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LETTER TO THE EDITOR

A brief review of the evolution of GIScience since the NCGIA research agenda initiatives

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Abstract: Geographical information science (GIScience) is progressively acknowledged as a scientific field based on a wide range of theories and methods that are constantly evolving. This motivates our attempt at a tentative observation of the research progress and challenges that have gone along with its gradual recognition as a domain of its own. The brief critical review presented in this paper develops an observation of such evolution. The peculiarity of our approach is that it is not based on a quantitative evaluation of the research outputs as identified by usual journal production metrics, but rather on a progressive identification of the research questions and their evolution, which the GIS academic community has been addressing over the past 30 years since the landmark NCGIA initiatives' research agendas have largely inspired and contributed to the development of geographical information science as a field.

Keywords: GIScience, NCGIA research initiatives, research agenda

1 Introduction

Three decades after GIS has been redefined as a science [22], we believe it is time to conduct a critical examination of the successive research advances that successively contributed to its progression and recognition as a specific scientific domain, as most similar emerging disciplines frequently question themselves in terms of the boundaries that define their core scientific roots. While scientometric and bibliometric studies provide quantitative evaluations of the respective trends that appear in published papers, and as this has been done elsewhere (e.g., [31, 58, 60]), we primarily focus on the successive theoretical and methodological questions that our whole community has been addressing over the last three decades, to derive a qualitative and specific view of our field and its evolution. More practically, our objectives and assumptions are as follows:

- We intend to identify and qualify the theoretical, methodological, and computational questions the GIScience research community has addressed over the past 30 years, and to what extent they were dealt with.
- The GIScience research contributions considered for our study are the ones that have played a major role in terms of scientific coverage and general contribution to the field. They are mostly based on the NCGIA (National Center for Geographical Information and Analysis) research initiatives that attempted to lay the foundations for an emerging GIScience from 1988 to 1997 [39], and that can be considered jointly as a landmark starting effort for the discipline. A few additional successive proposals are being considered to complement the NCGIA initiatives over time, such as the European Agile research agenda [11], the Varenius conceptual framework [26], the Canadian Geoide research network priorities that covered a period from 1998 to 2012 [53], and the United Nations Committee of Experts on Global Geospatial Information management research and development priorities [51].
- To complement the aforementioned research agendas, several prospective views—often the result of panels and/or invited papers to major international journals and specialized workshops—are also considered. They reflect recent thoughts, ideas, and future research avenues and supplement our critical evaluation.

By no means should our approach be considered exhaustive and complete, but we attempt to give a representative view of the evolution of the field, or at least support a *fil conducteur* that traces a broadly shared vision of the evolution of the GIScience research domain. This study describes how GIScience research agendas developed from NCGIA research initiatives, as well as how technological and societal evolutions influence the specific subjects to address.

2 Preliminaries

GIScience has been defined as the scientific discipline that studies the data ideas, foundations, concepts, structures and computational techniques that capture, represent, process, and analyze geographic information [24]. A major peculiarity that should be mentioned to understand this field is that GIScience originated in a system-oriented domain (Geographic Information Systems – GIS) that progressively turned into a science. While it has been generally observed that science gives rise to innovation [5], GIScience could be described as a history of the reverse: a series of innovations that gave rise to a coherent scientific discipline. This is illustrated by the International Journal of Geographical Information Science and its evolution: originally labelled as systems instead of science until 1996. Geographical information systems were initially considered as computerized systems to process and produce cartographical knowledge [50], before being progressively more broadly defined as advanced computerized systems with principles and applications, and then later progressively redefined as a science [37].

3 Experimental qualitative evaluation

As arguably the most important initial collective brainstorming of the forthcoming research challenges associated with the field of GIScience, the NCGIA initiatives established by the National Science Foundation generated a series of specialist meetings that identified the primary challenges and approaches in a series of specific domains [1]:

- The need for a better evaluation of GIS data sources was clearly identified in the original NCGIA initiatives. Initially, part of the discussions of the NCGIA focused on data quality and error propagation. Spatial data quality principles and standards have been progressively identified and defined as a requirement of many implementations of institutional GISs [28]. As technology and the range of applications have dramatically changed over the last three decades with the emergence of a large diversity of heterogeneous geographical data, applications and users, the need for stringent precision and accuracy has evolved with the emergence of flexible, user-oriented, on-the-fly systems that align more cognitively with day-to-day tasks, and practically with participatory and volunteered data environments, straying away from high-quality geographical outputs [24]. Visualizing the quality of spatial information is a striking illustration of the influence of the quality dimension associated with the processing and delivery of geographical data, which is closely connected to the interface level and remains a niche subject [36]. Spatial data quality principles standards have been progressively identified and defined as a requirement of many implementations of institutional GISs [28].
- The initial original remote sensing/GIS major subject was extended to the search for different forms of geographical data, and not only limited to data integration capabilities. The integration of remote sensing and GIS, defined as an initial NCGIA research initiative, is still an active subject, but with a different form and scope, as it is not only restricted to satellite and cartographic data as in the early days [54], but more broadly extended to all multiple forms of institutional or open data, static or real-time. With continuous progress in the development of high-resolution sensors, as well as novel opportunities offered by autonomous devices, many coupling possibilities and research challenges emerge in close association with Artificial Intelligence (AI) capabilities [22].
- Core among the NCGIA initiatives was a need to integrate and formalise cartographic knowledge using cartographic generalisation and visualisation of multiple representations. With this need, consistency issues as well as the implementation of reasoning rules became paramount [6]. Progress is still expected in the representation of uncertainty and fuzzy objects which are complex modelling issues that have not been completely resolved [25]. These theoretical concepts have largely stayed in the cartographic realm, but have moved into the computer science domain as well for their algorithmic implementations.
- A large swath of the NCGIA initiatives focused on cognitive and linguistic aspects of systems. It was initially essentially oriented toward the development of abstract models from linguistic representations, and elementary spatial entities and reasoning mechanisms based on topological primitives [16]. Great effort has been put into identifying the language of spatial relations [15,18], using those mathematical models to motivate ontologies, building reasoning systems from these ontologies, and ultimately better designing user interfaces to help humans acquire these insights from

spatial data [27,47]. All of these require a salient understanding of the human mind on multiple levels. This has since evolved gradually towards broader issues via the emergence of spatial ontologies and the Semantic Web [27], approaches based on the notions of enduring and perduring that gave rise to novel reasoning processes at higher levels of abstraction, in which the temporal dimension plays a substantial role, and human-intuitive solutions are favoured [16]. Navigation knowledge and wayfinding nowadays find novel opportunities with the emergence of many portable devices that favour the development of practical solutions for intelligent navigation [49]. This is a demonstrative example of how early theoretical findings can be later implemented when the technology is ready to do so.

- The search for understanding the architecture of spatial databases started with the computer science communities [29], and has slowly moved toward the private sector, demonstrating a move toward the development of an active GIS industry with not only major software solutions but also open-source systems and reproducible research [37]. This exemplifies specific domains not only being addressed exclusively by the scientific community but also by the well-established GIS software industry, which can also act as a major innovator. Subjects that appeared promising in the early 1990s such as object-oriented and temporal GISs have not received as much attention in recent years. This is probably due to the difficulty of mapping theoretical advancements towards supporting data infrastructures and readily available software environments. Research today in this area focuses on paradigms that go beyond georelational database paradigms and move toward innovative data abstractions such as spatial graph-based models [13, 46, 57], database streaming engines for the real-time integration of location-based data [40], and innovative and participatory interfaces for the user-oriented manipulation of geographical data over the Web [59]. One should keep in mind that in the early 1980s, computers were far less computationally efficient than they are today, sensors were rarely distributed and integrated into GIS environments, and the Internet was still in its infancy. This not only generates specific research issues in the early days such as the search for efficient database engines, computational data structures and query languages on the one hand, but also, on the other hand, novel challenges arising from recent and fast-growing development of location-based GIS, Web GIS and services, spatial-social media, and human-based sensor GISs. Cyberinfrastructures are nowadays instrumental in the development of geospatial clouds that favour the integration of heterogeneous data sources over the Web, favouring collaborations and knowledge sharing across different user communities [59]. Also important is the identification of the fundamental role that spatial data modelling should play, and this domain has widely contributed to twenty years of research both from the conceptual database community [44] and modelling languages developed by the Open Geospatial Consortium [45].
- Many of the initiatives of the NCGIA referenced the need to consider the usage and value of spatial data [23]. To fully realise that potential, laws and ethics have had a seminal role in the discussion [40]. While laws are important, we also must consider policies, most importantly how institutions and organisations share data amongst themselves and generally with the public [43]. This subject has been gradually appropriated by conventional organizational approaches and treated within the framework of methodological processes for the implementation of GIS in different levels of an organization. Geographical data and metadata standards, geo-portals, and geo-

graphical data infrastructures have been widely developed at the local, regional and national levels, enabling widespread diffusion and sharing of geographic information. Standards, management, and governance rules are difficult to implement in cyberspace. This raises significant issues with vulnerability, transparency, security and data protection issues that GIScience should research. As we have moved to a more citizen science climate with lots of volunteered geographic information, these needs remain important today, be it as basic accuracy issues or even further into the realms of copyright and privacy. FAIR data principles are a set of guiding principles to make data findable, accessible, interoperable and reusable so that data can be found, understood and reused by others, and driving factors progressively adopted by the GIS community [55]. Openness to other sciences and disciplines such as environmental sciences was also mentioned by the European Agile agenda [11]. Ethical and privacy issues were also first mentioned by Goodchild and have since continued to play a more and more substantial role, as well as one of the impacts of GIS on society [52], as there is a need to understand how different groups are impacted by, have access to, or otherwise are exposed to GIS.

- Spatial analysis is still one of the most important areas of GIScience [17], closely connected to the need for a sound integration of the temporal dimension [32]. This subject has been explored in a broader sense from language, culture, modelling, manipulation to implementation issues in space and time to the search (still active) for new spatio-temporal data representation and reasoning, mechanisms, either formal or coupled with new geo-computation, geo-analytics and AI often closely connected to high-computing algorithms and resources [34]. Nowadays, spatial analysis and visualisation open up to the many perspectives offered by the opening to the third dimension, the integration of interactive, real-time, and dynamic visualization processes, and immersive systems, and where technologies finally open a wide range of interface opportunities while favouring additional interactions with new fields of research, particularly when coupled with AI [9]. There is still much to be done and this subject is not yet completely developed with many extensions such as geo-computation and geo-analytics, and now expanding to AI capabilities with new avenues of opportunities.
- Spatial Decision Support systems, multi-criteria analysis and collaborative decision-making were already thought to be inherent to the sciences of geographic information, but notably in their shared relation to many disciplines and applications such as retailing, marketing, socioeconomic and environmental modelling [12]. This is still the case with probably an extension of the opportunities for multidisciplinary research and citizen involvement with complementary fields (e.g., health, transport, environment). These trends contribute to the explicit recognition of GIScience by many scientific fields, a strong opening and an extension of the perimeter of origin of the sciences of the geographical information, while also calling into its own identity. It has been recognized that decision processes are intimately linked to the organizations in which such processes happen and should be preferably collaborative processes [21]. We should think about the processes by which decisions are made. Are decisions made unilaterally or collaboratively? Is that collaboration between different human interests or between methodological slants and analyses? Ultimately, the right decision may not be the same in all contexts, varying with disciplines and applications. These assumptions are revisited in a different way but as baselines of

emerging collaborative digital representations. This reality leads to the necessity of numerous formal and informal models to allow humans the flexibility to make appropriate decisions while still exhibiting control of the outcome.

- Core to the future of the NCGIA initiatives is GIScience education. GIScience education is a key issue to address as the development of successful teaching methods requires the integration of continuously evolving GIScience principles. This requires the identification of a common or minimum theoretical and methodological framework, practices and a body of knowledge that can reconcile the diversity of disciplines involved in the field and a sound basis for a wide range of audiences and expertise [2]. This in effect can challenge the entire GIScience community.

Overall, it appears that many of the initial research subjects that were identified by the NCGIA initiatives remain subjects of interest today with broad contributions across many scholars and institutions, a core signal of disciplinary vision. This noteworthy evolution in the analysis of GIScience research directions can be related to the conceptual triangle initially suggested by the Varenius conceptual framework that displaces the focus from solely the human, society, and the system to the interplay of the three (Figure 1). This conceptual construction remains relatively valid in its root principles, but its scope has significantly evolved with changes in society and the emergence of major environmental concerns, the diversity of technologies, processing resources and systems, and the multiplicity and heterogeneity of the communities involved.

As a first macro-summary of this analysis, there appear to be several broader themes at play over the past 30 years of the research agenda. The research subjects from NCGIA have continuously evolved in three core planes: *society*, *technology*, and *humans*.

- On the *societal level* it appears that many of the initial research subjects that were identified by the NCGIA initiatives remain subjects of interest today with broad contributions across many scholars and institutions, a core signal of disciplinary vision. This noteworthy evolution in the analysis of GIScience research directions can be related to the conceptual triangle initially suggested by the Varenius conceptual framework that displaces the focus from solely the human, society, and the system to the interplay of the three (Figure 1). This conceptual construction remains relatively valid in its root principles, but its scope has significantly evolved with changes in society and the emergence of major environmental concerns, the diversity of technologies, processing resources and systems, and the multiplicity and heterogeneity of the communities involved.e been changes in volunteered or unvolunteered data initiatives such as citizen science and social media. This generates a major methodological shift: from the modelling of well-defined and bounded geographical data infrastructures toward digital geographical information infrastructures and digital twins that combine institutional and social media data with a higher diversity of collaborative and volunteer data integration pathways, some of which are not always well-defined, and that open many data integration and sharing issues. Data flows nowadays are either structured or unstructured, and they have even come from new social media pathways that generate unprecedented volumes of potentially geo-located semantic data. Similarly, this induces challenges in computational data quality. It should be noted, however, that computational data quality may not detract from the actual quality of that data to a human or society.

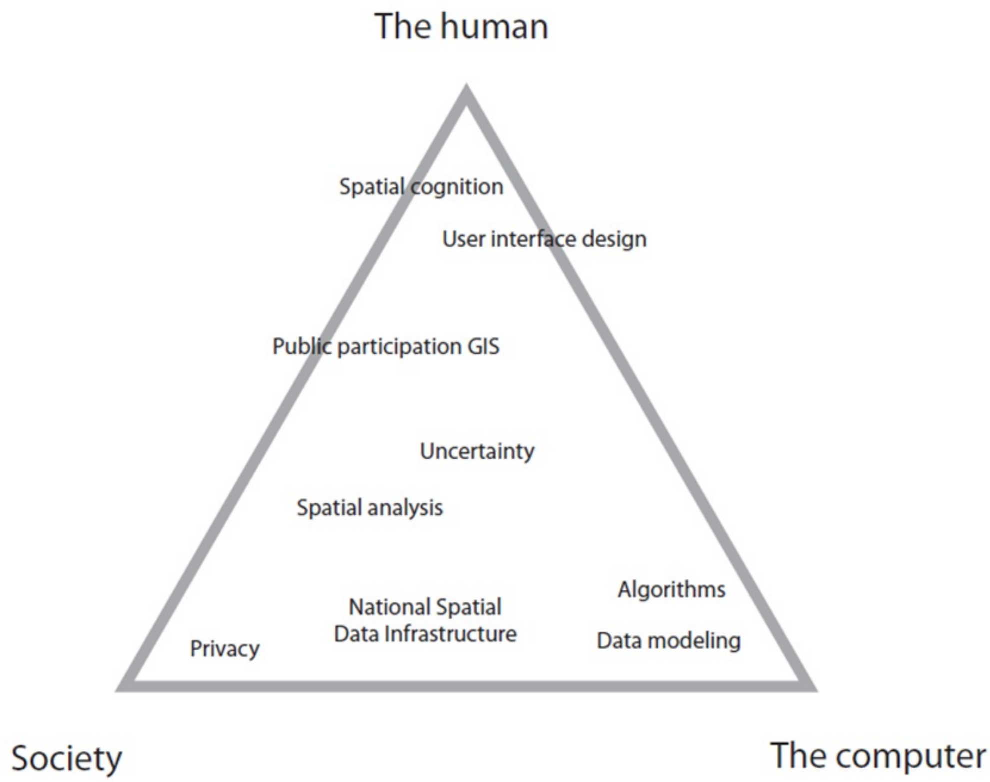

Figure 1: Varenius' conceptual framework.

- On the *technological level*, there have been major advances that have grown or usurped research subjects. There are, however, novel opportunities and research issues offered by new technological possibilities (e.g., sensors, wireless networks, location-based services, visualization, and exploratory tools), with a close association of cyberspace and geographical space [35].
- On the *human level*, there is a much wider geographic dispersal of contributors, spanning not only Western cultures but also vibrant research communities in Asia. As science advances and knowledge accumulates, a general trend observed in many scientific domains is that there is a ubiquitous shift toward teamwork [30], decreasing the role of individual landmark contributions as this was the case in the early GIScience days. The spirit of collaboration has steered away from seminal work, and more toward collaborative scholarship spanning many perspectives. There is also a need for considering balanced gender and diversity issues in the development of GIScience, a challenge that occurs in many disciplines [19].

As with many disciplinary tracks from urban to environmental sciences, interdisciplinarity has provided fruitful opportunities for innovative research. On the lowest level, we see transdisciplinary efforts that link areas of study (such as health GIS). As more and more specialised areas emerge, particularly in computer science, more and more research subjects are emerging around areas concerning artificial intelligence, data science, and mobile computing. Other parts of the disciplinary research track have either faded from disciplinary focus (such as cartographic topics) or have shifted to predominant concerns in other communities (such as data sharing or legal concepts) [42]. The Canadian Geoide research agenda introduced a major evolution in the way GIScience research should be conducted [53]. The focus was voluntarily put on three complementary dimensions that finally announce a major evolution: mobility, environmental change, and sensors. A notable tendency is that the focus was on a specific emerging area (i.e., mobility) that has driven massive efforts in developing real-time data integration of moving objects for many transportation-related applications. Over the past ten years, ontologies, big data, volunteer GIS, cyber GIS and AI have played a major role in the development of GIScience research [14]. This vision is still extraordinarily valid as these open many research avenues that open a series of forthcoming areas to explore.

The environment domain is currently acting as a major application area because of its societal impact. Another significant trend which is a critical example of the evolution of GIScience research, is the diversity of disciplines involved, to mention a few: Geomatics, Earth Science, Civil Engineering, Computer Science, Statistics, Forestry, Environment Science, Medicine, Physics, Planning, Archaeology, Business. This prompts the question of how GIScience fits into the interaction with all these domains. Does GIScience exist, or is it just a conglomeration of other recognized disciplines?

4 The routes to the future

A major trend also specific to GIScience is that most research developments came from individual and opportunistic developments rather than the result of major research efforts. In that sense, the balance is much more on discovery-led research and not major theoretical and organised advances [20]. Re-usability is becoming a major trend as many major international journals require the availability of codes and data for accessibility and re-utilization purposes [38, 55], this is exemplified by the new policy developed by the *International Journal of Geographical Information Science*. The next few years will be still influenced by the continuous emergence of novel technologies and novel opportunities in ways that are currently hard to imagine. For instance, amongst many current technological advances that are likely to impact GIScience research over the next few years let us mention autonomous, mobile, and distributed sensors as well as novel exploratory interfaces are likely to strongly impact the GIS world [41]. The emergence at unprecedented scales of many sensor-based environments offers many possibilities for the integration of geographical data, but also new research issues to address such as the real-time distribution and integration of large incoming datasets. The future of GIS requires close integration with data sciences and emerging technologies, which are likely to offer considerable application perspectives and routes for innovation [35]. Still, there is a need to develop methodological bridges and pathways among geography, AI, and cognitive science [4], and strengthen connections between geographical space and cyberspace [33]. This creates novel behavioural and cognitive research and methodological challenges to explore the behavioural, cognitive and psychological processes involved. Moreover, emerging and major societal impacts and challenges, such as climate and the environment, are very likely to impact future GIScience research [10]. Cyberspace and the metaverse significantly impact the way humans interact with and behave in virtual geographical space, but also create learning opportunities. This generates in fact new learning and knowledge acquisition processes that can be then transferred to and replicated in the real world under specific modalities still to be studied. Sustainable Development Goals (SDGs) require huge amounts of spatial-temporal data, methods, and analytics to reach their objectives, creating many opportunities for GIScience.

The GIScience community, as proof of its relative youth, is always keen to identify major forthcoming research challenges that will stand over the next few years (e.g., [8]). The emergence of big geographical data, volunteer geographical data, Web-based and social geographical data, and the metaverse are very likely to impact the way most GIScience research issues should be addressed as the level of scalability and processing to consider already has a different degree of magnitude and then of representation complexity [56]. Promising GIScience experiments will arise from virtual communities and metaverses, whose spatial properties are likely to generate a need for the exploration of the structural patterns that emerge at different scales and levels of granularity. Clearly, and as anticipated, GIScience is very likely to evolve when the virtual space permeates a wide range of human activities [3]. Placeless Internet gives room to many more international scientific collaborations at unprecedented speeds, thus facilitating cross-cultural approaches and maximising efforts over time. GIScience is changing as the world is evolving with increasing needs in the age of sustainable development and the need to follow the emergence of big data challenges, thus resulting in a constant increase of academic publication flows [60].

5 What we have learned

What this prospective paper intends to achieve is an observation of the field of GIScience, through personal observation of the research issues that have been considered relevant over the past thirty years. The effort is noteworthy as far as we learned something from the exercise, especially in the understanding of the scientific patterns that drive GIScience. Indeed, there is a part of subjectivity in it, but it supports the identification of evolutionary trends in the way GIScience questions itself from a meta-scientist point of view. A major finding is that in all cases GIScience research should not be considered as a closed and monolithic domain, but rather a subject open to a wide diversity of other scientific domains, thus making the identification of the research boundaries of GIScience as a research subject a non-straightforward task. It will be wise to observe to what degree GIScience advances generalise across other fields [8]. As GIScience is a relatively new area, and as compared to well-established and strong scientific domains and fundamental sciences, the identification of its exact role in the general frame of science is also a difficult task, and it is still the object of some debates [48]. Geographical information science lies at the crossroads or convergence of several scientific domains and greatly benefits from them, and a challenging subject is to which degree other disciplines will benefit from GIScience research breakthroughs; GIScience observatories should be developed to observe the underlying theoretical and methodological processes so that they can be reproduced, and their findings better understood [7]. It becomes crucial to properly document the proliferation of geographic data of all kinds. The conservation of this data is also a complex issue insofar as it is difficult to anticipate the questions that researchers will likely address [7]. GIScience must integrate several disciplines around common research interests to broaden its scope and allow for the integration of complementary views. An often-latent question is whether the issues addressed by GIScience are specific to our field or more generic and shared by other disciplines: Are the spatiotemporal concepts, models, and reasoning frameworks developed so far, generalizable across all fields? Is a unified theory of spatiotemporal information feasible and a worthwhile goal across all disciplines?

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References

[1] ABLER, R. F. The national science foundation national center for geographic information and analysis. *International Journal of Geographical Information System 1*, 4 (1987), 303–326.

[2] BALRAM, S., AND BOXALL, J. *GIScience Teaching and Learning Perspectives*. Springer, 2019.

[3] BATTY, M. Virtual geography. *Futures 29*, 4-5 (1997), 337–352.

[4] BHATT, M., AND WALLGRÜN, J. O. Geospatial narratives and their spatio-temporal dynamics: Commonsense reasoning for high-level analyses in geographic information systems. *ISPRS International Journal of Geo-Information 3*, 1 (2013), 166–205.

[5] BROOKS, H. The relationship between science and technology. *Research policy 23*, 5 (1994), 477–486.

[6] BUTTENFIELD, B. P., AND MCMASTER, R. B. *Map Generalization: Making rules for knowledge representation*. Longman Scientific & Technical, 1991.

[7] CLARAMUNT, C., ADAMS, B., AND GAHEGAN, M. Geographical information science observatories, theoretical and methodological transitions. *Journal of Interdisciplinary Methodologies and Issues in Sciences 6* (2020).

[8] CLARAMUNT, C., AND STEWART, K. Special issue on spatio-temporal theories and models for environmental, urban and social sciences: where do we stand? *Spatial Cognition & Computation 15*, 2 (2015), 61–67.

[9] ÇÖLTEKIN, A., LOCHHEAD, I., MADDEN, M., CHRISTOPHE, S., DEVAUX, A., PETTIT, C., LOCK, O., SHUKLA, S., HERMAN, L., AND STACHOŇ, Z. Extended reality in spatial sciences: A review of research challenges and future directions. *ISPRS International Journal of Geo-Information 9*, 7 (2020), 439.

[10] COUCLELIS, H. Climbing on a milestone for a better view: Goodchild's 'Geographical Information Science' paper as vantage point and ground for reflection. *International Journal of Geographical Information Science 26*, 12 (2012), 2291–2300.

[11] CRAGLIA, M., GOULD, M., KUHN, W., AND TOPPEN, F. The AGILE research agenda. In *7th ECGI&GIS Workshop* (2001).

[12] DENSHAM, P., AND GOODCHILD, M. Spatial decision support systems: scientific report for the specialist meeting. Tech. rep., NCGIA Technical Report 90, 1990.

[13] DUBE, M. P., AND EGENHOFER, M. J. Surrounds in partitions. In *Proceedings of the 22nd ACM SIGSPATIAL international conference on advances in geographic information systems* (2014), pp. 233–242.

[14] EGENHOFER, M. J., CLARKE, K. C., GAO, S., QUESNOT, T., FRANKLIN, W. R., YUAN, M., AND COLEMAN, D. Contributions of GIScience over the past twenty years. *Advancing geographic information science: The past and the next twenty years* (2016), 9–34.

[15] EGENHOFER, M. J., AND FRANZOSA, R. D. Point-set topological spatial relations. *International Journal of Geographical Information System 5*, 2 (1991), 161–174.

[16] EGENHOFER, M. J., AND MARK, D. M. Naive geography. In *Spatial Information Theory A Theoretical Basis for GIS: International Conference COSIT'95 Semmering, Austria, September 21–23, 1995 Proceedings 2* (1995), Springer, pp. 1–15.

[17] FOTHERINGHAM, S., AND ROGERSON, P. *Spatial analysis and GIS*. CRC Press, 2013.

[18] FRANK, A. U. Qualitative spatial reasoning with cardinal directions. In *Österreichische Artificial-Intelligence-Tagung/Seventh Austrian Conference on Artificial Intelligence: Wien, Austria, 24.–27. September 1991 Proceedings* (1991), Springer, pp. 157–167.

[19] FRANKLIN, R. S., HOULDEN, V., ROBINSON, C., ARRIBAS-BEL, D., DELMELLE, E. C., DEMŠAR, U., MILLER, H. J., AND OÂĂŹSULLIVAN, D. Who counts? gender, gatekeeping, and quantitative human geography. *The Professional Geographer 73*, 1 (2021), 48–61.

[20] GAHEGAN, M. Experiments using context and significance to enhance the reporting capabilities of GIS. In *Spatial Information Theory: A Theoretical Basis for GIS: International Conference COSIT'97 Laurel Highlands, Pennsylvania, USA, October 15–18, 1997 Proceedings 3* (1997), Springer, pp. 485–496.

[21] GOLAY, F., AND NYERGES, T. L. Understanding collaborative use of GIS through social cognition: "Do you see what I see?". *Cognitive aspects of human-computer interaction for geographic information systems* (1995), 287–294.

[22] GOODCHILD, M. F. Geographical information science. *International journal of geographical information systems 6*, 1 (1992), 31–45.

[23] GOODCHILD, M. F. The nature and value of geographic information. *Foundations of Geographic Information Science* (2003), 19–31.

[24] GOODCHILD, M. F. Spatial thinking and the GIS user interface. *Procedia-Social and Behavioral Sciences 21* (2011), 3–9.

[25] GOODCHILD, M. F. A GIScience perspective on the uncertainty of context. *Annals of the American Association of Geographers 108*, 6 (2018), 1476–1481.

[26] GOODCHILD, M. F., EGENHOFER, M. J., KEMP, K. K., MARK, D. M., AND SHEPPARD, E. Introduction to the Varenius project. *International Journal of Geographical Information Science 13*, 8 (1999), 731–745.

[27] GRENON, P., AND SMITH, B. SNAP and SPAN: Towards dynamic spatial ontology. *Spatial cognition and computation 4*, 1 (2004), 69–104.

[28] GUPTILL, S. C., AND MORRISON, J. L. *Elements of spatial data quality*. Elsevier, 2013.

[29] GÜTING, R. H. An introduction to spatial database systems. *the VLDB Journal 3* (1994), 357–399.

[30] JONES, B. F. As science evolves, how can science policy? *Innovation policy and the economy 11*, 1 (2011), 103–131.

[31] KESSLER, C., JANOWICZ, K., AND KAUPPINEN, T. spatial@linkedscience–exploring the research field of GIScience with linked data. In *Geographic Information Science: 7th International Conference, GIScience 2012, Columbus, OH, USA, September 18-21, 2012* (2012), Springer, pp. 102–115.

[32] LANGRAN, G. A review of temporal database research and its use in GIS applications. *International Journal of Geographical Information System 3*, 3 (1989), 215–232.

[33] LIU, X., CHEN, M., CLARAMUNT, C., BATTY, M., KWAN, M.-P., SENOUSI, A. M., CHENG, T., STROBL, J., ARZU, C., WILSON, J., ET AL. Geographic information science in the era of geospatial big data: A cyberspace perspective. *The Innovation 3*, 5 (2022), 100279.

[34] LONGLEY, P. A., BROOKS, S., MACMILLAN, W., AND MCDONNELL, R. *Geocomputation: a primer*. Wiley, 1998.

[35] LÜ, G., BATTY, M., STROBL, J., LIN, H., ZHU, A.-X., AND CHEN, M. Reflections and speculations on the progress in geographic information systems (GIS): a geographic perspective. *International Journal of Geographical Information Science 33*, 2 (2019), 346–367.

[36] MACEACHREN, A. M. Visualizing uncertain information. *Cartographic perspectives*, 13 (1992), 10–19.

[37] MAGUIRE, D. J., GOODCHILD, M. F., AND RHIND, D. W. *Geographical information systems: principles and applications*. Longman scientific & technical, 1991.

[38] MUENCHOW, J., SCHÄFER, S., AND KRÜGER, E. Reviewing qualitative GIS research–toward a wider usage of open-source GIS and reproducible research practices. *Geography Compass 13*, 6 (2019), e12441.

[39] NATIONAL CENTER FOR GEOGRAPHIC INFORMATION AND ANALYSIS. *Short Summaries of Key NCGIA Research Results*. eScholarship, University of California, 1998.

[40] Nittel, S. Introduction to this special issue: geosensor networks. *SIGSPATIAL Special 7*, 2 (2015), 2.

[41] Nittel, S. Real-time sensor data streams. *SIGSPATIAL Special 7*, 2 (2015), 22–28.

[42] Onsrud, H. J., and Reis, R. Law and information policy for spatial databases: a research agenda. *Jurimetrics Journal 35* (1994), 377.

[43] Onsrud, H. J., and Rushton, G. Institutions sharing geographic information. *National Center for Geographic Information and Analysis, Closing Report, Research Initiative 9* (1996).

[44] Parent, C., Spaccapietra, S., and Zimányi, E. *Conceptual modeling for traditional and spatio-temporal applications: The MADS approach*, vol. 3882. Springer, 2006.

[45] Percivall, G. The application of open standards to enhance the interoperability of geoscience information. *International Journal of Digital Earth 3*, S1 (2010), 14–30.

[46] Rahimi, M., Malek, M. R., Claramunt, C., and Le Pors, T. A topology-based graph data model for indoor spatial-social networking. *International Journal of Geographical Information Science 35*, 12 (2021), 2517–2539.

[47] Raubal, M. Cognitive engineering for geographic information science. *Geography Compass 3*, 3 (2009), 1087–1104.

[48] Reitsma, F. Revisiting the 'Is GIScience a science?' debate (or quite possibly scientific gerrymandering). *International Journal of Geographical Information Science 27*, 2 (2013), 211–221.

[49] Timpf, S., Volta, G. S., Pollock, D. W., and Egenhofer, M. J. A conceptual model of wayfinding using multiple levels of abstraction. In *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space: International Conference GISâĂŤFrom Space to Territory: Theories and Methods of Spatio-Temporal Reasoning Pisa, Italy, September 21–23, 1992 Proceedings* (1992), Springer, pp. 348–367.

[50] Tomlinson, R. Computer mapping: an introduction to the use of electronic computers in the storage, compilation and assessment of natural and economic data for the evaluation of marginal lands. In *Proceedings of the National Land Capability Inventory Seminar* (1962).

[51] UN-GGIM. United nations committee of experts on global geospatial information management-working group on marine geospatial information. In *Summary Report of First Expert Meeting of the WGMGI. Busan, Coréia do Sul* (2019).

[52] University Consortium for Geographic Information Science. Research priorities for geographic information science. *Cartography and Geographic Information Systems 23*, 3 (1996), 115–127.

[53] Wachowicz, M., and Chrisman, N. The added value of scientific networking: perspectives from the geoide network members 1998-2012. Tech. rep., Geoide Network, QuÃľbec, Canada, 2012.

[54] WILKINSON, G. A review of current issues in the integration of GIS and remote sensing data. *International Journal of Geographical Information Science 10*, 1 (1996), 85–101.

[55] WILKINSON, M. D., DUMONTIER, M., AALBERSBERG, I. J., APPLETON, G., AXTON, M., BAAK, A., BLOMBERG, N., BOITEN, J.-W., DA SILVA SANTOS, L. B., AND BOURNE, P. E. The FAIR guiding principles for scientific data management and stewardship. *Scientific data 3*, 1 (2016), 1–9.

[56] WOOD, Z. Profiling spatial collectives. In *Research and Development in Intelligent Systems XXX: Incorporating Applications and Innovations in Intelligent Systems XXI Proceedings of AI-2013, The Thirty-third SGAI International Conference on Innovative Techniques and Applications of Artificial Intelligence* (2013), Springer, pp. 95–108.

[57] WORBOYS, M., AND DUCKHAM, M. Qualitative-geometric 'surrounds' relations between disjoint regions. *International Journal of Geographical Information Science 35*, 5 (2021), 1032–1063.

[58] WU, X., DONG, W., WU, L., AND LIU, Y. Research themes of geographical information science during 1991–2020: a retrospective bibliometric analysis. *International Journal of Geographical Information Science* (2022), 1–33.

[59] YANG, C., RASKIN, R., GOODCHILD, M., AND GAHEGAN, M. Geospatial cyberinfrastructure: past, present and future. *Computers, Environment and Urban Systems 34*, 4 (2010), 264–277.

[60] YUAN, M. 30 years of IJGIS: the changing landscape of geographical information science and the road ahead. *International Journal of Geographical Information Science 31*, 3 (2017), 425–434.