DGGS), which are hierarchical subdivisions of the Earth's surface in which elements are approximately uniform in size and shape at every level of the hierarchy. Recent research has developed 3D DGGSs for the solid Earth. Kevin described Esri's efforts to develop support for hexagonal grids (for which the same arguments about the curved surface also apply), although unfortunately hexagons do not nest hierarchically as conveniently as rasters. He then gave a brief discussion of some recent developments at Esri.

Kevin closed with a comment on the significance of legacy in GIS. Many of the design decisions and architectural choices that underlie GIS today were made in an earlier era of very limited computational resources. Many statistical methods were developed long before computers, and techniques such as least-squares optimization and the use of variance can be attributed to their advantages in a world in which all calculations had to be made by hand—but default use of these methods persists long after those arguments lost their validity. In the GIS world similar arguments can be made about the use of Cartesian distances rather than geodesic distances, on the grounds that the latter require extensive use of slower trigonometric functions.

The lightning talks

Two sessions of short talks were included in the program in order to broaden the discussion beyond the content of the seven keynotes:

Seth Spielman used two short videos to make the point that our view of social geography is a view of averages, over reporting zones such as census tracts, or what he described as "beige data". Herb Simon argued that complex systems have natural units of organization, which could be seen as a major challenge to quantitative human geography. Complexity is clearly increasing through time, yet we continue to base our work on a legacy of earlier concepts, such as the partitioning of cities into homogeneous neighborhoods.

May Yuan argued that it is the relationship between the scale of observation and the scale of analysis that is critical at the present time, because of dramatic improvements in our ability to observe. She used several examples from different disciplines to show how finer-resolution data are revolutionizing knowledge. In GIScience similar developments are occurring, creating a pressing need for updated concepts, analytical methods, and theories.

Yi Qiang began by showing how simple queries, such as "find the most densely populated place in the US", lead to conflicting results depending on scale. He advocated a cross-scale framework in which all studies are characterized by four variables: location, time, spatial scale, and temporal scale. Current research tends to combine one or at most two of these.

Taylor Oshan and Levi Wolf based their talk on the question of whether scale was ontological or epistemological: was scale a constraint placed on analysis because of the availability of data and analytical practices (ontological), or was it a property of reality to be discovered (epistemological)? They saw some methods of spatial analysis as grounded in one and some in the other. They introduced the metaphor of the prism, and its ability to separate the different components of light. MGWR clearly attempts to do this, and other techniques might be devised with a similar goal. How might prisms be compared, and what might be the role of uncertainty?

Xiang Ye focused his talk on the modifiable areal unit problem (MAUP), and the implications of recent work by economists which showed that in the absence of omitted variables all arrangements of spatial units produce unbiased estimates. Yet in the quantitative social and environmental sciences all models can be expected to have omitted variables, or some amount of mis-specification. He demonstrated the effect of omissions and scale using a series of simulations.

Amy Frazier used some of her work on chimpanzee habitat in Liberia to demonstrate the effects of scale. She then returned to the concept of scaling, the Batty presentation, and the Stommel diagram. Geographic research has traditionally emphasized description and explanation, but it is clear that science needs to move more toward prediction and intervention if it is to have greater influence. She argued that scaling laws are a powerful basis for prediction, especially if they can be used to extend scaling relationships.

Ethan Shavers discussed recent work at the US Geological Survey on automated characterization of landscape features, using river meanders as a case study. The theory of fractals allows representations of a feature at different scales to be related algebraically, providing a useful framework for automated characterization.

Jill Kelly's talk focused on the estimation of forest biomass using LiDAR data. Standard techniques examine a point cloud of LiDAR returns within a defined area on the ground, but what is the appropriate size of the defined area?

Somayeh Dodge and Sean Ahearn discussed their recent work on representations of movement, or trajectories. The trajectory of a tiger or turkey vulture, for example, can be examined at multiple scales, and different activities, such as migration and foraging, create very different trajectories. Thus the Stommel concept relating spatial and temporal scales may not be as useful for the analysis of mobility.

Elizabeth Groff explained her interest in crime patterns, and the use of the spatial unit of analysis as a surrogate for scale. In criminology interest has been shifting from the macro, with large spatial units, to the micro and to the analysis of individual blocks and the influence of individual points of interest such as bars or parks. For a crime to occur there must be convergence in space and time between the criminal, the victim, and the lack of intervention.

Enki Yoo discussed her work on human exposure to air pollution, which requires observation of levels of air pollution as well as human mobility. Accurate observation of air pollution depends on a number of sources, each having its own issues of data quality, and the integration of these sources into optimal estimates in space and time. She discussed the importance of temporal scale, in the senses of both extent and granularity, and the computational complexity of integrating the large numbers of data involved.

Patricia Solis urged greater attention to how research results are used. Who draws the boundaries that will determine policy decisions, and how should we capture the uncertainty of the geographic context in which research results wihe ll be implemented? Both of these issues suggest problems of at least equal importance to the MAUP, and with important implications for spatial scale.

Mary Donovan discussed her recent work on the coral reefs surrounding the island of Moorea in French Polynesia. The reefs can be studied at a range of scales; processes can be studied from the biological cell to the polyp to the coral to the reef, and observations can be gathered at scales from a coral colony to a field site to an entire habitat and to an entire coastline. Her recent discoveries were critically dependent on the use of the field site, a scale of about 200m.

Discussions

The workshop program included two discussion sessions, giving the group a chance to explore some of the implications of the presentations and some of the broader issues. The following paragraphs give a brief summary of some of the major points that emerged in these sessions.

The ontology versus epistemology debate was revisited: was research concerned with the implications of the various scales of observation built into the analysis, or was it more concerned with searching for an optimal scale that reflected something fundamental about the way the geographic landscape was organized? Should one attempt to fit a model at multiple scales (if the data allowed) to see which scale or scales fitted best (and assuming that the problems of comparing apples and oranges could be addressed in a satisfactory way)?

Several participants were concerned to give a more rigorous meaning to the concept of process, and with it causality. What, for example, did the structure of GWR imply about the nature of process? Is what happens at a point influenced more by what happens at nearby points than at more distant points, and does influence decline in a manner that matches the GWR weighting function? If this is one model of process, how many other kinds of spatial processes are there? How might longitudinal data help in sorting out these questions? How might a process-based interpretation of GWR compare with a similarly process-based interpretation of multi-level modeling? Is place a more appropriate conceptual framework than space for the discussion of social processes? Can we devise ways in which any of these questions might be resolved by controlled experiments?

Interest was also expressed in the relationship between scale and scaling. In one view there is not necessarily any relationship, and much of the recent work in the physics literature on scaling laws in social science has no link to spatial scale. The concept of scaling in computer science is similarly unrelated to spatial scale. Scaling laws also appeared to have no direct link to process and explanation.

Final plenary

The workshop closed with a final plenary session, giving participants an opportunity raise any additional issues and to think about possible follow-on activities. The Corona virus crisis has had a dampening effect on many ideas, including discussions at the now-canceled AAG meeting in Denver in April. Three possible publication projects emerged from the discussion:

- A major paper updating the literature on scale in geographic research to reflect many of the fundamental trends that motivated this workshop: fine-resolution data, the decline of traditional high-quality sources of spatio-temporal social data, new analytic methods, and the need for new theory. This could be a collaborative effort among the participants;
- Papers drawing attention to the issues discussed at the meeting and adapted to the

needs of specific domain sciences. The comments on landscape ecology from Jianguo Wu may have motivated some participants to write papers that address their own disciplines; and

- A special issue or section of a GIScience journal on multi-scale methods, including GWR and multi-level modeling.

A follow-up email was sent to all participants shortly after the meeting, and several responses were received from people willing to contribute to one or more of these options.

The workshop adjourned after thanks were voted to the sponsors, and to Nick Ray and Aryn Musgrave for outstanding staff support.

List of participants

Sean	Ahearn	Hunter College
Sarah	Bardin	ASU
Mike	Batty	University College London
Kevin	Butler	Esri
Dylan	Connor	ASU
Somayeh	Dodge	UC Santa Barbara
Mary	Donovan	ASU
David	Folch	Northern Arizona University
Stewart	Fotheringham	ASU
Amy	Frazier	ASU
Charlie	Frye	Esri
Michael	Goodchild	ASU
Elizabeth	Groff	Temple University
Peter	Kedron	ASU
Jill	Kelly	Harvard/Yale
Phaedon	Kyriakidis	Cyprus University of Technology
Nina	Lam	Louisian State University
Wenwen	Li	ASU
David	Manley	University of Bristol
Soe	Myint	ASU
Trisalyn	Nelson	ASU
Taylor	Oshan	University of Maryland
Yi	Qiang	University of Hawaiʻi at Mānoa
Matthew	Quick	ASU
Mehak	Sachdeva	ASU
Ethan	Shavers	US Geological Survey
Patricia	Solis	ASU
Seth	Spielman	University of Colorado
Daoqin	Tong	ASU
Matthew	Toro	ASU
Libby	Wentz	ASU

Levi	Wolf	University of Bristol
Jianguo	Wu	ASU
Xiang	Ye	SUNY Buffalo
Enki	Yoo	SUNY Buffalo
Hanchen	Yu	ASU
May	Yuan	UT Dallas
Michael	Branion-Calles	ASU

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