Social Network Analysis of the Academic GIScience Community*

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There is mounting interest among scientists regarding the use of scientometric social network analysis, or quantitative analysis of the evolution of science as defined by individual researchers and the networks they form. Given that geographers have seldom used this approach compared to researchers in other fields, its implications for research and policy need to be assessed. We applied scientometric social network analysis to geographic information science (GIScience) to understand how the field has evolved over the last sixteen years and to assess the applicability of the standard logistic model of the growth of scientific disciplines. In particular, we examined collaboration in the field at multiple scales, namely, the evolution of the entire research network structure, the nature of subnetworks in defining geographic information science, and the roles individuals play within the community. By delineating how collaborations and research networks have evolved in GIScience, the study addresses the potential of scientometric social network analysis for geography. **Key Words: coauthorship network, GIScience community, scientometric social network analysis.**

科学计量的社会网络分析，或被个别研究人员和他们形成的网络所定义的演变定量分析，已引起越来越多的科学家的兴趣。鉴于地理学家，与其他领域的研究人员相比，很少使用这种方法，此方法对地理研究和政策的影响还待评估。我们把科学计量的社会网络分析应用到地理信息科学（GIScience）以了解该领域过去 16 年的发展和评估科学学科发展标准的物流模型的适用性。特别是，我们研究该领域在多尺度的合作，即整个研究网络结构的演变，在定义地理信息科学的子网的本质，和个人在社区内扮演的角色。通过划定合作和研究网络是如何在地理信息科学领域的发展，本研究探讨了科学计量社会网络分析的地理的潜力。**关键词：合著著作权网络，地理信息科学界，科学计量社会网络分析。**

Existe un creciente interés entre los científicos sobre el uso del análisis cienciométrico de redes sociales, o análisis cuantitativo de la evolución de la ciencia según se defina ésta por investigadores individuales, y las redes que ellos forman. Tomando en cuenta que los geógrafos rara vez han utilizado este enfoque, en comparación con lo que hacen investigadores de otros campos, es necesario evaluar sus implicaciones para investigación y política. Aplicamos el análisis cienciométrico de redes sociales en ciencia de la información geográfica (*GIScience*, en inglés) para entender cómo ha evolucionado el campo durante los pasados dieciseis años y para evaluar la aplicabilidad del modelo logístico estándar del crecimiento de las disciplinas científicas. En particular, examinamos la colaboración en el campo a escalas múltiples, o sea la evolución de la estructura de la red de investigación completa, la naturaleza de subredes para definir la ciencia de la información geográfica, y los papeles que juegan los individuos en la comunidad. Al delinear cómo han evolucionado las colaboraciones y las redes de investigación en GIScience, el estudio aboca el potencial que tiene el análisis cienciométrico

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de redes sociales para la geografía. **Palabras clave: redes de coautoría, comunidad de GIScience, análisis cienciométrico de redes sociales**.

Scientific fields are born, grow, and sometimes stagnate or all but disappear. These events have long been studied in the history and philosophy of science and science and technology studies. Recently, researchers have turned to scientometric social network analysis (SSNA) as a way to examine research trends based on the collaboration networks formed by individual researchers. Compared to other disciplines, there has been little SSNA in geography, so we applied this approach to geographic information science (GIScience), which is both a subfield of geography and an emerging discipline in its own right.

Specifically, we use SSNA to determine how the discipline has evolved over the last sixteen years and assess the applicability of the standard logistic model of the growth of scientific disciplines. We found that although the evolution of GIScience so far maps onto the logistic model of growth, SSNA highlights fundamental transitions not evident in this general model, including a large increase in multiple authorship and the varying pace of collaboration alongside the uneven development and consolidation of subnetworks including engagement with other fields. We also established how trends in international collaboration can be better understood by applying social network measures to individual researchers within the GIScience collaboration network. More broadly, use of SSNA allows us to evaluate how effectively it illuminates research trends in geography and GIScience and address questions about what SSNA means for policy in academia overall and geography in particular.

We review the concepts and techniques of SSNA with an eye toward assessing its strengths and weaknesses as a general approach to knowledge, as well as a way to understand geography and GIScience. We then describe an SSNA of GIScience, including data development and construction of the coauthorship network that defined the evolution of the field from 1992 to 2007, to understand research collaboration trends in GIScience and to explore the general usefulness of SSNA in geography, including policy implications and future research needs.

Why Should Geographers Care About Scientometric Social Network Analysis?

There has been little SSNA in geography despite the rapid increase in its use across the sciences. Social network analysis is used to examine how relationships among elements of a social system, such as people and organizations, define the system's structure and evolution (Rogers 1987). Quantitative social network analysis examines networks as mathematical graphs in which each person or organization is a node connected to other nodes via links (Wasserman and Faust 1994; Scott 2000). The last decade has seen a tripling of publications in this area (Watts 1999; Barabasi et al. 2002; Borgatti et al. 2009). Within geography, this analysis is increasingly important although largely untapped (Ter Wal and Boschma 2009), whereas other disciplines are blending spatial and social definitions of networks (Autant-Bernard et al. 2007). With origins in library research, SSNA complements science and technology studies and the history and philosophy of science (Kessler 1963; Price 1963). A number of journals focus on scientometric research, including *Infometrics*, *Scientometrics*, and *The Journal of Information Science*. Growing digital publication has spurred growth because the core scientometric methodology is *bibliometrics*, the examination of interconnections among texts and authorship (Broadus 1987; Glänzel and Schubert 2005; Harnad 2009).

SSNA fuses scientometrics and social network analysis. It relies on coauthorship network analysis, which examines authors as nodes in a research network defined by collaboration. Coauthorship research gained impetus with the creation of large digital archives of citations in the 1990s (Melin and Persson 1996) and is now a critical approach for understanding the structure of academic networks and knowledge (Newman 2004; Glänzel and Schubert 2005). Coauthorship is the most common measure of connection within academic networks (Glänzel and Schubert 2005; Cardillo, Scellato, and Latora 2006).

Geographers have published comparatively little SSNA. There is a stream of scientometric research focused on geographical publishing, ranking of departments, and journal outlets for subfields (Turner and Meyer 1985; Turner 1988; Quiring 2007; Rohli and Liu 2008; Bosman 2009). Coauthorship research is limited to a study examining the spread of GIScience in Greece during the 1990s (Assimakopoulos 2000) and another regarding collaboration in the *International Journal of Geographic Information Science* (Arciniegas and Wood 2006a). To the best of our knowledge, ours is the first SSNA study of an entire geographic subfield.

The most likely reason for limited scientometric research in geography is that it has long been considered less applicable to the social sciences and humanities. Use of scientometrics in quantitative fields is successful because their primary forms of communication—articles and patents—are well enumerated by digital databases. In the social sciences and humanities, articles account for less than half of publications, and these fields are therefore underrepresented in the citation databases that fuel scientometrics (Nederhof et al. 1989; Hicks 1999, 2005; Kosmopoulos and Pumain 2008). Relatedly, researchers in these areas employ approaches beyond scientometrics for understanding social networks, such as interviews with researchers (e.g., Barnes 2001). Although scientometric research has lagged in the social sciences and humanities, it is gaining recognition. The European Scientific Foundation, for example, has started to scientometrically evaluate humanities journals (Howard 2008). Better indexing of nonarticle publications and their citations has come about from the creation of digital editions of books and book digitization projects (Harnad 2009) and new forms of indexing and publication online, such as Web-based journals and automatic tracking of citations by publishers (Bollen et al. 2009).

It is important for geographers to understand SSNA not only because use of scientometric measures is on the rise in general but also because they are used in academic administration. These measures are increasingly employed to evaluate research productivity (Costas and Bordons 2007; Harzing and van der Wal 2008), with the result that some researchers game the system, such as when authors trade citations or editors ask authors to cite to the journal in which they wish to publish (Lawrence 2003, 2007; Ioannidis 2008). Evaluations such as the U.K. Research Assessment Exercise (RAE) or U.S. National Research Council Assessment of Research Doctorate Programs (ARDP) are placing greater emphasis on bibliometrics to judge the quality of universities and individual programs (Todd and Ladle 2008; Harnad 2009). Academic programs in turn hire researchers who score well on scientometric criteria and encourage researchers to shift their work toward these criteria (Holcombe 2004; Bosman 2009). Overall, scientometric approaches are useful but must be used with care (Moed 2005).

Evolution of Science: The Case of GIScience

The growth of scientific fields has been found to follow a logistic (S-shaped) curve that charts slow initial growth, rapid expansion as a field takes off and builds on its own momentum, and transition to a steady state as competing ideas take hold and limit the resources available to the field (Price 1963; Braun, Bujdosó, and Schubert 1987). Innovation diffusion theory posits that logistic growth results from the way individuals vary in their willingness to adopt new practices, ranging from early adopters through to members of the late majority and finally to holdouts (Hägerstrand 1967; Rogers 1995). Epidemiological models hold that the transmission of new ideas defining a field can be treated as a disease-like process (Goffman and Newill 1964; Garfield 1980; Bettencourt et al. 2008), where active researchers (analogous to disease carriers) transmit ideas to researchers who are new to the area (those susceptible to the disease) within a larger population of researchers who are either uninterested or opposed to the ideas (the immune) or who have already moved on to other research (the recovered).

SSNA can be used to explore network dynamics within this general logistic formulation, thereby enhancing our knowledge of network structural changes over time, the importance of subnetworks, and the significance of individuals. In regard to temporal changes, SSNA assesses whether growth is as uniform as suggested by the logistic curve by finding hidden dynamics in the morphology of the network. It also addresses the importance of subnetworks by examining how they affect the structure of the overall community. Regarding individuals, those who have a central role in subnetworks affect those to whom they are connected and exemplify broader trends within the research network. Overall, by allowing simultaneous assessment of the entire network, subnetworks, and individuals, SSNA grants unique insights into the evolution of a research community.

GIScience is an excellent candidate for understanding the potential and caveats of SSNA. GIScience is a prominent component of geography and a burgeoning field in its own right. About one in five members of the Association of the American Geographers belongs to the Geographic Information Systems and Science Specialty Group (Pandit 2004, 18). Many other disciplines are turning to GIScience, making it a key entry point into the discipline and core geographic themes such as the importance of place and space (Clarke and Langley 1996; Naesset 1997; Hartkamp, White, and Hoogenboom 1999; Longley 2000; Thill 2000; Paul et al. 2003; Argent 2004). GIScience is amenable to SSNA because it relies on articles as the primary form of communication, and it emerged as a distinct field during the development of digital archives commonly utilized for SSNA (Arciniegas and Wood 2006a, 2006b).

Data

We used two academic databases to construct the GIScience coauthorship network. The first, *Geobase*™, is one of the most comprehensive bibliographic sources for geography and cognate disciplines that encompass GIScience research, covering 20,000 international journals (Elsevier 2010). The second, *ISI Web of Knowledge*™, covers more than 23,000 journals and 10,000 unique titles (Thomson Reuters 2010). Together, they include a very large range of journals and almost all of the recognized journals in GIScience and related fields such as ecology, environmental planning, and urban studies (Table 1). Records extracted from these two databases provide a credible snapshot of the internal structure of the GIScience community. We examine this community in the English-speaking world, mainly in North America and Western Europe, in part because much of the early development of GISc was centered in these regions and in part because database coverage is biased toward these regions and language.

We start our analysis in 1992, the year when the term *geographic information science* was formally coined (Goodchild 1992) and extend it to 2007, the latest year for which we have complete records. We queried the two databases with keywords (Geobase) or topic (ISI) being "GIS" or "geographic information," language being English, document type being Article, and from 1992 to 2007 inclusive. *Geobase*™ yielded 7,622 records and the *ISI Web of Knowledge*™ returned 16,904. We merged these two data sets and removed 3,252 duplicates and 1,093 nonacademic records like communications in magazines, leaving 20,181 distinct articles. Of course, there are articles that relate to GIScience that do not use these search terms, such as those on analytical cartography or spatial databases. Given that the goal of this analysis is to get a snapshot of coauthorship trends in the community as a whole, these terms provide good coverage overall without casting too wide a net. For example, the search term "spatial information" extracts many records from fields that have little relation to GIScience, such as physics, planetary science, and neurology.

We imported the bibliographic records into a topological graph format. A node denotes an individual with one or more connections identified by links, whereas a chain is a string of connections between nodes. For large-scale networks, the graph format is more efficient and several different software packages, most notably Pajek, NetMiner, and InFlow, are available for their development and analysis (for a summary, see Huisman and van Duijn 2004). In this study, we implemented our own arc-node structure and analysis software in C++ to handle the unique structure and large volume of the data necessary to build the collaboration network within the GIScience community.

Methods

The chief means of examining social networks is use of network statistics, but we can also perform simple trend analyses to illustrate the dynamics of GIScience publication (after Quiring 2007). We therefore focus on two groups of indicators—trend measures and social network statistics—to understand the evolution of GIScience. For the trend analysis, we feature the number and percentage of multiauthor papers and coauthors, whereas for the SSNA, we examine mean degree, mean separation, global efficiency, clustering coefficients, and maximum subcommunity for the entire GIScience research network. We also examine metrics for individual researchers as they relate to the larger community.

For the trend analysis, we calculated key indicators of publication and collaboration within the GIScience community. *Number of multiauthor papers* is the number of unique papers that have more than one author. We compare this number with *number of single-author papers* and categorize it by year to examine the dynamics of GIScience collaboration.

Whereas trend measures are relatively straightforward, social network statistics must be understood within the context of social networks.

Degree of connected authors is the number of researchers with whom a particular GIScience researcher has a coauthoring relationship, which reflects how broadly a GIScience researcher collaborates with colleagues.

Separation, also known as characteristic path length, is the average shortest network distance from one node to all connected nodes (think "six degrees of separation"). The mean value of separation coefficients of all network nodes measures how loosely the nodes in a network are connected. The formal definition of the coefficient of separation is

$$S(i) = \frac{1}{N-1} \sum_{j=1, j \neq i}^{N} d(i, j) \qquad (1)$$

where $S(i)$ is the separation coefficient for node i, N is the total number of nodes in the network that node i belongs to, and $d(i, j)$ is the shortest network distance between node i and node j. For nodes in a fully connected network, N is equal for each node in the entire network; however, when subnetworks exist (i.e., isolated subgroups of nodes) this definition is problematic and requires modification. For example, if author A is connected to 100 authors via coauthorship but 90 are indirect connections, $S(A)$ would be greater than one, because among the 100 distances to other nodes from A, 10 are one and 90 are greater than one. In comparison, if author B only coauthors one paper with one single author C, then $N = 2$ and $S(B) = 1$. According to the formal definition, $S(A) > S(B)$. To claim, however, that A is more separated from the GIScience community than B seems

Table 1 *Journals publishing GIScience papers, 1992–2007*

Year	Journals	Total papers	Top 10		Top 30		Top 60	
			Papers	%	Papers	%	Papers	%
1992	170	356	138	38.76	199	55.90	246	69.10
1993	191	390	136	34.87	206	52.82	259	66.41
1994	251	443	108	24.38	185	41.76	245	55.30
1995	307	601	136	22.63	240	39.93	321	53.41
1996	408	904	194	21.46	337	37.28	457	50.55
1997	466	1,049	243	23.16	398	37.94	525	50.05
1998	478	1,046	195	18.64	355	33.94	494	47.23
1999	511	1,085	143	13.18	285	26.27	435	40.09
2000	548	1,280	230	17.97	426	33.28	590	46.09
2001	591	1,359	221	16.26	423	31.13	573	42.16
2002	668	1,538	235	15.28	438	28.48	622	40.44
2003	672	1,721	255	14.82	524	30.45	733	42.59
2004	757	1,802	229	12.71	480	26.64	709	39.35
2005	715	1,678	248	14.78	503	29.98	705	42.01
2006	970	2,440	340	13.93	656	26.89	916	37.54
2007	948	2,489	320	12.86	637	25.59	932	37.44
Total	3,183	20,181	2,717	13.46	5,159	25.56	7,234	35.85

Note: The total number of GIScience papers in top ten journals for 1992–2007 is not equal to the summation of the numbers for each year because the list of top ten journals changes over time and is different from the one that includes all sixteen years. The same applies to the top thirty and top sixty.

inappropriate when A is connected to more authors.

To adjust for this bias, we allowed for situations where author A has a smaller separation statistic if he or she has more coauthors *overall* than B. Authors connected to the same subcommunity still follow the basic definition of S in Equation 1, the average of the shortest paths to any connected author. For a subcommunity of size n, the situation with the least separation occurs with the unadjusted definition of S, meaning the node has a direct connection with any other node, and the most ($S_{\max}$) when the network is a chain, or

$$S_{\max} = \frac{1}{n-1}\left[1+2+3+\ldots+(n-1)\right] = \frac{n}{2} \tag{2}$$

To reduce bias in S, we first adjusted it toward (0, 1] by dividing by $S_{\max}$. We further introduced a logarithm denominator to compress large differences in scale among subnetworks.

$$S'(i) = \frac{S(i)}{\log_2(n+1)\times S_{\max}} = \frac{2}{n\times(n-1)\times\log_2(n+1)}\sum_{j=1, j\neq i}^{n} d(i,j) \tag{3}$$

After this adjustment, separation is uniform within subnetworks and under the worst-case scenario, the largest separation in variously sized communities is 1, or $S'_{\max} = 1$.

Global efficiency is an overall network statistic reflecting average distance of each node to every other node; the shorter the distance, the higher the efficiency, namely,

$$E_{global}(i) = \frac{1}{N}\sum_{j=1, j\neq i}^{N}\frac{1}{d(i,j)} \tag{4}$$

where $E_{global}(i)$ is the global efficiency of node i, and N and $d(i,j)$ are the number of nodes and shortest distance between nodes i and j respectively. This measure accommodates the potential for the shortest length between disconnected nodes (i.e., infinity) and subcommunities. In this case, global efficiency is just zero with infinite distances, which is unlike the separation statistic, in which infinite distance leads to infinite separation not suitable for comparison.

The *clustering coefficient*, unlike separation and efficiency, is a local indicator of the degree of direct connections among nodes connected to a shared node, or

$$C_{\text{clustering}}(i) = \frac{\sum_{s=1}^{m}\sum_{t=1, t\neq s}^{m} c(s,t)}{m\times(m-1)} \tag{5}$$

where $C_{\text{clustering}}(i)$ is the clustering coefficient at i, s and t are nodes directly connected to node i, m is the number of nodes that directly connect to i, and $c(s,t)$ is 1 if node s and node t are directly connected and 0 if not. Clustering coefficients measure the cooperation between authors who coauthor with the same GIScience researcher. For example, if researcher A has four coauthored advisees, all of whom coauthor with each other at least once, A will have a clustering coefficient of one; if none of the advisees collaborate, the coefficient will be zero.

The *maximum subcommunity* is the one with the largest number of nodes or, in other words, the most populous subnetwork. We can treat this network as the core GIScience community composed of those researchers who consistently conduct research and publish papers in GIScience. Increased size of the maximum subcommunity is an indicator of how well core GIScience researchers train new scientists and collaborate with researchers from other fields, in that growth indicates bringing in researchers who were previously not publishing on GIScience. In addition, the ratio of the number of nodes in the maximum subcommunity to the number of nodes in the whole network provides a relative measure of the breadth and cohesiveness of this community.

Finally, the *author number* measures the shortest path length from a given author to others in the coauthorship network (Goffman 1969; Grossman 2009). The author number illustrates features of the larger network of which he or she is part, and so we chose six authors on whom to focus. We separated nonnative English speakers from native speakers because we expected that the former, on average, would be more isolated in the GIScience coauthorship network. We distinguished among researchers working in the United States versus those outside of the country. We also roughly categorized GIScience researchers according to the time since they obtained their PhD degree to examine network building as a function of career stage. As a result of this approach, Wenzhong Shi was selected as a Chinese scholar working in Hong Kong and Andrew Lovett as a scientist in the United Kingdom. Of the remaining researchers, all working in the United States, we selected Michael F. Goodchild, David M. Mark, Max J. Egenhofer, and Alan T. Murray, who obtained their doctorates respectively in 1969, 1977, 1989, and 1995.

Before continuing, it is important to note some caveats that apply to the analysis here and SSNA in general when applied to individuals. We chose these six cases to examine in greater detail some of the general dynamics of the GIScience network, but there are many other individuals with similar records who meet the selection criteria. Furthermore, although data provided by Geobase and ISI are representative of the GIScience community as a whole, omissions exist on an individual basis. Finally, this analysis examines the position of these six individuals within the coauthorship network, and not quality of their research. As noted earlier, the use of scientometrics to examine an individual's research only makes sense as part of a broader analysis, whereas this article focuses on the insights SSNA offers on GIScience research.

Another caveat arises when the problems inherent in name searches get carried over into the network topology. The same name possessed by different people and the translation of different foreign names into the same English names are the most common problems, both of which lead to different authors being represented by the same node and the consequent inclusion of unconnected researchers in the same subnetwork. This problem is exacerbated when databases record only the first letters of given and middle names and scientists share the same family names. Other common database errors compound the problems. Records scanned from paper media can generate errors in the optical character recognition process used to compile most digital databases. For example, Goodchild, M. F. might be recognized as Goodchild, M. E. Some bibliographic records confuse given and family names, generating different identifiers for the same author. This is especially true for East Asian authors. For example, an article in *IJGIS* (Siyuan, Jingshi, and Cunjian 2007) has reversed the names of its three Chinese authors, Siyuan Wang, Jingshi Li, and Cunjian Yang. In addition, authors sometimes abbreviate their names in different ways, so that the name Xiao-Ping Deng might be recorded as X.-P. Deng, X. P. Deng, or X. Deng. Databases typically do not correct for such inconsistencies. Databases inherit these inconsistencies unless their maintainers manually eliminate them or use an ID number in place of a researcher's name. We made no manual corrections because these errors offset one another and, more important, are likely to be systematic across years.

Results

We found that the evolution of GIScience can be characterized in general by the first and second parts of the logistic growth model, but fundamental transitions not evident in the overall logistic model were present in the GIScience community, namely, a clear trend toward multiple authorship and the varying pace of the collaboration alongside the development and consolidation of subnetworks, including engagement with other fields. We also found that the nature of international variation in research can be gleaned from closer examination of individual researchers within the broader collaboration network. In sum, these results describe the rise of GIScience and, more broadly, demonstrate the value of SSNA in understanding the nature of a field.

Logistic Growth and Underlying Transitions

GIScience in the period 1992 to 2007 saw tremendous growth that approximates the first and second parts of the classic logistic curve, characterized by a rapid takeoff and increase, but it is too early to tell whether or when the field will begin to plateau. This growth is evident in how the number of GIScience papers grew from 356 to 2,489 (Figure 1), and the number of GIScience researchers participating in academic collaborations rose from 766 to 7,403. The growth of GIScience is marked by a

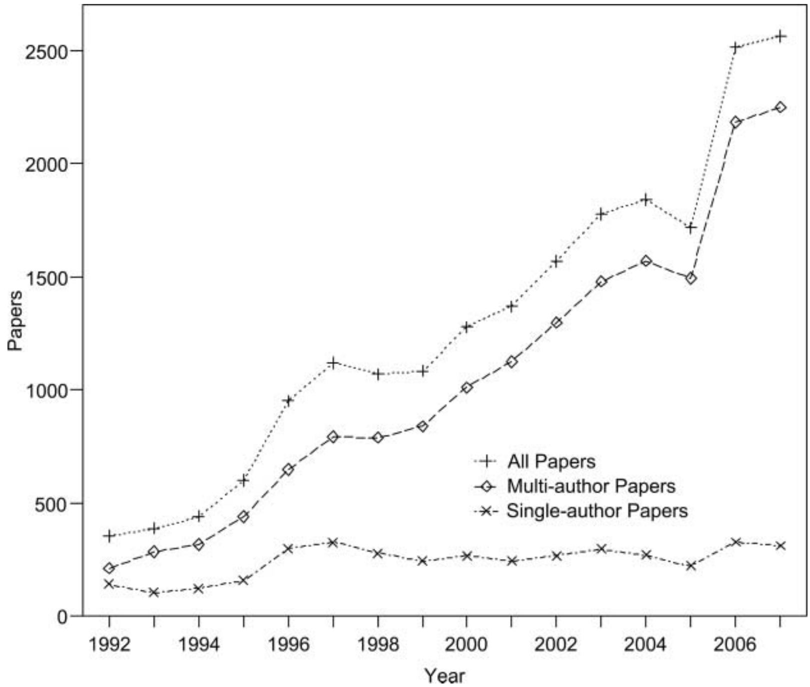

Figure 1 *Single- and multi-author papers, 1992–2007.*

remarkable increase in collaboration via coauthorship and attendant growth in the number of authors per paper. This transition is important not only in defining the evolution of the community via shared research but also has ramifications for scientific practice. Several waves of succession are evident: In 1993, two-author papers exceeded single-author papers for the first time and by 1998 were consistently more common than sole-authored papers; three-author

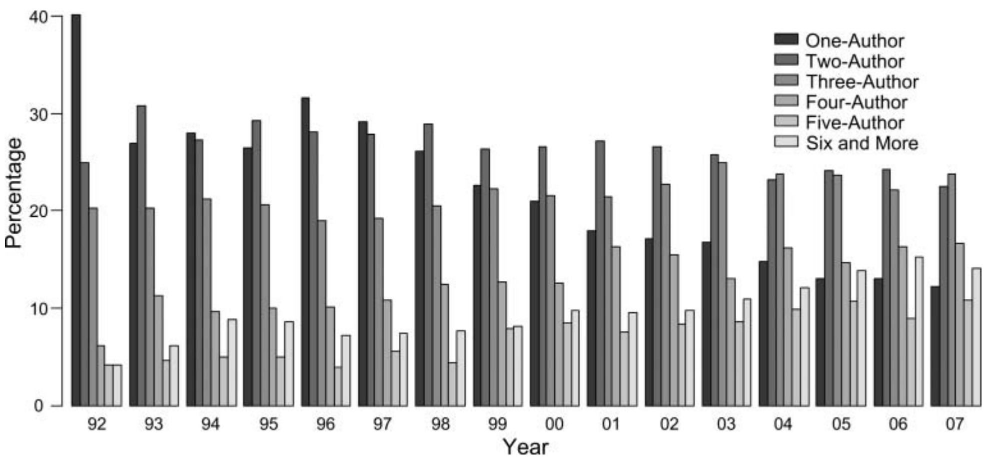

Figure 2 *Distribution of n-author papers by the number of authors.*

papers exceeded single-author ones in 2000; four-author papers followed a year later, and five-author papers almost overtook one-author papers in 2007 (Figure 2).

This work appeared in a wide array of journals with some specialization, with a growing trend of dispersal over time in keeping with logistic growth (Table 1). The ten journals that published the largest number of GIScience papers constitute only 0.3 percent of the total number of journals but accounted for over 13 percent of papers for 1992 to 2007. The top thirty accounted for 0.94 percent of total journals but published 26 percent of GIScience papers, and the top sixty published 36 percent. Over time, GIScience papers were dispersed over a broader range of journals, growing from 170 to 948. The concentration of papers in journals is correspondingly diluted, with the top ten accounting for almost 39 percent of papers in 1992 and only 13 percent in 2007. Overall, GIScience fits within the classic logistic model of scientific growth, although determination of if or when it will reach the model's final stage cannot be ascertained based on the study time period.

SSNA is crucial to understanding fundamental transitions in the GIScience research community that are not evident in the overall logistic model. Particularly important is the varying pace of the collaboration alongside the development and consolidation of subnetworks, including engagement with other fields. The smooth progression implied by the logistic model of growth in GIScience is complicated by the varying pace of subnetwork consolidation and collaboration with other fields over three periods.

In the first period, community size increases from 1994 and 1997 but separation does not decline accordingly, a trend that implies the weak connection of newly added authors to the core community, who instead formed isolated subnetworks (Figure 3B; Table 2). The most likely explanation is that researchers outside of core GIScience disciplines started to use geographic information systems as a tool but were not focused on advancing GIScience. The accompanying decline of global efficiency (Figure 3C) supports this interpretation, as does the growth in average clustering coefficient, which indicates collaborations within, if not among, many subfields (Figure 3D). Not surprisingly, this

Table 2 *Geographic information science collaboration network, 1991–2007*

Year	Coauthors (*M*)	Coauthorships (*M*)	Multiauthor papers (*M*)	Single-author papers (*M*)	Maximum connected authors	Separation (*M*)	Global efficiency (*M*)	Clustering (*M*)
1991	2.951	3.110	1.038	0.115	16	0.489	0.0050	0.0077
1992	2.634	2.842	1.064	0.187	18	0.583	0.0038	0.0041
1993	2.940	3.090	1.057	0.108	24	0.470	0.0033	0.0103
1994	3.247	3.416	1.070	0.110	28	0.450	0.0032	0.0121
1995	3.457	3.610	1.063	0.101	18	0.438	0.0023	0.0128
1996	3.111	3.355	1.103	0.136	27	0.472	0.0015	0.0112
1997	3.334	3.641	1.114	0.123	25	0.443	0.0014	0.0145
1998	3.222	3.537	1.091	0.106	24	0.436	0.0013	0.0105
1999	3.265	3.595	1.106	0.088	26	0.397	0.0013	0.0115
2000	3.537	3.899	1.126	0.079	27	0.364	0.0012	0.0165
2001	3.796	4.214	1.132	0.065	43	0.338	0.0012	0.0160
2002	3.473	3.771	1.115	0.062	24	0.343	0.0009	0.0172
2003	3.721	4.116	1.124	0.060	48	0.336	0.0009	0.0145
2004	3.779	4.212	1.139	0.051	174	0.305	0.0011	0.0127
2005	3.928	4.322	1.142	0.044	299	0.286	0.0015	0.0160
2006	4.161	4.672	1.158	0.045	541	0.274	0.0017	0.0151
2007	4.115	4.681	1.178	0.042	693	0.265	0.0022	0.0177
Total	4.591	5.412	1.496	0.092	17275	0.226	0.0203	0.0426

Note: Coauthors *are the number of researchers with whom a particular author publishes papers within the given period.* Coauthorships *counts both coauthors and coauthored papers; every single time when an author publishes a paper with others, it will be added to coauthorships. For example, A and B publish two papers and A and C publish one paper; the coauthors of A will be two and coauthorships of A will be three. The* mean multiauthor *papers is the average number of multiauthor papers by all unique authors and the* mean single-author papers *is of single-author papers.*

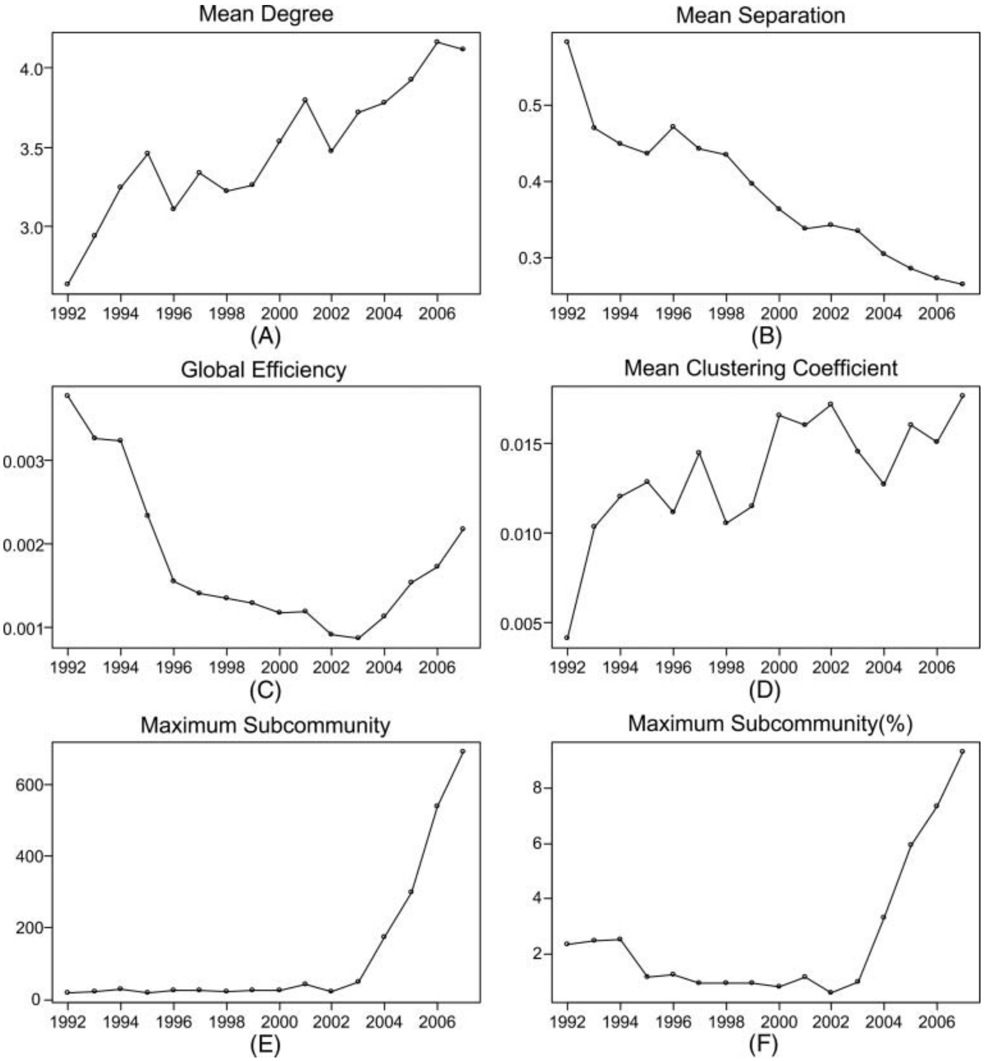

Figure 3 *Evolution of GIS community in terms of (A) degree, (B) separation, (C) global efficiency, (D) clustering coefficient, and maximum subcommunity measured as (E) numbers and (F) percentage, 1992–2007.*

period was marked by continued dissemination of GIScience approaches begun several years earlier (Abler 1987) and the transition from geographic information systems to GIScience (Goodchild 1992). It also was a time of debate regarding the relationship of GIScience to geography as a whole (Schuurman 2000) and calls for better integration of GIScience and other quantitative approaches with the rest of the geographic discipline (e.g., Brown 1999; Gober 2000).

In the second period, 1997 to 2002, we see the beginning of the consolidation of subnetworks. The first several years of this period are marked by fairly stable community size while separation starts to decline and global efficiency begins to stabilize. Fluctuations in the mean degree of the number of coauthors imply that there was much temporary collaboration within the community instead of a gradual and uninterrupted expansion of existing collaborations (Figure 3A). This is likely due in part to the small size of the GIScience community in the 1990s and a sign that the field became important to other disciplines in the late 1990s (see also Unwin 2005). Global efficiency, which measures global connectivity and compactness, demonstrates an overall pattern of increasing coauthorship and increasing closeness. Its decline between 1997 and 2002 implies the existence of a fundamental structural transition within the community marked by increased coauthorship and a growing number of authors (Figure 3C). The transition over this time was accompanied, and driven, by a variety of initiatives including research projects like Varenius (Goodchild et al. 1999), interdisciplinary research platforms like Center for Spatially Integrated Social Science (Goodchild and Janelle 2004), and a renewed University Consortium for Geographic Information Science (UCGIS) research agenda (McMaster and Usery 2004).

In the third period, consolidation is complete, evidenced by the decline of separation and rise of global efficiency after 2003 as the decrease in total social distance outpaces the growth in size of the community. The drop in clustering coefficients in 2003 and 2004 alongside rising global efficiency implies that the process of isolated subcommunities merging with the core community drove the rapid growth of the maximum subcommunity (Figure 3E and 3F). In aggregate, social network measures capture the underlying dynamics of the logistic model by identifying a small group of GIScientists at the core of an emerging discipline who increasingly worked with isolated subcommunities. After the expansion, adjustment, and consolidation of subnetworks, the GIScience community became a fast-growing but well-integrated and connected community with an increasingly stable set of core researchers.

This analysis makes clear that GIScience research increasingly involves large collaborative projects. This aligns with trends in most of the natural sciences and an increasing number of subfields within the social sciences (Wuchty, Jones, and Uzzi 2007). If collaborative research and writing is becoming the norm, the general and long-held emphasis on sole authorship in evaluation of research and researchers in geography should be reexamined within the larger context of GIScience as an evolving subfield. Similarly, the costs incurred during collaborative research should be better recognized; workload management, task delegation, and determination of shared research goals are just a few of the collaborative research components that are less common in solo research (Nicolson et al. 2002). There is a need for greater emphasis on institutional mechanisms that support collaborative research, such as travel for project meetings, foreign research collaboration (including salary and travel), and mediating technologies such as videoconferencing. Although collaboration is on the rise in GIScience, there will always be solo researchers and those who employ a broader array of methods from the humanities and social sciences (Persson, Glänzel, and Danell 2004; Papatheodorou, Trikalinos, and Ioannidis 2008). In these cases, enacting policies that privilege collaborative research should not inadvertently harm solo research.

Individuals and Nations

When applied to individual researchers, social network analysis sheds light on features of collaboration networks including the effects of language, international divides, and the relative advantages and disadvantages of social network measures. As described earlier, we considered the *author number* of six researchers. The most common path length is four or five, which indicates an important characteristic of small-world networks (Watts and Strogatz 1998; Watts 1999), namely, that the majority of the GIScience community members can be connected to the core researchers within a small number of jumps (Figure 4).

There is growing literature on the importance of understanding the role language plays in the academy and the obstacles for non-English speakers (Short et al. 2001; Helms, Lossau, and Oslender 2005; Alberts 2007). We therefore expected, incorrectly, that Dr. Shi would be less connected to other authors, being a nonnative English speaker working outside North America. In fact, Dr. Shi is more closely connected to the coauthorship network than the other authors. More broadly, judging by family names, many authors who rank

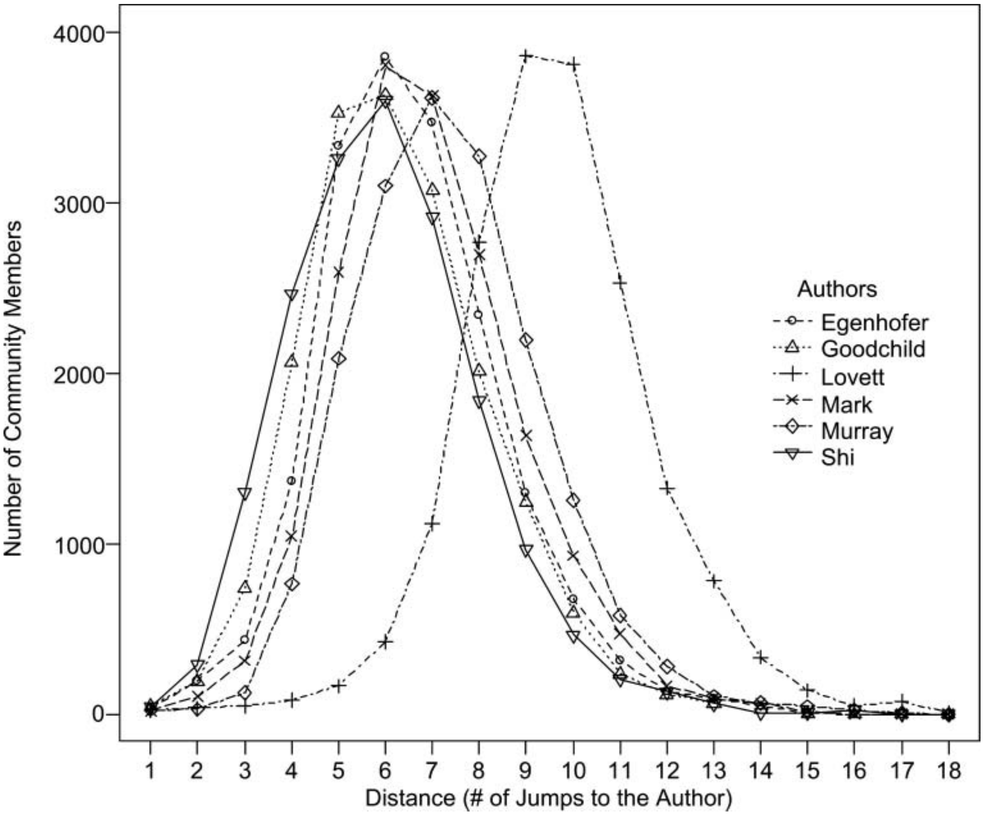

Figure 4 *Shortest path lengths for six authors.*

highly in global efficiency are of Asian descent, although further research is necessary to build on this informal observation. Two possible factors might explain why our underlying assumption was incorrect. First, many nonnative English-speaking researchers who end up publishing in English often have gained PhDs in Anglo-American programs, have access to senior researchers who are generally more connected, or both. Second, they sometimes might want to work with native English speakers if they expect that the research will eventually need to be published in an English language journal.

There is also evidence of international divides. Dr. Lovett has an exceptional record of publication without a corresponding distance distribution. This discrepancy might be caused by differentials in the size of the GIScience research community in the United Kingdom versus the United States. For instance, the UCGIS has seventy-four American educational members (UCGIS 2010), whereas the U.K. RAE 2001 lists sixty-two general geography programs (RAE 2001) and the Association of Geographic Information has only twenty-seven British academic institutional members (Association of Geographic Information 2010). Practically speaking, funding organizations such as the National Science Foundation in the United States and the Economic and Social Research Council and Engineering and Physical Sciences Research Council in the United Kingdom limit the salaries and travel funds that can be used to support foreign researchers, which impedes international collaboration.

Finally, individual-scale analysis demonstrates pros and cons of SSNA. The seemingly low number of papers authored by Dr. Mark, one of the founders of GIScience and a prolific

Table 3 *Social network analysis profiles of six authors*

Name	Papers	Coauthorships	Sole authorships	Degree	Separation	Global efficiency	Clustering coefficient
Egenhofer, M. J.	19	35	3	28	6.82	2,786.23	0.0106
Goodchild, M. F.	32	47	6	28	6.71	2,850.90	0.0079
Lovett, A.	11	35	0	20	9.67	1,903.18	0.0053
Mark, D. M.	5	15	0	13	7.14	2,636.57	0.0513
Murray, A. T.	24	38	2	28	7.42	2,538.69	0.0079
Shi, W. Z.	25	51	1	34	6.15	3,178.38	0.0125

researcher, is an artifact of publishing numerous papers that would have been included in the database had we used terms like *fractal*, *scale*, *spatial search*, and *ontology* instead of just variations of "geographic information." Nevertheless, other network metrics captured his importance in the field, such as high efficiency and low separation, even when the database did not capture many of his publications (Table 3). Dr. Mark also has a high clustering coefficient, implying that those who coauthor with him tend to work together as well, which indicates a key role in establishing research networks. This availability of multiple measures is another advantage of SSNA over simple publication analysis.

Our small sample size notwithstanding, social network analysis that ties individuals to the network highlights the ways in which language, origin, and country of practice are related to the collaboration process and article publication. Collaboration among researchers continues to grow as GIScience takes more sophisticated approaches to analytical inquiry, even as articles remain a critical means for disseminating research and permitting a more streamlined approach to evaluating the performance of individual researchers and departments. The role of language and other features of authors should therefore be considered when making decisions that range from editorial practices (e.g., the growing use of free or subsidized English-language editing, publishing abstracts in languages other than English) to hiring and promotion (e.g., closely examining contributions to collaborative research and perhaps better valuing such research).

Conclusion

We used SSNA to examine the evolution of the academic GIScience community. Although we addressed the general applicability of the standard logistic model of development of a scientific field, use of a coauthorship network approach allowed us to identify a number of underlying dynamics. First, collaboration among GIScience community members has increased dramatically, as demonstrated by the number of coauthored papers and by how close researchers are within the network. Second, the observed changes in several SSNA indicators demonstrate the importance to GIScience of the rapid shifts in subnetwork structure and the role of GIScience software being adopted as a tool in other fields. Finally, the network of the late 1990s was more fluid than would be suggested by the logistic model, even as more researchers joined the GIScience community, internal cohesion increased, and the field matured. Social network statistics reveal the fluctuations and changing internal configuration of the GIScience community as it developed.

SSNA is a powerful approach to understanding the evolution of scientific fields. Still, it has shortcomings that need to be addressed, particularly as academic administrators increasingly turn to SSNA to evaluate the performance of individual researchers. Geographers must better engage with the research and practice of scientometrics when applying SSNA to the humanities and social sciences. A related future research direction is temporal analysis at the individual level that would better depict the evolution of the core academic GIScience community composed of those who publish GIScience papers consistently in multiple years. Moreover, we do not situate GIScience researchers in their institutions, which means there are likely different forms of collaboration defined by alma mater, current institutions, or some other mechanism for generating social networks. Institutional affiliation or use of a single unique identifier for a given researcher (such as Thomson Reuters's ResearcherID^{TM}) would help differentiate among authors with the same name and identify a single author with multiple naming variants. These aspects of collaboration among GIScience researchers are topics for further inquiry. ■

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